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Modeling vapor diffusion within cold and dry supraglacial tills of Antarctica: Implications for the preservation of ancient ice

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ABSTRACT

We modeled water–vapor diffusion within Mullins till, a relatively dry supraglacial till in southern Victoria Land, Antarctica, that rests directly on Mullins Glacier, purportedly one of the oldest alpine glaciers in the world. Like most supraglacial tills in cold-desert environments, Mullins till contains three characteristic facies: a weathered facies representing the oxidation of iron-bearing minerals and the physical disintegration of surface rocks; a sand-wedge facies representing the episodic infill of thermal cracks associated with contraction-crack polygons; and an underlying fresh facies representing the addition of englacial debris (sourced from rockfall) as overlying ice sublimes. Using a one-dimensional model for Fickian vapor diffusion through porous media, we show that the rate of subsurface ice sublimation varies by ~5.5% beneath till facies and that over timescales of 10^5 years diffusion through "porous" sand wedges contributes to the development of deep troughs surrounding high-centered polygons. Applying site-specific meteorological data collected over a four-year period, we show that ice loss at the stagnant terminus of Mullins Glacier is $\sim 6.6\times10^{-5}$ m a^{-1}, a value that (although low and assuming an ice thickness of ~150 m) is consistent with complete ice loss under current environmental forcing in ~2.5 Ma. Our sensitivity tests indicate that the vast majority of sublimation occurs during the summer months. Calculated summertime losses drop to zero with either a reduction in soil and ice surface temperatures of ~6.4 °C or an increase in atmospheric relative humidity from 44% to 75%, both of which could arise from an increase in cloud cover over Mullins Glacier. Sublimation responses to meteorological forcing are not uniform across Mullins Glacier. A summer increase in soil temperature of 2 °C results in negligible change in ice sublimation at Mullins terminus, but a 27% increase in ice loss in upper Mullins Valley. The key factor is the thickness of Mullins till, which is greater near the glacier terminus. For till thicknesses exceeding ~25 cm, non-linear variations in soil temperature result in downward vapor fluxes, capable of producing thin, cm-scale lenses of secondary pore that cap the surface of buried glacier ice. This downward vapor flow, sourced from modern snowfall and/or elevated atmospheric relative humidity, is one of the key factors that enable long-term preservation of buried glacier ice. Overall, our results highlight the subtle relations among changes in till texture, till thickness, and meteorological forcing on the rate of subsurface ice loss and provide insight into the plausible range of conditions under which multi-million-year-old ice can exist beneath thin supraglacial tills, <~50-cm thick, in southern Victoria Land, Antarctica.

1. Introduction

Multiple reports suggest that stagnant glacier ice of late Miocene age exists beneath dry supraglacial tills in the Dry Valleys region of the Transantarctic Mountains, southern Victoria Land (Sugden et al., 1995; Schaefer et al., 2000; Marchant et al., 2002; Bockheim et al., 2007). If correct, the ice is considerably older than samples recovered from even the deepest ice cores in interior East Antarctica, estimated at ~900,000 years (Augustin et al., 2004; Lambert et al., 2008). However, the age of buried ice in the Dry Valleys has been called into question on the basis of theoretical arguments that call for rapid and unsustainable ice loss via sublimation, especially as would occur in a dry, polar climate (e.g., Hindmarsh et al., 1998). These theoretical arguments rely on assumed thermomechanical properties of supraglacial tills (tills on top of buried ice) and synthetic environmental forcing; results suggest that ice losses are ~1.0 mm a^{-1} (Hindmarsh et al., 1998). Although very low, the value still carries with it the implication that most (if not all) buried ice deposits in the central Transantarctic Mountains are very likely $<10^5$ years (Hindmarsh et al., 1998).

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