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Decameter-scale pedestal craters in the tropics of Mars: Evidence for the recent presence of very young regional ice deposits in Tharsis

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A B S T R A C T

Global climate models predict that ice will be deposited in tropical regions during obliquity excursions from the current mean obliquity of ~25° to ~35°, but no geological evidence for such deposits has been reported. We document the presence of very small (decameter scale) pedestal craters in the tropics of Mars (the Daedalia Planum–Tharsis region) that are superposed on an impact crater dated to ~12.5 Ma ago. The characteristics, abundance, and distribution of these small pedestal craters provide geological evidence that meters-thick ice accumulations existed in the tropical Tharsis region of Mars in the last few million years when mean obliquity was ~35° (~5–15 Ma) before it transitioned to a mean of ~25° (~0–3 Ma). A reconnaissance survey reveals similar small pedestal crater examples superposed on the older Amazonian Arsia Mons tropical mountain glacier deposit, suggesting that ice can accumulate in these tropical regions without initiating large-scale glacial conditions. These results support the predictions of general circulation models that ice can migrate to the equatorial regions during periods of moderate obliquity and then serve as a source for mid-latitude deposits.

1. Introduction

Currently, Mars is a hyperarid, hypothermal desert and the largest reservoir of surficial water ice on Mars resides at the poles. It is known, however, that variations in spin-axis/orbital parameters (obliquity, eccentricity, and precession) (Laskar et al., 2004) can cause mobilization of water ice, transport in the atmosphere, and redeposition at lower latitudes. Evidence has been presented that a recent, meters-thick, ice-rich mantle was emplaced from the poles down to about 30° N and S latitude in the last several million years during an "ice age," and that it has been undergoing modification in the 30°–50° latitude region in the last few hundred thousand years, as Mars' obliquity amplitude decreased and ice returned to the poles (Head et al., 2003). During earlier periods of higher obliquity (mean obliquity of ~35°) in the Late Amazonian, ice was deposited in the mid-latitudes, and formed widespread valley and plateau glacial land systems (Head et al., 2010; Madeleine et al., 2009). Somewhat earlier in the Amazonian, during periods when the mean obliquity was thought to have been ~45°, vast tropical mountain glaciers formed on the flanks of the major Tharsis volcanoes (Head and Marchant, 2003; Kadish et al., 2008a; Milkovich et al., 2006; Shean et al., 2005, 2007).

Unknown, however, has been the exact pathway and residence time of volatiles during transitions from one regime to another. Geological evidence, for example, has suggested that the higher amplitude obliquity of the past few million years caused ice stability conditions to migrate equatorward, and resulted in the deposition of a dust–ice mixture as a broad circum-polar high latitude mantle during periods of high obliquity (Head et al., 2003; Kreslavsky and Head, 2000; Mustard et al., 2001). In contrast, atmospheric general circulation models suggest that during periods of higher obliquity (mean obliquity ~25° and high amplitude variation) ice migrates directly to equatorial regions and then works its way back to the mid to high latitudes to be deposited in a more stable environment (Levrard et al., 2004). In a similar manner, mid-latitude glaciation is best explained in Mars general circulation models if mean obliquity is ~35° and the source of ice is at the equator, not at the poles (Madeleine et al., 2009). However, direct evidence of the presence of large quantities of ice that could serve as equatorial sources in the recent geologic past has not yet been documented. Finally, at mean obliquity of ~45°, ice is predicted to be deposited directly in the equatorial regions and to remain there as long as these conditions prevail (Forget et al., 2006), accumulating sufficient ice to produce the observed tropical mountain glaciers (e.g., Head and Marchant, 2003).

How can the differences between the equatorial ice predicted to occur by the models, and the lack of geological observations for the presence of such deposits, be reconciled? One difficulty recognized by both geologists and climate modelers is that ice mantles and glacial deposits are destined to be cold-based in the hypothermal, hyperarid Mars environment (Marchant and Head, 2007). Cold-based ice deposited at high polar latitudes on Earth and over much of Mars does not erode its substrate in any substantial manner (Marchant and Head, 2007) and

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thus contains little to no debris unless such debris is deposited from the atmosphere or falls on the ice surface from adjacent high topography exposing cliffs of rock and debris. Thus, for typical cold-based deposits without debris, when the climate changes from mean accumulation to mean ice loss, the ice deposits are destined to sublimate, returning to the atmosphere and leaving no geological record. On the other hand, if the cold-based ice contains debris from adjacent cliffs (Head et al., 2010; Marchant et al., 2002), tephra from adjacent volcanoes (Shean et al., 2007; Wilson and Head, 2009), atmospheric dust co-deposited with ice (Head et al., 2003), or is armored by processes related to impact cratering (Kadish et al., 2008b; Schaefer et al., 2011), then evidence of the presence of preexisting cold-based ice can be preserved.

One well-documented example of this type of preservation of evidence for cold-based ice occurs in the form of pedestal craters, a unique crater form that was first identified in Mariner 9 data (McCauley, 1973). Initially pedestal craters were thought to result from eolian deflation of fine-grained intercrater material surrounding armored pedestals (Arvidson et al., 1976; McCauley, 1973). More recent studies have favored impact craters that formed in ice-rich substrates in conjunction with armoring that inhibits sublimation for higher latitude pedestal craters (e.g., Kadish et al., 2008b, 2009, 2010a; Nunes et al., 2011; Wrobel et al., 2006). The ice rich substrate in which an impact crater formed has subsequently eroded in the region, leaving a crater perched on a plateau or mesa-like pedestal of material that terminates at an outward facing scarp located up to several crater radii from the rim crest (Barlow et al., 2000). Formation of pedestal craters requires an armoring mechanism induced by, or related to, the impact event that improves the preservation potential of the impact substrate in the immediate vicinity of the crater relative to unperturbed areas. Both pedestal substrates (material composition) and armoring mechanisms have been the subject of extensive investigation (e.g., Barlow, 2006; Boyce et al., 2008; Head and Roth, 1976; Mouginis-Mark, 1987; Osinski, 2006; Schultz and Mustard, 2004). In summary, following crater formation in the ice-rich substrate, when climate conditions changed sufficiently to cause regional ice loss, the intervening ice deposits between pedestal craters disappeared, but the armoring protected the ice in the substrate around the crater, leaving the pedestal crater as evidence of the presence and thickness of the ice deposit.

During an analysis of the nature of very young impact craters (Schon and Head, 2011) in relation to the latitude-dependent ice-rich mantle (Head et al., 2003), we discovered a population of very small (decameter-sized) pedestal craters in the tropics of Mars, superposed on ejecta from a 5.3-km diameter crater that formed about 12–13 Ma ago. While km-scale mid-latitude pedestal craters are likely to have formed over Amazonian climate epochs of ~100 Myr duration (Kadish et al., 2009), because of their substantially smaller size, the newly observed pedestal craters examined here are sensitive to meters-scale substrates (now substantially removed) that are of keen interest because of their potential relation to late Amazonian climate conditions and volatile transport pathways. Here we present evidence that these small pedestal craters formed when a meters-thick layer of ice was present in the tropics of Mars in the last few million years. These features provide the first observational evidence that an ice reservoir existed in the tropics in the very recent geological history of Mars.

2. Observations

In the Daedalia Planum region of Mars (23° S, 230° E) on the Tharsis rise (Fig. 1), decameter-scale pedestal craters are observed superposed on the ejecta deposit of a recent 5.3-km diameter crater (Fig. 2). These features (Fig. 3) are morphologically similar to larger pedestal craters, but occur at a low-latitude location that is significantly equatorward of typical higher-latitude pedestal craters (poleward of ~40° S). Commensurate with their smaller diameters, these pedestal craters have much thinner pedestals.

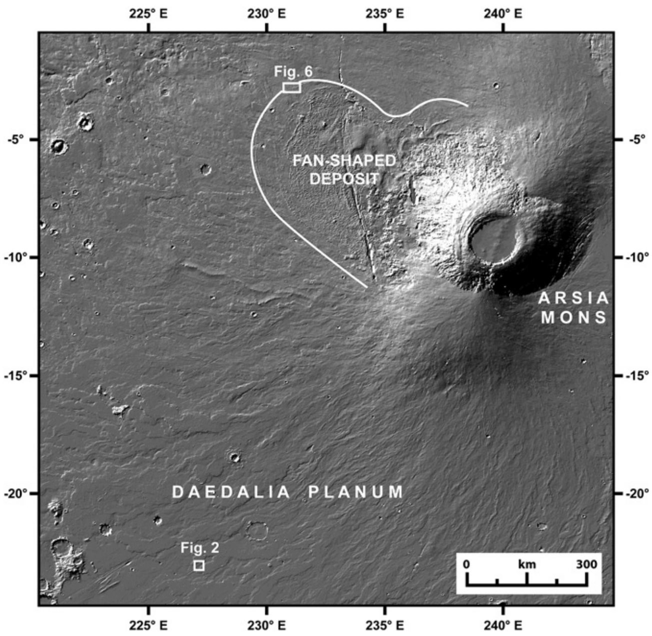

Fig. 1. The Arsia Mons and Daedalia Planum region. The northwest flank of Arsia Mons hosts a ~166,000-km^2 fan shaped deposit interpreted as evidence of cold-based mountain glaciers. Daedalia Planum is an Amazonian volcanic plain on the southwest side of the Tharsis rise; lavas are derived from Arsia Mons.

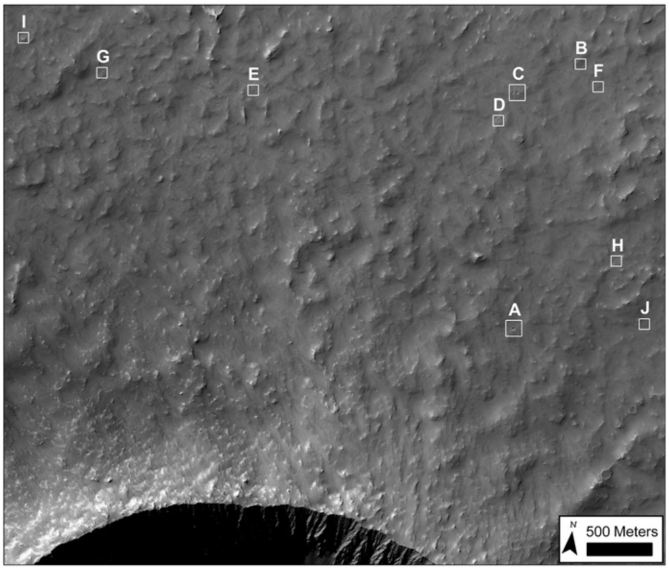

Fig. 2. The ejecta-deposit of a recent 5.3 km-diameter impact crater (23° S, 230° E) (rim crest visible at bottom) underlies decameter-scale pedestal craters observed in the Daedalia Planum region. The locations of pedestal craters shown in Fig. 3 are labeled here with corresponding letters. Portion of HiRISE: PSP_007735_1570.

2.1. Decameter-scale pedestal craters

Unambiguous examples of decameter-scale pedestal craters (Figs. 2 and 3) are observed ranging in diameter from 7.9 m to 29.5 m with pedestals extending from 1.9 to 3.2 crater radii beyond the rim crest (Table 1). Shadow measurements were used to estimate crater depths and pedestal thicknesses (Table 1). Given a pedestal thickness of one to several meters, the crater depths (1.6–4.6 m) suggest that these craters have excavated through the pedestal substrate and into the underlying material. Depth-to-diameter ratios (Table 1) are consistent with the typical value of ~0.20 for simple craters on Mars (Garvin et al., 2003; Strom et al., 1992). Pedestal to crater radius