Antarctic ground ice in a changing climate

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Abstract

Ground ice is one of permafrost's most important and dynamic geologic components. Its occurrence and distribution are essential to understand landscape evolution. Early investigations of permafrost and ground ice in the McMurdo Dry Valleys of Antarctica identified ice-cemented permafrost, ice wedges, buried glacier ice, and buried remnants of the Ross Sea ice sheet in low elevations. At high elevations (> 1000 m a.s.l), it was initially thought that dry permafrost dominated the region, but recent studies discovered ubiquitous ice-cemented permafrost at shallow depths. Here, we review the current state of knowledge of permafrost and ground ice in the McMurdo Dry Valleys and other ice-free areas in Antarctica to understand the role of ground ice in a changing climate. The study presents a summary of depths to icy permafrost, vertical distribution of ground ice, and δD-$\delta^{18}O$ profiles for a range of Antarctic sites. Mechanisms of ground ice emplacement are discussed over various timescales, including the freezing of evaporated snowmelt and the condensation of vapour diffusion into the permafrost. The variability in the distribution and origin of ground ice is attributed to ground surface temperature and moisture conditions, which separate Antarctic permafrost into three distinct zones: upland, mixed and coastal zones. Ground ice of vapour-deposition origin is predominantly situated in the stable upland zone, whereas ground ice formed by the freezing of evaporated snow meltwater is predominantly found in the coastal thaw zone.

1 Introduction

Ground ice is a general term used to define all types of ice contained in frozen ground (French 2017; Harris et al. 1988). It plays a central role in landscape development of permafrost environments and geohazard risks. Unlike the Arctic, where the distribution and origin of ground ice have been extensively studied (French 2017), relatively few studies about ground ice have been conducted in cold and hyper-arid Antarctica (e.g., Bockheim et al. 2007). Campbell et al. (1998) and Bockheim et al. (2007) classified permafrost in Antarctica as either (1) dry permafrost (contains negligible moisture, < 3% wt; Campbell et al. 1998); (2) ice-cemented permafrost; and (3) massive ground ice or buried ice. In the Arctic, ice-cemented permafrost is typically sub-divided based on volumetric ice content (see full classification in French and Shur 2010). Here, the term ice-cemented permafrost (or *icy*) is used as an umbrella term to describe permafrost that harbours ice, irrespective of ice content (e.g., McKay et al. 2019). Muller (1945) introduced the concept of dry permafrost as a geotechnical application for engineering projects. Pewe (1959) later suggested its occurrence in Antarctica, but dry permafrost was first observed with the use of thermistors at Linnaeus Terrace in Upper Wright Valley (McKay et al. 1998). Dry permafrost has subsequently been observed in most regions in the Transantarctic Mountains, notably in the McMurdo Dry Valleys (MDV; Campbell et al. 1998; Marinova et al. 2013), Ellsworth Mountains (e.g., McKay et al. 2019), Queen Maud Land (e.g., Kotze and Meiklejohn 2017), Enderby Land, MacRobertson Land (e.g., Alekseev and Abakumov 2020) and Wilkes Land (e.g., Alekseev and Abakumov 2020). The occurrence of massive ground ice and buried ice in Antarctica typically relates to the presence of ice wedges (e.g., Raffi and Stenni 2011), buried glacial ice (Gardner et al. 2022; Swanger 2017; Swanger et al. 2019; Swanger et al. 2010) or buried remnants of the Ross Sea ice sheet (Levy et al. 2013).

The only attempt at classifying ground ice distribution in the uppermost meter was from the MDV (Bockheim et al. 2007). In this region, dry permafrost and ice-cemented permafrost occupied 43% and 55%, respectively of the area. However, recent studies have since observed ice-cemented permafrost (e.g., Lacelle et al. 2013; Lapalme et al. 2017; Verret et al. 2021) or massive ice (Gardner et al. 2022; Swanger 2017; Swanger et al. 2010) in locations previously classified as dry permafrost. This suggests that ground ice abundance might be underestimated in the MDV and elsewhere in Antarctica (Figure 1). Here, we present a summary of the active layer thickness and depth to the ice table and discuss the concept of a transient layer. We then present a summary of the vertical distribution of ground ice and δD-$\delta^{18}O$ profiles for a range of Antarctic sites, discuss mechanisms of ground ice emplacement and the role of Antarctic ground ice in a changing climate.

2 Active layer and ice table

Permafrost is defined as ground that remains at or below 0 °C for two or more consecutive years, and the active layer corresponds to the near-surface soils that warm above 0 °C during the summer season (Harris et al. 1988). The thickness of the active layer corresponds to the maximum

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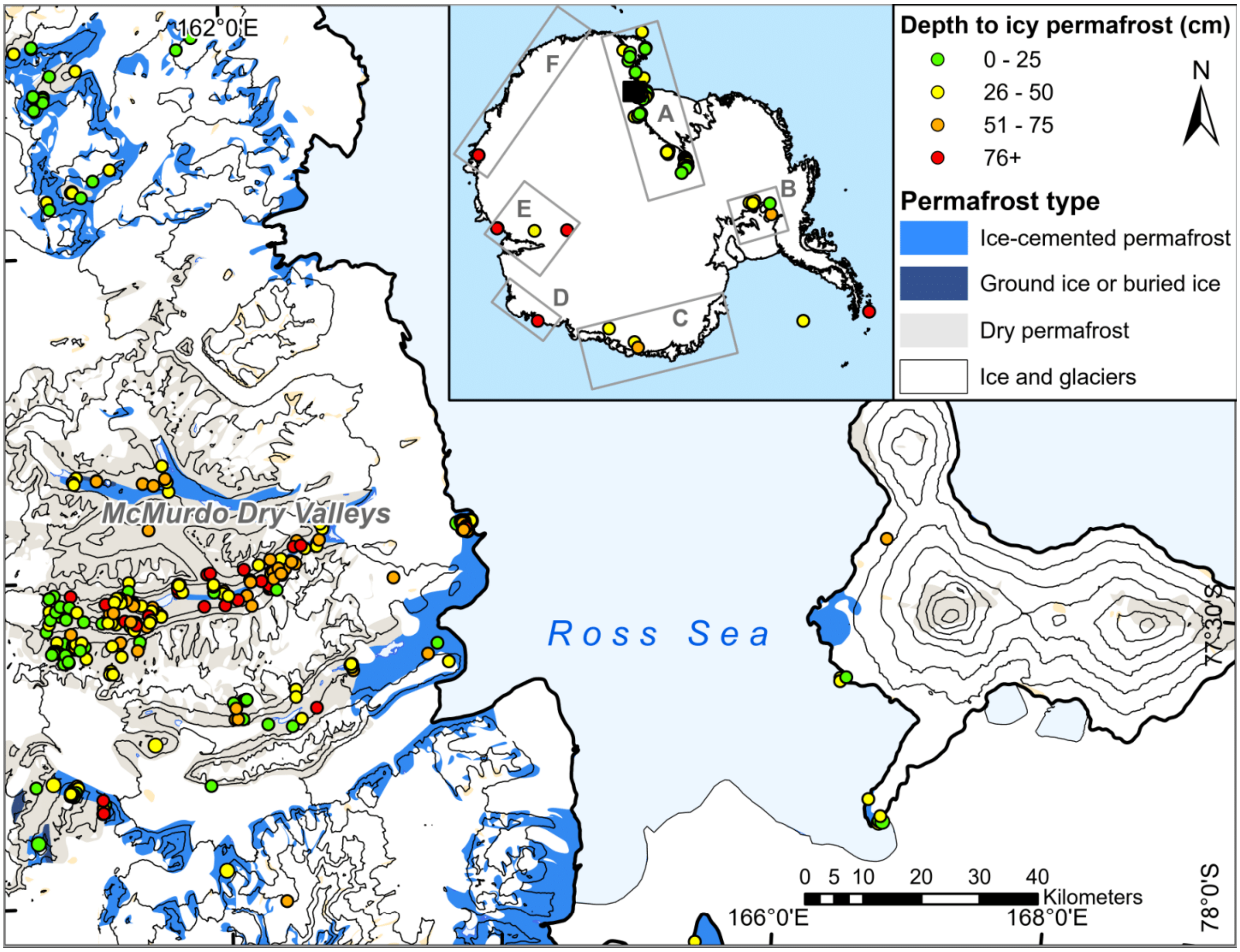

Figure 1. Predicted distribution of ground ice (modified from Bockheim et al. 2007) with compilation of depths to icy permafrost measurements in different sectors of Antarctica: A. Transantarctic Mountains (Campbell and Claridge 1964–1999; Denton et al. 1986; Dickinson and Rosen 2003; Lacelle et al. 2013; Marchant et al. 2002; McLeod et al. 2004–2007; Verret et al. 2021), B. Ellsworth Mountains (Campbell and Claridge 1964–1999; McKay et al. 2019), C. Queen Maud Land (Lacelle et al. in press; Matsuoka et al. 1990; Vtyurin 1986), D. Enderby Land (Alekseev and Abakumov,2020; MacNamara 1969), E. MacRobertson Land (Alekseev and Abakumov 2020; Li et al. 2003) and F. Wilkes Land (Alekseev and Abakumov 2020). The depth to icy permafrost corresponds to the thaw depth and active layer depth in the coastal thaw zones but represents a sublimation unconformity in stable upland sites.

depth of the 0 °C isotherm; the boundary with the underlying permafrost is termed the permafrost table (Brown and Kupsch 1974). In Antarctica, the thickness of the active layer estimated from soil thermistors varies from zero to a few centimeters in the coldest high elevations of the Transantarctic Mountains, and up to > 5 m in bedrock sites of the Antarctic Peninsula (Hrbáček et al. 2023). As a general trend, active layer thickness decreases with increasing elevation and continentality (Adlam et al. 2010; Hrbáček et al. 2023). Marchant and Head III (2007) define three climatic zones which can be applied to Antarctic permafrost: (1) the coastal thaw zone (CTZ), where temperatures regularly exceed 0 °C resulting in seasonal melt, (2) the intermediate mixed zone (IMZ), where temperatures may rise above 0 °C only for short periods resulting in the periodical presence of liquid water and (3) the stable upland zone (SUZ), where maximum air temperatures do not exceed 0 °C resulting in little or no melting of snow and/or ice. The absence of vegetation and surface organic matter, and lack of snow cover and/or moist active layer (e.g., Fountain et al. 2010) result in a small to negligible surface offset (i.e., mean annual ground temperature ~ mean annual air temperature; Lacelle et al. 2016).

Permafrost has also been defined as ground that remains frozen for two or more consecutive year (Muller 1945). Under this definition, the active layer corresponds to the near-surface soils that seasonally thaw and freeze and its depth equals or exceeds that defined by the 0 °C isotherm, the difference is caused by the soil water salinity and the associated freezing point depression (Anderson and Morgenstern 1973; Brown and Kupsch 1974). However, in

Antarctica, the cryotic soils above the icy permafrost are often dry and the soil water salinity cannot explain this difference. Considering that the Arctic-centric perspective of frozen ground did not translate to regions with dry permafrost, terms like “dry-frozen permafrost” (Muller 1945) and “dry and wet shell” (Ward et al. 1969) were introduced to describe permafrost in hyper-arid regions, and the term “ice table” was introduced to define the boundary between dry and icy permafrost (first introduced in lunar and planetary science; Gold 1962; Smoluchowski 1968). Thus, when using the thermal definition of the active layer in Antarctica, the depth to the ice table (icy soils) can exceed that of the 0 °C isotherm, the two being separated by dry permafrost. The depth to the ice table varies from a few centimeters to more than two meters (e.g., Campbell and Claridge 1964–1999; Figure 1). As a general trend, the ice table is observed mainly in the stable, high elevation, SUZ and corresponds to a sublimation unconformity; in the CTZ, the depth to icy permafrost mainly corresponds to the thaw depth. The depth of the ice table in the SUZ is set by the water vapour density gradient between the ground surface and the ice-bearing ground (Fisher et al. 2016; McKay et al. 1998), although it can be recharged periodically by snowmelt (Hagedorn et al. 2010; Marinova et al. 2013). Fisher et al. (2016) developed a numerical model (REGO) to predict the depth of the ice table based on ground surface temperature and humidity as the boundary conditions, along with damping of diurnal and annual temperature cycles within sandy soils. The measurements from three sites fit well the predicted ice table depth for the surface relative humidity or difference in frost point values between the surface and ice table (Figure. 2).

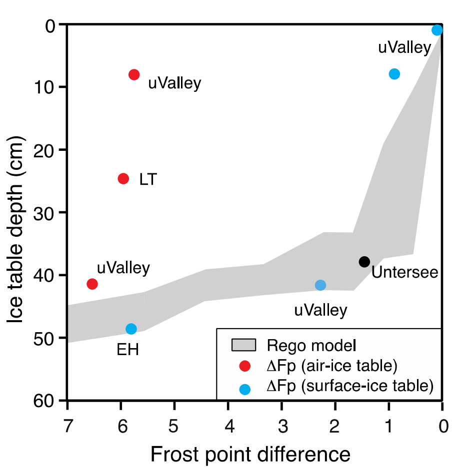

Figure 2. Measured ice table depths at sites with known frost point differences in the Transantarctic Mountains (University Valley) and Queen Maud Land (Untersee Oasis), along with *Linnaeus Terrace* and *Ellsworth Mountains* compared with those predicted by the REGO model.

2.1 Depth of ice table and diameter of polygons

Geophysical approaches (i.e., ground-penetrating radar) have been used to attempt to identify the presence of ground ice in Antarctic permafrost, but they have only been successful at identifying thick bodies of massive ice (Drake 2015; Winsor et al. 2020). Polygonal terrains are features visible from satellite imagery and could allow for an efficient method to map ground ice in areas where data are lacking. Mellon et al. (2014) observed a relationship between the depth to the ice table and the diameter of polygons, and numerical modeling of seasonal stress in permafrost showed that the ice table depth is the main parameter that controls the diameter of polygons. Much like the polygons studied in University and Farnell valleys within the upper MDV (Mellon et al. 2014), data on polygon size from Pritzker Valley in Untersee Oasis and other MDV locations—such as McKelvey Valley, Andrew Ridge, Taylor Valley, Barwick Valley and Victoria Valley—reveals a consistent positive correlation between the size of the polygons and the depth of the ice table. In fact, the sizes and depths of the 14 surveyed sites align closely with the predictions made by Mellon et al. (2014) in their study (Figure 3).

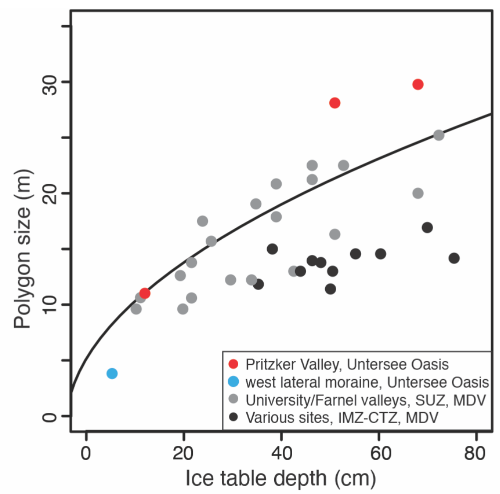

Figure 3. Relationship between polygon diameter and ice table depth at various Antarctic sites: University and Farnell valleys (Mellon et al. 2014), Pritzker Valley (Lacelle et al. in press) and various MDV sites, where ice table depths are obtained from Campbell and Claridge (1964–1999) and average polygon diameter are measured using Lidar data from Fountain et al. (2017).

2.2 A transient layer in Antarctic permafrost?

The transient layer has been defined as the zone in which the active layer thickness experiences interannual fluctuations over decadal to centennial time-scale (Shur et al. 2005). The transient layer is often ice-rich and described as essential to permafrost’s long-term stability. Shur et al. (2005) suggested that interannual variations in active layer thickness over decadal timescales could be assessed from the maximum variation (%) as a function of average active layer thickness. We examined whether the year-to-year changes in the thickness of the active layer in Antarctica are comparable to those in the Arctic. We used data on active layer thickness from the Circumpolar Active Layer Monitoring (CALM) Programme dataset, focusing on sites with over a decade of measurements. The data show that the relative changes in active layer thickness can vary widely, ranging from 4% to 114% (Figure 4). With the exception of Mount Fleming (1697 m a.s.l. and a very shallow active layer thickness), the range in variations is within those calculated for sites in the Arctic, and like in the Arctic, a negative relationship is observed with increase mean active layer thickness (i.e., Shur et al. 2005). Shur et al. (2005) suggested that % variations in active layer thickness are affected by climate and soil types and are greater in organic soils. The latter can be ruled out for Antarctica given the absence of a surface organic layer. As such, future work should explore environmental parameters that might affect the % variations in active layer thickness (depth to ice table, thickness of dry permafrost, soil types, soil moisture).

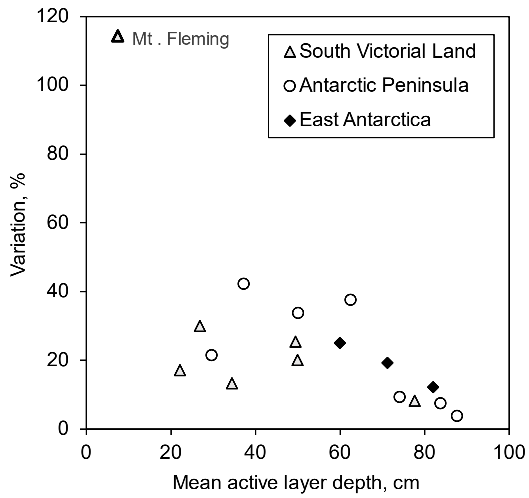

Figure 4. Variations of active layer thickness and average active layer thickness. Monitoring period is minimum 10 years. Data retrieved from the Circumpolar Active Layer Monitoring (CALM) Programme.

3 VERTICAL DISTRIBUTION OF GROUND ICE

Antarctica's earliest and most extensive survey for permafrost and ground ice was the *Dry Valleys Drilling Project* (DVDP), where cores were retrieved from the three main valleys (Taylor, Wright and Victoria valleys). Ground ice was found in all three valleys and up to depths of 320 m in Taylor Valley (Stuiver et al. 1976). Subsequently, the boreholes of the *Coring for microbial records of Antarctic climate* (COMRAC) project (5–20 m) from Taylor Valley, Miers Valley, Mount Feather and Beacon Valley were all drilled in icy permafrost and had ice contents in 25 to 50 wt% (i.e., gravimetric water content expressed in weight%) range immediately below the dry permafrost layer (Gilichinsky et al. 2007). More recently, the Table Mountain drill cores (Dickinson et al. 2012), the Friis Hills Drilling Project (FHDP; Verret et al. 2021) and a University of Washington-led drilling project in Beacon Valley (Cuozzo et al. 2020) reached depths of 5 m, 50 m and 30 m respectively and the cores were mostly ice-cemented, with discrete ice lenses (20 to 80 wt%).The Friis Hills cores showed interesting ice content trends with depth with icy permafrost down to 5 m depth, followed by near-dry permafrost (5–20 m depth), and, again, ice-poor to ice-rich permafrost with distinct thin ice layers below 20 m depth (Figure 5). Overall, below the dry permafrost, the distribution and content of ground ice in Antarctic permafrost is similar to that in the Arctic (e.g., Lacelle et al. 2022).

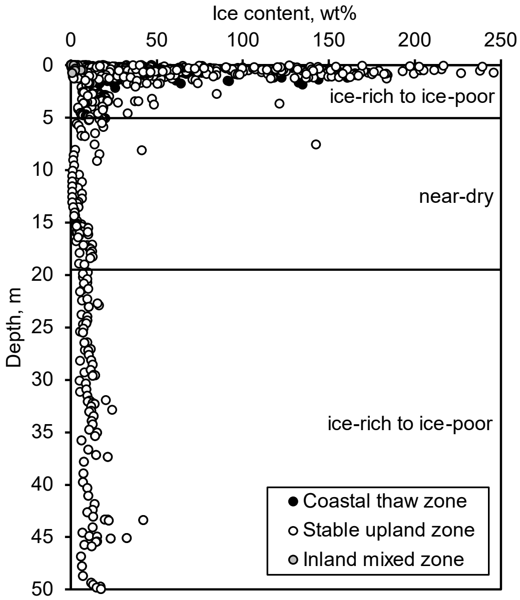

Figure 5. Ice content at different sites from the three different climatic zones in the McMurdo Dry Valleys (defined by Marchant and Head III 2007): the coastal thaw zone (n = 366 from 66 sites), the inland mixed zone (n = 16 from 3 sites) and the stable upland zone (n = 966 from 98 sites). Data from Campbell and Claridge (1964–1999), Dickinson and Rosen (2003), Lacelle et al. (2013), Lapalme et al. (2017) and Verret et al. (2021).

4 ORIGIN OF GROUND ICE

The CTZ harbours ice emplacement mechanisms similar to those found in the Arctic (French 2017). Thus, the following sections will focus on the origin of ground ice in the SUZ. Early investigations of permafrost and models describing ground ice in Antarctica suggested that that ground ice should persist for only a few thousand years as sublimation would eventually remove it from the ground (e.g., Hagedorn et al. 2007; Hindmarsh et al. 1998; McKay et al. 1998; Schorghofer and Aharonson 2005). Yet, in sediments dating back to the mid-Miocene (Dickinson and Rosen 2003; Verret et al. 2021), ground ice was found in abundance at shallow depths (30 to 70 cm). This suggests that there may either be an error in the boundary layer of the model parameters—specifically, using air-based parameters instead of those at the ground surface—or that there has been a recent deposition of ice in the soils. The latter mechanism has been found to be of marginal importance, since a recent study using meteoric Beryllium-10 as a tracer for water infiltration concluded that minimal liquid water has penetrated the ground for at least a few million years at the high-elevation sites of the MDV (Schiller et al. 2019; Verret et al. 2023). In addition, the most recent modeling studies show that the depth of the ice table can be explained using the ground surface as the boundary layer (Fisher et al. 2016). There are three known mechanisms of ice emplacement in SUZ permafrost: (1) episodic freezing of snow meltwater, (2) diffusion of water vapour and (3) burial of glacier ice.

4.1 Freezing of snow meltwater

Although instances of wedge ice have been observed in Northern Victoria Land (Raffi and Stenni 2011), two main types of ground ice originate from the freezing of liquid water in the SUZ: segregated ice and pore ice (e.g., Dickinson and Rosen 2003; Lacelle et al. 2013; Marchant et al. 2002; Verret et al. 2021). These types of ice are widely present in the Arctic (French and Shur 2010); however, their presence in Antarctic permafrost at sites where mean annual air temperatures remain below < 0 °C have raised questions about mechanisms of ice emplacement and the source of water. A number of studies have inferred the source of liquid water for ground ice in the near-surface of hyper-arid sites using stable water isotopes coupled with soluble ions in the ice (Cuozzo et al. 2020; Dickinson and Rosen 2003; Hagedorn et al. 2010; Lacelle et al. 2013; Verret et al. 2021). Stable isotope depth profiles displayed a higher isotopic composition near the surface throughout these studies. This trend results from the infiltration of highly evaporated (up to 95%) snowmelt (Cuozzo 2021; Lacelle et al. 2013; Verret et al. 2021). Ice that forms from evaporated snowmelt is usually characterized by high solute load (on the order of 1 to 10 mg g^{-1} dry soils), enriched $\delta^{18}O$ and δD values plotting well below the local meteoric water line (LMWL; $\delta D = 7.9\delta^{18}O+0.8$; Figure 6). In fact, D-excess values are amongst the lowest reported on Earth (–105.8‰; Lacelle et al., in press). This process has been observed in both low and high elevations of the MDV sector (Victoria Valley, 450 m a.s.l.; Friis Hills, 1200–1500 m a.s.l; University Valley, 1600–1800 m a.s.l; Table Mt) and it most likely also occurs in other regions, such as in Pritzker Valley (800–1100 m a.s.l.), situated in Queen Maud Land (Figure 6).

The snow meltwater that enters the icy permafrost may then be redistributed along thermal and stress fields. Fisher et al. (2020) employed a model to track the migration of unfrozen water in icy permafrost, aiming to estimate how ground ice content profiles change over time. This movement of unfrozen water leads to ice-rich and ice-poor zones forming at specific depths over time, primarily influenced by the thermal diffusivity, water chemistry and soil type of the icy permafrost. Evidence of this process was found in the Friis Hills Drilling Project cores, where nearly dry permafrost across 5–20 m depth originated from the redistribution of unfrozen water (Figure 5).

4.2 Vapour diffusion

In the SUZ of Antarctic permafrost, where ground temperatures remain cryotic year-round and little surface melt occurs, ground ice was found to originate from the diffusion of water vapour into the soils. Vapour diffusion creates closed-cavity ice, which is indifferentiable structurally to pore ice. All sites showed similar ground ice profiles, including a shallow and narrow ice-rich horizon at 5–10 cm depth (> 50% excess ice content), that then progressively decreased with depth. All these sites yielded δD-$\delta^{18}O$ regression slope values similar to the LMWL but with low D-excess values such that the data plot well below the LMWL. The very low D-excess values suggest that the source of water vapour is either from direct condensation of atmospheric moisture in the soils, which would plot along the LMWL but with D-excess near -35‰ and/or from transient frost that forms just at and under the ground surface in winter (Fisher et al. 2016). This mechanism of ground ice accumulation in sediments within cold–dry settings can still result in overfilled pore ice (excess ice), even without the presence of liquid water, following repeated thermal cycling in the icy soils.

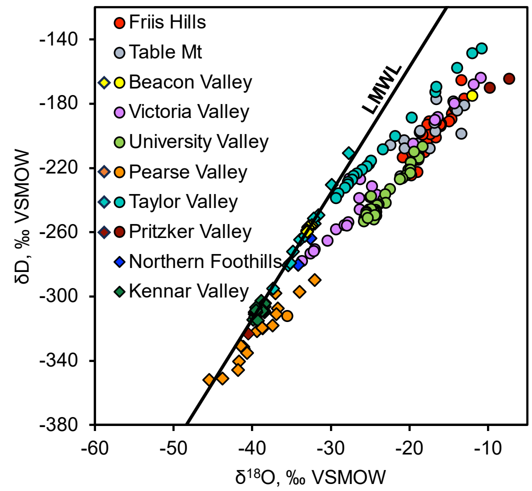

Figure 6. Stable isotope composition for selected buried ice (diamonds) and pore/segregated ice (circles) in Antarctic permafrost: Friis Hills (77°45′S 161°28′E; Verret et al. 2021), Table Mountain (77°57'S, 161°57'E; Dickinson and Rosen 2003), Beacon Valley (77°50'S, 159°30'E; Marchant et al. 2002), Victoria Valley (77°22'S, 161°35'E; Cuozzo 2021; Hagedorn et al. 2010), University Valley (77°52'S, 163°45'E; Lacelle et al. 2013; Lapalme et al. 2017), Pearse Valley (77°42'S, 161°36'E; Heldmann et al. 2012; Swanger et al. 2010), Taylor Valley (77°37′S, 163°00′E; Gardner et al. 2022; Levy et al. 2011; Toner and Sletten 2013), Pritzker Valley in Queen Maud Land (71°17'S, 13°43'E; Lacelle et al. in press), Northern Foothills in Northern Victoria Land (74°44′S 163°55′E; Guglielmin and French 2004) and Kennar Valley (Swanger 2017). Note: we use the LMWL from the MDV (Lacelle et al. 2011), which encompasses most sites, unless specified otherwise.

4.3 Buried glacier ice

Buried ice is a sub-group of ground ice, where ice, such as glacier ice, is preserved in permafrost (emplacement conditions and mechanisms dicussed in Harris and Murton 2005). Two types of buried glacier ice have been found, debris-covered (or basal) glacial ice and surface (firn-derived) glacial ice. Debris-covered glacial ice has been observed in multiple locations in Antarctica, particularly in the MDV sector, where ice from Ross Sea ice sheet and other glaciers have been preserved for thousands of years (e.g., Lacelle et al. 2013; Swanger 2017; Swanger et al. 2019), and even > 1 million years in the case of Beacon Valley (Yau et al. 2015), Ong Valley (Bergelin et al. 2022) and Allan Hills (Yan et al. 2019). Buried surface glacial ice typically has low dissolved ion concentrations and meteoric isotopic signatures (Figure 6).

5 Ground ice in a warming climate

This review has highlighted the widespread presence of ground ice in Antarctica. We will now explore advancements related to ground ice in the context of a warming climate.

5.1 Relict ground ice to predict future Antarctic terrestrial climate

Relict ground ice which has preserved its original meteoric water can be used to reconstruct paleo air temperatures (Porter and Opel 2020). In Antarctica, particularly in the MDV, air temperatures have remained cold enough to sustain continuous permafrost since the mid-Miocene (Verret et al. 2021). Subsequent alteration of ground ice by vapour diffusion through diurnal and annual temperature cycles is only possible to a certain depth that can be modeled (Fisher et al. 2016). Additionally, ground ice accumulation rate decrease following an e-folding function following decrease in porosity as ice accumulates (Fisher et al. 2020). This implies that drilling deep (>30 m; depending on the ground's thermal properties) into Antarctic permafrost could potentially uncover meteoric ground ice that kept its original isotopic signature, like the ice found at the bottom of the Friis Hills cores (Verret et al. 2021). This finding offers the potential to use meteoric ground ice as a paleotemperature proxy dating back to the early Miocene, which extends beyond the oldest ice core record (currently 800,000 yrs at EPICA Dome C; Wolff et al. 2010). Buried glacier ice, which represents long-term archives of glacial ice, could be used to reconstruct past glacial advances (Swanger et al. 2019).

However, paleoclimate inferences from ground ice stable isotope records remain a mostly underutilized due to the lack of dating methods for relict ice. Meteoric Beryllium-10 has been used as a tracer for water infiltration (along with other cosmogenic nuclide dating methods), which allows one to constrain the timing of the emplacement of the ground ice (Verret et al. 2023). However, this indirect dating method relies on a complete understanding of the periglacial history for interpretation. Development of a suitable isotope methods for dating old ice will be required to make more direct interpretations. Ground ice may, however, offer rare glimpses of the terrestrial climate systems during intervals that are simply not captured by any other terrestrial archives. This may become critical to our understanding of future climate change.

5.2 Role of ground ice in Antarctic terrestrial ecosystems

Antarctic ground ice has long been considered stable. However, recent studies suggest accelerated thermokarst formation driven by increased insolation in coastal areas (Levy et al. 2013). Under mild 1–2 °C warming conditions in the MDV sector, active layer could increase up to 20 cm (Levy et al. 2013), potentially reaching ice table depths at certain sites. Increasing moisture availability in hyper-arid sites would have significant impacts on soil ecosystems (Andriuzzi et al. 2018; Wlostowski et al. 2018). Moreover, recent studies using lipid biomarkers, have suggested that legacy carbon locked-in at depth in permafrost has been bioavailable under past warmer climate (Verret et al., in prep). Carbon being one of the key physiochemical factors in the development of soil microbial communities (Cary et al. 2010), future climate warming could lead to considerable changes in the structure and function of ecosystems in the MDV.

5.3 Transient layer in degrading Antarctic permafrost

The impact of Antarctic ground ice on the ground's thermal regime is not yet fully understood. Ice-rich permafrost in the transient layer at many coastal thaw zone locations could serve as a thermal buffer by releasing latent heat during phase change, similar to phenomena observed in the Arctic (Shur et al. 2005). Conversely, an increase in water content in the stable upland zone, which has a layer of dry permafrost, could also significantly influence the ground thermal regime in the transient layer. Dry permafrost acts as a short-term buffer, as dry soils have a lower thermal conductivity than moist soils, mitigating the effects of rising ground temperatures (Andersland and Ladanyi 1994). In summary, the distribution and content of ground ice and the presence of unfrozen water are key variables for understanding the terrestrial Antarctic environment and its response to a warming climate.

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