Sensitivity of ice-cemented Antarctic slopes to increases in summer thaw

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Summary We employed a Mohr-Coulomb safety factor equation to assess the response of ice-cemented slopes in the stable upland zone of the McMurdo Dry Valleys (MDV) to artificial increases in mean summertime soil surface temperatures (MSSST). Results show that ice-rich, silty tills on slopes ≥20° could fail by planar sliding with an increase in MSSST of ~5º to 9ºC. This change corresponds to an atmospheric increase of ~5º to 9ºC, which lies just outside the envelope of warming predicted to occur in this region over the next century. If we assume that current soil-moisture conditions can be applied to slope deposits in the distant past, and that these slope deposits have remained physically stable for millions of years, then our results suggest that MSSST in the upland zone did not increase by more than ~5º to 9ºC since deposition of most deposits, perhaps as much as 10 million years ago.

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Introduction

The western region of the McMurdo Dry Valleys (MDV) is one of the coldest and driest places on Earth. Rates of bedrock erosion, as deduced from cosmogenic-nuclide exposure studies, are as low as 5–10 cm Myr^{-1} (Brook et al., 1993; Ivy-Ochs et al., 1995; Summerfield et al., 1999), and the preservation of in-situ, near-surface ashfall as much as 10–15 Ma ($^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ dating) implies that there has been limited bedrock erosion and colluviation in some regions for millions of years (Fig. 1) (Marchant et al., 1993a). Given the long-term geomorphic stability of the region, and by inference its climatic stability, how might an increase in atmospheric temperature influence the morphology and preservation of unconsolidated deposits?

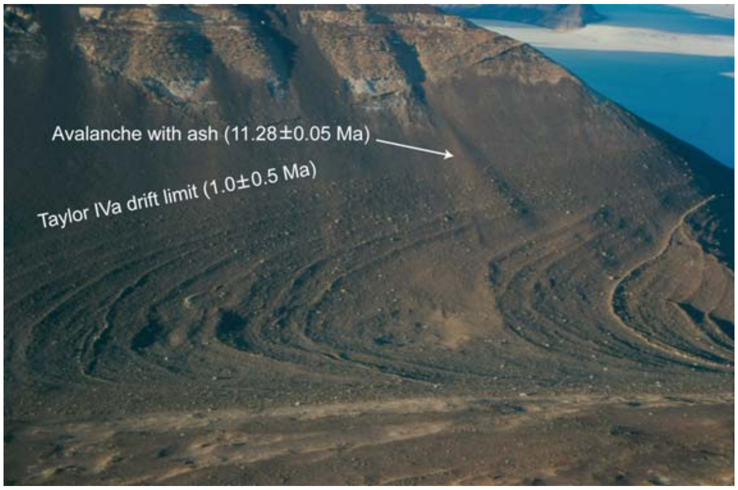

Figure 1. Oblique aerial photograph of lower Arena Valley, Quartermain Mountains, MDV. On the valley wall and bottom are a series of arcuate moraines; the minimum age for the uppermost moraine is 1.0±0.5 Ma, based on $^{10}\mathrm{Be}$ cosmogenic exposure age analyses (Brook et al., 1993). This moraine and several others cross a well-preserved avalanche deposit containing volcanic ash that dates to 11.28±0.05 Ma ($^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ dating) (Marchant et al., 1993a). Neither the moraines, nor the ash avalanche show morphologic evidence for post-depositional modification from downslope movement.

Setting

The MDV are commonly subdivided into discrete microclimate zones (Marchant & Denton, 1996). The sensitivity of unconsolidated deposits to thaw-induced planar sliding is dictated by local environmental conditions within each zone. The three zones include a coastal thaw zone, in which soils exhibit a saturated active layer, a stable upland zone, in which soil-moisture and temperature are too low to generate typical active layer processes, and an intermediate mixed zone that represents the transition between the two end members. Ice cement is ubiquitous throughout all microclimatic zones. Ice-cement tables, while variable, often lie at 10–50-cm depth and contain >>10% gravimetric water content (GWC) (Campbell et al., 1997). The depth to the base of the ice cement is generally unknown, but most probably exceeds 2 m (based on direct examination of shallow cores from throughout the MDV) (Stuiver et al., 1981; Pringle et al., 2006). On average, soils in the coastal thaw zone contain greater moisture and have shallower ice-cement tables than soils in the inland mixed and upland stable zones (Campbell et al., 1997; Campbell & Claridge, 2006).

Methods and Numerical Models

Slope stability analyses were conducted for six deposits, including dolerite colluvium (e.g. Fig. 1) and three silt-rich tills, Asgard till, Altar till, and Sessrumnir till. Asgard till is a mid- to late-Miocene age deposit (14.8–13.6 Ma) that crops out in north-facing valleys of the Asgard Range (Marchant et al., 1993b; Ackert, 1990). Altar till is a highly-oxidized, silt-rich till in upper Arena Valley, likely deposited during the mid-Miocene (>14.8 Ma) (Marchant et al., 1993a). Sessrumnir till was deposited in the mid-Miocene (>14.8 Ma) throughout the western MDV by wet-based alpine glaciers (Marchant et al., 1993b).

Modeling efforts were divided into three parts. First, we modeled seasonal increases in thaw depths that would arise from prescribed increases in mean summertime soil-surface temperatures (MSSST). Second, we modeled the minimum thaw depths required to facilitate failure by shallow planar sliding in each deposit; for this, we assumed that the present soil moisture conditions were maintained; i.e., that during the interval of prescribed warming, years to decades long, soils maintained their current GWC (this is likely an oversimplification, but one that makes our results conservative). Third, we modeled subsurface water flow as a function of sediment texture; this is required because hydraulic conductivity bears critically on pore pressures and the stability of ice-cemented deposits.

Soil-temperature calculations

The depth- and time-dependent variations in subsurface soil temperatures that arise from prescribed increases in mean summertime soil surface temperature (ΔMSSST) were solved using a one-dimensional heat diffusion equation:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} \qquad \text{Eq. 1}$$

where T is temperature, t is time, κ is thermal diffusivity, and z is depth. Latent heat of fusion is an important factor controlling ground temperatures in permafrost regions (Nixon & McRoberts, 1973). To account for latent heat, we calculated the mass of ice at each node in our finite difference temperature model, set the phase change between ice and water at $T(z)$ = 0ºC, then converted temperature changes over each time-step into heat energy by the following relationship:

$$Q = mc_t \Delta T \qquad \text{Eq. 2}$$

where Q is heat energy, m is total mass, c_t is total specific heat capacity of the soil and ΔT is change in temperature. The energy was then used to melt the ice at each node, buffering the node at 0ºC until all of the ice had melted.

Slope stability calculations

Slope stability is described in terms of a safety factor (F_S), a unitless ratio of shear strength to applied shear stress that can be defined as:

$$F_S = \frac{c' + (\gamma - m\gamma_W) z_P \cos^2\theta \tan\phi'}{\gamma z_P \sin\theta \cos\theta} \qquad \text{Eq. 3}$$

where c' is effective cohesion, γ is unit weight of soil, m is ratio of the height of the water table (fully saturated conditions) above the slip plane to the total height of the soil column, γ_W is unit weight of water, z_P is depth to slide plane, θ is slope angle and ϕ' is effective angle of internal friction. Because the moisture source is internal, the degree of saturation (m) varies as a function of thaw depth according to the following equation:

$$m = \frac{W}{p}\left(1 - \frac{z_{IC}}{z}\right) \qquad \text{Eq. 4}$$

where W is volumetric water content, p is porosity, z_{IC} is the initial depth of the ice-cement table, and z is depth.

Subsurface water flow

A key question is whether rapid rates of subsurface water flow would prohibit the build up of subsurface moisture. For each deposit, we examined downslope water flow using Darcy's flow law through porous media:

$$q = -k_H \frac{dh}{dl} \qquad \text{Eq. 5}$$

where q is specific discharge, k_H is hydraulic conductivity and dh/dl is the hydraulic gradient (here equivalent to slope angle).

Results

Dolerite colluvium

The colluvial deposits studied here contain sufficient subsurface ice such that planar sliding should theoretically occur when thawing reaches 30–35 cm, equivalent to a change in mean summertime soil surface temperatures (ΔMSSST) of 4° to 6°C. However, due to the coarse sediment texture of these deposits, the flux of water downslope can be as high as 40 m/day and would prohibit the build-up of subsurface water and increased pore pressures, making slope failure unlikely.

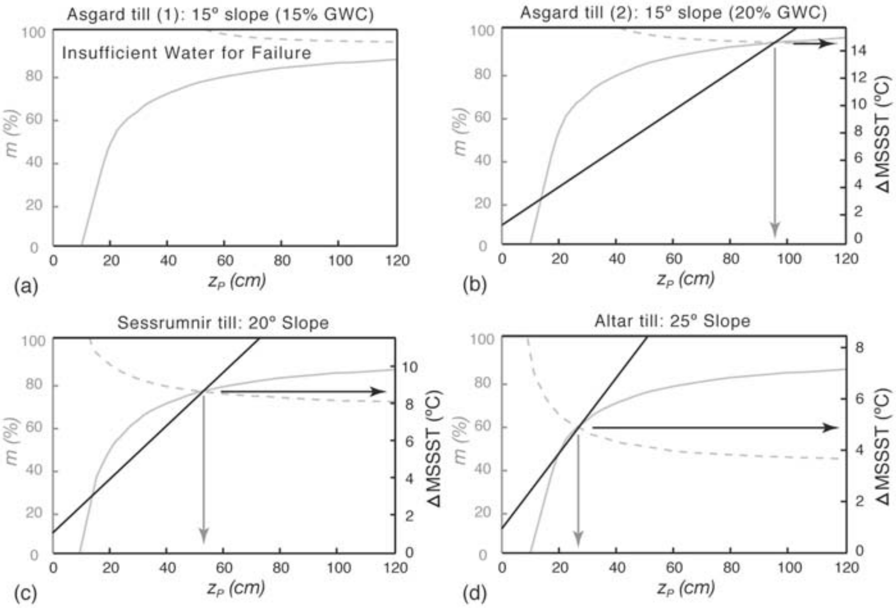

Figure 2. Results for minimum thaw depth required to induce planar sliding for the silt-rich deposits and the corresponding ΔMSSST for the given thaw depth. Primary y-axis corresponds to the level of saturation (*m*) as a function of depth, with the dotted grey line representing saturation required to induce failure and the solid grey line showing the amount of saturation as a function of depth in each modeled slope (the intersection of these lines is the minimum potential slide depth). The secondary y-axis represents ΔMSSST vs. thaw depth (with latent heat of fusion included). The black line shows how thaw depths will change depending on ΔMSSST (adapted from Swanger & Marchant, 2007).

Silt-rich tills

Calculated rates of Darcy flow are significantly less for silt-rich deposits (30–80 cm/day), suggesting that requisite pore pressures for failure could be produced. Results for slope stability tests are shown in Figure 2a through 2d. Silt-rich tills on slopes ≥20°, and with gravimetric water contents (GWC) ≥15% would most likely fail by planar sliding given a ΔMSSST of 5° to 9°C. For example, a deposit of Sessrumnir till that exhibits a shallow ice-cement table at 10-cm depth, and with a GWC of 15%, could fail with thaw to ≥52 cm, which corresponds to a ΔMSSST of 8.5°C (Fig. 2c). Likewise, Altar till that exhibits a shallow ice-cement table at 10-cm depth (GWC 15%) on a slope of 25° could fail with thaw to ≥28 cm, corresponding to a ΔMSSST of 5°C (Fig. 2d). In contrast, deposits of Asgard till that rest on a gentle slope of 15° and exhibit ice-cement tables at 10-cm depth (15% GWC) would contain insufficient moisture to experience planar sliding (Fig. 2a).

Discussion and Implications

The results of our six sensitivity tests highlight the importance of soil texture, gravimetric water content, slope angle, and the depth to the ice-cement table on slope stability. In general, the most sensitive deposits are silt-rich, occur on steep slopes, and contain ice cement with ≥15% GWC at <20-cm depth.

Given that a change of 5° to 9°C in MSSST would occur over decades, if not centuries, it is unlikely that soil-moisture conditions prior to thawing would be the same as they are today. However, we expect that an increase in summer temperatures would be accompanied by an overall increase in soil moisture, both in terms of an increase in GWC of the ice cement and a shallowing of the ice-cement table. Analogs for increased moisture with increasing temperatures can be found in the coastal regions of the MDV, where ice-cement tables are generally shallower and contain greater GWC (Campbell et al., 1997; Campbell & Claridge, 2006).

Atmospheric warming in the MDV could reach as much as 2º to 5ºC in the next century (e.g., IPCC, 2001). If such warming is realized, then our results suggest that some slopes in the upland region that have remained physically stable for millions of years could experience shallow planar slides in the next few centuries. Futhermore, if we assume that soils in the stable upland zone have not been drier in the past than they are currently, then our results shed light on the maximum possible summertime warming achieved since the drifts were deposited in the middle Miocene. Assuming that the physical evidence for shallow planar slides would be retained in the geomorphic record, and given that we see no evidence for discrete downslope movements in the deposits studied, we tentatively conclude that mean summertime soil surface temperatures in this region did not rise more than 5º to 9ºC above current values, for an extended period of time since the middle Miocene.

Summary

We employed a Mohr-Coulomb based equation of safety factor to assess the response of ice-cemented slopes in the stable upland zone of the MDV to increases in mean summertime soil surface temperatures (MSSST). Our results show that although many colluvial deposits appear to contain sufficient near-surface ice for thaw instability (ice-table at ~10–20 cm depth and GWC of ~20%), the coarse texture of these deposits enables rapid moisture loss upon thawing, preventing failure by planar sliding. Ice-rich, silty deposits, on the other hand, are sensitive to thaw-induced sliding. Results show that silty deposits on slopes ≥20° and with shallow ice tables (<20 cm depth) containing ~15% GWC, all of which are common conditions in the western MDV region, could fail by sliding with an increase in MSSST of ~5º to 9ºC. This change corresponds to an atmospheric increase of ~5º to 9ºC, and lies just outside the broad envelope of future warming expected to occur in the next century due to greenhouse-gas emissions. If we assume that the current soil-moisture conditions can be applied to slope deposits in the distant past (i.e., millions of years ago), then our results suggest that MSSST, and by inference atmospheric temperatures, in the stable upland zone did not increase by more than ~5º to 9ºC above present values since at least late Miocene time.

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