MODELING VAPOR DIFFUSION IN SUBLIMATION TILLS OF THE ANTARCTIC DRY VALLEYS: IMPLICATIONS FOR THE PRESERVATION OF NEAR-SURFACE ICE ON MARS.

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Introduction: Interest in buried glacial ice has gained considerable attention in recent years due to its potential as an archive for long-term climate change and as a consequence of recent suggestions that call for relatively young, near-surface buried ice on Mars. Geochemical analyses of ice stored in stagnant debris-covered glaciers in the western Dry Valleys region of Antarctica (stable upland zone, [1]) may ultimately extend records back into the Miocene, well beyond that now possible from analyses of ice at Vostok and Dome C (e.g. [2]). At issue, however, is whether these stagnant debris-covered glaciers can maintain a core of glacier ice for millions of years, or whether ice sublimation would remove all traces of original glacier ice over these time scales (e.g., [3,4,5]).

In order to address the question of the longevity of buried glacier ice in the Dry Valleys, we modeled summertime vapor flow through an ancient sublimation till that caps a buried glacier in central Beacon Valley (Fig. 1). The age of this underlying glacier ice is debated (e.g., [6]), with published ages ranging from ~300 ka [7], to > 2.3 Ma [5,8], to > 8.1 Ma [3]. In this paper we outline the range of climate conditions necessary to preserve the buried ice for millions of years. Our approach is to first calculate rates of summertime sublimation and vapor flow under existing climate conditions (atmospheric temperature and relative humidity, solar radiance, soil temperature and moisture) and then calculate sublimation rates for a range of plausible climate scenarios that may have occurred in this sector of Antarctica over the last several million years.

Geologic setting: The buried ice in central Beacon Valley is stagnant (zero horizontal motion, [9]) and contains 3-wt% debris; it rests beneath a thin sublimation till that is on average 50-cm thick. Debris within the ice is commonly concentrated in bands up to 10-cm thick and includes clay-to-cobble-sized clasts of Ferrar Dolerite, Beacon Heights Orthoquartzite, and granite erratics foreign to Beacon Valley [8]. Sublimation of the ice has thus far produced the thin protective cap of sublimation till that mantles the ice (Fig. 1). Schaefer *et al*. [5] showed ice sublimation decreases with increasing till thickness and [8] found that the development of high-centered polygons at the till surface also exerts a strong control on ice sublimation. Initially rates of sublimation are highest at immature polygon troughs, but as troughs deepen via sublimation, they become preferred sites for windblown snow; this snow cover reduces underlying ice sublimation and in many cases leads to the formation of secondary ice [8]. To a first order, then, ice sublimation is controlled by the rate of ice loss at polygon centers (see also Fig. 1). Hence we have focused our analyses on sublimation processes at polygon centers.

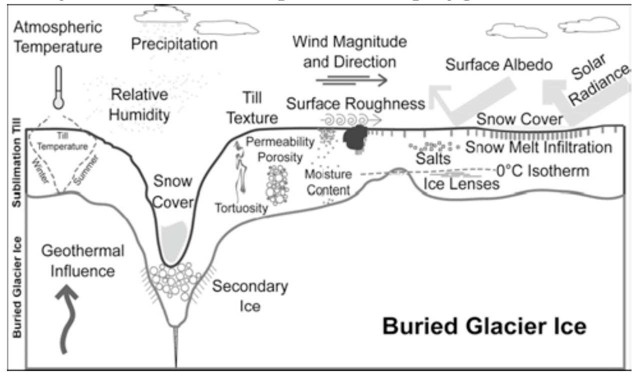

Fig. 1. Factors that influence the stability of buried glacier ice. Meteorological factors include wind speed and direction, solar radiance, precipitation, atmospheric temperature, and atmospheric relative humidity. Geological factors include till texture, till thickness, surface albedo, the formation of ice lenses and secondary salts, the development of thermal contraction cracks, and geothermal heat. Isotopic analysis ($\delta^{18}O$ and δD) can be used to differentiate buried glacier ice from secondary ice lenses [8].

Methods: We deployed a series of HOBO Micro Station data loggers and "Smart Sensors" (manufactured by Onset Computer Corporation) along a vertical profile at the center of a well-formed polygon in central Beacon Valley. The diameter of the polygon is ~17 m and the nearest trough from the profile is about ~6 m distant. Data for solar radiance, relative humidity, atmospheric and soil temperature, and soil moisture were collected at 15-min increments from 18 Nov. to 29 Dec. 2004.

Calculated vapor flux through sublimation till: The vapor flux within sublimation till is governed primarily by two mechanisms: molecular diffusion of water vapor in the pore space and advection of air through the till. Our model does not specifically track vapor pressures beyond saturation (as may occur with the formation of hoar frost), but results can be used to infer times when secondary ice would likely form in pore spaces within the sublimation till. Such secondary ice would decrease till porosity and increase tortuosity, both of which would tend to retard vapor diffusion (Fig. 1). Given the very dry soil conditions of this till (in comparison with seasonally wet and frozen tills with dynamic active layers in Arctic regions, e.g. [10, 11]), phase changes associated with the development of minor pore ice would not significantly alter the thermal profile of the sublimation till. Our parameters for porosity, tortuosity, and the diffusion coefficient are 0.41, 2, and 9.6 x 10^{-4} m^2/min respectively, and are all within published values for Dry Valley soils [4,12,13]. We assume that the temperature of air in pores within the sublimation till is the same as that recorded for surrounding sediment; we also assume that RH is 100% just above the buried-ice surface and that it varies linearly within the till to measured RH values 2 cm above the ground surface. Our model stresses Fickian diffusion, which is the dominant vapor-transport process in sublimation tills [14] and ignores the very minor effects of Knudsen diffusion.

Conclusions: Our results suggest that buried ice in central Beacon Valley could survive for millions of years given very minor changes in local climate conditions: current year-long sublimation rates at the study site are most likely <1.4 x 10^{-4} m a^{-1} [15]. A stable, buried ice surface (no net gain or loss of ice during summer months) is achieved with any one of the following summertime changes: atmospheric temperature drops ~5.5ºC (from -7ºC to -12ºC); RH rises 22% (from 36% to 58%); snowmelt equals ~0.002 mm day^{-1}. Assuming that there is no significant departure in seasonality and that rates for summertime sublimation can be applied year-round (an overestimate for annual ice sublimation), a 400 m ice loss over the past 8.1 Ma (e.g. [16]) could be achieved with any one of the following changes: atmospheric temperature drops ~3ºC; RH rises 15%; snowmelt equals ~0.001 mm day^{-1}. Such changes are reasonable, given that Antarctic ice-core records show that air temperatures over the last 5 glacial-interglacial cycles were on average ~3°C colder than today [17]. An increase in cloud cover alone might yield the requisite conditions for long-term ice preservation; this would likely lead to an overall decrease in air temperature, an increase in RH, and if accompanied by precipitation as would be expected, a potential increase in the magnitude of snowmelt. The results presented here are conservative in that our model does not consider the reduction in vapor diffusion (ice loss) that would accompany 1) the progressive increase in tortuosity that might arise from the development of salt and/or ice crystals in pore spaces (e.g., [18,19]), 2) the burial of ice and sublimation till beneath long-lived perennial snow banks and/or ice [7], and 3) the influence of surface roughness on atmosphere-till boundary layer conditions that could result in elevated RH across the till surface.

These observations have important implications for Mars, and the possibility of preservation of buried ice in the subsurface. Recent spacecraft data have revealed a wide range of evidence of ice playing a role in the geomorphic evolution of the surface during the Amazonian, the most recent period of the history of Mars. Tropical mountain glacier deposits have been mapped in the Tharsis region [20], evidence for regional glacial landsystems has been described in the mid-latitudes [21], features interpreted to be rock glaciers and debris-covered glaciers have been mapped in the mid-latitudes [22,23], and a recent, thin, apparently ice-rich mantling deposit at mid to high latitudes has been interpreted to be from ice-ages on Mars [24]. Evidence from Odyssey [25] indicates the presence of buried ice in the regions suspected to contain remnants of ice from recent ice ages. Together, these data strongly suggest the presence of near-surface ice that dates from earlier in the geologic history of Mars and contains evidence of conditions during these times. The results of quantitative field studies in the ADV, the most Mars-like region on the Earth [1], suggest that ice may well remain in the subsurface for millions of years and may help to provide insights into the interpretation of the Mars geological and climatic record.

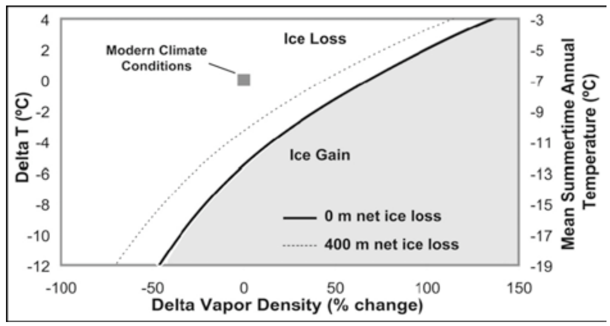

Fig. 2. Stability field for buried glacier ice in central Beacon Valley relative to changes in summertime atmospheric temperature and atmospheric vapor density (2 cm above the ground surface). Scale on right reflects the mean summertime air temperature at 2 cm (mean summertime temperature at 2 cm is currently -7°C). Modern climate conditions, represented by grey square, plot in region of net ice loss. Solid black line shows the combination of atmospheric temperature and atmospheric vapor density required for zero net loss/gain of ice (stable ice surface). Dashed line shows the conditions required to achieve a vertical ice loss of 400 m, consistent with geologic data presented in [16].

References: [1] Marchant and Head, *Icarus*, in review, 2006; [2] Epica Community Members, *Nature* 429, 623, 2004; [3] Sugden et al., *Nature*, 176, 412, 1995; [4] Hindmarsh et al., *Geografiska Ann*., 80(A), 209, 1998; [5] Schaefer et al., *EPSL*, 179, 91, 2000; [6] van der Wateren and Hindmarsh, *Nature*, 375, 389, 1995; [7] Ng et al., *Geology*, 33, 121, 2005; [8] Marchant et al., *GSA Bull*. 114, 718, 2002; [9] Rignot et al., *GRL*, 29 doi:10.1029/2001GL013494, 2002; [10] Beyer et al., *Ant. Sci*., 4, 387, 1999; [11] Bockheim and Hall, *South Afr. Jour. Sci*., 98, 82, 2002; [12] McKay et al., *Ant. Sci*., 10, 31, 1998; [13] Pringle et al., *Jour. Geophys. Res*., 108, doi: 10.1029/20022JB002364, 2003; [14] Schorghofer and Aharonson, *Jour. Geophys. Res*., 110, doi:10/1029/ 2004JE002350, 2005; [15] Kowalewski et al., *Ant. Sci*., 18(3), 421, 2006; [16] Potter et al., *GSA Abstract*, *2003 Ann Mtg*, 463, 2003; [17] Petit et al., *Nature*, 399, 429, 1999; [18] Bao et al., *Nature*, 407, 499, 2002; [19] Bao and Marchant, *Jour. Geophys. Res*., 111, D16301, doi:10.1029/ 2005JD006669, 2006. [20] Head and Marchant, *Geology*, 31, 641, 2003; [21] Head et al., EPSL, 241, 663, 200; [22] Pierce and Crown, *Icarus*, 163, 46, 2003; [23] *Head* et al. (2005) Nature, 434, 346; [24] Head et al., *Nature*, 426, 797, 2003; [25] Boynton et al., *Science*, 296, 81, 2002.