

# A physical mechanism for long-term survival of ground ice in Beacon Valley, Antarctica

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Received 21 June 2005; revised 24 August 2005; accepted 29 August 2005; published 7 October 2005.

[1] Radiometric dating, geomorphology, biostratigraphy, and diffusion physics provide conflicting evidence for the age of the ground ice found in Beacon Valley, Antarctica. The rate of vapor diffusion into a dry atmosphere is incompatible with a minimum radiometric age of 8 Ma. Recent measurements of meteorological conditions in Beacon Valley show that the humidity of the atmosphere, although small, is comparable to the saturation vapor pressure at the ice. Analogous conditions explain the survival of ground ice at the high latitudes of Mars. At the study site, atmospheric vapor slows the sublimation loss by a factor of three and the retreat will cease entirely if temperatures are lower by 5°C. Detailed model simulations show that advection, including the advection from changes in surface pressure caused by winds, has a negligible effect on sublimation loss. **Citation:** Schorghofer, N. (2005), A physical mechanism for long-term survival of ground ice in Beacon Valley, Antarctica, *Geophys. Res. Lett.*, 32, L19503, doi:10.1029/2005GL023881.

## 1. Introduction

[2] The Dry valleys of Antarctica experience mean annual temperatures of  $-15$  to  $-30^{\circ}\text{C}$  [Doran *et al.*, 2002a], but due to the low atmospheric humidity they remain ice free through most of the year. Radiometric ages and geomorphology suggest their landscapes are very old [Sugden, 1996, and references therein]. Beacon Valley, located at  $77^{\circ}\text{S}$ ,  $161^{\circ}\text{E}$ , and  $\sim 1200$  m above sea level, harbors ground ice in the shallow subsurface. Radiometric dating of in-situ ashes in the upland frozen zone of Beacon Valley indicates the ice is at least 8 Ma old [Sugden *et al.*, 1995]. If true, it would be the oldest ice known on Earth, buried only decimeters beneath a surface which is currently free of perennial ice. However, biostratigraphy and diffusion physics argue for a younger age [Webb and Harwood, 1991; van der Wateren and Hindmarsh, 1995; see also Ng *et al.*, 2005]. This letter addresses the diffusion physics aspect and proposes a possible mechanism which allows for long-term survival of ground ice.

[3] A back-of-the-envelope estimate of the rate of vapor diffusion from the ice into a dry atmosphere indicates the ground ice should retreat at a rate inconsistent with an age of 8 Ma [van der Wateren and Hindmarsh, 1995]. The rate of ice loss through the porous soil is approximately described by  $r = -D\Delta\rho/(\rho_{\text{ice}}\Delta z)$ , where  $D$  is the diffusion coefficient,  $\Delta\rho$  the difference between the vapor density in the atmosphere and the air in immediate contact with the ice,  $\Delta z$  the burial depth of the ice, and  $\rho_{\text{ice}}$  the density of the ground ice. For example, with  $D = 0.1 \text{ cm}^2 \text{ s}^{-1}$ ,  $\Delta z = 0.5 \text{ m}$ , and a mean temperature of  $253 \text{ K}$  ( $-20^{\circ}\text{C}$ ), the retreat rate is  $0.60 \text{ m ka}^{-1}$ . The vapor

density difference depends strongly on the temperature of the ice, because of the exponential dependence of the saturation vapor curve. For  $238 \text{ K}$  ( $-34^{\circ}\text{C}$ ), at the low end of what is assumed for the region [Marchant *et al.*, 2002], the retreat is still  $0.15 \text{ m ka}^{-1}$ .

[4] To systematically address the validity of diffusion calculations, one can scrutinize: 1) the value of the diffusion coefficient, 2) the validity of the assumed physics and the resulting governing equations, and 3) the atmospheric humidity.

[5] Vapor transport through the soil occurs through interstitial void spaces. The review of Massman [1998] recommends a diffusion coefficient for  $\text{H}_2\text{O}$  in air of  $0.2178(T/T_0)^{1.81}$  (in units of  $\text{cm}^2 \text{ s}^{-1}$ ;  $T_0 = 273.15 \text{ K}$ ) with an uncertainty of  $\pm 7\%$ . The diffusion coefficient is inversely proportional to the pressure. In a porous medium, the diffusion coefficient can be written as  $D = (\phi/\tau) D_{\text{free gas}}$ , where  $\phi$  is the porosity and  $\tau$  the tortuosity. The obstruction by porosity and tortuosity amounts typically to a factor of a few [Moldrup *et al.*, 2000]. For  $\phi = 0.4$  and  $\tau = 1.5$ , the estimated diffusion coefficient is  $0.2178 \times (252/273)^{1.81} \exp(1.2/10) \times 0.4/1.5 \approx 0.06 \text{ cm}^2 \text{ s}^{-1}$ . The exponential factor arises from the reduced pressure at an elevation of 1.2 km. To reconcile the calculated sublimation loss with the dating, the diffusion coefficient would have to be smaller by several orders of magnitude. Mechanisms that do that have been hypothesized (adsorption, soil moisture, sublimation till with extremely low porosity), but their applicability remains to be demonstrated.

[6] Hindmarsh *et al.* [1998] compute the vapor flux with a detailed numerical model, which simulates vapor diffusion with a temperature dependent diffusion coefficient and the advection of water vapor due to the thermal expansion and contraction of air. They found that the back-of-the-envelope estimate approximates the more accurate calculations of the vapor flux well.

[7] The calculations by van der Wateren and Hindmarsh [1995] and Hindmarsh *et al.* [1998] consider a completely dry atmosphere. However, the atmospheric vapor content can prolong the survival time of ice, even if the (absolute) humidity is tiny. McKay *et al.* [1998] include the atmospheric humidity in their calculation of the recession rate of ground ice in the nearby Asgard Range of Antarctica, and suggest the ice is of recent origin. In the following, methods similar to Hindmarsh *et al.* [1998] and McKay *et al.* [1998] are applied to the meteorological data now available for Beacon Valley.

## 2. The Survival Mechanism

[8] The McMurdo LTER Automatic Weather Network [Doran *et al.*, 1995, 2002a] provides measurements of air

**Table 1.** Mean Annual Temperatures and Vapor Content From Meteorological Station Measurements [Doran *et al.*, 1995] in Beacon Valley, Antarctica<sup>a</sup>

year	2001	2002	2003	3-Year Average
$\langle T_{\text{air}} \rangle$ (°C)	-21.6	-21.8	-21.2	-21.6
$\langle T_{\text{soil}} \rangle$ , 0 cm (°C)	-21.8	-22.1	-21.1	-21.6
$\langle T_{\text{soil}} \rangle$ , 5 cm (°C)	-21.4	-21.8	-21.0	-21.4
$\langle T_{\text{soil}} \rangle$ , 10 cm (°C)	-21.3	-21.6	-20.9	-21.3
$\langle p \rangle^b$ (Pascal)	58	58	66	61
$p_{\text{sv}}(\langle T_{\text{soil}} \rangle)^c$ (Pascal)	91	88	94	91
$\langle \rho \rangle^d$ (kg m <sup>-3</sup> )	$4.8 \times 10^{-4}$	$4.9 \times 10^{-4}$	$5.6 \times 10^{-4}$	$5.1 \times 10^{-4}$
$\rho_{\text{sv}}(\langle T_{\text{soil}} \rangle)^e$ (kg m <sup>-3</sup> )	$7.8 \times 10^{-4}$	$7.6 \times 10^{-4}$	$8.1 \times 10^{-4}$	$7.8 \times 10^{-4}$

<sup>a</sup>Angle brackets indicate time averages.

<sup>b</sup> $p$  partial pressure of H<sub>2</sub>O in the atmosphere.

<sup>c</sup>Saturation vapor pressure at the mean ice temperature.

<sup>d</sup> $\rho$  vapor density in the atmosphere.

<sup>e</sup>Vapor density of saturated air at mean temperature.

temperature, soil temperature, relative humidity, and wind speed from meteorological stations in the Dry Valleys of Antarctica. Thanks to these field data several thermodynamic relations can be determined. The automated meteorological station in Beacon Valley stores a data point every 15 minutes, without gaps. It is located in the region where the age of the ash overlying the ice has been determined. Air temperature and humidity are measured 3 m above ground. Soil temperatures are available at 0 cm, 5 cm, and 10 cm depth. The last calendar day of 2003 is missing from the publicly released data and is replaced with a copy of the data from Dec 30, 2003. Table 1 lists mean temperatures, partial pressures, and vapor densities. The partial pressure of H<sub>2</sub>O in the atmosphere is obtained by multiplying the measured relative humidity with the saturation vapor pressure over ice (when < 0°C) or water (when > 0°C). Vapor densities are calculated using the ideal gas law.

[9] The mean partial pressure in the atmosphere in the period 2001–2003 is 61 Pascal, the mean vapor density  $5.1 \times 10^{-4}$  kg m<sup>-3</sup>. The atmosphere contains the most vapor during the warmest months, November to February. Since mean temperatures are constant with depth, the mean temperature of the ground ice is the same as on the surface. Evaporative cooling of the ice is negligible. The saturation vapor pressure at -21.3°C is 91 Pascal, the corresponding vapor density  $7.8 \times 10^{-4}$  kg m<sup>-3</sup>. Although the humidity in the atmosphere is lower than at the ice surface, the two quantities are comparable.

[10] The retreat rate is

$$r = \frac{D}{\Delta z} \langle \rho_{\text{sv}}(T) - \rho \rangle \frac{1}{\rho_{\text{ice}}}, \quad (1)$$

with  $\rho_{\text{ice}} = 920$  kg m<sup>-3</sup> (at -20°C), and  $\rho_{\text{sv}} = 18p_{\text{sv}}(T)/RT$ , where  $R$  is the universal gas constant. Angle brackets indicate time averages. The retreat rate vanishes when  $\langle \rho \rangle = \langle \rho_{\text{sv}}(T) \rangle$  [Mellon and Jakosky, 1993]. Ground ice is stable when it is not exposed to any temperature variations, because  $\langle \rho_{\text{sv}}(T) \rangle \geq \rho_{\text{sv}}(\langle T \rangle)$ . These variations become smaller with increasing depth. A comparison of  $\langle \rho \rangle$  with  $\rho_{\text{sv}}(\langle T \rangle)$ , both available from measurement, shows whether or not ice is stable at some depth.

[11] Sublimation loss will stop if the mean atmospheric humidity is about 50% higher than in 2001–2003 or if mean

temperatures drop by 5°C to -26°C, which would lower the saturation vapor density to  $5 \times 10^{-4}$  kg m<sup>-3</sup>. When subject to time varying temperatures, the atmosphere does not need to be close to saturation to stop the retreat. The current average relative humidity is 56% and the extrapolated relative humidity when temperatures are lower by 5°C is 80%. These 80% would be enough to stop the retreat completely.

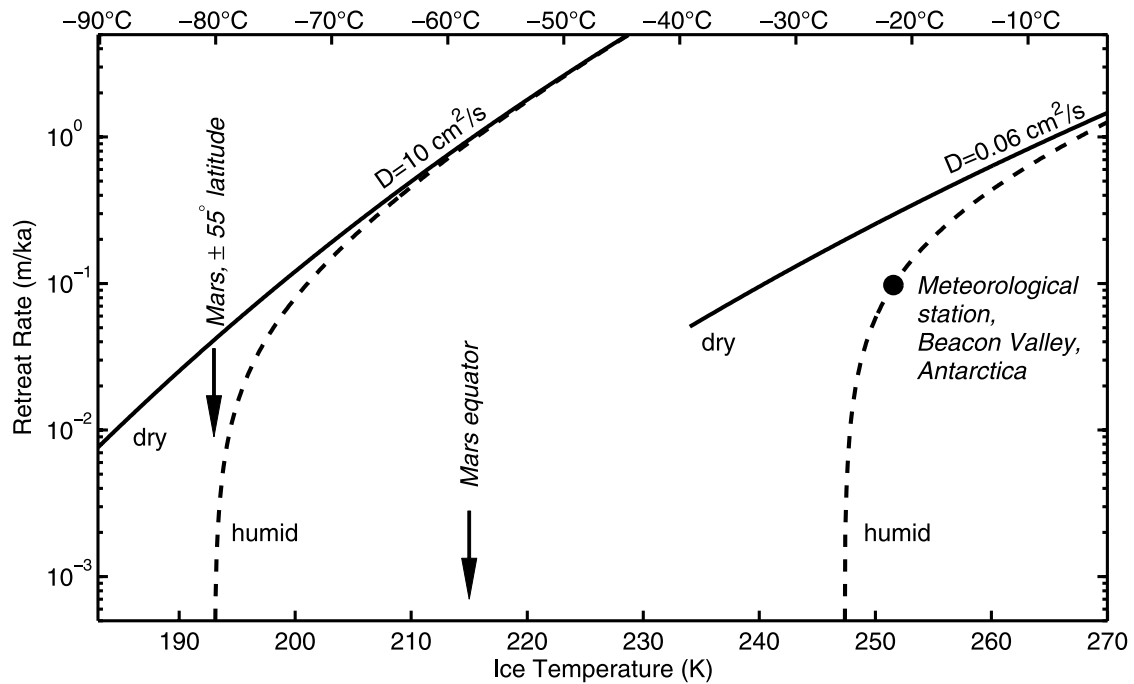
[12] Figure 1 illustrates the retreat rate for a dry and a humid atmosphere as a function of mean temperature. Retreat rates for martian ground ice are also shown, for comparison. At sufficiently cold temperatures, the humidity of the atmosphere prevents sublimation loss.

[13] The meteorological station at the floor of Beacon valley provides the vapor content at one site and for one mean temperature (large solid dot in Figure 1). In Figure 1, the same absolute vapor content is assumed for different temperatures. When the mean temperature, of the ice and the atmosphere, drops, the mean vapor content has to change too, because the atmosphere is more often saturated beyond its capacity to hold vapor. The relative humidity recorded by the station is rarely close to 100%, and the reduction of atmospheric vapor content forced by lower temperatures is small. Increased relative humidity will tend to increase precipitation, but does not necessarily lead to perennial ice on the surface. Also, the sublimation temperature depends only weakly (approximately logarithmically) on the atmospheric vapor content.

[14] Permanent ground ice beneath an ice-free surface is common on Mars. On Mars, the globally averaged partial pressure of H<sub>2</sub>O on the surface is ~0.13 Pascal at daytime. This amount of vapor saturates the atmosphere at 198 K. Due to nighttime saturation the mean vapor content is lower than the daytime average, reducing the mean temperature required to retain the ice below 198 K. Figure 1 uses globally averaged values for illustration, although quantities vary with geographic longitude and are different on the two hemispheres. Arrows indicate the approximate temperatures at the equator and at latitudes of  $\pm 55^\circ$ . Ground ice is found polewards of these latitudes. The same mechanism that accounts for the persistence of ground ice at the high latitudes on Mars [Boynton *et al.*, 2002; Mellon *et al.*, 2004; Schorghofer and Aharonson, 2005] could explain fossil ice in Beacon Valley.

### 3. Detailed Model of Vapor Transport

[15] There are four causes of vapor transport: concentration diffusion, thermal diffusion, pressure diffusion, and advection [Cunningham and Williams, 1980; Landau and Lifshitz, 1987]. Thermal and pressure diffusion are negligible in terrestrial environments. Diffusion describes the relative motion of two or more gases, while advection refers to the bulk motion of the gas. In the following,  $\rho_1$  indicates the vapor density of H<sub>2</sub>O (denoted with  $\rho$  above,  $\rho \equiv \rho_1$ ),  $\rho_2$  the mass density of air (without the water), and  $\sigma_1$  the density of ice. Subscript 1 stands for H<sub>2</sub>O and subscript 2 for air, which is treated as a single gas with molecular weight 28.9. A zero index indicates the total quantity, e.g.,  $\rho_0 = \rho_1 + \rho_2$ . The densities are relative to the void space.



**Figure 1.** Theoretically calculated rate of ice retreat due to sublimation loss at Earth and Mars pressure. For a perfectly dry atmosphere (solid lines) the sublimation loss is always larger than zero. A humid atmosphere (dashed lines) can stop the retreat, if the ice is cold enough. Retreat rates are calculated from equation (1) and assume a diffusion coefficient  $D = 0.06 \text{ cm}^2 \text{ s}^{-1}$  for Earth and  $D = 10 \text{ cm}^2 \text{ s}^{-1}$  for Mars and a burial depth of  $\Delta z = 0.5 \text{ m}$ . The retreat rate is proportional to  $D$  and the threshold temperature is independent of  $D$ .

[16] The temperature is determined from the heat equation, using measured surface temperatures as a boundary condition. The vertical velocity  $w$  in the ground is

$$w = -\frac{\epsilon}{\eta} \frac{\partial p_0}{\partial z}, \quad (2)$$

where  $\epsilon$  is the permeability,  $\eta$  the viscosity  $\sim 1.6 \times 10^{-5} \text{ Pa s}$ , and  $p_0$  the total pressure. The mass fluxes  $J_i$  due to diffusion and advection are [Landau and Lifshitz, 1987]

$$J_i = -D\rho_0 \frac{\partial}{\partial z} \left( \frac{\rho_i}{\rho_0} \right) + w\phi_i \quad i = 1, 2 \quad (3)$$

Conservation of mass requires

$$\phi \frac{\partial}{\partial t} (\rho_1 + \sigma_1) + \frac{\partial}{\partial z} J_1 = 0 \quad (4)$$

$$\phi \frac{\partial}{\partial t} \rho_2 + \frac{\partial}{\partial z} J_2 = 0. \quad (5)$$

[17] For constant  $\rho_0$  and negligible advection, the flux of water vapor through the interstitial air, equation (3), is given by  $J_1 = -D\partial\rho_1/\partial z$ . The vapor density can be decomposed into a mean and a fluctuating component. The average gradient is then  $\langle \partial\rho/\partial z \rangle = \partial\langle\rho\rangle/\partial z$ . By mass conservation, the annual mean flux  $\langle J_1 \rangle$  is constant with depth, hence  $\partial\langle\rho\rangle/\partial z = \Delta\rho/\Delta z$ . This justifies formula (1) for the retreat rate used above,  $\langle J_1 \rangle = r\rho_{\text{ice}} \approx \langle D \rangle \Delta\langle\rho\rangle/\Delta z$ .

[18] The ideal gas law connects partial pressure and density

$$p_i = \rho_i RT / \mu_i \quad i = 1, 2 \quad (6)$$

where  $\mu_i$  are the molecular weights. Equations (2)–(6) lead to

$$\phi \frac{\partial}{\partial t} (\rho_i + \sigma_i) = \frac{\partial}{\partial z} \left[ D\rho_0 \frac{\partial}{\partial z} \left( \frac{\rho_i}{\rho_0} \right) + \phi\rho_i \frac{\epsilon}{\eta} \frac{\partial p_0}{\partial z} \right]. \quad (7)$$

These model equations are more detailed than the calculations by [Hindmarsh et al., 1998] and incorporate surface winds. In the presence of wind, the upper pressure boundary condition becomes  $p_0(v) = p_0(0) - \rho_0 v^2/2$ , where  $v$  is the the wind velocity. The average measured wind velocity is  $4.2 \text{ m s}^{-1}$ .

[19] The equations are solved numerically by discretizing the spatial derivatives in equation (7). The explicit scheme is restricted in step size to low diffusivity and low permeability, but realistic parameter values can be reached. Measured temperature, humidity, and wind speed are used as boundary condition and interpolated if the time step is smaller than 15 minutes. The same 3 years of data are used repeatedly until model quantities equilibrate and averages are formed from the last 3-year period. Ice is assumed to exist at the bottom boundary, where there is no heat flux, the partial pressure of  $\text{H}_2\text{O}$  equals the saturation vapor pressure, and the ice is impermeable,  $J_2 = 0$ . The total flux  $J_1 + J_2$  does not vanish at the ice surface, because the vapor loss causes a center of mass motion,  $J_1 \neq 0$ .

[20] Table 2 shows the retreat rate multiplied with the burial depth from detailed model calculations in comparison

**Table 2.** Sublimation Loss From Detailed Model Calculations<sup>a</sup>

	$\epsilon$ , darcy	$\langle v \rangle$ , m/s	$\langle p \rangle$ , Pa	$r\Delta z$ , $\text{m}^2 \text{ka}^{-1}$	$\frac{\langle w \rangle \Delta z}{D}$
Estimate	0	0	61	0.048	0
Detailed	0.001	0	61	0.045	0.0003
Detailed	1	0	61	0.045	0.0003
Detailed	0.001	4.2	61	0.045	0.0003
Detailed	1	4.2	61	0.045	0.0003
Estimate, dry	0	0	0	0.143	0
Detailed, dry	0.001	0	0	0.147	0.0009
Detailed, dry	0.001	4.2	0	0.147	0.0009
Detailed, $-2^\circ\text{C}^{\text{b}}$	0.001	4.2	59	0.023	0.0001
Detailed, $-5^\circ\text{C}^{\text{b}}$	0.001	4.2	55	0	0
Detailed, $3p^{\text{c}}$	0.001	4.2	90	0	0

<sup>a</sup>Permeability  $\epsilon$  and wind velocity  $v$  are input parameters.

<sup>b</sup>Surface and air temperatures are artificially lowered. Absolute humidities in the atmosphere remain the same, except when limited by saturation.

<sup>c</sup>Atmospheric partial pressures are artificially increased, but not beyond saturation,  $p \rightarrow \min(3p, p_{\text{sat}}(T))$ .

with the back-of-the-envelope estimate. There is little difference between the estimate and detailed simulations, for low and for moderate permeability. Table 2 also shows the retreat rate when measured wind velocities are included in the model calculations. The pressure drop caused by the wind does not have a notable effect on the mean sublimation loss.

[21] The mean vertical velocity  $\langle w \rangle$  is small compared to the speed of diffusion  $D/\Delta z$  in all model calculations and the transport is always dominated by diffusion. Advection contributes little to the vapor loss, because there is no supply of air from beneath the ice. In fact, the mean vertical bulk velocity of the gas column is set by the outgoing flux of  $\text{H}_2\text{O}$  vapor and is independent of permeability.

[22] Lowering the temperature by  $5^\circ\text{C}$  stops sublimation loss entirely. Alternatively, the mean absolute humidity would need to increase by 50% to stop sublimation loss, but the limited capacity of the air to hold water requires instantaneous humidities be tripled. Stabilizing the ice by a humidity increase appears hence less realistic than a temperature drop.

#### 4. Discussion

[23] The sublimation loss is to a good approximation determined by the mean conditions on the surface and in the subsurface. The net flux consists of an outgoing and an incoming component, and it is exactly this incoming vapor which previous calculations had neglected. The seasonal, atmospherically derived frost may exist as adsorbed water, may form interstitial frost in the pores, or condense on the ground ice. This depends in detail on the adsorption behavior of the soil [Schorghofer and Aharonson, 2005]. The seasonal subsurface frost has probably disappeared in southern summer, but could be observable at other times, most likely around the time when the soil is coldest. The amount of transient incoming  $\text{H}_2\text{O}$  should currently be on the order of  $0.2 \text{ kg m}^{-2}$ , the equivalent of a 0.2 mm thick layer.

[24] How is it possible there is no or little precipitation on the surface during the year, while the ice beneath is close to

permanently stable? At mean conditions the atmosphere must at least be close to saturation, implying that there should be precipitation seasonally. Seasonal surface precipitation is not a reliable indicator for the persistence of ground ice for several reasons. Most of the vapor is supplied in the warm months. There is in fact a negative correlation between absolute and relative humidity. The answer lies, in part, also in the presence of two temperature cycles, diurnal and seasonal. The diurnal temperature cycles interrupt the accumulation of surface frost or snow. Polar winter blurs this distinction, but some precipitation actually does occur in Beacon Valley.

[25] The proposed mechanism does not argue that the ice should be millions of years old, it merely allows for this possibility. Currently, ice beneath the meteorological station should retreat. The sublimation loss depends sensitively on temperature and can quickly switch between perennial stability and rapid retreat. Temperatures in the Dry Valleys have recently decreased by  $0.7^\circ\text{C}$  per decade [Doran et al., 2002b]. Temporal uncertainties include perennially stable conditions. There could be locations in the Dry Valleys where no sublimation loss occurs today and it is plausible that ice has survived even longer than known to date.

[26] **Acknowledgments.** It is a pleasure to thank Oded Aharonson, Peter Doran, Dave Marchant, and Asmin Pathare for helpful discussions. This material is based upon work supported by the National Aeronautics and Space Administration through the NASA Astrobiology Institute under Cooperative Agreement No. NNA04CC08A issued through the Office of Space Science.

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