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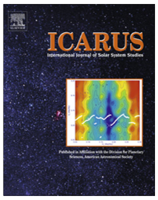

Initiation and growth of martian ice lenses

Hanna G. Sizemore [a],*, Aaron P. Zent [b], Alan W. Rempel [c]

[a] Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, United States
[b] MS 245-3, NASA Ames Research Center, Moffett Field, CA 94035, United States
[c] Dept. of Geological Sciences, 1272 University of Oregon, Eugene, OR 97403-1272, United States

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ABSTRACT

Water ice in the upper meters of the martian regolith is a major volatile reservoir. Although the geographic extent, burial depth, and thermal stability of this shallow ice are well understood, its origin, history, and stratigraphy are not. Over the past decade, a growing body of observational evidence has indicated that shallow ground ice exceeds the pore volume of its host soil over large regions of both martian hemispheres. This is confounding, given that (1) the physical theory that accurately predicts the location of ground ice also assumes that ice should be pore-filling in the upper meter of regolith, and (2) the Phoenix spacecraft uncovered far more pore-filling ice than excess ice at its landing site in the northern hemisphere. The development of ice lenses by low-temperature *in situ* segregation – analogous to the processes that generate frost heave on Earth – has been hypothesized to explain shallow excess ice on Mars. We have developed a numerical model of ice lens initiation and growth in the martian environment, and used it to test this hypothesis for the first time. We carried out a large suite of numerical simulations in order to place quantitative constraints on the timing and location of ice lens initiation, and on the magnitude of ice lens growth in a variety of host soils. We find that ice lens initiation is a ubiquitous process in the martian high latitudes, but the ultimate magnitude of lens growth, or frost heave, is sensitive to the properties of the host soil. Depending on the specific properties of martian soils, *in situ* segregation may be a very slow process sufficient to explain the excess ice observed in the Dodo–Goldilocks trench at the Phoenix landing site, but without regionally significant effects. Alternatively, if clay-sized particles or perchlorate salts are present, *in situ* segregation may be a vigorous process that has significantly affected the stratigraphy of ground ice in the upper meter of regolith throughout the high latitudes.

1. Introduction

Excess ground ice, or ice that exceeds the undisturbed pore volume of its host soil, has been observed at several locations on Mars, and is a topic of major interest both from a climatological and an astrobiological standpoint. Data from the Mars Odyssey Gamma Ray Spectrometer (GRS) indicates that ice occupies >90% of the regolith by volume over large regions of the high latitudes (>50°) in both hemispheres (Boynton et al., 2002). Thermal and optical observations of fresh impact craters also indicate the presence of relatively pure sub-surface ice at mid to high latitudes (Byrne et al., 2009). At the Phoenix landing site (68°N), trenching activities primarily revealed ice that was pore-filling. However, excess ice (98–99% water by volume) was found in the Dodo/Goldilocks trench complex (Mellon et al., 2009).

The origin of excess ice at its various locations is not well understood. Excess ice is unlikely to be cold-trapped from atmospheric water vapor. Its presence implies either bulk deposition or *in situ* segregation of pre-existing pore ice. Mellon et al. (2009) examined the properties of the Dodo/Goldilocks ice and evaluated several formation hypotheses. They concluded that *in situ* segregation was the most likely formation mechanism at that location. It is unclear whether this interpretation of the Dodo/Goldilocks ice may be extensible to the excess ice observed throughout the mid- and high latitudes. To date, there have been no theoretical investigations of the physical mechanisms by which *in situ* ice segregation might occur in the martian environment. Here, we employ numerical simulations of climate and soil–ice interactions to place the first quantitative constraints on the growth of segregated ice lenses at the Phoenix landing site and in the northern mid to high latitudes.

Over the past four decades, a remarkably consistent picture of the global distribution of near-surface ground-ice on Mars has emerged from remote sensing and theory. Leakage neutron and

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* Corresponding author.
E-mail addresses: sizemore@psi.edu (H.G. Sizemore), rempel@uoregon.edu (A.W. Rempel).

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gamma ray emission data from the GRS instrument suite indicate the presence of an ice-rich subsurface soil layer extending throughout the high latitudes in both martian hemispheres (Boynton et al., 2002; Mellon et al., 2004; Feldman et al., 2008). Specifically, these data are most consistent with a two-layer subsurface in which hydrogen-poor (dry) soil overlies a hydrogen-rich (icy) deeper layer. The dry and icy layers are separated by a sharp boundary called the "ice table." The depth of the ice table increases with distance from the poles; lower latitudes lack abundant concentrations of hydrogen that would indicate near-surface ground-ice. A variety of theoretical studies (Leighton and Murray, 1966; Farmer and Doms, 1979; Fanale and Cannon, 1974; Zent et al., 1986; Paige, 1992; Mellon and Jakosky, 1993, 1995) predicted the occurrence of shallowly buried ground-ice in the same latitudinal bands indicated by GRS data, with the same trend of increasing depth toward the equator, based on the assumption that ground-ice is in diffusive equilibrium with the atmosphere. More recent simulations incorporating variable surface thermophysical properties (e.g., Mellon and Jakosky, 1993; Chamberlain and Boynton, 2007; Schorghofer and Aharonson, 2005) even capture longitudinal variations in the equatorward extent and depth of ground-ice similar to those inferred from GRS data.

Prettyman et al. (2004) examined leakage neutron energy spectra from GRS, and concluded that the shallow regolith poleward of 60°S latitude contained 70–85% ice by volume, far in excess of the expected maximum porosity of dry soil, ~65% (Sizemore and Mellon, 2008). Feldman et al. (2008) reported similar findings for large regions of the northern hemisphere. On Earth, three main processes can lead to the development of excess ice: precipitation and subsequent burial of snow/ice, outright melting and flow of liquid water, or temperature-dependent suction that develops in saturated soils as they freeze (Zent, 2003; Dash et al., 2006). The first two processes likely cannot explain the excess ice detected by GRS.

Burial of glacial ice or snow packs is difficult to reconcile with the current understanding of periodic diffusive exchange of H_2O between the atmosphere and the upper 1–2 m of regolith; it likewise appears inconsistent with the extensive boulder fields that forced abandonment of the originally-planned Phoenix landing site (Arvidson et al., 2009). At the scale of the lander workspace, the Dodo/Goldilocks excess ice was found beneath surface cobbles that could not have been deposited from atmospheric suspension (Fig. 1).

A variety of processes associated with bulk flow of liquid water can result in excess ground ice, but none are wholly consistent with GRS observations. Pingos, ice-cored hills formed from the flow of pressurized ground water and often associated with lakes, can contain large volumes of pristine ice. A variety of domed features on Mars have been interpreted as possible pingos (Judson and Rossbacher, 1979; Soare et al., 2005; Page and Murray, 2006; Dundas et al., 2008), but like their terrestrial counterparts, they are small (meters to kilometers in diameter) and geographically isolated. In terrestrial permafrost regions, vertical ice wedges can form when surface melt water drains into thermal-contraction fractures associated with polygonal patterned ground (e.g. Marchant and Head, 2007). Ice wedges can account for up to 50% of the volume of the uppermost three meters of terrestrial soil (MacKay, 1972) and polygonal patterned ground is ubiquitous in the martian high latitudes (Mellon et al., 2008). However, given the low humidity and temperature in the mid to high latitudes of Mars over the past several million years, it is difficult to envision processes involving bulk surface or subsurface melting. Indeed, active thermal contraction polygons on Mars are generally thought to be of the sand-wedge rather than ice-wedge type (Mellon, 1997; Marchant and Head, 2007; Mellon et al., 2008). In the event that cold-trapping of atmospheric H_2O dominates the infill of cracks with dust or sand, ice wedges have been hypothesized to form without near-surface melt (Fisher, 2005). Ice wedges have not been observed in terrestrial environments that experience perennially sub-freezing temperatures. Lacelle et al. (2013) examined excess ice in University Valley, Antarctica, a rare martian analog site where temperatures do not exceed 0 °C. They concluded that a condensation–diffusion process like that hypothesized by Fisher contributed to the heterogeneous excess ice in University Valley.

Horizontal ice lenses have been of long-term interest for Mars, because they can account for up to 75% of the volume of the upper meter of terrestrial soils (Pewe, 1974). Terrestrial ice lenses are also commonly associated with polygonal patterned ground, but their development does not require gravity driven drainage of surface water. At present, ice lens formation appears to be the least problematic process that might contribute to excess H_2O in the upper 1–2 m of the martian regolith (Mellon et al., 2009). On Earth, the growth of ice lenses is typically associated with inflation of the host soil, or frost heave. A variety of physical models have been developed to predict the rate and magnitude of frost heave in terrestrial environments (e.g., Gilpin, 1980; O'Neil and Miller, 1985; Nakano and Tice, 1990; Konrad and Duquennoi, 1993; Rempel, 2007). These models typically require a freezing front that propagates downward into liquid-saturated soil to produce ice lenses and heave. The most recent and physically complete models

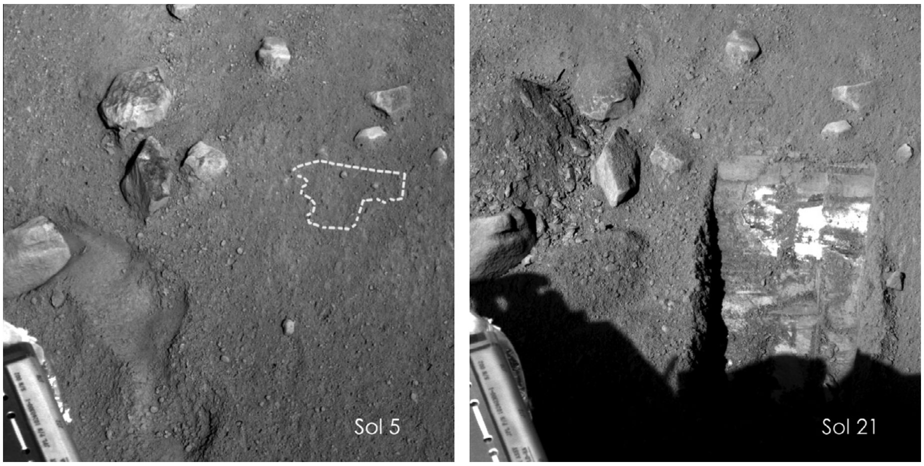

Fig. 1. The excess ice observed by Phoenix. The outline on the left indicates the regolith beneath which excess ice was observed. Its proximity to the surface cobbles suggests that it is not a residual snowbank blanketed with aeolian dust.

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