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Modeling the development of martian sublimation thermokarst landforms

Colin M. Dundas [a,*], Shane Byrne [b], Alfred S. McEwen [b]

[a] Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA
[b] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

Sublimation-thermokarst landforms result from collapse of the surface when ice is lost from the subsurface. On Mars, scalloped landforms with scales of decameters to kilometers are observed in the mid-latitudes and considered likely thermokarst features. We describe a landscape evolution model that couples diffusive mass movement and subsurface ice loss due to sublimation. Over periods of tens of thousands of Mars years under conditions similar to the present, the model produces scallop-like features similar to those on the martian surface, starting from much smaller initial disturbances. The model also indicates crater expansion when impacts occur in surfaces underlain by excess ice to some depth, with morphologies similar to observed landforms on the martian northern plains. In order to produce these landforms by sublimation, substantial quantities of excess ice are required, at least comparable to the vertical extent of the landform, and such ice must remain in adjacent terrain to support the non-deflated surface. We suggest that martian thermokarst features are consistent with formation by sublimation, without melting, and that significant thicknesses of very clean excess ice (up to many tens of meters, the depth of some scalloped depressions) are locally present in the martian mid-latitudes. Climate conditions leading to melting at significant depth are not required.

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1. Introduction

Ground ice on Mars represents a key link between martian geology and climate history, and is a potential resource for future exploration. The theoretical basis for the distribution of ground ice on Mars was established by Leighton and Murray (1966) and has been refined by many subsequent workers (e.g., Mellon et al., 2004; Schorghofer and Aharonson, 2005; Chamberlain and Boynton, 2007). The distribution of near-surface ice is expected to change substantially with variations in Mars' orbit and climate; at present, ice is thought to be stable at a depth of decimeters in the mid-latitudes, and millimeters to centimeters near the poles (e.g., Mellon and Jakosky, 1995; Head et al., 2003; Chamberlain and Boynton, 2007; Schorghofer, 2007). The presence of ground ice can have a dramatic effect on the geomorphology, resulting in a diverse range of landforms.

Excess ice is ground ice exceeding the natural pore space of unfrozen soil (van Everdingen, 1998). A number of lines of evidence now indicate widespread excess ice on Mars (e.g., Boynton et al., 2002; Byrne et al., 2009; Mouginot et al., 2010; Dundas et al., 2014). Excess ice with only ~1 vol% regolith was also directly excavated by the Phoenix lander (Smith et al., 2009; Mellon et al., 2009; Cull et al., 2010). The distribution and origins of this ice, however, are still not understood. Geomorphology provides another avenue for learning about this ice. Thermokarst landforms develop when ice is lost from ice-rich ground in a spatially heterogeneous way, leading to local surface subsidence and collapse. Therefore, they can serve as indicators of the loss of excess ice and provide insight into the conditions and processes forming and removing the ice. Thermokarst features on Mars were proposed by several authors based on Mariner and Viking imagery (e.g., Sharp, 1973; Anderson et al., 1973; Costard and Kargel, 1995). Most recent analyses of potential thermokarst have focused on concentrations of large scalloped depressions in Utopia Planitia and south of the Hellas basin (Plescia, 2003; Morgenstern et al., 2007; Soare et al., 2007, 2008, 2011; Lefort et al., 2009, 2010; Ulrich et al., 2010; Zanetti et al., 2010; Séjourné et al., 2011, 2012). In their simplest form, these rimless depressions have shallow, equator-facing slopes, somewhat steeper, pole-facing scarps, and are meters to tens of meters deep, although they may merge to produce much more complicated landscapes (Figs. 1–4). Because Mars is a cold and dry planet, most recent authors have suggested that these form through sublimation, although Soare

* Corresponding author.
E-mail address: cdundas@usgs.gov (C.M. Dundas).

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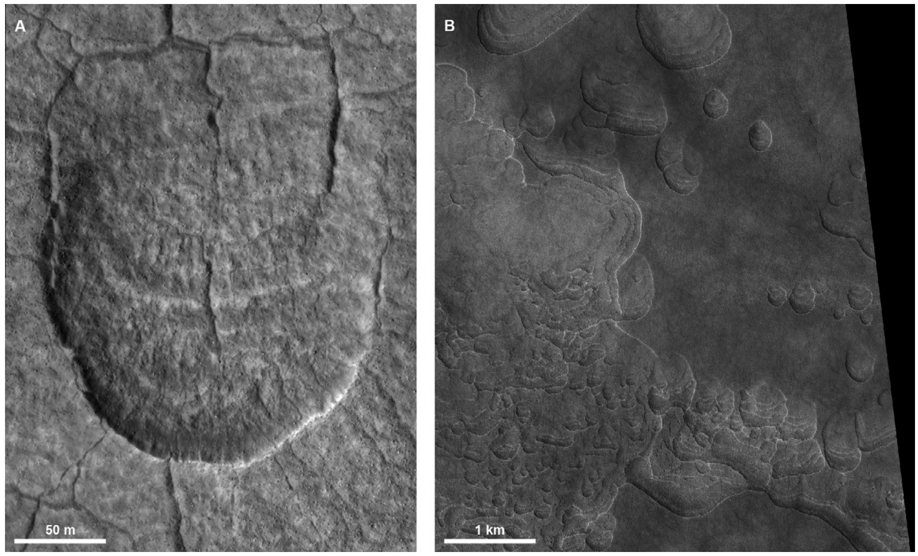

Fig. 1. Scalloped depressions in Utopia Planitia. Illumination is from the left and north is up in both panels. (A) Archetypal simple scalloped depression, with relatively steep pole-facing scarp and gentle equator-facing slope (HiRISE image PSP_001582_2245). (B) Scalloped landscape, with simple scalloped depressions (right) and complex landscape likely formed by mergers and interactions of many smaller landforms (HiRISE image PSP_001938_2265). All HiRISE images and anaglyphs in this paper credit NASA/JPL/University of Arizona. Images in all figures have been stretched to best show surface features; original images are available via the Planetary Data System or at www.hirise.lpl.arizona.edu.

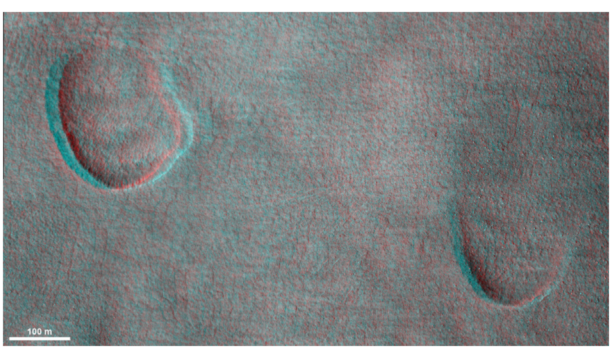

Fig. 2. Red–blue anaglyph of simple scalloped depressions in Utopia Planitia. North is up and illumination is from the left. Right: an ideal example with a steeper pole-facing scarp and shallow equator-facing slope that merges with surrounding terrain. Left: scalloped depressions commonly deviate somewhat from this form. While the pole-facing scarp remains most prominent, the floor is relatively flat and there is an equator-facing scarp. (Anaglyph constructed from HiRISE stereo images PSP_001938_2265 and PSP_002439_2265.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

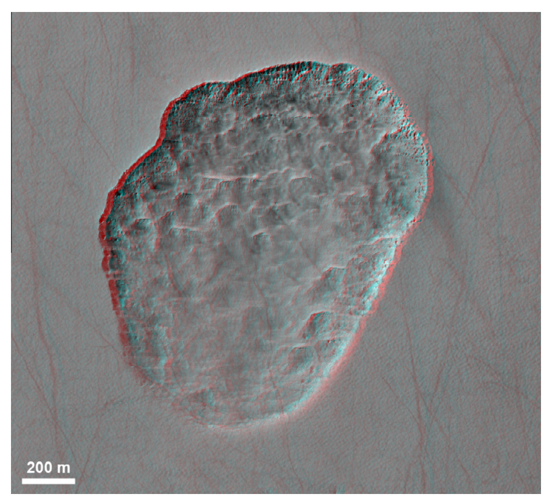

Fig. 3. Red–blue anaglyph of simple scalloped depression at Peneus Patera. In the southern hemisphere, the orientation is reversed. (Anaglyph constructed from HiRISE images stereo ESP_013873_1225 and ESP_014005_1225. North is up and illumination is from the left.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al. (2007, 2008) proposed melting ground ice instead, and argued for stable, ponded surface water.

A number of terrestrial thermokarst landforms are known, including alases (depressions with steep sides and flat floors) and oriented thaw lakes (e.g., French, 2007). The formation of terrestrial thermokarst features normally results from melting rather than sublimation, and on Earth, excess ground ice primarily results from processes involving liquid water, such as ice segregation or the growth of ice wedges (e.g., French, 2007). Soare et al. (2011) raised several questions about sublimation models for martian scalloped depressions and considered such "wet" periglacial processes to be a more effective terrestrial analog. Consequently, the formation of martian thermokarst features is of importance not only for understanding the state of ground ice but also the climate of the geologically recent past.

Studies of martian thermokarst have been hindered by the qualitative nature of formation models. Landscape evolution modeling offers the ability to assess the way in which a landform will evolve, and early applications to Mars have led to insights into a variety of landforms (e.g., Byrne and Ingersoll, 2003; Forsberg-Taylor et al., 2004; Pelletier, 2004; Howard, 2007). In this paper we report on results of landscape evolution modeling of martian sublimation-thermokarst processes that allow us to better understand the three-dimensional evolution of a landform. In Section 2, we summarize observations of scalloped depressions and models of their origins, and then give a brief description of evidence for thermokarstic crater expansion on the martian northern plains. The landscape evolution model is described in Section 3, and the scenarios we consider in Section 4. Section 5 gives the model results, and Section 6 discusses their broader significance for martian geomorphology and ground ice.