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Formation and mantling ages of lobate debris aprons on Mars: Insights from categorized crater counts

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ABSTRACT

Lobate debris aprons in the Martian mid-latitudes offer important insights into the history of the Martian climate and the role of volatiles in Martian geologic activity. Here we present the results of counts of small impact craters, categorized by morphology, on debris aprons in the Deuteronilus Mensae region and the area east of Hellas basin. Mars Reconnaissance Orbiter (MRO) ConTeXt Camera (CTX) images were used to document crater populations on the apron surfaces. Each crater was assessed and categorized according to its morphological characteristics (fresh, degraded, or filled). Fresh and most degraded craters likely superpose recent mantling deposits, whereas filled craters contain mantling deposits and thus indicate a minimum formation age for the apron (i.e., the age since stabilization of the debris apron surface following some modification but prior to mantling). Size-frequency distributions (SFDs) were compiled using established methodologies and plotted to assess their fit to the isochrons. The range or ranges in crater diameter over which each distribution paralleled the isochrons was determined by visual inspection, and general age constraints were noted from SFDs for all craters on a given surface and from each morphological class. The diameter range of each SFD segment observed to parallel an isochron was then input into the Craterstats2 analysis tool to calculate specific age estimates. The aprons were assessed both individually and as regional populations, which improved interpretation of the results and demonstrated the value and limitations of both approaches. The categorized counts reveal three groups of ages: (a) filled impact craters at larger diameters ($>\sim$500 m) typically show the oldest ages, between $\sim$300 Ma and 1 Ga, (b) smaller diameter filled and degraded craters reveal ages of resurfacing events between $\sim$10 Ma and 300 Ma, and (c) fresh crater populations ($<\sim$100 m diameter) indicate mantling deposits of less than $\sim$10 Ma in age. These results indicate that the lobate debris apron populations formed (or their surfaces became stable) in the Early to Middle Amazonian Epochs, and were subsequently subjected to complex degradation by erosion and sublimation and/or melting of contained ice, culminating in episodes of deposition of ice-rich mantles in the Late Amazonian Epoch.

1. Introduction

The history of water on Mars is a fundamental topic that has driven exploration of the Red Planet. Previous and current spacecraft missions have shown diversity in the distribution and abundance of volatiles on the Martian surface. Both liquid water and water–ice have likely had significant roles in shaping Martian landscapes, with specific landforms and deposits interpreted to result from fluvial, lacustrine, periglacial, and glacial processes (e.g., Baker et al., 1991; Kargel and Strom, 1992; Scott et al., 1995; Carr, 1996; Baker, 2001; Malin and Edgett, 2001; Head et al., 2003, 2005). Water or ice has also influenced mass-wasting processes, volcanism, and degradation of surficial materials (e.g., Lucchitta, 1987; Squyres et al., 1987; Crown et al., 1992; Mangold, 2003; Milliken et al., 2003; Tanaka et al., 2005). Geomorphic indicators of ice-related flow, such as lobate debris aprons, have been identified and described (e.g., Carr and Schaber, 1977; Squyres and Carr, 1986; Mangold, 2003; Pierce and Crown, 2003), constraints have been developed for the distribution of subsurface ice (e.g., Squyres et al., 1992; Clifford, 1993; Mellon and Jakosky, 1995; Barlow and Perez, 2003), and spacecraft observations have been used to map the variability of ice content in the regolith (e.g., Boynton et al., 2002).

The Martian mid-latitudes are of high scientific interest as they are regions where the effects of ice on the surface geology are prominent (e.g., Malin and Edgett, 2000; Mustard et al., 2001; Christensen, 2003; Head et al., 2003; Berman et al., 2005, 2009). Recent research has focused on descriptions of small-scale landforms observed in high-resolution images, including gullies, arcuate ridges, and viscous flow features, as well as widespread ice-cemented mantling deposits (Christensen, 2003) interpreted to be relicts from

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geologically recent (i.e., Late Amazonian), obliquity-driven ice ages (e.g., Mustard et al., 2001; Head et al., 2006a; Madeleine et al., 2009, 2014). Extensive mid-latitude glaciation has been proposed on the basis of analyses of these latitude-dependent mantles (Dickson et al., 2012), debris aprons and lineated valley fill in eastern Hellas (Head et al., 2005) and in the fretted terrain along the dichotomy boundary (Head et al., 2006a,b; Levy et al., 2007; Dickson et al., 2008; Morgan et al., 2009; Baker et al., 2010; Dickson et al., 2012), rock glaciers at the base of Olympus Mons (Head and Marchant, 2003), and fan-shaped, cold-based glacial deposits on the northwest flanks of the Tharsis volcanoes (Shean et al., 2007; Fastook et al., 2008). Subsurface radar sounding data suggest that lobate debris aprons in the eastern Hellas and Deuteronilus Mensae regions are composed predominantly of water ice (Holt et al., 2008; Plaut et al., 2009, 2010). From analyses of image, radar, and topographic datasets of Mars coupled with modeling studies of the Martian atmosphere, a new story is emerging regarding the geology of Mars in the Amazonian Period.

The studies described above have provided a framework for further in-depth analyses of the specific style(s), magnitude(s), and timing of potential glacial activity on Mars. Although the use of small craters revealed in high-resolution datasets has the potential to reveal new information about apron geology and age, studies to-date have not necessarily used the same techniques (i.e., types of craters, crater diameter range) to determine age information. In conjunction with mapping, morphologic, and textural analyses of the surfaces of lobate debris aprons (Chuang and Crown, 2005a,b, 2006, 2009; Chuang et al., 2013; Joseph et al., 2013), we have counted and categorized the morphologies of craters on apron surfaces in order to constrain their geologic histories. By examining the size-frequency distributions (SFDs) of craters on apron surfaces by morphologic category, we are able to discern the crater retention ages and thus minimum formation ages for individual debris aprons (i.e., the age since stabilization, or cessation/slowing of apron degradation, ice deposition, and/or flow of the apron, after which craters accumulate and are preserved) as well as ages for subsequent episodes of mantling and erosional modification.

Our approach utilizes analyses of crater SFDs coupled with morphologic categorization of craters on individual debris aprons to answer the following questions: (1) What are the ages and range in ages of Martian debris aprons, both within a given apron population and between different populations? Viking-based analyses of lobate debris aprons (e.g., Crown et al., 1992) indicated ages in the Early to Middle Amazonian, whereas more recent studies suggest younger, Late Amazonian ages (e.g., Head et al., 2005). (2) What is the history of surface mantling and degradation of apron deposits and are there spatial patterns that can be linked to geologically young obliquity-driven resurfacing? Studies of apron surface textures (e.g., Chuang and Crown, 2005a, 2006) suggest a similar suite of textures but much better preservation of mantling materials in the north relative to the south mid-latitudes. (3) What are the temporal relationships between the apparently older apron deposits in a given region and younger mantling deposits? What is the duration of glacial activity and is there clear evidence for discrete episodes or a progression from one style of ice-driven process to another? Our current approach is complementary to global or large-scale analyses of lobate debris apron ages and provides a check on theories of contemporaneous widespread glaciation on Mars (e.g., Head et al., 2003; Fasset et al., 2014). Our results show evidence for debris apron formation in the eastern Hellas and Deuteronilus Mensae regions in the Early to Middle Amazonian Epochs followed by a complex history of degradation by erosion (primarily by eolian activity) and sublimation and/or melting of contained ice (Mangold, 2003; Pierce and Crown, 2003; Chuang and Crown, 2005a,b), culminating in the deposition of ice-rich mantling deposits on apron surfaces in the Late Amazonian Epoch.

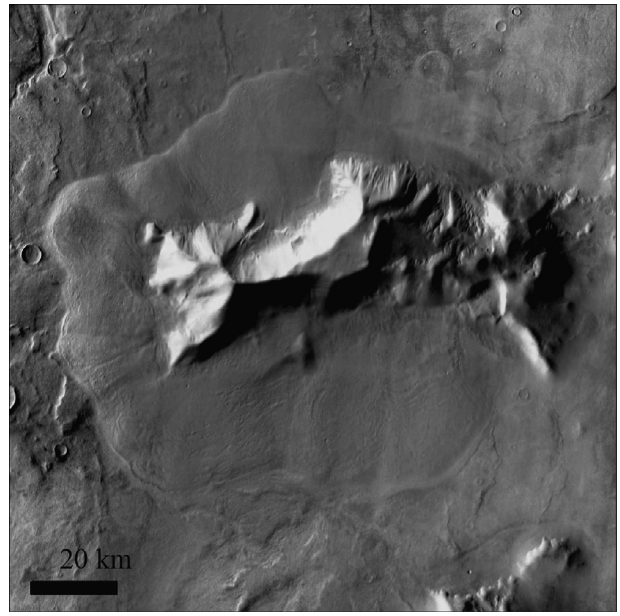

Fig. 1. Martian debris apron surrounding rugged highland massif Euripus Mons in the eastern Hellas region (east Hellas Apron 1), centered at 45°S, 105°E. THEMIS IR daytime 512 pixel/deg mosaic.

1.1. Geologic setting

From analyses of Viking Orbiter images, lobate debris aprons (Fig. 1), lineated valley fill (LVF), and concentric crater fill (CCF) are known as prominent geomorphic indicators of ice on Mars (e.g., Squyres, 1978, 1979). These features are most commonly found in the fretted terrain of the northern hemisphere (including Deuteronilus Mensae, Protonilus Mensae, and Nilosyrtis Mensae) and in areas associated with the Argyre and Hellas impact basins in the southern hemisphere, with smaller occurrences in the Tempe/Mareotis and Phlegra Montes regions (Sharp, 1973; Carr and Schaber, 1977; Squyres, 1978, 1979, 1989; Lucchitta, 1981, 1984; Kochel and Peake, 1984; Squyres and Carr, 1986; Crown et al., 1992). The climatic implications of their interesting flow-like morphologies as well as their geographic distribution in the Martian mid-latitudes were apparent to early researchers (e.g., Squyres, 1979). Climate modeling shows a specific volatile accumulation zone in eastern Hellas that directly corresponds to a concentration of these features (Colaprete et al., 2004; Forget et al., 2006).

Studies based on Viking Orbiter images suggested that lobate debris aprons and lineated valley fill formed by flow of rock and ice mixtures, with latitudinal control initially attributed to seasonal frost deposition (Squyres, 1978, 1979, 1989; Lucchitta, 1984; Squyres and Carr, 1986; Crown et al., 1992, 2005). Debris aprons extend from massifs, mesas, canyon walls, and crater rims. Aprons frequently form complexes, in which multiple debris masses or lobes have coalesced to form a composite feature, with variable preservation of individual debris lobes (Pierce and Crown, 2003; Chuang and Crown, 2005a, 2006; Crown et al., 2006; van Gasselt et al., 2007). Detailed studies of the Deuteronilus Mensae (Mangold and Allemand, 2001; Mangold, 2003; Chuang and Crown, 2005b; Li et al., 2005), Tempe/Mareotis (Chuang and Crown, 2005a), and eastern Hellas (Crown et al., 2002, 2003, 2006; Pierce and Crown, 2003) regions have incorporated high-resolution image datasets (primarily MOC) and MOLA topography into apron analyses. Apron planform shapes, surface lineation patterns, and topographic profiles suggest viscous flow/deformation of apron masses, and surface textures indicate a complex history of surface mantling and subsequent degradation by aeolian processes and melting and/or sublimation of contained ice (Chuang and Crown,