A 2D Model for Characterising First-order Variability in Sublimation of Buried Glacier Ice, Antarctica: Assessing the Influence of Polygon Troughs, Desert Pavements and Shallow Subsurface Salts

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ABSTRACT

To assess the role of thermal contraction-crack polygons (sublimation polygons) in modulating sublimation of buried glacier ice in Antarctica, we applied a 2D numerical model using COMSOL Multiphysics that calculates the rate and spatial variability of vapour diffusion through porous media. Specifically, we examined vapour transport through Granite drift, a dry supraglacial till marked with thermal contraction-crack polygons that rests on glacier ice reportedly ≥8-million years in age. The model results show that sublimation varies with drift texture and surface topography. Initially, the rates are highest beneath relatively coarse-grained sand-wedge deposits at polygon margins, creating deep, surface troughs. As troughs approach ~1-m depth, the cooler atmospheric and soil temperatures that arise from solar shielding reduce the rates of ice sublimation to levels below that at polygon centres, preventing runaway ice loss at polygon margins. Including the effects of a salt-cemented horizon at 10–15-cm depth (porosity 20%) and a rocky surface pavement (75% ground coverage), our modelled ice loss at polygon centres, for example, is 0.022 mm a−1, an order of magnitude lower than previous estimates (0.14 mm a−1). This finding highlights the importance of including field-based data for drift texture, topography and microclimate variation in modelling ice sublimation. The results also suggest that stable conditions (no ice loss) at polygon centres are possible with either a 1.9°C decrease in mean annual atmospheric temperature or a 12 per cent increase in mean annual relative humidity. These results indicate that the preservation of buried, multi-million-year-old ice is plausible in the coldest and driest regions of Antarctica. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: Antarctica; Beacon Valley; ancient ice; sublimation; thermal contraction-crack polygons; numerical modelling

INTRODUCTION

Recent findings of shallow, buried glacier ice beneath dry tills <1 m thick in Antarctica have prompted numerous inquiries regarding the physical and environmental factors that modulate vapour diffusion through porous media (Hindmarsh et al., 1998; McKay et al., 1998; Marchant et al., 2002; Pringle et al., 2003; Schorghofer, 2005; Kowalewski et al., 2006; Hagedorn et al., 2007, 2009; McKay, 2009; Lacelle et al., 2011; Morgan et al., 2011). Some of the oldest buried ice deposits in Antarctica are reportedly up to 8.1-million-years old (Sugden et al., 1995). Although the age is debated (Hindmarsh et al., 1998), the possibility of Miocene-aged buried ice has led to much discussion regarding long-term climate variability (or lack thereof) within high-elevation regions (>1200 m) of the Transantarctic Mountains (Lewis et al., 2007, 2008; Naish et al., 2009). In addition, results from the analyses of such buried ice deposits have helped frame discussions on the origin of similar appearing, postulated ice-rich deposits on Mars (Head and Marchant, 2003; Marchant and Head, 2007; Holt et al., 2008; Plaut et al., 2009; Smith et al., 2009; Head et al., 2010). It is within this framework that we modelled sublimation of ancient buried glacier ice in the McMurdo Dry Valleys, Antarctica.

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GEOLOGIC SETTING

Ancient Ice

Ancient buried glacier ice occurs in the central Beacon Valley (Figure 1) (Sugden et al., 1995). The ice is derived from Taylor Glacier, which advanced southwards into Beacon Valley during Miocene time (>8.1 Ma; Sugden et al., 1995) (Figure 2). The remnant ice is not physically connected with the modern Taylor Glacier, but instead appears as a detached, stagnant block ~5 km from the margin of Taylor Glacier at the valley mouth (Figure 2). The buried ice surface lies beneath ~50 to 100 cm of dry supraglacial till, informally termed Granite drift (Sugden et al., 1995). Ice thicknesses beneath Granite drift are unknown, but geophysical measurements of nearby buried glaciers in the upper Beacon Valley (Figure 2) suggest values of at least ~150 m are plausible (Shean and Marchant, 2010).

Sublimation Polygons

The surface of Granite drift displays well-developed ‘sublimation polygons’ (Figure 3). The term sublimation polygon is used for a subset of thermal contraction-crack polygons that form over buried glacier ice (or excess ice) and in regions lacking saturated active layers (Marchant et al., 2002; Marchant and Head, 2007; Levy et al., 2008). These conditions are met in the highest and driest regions of the McMurdo Dry Valleys, for example, Beacon Valley and the stable upland zone of Marchant and Head (2007). Sublimation polygons are essentially sand-wedge polygons that form over buried ice. As is the case for all contraction-crack polygons, abrupt cooling induces tensile stresses that, in competent debris, result in near-vertical cracks; in this case, the cracks truncate the buried surface of glacier ice beneath the Granite drift. Persistent subsurface temperatures well below 0°C ensure that ice loss is via sublimation. The absence of freezing and thawing restricts cryoturbation, and the dominance of ice sublimation generates a relatively simple, three-fold internal stratigraphy common to all examined sublimation polygons:

1. a fresh (pristine) facies that rests directly above buried ice (this forms as sublimation concentrates englacial debris at the top of downwasting ice, for example, a lag deposit that forms as dirty ice sublimes (Schaefer et al., 2000));
2. a weathered facies that forms at, and near, the ground surface via physical disintegration of rocks from aeolian deflation, oxidation of iron-bearing minerals and salt formation via minor snowmelt on solar-heated rocks; and
3. a sand-wedge facies that forms at polygon margins via episodic infill of thermal cracks (the sand wedges are identical to those that form in classic sand-wedge polygons (Murton et al., 2000; Marchant et al., 2002; Marchant and Head, 2007)). Gravitational sliding at the margin of steep polygon troughs

Figure 1  The McMurdo Dry Valleys (MDV). The MDV lie between the McMurdo Sound sector of the Ross Sea and the East Antarctic Ice Sheet (EAIS). Black outline in the Quartermain Mountains shows Beacon Valley and the region depicted in Figure 2. Upper left inset: location of MDV plotted on map of Antarctica.
admixes the fresh and weathered facies (Figure 4). Because the location of thermal contraction shifts over time (Berg and Black, 1966), relict sand-wedge deposits (i.e. those no longer associated with active thermal contraction) truncate this three-fold stratigraphy (see also Kowalewski et al., 2011).

As initially hypothesised in Marchant et al. (2002), textural variations among these three facies impart first-order control on vapour diffusion and loss of subsurface ice. Of particular interest (and modelled here) are the sand-wedge deposits, which, if coarser grained than pristine lags (which is the case for Granite drift, see below), would increase vapour diffusion and ice loss at polygon margins. Ultimately, this process would lead to elevated polygon centres surrounded by deep, marginal troughs (Marchant et al., 2002). We emphasise that although sublimation polygons may appear morphologically similar to the well-known, high-centred polygons of the Arctic, they differ in origin: the elevated centres of sublimation polygons arise from enhanced ice loss at polygon margins, whereas high-centred polygons of the Arctic typically arise from widespread active-layer cryoturbation, including diapirism at polygon centres (Mackay, 2000; Singleton et al., 2010).
Figure 3 Oblique aerial view of Granite drift in central Beacon Valley. “Sublimation polygons” (e.g., Marchant et al., 2002) mark the drift surface; the average polygon diameter in this image is ~18 m (see also Supplemental Table 3). Inset: the surface of buried-glacier ice beneath Granite drift; tape is 1 m long. Although sublimation polygons are morphologically similar to classic high-centered polygons of the Arctic, they differ in origin: elevated centers of sublimation polygons arise from enhanced ice loss at polygon margins, rather than from saturated active layer processes, including diapirism at polygon centers.

Figure 4 COMSOL Multiphysics model geometry. (a) Basic geometry for instrumented polygon showing polygon plateau, polygon trough, and the array of HOBO™ Smart Sensors. (b) The same instrumented polygon as shown in (a) but with alterations for the following tests: Test 1, snow in the polygon trough; Test 2, relict sand-wedge deposits at polygon centers; Test 3, shallow subsurface salts; and Test 4, rocky surface pavements. The weathered facies is represented by the rocky pavement and subsurface salt horizon; the fresh facies in noted simply as Granite drift; the sand-wedge facies occurs at the base of the polygon trough and continues for an unknown depth in glacier ice (not shown); and, the admixture of the fresh and weathered facies at trough walls is noted as slumped Granite drift (see text for details). Standard porosity values used in our baseline model run (section 4.1) are 30% for Granite drift, 45% for sand-wedges, and 40% for slumped Granite drift (see also Supplemental Documents).
Table 1 Monthly and annual meteorological data, polygon centers versus polygon troughs, Beacon Valley.

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<th>Mean</th>
<th>Difference (trough-centre)</th>
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Climate data were recorded from 8 December 2005 to 8 December 2006.
Temperatures recorded in °C.
T = Temperature; RH = relative humidity.

Local Climate Conditions

Table 1 and Figure 5 show details regarding local microclimate conditions at the study site (77.84939E, 160.59826S, ~1300-m elevation). The mean annual atmospheric temperature (MAAT), as recorded over the 12-month study interval (8 December 2005 to 8 December 2006) is −24.1°C; summertime air temperatures rarely rise above 0°C (Table 1; Figure 5) and precipitation is <50-mm water equivalent per year (Fountain et al., 2010). Atmospheric absolute humidity typically ranges from 0.0148 × 10⁻³ to 0.0036 kg m⁻³. Given these conditions, Granite drift is exceptionally dry and lacks the typical freeze-thaw cryoturbation associated with nearly all other supraglacial deposits worldwide (Paul and Eyles, 1990). The buried ice surface beneath Granite drift is smooth, dry and <0°C (Figure 3). See also supplementary documents for additional microclimate information.
Figure 5 A subset of measured meteorological conditions for central Beacon Valley. (a) Relative humidity (RH); black line shows the RH at the polygon center; gray line shows the difference in RH between the polygon center and the base of the polygon trough. (b) Atmospheric temperature; black line shows the atmospheric temperature at the polygon center; gray line shows the difference in atmospheric temperature between the polygon center and the base of the trough. All RH and temperature data were collected from a height of 10 cm above the ground surface. See supplementary document for sensor specifications.

Table 2 COMSOL simulation output for polygon centres and troughs in the Beacon Valley

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<tr>
<th>Model run</th>
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<th>Vertical relict sand wedge</th>
<th>Salt lens 45% porosity</th>
<th>Salt lens 20% porosity</th>
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Model does not include latent heat; negative modelled values predict a net downward vapour flux.

Ice loss is reported for a relict sand wedge in the centre of a polygon (see Test 2 in text).

RH = Relative humidity.
MODELLING STUDY

Model Overview

Our model simulates vapour transport via Fickian diffusion across a 2D domain as noted in Figure 4. Measured values for temperature and relative humidity (RH) are explicitly incorporated into the model to establish: (a) initial conditions at $t = 0$ throughout the domain, and (b) boundary conditions for the ice surface and the till surface at each model time step. Model output includes calculated vapour densities within the domain at each time step.

Model Detail

Our model for vapour diffusion through Granite drift assumes ice loss is accommodated solely by sublimation and that vapour transport is dominated by non-steady state Fickian diffusion (Schorghofer, 2005; Kowalewski et al., 2006). We follow Albert and Perron (2000) and Schorghofer and Aharonson (2005) in noting that the effects of advection and/or Knudsen diffusion are minor for relatively coarse-grained deposits like Granite drift, and therefore these are not included. We thus express vapour diffusion as:

$$\frac{\partial \rho}{\partial t} = D \frac{\partial^2 \rho}{\partial z^2}$$  \hspace{1cm} (1)

where $\rho$ represents water vapour density, $t$ the time, $D$ the diffusivity of water vapour (0.16 cm$^2$ s$^{-1}$) and $z$ is equal to depth. Introducing a porous medium into Equation 1, we assign values for porosity ($\phi$) as deduced from thin-section analyses (Kowalewski et al., 2011; Supplemental Table 2), and we assume a constant tortuosity ($b$) of 2, consistent with earlier studies (Hindmarsh et al., 1998; Schorghofer, 2005; Kowalewski et al., 2006). Vapour flux through the medium is thus expressed as:

$$\frac{\partial \rho}{\partial t} = \left( \frac{\phi D}{b} \right) \frac{\partial^2 \rho}{\partial z^2}.$$  \hspace{1cm} (2)

Our model does not consider vapour density exceeding saturation, as would be required for studies of relatively wet supra-glacial deposits (Hagedorn et al., 2007, 2009; Hunt et al., 2010; Swanger et al., 2010).

The vapour density for initial and boundary conditions is calculated from the water vapour pressure ($e$), which can be derived using the Clausius-Clapeyron equation:

$$e = e_0 \exp \left[ \frac{L}{\mathcal{R}_v} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \cdot \frac{RH}{100}$$  \hspace{1cm} (3)

where $e_0$ and $T_0$ are constant parameters equal to 0.611 kPa and 273 K, respectively. $L/\mathcal{R}_v$ is equal to the latent heat of deposition divided by the gas constant of water vapour (6139 K). $T$ is the measured temperature. The relationship between vapour pressure and vapour density can be
calculated using the ideal gas law for any given temperature as follows:

\[ e = \rho R_s T \]  

(4)

where the equation is solved for the vapour density, \( \rho \). We assume the recorded till temperature is a strong approximation for the temperature of the air in pores within the Granite drift.

COMSOL Multiphysics was used to solve Equation 2 with the finite element method run in 2D non-steady state diffusion-only mode for the initial model geometry as noted in Figure 4a (see also Supplemental Table 3). Boundary and initial vapour densities were established from field data. For initial conditions, we assume that pores within Granite drift just above the buried ice surface are saturated with water vapour. Therefore the initial ice surface RH is set to 100 per cent and interpolated linearly to the measured RH at the ground surface. The initial conditions for temperature are derived from interpolation between measured soil temperature data points (Figures 4a and 5; Table 1). Boundary conditions for RH at the till surface are taken from measured data at the till surface above the trough. We assume that RH at the ice surface is 100 per cent at all time steps. The boundary conditions for temperature are taken from measured data at the till surface and buried ice surface.

RESULTS

Figure 7 Details for incoming solar radiation measured for the polygon center and polygon trough. Values for the polygon center are shown in black and the dotted line represents solar radiance at the base of the polygon trough. The sinuous pattern observed for polygon center (as especially seen on the right side of the figure) represents a period of cloudless days. The sharp decrease/increase in solar radiance at the base of polygon troughs is a product of localized shielding from adjacent polygon-trough walls. Spikes within the data are caused from increased diffuse radiation or sunlight passing through the periphery of clouds that may cause a short-lived intense focusing of incoming solar radiance.

Model Rationale

The strength of our modelling study stems from the robust boundary conditions derived from our meteorological dataset. The dataset enables us to capture diurnal variations in vapour flux as a result of the non-linear relationship between temperature and vapour density. Ignoring latent heat is one limitation of our model and its absence prevents us from calculating true ice gain as vapour moves downward though the till (at times). However, this limitation does not influence our first-order results regarding net ice loss on seasonal and/or annual timescales. An additional limitation is that our model does not apply different thermal conductivities with depth; for example, it ignores variations that might be associated with variable lithologies for rocks at the ground surface and for salts at depth. Finally, our measured internal temperatures are not used explicitly to validate model results; however, they do help determine conditions where and when supersaturation in the till is likely to occur, and whether pore ice could likely form. Notwithstanding these limitations, our 2D model provides the first semi-quantitative assessment of sublimation of shallow, buried glacier ice in the Dry Valleys as a function of surface topography, rocky pavements, snow cover and near-surface salts. In all, over 60 different solutions were generated for six different model configurations (Table 2).

We first describe model results for our baseline geometry, and then compare these with more advanced simulations that take into consideration variable snow cover, till porosity, the presence of near-surface salts and rocky desert pavements, and the aspect of polygon trough walls.
(north facing, south facing, etc.). None of these additional parameters has been incorporated in previous modelling studies (Hindmarsh et al., 1998; Kowalewski et al., 2006; Schorghofer, 2005).

**Baseline Model**

For the baseline model run, we calculated ice loss as a function of the simple polygon geometry and facies distribution as noted in Figure 4a. (In this run, we start with an established polygon trough; for model results on initial trough development, see Test 2 below). Results show that sublimation varies considerably with topography. Maximum ice loss occurred along polygon trough walls (0.098 mm for the 12-month study interval), followed by diminished losses at the polygon plateau (0.059 mm); the lowest rates were recorded at the base of the polygon trough (0.039 mm) (the latter being a 34% reduction from the sublimation rate at the polygon centre) (Figure 6). The very low rate of ice sublimation at the base of deep polygon troughs arises from local cooling at the till and buried ice surfaces – a negative feedback to runaway ice loss at polygon troughs related to self-shadowing (solar shielding) alongside elevated polygon centres (Figure 7; see also temperature data in Table 1; Supplemental Table 4; and the Discussion).

**Test 1: Snow in Polygon Troughs**

To simulate the effects of trapped snowfall on subsurface ice loss (Figure 4b), we adjusted the saturation vapour density at the base of the modelled polygon trough to reach 100 per cent (while maintaining consistency with measured atmospheric temperatures). We retained all other variables as noted in the baseline model. Field observations show that snow typically collects in polygon troughs; polygon centres are windswept and snowfall there rarely remains for more than a few hours/days.

Results of our snowfall test predict a net downward flux of water vapour (for the 12-month period) at the top of buried glacier ice in the polygon trough. The volume of water, if deposited as secondary ice (ignoring the local influence of latent heat), would be equivalent to a lens of ice ~0.012 mm thick. Also predicted is a slight reduction in ice loss along...
adjacent polygon trough walls by 0.020 mm (i.e. reduced by 20%). As expected, the addition of snow in the polygon trough had a negligible effect on ice loss at the polygon centre (Figure 8).

Test 2: Sand Wedges and Relict Sand-wedge Deposits at Polygon Centres

To understand better the changes in vapour flux and ice loss near sand-wedge deposits (Marchant et al., 2002; Kowalewski et al., 2011; Figure 4b), we adjusted the modelled porosity at polygon centres to include two relict sand wedges: one 10 cm wide and a second 50 cm wide. These widths span measured values for relict sand-wedge deposits observed in Granite drift. All other variables remained identical to those of the baseline model run.

Results show that sublimation is enhanced beneath sand-wedge deposits, though deposit width has a negligible impact on ice loss. For sand-wedge deposits of 40 per cent, 45 per cent, 50 per cent and 60 per cent porosity (i.e. the maximum range of reported values in the region; Marchant et al., 2002; Kowalewski et al., 2011), the model predicts an annual increase in ice loss of 0.016 mm (27% increase), 0.026 mm (44% increase), 0.035 mm (59% increase) and 0.051 mm (86% increase), respectively (Figure 9).

Test 3: Salt-cemented Horizons

To simulate the physical effect of shallow, salt-cemented horizons within the Granite drift (Bockheim, 2002; Bockheim et al., 2009; Bao and Marchant, 2006), we reduced model porosity between 10- and 15-cm depths at the centre of our modelled polygon (Figure 4b).

Results show that the addition of a 5-cm thick, salt-cemented layer with a porosity of 20 per cent (i.e. reduced from 30%) decreases annual ice loss by 7 per cent (by 0.004 mm a⁻¹); likewise, lowering the porosity of the salt lens to 10 per cent decreases sublimation losses by 20 per cent (by 0.012 mm a⁻¹).

Test 4: Rocky Pavements

To simulate the effect of a rocky pavement on subsurface ice sublimation, we ran a model simulation with 75 per cent of the ground surface capped with dolerite clasts. Visually, this translates to a uniform spacing of clasts, with each clast being 15 cm long and spaced 5 cm from adjacent clasts (Figure 4b); this approximates conditions observed in the field (Marchant et al., 2002). We assigned a value of 0 per cent porosity for the clasts, with 30 per cent porosity (unchanged from the baseline model) for intervening regions. Results show a ~60 per cent
reduction in ice loss over the 12-month study period, with ice loss decreasing from 0.059 mm to 0.023 mm (Figure 10).

Test 5: Varying the Aspect of Polygon Trough Walls

To simulate the effect of enhanced solar insolation on north-facing polygon trough walls, we artificially increased soil and underlying ice surface temperatures on the north-facing side of our modelled polygon trough for the month of January by 4°C. The choice of 4°C comes from direct temperature measurements on a similar north-facing polygon trough wall <1 km from the study site. Temperatures were measured just below polygon rims (i.e. high enough to avoid complications associated with self-shielding from polygon geometry). Given this change, our model results show that ice loss along the warmed polygon trough wall increased by ~275 per cent during the month of January (see also Levy et al., 2008).

DISCUSSION

The Role of Textural Variation and Surface Morphology on Subsurface Ice Loss

Our 2D model results suggest a complex, though predictable, dynamic among subsurface ice loss, ground-surface morphology and textural variation within Granite drift. In general, the results provide a physical mechanism that yields high-centred polygons (Marchant et al., 2002) in the absence of saturated, active-layer cryoturbation as described by Hallet and Waddington (1991). Taken together, our results show that during the initial stages of polygon formation, locally enhanced sublimation beneath immature sand wedges leads to the development of marginal sublimation troughs (this conclusion arises from Test 2, in which isolated sand wedges result in enhanced subsurface ice loss). Continued ice loss, however, generates deeper troughs, and basal portions of such troughs are ultimately shielded from direct solar insolation, providing a negative feedback for enhanced ice loss (Table 1). Indeed, at the base of deep polygon troughs, which at >1-m depth typically remain largely in shadow and experience colder-than-average microclimate conditions (Table 1), sublimation is reduced to levels below that modelled for polygon centres (Figures 6 and 8). If windblown snow becomes trapped in such troughs, ice loss is further reduced (Table 2). Moreover, windblown snow in polygon troughs may actually result in ice accretion at depth (from downward movement of vapour). Given our model limitations, we cannot quantify potential ice accretion. However, we note that lenses of secondary ice have been observed at the base of polygon troughs in Beacon Valley (Marchant et al., 2002), and that δD and δ18O analyses corroborate an origin via downward vapour transport from the surface snow (Marchant et al., 2002;
The Role of Rocky Pavements and Salt-cemented Horizons in Subsurface Ice Loss

Most modelling studies that have examined sublimation of buried ice in Antarctica have ignored the effects of rocky surface pavements and/or shallow, salt-cemented horizons in modulating ice loss (Hindmarsh et al., 1998; Schorghofer, 2005; Kowalewski et al., 2006). Here, we modelled pavements and salts as distinct horizons with reduced porosity (Tests 3 and 4). Results show that by adding a realistic pavement with subsurface salts, the levels of ice sublimation are reduced by as much as 60 per cent. Even greater declines in net annual ice sublimation are probable if secondary factors beyond simple reductions in porosity are considered. For example, the addition of rocky pavements would tend to increase surface roughness, resulting in the deposition of windblown snow in the lee of the largest clasts. Episodic snowmelt along the margin of solar-heated clasts (especially along low-albedo Ferrar Dolerite) would create a moist, near-surface horizon that would tend to elevate near-surface soil vapour pressures and suppress subsurface ice loss (see also Kowalewski et al., 2006; McKay, 2009; Schorghofer, 2009). In addition, the snow and minor meltwater thus established would add salts to the shallow subsurface (Claridge and Campbell, 1977; Campbell et al., 1997; Bockheim, 2002; Bao and Marchant, 2006; Campbell and Claridge, 2006), facilitating the movement of brines at subfreezing temperatures. Finally, episodic hydration of soil salts could also lead to further reductions in soil porosity and tortuosity, thereby further diminishing sublimation of buried glacier ice.

The Role of Polygon Trough Wall Aspect on Sublimation of Buried Ice

Results from Test 5 show that ice loss along a north-facing polygon trough wall (i.e. oriented favourably to solar radiation) can increase by as much as ~275 per cent relative to that along a south-facing polygon trough wall. Field inspection, however, shows no obvious and consistent trends in the slope of polygon trough walls with respect to aspect in the central Beacon Valley. Levy et al. (2008) report a subtle variation in polygon trough wall geometry with aspect (by a few degrees), but the magnitude of this slope change is not in keeping with the expected variations that would arise from enhanced ice sublimation on the north-facing trough wall. As one hypothesis to test, we suggest that secondary processes, such as marginal slumping along trough walls, likely counteract the potential for dramatic solar-induced trough asymmetry. In this regard, episodic mass wasting via gravitational sliding and slumping would tend to maintain slope angles at the angle of repose (~30°), as noted in the field. We also note that the depth to buried ice observed on polygon trough walls with slumped debris (Marchant et al., 2002) varies considerably, suggesting that slumping locally thickens and thins Granite drift.

The Potential for Long-Term Preservation of Buried Glacier Ice

Results from our 2D modelling exercises suggest that under current environmental forcing, ice loss beneath Granite drift at polygon centres (modelled with the addition of a rocky surface pavement and shallow subsurface salts) approaches 0.022 mm a⁻¹ (Table 2). We have shown that ice loss is extremely sensitive to minor changes in MAAT and RH. Consider the modelled scenario in which Granite drift at a polygon centre is capped by a rocky pavement (75% coverage) and contains a salt-cemented horizon at 10–15-cm depth (20% porosity). In such a situation, a stable ice surface (zero net annual ice loss) is achieved with either a 1.9 °C decrease in MAAT (from present conditions) or a 12 per cent increase in mean annual RH. If we assume that wintertime conditions remain unchanged, then a stable ice surface could be achieved by decreasing summertime temperatures (October-March) by 2.3 °C or by increasing summertime RH by 14 per cent. Both of these conditions could occur with a modest increase in summertime cloud cover (Kowalewski et al., 2006). In addition, the greater surface snowmelt expected under such conditions would tend to elevate soil moisture and further retard sublimation of underlying ice (McKay, 2009; Schorghofer, 2009). Collectively, the results demonstrate complex, but quantifiable, relations among ice loss, polygon formation, and subtle changes in atmospheric temperature and RH. Although these results do not prove the hypothesised great antiquity of buried glacier ice in the central Beacon Valley (Sugden et al., 1995), they do suggest that the preservation of multi-million-year-old ice is plausible in the coldest and driest regions of the Transantarctic Mountains (Schorghofer, 2005; Kowalewski et al., 2006; Marchant and Head, 2007; Swanger et al., 2010; Morgan et al., 2011).

SUMMARY AND CONCLUSIONS

(1) We applied a relatively simplistic 2D model for vapour diffusion through porous media to calculate the sublimation rates for buried glacier ice in the central Beacon Valley, Antarctica. The results show that the development of thermal contraction-crack polygons modulates subsurface ice loss. During the initial stages of polygon formation, locally enhanced sublimation beneath immature sand wedges leads to the development of deep, marginal troughs (and high polygon centres). Continued ice loss, however, deepens troughs so that basal portions are shielded from direct solar insolation. This shielding results in local
cooling, which in turn acts to suppress sublimation and provides a negative feedback for runaway ice loss at polygon margins. Windblown snow, which is trapped preferentially in deep polygon troughs, reduces sublimation even further, and may lead to ice accretion at depth. At polygon shoulders (i.e. high enough on trough walls to avoid the consequences of self-shielding) solar warming on north-facing trough walls can elevate rates of sublimation by up to 275 per cent relative to south-facing trough walls. Field data from the central Beacon Valley, however, show no obvious slope asymmetry for opposing north- and south-facing trough walls. One explanation is episodic mass wasting from gravitational sliding and slumping, which would tend to maintain slope angles at the angle of repose (~30°), as noted in the field. Taken together, the results point toward self-organisation as a mechanism that controls the geometry of polygon troughs.

(2) Results from our 2D model show that the surface of remnant glacier ice beneath Granite drift at polygon centres lowers by 0.022 mm a\(^{-1}\). This rate is significantly lower than that first modelled by Hindmarsh et al. (1998) (~1 mm a\(^{-1}\)) and Kowalewski et al. (2006) (0.14 mm a\(^{-1}\)), who used either generic temperatures and/or assumed homogeneous till textures in model domains. Our results, however, are consistent with recent estimates of ice loss based on the abundance of cosmogenic nuclides in Granite drift in the central Beacon Valley (e.g. 0.005 to 0.09 mm a\(^{-1}\); Marchant et al., 2002) and elsewhere in the western Dry Valleys region (e.g. suggested ice losses from 0.0007 mm a\(^{-1}\) to 0.012 mm a\(^{-1}\); Morgan et al., 2011). The implication is that adding realistic, field-documented parameters for drift texture, surface topography and microclimate conditions yields considerable improvement in the model results.

(3) Our findings suggest that equilibrium conditions for the surface of buried glacier ice beneath Granite drift in the central Beacon Valley (i.e. no net ice loss) might be achieved with either a 1.9°C decrease in MAAT or a 12 per cent increase in mean annual RH. Although these model results do not prove the hypothesised great age for buried glacier ice beneath Granite drift in the central Beacon Valley (e.g. ≥ 8.1 Ma; Sugden et al., 1995), they do indicate that the preservation of buried, multi-million-year-old ice is indeed plausible in the coldest and driest regions of the McMurdo Dry Valleys, Antarctica.

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