Rock glacier surface motion in Beacon Valley, Antarctica, from synthetic-aperture radar interferometry

Eric Rignot
Radar Science and Engineering, Jet Propulsion Laboratory, Pasadena, CA, USA

Bernard Hallet
Quaternary Research Center, University of Washington, Seattle, WA, USA

Andrew Fountain
Department Geology and Geography, Portland State University, Portland, OR, USA

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[1] We present radar interferograms of rock glaciers in the Beacon Valley sector of the McMurdo Dry Valleys, in East Antarctica, as part of a comprehensive study of surface processes in the area. Due to the relative absence of net precipitation (snow) in this region and the stability of the surface, the rock glaciers maintain excellent coherence of the radar returns over several years. As a result, we obtain a spatially continuous surface velocity field with a precision of fractions of a millimeter per year. On distinct rock glaciers entering Beacon Valley, we find coherent velocity patterns, with peak velocities approaching 40 mm per year. The ice supply from these rock glaciers nourishes the central portion of Beacon Valley, where velocities are found to be vanishingly small, and partly compensates for mass losses induced by sublimation. This analysis is consistent with the tantalizing notion that Beacon Valley ice is the oldest on Earth. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1824 Hydrology: Geomorphology (1625); 1645 Global Change: Solid Earth; 6924 Radio Science: Interferometry

1. Introduction

[2] Interferometric Synthetic-Aperture Radar (InSAR) has gained wide recognition as a leading technique to document ground surface displacement patterns in areas with active faults, volcanism, or land subsidence [e.g., *Rosen et al.*, 2000]. In glaciology, the technique has been used widely to document the spatial pattern of surface velocities typically measured over intervals of a few days on valley glaciers [*Michel and Rignot*, 1999], ice streams and ice sheets [*Joughin et al.*, 1999], and the patterns of tidal motion of ice shelves and floating ice tongues [*Rignot et al.*, 2000]. In contrast, the technique has only been used in few studies of geomorphic interest, including vertical soil motion due to freeze/thaw [*Zhijun and Shusun*, 1999], slow slope motion [*Rott et al.*, 1999] and landslide displacements [*Fruneau et al.*, 1996].

[3] Herein we focus on the rate of surface motion of a rock debris surface underlain by ice, in an area that includes distinct rock glaciers, as well as extensive permafrost with regions that lack obvious signs of coherent down-valley motion. Significant motion may, however, occur in these areas due to slow deformation of ice or frozen soil at depth.

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2. Rock Glaciers in Beacon Valley

[4] Rock glaciers are of interest because they are conspicuous but poorly understood geomorphic features in many alpine areas [e.g. *Wahrhaftig and Cox*, 1959]. They may contain rich ice-core records of past climates for alpine areas [*Steig et al.*, 1998; *Haeberli et al.*, 1999] and for vast regions where no glaciers or ice sheet exist. Moreover, the origin and spatial distribution of the ice in rock glaciers remains a source of lively controversy after decades of research [e.g., *Clark et al.*, 1998; *Steig et al.*, 1998; *Haeberli et al.*, 1998].

[5] Although subsurface ice in Beacon Valley has long been known [*Linkletter et al.*, 1973], a recent investigation suggests the ice is of Miocene age [*Sugden et al.*, 1995] making it perhaps the oldest ice on Earth. According to this recent report, the ice is a remnant of a large ice tongue that once flowed up Beacon Valley from Taylor Glacier, which now enters only the lower part of Beacon Valley, and is older than underlying rock debris that contains a seemingly undisturbed ash layer, with a $^{40}Ar/^{39}Ar$ age of 8.1 Myr. The notion that Beacon Valley ice is old, say older than 1 Myr, receives support from cosmogenic isotope data from the rock debris overlying the ice [*Schafer et al.*, 2000] and from paired samples of ice and quartz grains from an ice core [*Stone et al.*, 2000].

[6] This interpretation and Miocene age of the ice has been questioned, however, because the long-term survival of ice overlain by debris with a seemingly undisturbed ash layer precludes much sublimation and significant reworking of the surface, and yet both processes appear significant. Estimates of sublimation rates in Beacon Valley [*Stone et al.*, 2000; *Hindmarsh et al.*, 1998] and a nearby area [*McKay et al.*, 1998] show that so much ice (10's to 100's of meters) would be lost over several million years that the surface material would probably be reworked. Moreover, ongoing studies of active periglacial processes suggest that the repeated cracking of the ground in Beacon Valley due to thermal contraction and infilling of the cracks by wind-blown sand and snow would pervasively rework the surface relatively quickly. This reworking would make the reported preservation of an 8.1 Myr-old ash layer at the surface [*Marchant et al.*, 1996] nearly impossible.

[7] Interest in the buried ice and these issues, led us to launch a comprehensive study of contemporary processes in the area, which was largely guided by the following requirement. The presence of such ancient ice close to the surface and the apparent lack of disturbance of the ash layer require extreme stability of the surface, low sublimation rates, and negligible ice velocities. InSAR is ideally suited for examining the latter requirement. The interferometry results also bear on sublimation rates and, hence, on the potential for the long-term survival of ice close to the surface in very cold and dry environments. This is of considerable interest not only for researchers working in Antarctica, but also for those

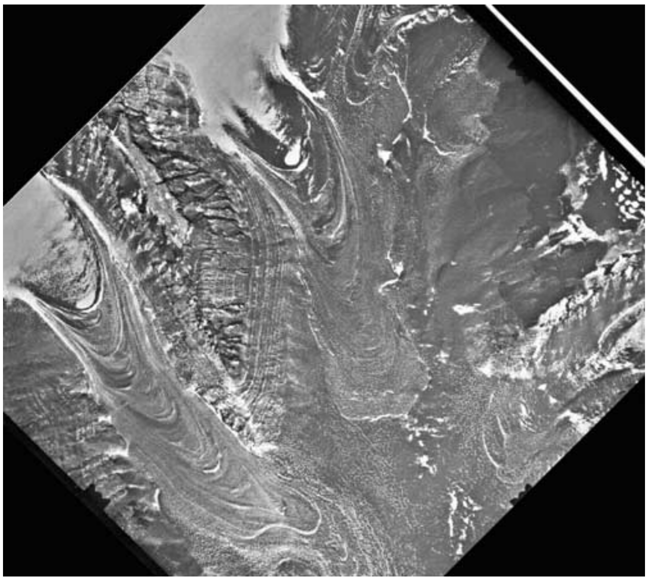

Figure 1. Aerial photograph of Mullins and Friedmann rock glaciers, Antarctica. TMA 3080 Frame 276 taken on November 21, 1993, part of the Taylor Valley LTER series, U.S.G.S. SCAR library.

examining the possibility for long-lived buried ice on Mars as a likely source of water to account for the new evidence for relatively recent seepage and runoff [*Malin and Edgett*, 2000].

[8] Beacon Valley is in the McMurdo Dry Valleys region of Antarctica. Figure 1 shows two rock glaciers entering and merging into the central portion of the valley, which consists of two distinct sections (not shown in the figure). The upper section is about 1.9 km wide and 3.1 km long, and is distinguished by its vanishing surface gradient. On a scale of hundreds of meters, the surface is essentially flat, dropping only 10 m in 3.1 km. The old subsurface ice reported in this area [*Sugden et al.*, 1995] is located in the center of the upper section. The lower section drops 300 m in 5 km and its down valley end extends under Taylor Glacier.

3. Methods

[9] Surface displacements, which reflect the presence and deformation of ice and permafrost at depth, have long been studied on rock glaciers through direct surveying of surface markers [*Wahrhaftig and Cox*, 1959; *Konrad et al.*, 1999]. Recently, modern photogrammetric techniques have been used with high-quality aerial photographs to document surface velocity fields [*Kaab et al.*, 1997]. The InSAR technique complement these studies by providing convenient means of defining surface velocity fields at the millimeter scale [*Rott and Siegel*, 1999], at high spatial resolution, over extensive areas, from a vantage point in space.

[10] The interferogram used in this analysis (Figure 2) combined radar images acquired at the C-band frequency (wavelength, $\lambda = 5.6$cm) by the Earth Remote Sensing Satellite ERS-1 on March 4, 1996 and ERS-2 on July 13, 1999, i.e. 3.36 years apart. The baseline separation between the ERS-1 and ERS-2 orbits, measured in the direction perpendicular to the radar illumination, was $B_{\perp} = 7$ m. In these near-ideal imaging conditions, a 500-m variation in terrain elevation is necessary to produce one cycle of interferometric phase, or 28-mm displacement of the surface toward the radar illumination. The topographic signal present in the interferogram was effectively removed using a U.S.G.S. Digital Elevation Model (DEM) at 30-m spacing (Figures 2, 3a and 3d), with a vertical precision of 10 m, to reveal ground deformation over 3.36 years, plus noise.

[11] In the relatively flat portions of the scene (e.g., Beacon Valley), phase noise is less than 2 mm in 3.36 years (Figures 3b and 3e). Phase noise increases to 6 mm over mountainous terrain, where the DEM is less precise. We find no visual evidence for phase disturbances possibly caused by turbulent water vapor mixing or ionospheric activity in the data, as expected in the cold, dry regions of Beacon Valley, during a period of low solar activity (last solar maxima were in 1992 and 2000).

4. Ice Motion in Beacon Valley

[12] The results in Figure 2 show clear patterns of surface motion in the valleys occupied by rock-glaciers that resemble the deformation pattern typical of glacier ice, and a relatively flat signal reflecting little or no motion in Beacon Valley proper. Areas that exhibit little phase coherence include: 1) mountainous terrain shadowed or foreshortened by the radar illumination because of excessive surface slope; and 2) snow/ice-covered terrain, which lost coherence due to snow densification, ablation and wind scouring, and large displacements in 3.36 years. In contrast, phase coherence is high on ice/snow free terrain.

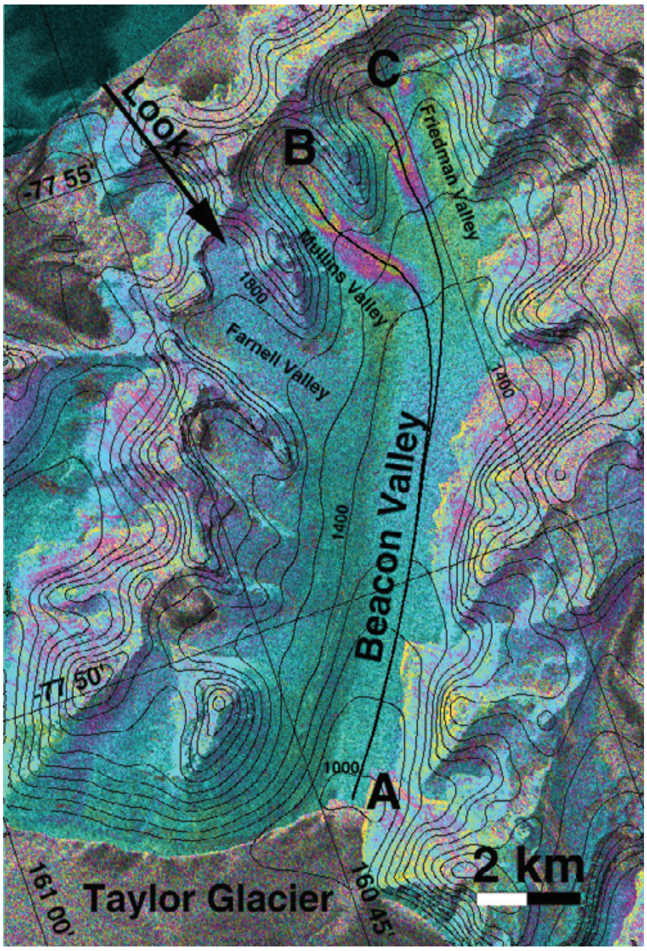

Figure 2. Interferogram of Beacon Valley, extending to the Taylor Glacier. Phase variations of +360° (or +28-mm displacement along the radar illumination) are colored from blue to purple, yellow and blue again, with a color intensity modulated by radar brightness. A, B, C denote the profile locations used in Figure 3. Thin, black, 100-m contour lines represent the terrain topography from the U.S.G.S. DEM. The radar looking direction is indicated by a black arrow in the upper left corner of the figure.

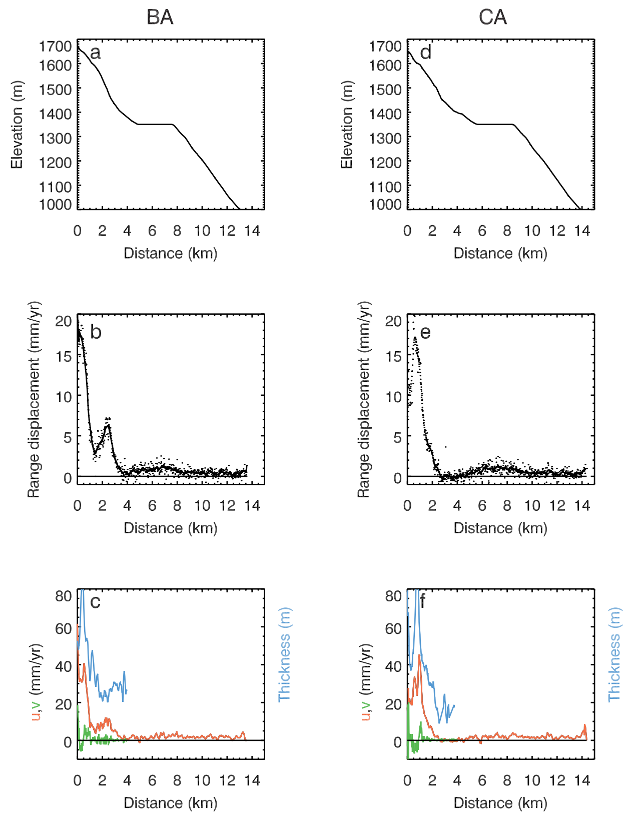

Figure 3. (a) Surface elevation (m) along profile A–B, (b) range displacement (mm); (c) calculated surface-parallel velocity, u in red (mm/yr), surface-normal velocity, v in green (mm/yr), and ice thickness, h in blue (m). (d–f) are, respectively, the same variables for profile A–C in Figure 2.

[13] It is instructive to compare the pattern of fringes on the rock-glaciers (Figure 2) with the micro-topography (Figure 1). The fringes roughly parallel some of the transverse ridges and lobes that are conspicuous on the rock-glacier surfaces, reflecting transverse as well as longitudinal gradients in surface velocity. The clear fringes do not extend into the main portion of Beacon Valley, suggesting little or no relative motion there, which is consistent with more subdued microtopography, and distinct soil development reported by *Linkletter et al.* [1973] in Beacon Valley proper.

[14] The measurements shown in Figure 2 are line-of-sight displacements of the reflecting surface, i.e. a one-dimensional measurement, in a direction 23° away from the vertical. Taking into account the time between images, these surface displacements can be expressed as two velocity components in a vertical plane along the local valley orientation, one parallel to the surface, u, and one normal to it, v. The two components for each pixel can be calculated from a single phase-shift value because they are inter-related in a manner consistent with the conservation of mass and flow of rock glaciers. Ice mass can be assumed to be conserved because sublimation rates are insignificant ($\ll$1mm/yr) relative to flow rates, where they are resolvable with InSAR. These rock glaciers consist of a debris layer about a meter-thick underlain by massive ice with rheological properties assumed to be similar to those of glaciers [*Konrad et al.*, 1999]. This assumption is questionable because the few data available on internal deformation of rock glaciers in the Alps reveal considerably more complex velocity profiles than in glaciers [e.g., *Haeberli et al.*, 1998, 1999], and yet it seems quite reasonable elsewhere [*Konrad et al.*, 1999]. For the Beacon Valley rock glaciers, the assumption appears permissible because shallow excavations reveal clean ice indistinguishable from glacier ice under a thin mantle of rock debris and aerial photographs show that the rock glaciers grade up valley into distinct cirque glaciers.

[15] Noting that basal sliding is most likely to be insignificant at the extremely low temperatures of Beacon Valley, we use the InSAR-derived surface displacements and DEM-derived surface slopes to estimate the surface velocity components, and the thickness and flux of deforming ice. Following *Konrad et al.* [1999], we used Glen's flow law with a flow-law parameter, n = 3, and a deformation constant, $A = 1.36 \times 10^{-24}$ s^{-1} kPa$^{-1/3}$ (consistent with the mean annual ground temperature of −23°C measured in the central portion of Beacon Valley several hundred meters lower than the rock glaciers), and considered simple laminar flow, to calculate a first approximation of the surface-parallel velocity component, u, and the depth of the deforming portion of the rock glacier, h. The normal component, v, is simply related to the divergence in ice flux, q, as follows: $v = -dq/dx$, where $q = \bar{u}h$, the product of the vertically averaged velocity, $\bar{u}$ and ice thickness, h. The notion that the shearing rate of the ice depends on both the gravitational driving stress and gradients in longitudinal stress, was represented simply by using a smoothed surface velocities and surface slopes, instead of using local values only; a linear taper that extends over approximately 250 m, 5 to 10 times the estimated rock glacier thickness, was used in the smoothing. Estimates of the two velocity components and ice depth that were consistent with both the radar signal and the ice flux divergence were then improved itteratively by minimizing the mismatch between computed and observed radar signals.

[16] In the upper part of the valley, between km 0 and km 4 in Figures 3c and 3f, velocities are well above noise in the radar data (Figure 3), in which case the thickness and flux of ice can be calculated reliably. The thickness of the deforming ice layer ranges from 100 m where the main rock glaciers form directly below the cirque to about 40 m where the rock glaciers enter Beacon Valley. Integrating the velocity profile with depth and taking into account the rock glacier width within the 1500–1600 m elevation band, we calculate that 100 to 1000 m^3 of ice enters the valley per year.

5. Age of Beacon Valley Ice

[17] Based on InSAR-determined surface-parallel velocities that average around 10–20 mm/yr for the rock glaciers (Figures 3c and 3f), and their length of about 3 km, it would typically take 0.15–0.30 Myr for ice to descend from the cirques to the lowest distinct portion of the rock-glaciers. This time scale is only approximate because rock glaciers have most probably varied through time because of variations in ice accumulation and temperature. Nevertheless, the ice in the rock glaciers is expected to be much younger than ice in the center part of Beacon Valley, and it should be considered quite distinct [*Stone et al.*, 2000].

[18] The residence time for ice in Beacon Valley can be estimated from the flux of ice entering the central portion of Beacon Valley from the rock glaciers at the upper end. Here, we focus on the upper section of Beacon Valley where ancient ice is located and where the surface gradient is negligible. Consistent with the interferogram, we assume that down-valley ice motion is negligible at least at the down-valley end of this section, and that the rock glaciers constitute the only current source of ice for this valley section. Little information exists about the thickness of ice in Beacon Valley, hence we consider a range of depths to estimate the volume of ice in this upper section of the valley. The residence time is then simply the ratio of this ice volume to the flux of ice from the rock glaciers at the upper end. The result increases linearly with the assumed depth of ice in Central Beacon, from 0.3 to 12 Myr for ice thickness ranging from 50 to 200 m. This thickness range is not well constrained but it is deemed reasonable in view of ground-penetrating radar data suggestive of ice depths of at least 50 m, and of conservative extrapolation of the steep

bedrock valley walls that point hundreds of meters below the surface at the center of the valley. The upper age is similar to a minimum transit time of 10 Myr for ice through Beacon Valley estimated from the ratio of the valley length (10 km) to the highest surface velocity (1 mm/yr) that is consistent with the interferogram.

[19] If we consider the flat upper part of Beacon Valley to be equivalent to a puddle of ice with no outflow down valley, as suggested by InSAR as well as by the flat topography of the area in the DEM, the puddle would thicken with time due to the influx of ice from the rock glaciers that supply this section of Beacon. Based on our estimate of this ice flux and the 6-km^2 area of the puddle, the rate of thickening is 0.02–0.2 mm/yr in the absence of sublimation or accumulation. Alternatively, a steady-state thickness (and surface elevation) could be attained if net sublimation (sublimation minus accumulation) occurred at that rate.

6. Conclusions

[20] The 0.02–0.2 mm/yr sublimation rate over 8 Myr would amount to 160–1,600 m of ice loss. These rates bracket the robust net sublimation rate of 0.05 mm/yr which has been obtained using cosmogenic isotopes in subsurface ice [*Stone et al.*, 2000]. These observations hence suggest that the elevation of the Beacon Valley surface may be near a steady state with ice influx from rock glaciers being offset by sublimation. The fact that velocities are vanishingly small for the entire central portion of Beacon Valley makes it possible for ice and rock to persist there essentially indefinitely, and does not conflict with the tantalizing notion that ice in Beacon Valley is the oldest on Earth. The loss of hundreds of meter of ice by sublimation, however, makes it difficult to accept the interpretation that the surface is largely undisturbed [*Sugden et al.*, 1995].

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References

Clark, D. H., E. J. Steig, N. Potter, and A. R. Gillespie, Genetic variability of rock glaciers, *Geografiska Annaler*, *80A*(3–4), 175–182, 1998.

Fruneau, B., J. Achache, and C. Delacourt, Observation and modelling of the Saint-Etienne-de-Tinée landslide using SAR interferometry, *Tectonophysics*, *265*(3–4), 181–190, 1996.

Haeberli, W., et al., Pollen analysis and ^{14}C age of moss in a permafrost core recovered from the active rock glacier Murtel-Corvatsch, Swiss Alps: Geomorphological and glaciological implications, *J. Glaciol.*, *45*(1–8), 1999.

Haeberli, W., M. Hoelzle, A. Kaab, F. Keller, D. Vonder Muhll, and S. Wagner, Ten years after drilling through the permafrost of the active rock glacier Murtel, Eastern Swiss Alps: Answered questions and new perspectives, in *Proceedings of the Seventh International Conference on Permafrost*, Yellowknife, Canada, Collection Nordicana, 57, 403–410, 1998.

Hindmarsh, R. C. A., F. Van der Wateren, and A. L. M. Verbers, Sublimation of ice through sediment in Beacon Valley, Antarctica, *Geogr. Ann. A*, *80A*(3–4), 209–219, 1998.

Joughin, L., et al., Tributaries of West Antarctic Ice streams revealed by RADARSAT interferometry, *Science*, *286*(5438), 283–286, 1999.

Kaab, A., W. Haeberli, and G. H. Gudmundsson, Analysing the creep of mountain permafrost using high precision aerial photogrammetry: 25 years of monitoring Gruben Rock Glacier, Swiss Alps, *Permafrost and Periglacial Processes*, *8*, 409–426, 1997.

Konrad, S. K., N. F. Humphrey, E. J. Steig, D. H. Clark, N. Potter, and W. T. Pfeffer, Rock glacier dynamics and paleoclimatic implications, *Geology*, *27*(12), 1057–1184, 1999.

Linkletter, G., J. Bockheim, and F. C. Ugolini, Soils and glacial deposits in the Beacon Valley, Southern Victoria Land, Antarctica, *New Zealand Jour. Geology and Geophysics*, *16*(1), 90–108, 1973.

Malin, M. C., and K. S. Edgett, Evidence for recent groundwater seepage and surface runoff on Mars, *Science*, *288*(5475), 2330–2335, 2000.

Marchant, D. R., G. H. Denton, C. C. Swisher, and N. Potter, Late Cenozoic Antarctic paleoclimate reconstructed from volcanic ashes in the Dry Valleys region of southern Victoria Land, *Geol. Soc. Am. Bull*, *108*(2), 181–194, 1996.

McKay, C. P., M. T. Mellon, and E. I. Friedmann, Soil temperatures and stability of ice-cemented ground in the McMurdo Dry Valleys, Antarctica, *Antarctic Science*, *10*(1), 31–38, 1998.

Michel, R., and E. Rignot, Flow of Moreno Glaciar, Argentina, from repeat-pass Shuttle Imaging Radar images: Comparison of the phase correlation method with radar interferometry, *J. Glaciol.*, *45*(149), 93–100, 1999.

Rignot, E., L. Padman, D. R. MacAyeal, and M. Schmeltz, Observations of ocean tides below the Filchner and Ronne Ice Shelves, Antarctica, using synthetic aperture radar interferometry: Comparison with tide model predictions, *J. Geophys. Res.*, *105*(C8), 19,615–19,6130, 2000.

Rosen, P., et al., Synthetic aperture radar interferometry - Invited paper, *Proc. IEEE*, *88*(3), 333–382, 2000.

Rott, H., B. Scheuchl, A. Siegel, and B. Grasemann, Monitoring very slow slope movements by means of SAR interferometry: A case study from a mass waste above a reservoir in the Otztal Alps, Austria, *Geophys. Res. Lett.*, *26*(11), 1629–1632, 1999.

Rott, H., and A. Siegel, Analysis of Mass Movement in Alpine Terrain by means of SAR Interferometry, *IEEE Geosc. Rem. Sens. Symp.*, IGARSS99, Hamburg, 1933–1936, 1999.

Schafer, J. M., et al., The oldest ice on Earth in Beacon Valley, Antarctica: New evidence from surface exposure dating, *Earth Planet. Sci. Lett.*, *179*(1), 91–99, 2000.

Steig, E. J., J. J. Fitzpatrick Jr., N. Potter, and D. H. Clark, The geochemical record in rock glaciers, *Geografiska Annaler*, *80A*, 277–286, 1998.

Stone, J. O., R. S. Sletten, and B. Hallet, Old ice, going fast: Cosmogenic isotope measurements on ice beneath the floor of Beacon Valley, Antarctica, *Eos. Am. Geophys. Union Meeting*, H52C-21, San Francisco, Dec. 15–19, 2000.

Sugden, D. E., et al., Preservation of Miocene glacier ice in East Antarctica, *Nature*, *376*, 412–414, 1995.

Wahrhaftig, and A. Cox, Rock glaciers in the Alaska Range, *Bull. Geological Soc. Am.*, *70*, 383–436, 1959.

E. Rignot, Jet Propulsion Laboratory, Radar Science and Engineering Section, MS 300-235, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA. (eric@adelie.jpl.nasa.gov)

B. Hallet, Quaternary Research Center, University of Washington, Seattle, WA, USA. (hallet@u.washington.edu)

A. Fountain, Departments of Geology and Geography, Portland State University, Portland, OR, USA. (andrew@pdx.edu)