

Introduction:

Water on Mars has played a central major role in most aspects of the planet's surface geology, geochemistry, and climate throughout history. Liquid water has eroded the surface, carved canyons, and ponded to collect vast sedimentary deposits. Ground water has redistributed ions and altered the mineralogy. The climate depends strongly on water as a greenhouse gas, and for clouds that block the sun and precipitate onto the surface as rain or snow. Water ice, slowly but no less dramatically, has altered the landscape through regional and alpine glaciation, the formation and evolution of polar caps, and through the growth and retreat of shallow subsurface ice, called "ground ice".

In the modern martian climate water plays no small role. While liquid water is generally thought to be absent, water vapor and ice are active and dynamic forces influencing the landscape, atmosphere, and polar deposits. Ground ice is a major reservoir of modern water and is able to actively exchange with the atmosphere-polar-cap system on relatively short timescales.

Presently ground ice is stable in the middle and high latitudes of Mars. Indeed, more than 45 years of theoretical predictions of the stability and dynamics of ground ice correlate extremely well with the now observed geographic and depth distribution of subsurface water [Boynton *et al.*, 2002; Feldman *et al.*, 2008; Mellon *et al.*, 2009a; Byrne *et al.*, 2009]. This strong correlation shows that we understand why ice is stable within the soil and the fundamental physical processes which control that stability [Mellon *et al.*, 2009a]. The key process is the diffusive equilibrium which is maintained between atmospheric water vapor and the subsurface ice. In short, warm ice will sublimate and be diffusively lost to the "dry" atmosphere through the porous soil overburden. Conversely, in regions where the ground temperatures are adequately cold, water vapor from the atmosphere will diffuse into the regolith and condense in the pore space as ice. The depth of this equilibrium is defined as the depth where the annual-mean vapor density in the pore space equals that of the atmosphere [Mellon and Jakosky, 1993]. Annual-mean values are considered because diffusion of appreciable water is typically slower than one year. This depth is also referred to as the "ice table" (analogous to a water table) above which soil is ice free and ice saturated below [Leighton and Murray, 1966]. A similar distribution of ground ice is observed in the Antarctic Dry Valleys, where similar climate conditions persist [McKay *et al.*, 2008].

However, this equilibrium is dynamic in that if the climate changes gradually, for example over orbital cycles, it will result in cyclic changes in ground tem-

perature and atmospheric humidity which drive the system to a new ground-ice depth equilibrium. Oscillations in the martian orbit (such as eccentricity, perihelion, and obliquity) are known to occur on 10^4 - 10^5 year time scales [e.g., Laskar, 2004]. Theoretical studies have shown that readjustment of the ice table is fast on these time scales and that it will steadily track the new equilibrium depth [Mellon and Jakosky, 1995; Chamberlain and Boynton, 2006; Zent, 2008] (see Figure 1). As a result, ground ice depth can oscillate within the upper meter or more of the regolith and ground ice may occur periodically in equatorial regions. The range of ground-ice distribution will depend on the range of humidity conditions, largely controlled by polar cap sublimation and atmospheric transport of water vapor.

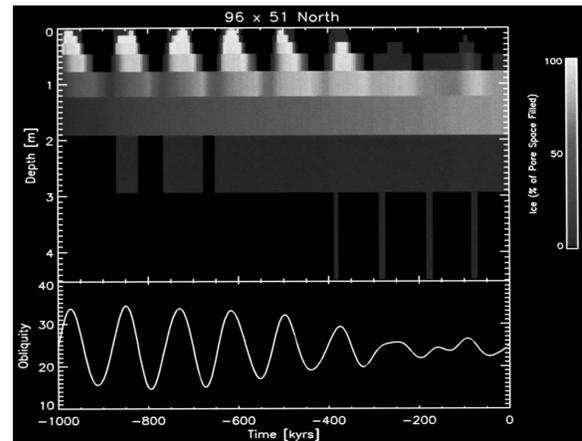


Figure 1. A theoretical model of ice-table variations over recent obliquity cycles [from Mellon and Jakosky, 1995].

From these numerous passed studies a consistent story of ground ice has emerged:

- Ground ice should condense from atmospheric water, or remain stable, poleward of $\sim 45^\circ$ latitude;
- Equatorial ground ice is unstable on average should ultimately sublimate away over time;
- Dry soil should overlie ice-rich soil with a sharp boundary called the ice table representing a diffusive equilibrium depth with the atmosphere; and
- As much as the top meter of ice within the soil should come and go with cyclic climate changes.

Recent Observations of Water:

During the last decade several observations have been made that directly or indirectly measured the occurrence and distribution of ground ice in the martian shallow subsurface: orbital measurements of gamma rays and leakage neutrons, identification of small-scale

periglacial geology, direct probing and sampling, and identification of fresh few-meter-scale impact craters exposing subsurface ice. These observations have provided important ground truth and verification of theoretical predictions. They have also raised new questions and challenge our understanding of ground ice.

The Gamma Ray Spectrometer and Neutron Spectrometer instruments on Mars Odyssey were the first to detect the presence of vast quantities of subsurface hydrogen through its influence on high-energy neutrons which result from collision of the surface with galactic cosmic rays [Feldman *et al.*, 1993]. Such large quantities of hydrogen can only be explained by the presence of water. Results from these measurements showed that water (assumed to be ice at martian temperatures) was abundant within the upper meter of the regolith at latitudes above 45° and essentially absent in the equatorial regions [Boynton *et al.*, 2002; Feldman *et al.*, 2002; Mitrofanov *et al.*, 2002], in excellent agreement with theoretical predictions. Even predictions of more subtle geographic variability in the boundary between ice stability and equatorial instability well fit these data [Boynton *et al.*, 2002; Mellon *et al.*, 2004]. Additionally, the depth of ground ice, inferred from neutron data, agreed with the predicted depth [Mellon *et al.*, 2004; Feldman *et al.*, 2008].

The gamma ray and neutron data also indicated that in many regions of the high latitudes of both hemispheres, ground ice occurred in concentrations of 75-90% by volume, vastly in excess of the pore space expected in typical martian soils [Prettyman *et al.*, 2004; Feldman *et al.*, 2008]. This concentration was unexpected and currently remain unexplained.

Polygonal patterned ground is a ubiquitous landform in terrestrial permafrost which forms by seasonal thermal-contraction cracking in permanently ice-cemented ground [e.g., Lachenbruch, 1962]. Cracks, open no more than a few millimeters in any one year, but form a honeycomb network (spaced a few to tens of meters) to relieve thermal-contraction stress. In terrestrial regions where a thaw layer and runoff occur at the surface above the fractured permafrost, liquid water can infiltrate the cracks and freeze to form a subsurface “ice wedge” [Black, 1976]. In arid regions analogous to Mars, dry surface soil falls into the open cracks, forming a subsurface accumulation of fine material often termed a “sand wedge” [Péwé 1959; 1974]. Repeated cracking and wedge growth in the same locations each year integrates the seasonal strain and develops pronounced relief over thousands of years.

On Mars, high-latitude polygons have been observed from orbit since the Viking missions. Close up analysis by the Phoenix lander showed that sand-wedge formation is responsible [Mellon *et al.*, 2009b]. Globally, an array of morphologies are observed [Mangold, 2005] (Figure 2). Regional differences in

polygon morphology, such as diameter [Mellon *et al.*, 2008] and trough depth [Marchant *et al.*, 2002; Levy *et al.*, 2009] can be linked in part to variability in subsurface ice concentration. In some cases ice concentrations in excess of the expected soil pore space is implied.

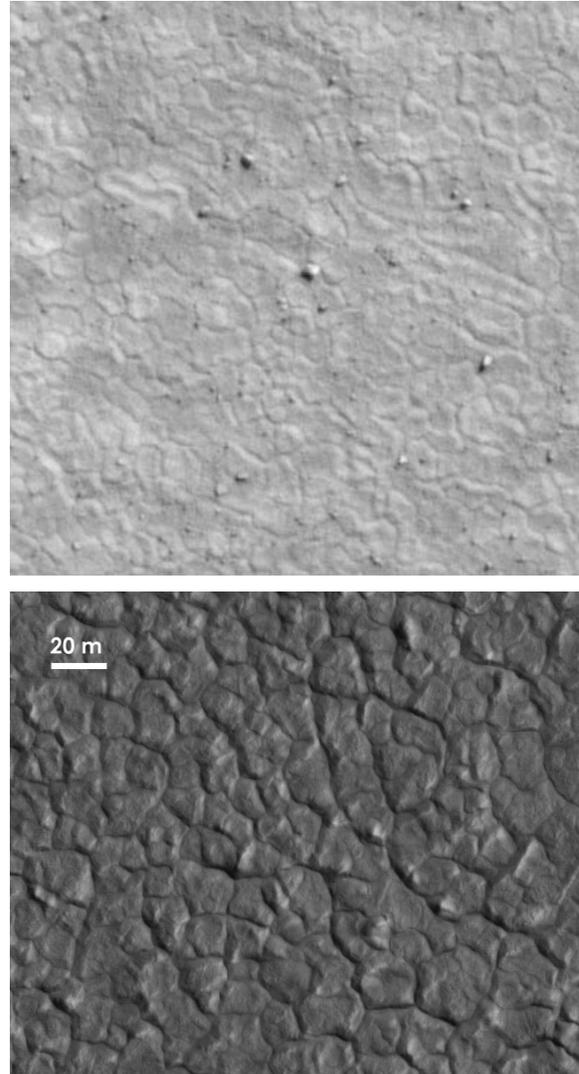


Figure 2. Examples of polygonal ground on Mars. Regional variations in polygon size and trough depth may result in part from changes in ice concentration. HiRISE images (top) PSP_001525_2475 and (bottom) PSP_001334_2645.

The Phoenix mission to Mars landed in a northern high latitude region where ground ice is inferred from gamma ray and neutron data, and where orbital imaging showed extensive polygonal ground. The spacecraft excavated into the soil to characterize and sample the subsurface ice. The ice table was found at a depth of about 5 cm below the soil surface beneath an ice-free soil overburden, in excellent agreement with theoretical predictions [Mellon *et al.*, 2009a].

What was not predicted, however, was that the ground ice would be found in two distinct forms. Figure 3 shows Phoenix images of these two types ground ice. Dark-toned ice appears to be ice-cemented soil (Figure 3a), while light-toned ice appears to be relatively-pure ice (Figure 3b). No gradation between these endmembers was observed [see *Mellon et al.*, 2009a].



Figure 3. Dark and light toned ice deposits at the Phoenix landing site.

The dark-toned ice was hard and left behind a thick residual soil lag as it sublimated. The ice was estimated to fill the pore space of the existing soil, as predicted by vapor diffusion theory. Dark-toned ice represented about 90% of the area of excavated ground ice. [see *Mellon et al.*, 2009a for a complete discussion of these ice deposits].

The light toned ice (Figure 3b) presents a puzzle. It exhibited characteristics of being weak and friable.

When it sublimated it left a barely perceptible lag suggesting the ice was is about 99% pure. With its higher albedo these observations suggest the ice is porous and relatively soil free. About 10% of the excavated ice consisted of this endmember [see also *Mellon et al.*, 2009a]. The origin of this ice and the remarkable local bimodal heterogeneity remains unknown.

Recent small impacts have been discovered that appear to excavate subsurface-ice deposits [*Byrne et al.*, 2009]. Analysis of the rate of decay of the bright icy ejecta, returning to the albedo of the native surface soils, suggests that the excavated ice is about 90-99% pure, similar to the light-toned ice found at the Phoenix landing site. These icy impacts are found at latitudes consistent with models of ground-ice stability (or close to the boundary within the theoretical uncertainty). However, the inferred concentration of ice exceeds that predicted by those theoretical modes. In addition, in at least one case of a crater cluster, not all the craters excavated into this concentrated of ice, indicated decameter scale variability to the occurrence of excess ice.

Overall, these observations indicate that ground ice is found geographically and at depths consistent with ice in diffusive equilibrium with the atmosphere. However, the concentration of ice in many locations is in excess of that predicted by these same diffusion models. In addition, substantial variability in the ice concentration is observed on spatial scales from regional ~1000 km (as in the neutron data), to local meter scale (as in the Phoenix excavations). Neither the occurrence of excess ice nor its geographic heterogeneity are predicted by existing theories of martian ice.

Theories to Explain Excess Ice?

A number of theories have been put forth to explain the paradox of excess ice [see *Prettyman et al.*, 2004; *Feldman et al.*, 2008; *Boynton et al.*, 2008; *Mellon et al.*, 2009a], ranging from exogenic sources (in place freezing of ancient flood waters and formation of a protective lag, or formation of dusty snow pack during high-obliquity) to endogenic sources (formation of ice segregation such as ice lenses, vapor deposition within unusually high-porosity soils). The range of hypotheses represented here implies a dramatic spectrum of climate conditions, some of which are in conflict with present-day cold, dry Mars. However, each of these mechanisms have unexplained aspects warranting consideration [see *Mellon et al.*, 2009a].

The idea of a northern ocean has been around for some time. Catastrophic flood channels discharged water toward the northern plains, where water may have ponded and frozen in place, now hidden from view by a protective sublimation lag of soil particles [see *Carr*, 1996]. While the occurrence of such an ocean continues to be debated, excess ice is

found in both northern lowlands and southern highlands. Southern highlands excess ice does not fit this model of ponding. In addition, subsequent obliquity cycles will periodically desiccate the subsurface, causing the soil lag to thicken and back fill with pore ice. Since measurements such as neutron spectroscopy only sense the upper meter at most, the observed excess ice must have been deposited more recently.

Orbital cycles may have resulted in the periodic accumulation of a dusty snow at middle and high latitudes in modern times. Similar subsequent sublimation of the snow would leave behind a dusty lag. However, in the example of light-toned ice at the Phoenix site, decimeter scale rocks are found on the surface and within the soil above the ice, inconsistent with a dusty airfall source of the lag. Evidence of aeolian activity and recent nearby craters are absent, thus the widespread occurrence of rocks above the excess ice deposit argues for excess ice developing in place under rocks.

Laboratory measurements of the porosity of Mars-analog fine-grained soils suggest that naturally high-porosity (~75% by volume) can occur within dry fine-grained soils due to electrostatic bonds between grains [Sizemore and Mellon, 2008]. However, these porosities are still not high enough to explain observations of 75-99% ice, and such high porosity soils have not yet been observed on Mars.

On Earth, the most common form of excess ice in permafrost are ice lenses, thin mm to cm thick horizontal to subhorizontal repeating layers of nearly pure ice. These structures form rapidly in terrestrial conditions of overnight freezing of wet sediments by migration of water films in soils at temperatures just below freezing. Theoretical studies applying this process to Mars suggest that it may also work at martian temperatures [Zent et al., 2011; Sizemore et al., 2012]. However, the exact kinetics of the process remain relatively unconstrained. Soluble salts may also play an important role in depressing freezing and increasing water mobility.

To date, none of the proposed mechanisms can be entirely ruled out or proven, nor have they been evaluated in adequate detail. Indeed, depending on the geographic context, more than one process may be active.

What's With All the Ice?

At this stage we can clearly outline what we now know and what we would like to know.

We know that Mars is generally cold and dry. While climate oscillations have likely persisted causing dynamic shifts and periodic redistribution of ground ice, a cold "periglacial" climate has persisted for at least the last millions of years if not substantially. We have confirmed that ground ice is present in the middle and high latitudes, and at the locations and depths we predict. This finding supports the idea that

diffusive equilibrium with the atmosphere in a climate similar to today's relatively cold and dry Mars.

Despite our growing knowledge of ground ice stability and dynamics, many questions remain and new questions have emerged. How much ice is really contained within the permafrost and how is it distributed on scales from soil grains to tens of meters? Present day observations have only examined the ice at the ice table. Neutron and gamma ray spectroscopy is only sensitive to the upper few cm of ice-rich material due to the short collisional path length of neutrons in ice.

What are the dominant geophysical and geochemical processes controlling the distribution of ice and on what time scales? What is the role of liquid water in the modern martian climate? The presence of excess ice is not understood. Nevertheless, recent formation of this ice is implied by recent climatic cycles. If liquid water is required, the occurrence of excess ice has significant implication for climate conditions and habitability of the martian soil in modern times.

To address these questions future research should focus on a variety of front. Geomorphic and geophysical analysis will help to constrain the relationship between the states of water and the observed landforms. Microphysical investigations of water transport at the soil-grain level will help to constrain the role of liquid water in the current martian climate. Investigations of the martian climate, present and past, will define key boundary conditions for subsurface ice. And examinations of terrestrial-analogs in the Antarctic Dry Valleys will provide ground truth to understand Mars.

References: [1] Black, *Quatern. Res.*, 6, 3-26, 1976. [2] Boynton et al., *Sci.*, 297, 81-85, 2002. [3] Boynton et al., in *The Martian Surface: Composition, Mineralogy, and Physical Properties*, 105-124, 2008. [4] Byrne et al., *Sci.*, 325, 1674-1676, 2009. [5] Carr, *Water on Mars*, 1996. [6] Chamberlain and Boynton, *JGR*, 112, E06009, 2006. [7] Feldman et al., *JGR*, 98, 20,855-20,870, 1993. [8] Feldman et al., *Sci.*, 297, 75-78, 2002. [9] Feldman et al., in *The Martian Surface: Composition, Mineralogy, and Physical Properties*, 125-148, 2008. [10] Lachenbruch, *Geol. Soc. Am. Spec. Paper*, 70, 69 p., 1962. [11] Laskar et al., *Icarus*, 170, 343-364, 2004. [12] Leighton and Murray, *Sci.*, 153, 136-144, 1966. [13] Levy et al., *JGR*, 114, E01007, 2009. [14] Mangold, *Icarus*, 174, 336-359, 2005. [15] Marchant et al., *Geol. Soc. Amer. Bull.* 114, 718-730, 2002. [16] McKay et al., *Antarctic Sci.*, 10, 31-38, 1998. [17] Mellon and Jakosky, *JGR*, 98, 3345-3364, 1993. [18] Mellon and Jakosky, *JGR*, 100, 11,781-11,799, 1995. [19] Mellon et al., *Icarus*, 169, 324-340, 2004. [20] Mellon et al., *JGR*, 113, E00A23, 2008. [21] Mellon et al., *JGR*, 114, E00E07, 2009 [22] Mellon et al., *JGR*, 114, E00E06, 2009. [23] Mitrofanov et al., *Sci.*, 297, 78-81, 2002. [24] Péwé, *Amer. J. Sci.*, 257, 545-552, 1959. [25] Péwé, in *Polar Deserts and Modern Man*, 1974. [26] Prettyman et al., *JGR* 109, E05001, 2004. [27] Sizemore and Mellon, *Icarus*, 197, 606-620, 2008. [28] Sizemore et al., *LPSC*, 43rd, 2012. [29] Zent, *Icarus*, 196, 285-408, 2008. [30] Zent et al., *LPSC*, 42nd, 2011.