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Excess ground ice of condensation–diffusion origin in University Valley, Dry Valleys of Antarctica: Evidence from isotope geochemistry and numerical modeling

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Abstract

This study investigates the origin and age of ground ice in the uppermost 1 m of permafrost in University Valley, one of the upper valleys in the McMurdo Dry Valleys of Antarctica. In contrast to other regions in the MDV, mean daily air and soil temperatures at the coring sites are always below 0 °C, which allows for unique cryogenic processes to occur. In the two cores that were analyzed, excess ground ice was measured throughout, ranging between 23% and 85%. Isotope geochemical trends in the ice-rich permafrost indicate that the ground in Core 5 (65 cm long) and the uppermost 52 cm of Core 7 originated from condensation–diffusion of water vapor; whereas the ground ice between 57–90 cm in Core 7 originated from freezing of liquid water. Using numerical modeling, we show that the excess ground ice of condensation–diffusion origin formed by the long-term thermal contraction–expansion of the cryotic sediments, which allowed for the ice content to exceed pore-filling capacity. Absolute age estimates of the sandy-loam sediments based on Optically Stimulated Luminescence dating indicate that soils have been accreting at the site for at least the last 170 ± 36 ka years, and this places an upper limit to the age of the ground ice. Absolute soil ages allowed us to link the change in ground ice origin in Core 7, which took place around 152 ± 12 ka years, with shifts in climate conditions since marine isotope stage 5e interglacial period. Our findings offer a new process of ground ice emplacement in sediments in cold–dry environments and allow an alternative explanation regarding the enigmatic origin of excess ground ice identified by Mars Odyssey and Phoenix in the northern martian plain, which is that overfilled pore ice can form by vapor deposition and repeated thermal cycling without the presence of melt water.

1. INTRODUCTION

The McMurdo Dry Valleys (MDV) comprise the largest ice-free region in Antarctica, despite pervasive ground ice. According to Campbell and Claridge (2006), ground ice takes the form of ice-cemented soils (defined as ice occupying the pore spaces of soils; ACGR, 1988), massive ground ice bodies, or saline frozen ground associated with the presence of brines or seawater. Massive ground ice bodies occur predominantly as local ice wedges or buried relict glacial ice (e.g., Sugden et al., 1995; Bockheim, 2002; Marchant et al.,

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2002; Guglielmin and French, 2004; Lacelle et al., 2011; Raffi and Stenni, 2011), whereas ice-cemented permafrost occupies approximately 55% of the upper 1 m of the landscape (Bockheim et al., 2007).

Despite the widespread distribution of ground ice in the MDV, and its key role in landscape evolution (i.e., Sletten et al., 2003; Marchant and Head, 2007; Levy et al., 2010; Swanger et al., 2010), little is know about its origin and age. Most of the available data comes from numerical models using relatively short-term climate data (post 1986) (Hindmarsh et al., 1998; McKay et al., 1998; Hagedorn et al., 2007), which, together with a limited number of field-based studies, point to a temperature control in the origin and stability of the ice. Studies conducted in the low and mid elevation valleys (i.e., <1000 m), where summer air temperatures often exceed the freezing point, suggest that water was supplied to the subsurface by seawater incursion in a deltaic environment (Stuiver et al., 1976) or by brines derived from evaporated snowmelt that periodically infiltrates the cryotic sediments (i.e., Hagedorn et al., 2010). The presence of ground ice in the higher elevation valleys (i.e., >1000 m), which are also drier and colder than the lower valleys, is less well understood. Based on isotopic and geochemical analyses, Dickinson and Rosen (2003) suggested that ice-cemented permafrost in these upper valleys formed from the diffusion and condensation of water vapor, as well as the downward migration and freezing of briny films of snowmelt. In the upper valleys, the mechanisms controlling the depth to ground ice (i.e., McKay, 2009; Marinova et al., 2013), the long-term stability of the ice (i.e., Marchant et al., 2002; Ng et al., 2005; Kowalewski et al., 2006, 2012 and the relative age of the ice compared to that of the soils, are still open questions.

In this study, we investigate the cryostratigraphy and isotope geochemistry of ground ice in University Valley (c.a. 1650–1700 m a.s.l), by combining high-resolution measurements of ice content and isotope geochemistry with the age of sediments constrained by Optically Stimulated Luminescence (OSL) dating. To account for the observed trends, we applied a numerical model of vapor transport through thermally contracting and expanding sediments, which includes condensation, sublimation and diffusive migration of water vapor with phase changes and associated temperature-dependent isotope fractionation. Our findings offer an alternative explanation regarding the enigmatic origin of excess ground ice identified by Mars Odyssey and Phoenix in the northern martian plains (Boynton et al., 2002; Smith et al., 2009).

2. STUDY AREA

The study site is located in University Valley (77°52′S; 160°45′E), one of the upper valleys in the Quartermain Range in the MDV of Antarctica (Fig. 1). University Valley is a 1.5 km long and 500 m wide northwest facing hanging glacial valley situated ca. 450 m above the floor of Beacon Valley. The local geology in University Valley consists of sedimentary rocks of the Beacon Supergroup (Devonian to Triassic age sandstones, siltstones, and conglomerates) and sills of Ferrar Dolerite (Jurassic age intrusives) (Elliot and Fleming, 2004). Spatially, surface sediments in the valley are relatively heterogeneous, with areas dominated by large boulders and rocks, and other areas composed mainly of sand-size particles in which polygonal terrain and desert-pavement developed. A small glacier partially covers the head of the valley and permanent snow patches are also found scattered in depressions on the valley floor. Ground ice is extensive across the entire valley floor, as evidenced from polygonal terrain. The ground ice is overlain by dry permafrost of variable thickness (here, dry permafrost is defined as cryotic soils containing negligible amount of water; ACGR, 1988). The depth to ground ice increases as a function of distance from the glacier, being less than 1 cm near the glacier, and more than 70 cm at the mouth of the valley (McKay, 2009; Marinova et al., 2013). In addition, two distinct bodies of massive ground ice were discovered, one located adjacent to the glacier and the other located near the mouth of the valley (Lacelle et al., 2011; Pollard et al., 2012).

University Valley is located within the “stable upland” micro-climatic zone defined by Marchant and Head (2007). One-year climate data from an automated Campbell environmental station deployed in December 2009 indicated a mean annual air temperature and relative humidity of −24.3 °C and 48%$_{\text{water}}$, respectively (Fig. 2). Summer air temperature was always below the freezing point (maximum hourly air temperature −2.8 °C). Additionally, soil temperature and moisture were measured at two locations (shallow ice table depth: 8 cm; deep ice table depth: 42 cm) at different soil depths using Hobo soil temperature-moisture sensors (Fig. 2). At both sites, average daily surface soil temperatures did not raise above 0 °C during the summer. However, the maximum hourly surface soil temperatures were different at both sites (Fig. 3), being always less than 0 °C at the shallow ice table site (maximum of −0.5 °C), and reaching values above 0 °C at the deep ice table site (maximum of 8 °C) due to solar heating. The reason for the difference in surface soil temperatures is that the shallow ice table site is situated along the eastern side of the valley, an area that is nearly always shadowed due to the valley walls (Fig. 1A). The relative humidity conditions are also different between the atmosphere and those measured near the soil surface at both sites (Fig. 3). The mean annual relative humidity in the atmosphere is 57.5 ± 17%. At the shallow ice table depth site, the relative humidity at 4 cm depth fluctuates between 89%$_{\text{ice}}$ in summer and near 100%$_{\text{ice}}$ in winter (annual average: 97 ± 1.8%$_{\text{ice}}$), whereas at the deep ice table depth site, the mean annual relative humidity at the soil surface is 88 ± 16%$_{\text{ice}}$ (ranging between 25% and 99%$_{\text{ice}}$). The different temperature and humidity conditions between the shallow and deep ice table sites suggest that distinct hydrologic processes can occur; the present-day surface soil temperature being unfavorable to melt surface snow and ground ice at the shallow ice table depth site, whereas at deeper ice table depths, melting of snow and ice is likely to occur as soil surface temperatures can be above 0 °C for a few hours each day in the summer.