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Remnant buried ice in the equatorial regions of Mars: Morphological indicators associated with the Arsia Mons tropical mountain glacier deposits

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ABSTRACT

The fan-shaped deposit (FSD) on the western and northwestern flanks of Arsia Mons is the remnant of tropical mountain glaciers, deposited several tens to hundreds of millions of years ago during periods of high spin-axis obliquity. Previous workers have argued that the Smooth Facies in the FSD contains a core of ancient glacial ice. Here, we find evidence that additional glacial ice remains preserved within several other landforms in the Smooth Facies and Ridged Facies. These include landforms that we interpret as kame and kettle topography on the basis of their distribution, size, and morphologies ranging progressively from knobs to degraded knobs to pits. We argue that some moraines in the Ridged Facies are ice-cored on the basis of their interactions with lava flows and the axial troughs at the crests of some moraines. We also argue that dunes with axial troughs, found in and surrounding the FSD, are the remnants of sediment-covered snow dunes formed by reworking of snow or glacial ice, and that the axial troughs form as tension cracks in the sediment and deepen by sublimation of the underlying ice. Long-term preservation of water ice in equatorial environments is assisted by a meters- to decameters-thick debris cover (lag) formed from sublimation of dirty ice, as well as burial beneath volcanic tephra and aeolian deposits. This ancient ice could contain preserved biosignatures, provide information on Martian climate and atmospheric history, and serve as a resource for human exploration.

1. Introduction

The western and northwestern flanks of the equatorial Tharsis Montes volcanoes were covered by cold based mountain glaciers as recently as 125–220 million years ago (Kadish et al., 2014), as evidenced by the morphology, stratigraphic relationships, and spatial distribution of landforms in the fan-shaped deposits (FSDs) on each volcano (Williams, 1978; Lucchitta, 1981; Head and Marchant, 2003; Shean et al., 2005, 2007; Kadish et al., 2008a; Scanlon et al., 2014, 2015). This geomorphologic evidence is bolstered by climate and glacial flow models that predict snow accumulation and ice flow in those regions during periods of high spin-axis obliquity (Forget et al., 2006; Fastook et al., 2008). Following a return to lower obliquity and the resulting change in climate conditions, the glacial ice ablated and returned to higher latitudes and the poles (Head et al., 2003, 2006a, b), leaving the Tharsis Montes fan-shaped deposits. A major question is whether buried ice still remains in some of these deposits, despite the peak insolation and relatively high temperatures expected at equatorial latitudes now and in the recent past (e.g. Mellon and Jakosky, 1993, 1995; Mellon et al.,1997).

Morphological evidence for buried present-day water ice in the tropics and mid-latitudes of Mars can be generally divided into three categories, as follows:

(1) Surface textures attributed to partial removal of ice. These include sublimation pits or hollows (e.g. Mustard et al., 2001; Mangold, 2003; Kadish et al., 2008b), scalloped depressions (e.g. Lefort et al., 2010; Séjourné et al., 2011), sublimation polygons and “brain terrain” (e.g. Levy et al., 2008, 2009), and other dissected terrains such as “basketball texture” (e.g. Head et al., 2003) or “ridge and valley texture” (Pierce and Crown, 2003; Chuang and Crown, 2005).
(2) Topographic profile. Lobate debris aprons (LDA), lineated valley fill (LVF), and concentric crater fill (CCF) on Mars have been interpreted as debris-covered glaciers with remnant ice cores, partially on the basis of the glacier-like convex upward topographic profiles at their margins (e.g. Mangold and Allemand,

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2001; Holt et al., 2008; Head et al., 2010; Levy et al., 2010).

(3) Unusual crater morphologies. “Ring-mold” craters (Kress and Head, 2008) have been interpreted as resulting from impacts into buried ice on the basis of their size-frequency distribution, which is consistent with smaller impacts not penetrating far enough to reach the buried ice; their annular moats, which are a characteristic feature of experimental impacts into ice-rich substrates; and the apparent degradation sequence represented by the range of ring-mold crater morphologies (Pedersen and Head, 2010). Pedestal craters, perched craters and excess ejecta craters (e.g. Kadish and Head, 2011) are interpreted to form by impacts into an ice-rich substrate, where either the impact process itself (in the case of pedestal craters) or the excavation of rocky material from underneath the ice-rich layer (in the case of perched and excess ejecta craters) creates a surface deposit that protects the ice-rich material immediately surrounding the crater against sublimation.

Remnant ice at equatorial latitudes on Mars is of potential interest as an exploration target for several reasons. Gas bubbles preserved in terrestrial ancient ice can be used to develop time series for the molecular and isotopic composition of the atmosphere (e.g. Alley, 2000; Lüthi et al., 2008; Kobashi et al., 2011; Capron et al., 2012; Bazin et al., 2013; Rhodes et al., 2013). If a reliable chronology and isotopic baseline could be developed for Mars, then these data would be particularly useful, as they could potentially help constrain orbital parameter variations prior to those that can be calculated a priori (Laskar et al., 2004). The Arsia Mons FSD has been suggested as a well-suited target for future human missions (e.g. Levine et al., 2010), and ice deposits within the FSD would offer a potential water and fuel resource for human exploration (e.g. Sridhar et al., 2004).

At ~166,000 km^2 in area, the Arsia Mons FSD (Head and Marchant, 2003; Shean et al., 2005, 2007; Scanlon et al., 2014, 2015) is the largest of the Tharsis Montes FSDs (Fig. 1). Crater counts indicate that the FSD has been in place for ~210 Ma (Kadish et al., 2014). The Smooth Facies, one of the geomorphologic units in the FSDs (Zimbelman and Edgett, 1992; Scott and Zimbelman, 1995), has been interpreted as remnant alpine-like debris-covered glaciers (Head and Marchant, 2003). Likewise, Shean et al. (2007) suggest that lineated debris displaying concentric ridges and partially filling tectonic graben higher up the volcanic edifice is also cored by glacier ice. The convex topography of these deposits (Shean et al., 2007), as well as the morphologic indicators of active flow (Head and Marchant, 2003; Marchant and Head, 2007) and the unique morphology of superimposed craters (Head and Weiss, 2014), suggest that buried ice 100–300 m thick may still be present at depth. In this contribution, we expand the search for buried ice and review several other classes of landforms in the FSD that have not been previously described, and whose morphology indicates that remnant ice may still be present.

2. Data and methods

Images in this study are from the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX), with ~5 m per pixel resolution (Malin et al., 2007), augmented with images from the High Resolution Stereo Camera (HRSC) at 10–30 m per pixel resolution (Neukum and Jaumann, 2004). Topographic data is from the Mars Orbital Laser Altimeter (MOLA) at ~463 m per pixel resolution (Zuber et al., 1992; Smith et al., 1999) and, where available, HRSC-derived Digital Elevation Maps (DEMs) with ~100 m per pixel resolution (Dumke et al., 2008). Contour maps were created using the Spatial Analyst toolkit in ArcMap 10.0.

3. Landforms interpreted to be indicative of remnant ice

On Earth, remnant patches of buried glacier ice may occur wherever overlying debris is sufficiently thick to retard ice ablation. Examples include ice-cored moraines, detached blocks of ice buried beneath proglacial sediment, and remnant, stagnant ice buried beneath thick sublimation till (e.g. Hambrey, 1984; Marchant et al., 2002; Evans, 2009; Swanger et al., 2010; Irvine-Fynn et al., 2011; Lacelle et al., 2011; Monnier et al., 2008).

In the coldest and driest region of the Mars-like Antarctic Dry Valleys, $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ ages of volcanic ash deposits indicate that underlying remnant glacier ice has been preserved for millions of years (Sugden et al., 1995; Marchant et al., 2002; Kowalewski et al., 2006, 2012). We propose that the morphology of several landforms adjacent to Arsia Mons suggests that ice millions of years old is also present in the Arsia Mons FSD.

3.1. *Pit-and-knob terrain*

Near the northern edge of the FSD is a field of mounds (“knobs”) and shallow topographic depressions (“pits”; Figs. 1 and 2). Each knob is up to 1 km in diameter. Interspersed among the knobs are pits of similar size and shape to the knobs (Figs. 2 and 3). The pits and knobs are generally aligned, and the lines on which they fall are concentric with the outline of the Smooth Facies (Figs. 1 and 2) and with drop moraines left by a relatively young debris-covered glacier extending from a nearby graben (Shean et al., 2007). Many of the smaller knobs are surrounded by shallow annular depressions (“moats”), and some pits have what appear to be degraded knobs at their centers (Fig. 3). We propose that the pit-and-knob terrain is ice-cored and that the landforms represent a progression in which gradual loss of ice via sublimation causes topographic inversion, with knobs becoming moated knobs, then pits with degraded knobs, and finally pits (Fig. 4).

In terrestrial zones of rapid ice retreat, blocks of ice detached from the retreating edge of a glacier may become partially buried beneath glacial outwash (Thwaites, 1926; Price, 1969; Fay, 2002; Russell et al., 2010; Evans, 2011; Knight, 2012). When the blocks eventually melt, they leave “kettle holes” where the blocks formerly stood. Fields of pits interpreted as kettle holes have been observed on Mars in the circumpolar Dorsa Argentea Formation (Dickson and Head, 2006). The morphological evidence suggests that the Arsia FSD pit-and-knob terrain may have resulted from backwasting of ice in the Smooth Facies and subsequent burial of the isolated ice blocks, analogous to the formation of terrestrial kettled outwash plains (Fig. 5). This evidence comprises (1) the similarity in size and shape between the pits and knobs, (2) the genetic relationship implied by the presence of knobs with moats, and (3) the co-alignment of the pits and knobs with the outline of the Smooth Facies and with lineations in the Smooth Facies (Fig. 6). Because of the cold Amazonian climate, however, the ice blocks would have sublimed rather than melted to leave the pits behind, and the sediment that embayed them would have been volcanic tephra, englacial debris, or aeolian sediment, rather than glacial outwash as in terrestrial kettled plains. The concentric fractures surrounding many of the pits (Fig. 3) suggest that near-surface sediment, possibly cemented by pore ice, moved downslope toward pit centers as underlying ice sublimed; similar patterns can be observed on Earth where the removal of blocks of buried ice causes concentric fractures to form in the overlying sediment (Sanford, 1959; Dickson and Head, 2006). This sediment cover could have armored some of the ice blocks against further sublimation, leaving the present-day knobs.

Alternatively, the pit-and-knob terrain may have formed in a manner analogous to terrestrial “controlled moraine” (e.g. Evans, 2009; Szuman and Kasprzak, 2010; Bennett and Evans, 2012; Lakeman