DATING THE WORLD'S OLDEST DEBRIS-COVERED GLACIER: IMPLICATIONS FOR INTER-PRETING VISCOUS-FLOW FEATURES ON MARS.

D. R. Marchant[1], W. M. Phillips[2], J. L. Fastook[3], J. W. Head, III[4], J. M. Schaefer[5], D. E. Shean[1], D. E. Kowalewski[1]. [1]Dept. of Earth Sci., Boston University, Boston, MA 02215 (marchant@bu.edu); [2]Idaho Geological Survey, Moscow, ID 83844-3014; [3]Climate Change Institute, University of Maine, Orono, ME 04469 (fastook@maine.edu); [4]Dept. Geol. Sci., Brown Univ., Providence, RI 02912 (James_Head@Brown.edu); [5]Lamont-Doherty Earth Observatory, Palisades, NY 10964.

Introduction: The Antarctic Dry Valleys (ADV) are generally classified as a hyper-arid, cold-polar desert. The region has long been considered an important terrestrial analog for Mars because of its generally cold and dry climate and because it contains a suite of landforms at macro-, meso-, and microscales that closely resemble those occurring on the martian surface. Subtle variations in climate parameters in the ADV result in considerable differences in the distribution and morphology of viscous-flow features, including solifluction lobes, gelifluction lobes, and debris-covered glaciers [1]. Here we provide chronologic control documenting the age of the Mullins Valley debris-covered glacier, purportedly the world's oldest alpine glacier, located in the stable upland zone of the Antarctic Dry Valleys.

Mullins Valley is a west-facing tributary to upper Beacon Valley. The Mullins Valley debris-covered glacier ranges from approximately 500 m to 800 m wide; it flows down the length of Mullins Valley and displays a notable, northeast bend at the entrance to Beacon Valley proper (Fig. 1). The till overlying the glacier is derived from rockfall at the head of Mullins Valley. Most clasts travel englacially before being brought to the 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 [2]. A general consequence of this flow path is that the till thickens from the bottom up, and clasts at the ground surface ride passively down glacier (unless affected by patterned-ground formation (e.g., [3,4]).

Cosmogenic [3]He analyses of surface boulders: A chronology for the Mullins Valley debris-covered glacier was established using cosmogenic [3]He measured in clinopyroxene from Ferrar dolerite boulders 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 over 730 ka near its contact with drift from Taylor Glacier (Granite drift, [5]) in central Beacon Valley. However, the [3]He ages do not increase smoothly with distance down valley as might be expected with the steady flow of an active glacier. Nuclide inheritance from exposure before deposition onto the rock glacier may be responsible for producing some of the scatter. While nuclide inheritance has not been observed in surface exposure studies of Granite drift in lower Beacon Valley [4,6], deposition of Mullins Valley drift as rock fall at the valley headwall may make it

more likely that pre-exposed boulders are sampled by chance. The anomalous ages could also 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 [6,7]. Exposure ages that are too young for their landscape position are also clearly present. These ages are readily 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, just south of core-00-01). These boulders yielded an average exposure age of 306 ± 29 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. Further down ice flow, the oldest dated boulders yield ages of about 640 ka and 730 ka (Fig. 1); so far these are the oldest ages recovered from cobbles on an "active" alpine glacier.

Synthetic aperture radar interferometry (InSar): In an earlier assessment of the Mullins Valley debris-covered glacier, Rignot et al. [8] 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, the latter being entirely consistent with the cosmogenic data presented above (Fig. 1).

[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 form local volcanic centers, less than 100 km distant [9]. As reported in [4,10], 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 six separate ash fall deposits on the floor of Beacon Valley 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.
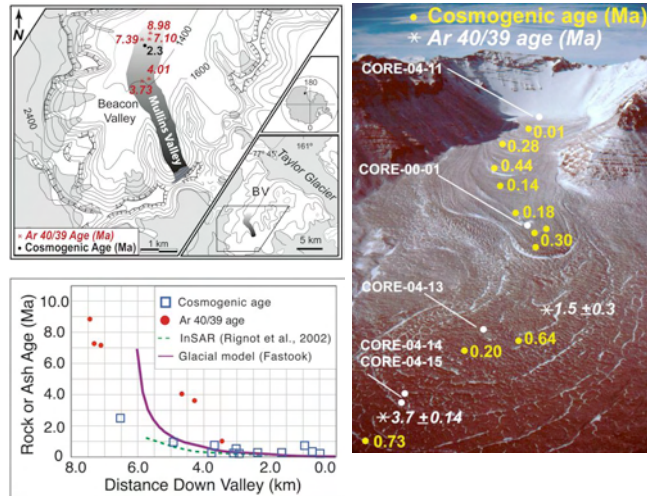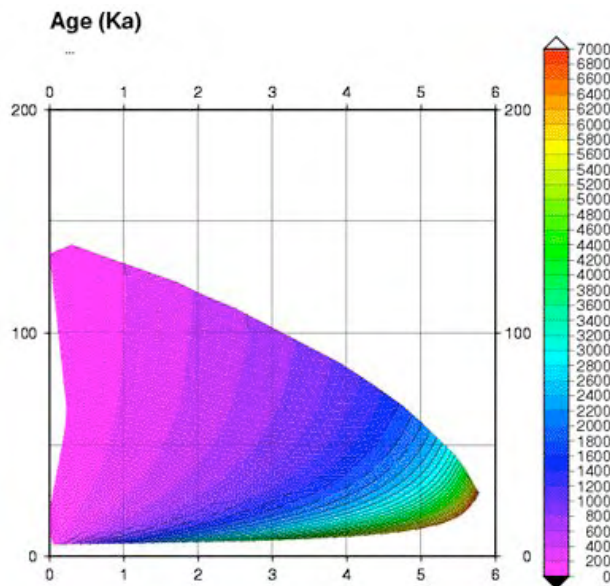
Fig. 1. Top left: Location map of Mullins Valley, Quartermain Mtns, showing age control for distal regions of Mullins glacier. Right: Oblique aerial photograph showing locations for age control and established ice-core sites in upper Mullins Valley. Center: All age data plotted as a function of distance down Mullins Valley. Below: Glaciological model, showing variation in age of glacier ice as a function of distance down valley; colors represent ice ages, x-axis in km.

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. 1, bottom). 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 tracers released at the surface in the accumulation area as they move to and are ultimately released from 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}. Model results presented in Fig. 1 yield ages that are entirely consistent with those based on cosmogenic dating of surface boulders, measurements of modern horizontal flow rates (InSar, [8]), and ^{40}Ar/^{39}Ar of overlying ash fall deposits.

Conclusions and broader implications: The consistent ages provided by four different dating methods, 1) cosmogenic-nuclide dating of surface boulders, 2) horizontal ice-flow velocity from satellite data [8], 3) ^{40}Ar/^{39}Ar analyses of surface ash fall, and 4) numerical ice-flow modeling together provide strong support for the preservation of million-year old ice in Mullins 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 ADV and may shed light on the nature, origin, and long-term preservation of some near-surface ice deposits in the stable-upland-zone-like environment of Mars [e.g., 1]. Specifically, a wide range of surface features on Mars have been interpreted to represent rock glaciers and debris-covered glaciers that may have formed in earlier climate regimes [e.g., 11-14]; features associated with the Mullins and related ADV examples of debris-covered glaciers can be used to distinguish between these multiple origins of viscous flow features, to understand the related processes involved in ice preservation [e.g., 2], and to assist in the location of the ancient climate ice record on Mars.

References:
[1] D. Marchant and J. Head, *Icarus*, in revision, 2007; [2] D. Kowalewski et al., *Ant. Sci*. 18(3), 421, 2006; [3] Levy et al., *Ant. Sci.* 18(3), 385, 2006; [4] D. Marchant et al., *GSA Bull.* 114, 718, 2002; [5] D. Sugden et al., *Nature* 376, 412, 1995; [6] J. Schaefer et al., *EPSL* 179, 91 2000; L. Bruno et al., *EPSL* 147, 37, 1997; [8] E. Rignot et al., *GRL* 29(12), 10.1029/ 20001GL013494, 2002; [9] P. Kyle, *AGU Ant. Res Ser.*, 48, 19, 1990; [10] D. Marchant et al., *GSA Bull.,* 108, 181, 1996; [11]; J. Head et al., *Nature*, 434, 346, 2005; [12] J. Head et al., *Nature*, 426, 797, 2003; [13] J. Head and D. Marchant, *Geology*, 31, 641, 2003; [14] T. Pierce and D. Crown, *Icarus*, 163, 46, 2003.