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Distribution of depth to ice-cemented soils in the high-elevation Quartermain Mountains, McMurdo Dry Valleys, Antarctica

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Abstract: We report on 475 measurements of depth to ice-cemented ground in four high-elevation valleys of the Quartermain Mountains, McMurdo Dry Valleys, Antarctica. These valleys have pervasive ice-cemented ground, and the depth to ice-cemented ground and the ice composition may be indicators of climate change. In University Valley, the measured depth to ice-cemented ground ranges from 0–98 cm. There is an overall trend of increasing depth to ice-cemented ground with distance from a small glacier at the head of the valley, with a slope of 32 cm depth per kilometre along the valley floor. For Farnell Valley, the depth to ice-cemented ground is roughly constant (*c.* 30 cm) in the upper and central parts of the valley, but increases sharply as the valley descends into Beacon Valley. The two valleys north of University Valley also have extensive ice-cemented ground, with depths of 20–40 cm, but exhibit no clear patterns of ice depth with location. For all valleys there is a tendency for the variability in depth to ice-cemented ground at a site to increase with increasing depth to ice. Snow recurrence, solar insolation, and surface albedo may all be factors that cause site to site variations in these valleys.

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Introduction

The McMurdo Dry Valleys occupy an area of 6700 km^2 and are the largest ice-free region in Antarctica. However, the soils in the Dry Valleys often contain subsurface ice both as ice-cemented ground and extensive bodies of massive ice (Campbell & Claridge 1987, 2006, Marchant *et al.* 2002, Bockheim *et al.* 2007, Bockheim 2007, Lacelle *et al.* 2011). Bockheim *et al.* (2007) reviewed the distribution of ground ice in the Dry Valleys based on more than 800 shallow (< 1.5 m) pits over the entire region. The area represented by each pit ranged from *c.* 1 to *c.* 30 km^2. They concluded that 55% of the permafrost is ice-cemented, 43% is dry frozen (dry cryotic), and 2% is ground or buried ice. The presence of dry permafrost is unique to the high-elevation Dry Valleys of Antarctica (e.g. Bockheim *et al.* 2007). Permafrost in the Arctic and coastal Antarctic is usually well cemented by ice and develops a wet active layer in the summer. The summer boundary between the active layer and the permafrost is the 0°C isotherm. To date it is only in the high elevations of the Dry Valleys that the climatic conditions are dry and cold enough that permanently cryotic (i.e. below 0°C) yet dry soil is found over ice-cemented ground (McKay *et al.* 1998, Bockheim 2007, Marinova *et al.* 2011).

Of particular interest is the nature of the near-surface permafrost in the high elevations (> 1200 m) of the Quartermain Mountains. This region, shown in Fig. 1, contains Beacon Valley, Arena Valley, and several smaller hanging valleys at higher elevations, such as University Valley, and Farnell Valley. Bockheim *et al.* (2007) estimated that 59% of near-surface permafrost in the Quartermain range is dry frozen and 37% is ice-cemented, with the remainder (4%) containing massive ground ice. Bockheim *et al.* (2009) reported measurements of depth to ice-cemented ground in Beacon Valley, and at least one of these (Polygon 7) represents a site with a dry permafrost layer. Dickinson & Hopkins (2005) dug pits throughout the Beacon Valley, Arena Valley, and Pearse Valley systems, and showed variability in the depth to ground ice. Their data for University Valley (two data points, shown in Fig. 2) and Farnell Valley (one data point: 14–44 cm depth to ice-cemented ground) are consistent with our observations. Year-round meteorological data collected at multiple

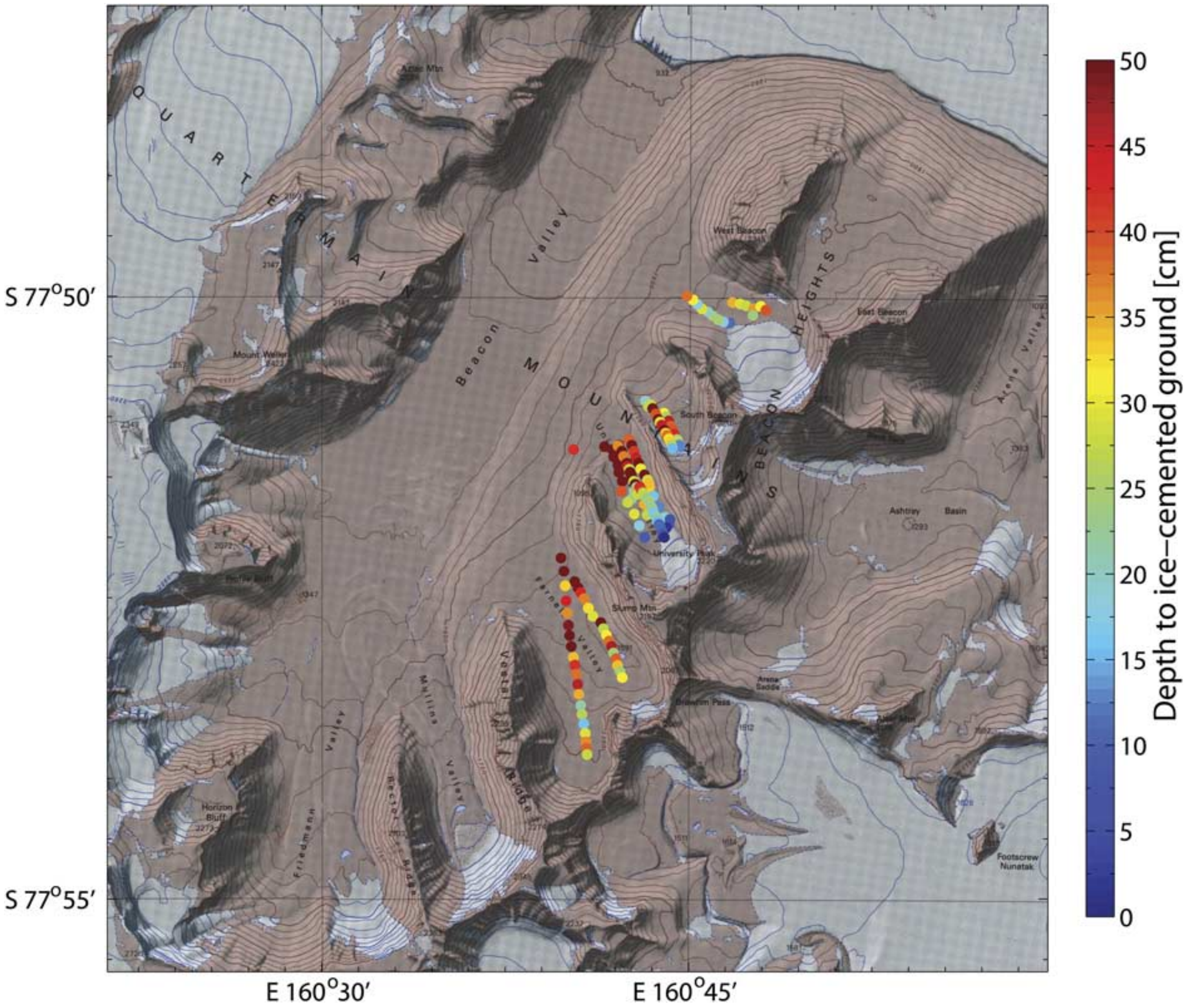

Fig. 1. Map of Beacon Valley and the smaller, overhanging valleys. Overlain are the mapped sites and measured depths to ground ice in Farnell Valley (southernmost), University Valley, and two unnamed valleys to the north. Arena Valley is located to the north-east of University Valley.

locations in University Valley (Marinova *et al.* 2011) show that the active layer ranges in depth from a few centimetres to a maximum of *c.* 20 cm. Thus ice-cemented ground with depths greater than *c.* 20 cm will be overlain by dry permafrost.

The origin and stability of near-surface ground ice in the high-elevation Quartermain Mountains is of interest for two reasons. First, it has been reported that the massive ice found in middle Beacon Valley may be 8 m.y. old, making it the oldest ice on Earth (Sugden *et al.* 1995, Schäfer *et al.* 2000, Marchant *et al.* 2002, Margerison *et al.* 2005). This claim is not universally accepted (e.g. Sletten *et al.* 2003, Ng *et al.* 2005, McKay 2009, Liu *et al.* unpublished data) but the nature, origin, and stability of this massive ice beneath *c.* 25–80 cm of soil have generated considerable study (e.g. McKay *et al.* 1998, Hindmarsh *et al.* 1998, Schorghofer 2005, Kowalewski *et al.* 2006, 2011) as have the biological implications of such old ice (Bidle *et al.* 2007, Gilichinsky *et al.* 2007). Second, the near-surface massive ice and ice-cemented ground in the Quartermain Mountains is of intrinsic interest because it is not expected to be stable at these elevations under current climatic conditions. Models of the stability of near-surface ground ice in the upper elevations of the McMurdo Dry Valleys, which are based directly on meteorological data (McKay *et al.* 1998, Hindmarsh *et al.* 1998, Kowalewski *et al.* 2006, 2011), predict that subsurface ice should evaporate at 0.2–0.5 mm yr^{-1} and thus any subsurface ice will evaporate over timescales that are at most a few thousand years. Thus the persistence of both massive ground ice in Beacon Valley, if 8 m.y. old, as well as observations of ice-cemented ground at higher elevations (McKay 2009), are a challenge to models. Models for the stability of the ice that invoke alterations in meteorological conditions (Schorghofer 2005, Kowalewski *et al.* 2006, 2011) require unsubstantiated changes in the air temperature and humidity.

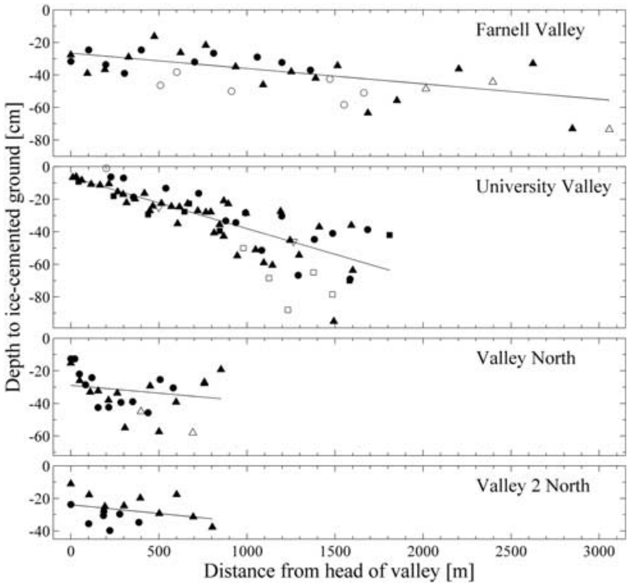

Fig. 2. Depth to ground ice and linear fits for Farnell Valley (slope of linear fit = -9 cm km^{-1}, *normRMS* = 16.9%, *P*-value 0.001, 26% increase in RMS if no change in depth is prescribed), University Valley (slope = -32 cm km^{-1}, *normRMS* = 11.5%, *P*-value 10^{-15}, 77% RMS increase if constant depth prescribed), and the unnamed valleys to the north, and two to the north, of University Valley (slope = -10 cm km^{-1}, *normRMS* = 25.0%, *P*-value 0.31, 2% RMS increase if constant depth; and slope = -11 cm km^{-1}, *normRMS* = 18.5%, *P*-value 0.22, 6% RMS increase if constant depth, respectively). The distance is measured from the head of the valley or the edge of the glacier/snowpack at the head of the valley. In each panel, the circles represent the northernmost transect in the given valley, up triangles are the next transect to the south in the same valley, and squares are the next further south transect (only available for University Valley). Empty symbols represent locations where the ground was probed to the given depth but no ice-cemented ground was reached, i.e. the ice is deeper than the indicated depth. These measurements are not included in the fits. Two data points from Dickinson & Hopkins (2005) for University Valley are plotted (empty down triangles at 500 and 1260 m distance) and are consistent with our data; these data are not included in the fits.

McKay (2009) reported on observations of ice-cemented ground in University Valley and the systematic increase in the depth to ice-cemented ground down the valley. McKay (2009) found a linear trend in depth to ice-cemented ground with a slope of about 70 cm of depth per kilometre distance from the small glacier at the head of the valley. However, this was based on only five observations over a 0.5 km distance. Snow with recurrence intervals of a few to many years was suggested by McKay (2009) as a plausible explanation for the ice table depth variations in University Valley, concluding that the University Valley subsurface ice is stabilized by occasional snow. The snow is redistributed throughout the valley as it is blown in from the polar plateau. The presence of snow means that the upper boundary condition corresponds to a transient relative humidity of 100%, much higher than the average humidity of the atmosphere (*c.* 50%). Thus snow has a stabilizing effect on the subsurface ice even if it does not melt and infiltrate into the subsurface.

In middle Beacon Valley massive buried ice is observed, but typically pervasive ice-cemented ground is not found nearby (field observations). Small amounts of ice-cemented ground are reported from the troughs of polygons (Marchant *et al.* 2002), presumably due to snow collecting in the lows. Thus McKay (2009) suggested that there is insufficient snow to stabilize widespread subsurface ice in middle Beacon Valley. This is an important general argument, independent of the meteorological data: if massive ground ice is stable then ice-cemented ground should also be stable and found at a similar depth. Conversely, if only dry permafrost and no ice-cemented ground is found in areas adjacent to subsurface massive buried ice, then this is an indication that any nearby massive ice is not stable either.

In this paper we report on a survey of the depth to ground ice in University Valley, Farnell Valley, and the two unnamed valleys north of University Valley (Fig. 1). These data provide a qualitative and quantitative contribution towards understanding the type and distribution of ground ice in the Quartermain Mountains at a high spatial resolution. The measurements can be used to improve and validate models of ice stability and distribution.

Methodology

The observations of depth to ice-cemented ground which are reported here are based on 475 measurements at 147 sites: 3–5 measurements were taken at each site over a *c.* 1 m^2 area and were averaged. The measurements were made during the first two weeks of December 2009 and December 2010. There were 36 sites in Farnell Valley, 68 in University Valley, 27 in the valley immediately north of University Valley, and 16 in the valley two to the north of University Valley. The typical distance between sites within each valley was 50–200 m.

The transects were started at the head of the valleys, and sample site spacing was kept constant with the distance between consecutive sites either 50, 100, or 200 m apart, depending on the valley and the meteorological conditions at the time. This approach ensures an even distribution of sample sites and minimized bias related to soil type and geomorphology. Sample locations were recorded to an accuracy of ± 3 m using a Garmin 60CSx GPS. Polygonal ground was present in all four valleys and since the depth to ice-cemented ground is known to be disrupted in polygon troughs, the measurements were standardized by choosing a flat area near the centre of the polygon. The depth to ground ice was determined by either digging a soil pit, using an active layer probe (sharpened metal rod), or drilling until the ice-cemented ground interface was reached. Soil pits readily confirmed the presence of ice-cemented ground, probe depths were based on resistance, and drill depths were based on the presence of ice in drill cuttings. Field observations of soil pits at drilling sites confirmed that drilling was a reliable method for determining the depth to ice-cemented ground. The least reliable method was the active layer probe, as the presence of subsurface rocks could confound this method. Whenever there was any doubt (i.e. greater-than-expected variability between measurements), a soil pit was dug. Drilling proved to be the most efficient and accurate method. We used a Hilti drill with a $\frac{1}{2}$ inch diameter, 1 m long drill string. The operator could tell when the drill reached ice-cemented ground due to the change in pressure required to advance the drill and changes in the frequency of vibrations during drilling. At this point a magnet was placed at ground level on the drill string, the drill was retrieved to confirm that ice was present at the tip of the string, and the distance between the magnet and the tip of the drill string was measured.

At some sites the ice-cemented ground could not be reached. These locations are identified with empty symbols in Fig. 2. Ideally, probing to about 3 m would have provided a definitive result as to whether ice-cemented ground is at all present at a location, based on thermal and vapour pressure models (e.g. McKay 2009). As a test of McKay's (2009) proposed stability zone, we report cases where the depth to ice-cemented ground is deeper than could be measured.

The precision of measurement for all methods is a couple of centimetres, due to the need to drill into the ice in the case of drilling and the difficulty of defining the reference surface plane in environments with significant surface roughness. The measured depth to ice-cemented ground is generally insensitive to the time of year during which the measurement was taken, since modelled ice evaporation rates (i.e. seasonal depth of ice-cemented ground fluctuations) are 0.2–0.5 mm yr^{-1} (McKay *et al.* 1998, Liu *et al.* unpublished data). These changes are significantly smaller than our measurement error. In measuring the depth to ice-cemented ground, annual and seasonal temperature variations are important only when the soil is water saturated to the surface. When a dry permafrost layer is present, seasonal and yearly variations in temperature will only affect the depth to the top of the dry permafrost layer but not the depth of the ice-cemented layer.

We examine trends in the data through linear fits. Reported are the normalized root mean square (RMS) errors (*normRMS*), *P*-value, and the percent increase in RMS error if we assert the null hypothesis that the depth to ice-cemented ground is constant (i.e. fitting the data with a line of slope zero). The normalized RMS error is the RMS value normalized by the range of observed values: $normRMS = RMS/(d_{max}\text{-}d_{min})$, where d_{max} and d_{min} are the maximum and minimum measured depths to ice-cemented ground, respectively. Note that for randomly distributed points, the normalized RMS of a best fit line is about 29%.

Results: depth to ice-cemented ground

The measurements from each site are shown in Fig. 1, colour coded for depth. Linear graphs, with distance down the valley, are shown in Fig. 2. Below we detail the results for each individual valley from the southernmost to the northernmost. The maximum probed depth was 98 cm in University Valley (drill measurement), and ice-cemented ground was reached at this site. For Farnell, the valley north, and the valley two to the north, the maximum probed depths were 78, 68, and 48 cm, respectively. In each case ice-cemented ground was reached.

Farnell Valley is at an elevation of *c.* 1600 m (*c.* 100 m lower than University Valley) and is the widest (*c.* 1000 m) of the mapped valleys, with an approximate area of 1.1 km^2. The head of Farnell Valley is marked by two distinct cirques: the northern cirque has a glacier at the head of the valley, as well as a perennially frozen pond, while the southern cirque has no snow or ice cover. In Farnell Valley, two transects were made, one starting from each cirque. The results are highly variable. The depth to ice-cemented ground is slightly shallower in the northern transect, near the perennial ice field. However, the shallowest ice-cemented ground (15 cm) was found near the head wall of the southern cirque, which does not contain a permanent ice field and is also slightly higher in elevation. Considering all sites where the ice-cemented ground was reached, the best fit change in depth to ice-cemented ground is 9 cm deepening per kilometre away from the head of the valley towards the mouth. The presence of a trend is statistically significant (*P*-value 0.001), although substantial variability in ice depths is present (*normRMS* = 16.9%). Visual inspection suggests that the data for Farnell Valley could also be well fit by a generally constant depth to ice-cemented ground in the main part of the valley and then a sharp increase in depth as the valley slopes towards Beacon Valley below (near the 2.5 km mark). Fitting the data with a constant depth trend increases the RMS error by 25% to *normRMS* = 21%.

University Valley, at an elevation of about 1700 m (width *c.* 550 m, approximate surface area = 0.6 km^2), was the most extensively mapped valley, following up on the trends reported by McKay (2009). Three transects were made lengthwise down the valley (Fig. 1). The mapping confirms the overall trend of increasing depth to ice-cemented ground with distance from the glacier, and this is the clearest trend seen from all of the mapped valleys (Fig. 2).

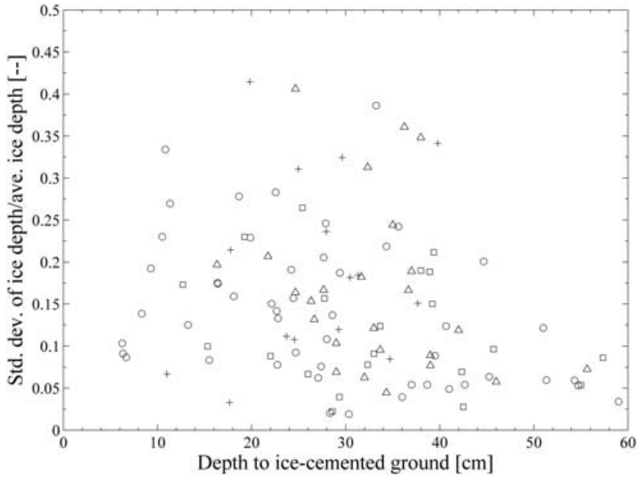

Fig. 3. Relationship between the variability (standard deviation) between all the measurements at a site, normalized by the average measured depth to ice-cemented ground at that site. Shown are the four valleys: Farnell (stars), University (circles), "Valley North" (squares; unofficial name), and "Valley 2 North" (crosses; unofficial name). A general decrease in normalized depth variability seems to be present with increasing ice depth.

The best fit slope to the data (sites where ice-cemented ground was reached) suggests a deepening of the ice-cemented ground by 32 cm per kilometre away from the glacier. The increasing depth with distance trend is statistically significant (*P*-value 10^{-15}), and the normalized RMS error is the lowest of all the valleys (*normRMS* = 11.5%). A fit assuming that the depth to ice-cemented ground is constant results in a 77% higher RMS error (*normRMS* = 20.4%). Note that our fitted trend of 32 cm km^{-1} is shallower than the trend of 70 cm km^{-1} found by McKay (2009) based on five sites. Past a distance of about 1.8 km from the glacier, the depth to ice-cemented ground is more than 70 cm and most attempts to reach the ice-cemented ground were unsuccessful due to extensive subsurface rocks. These sites occur where University Valley drops down to Beacon Valley.

The head of the valley just north of University Valley is about 250 m higher, but the floor and mouth of the two valleys are at about the same elevation. The north valley is much more steeply sloped (facing to the north-west). It has an area of about 0.4 km^2. In December 2010 there was no significant perennial snowfield anywhere in the valley. Near the head of the valley there is a sharp and linear drop of depth to ice-cemented ground with distance away from the head of the valley, however, this changes to a highly variable but generally constant depth for the remainder of the distance probed. At the mouth of the valley, there is some shallowing in the depth to ice-cemented ground, in sharp contrast with both University and Farnell valleys. No significant trends were found in the data (fitting sites where ice-cemented ground was reached, *P*-value 0.31, *normRMS* = 26%; note that a fit through a random set of points has a *normRMS* of 29%). Assuming a constant depth to ice-cemented ground resulted in only a 2% increase in the RMS error, consistent with any trend in the data not being statistically significant. This valley has an almost step-like topographic relief, however, observations in the field did not find a correlation of ice depth and aspect, as was expected due to its mostly north-west-facing exposure.

The valley two north of University Valley (northernmost in the Beacon Valley system) is at an elevation similar to Farnell Valley (*c.* 100 m lower than University Valley; approximate surface area = 0.7 km^2, with half covered by a snowpack), but is topographically and geomorphologically quite different. This valley is very hilly, with a range of material and boulder sizes mixed throughout. Surface and subsurface properties vary greatly over scales of metres to tens of metres. Bockheim (2007) suggested that this valley is a rock glacier, however, Marchant *et al.* (2002) did not mark it as such. Our observations suggest that the valley displays a series of subparallel till ridges representing ground moraine that could easily be mistaken for a rock glacier on satellite imagery or aerial photographs. The absence of shallow massive ice as seen in the Mullins Valley and Friedmann Valley rock glaciers supports our interpretation. Two transects were undertaken in this valley, the first was along the south side which is raised with respect to the central part of the valley. This transect appears to show a weak trend of increasing depth to ice-cemented ground with distance from the snowpack. The other measured points in the northern side of the valley are in heterogeneous terrain and show no apparent trend. The fit of 11 cm km^{-1} from the snowpack does not represent a significant trend (*normRMS* = 25%, *P*-value 0.22). If only the southern transect is fit, a significant trend with a slope of 23 cm km^{-1} is found (*P*-value 0.02), but there is still considerable variability in the depth (*normRMS* = 19%). It is interesting to note that both this valley and University Valley have small glaciers and snowfields which fill large parts of the heads of the valleys.

The small-scale ice variability at each site was determined by making three to five measurements in a *c.* 1 m^2 area. In Fig. 3 we plot the standard deviation at each site normalized by the average depth, as a function of the depth to ice-cemented ground. There is a tendency for the variability to increase with increasing depth to ice, however, the fractional (normalized) variability decreases slightly with increasing depth (Fig. 3). With increasing depth, the ice is expected to be more sensitive to small changes in the boundary conditions, such as presence of snow, and surface albedo and roughness. However, deeper ice is also affected by the (average) surface conditions over a larger area. The relative importance of each effect needs to be explored further.

The results presented here are listed in detail (GPS coordinates and depth to ice-cemented ground) in the supplemental material (which will be available at http://dx.doi.org/10.1017/S095410201200123X) and have been posted to the National Snow & Ice Data Center (http://nsidc.org/data/nsidc-0529.html).

Discussion

Our results show variability in the depth to ice-cemented ground on both small and larger scales, and a trend in University Valley. The variability in the measurements underscores the need for detailed mapping and for models to take into account a range of processes. Here we describe some of the many factors that could influence the depth to ice-cemented ground in the studied valleys.

Subsurface ice will grow if the mean water vapour density at depth is less than the mean vapour density at the surface. If the vapour density at the surface is reduced (lower temperatures or lower humidity values), the depth where ground ice is stable will be deeper. The reduction in mean water vapour density at the ice-cemented ground with depth is due to the reduction in the seasonal variation in temperature with depth and the non-linear dependence of vapour pressure on temperature (McKay 2009). At sufficient depth the ground temperature is virtually constant all year and equal to the frost temperature. McKay (2009) pointed out that the attenuation of the surface temperature fluctuations with depth implies that if an ice-table is stable at all, it will be present within the upper approximately two seasonal damping depths for dry soil. For the valleys mapped here, the seasonal damping depth in dry soil is *c.* 1.5 m (McKay *et al.* 1998, McKay 2009, Marinova *et al.* 2011), and thus mapping for stable ground ice would ideally probe to *c.* 3 m, but need not go deeper.

As suggested by McKay (2009) for University Valley and Hagedorn *et al.* (2007) for Victoria Valley (elevation 450 m), snow may play an important role in defining the stability and depth to ground ice by altering the relative humidity of the soil surface. However, the distribution and recurrence of snow in these areas is poorly understood and not routinely monitored by any of the environmental stations. At lower elevations, stations of the Long-term Ecological Research (LTER) network have been equipped with snow sensors with variable success (Fountain *et al.* 2009). It would be easier to monitor soil surface humidity to determine surface snow cover. Comparisons of the snow data as obtained from weather stations agrees well with predictions of the Antarctic Mesoscale Prediction System (AMPS), a weather prediction program that supports the daily operations of the US Antarctic Program (Powers *et al.* 2003, Monaghan *et al.* 2005), suggesting that AMPS may be used in the upper elevations to fill in the data gaps.

Many other factors, in addition to snow, may affect the depth to ground ice and could be variable over spatially small scales in these valleys. These include surface albedo, insolation, clouds, terrain shadowing, surface orientation (Marinova *et al.* 2011), and katabatic winds (Nylen *et al.* 2004). The surface albedo changes the total amount of radiation absorbed by the surface, thus changes in surface rock distribution and composition may have important effects. Cloud cover reduces the incident solar radiation during the sunlit summer, however, it also has the effect of significantly increasing incident longwave radiation, which is an especially important contribution during the dark winter months. Terrain shadowing alters the ability of the surface to radiate to the sky and cool down, as well as changing the incident solar radiation. The frequency and strength of wind events not only changes the sensible and latent heat flux components (effectively linking the air and surface temperatures; Marinova *et al.* 2011), but is also an important warming source as the air warms as it is carried down the valleys by the katabatic winds, and can cause significant warming events during winter (Doran *et al.* 2008). The interaction between all of the processes is complex. The extensive mapping performed here contributes to disentangling the relative effects of each of these processes on the depth to ice-cemented ground in the high-elevation Quartermain Mountains, and being able to extend this understanding to other vapour diffusion controlled environments.

In addition to the data presented here there has been extensive study of soils and active layers in Arena Valley (elevation 1100–1300 m; Fig. 1), where Bockheim (2007) and Bockheim *et al.* (2007) reported 73 pits of which 90% had no ice-cemented ground to a depth of a metre or more. Widespread ice-cemented ground is also not reported for middle Beacon Valley (elevation 1100–1300 m) - the area in Beacon Valley just below the hanging valleys investigated here where massive ice is reported. Measurements of depth to ice on Mullins glacier (unofficial name), stretching from Mullins Valley (south of Farnell Valley) into upper Beacon Valley, have also been reported (Kowalewski *et al.* 2011). The reported depths are 10–50 cm.

Models suggest that the ice-cemented ground at high-elevations in the Quartermain Mountains is exchanged with the atmosphere mainly by vapour diffusion (McKay *et al.* 1998, Hindmarsh *et al.* 1998, Schorghofer 2005, Kowalewski *et al.* 2006, 2011), even when the ground is ice-cemented all the way to the surface (Marinova *et al.* 2011). Since the boundary conditions, such as surface snow cover and aspect ratio, influence the vapour diffusion rates and thus depth of stability of the ice, ice depths in these vapour-exchange dominated environments are expected to have greater spatial variability than is typical in permafrost environments with wet active layers. Both this theoretical argument, and the *in situ* observations presented here, suggest that high-resolution mapping of the depth to ice-cemented ground is needed in order to understand the ice distribution in these environments.

Summer air temperatures in the McMurdo Dry Valleys follow the adiabatic lapse rate (9.8°C km^{-1}; Doran *et al.* 2002), thus elevation differences between the valleys have a direct influence on their summer air temperatures.

For example, Beacon Valley, located 300–400 m below University Valley has an average summer air temperature 3–4°C warmer, whereas Farnell Valley is 1°C warmer than University Valley. Since vapour diffusion rates are strongly set by summer season gradients, these elevation differences were expected to be an important variable in the depth of stability of ice in the studied valleys. However, we see no offset trend between the depths to ice-cemented ground in the four valleys that correlates with their relative elevations. This suggests that multiple effects are responsible for determining the depth to ice-cemented ground, and summer air temperature, while important, does not by itself set the depth to ice-cemented ground.

Extreme seasonality, which results in heightened recharge of ice-cemented ground during extreme warm and wet summers (e.g. Doran *et al.* 2008), followed by gradual evaporation in subsequent years may also explain ice-cemented ground in these high-elevation valleys. For this to be the case, the time interval since the last such event must be less than a few thousand years, based on the modelled ice evaporation rates of 0.2–0.5 mm year^{-1} (McKay *et al.* 1998, Liu *et al.* unpublished data). It should be noted, however, that the isotope data of Lacelle *et al.* (2011) and a sublimation-diffusion model yielded a net ice loss rate much lower than the climate-based sublimation rate, suggesting that both sublimation loss and re-condensation of water vapour is found in University Valley. Freezing of liquid water at the surface of the ice body was not suggested.

The formation and stability of ice-cemented ground by vapour exchange, while found on Earth only in the high elevations of the Antarctic dry valleys, is thought to characterize all ground ice on Mars (e.g. Mellon & Jakosky 1993, Mellon *et al.* 2004, Schorghofer & Aharonson 2005) and possibly the dark polar craters of the Moon (e.g. Vasavada *et al.* 1999). Recent work comparing the upper McMurdo Dry Valleys to Mars has focused on trying to model and understand the ice-cemented ground at the Phoenix landing site on Mars, 68°N (Smith *et al.* 2009, Levy *et al.* 2009, Tamppari *et al.* 2012) and the resulting implications for obliquity-driven climate change and correlations with observed surface geomorphological features. The high-elevation Dry Valleys may be an even better analogue for mid-latitude sites on Mars, near 50°N, where subsurface ice has been directly observed by gamma-ray spectrometer measurements (e.g. Feldman *et al.* 2002) and recent impact craters (Byrne *et al.* 2009), yet models suggest the ice is unstable (e.g. Byrne *et al.* 2009).

Conclusions

We have completed an extensive survey of the depth to ice-cemented ground in the upper valleys of the Quartermain Mountains, McMurdo Dry Valleys, Antarctica. We find that there is widespread ice-cemented ground in Farnell Valley, University Valley, and the two valleys north of University Valley. The depth to ice-cemented ground in all valleys is variable on small (*c.* 1 m) and larger (*c.* 100 m) scales. Based on these considerations, measurements of only a few sites within a valley may not be representative and must be used cautiously, particularly in areas of greater ice depth. Predicting ice stability and distribution requires models which can generate both variability and trends in the depth to ice on the metres to hundreds of metres scale. Conversely, the observations can be used for model validation.

Some trends are apparent in the data, in particular the deepening of the ice with distance from any permanent moisture source (snowpack or glacier), this is particularly the case in University Valley. In the neighbouring Farnell Valley, and in the two valleys north of University, there is no apparent trend in the data despite the presence of permanent snowfields in two of these valleys.

Determining the distribution of ice-cemented ground is of interest for furthering our understanding of past climates and the preservation of ancient ice of any type, including the purported 8 m.y. old massive ground ice in Beacon Valley. Furthermore, mapping the distribution of ice-cemented ground can contribute to characterizing the processes which stabilize subsurface ice in locations where the mean atmospheric meteorological conditions are unfavourable for subsurface ice preservation, as is the case for all of the mapped valleys.

Quantitative modelling of the stability of the ground ice could be further improved by more precise measurements of vapour flux and meteorological conditions using eddy covariance methods, as well as characterization and monitoring of snow fall and persistence, better topographical modelling, and measurement of subsurface properties.

In addition to the Antarctic Dry Valleys, dry permafrost over ice-cemented ground is found extensively on Mars and more sparsely on the Moon. Both the distribution of ice-cemented ground, and the processes which stabilize the ice, are key to understanding ice distribution and stability on other worlds. The conditions and stability analyses in University Valley are similar to those in the mid-latitudes of Mars, and our understanding of these extreme environments on Earth will directly contribute to a better understanding of planetary ice stability and distribution.

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Supplemental material

Supplemental data will be found at http://dx.doi.org/10.1017/S095410201200123X.

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