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The high elevation Dry Valleys in Antarctica as analog sites for subsurface ice on Mars

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A B S T R A C T

The high elevation valleys of the McMurdo Dry Valleys of Antarctica are the only locations on Earth known to contain dry permafrost. The Dry Valleys are a hyper-arid polar desert environment and above 1500 m elevation, air temperatures do not exceed 0 °C and thus, similarly to Mars, liquid water is largely absent and instead the hydrologic cycle is dominated by frozen ice and vapor phase processes such as sublimation. These conditions make the high elevation Dry Valleys a key Mars analog location where periglacial processes and geomorphic features, and their use as a diagnostic for subsurface ice, can be studied in situ. Two valleys in the upper Dry Valleys show a diversity of subsurface ice; University Valley is dominated by dry permafrost overlying ice-cemented to ice-bonded ground and nearby middle Beacon Valley is dominated by massive ground ice. In both cases the ice is 10–60 cm below the surface. Here we compare the surface features in these two valleys to assess any correlation with the nature of the subsurface ice and compare these features to similar features seen at the Phoenix landing site on Mars. We conclude that while surface features may be indicative of ground ice, no specific correlations are possible and more direct methods are required to determine the nature of subsurface ice on Mars.

1. Introduction

The Mars Phoenix spacecraft landed in the martian Arctic at 68.22°N latitude, 234.25°E longitude on 25 May 2008 (Smith et al., 2009). A main goal of Phoenix was to study the subsurface ice deposits thought to exist in this region of Mars based on previous orbital observations and modeling efforts. Of particular interest was the nature of the expected subsurface ice deposits (i.e., ground ice). In this study, we define massive ice as subsurface ice containing gravimetric water content in excess of 250%, whereas ice-cemented ground refers to ice filling the volume of pores of the enclosing sediments when the sediments are unfrozen, and ice-bonded permafrost refers to above pore-filling ice content in soils (National Research Council of Canada, 1988).

The presence of ground ice in the polar latitudes on Mars has been predicted since the time of Viking based on the thermal properties of the soil and the frost point of the martian atmosphere (Farmer and Doms, 1979; Fanale et al., 1986; Mellon and Jakosky, 1993). These models were based on the assumption of ground ice filling the pore spaces in the regolith and exchanging with the atmospheric moisture only by the exchange of vapor. Orbital measurements of hydrogen concentration from the Mars Odyssey neutron spectrometer (Boynton et al., 2002; Feldman et al., 2008) were consistent with these models. However, the data also indicated that in some polar locations ground ice exists in abundances of ˜75–80% by volume (Feldman et al., 2008), which would exceed the pore volume of most soils.

Ice-cemented ground was found at the Phoenix site as expected, and the depth below the surface appeared consistent with vapor deposited equilibrium. The mean depth to ice was 4.6 cm and varied considerably in a way that seemed to correlate with slope and thermal inertia variations in the overlying soil (Mellon et al., 2009a). However, in addition to ice-cemented soil there was relatively pure light-toned ice (Fig. 1). This ice was unexpected and Mellon et al. (2009a) suggested it appears most consistent with the formation of excess ice by soil ice segregation, although Lacelle et al. (in press) demonstrated from isotope geochemistry and numerical modeling that excess ice can also

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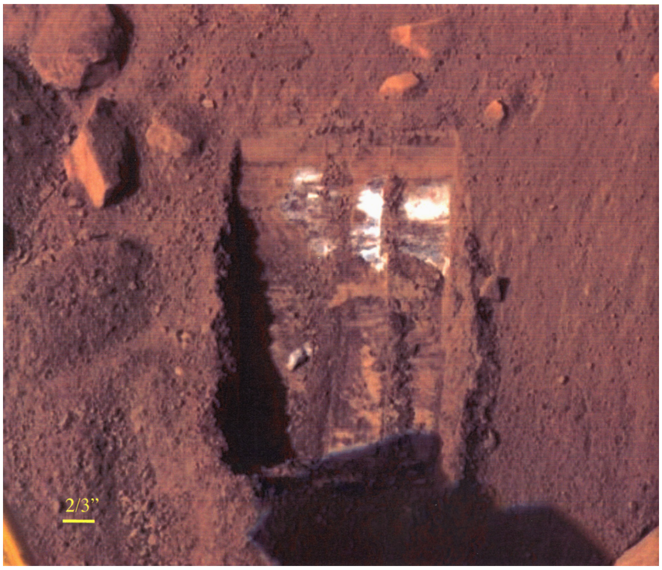

Fig. 1. Excavated ground ice at the Mars Phoenix lander site dug by the Robotic Arm on NASA's Phoenix Mars Lander. The trench is 22 cm (8.7 in.) wide and 35 cm (13.8 in.) long.

be formed by vapor exchange with the atmosphere following soil thermal contraction and expansion.

At the Phoenix site, the presence of ground ice was directly determined, but in general on Mars, indirect methods must be used to determine the presence of subsurface ice. In addition to modeling of the vapor exchange between the subsurface and atmosphere, which gives the depth to ice table equilibrium, orbital images of polygonal ground in the region (Mellon et al., 2008, 2009a, 2009b) are a surface manifestation of the presence of subsurface ice. Thermal conductivity measurement provides another indirect way to detect ground ice because the presence of ice increases the thermal conductivity of frozen soils which affects the surface temperature variations with season (Haberle et al., 2008). A relatively unexplored possibility is that surface geological features, as might be detected with a lander or rover imaging system, might indicate the presence and type of ground ice. In this paper, we explore a possible link between surface geological features and ground ice using the upper elevations of the McMurdo Dry Valleys as a relevant Mars analog environment.

2. The McMurdo Dry Valleys, Antarctica

The McMurdo Dry Valleys (MDV) of Antarctica are a hyper arid polar desert environment and are among the coldest and driest places on Earth (Fig. 2). These conditions make the Dry Valleys a key Mars analog location where periglacial processes and geomorphic features can be studied in situ (Anderson et al., 1972; Levy et al., 2009; Tamppari et al., 2011; Heldmann et al., 2012). The MDVs, located from 73°30′ to 78°30′ S and 160° to 164°E, are situated along the western coast of the Ross Sea in Antarctica and represent the largest ice-free region on the continent. The Dry Valleys span an area of 15,000 km^2 with approximately 30% of its area free of snow and ice (Vincent, 1996). The Dry Valleys are within a polar desert environment with mean annual air temperatures of −20 °C (Doran et al., 2002), typically less than 10 cm (water equivalent) of precipitation per year (Witherow et al., 2006; Fountain et al., 2010) and measured ice ablation rates of 150 to > 1000 mm yr^{-1} (Hendersen et al., 1965; Clow et al., 1988).

The MDV have been divided into three zones based on climate and soil properties (Campbell and Claridge, 1969, 1987; Marchant and Denton, 1996; Bockheim et al., 2007; Marchant and Head, 2007): (1) the coastal or subxerous zone, where summer temperatures routinely exceed 0 °C and hence a seasonal melt phase exists, (2) an intermediate, or xerous zone typical of the inland valleys where temperatures may rise above 0 °C for short periods and liquid water is periodically present, and (3) the ultraxerous zone (including the upper MDV) located adjacent to the polar plateau where maximum air temperatures do not exceed 0 °C and little or no melting of snow and/or ice occurs. The ultraxerous upper MDV are perhaps the best analog environment for the Mars Phoenix lander site in terms of climatic regime given the extremely cold and arid conditions of Mars (Marchant and Head, 2007; Tamppari et al., 2011).

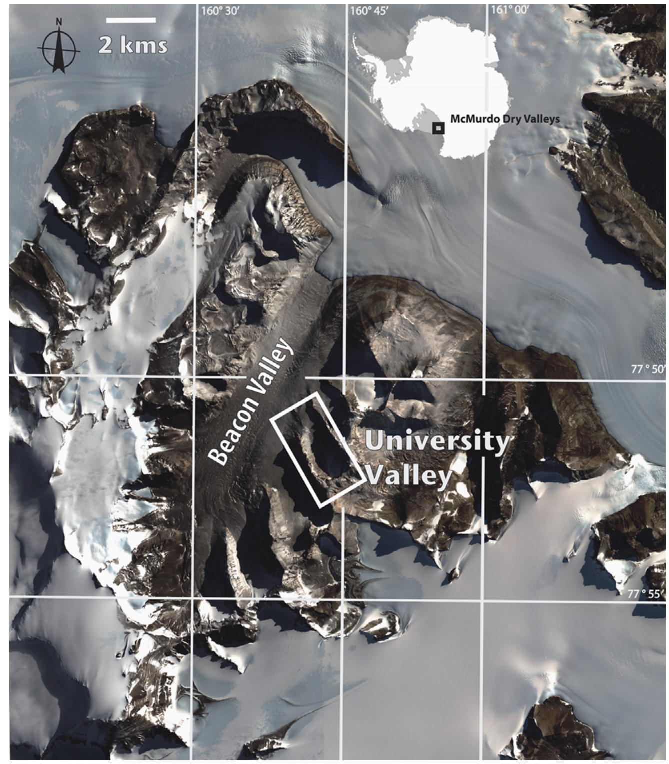

Fig. 2. The McMurdo Dry Valleys of Antarctica.

With respect to ground ice, Beacon Valley and University Valley are two of the most studied valleys in the upper elevations (Fig. 2). Beacon is a large W–E trending valley dominated by the Mullen Rock Glacier in the upper valley and by the presence of the Taylor Glacier in the lower valley. Of particular interest is Middle Beacon Valley which is dominated by massive ground ice typically found beneath an average 50 cm of fine grain ablation till (Kowalewski et al., 2006). The massive ground ice in Middle Beacon Valley is presumably of glacial origin and has been reported to be 8 million years old (Sugden et al., 1995; Schafer et al., 2000; Marchant et al., 2002), although the age and stability of this ice is still uncertain (Hindmarsh et al., 1998; Ng et al., 2005; Schorghofer, 2005; Kowalewski et al., 2006; McKay, 2009).

University Valley is a small glacial valley that trends N–S at ~1750 m elevation, which is ~300 m above Middle Beacon Valley (Fig. 2). The floor of University Valley is primarily (> 90%) composed of a dry permafrost layer abruptly underlain by ice-cemented to ice-bonded ground. The dry permafrost layer is composed of a veneer of regolith and weathered colluvium. There are also local deflation hollows and desert pavements suggesting some aeolian activity. The maximum summer air temperature in University Valley was −2.9 °C for 2009–2010, and is not expected to rise above 0 °C (Marinova et al., 2011). The depth to ground ice