Establishing a chronology for the world's oldest glacier ice

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Summary A cold-based, debris-covered alpine glacier in Mullins Valley, a tributary to upper Beacon Valley, contains ancient glacier ice. Four independent dating techniques confirm that the glacier age ranges from ~10 ka near the valley head, to >8 Ma at its diffuse terminus in central Beacon Valley (where it abuts opposing buried ice that originated from Taylor Glacier; e.g., Sugden et al., 1995). The dating methods include 1) cosmogenic-nuclide analyses of boulders from a sublimation till that caps the ice; 2) numerical ice-flow modeling of the glacier system; 3) $^{40}Ar/^{39}Ar$ analyses of in-situ ash fall from relict polygon troughs at the till surface; and, 4) modern horizontal ice-flow velocities as determined from synthetic aperture radar interferometry (InSar, from Rignot et al., 2002). Multi-channel seismic surveys demonstrate that the ancient ice is ~45 to ~100 m thick in Mullins Valley and ~150 m thick in upper Beacon Valley.

Introduction

   The McMurdo Dry Valleys are generally classified as a hyper-arid, cold-polar desert. Subtle variations in climate parameters throughout the region result in considerable differences in the distribution, origin, and morphology of buried ice (Marchant and Denton, 1996; Marchant and Head, 2007). In the coastal thaw zone, near-surface buried ice experiences seasonal melt and may have formed where pore water from surface snowmelt freezes underground (segregation ice). Characteristic landforms associated with this type of buried ice include thermokarst, shallow planar slides, and solifluction (e.g., Swanger and Marchant, 2007). In contrast, in the coldest and driest regions of the McMurdo Dry Valleys, the stable upland zone, there is insufficient meltwater to produce extensive segregation ice. Rather, widespread buried ice in this zone is typically buried glacier ice. Temperature data indicate that buried glacier ice remains frozen in this zone if buried beneath ~15 cm of debris (Kowalewski et al., 2006).

   The Mullins Valley debris-covered glacier is the largest debris-covered glacier in the Quartermain Mountains (Fig. 1). The glacier flows down the length of Mullins Valley, becoming debris covered ~1 km from the headwall, and displays a notable, northeast bend at the entrance to Beacon Valley proper (Fig. 1). The debris cover is derived from infrequent rockfall at the head of Mullins Valley; most rockfall debris travels englacially before being brought to the glacier surface as overlying ice sublimes. The rate of ice sublimation and of vertical particle trajectory in the ablation zone is most probably ~0.1 mm/yr (Kowalewski et al., 2006). Impact chips are still preserved on the surface of clasts entombed in the glacier ice. A general consequence of glacier flow in this setting is that the debris cover (sublimation till) thickens as material is added slowly to its base. Clasts at the ground surface ride passively down glacier, and are not buried unless disturbed by patterned-ground formation (e.g., Marchant et al., 2002; Levy et al., 2006). Hence, at any single location, the basal part of the sublimation till is the youngest. Likewise, the oldest part of the sublimation till occurs at the distal end of the glacier and at the ground surface (Marchant et al., 2002; Schaefer et al., 2000). The horizontal (along glacier) variation in till and ice age is considerably greater than the vertical variation in age at any one locality.

Cosmogenic ^{3}He analyses of surface boulders

   A chronology for the Mullins Valley debris-covered glacier was initially established using cosmogenic ^{3}He measured in clinopyroxene from cobbles of Ferrar Dolerite lying on concentric flow lobes. The cosmogenic ^{3}He exposure ages, which assume zero boulder erosion, exhibit a general increase from about 10 ka at the head of the glacier, to ~730 ka near its confluence with upper Beacon Valley, and finally to ~2.3 Ma near its contact with drift from Taylor Glacier in central Beacon Valley (Schaefer et al., 2000). With a few exceptions, the ^{3}He ages plotted in Figure 1 show a general increase down glacier (Fig. 1). Nuclide inheritance during exposure along the valley headwall prior to rockfall may be responsible for producing some of the older ages in upper Mullins Valley (Fig. 1). In addition, anomalous old ages might be explained by magmatic ^{3}He trapped during crystallization of Ferrar Dolerite in the Jurassic. However, good agreement between cosmogenic ^{21}Ne and ^{3}He ages for many other Ferrar Dolerite samples suggests that this problem is less likely (Schaefer et al., 2000; Bruno et al., 1997; Staiger et al., 2006). Exposure ages that are too young for their general position on the Mullins Valley debris-covered glacier can be explained by some combination of overturning of boulders, formation of polygon troughs, and surface erosion.

To clarify the issue of exposure-age reliability, we analyzed three surface boulders from a restricted area of several hundred m^2 in the middle third of the system, situated just upvalley from the sharp morphologic break in drift lobes (Fig. 1). These boulders yielded an average exposure age of ~306 ka. Since it is unlikely that each of these samples experienced the same prior exposure or erosion histories, we conclude that the minimum age for the buried glacier in this portion of the system is about 300 ka. Sample ages older than this upvalley are interpreted as containing a nuclide inheritance component and/or a magmatic [3]He component.

Synthetic aperture radar interferometry (InSar)

In an earlier assessment of the Mullins Valley debris-covered glacier, Rignot et al. (2002) used InSar to show that the maximum horizontal velocity of the Mullins glacier is ~40 mm a^{-1} at the valley head, and "vanishingly small" (i.e., < a few mm a^{-1}) out on the floor of upper Beacon Valley. Integrating these velocities over the length of the glacier provides age estimates that are entirely consistent with the cosmogenic data presented above (Fig. 1).
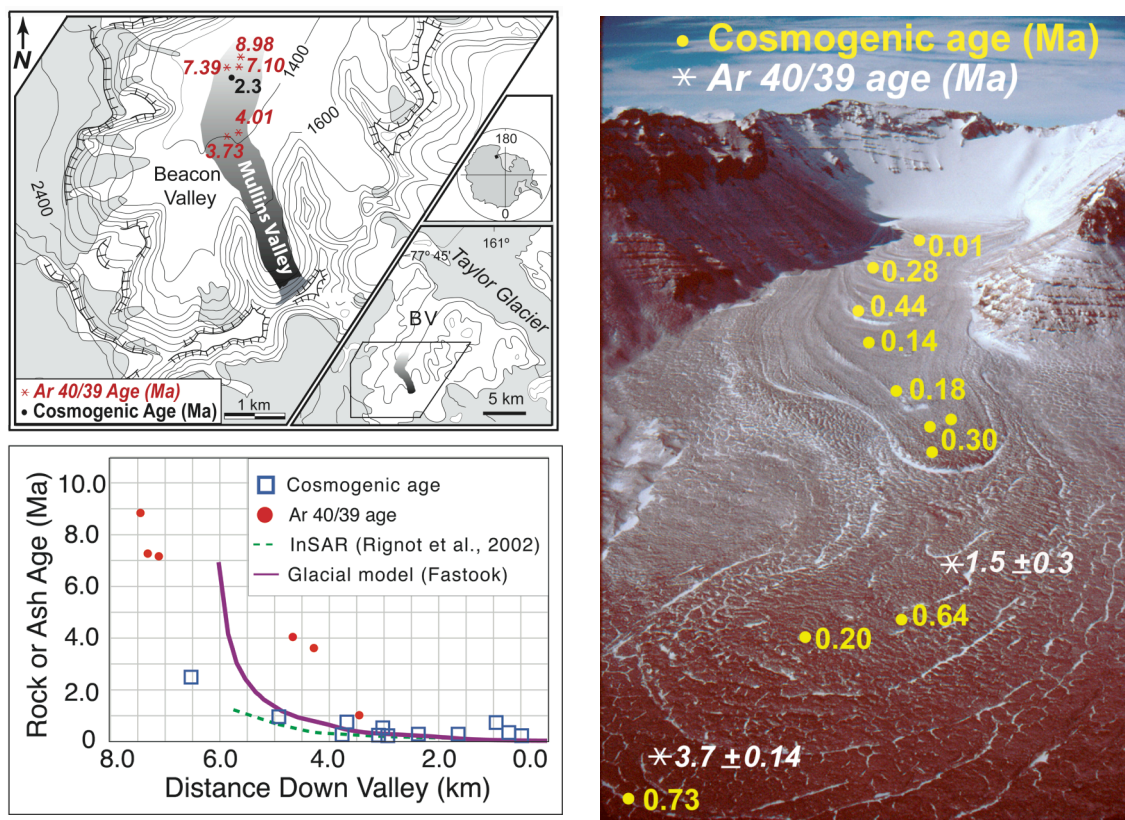

Figure 1. Top left: Location map of Mullins Valley, Quartermain Mountains, showing age control for distal regions of the Mullins Valley debris-covered glacier. Right: Oblique aerial photograph showing locations for age control in upper Mullins Valley. Bottom left: All age data plotted as a function of distance down Mullins Valley.

[40]Ar/[39]Ar analyses of overlying ash fall deposits

The distal portions of the Mullins Valley debris-covered glacier are overlain, in places, by in-situ volcanic ash fall. The ash fall is most likely derived from local volcanic centers less than 100 km distant (Marchant et al., 1996). Ash deposits occupy relict polygon troughs in the sublimation till and radiometric ages provide minimum age estimates for underlying glacier ice. As shown in Fig. 1, the age of five separate ash fall deposits from the distal portion of the Mullins Valley debris-covered glacier show that by the time the ice travels ~4.5 km from the valley head it exceeds ~4 Ma in age, and by the time it travels ~6 km it exceeds ~8 Ma.

Numerical modeling of ice flow

As a final test of the antiquity of the Mullins Valley debris-covered glacier, we performed a simple modeling experiment designed to predict ice age as a function of distance down valley (Fig. 2). To estimate surface ages of ice, we adopted a simple flow band analytic solution for a steady-state profile that includes as output the velocity field. From this we can follow the movement of hypothetical tracers released at the surface in the accumulation area as they move to and are ultimately released in the ablation area. As input to our model we used an accumulation rate of 1 cm a^{-1} and an

effective sublimation rate of ~0.1 mm a^{-1}. Ice thickness estimates for the profile were constrained by the results of several shallow seismic surveys (Shean et al., in press). Model results presented in Fig. 2 yield ages that are entirely consistent with those based on cosmogenic dating of surface boulders, measurements of modern horizontal flow rates (InSar, Rignot et al., 2002), and ^{40}Ar/^{39}Ar analyses of overlying ash fall deposits.

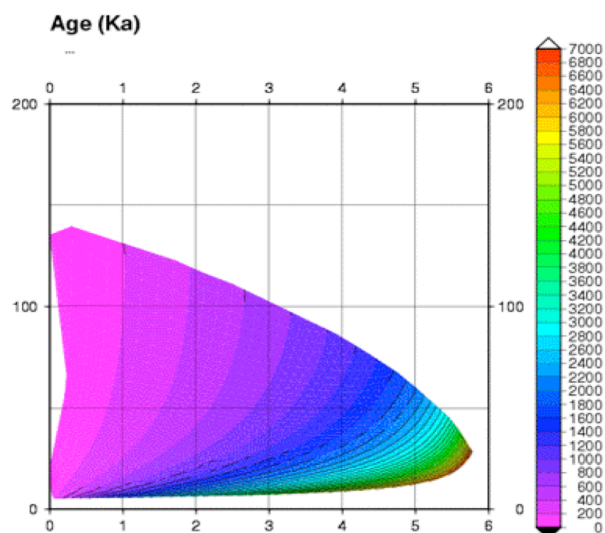**Figure 2**. Model results showing variation in ice age with distance down glacier. Colors refer to ages in ka (see text for details).

Conclusions and broader implications

The consistent ages provided by four different dating methods, 1) cosmogenic-nuclide dating of surface boulders, 2) present-day horizontal ice flow velocities from satellite data (Rignot et al., 2002), 3) ^{40}Ar/^{39}Ar analyses of surface ash fall, and 4) numerical ice-flow modeling together provide strong support for the preservation of multi-million-year old ice in Mullins Valley and Beacon Valley. The strong agreement among the varied data sets confirms earlier reports for long-term preservation of buried ice in the stable upland zone of the McMurdo Dry Valleys (Sugden et al., 1995). Shallow seismic and ground-penetrating radar (GPR) surveys suggest that the buried ice in Mullins Valley is presently ~45-100 m thick, and up to ~150 m in Beacon Valley (Shean et al., in press). Ice cores collected from this glacier are currently under analyses and the data may help resolve questions regarding long-term atmospheric evolution, ice-sheet stability, and climate change in Antarctica. In addition, geomorphological studies of the surface of debris-covered glaciers, like Mullins Glacier, may shed light on the nature, origin, and long-term preservation of some near-surface ice deposits on Mars (e.g. Head et al., 2003). Specifically, a wide range of surface features on Mars have been interpreted to represent debris-covered glaciers that may have formed under past climate regimes (e.g., Head et al., 2003, 2006; Head and Marchant, 2003; Shean et al., 2005, 2007; Marchant and Head, 2007).

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