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Vapor transport and sublimation on Mullins Glacier, Antarctica

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ABSTRACT

We utilize an environmental chamber capable of recreating the extreme polar conditions of the McMurdo Dry Valleys (MDV) of Antarctica to investigate the sublimation rate of the Mullins Valley debris-covered glacier (hereafter Mullins Glacier), reportedly one of the oldest debris-covered alpine glaciers in the world. We measure ice loss via sublimation beneath sediment thicknesses ranging from 0 to 69 mm; from this, we determine an effective diffusivity for Fickian vapor transport through Mullins till of $(5.2 \pm 0.3) \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$ at $-10\,^{\circ}\mathrm{C}$. We use this value, coupled with micrometeorological data from Mullins Valley (atmospheric temperature, relative humidity, and soil temperature) to model the sublimation rate of buried glacier ice near the terminus of Mullins Glacier, where the overlying till thickness approaches 70 cm. We find that the ice-lowering rate during the modeled year (2011) was 0.066 mm under 70 cm of till, a value which is in line with previous estimates for exceedingly slow rates of ice sublimation. These results provide further evidence supporting the probable antiquity of Mullins Glacier ice and overall landscape stability in upland regions of the MDV.

1. Introduction

The McMurdo Dry Valleys (MDV) of Antarctica have remained predominately ice-free and under hyper-arid polar desert climate conditions since the middle Miocene (Denton et al., 1993; Marchant et al., 1993, 1996, 2002; Sugden et al., 1999; Valletta et al., 2015). The preservation of *in situ* volcanic ash deposits >10.0 Myr in the Quartermain Mountains (Marchant et al., 1993; Sugden et al., 1995), as well as the concentration of meteoric beryllium-10 in ancient sediments (Valletta et al., 2015), demonstrates that saturated active-layer cryoturbation – typical of most periglacial regions in the world – has been essentially absent from much of the western MDV over this interval. These findings corroborate the slow rates of landscape change and long-term stability of the region that is afforded by cosmogenic nuclide analyses of surface rocks (Schäfer et al., 2000, 1999; Margerison et al., 2005) and glacial–geologic mapping (Lewis and Ashworth, 2015). Moreover, the presence of *in situ* ashfall in supraglacial debris suggests that, in places, buried glacier ice has survived for ∼8.1 Myr (Sugden et al., 1995). If such ancient ice could be analyzed reliably for gas content it would greatly extend our climate record beyond that possible through the analysis of existing ice cores (e.g., EPICA Dome C, Vostok, GISP). This possibility, along with recent field data suggesting that numerous buried glaciers survive in the coldest and driest parts of the Dry Valleys/Transantarctic Mountains (Bibby et al., 2016; Mackay and Marchant, 2016) has prompted renewed interest in defining the precise conditions that foster long-term ice preservation in hyper-arid deserts (Kowalewski et al., 2006; Yau et al., 2015; Mackay et al., 2014). The results have been mixed, with modeled estimates for sublimation rates of the same buried ice masses spanning two orders of magnitude, from $10^{-3}\ \mathrm{m\,yr^{-1}}$ (Hindmarsh et al., 1998) to $10^{-5}\ \mathrm{m\,yr^{-1}}$ (Kowalewski et al., 2012; Liu et al., 2015) (see also Hagedorn et al., 2007; Hindmarsh et al., 1998; Kowalewski et al., 2006, 2011, 2012; Schorghofer, 2005). If the former rates are correct, then it is unlikely that buried glaciers could survive for >∼1 Myr; if the latter are correct, however, then pockets of buried ice could be preserved for several million years. As yet, there have been no attempts to address this problem through experimental analyses.

In this study, we examine the sublimation rate of Mullins Glacier, a debris-covered alpine glacier located in the inland portion of the MDV, using an experimental approach that measures ice loss via sublimation in an environmental chamber. In its central region, Mullins Glacier is >1.6 Myr (Yau et al., 2015; Mackay and Marchant, 2016); near its terminus, it may be >3 Myr (Mackay and Marchant, 2016).

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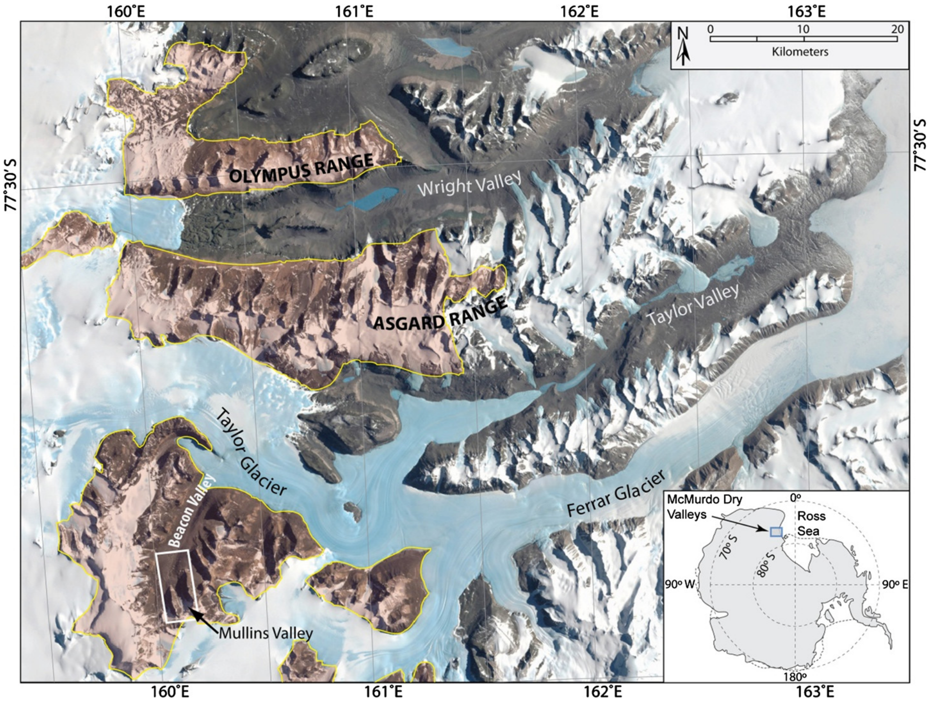

Fig. 1. Location of Mullins Glacier. Mullins Glacier occupies the region within the white box, in the lower left portion of the figure; the brown areas outlined in yellow highlight the stable upland zone of the McMurdo Dry Valleys, e.g., the region with negligible saturated active-layer cryoturbation (Marchant and Head, 2007). Inset map shows location of the McMurdo Dry Valleys (MDV); see Fig. 2 for details. Figure reproduced from Lamp et al. (2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Setting

Mullins Glacier is covered with a thin supraglacial till (Mullins till) that is derived from rockfall at the valley head; the till and underlying glacier ice move slowly down valley, decelerating from a maximum velocity of ~40 $\mathrm{mm\,yr^{-1}}$ near the valley head to <1 to 2 $\mathrm{mm\,yr^{-1}}$ on the floor of upper Beacon Valley (Fig. 1) (essentially stagnant, e.g., within measurement error of signals from interferometric synthetic aperture radar; Rignot et al., 2002). Mullins till is composed primarily of Ferrar Dolerite ($>93\%$) and undifferentiated sandstone fragments (Kowalewski et al., 2011). The mean annual and summertime atmospheric temperatures at the study site on the glacier are $-23\,^\circ\mathrm{C}$ and $-11\,^\circ\mathrm{C}$ respectively (Kowalewski et al., 2011; Mackay et al., 2014), and snowfall is <50 $\mathrm{mm\,yr^{-1}}$ water equivalent (Fountain et al., 2010). Strong katabatic winds flow from the East Antarctic Ice Sheet (EAIS) at speeds commonly approaching 50 $\mathrm{km\,h^{-1}}$ (Nylen et al., 2004; Speirs et al., 2010).

The ice in the upper reaches of Mullins Glacier (within ~4 km from the valley headwall) is relatively clean, showing only dispersed fines and episodic layers of concentrated debris; beyond ~4 km, the englacial content in Mullins Glacier increases markedly, with visual estimates of shallow ice cores and buried-ice surfaces in soil excavations, along with interpretations of ground penetrating radar, indicating up to 50% gravel and cobble sized clasts by volume (Mackay et al., 2014). The thickness of Mullins till generally shows a corresponding increase with increasing distance from the headwall (Mackay et al., 2014); at its maximum, Mullins till reaches ~70 cm in thickness in central and upper Beacon Valley (Kowalewski et al., 2011). Throughout its length, Mullins till is dotted with sublimation polygons, each of which increases in size and maturity with distance down glacier (Marchant et al., 2002). Previous studies have shown that these polygons play an important role in modulating subsurface ice loss (Kowalewski et al., 2012; Marchant et al., 2002): initially, sublimation rates at polygon troughs are high, due in part to elevated ice loss within unprotected thermal contraction cracks at these sites; as troughs deepen, however, they are in shadow most of the day and experience relatively cool temperatures. Further, deep troughs become preferred sites for snow entrapment, elevating local relative humidity (RH) (Marchant et al., 2002; Kowalewski et al., 2012). The relatively high RH values and cooler atmospheric temperatures tend to retard underlying ice sublimation (Kowalewski et al., 2006; Schorghofer, 2005). The result is that long-term sublimation rates for buried glacier ice with overlying sublimation polygons is limited by the rate of ice loss at polygon centers (Kowalewski et al., 2012).

3. Theoretical background

We assume that Fickian diffusion, characterized by impacts between molecules and driven by concentration gradients, is the dominate vapor transport mechanism from buried ice to the atmosphere at polygon centers in Mullins till (Schorghofer and Aharonson, 2005). Fickian processes dominate diffusive vapor transport through porous media when pore sizes are greater than the mean free path of vapor molecules (Ho and Webb, 2006). Previous studies of sediment in the MDV have shown that Knudsen diffusion, which takes into account molecular interactions with pore walls, can be neglected (Hagedorn et al., 2007; McKay et al., 1998). Thus, for Mullins till, Knudsen diffusion is insignificant. Additionally, we do not include the effects of thermally-driven vapor diffusion or advection, which previous researchers have shown to be less important than Fickian diffusion on annual (and longer) timescales (Schorghofer, 2005).

Fick's first law of diffusion is given as:

$$J = -D_f \frac{\partial \rho_{vap}}{\partial z} \tag{1}$$

where J is the diffusive flux ($\mathrm{mol\,m^{-2}\,s^{-1}}$), D_f is the Fickian diffusion coefficient ($\mathrm{m^2\,s^{-1}}$), ρ_{vap} is water vapor density ($\mathrm{mol\,m^{-3}}$)