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The formation of infilled craters on Mars: Evidence for widespread impact induced decompression of the early martian mantle?

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A B S T R A C T

Flat-floored craters have long been recognized on Mars with early work hypothesizing a sedimentary origin. More recently, high-resolution thermal inertia measurements show that these craters contain some of the rockiest materials on the planet, inconsistent with poorly consolidated sedimentary materials. In this study, the distribution, physical properties (morphology and thermal inertia), and composition of these craters are thoroughly investigated over the entire planet. The majority of the $\sim$2800 rocky crater floors identified are concentrated in the low albedo (0.1–0.17), cratered southern highlands. These craters were infilled at $\sim$3.5 Ga and are associated with the highest thermal inertia values and some of the most mafic materials identified on the planet. Although several processes may have led to the formation of the crater floors, the most likely scenario is volcanic infilling through fractures created by the impact event. The primitive magma source directly results from decompression melting of the martian mantle by the removal of the crustal material excavated by the impactor. Volcanic infilling of craters by decompression melting appears to only have occurred in early martian history when the lithosphere was still relatively thin and the thermal gradient was high. This process was widespread and responsible for the eruption of significant volumes of primitive material, inside and likely outside of craters. Impact induced decompression melting of the martian mantle accounts for the unusual infilling of martian craters and is a widespread planetary process that has gone previously undocumented.

1. Introduction

Deeply infilled craters were first observed by Mariner 4 in 1965 and have remained an enigma ever since. Various processes to fill martian craters have been proposed, including aeolian sedimentation (e.g. Arvidson, 1974; Christensen, 1983; McDowell and Hamilton, 2007), lacustrine sedimentation (e.g. Newsom et al., 1996; Cabrol and Grin, 1999; Fassett and Head, 2005; Pondrelli et al., 2005) and impact processes such as impact melt ponding or volcanism (e.g. Smrekar and Pieters, 1985; Wilhelms et al., 1987). However, these explanations appear inconsistent with other observations that show craters nearby which are not infilled and surrounding terrains that are typically unmantled. We investigate the physical and compositional properties of the crater-filling materials and propose that a different process – impact excavation induced decompression melting of the martian mantle – is responsible for the intra-crater materials as well as extensive volcanic materials of the inter-crater plains.

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2. Background

High-thermal inertia surfaces (defined for our purposes here as >1200 J K^{-1} m^{-2} $s^{-1/2}$), interpreted as exposed bedrock, have been characterized and mapped globally on Mars between 75°S and 75°N (Edwards et al., 2009) using Thermal Emission Imaging System (THEMIS, Christensen et al., 2004) nighttime infrared data. Edwards et al. (2009) identified three distinct morphologies associated with bedrock surfaces, including: (1) valley and crater walls on steep slopes, (2) flat crater floor surfaces with adjacent lower thermal inertia crater walls, and (3) plains surfaces not related to any major topographic feature that typically have wind scouring morphologies, such as rough and pitted textures. The distribution of these features suggests several factors control the exposure, creation, and destruction of bedrock on Mars, including periglacial processes and dust mantling (Edwards et al., 2009). There are many locations on the martian surface that meet conditions where bedrock is expected to occur yet is not observed, leading to the possibility that large-scale crustal processing, reworking, and/or mantling has destroyed or masked a majority of the bedrock on Mars (Edwards et al., 2009). However, effusive lavas that form in place rocky material may not be the dominant form of volcanic deposits observed on Mars. Instead, ancient martian volcanic materials may be primarily composed of primary or reworked volcanic ash (Bandfield et al., 2013).

High-thermal inertia, flat crater floors (Edwards et al., 2009), were previously identified using Viking Infrared Thermal Mapper (IRTM) data (Christensen, 1983) and Mariner 9 visible imaging data (Arvidson, 1974). These craters were originally characterized by their elevated thermal inertia, flat floors, lack of central peaks, and low albedo splotches occurring on the downwind side of the crater (Arvidson, 1974; Christensen, 1983). The definitive characteristics of these craters identified in this study include several fundamental and unique properties not common to other martian impact craters: (1) a flat-floor with no discernable central peak, (2) a rough, pitted meter scale morphology and aeolian materials infilling topographic lows, (3) elevated thermal inertia associated with the crater floor (as compared to the surrounding terrain and crater walls), and (4) extensive post-impact modification, with shallow sloped walls, little-to-no visible ejecta material, and occasional gullies and impact craters on both the walls and floor (Edwards et al., 2009).

The original mechanism proposed for the infilling of these craters was largely considered to be aeolian (Arvidson, 1974; Christensen, 1983). However, visible images and high-thermal inertia values suggest that these deposits are not mobile sediment or dune forms, but are instead in-place rocky material (Edwards et al., 2009). Edwards et al. (2009) proposed that these craters were filled with lithified sediment or with volcanic materials. Similar flat-floored craters have been identified on the Moon and may have formed by the infilling of impact melt or through volcanism (e.g. Schultz, 1976; Smrekar and Pieters, 1985; Wilhelms et al., 1987; Jozwiak et al., 2012). However, on Mars, no evidence for flow features (commonly associated with impact melt on the Moon) has been identified in association with this crater type.

In this work, approximately 2800 flat-floored, high-thermal inertia craters have been identified; we address several fundamental questions regarding their origin: (1) What is the geologic origin of the high-thermal inertia crater floor material (e.g. sedimentary, volcanic, impact melt)? (2) What geologic process or processes are responsible for the emplacement of these materials? and (3) What does the spatial and temporal distribution of flat-floored craters indicate about the planetary evolution of Mars?

Although portions of the southern cratered highlands that contain many flat-floored craters (e.g. Mare Serpentis (Rogers et al., 2009) and Tyrrhena and Iapygia Terrae (Rogers and Fergason, 2011)) have been characterized in detail, no study to date has specifically focused on the thermophysical and compositional properties of flat-floored craters over the entire planet.

Detailed compositional studies of isolated regions (e.g. Hamilton and Christensen, 2005; Rogers et al., 2005, 2009; Mustard et al., 2007; Edwards et al., 2008; Tornabene et al., 2008; Ehlmann et al., 2009; Rogers and Fergason, 2011; Wray et al., 2011) provide important details of regional geologic processes on Mars. Global-scale studies, such as this work, have the unique ability to alter the current understanding of planetary evolution and identify large-scale planetary wide processes. In this study, we describe the composition of all infilled craters on Mars that have flat-floors, no central peak, and elevated thermal inertia as compared to the surrounding terrain following techniques similar to those used in other studies (e.g. Bandfield, 2002; Rogers et al., 2005, 2009; Rogers and Christensen, 2007; Rogers and Fergason, 2011). This work relies heavily on Thermal Emission Spectrometer (TES, Christensen, 1999), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM, Murchie et al., 2007), and THEMIS spectral data in combination with THEMIS thermal inertia data (Fergason et al., 2006a) and crater age dates (Neukum and Wise, 1976; Neukum and Hiller, 1981; Hartmann and Neukum, 2001; Ivanov, 2001; Neukum et al., 2001) with the aim of constraining the process or processes responsible for the formation of high-thermal inertia, flat-floored craters on Mars.

3. Data and methods

3.1. Introduction

In this section, we provide a detailed description of each type of data used from each individual instrument (e.g. TES, THEMIS, etc.) that are grouped by measurement type. We have chosen this method, as multiple instruments and techniques were combined to quantitatively assess the compositional and physical characteristics of the crater floors under examination. Furthermore, we provide detailed discussions of the initial crater selection criteria, crater counting techniques, and methods by which datasets were compared and combined globally.

3.2. Crater selection criteria

The morphologic and thermophysical criteria used to initially identify infilled craters were: (1) higher-thermal inertia inside the crater than the surrounding terrain and crater walls, (2) relatively flat-floors with no identifiable visible central peak, (3) degraded rims with highly eroded or non-existent ejecta deposits, and (4) no other identifiable source for the high-thermal inertia material (e.g. volcanic centers, and sedimentary mounds, etc.).

In order to map the global distribution of craters with these characteristics, THEMIS daytime and nighttime relative temperature mosaics (Edwards et al., 2011) were used to assess the morphology and qualitatively examine the thermal inertia differences between the crater floors and the surrounding terrain (Fig. 1). While the THEMIS global mosaics only map the relative temperature, as they are normalized for season, atmospheric conditions, and local time, they are valuable for determining relative differences in thermophysical properties (Edwards et al., 2011). About 2800 craters were identified between 75°S and 75°N with crater floors that have warmer nighttime temperatures as compared to the surrounding wall materials (Fig. 2). The entire planet was

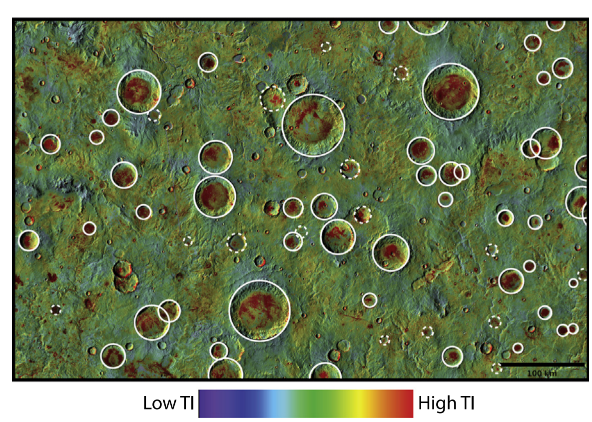

Fig. 1. Colorized THEMIS nighttime temperature overlain on THEMIS relative daytime temperature from the THEMIS global mosaic (Edwards et al., 2011, and references therein) of a region of the southern highlands centered near 83.5°E, 15°S. In this view, blue tones indicate lower nighttime temperatures and relatively low-thermal inertia surfaces while, red tones indicate higher nighttime temperatures and relatively high-thermal inertia and rockier surfaces. Temperatures are normalized. Craters classified with elevated floor thermal inertia values are identified by a solid white circle while potential candidates which were not examined in detail are identified by a dashed white circle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)