GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 14, 1747, doi:10.1029/2003GL017603, 2003

Ice-driven creep on Martian debris slopes

J. Taylor Perron,[1] William E. Dietrich,[1] Alan D. Howard,[2] James A. McKean,[3,4] and Jarg R. Pettinga[3]

Received 24 April 2003; revised 6 June 2003; accepted 10 June 2003; published 23 July 2003.

[1] Accumulations of rocky debris at the base of bedrock escarpments on Mars have mean inclinations of ∼20°, well below the angle of repose (∼35°). These inclinations decrease with increasing latitude, suggesting a climatic influence. We present evidence that these low inclinations are the result of gravitational creep driven by repeated deposition and sublimation of ground ice. We estimate the rates of bedrock erosion and ice-driven creep on Mars and use a simple model to show that the probable time scale for debris slope development is between 20 Myr and 2 Gyr. Our results suggest that water ice has shaped Martian landscapes throughout the late Amazonian period. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5470 Planetology: Solid Surface Planets: Surface materials and properties. **Citation:** Perron, J. T., W. E. Dietrich, A. D. Howard, J. A. McKean, and J. R. Pettinga, Ice-driven creep on Martian debris slopes, *Geophys. Res. Lett.*, *30*(14), 1747, doi:10.1029/2003GL017603, 2003.

1. Introduction

[2] The discoveries of relatively young erosional channels [*Malin and Edgett*, 2000] and evidence of shallow ground ice at high latitudes [*Boynton et al.*, 2002; *Mitrofanov et al.*, 2002] on Mars have sparked a debate over the role of water in shaping the Martian landscape in recent times [e.g., *Hoffman*, 2000; *Mellon and Phillips*, 2001; *Musselwhite et al.*, 2001; *Costard et al.*, 2002; *Stewart and Nimmo*, 2002]. Here we describe a landscape signal on Mars that is more pervasive than the young channels and suggests a more long-lived influence of near-surface water.

[3] High-resolution Mars Orbiter Camera (MOC) images of the Martian surface show extensive, steeply sloping deposits of debris at the base of bedrock escarpments in impact craters, outflow channels, and other contexts. Such debris slopes occur over much of the Martian surface but are most abundant at intermediate southern latitudes. They are typically several hundred meters long in the downslope direction and may continue for many kilometers in the cross-slope direction. A sharp break in slope at the toe of the debris (present in some but not all slopes) (Figure 1a) and V-shaped erosional chutes in many of the bedrock escarpments (Figure 1b) suggest that the slopes consist primarily of rocky debris shed from the escarpments and are not accumulations of wind-blown dust. Bedrock probably weathers by thermal stressing, growth of needle ice in fractures, or salt shattering. Material is then delivered to the debris slope by rockfall or small rockslides. Individual particles cannot be resolved even in the highest-resolution images (1.4 m/pixel), so the particles must be < ∼4 m (3 pixels) in diameter.

[4] These debris slopes appear to be geomorphically active. The near absence of craters implies recent resurfacing by emplacement of new material or reworking of existing material. Fissures that extend roughly along contour on a few slopes (Figure 1c) may be tensional cracks associated with transport of cohesive debris. Possible sources of cohesion include mineral cements, electrostatic effects, and ground ice.

2. Analysis of Martian Debris Slopes

2.1. Topographic Measurements

[5] We surveyed more than 300 debris slopes in a quadrant spanning 150°–180° W and 30°–60° S. By overlaying MOC images and Mars Orbiter Laser Altimeter (MOLA) elevation data, we constructed topographic profiles for 82 slopes (Figure 2a). Profiles typically consisted of 3 to 6 MOLA shots, which were used to calculate a mean inclination for each slope. This population of 82 mean inclinations has a mean and standard deviation of 19.1° ± 7.0°. The composite profile in Figure 2a also shows that the debris slopes are generally concave up. We have detected no systematic variation in these properties with slope aspect, geologic context, or the presence or absence of young erosional channels ("gullies"). There is, however, a significant decrease in the mean inclination of debris slopes with increasing latitude (Figure 2b).

2.2. Terrestrial Comparisons

[6] These low inclinations indicate that processes other than rockfall have modified Martian debris slopes. Figure 3 compares the mean inclination of Martian slopes with those of terrestrial debris slopes. Slopes that develop only by rockfall have straight profiles with inclinations of ∼35°, the typical angle of repose for cohesionless, naturally occurring granular material [*Van Burkalow*, 1945]. Because the static and dynamic friction angles should not differ significantly between Earth and Mars [*Klein and White*, 1988], dry rockfall alone probably did not form the ∼20° Martian slopes.

[7] Two terrestrial processes are known to produce debris slopes with concave-up profiles and inclinations as low as those observed on Mars: mass flows involving liquid water or snow [*Rapp*, 1960; *Caine*, 1969; *Kirkby and Statham*,

[1]Department of Earth and Planetary Science, University of California, Berkeley, California, USA.
[2]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA.
[3]Department of Geological Sciences, University of Canterbury, Christchurch, New Zealand.
[4]Now at United States Forest Service, Boise, Idaho.

0094-8276/03/2003GL017603$05.00

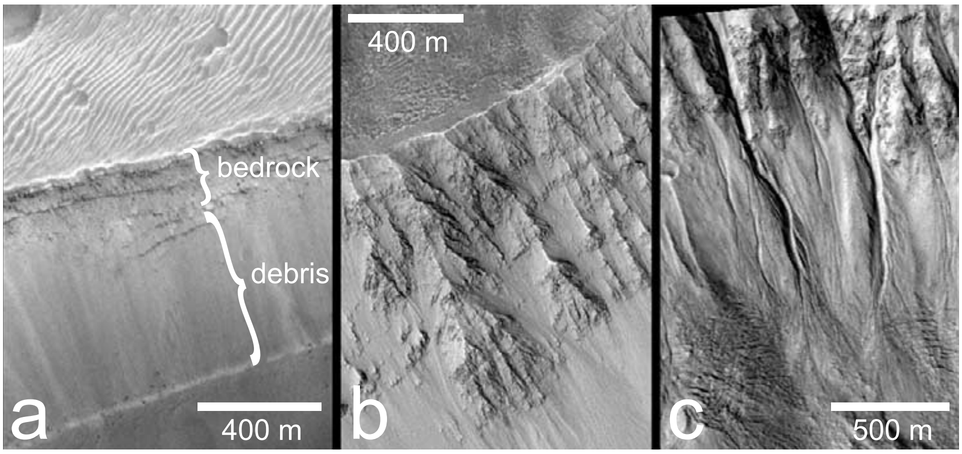

Figure 1. Features of debris slopes on Mars. (a) MOC M0902751. Some slopes have sharp contacts with the bedrock escarpment at the top of the debris and the subhorizontal surface at the base. (b) MOC M1501466. V-shaped chutes in bedrock escarpments suggest that the slopes consist primarily of rocky debris rather than wind-blown dust. (c) MOC M1700492. Fissures that extend along contour near the base of some slopes may be tensional cracks associated with downslope transport of frozen debris. The cracks appear to have formed prior to the most recent gullying episode.

1975; *Van Gassen and Cruden*, 1989], and gradual downslope displacement due to ground disturbance and gravity, often called "creep" [*Rapp*, 1960]. MOC images of ungullied slopes contain no evidence of the overlapping, lobate deposits that are commonly observed on terrestrial slopes shaped by mass flows [e.g., *Whitehouse and McSaveney*, 1983]. Subtle topographic features are visible in the depositional fans at the distal ends of gullies, which suggests that the resolution of MOC images is sufficient to reveal larger-scale deposits. Tensional cracks like those shown in Figure 1c may have been produced by deep mass movements in the debris [*Howard*, 2003], but their infrequent occurrence suggests that such processes are not responsible for the low debris slope inclinations.

2.3. Interpretations

[8] In the absence of evidence that debris slopes have been modified significantly by mass flows, we focus on the creep mechanism, in which gradual downslope movement of rock debris due to a spatially uniform disturbance process and gravity lowers the gradient of the debris slope. Likely sources of disturbance on Mars include ground motion due to "marsquakes" or impacts, thermal expansion of the rock debris, or frost heaving due to the formation of ground ice. The lack of surficial evidence of recent faulting suggests that shallow marsquakes do not occur with enough frequency and intensity to cause significant sediment transport. Impacts >1 km in diameter should cause downslope transport of unconsolidated material within several crater diameters of the impact [*Schultz and Gault*, 1975], but we have noted no qualitative relationship between debris slope inclinations and the proximity of large impact craters. Thermal expansion may contribute to bedrock weathering, but it probably does not cause appreciable sediment transport. If the rocky debris on Mars is basalt ($\alpha = 8 \times 10^{-6}\ K^{-1}$) with a porosity $\phi = 35\%$, a uniform temperature change ΔT as large as 100 K over a depth d of 2 m would cause a surface displacement $(1\text{-}\phi)\alpha d\Delta T = 1$ mm, which should not cause rearrangement of centimeter- to decimeter-sized clasts.

[9] Transport by repeated deposition and sublimation of ice in the Martian regolith is a more likely mechanism. "Frost creep" occurs when slope-normal expansion due to the formation of ice lenses or needle ice and subsequent vertical settling on ice removal causes net downslope movement at a rate proportional to the topographic gradient. Several lines of evidence suggest that frost creep occurs on Mars. Theoretical work by *Mellon and Jakosky* [1993, 1995] indicates that orbitally induced climatic and atmospheric variations should lead to cyclic sublimation and deposition of water ice in the Martian regolith. An abundance of landforms similar to those formed by repeated freeze-thaw cycles on Earth, such as polygons, have been identified in Viking [*Squyres and Carr*, 1986] and MOC [*Mustard et al.*, 2001; *Seibert and Kargel*, 2001] images. Mars Odyssey results [*Boynton et al.*, 2002; *Mitrofanov et al.*, 2002] suggest that water ice is present in the upper meter of regolith at high latitudes, with a spatial distribution that is consistent with theoretical predictions of ground ice stability [*Mellon and Jakosky*, 1993]. At high obliquity, the region of ground ice stability would extend to lower latitudes. Moreover, because frost creep is driven by changes in ground ice abundance rather than by long-term stability, it could be most intense at middle latitudes. Our observation that debris slope inclinations decrease with increasing latitude between 30° S and 60° S (Figure 2b) is consistent with this hypothesis. Odyssey results also indicate that ice volume fractions at high latitudes may exceed the porosity of the regolith, which would imply ice lens formation. *Boynton et al.* [2002] estimate that the upper meter of regolith contains ~60% (range 40–73%) water ice by volume, while porosity estimates derived from density measurements at the Viking 1 lander site range from 36 ± 16% for coarse debris to 54 ± 6% for dust [*Moore and Jakosky*, 1989].

3. Creep Model

[10] A simple, one-dimensional model offers constraints on the rate and duration of debris slope evolution. We

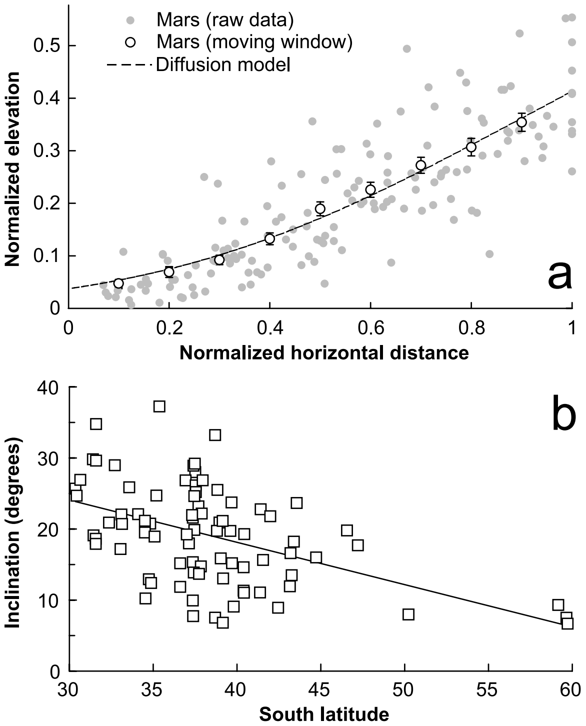

Figure 2. (a) Measured and modeled elevation profiles of debris slopes on Mars. To generate a composite profile, we normalized the raw data (small circles) by the horizontal length of each slope and passed a moving window of width 0.2 over the normalized data. Open circles with error bars show the mean and standard error for each window position. The dashed line shows the best-fit model profile for a debris slope shaped by diffusive sediment transport over 10^8 yr. Note that the slopes are generally concave up. (b) Plot of mean inclination vs. latitude for 82 debris slopes. A linear fit to the data shows a decrease in inclination of approximately 0.6° per degree of latitude ($p < 0.0001$). The significance of this trend does not depend on the points at ~60° latitude: excluding these points changes the slope of the regression line to 0.67° per degree of latitude ($p < 0.0005$).

assume that a debris slope forms by horizontal erosion of a bedrock escarpment that begins as a vertical cliff. Fresh debris accumulates at the angle of repose (35°), and the profile evolves according to

$$\frac{\partial z}{\partial t} = D\frac{\partial^2 z}{\partial x^2} \tag{1}$$

where z is elevation, x is horizontal distance from the top of the slope, and the coefficient D has the units of diffusivity (L^2/T). Equation (1) is based on the geometric assumption that downslope sediment flux is proportional to the topographic gradient, which should be valid for frost creep. It is widely used to describe the evolution of terrestrial hillslopes, and for low to moderate inclinations a number of studies have provided empirical support for the equation and field-parameterized values for the diffusivity [*McKean et al.*, 1993].

[11] Three parameters control the shape of the model profile: the amount of time the slope has been evolving, the escarpment erosion rate, and the diffusivity. We obtained model solutions by minimizing the misfit between the model profile and the composite profile in Figure 2a. The set of solutions predicts that the time of debris slope development t_d is inversely proportional to the escarpment erosion rate E and the diffusivity: $t_d = k_1/E = k_2/D$ with $k_1 = 160$ m and $k_2 = 8.1 \times 10^4$ m^2. By estimating the erosion rate and the diffusivity and identifying the solutions that fall within both ranges, we can bracket the time scale of debris slope development. Horizontal bedrock surfaces on Mars should erode much more rapidly than those on the Moon (10^{-9} m/yr [*Kohl et al.*, 1978]) and potentially as rapidly as those in cold, arid terrestrial environments such as Antarctica's Dry Valleys (10^{-7} to 10^{-6} m/yr [*Nishiizumi et al.*, 1991]). Thus we expect that erosion rates on horizontal bedrock surfaces on Mars are between 10^{-8} and 10^{-6} m/yr. In high alpine regions on Earth, near-vertical bedrock surfaces erode more rapidly than horizontal surfaces by roughly an order of magnitude [*Rapp*, 1960; *Carson and Kirkby*, 1972], and so escarpment erosion rates on Mars probably lie between 10^{-7} and 10^{-5} m/yr. This corresponds to times ranging from approximately 2×10^7 yr to 2×10^9 yr and diffusivities ranging from 5×10^{-5} m^2/yr to 5×10^{-3} m^2/yr.

[12] We can examine whether this range of diffusivities is reasonable by independently estimating the diffusivity due to frost creep on Mars. If the intensity of frost creep decreases exponentially with depth at a rate β, the slope-parallel sediment velocity $u(y)$ is

$$u(y) = \delta \tan(\theta) \int_y^\infty C_o e^{-\beta y} dy \tag{2}$$

where y is slope-normal depth, δ is the coefficient of volume expansion due to ice formation, θ is the slope angle, and C_o is the frequency of deposition and sublimation at the surface. We assume that the debris is cohesionless and that slope-normal displacements are at least on the order of the particle radius. The volumetric sediment flux q_s is the depth integral of the velocity

$$q_s = \left(\frac{\delta C_o}{\beta^2}\right) \tan(\theta) \tag{3}$$

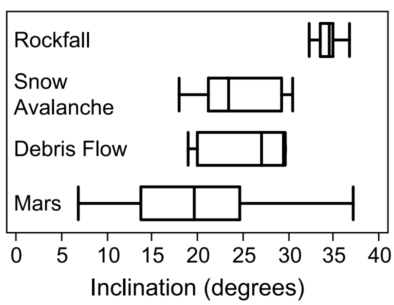

Figure 3. Quantile box plot showing inclination distributions of some terrestrial debris slopes subject to different sediment transport processes, based on a literature survey by *Sauchyn* [1986]. The distribution for 82 Mars slopes is also shown. Number of studies used to compile the terrestrial data set: rockfall, 8; snow avalanche, 10; debris flow, 5.

and the term in parentheses gives the diffusivity. *Kirkby* [1967] and *Anderson* [2002] have proposed similar expressions for the rate of transport by creep.

[13] The model of *Mellon and Jakosky* [1995] predicts cyclical desiccation and saturation of the Martian regolith to a depth of 1 to 2 m with a period of $\sim 10^4$ to 10^5 Earth years (the time scale for large variations in Mars' obliquity). Defining the active layer thickness as the distance over which the surface intensity of a disturbance is reduced by 90%, a 2 m active layer corresponds to a β value of 1.15 m^{-1}. Frost creep does not require total saturation and desiccation of the regolith, however; higher creep rates could result from smaller-amplitude oscillations in ice lens thickness tied to shorter-period orbital variations. For example, if a volume of ice equivalent to the upper meter of the north polar cap [*Zuber et al.*, 1998] were exchanged with the upper 2 meters of regolith poleward of 30° S every 100 Mars years, equation (3) predicts a diffusivity of 1.4×10^{-4} m^2/yr. This value is within the range predicted by our erosion rate estimates. The corresponding diffusive time scale for a 10 m topographic feature is <1 Myr, which may explain the scarcity of small impact craters on Martian debris slopes. This also indicates that frost creep could have erased evidence of earlier gullying episodes or other mass flows quite rapidly.

4. Conclusions

[14] Our analysis suggests that the concavity and low inclinations of debris slopes on Mars are signatures of creep that is driven by repeated deposition and sublimation of water ice in the regolith and has operated over 10^7–10^9 yr. The decline in debris slope inclinations with increasing latitude highlights a link between climate, hydrology, and erosional processes that should help to constrain models of Mars' climate history and hydrosphere. It appears that water ice has actively shaped Martian topography throughout the late Amazonian period.

[15] **Acknowledgments.** We thank F. Nimmo for thoughtful discussions and Jeff Moore and an anonymous reviewer for their helpful comments. N. van der Elst assisted with data analysis. This work was supported by the NASA Mars Data Analysis Program.

References

Anderson, R. S., Modeling the tor-dotted crests, bedrock edges, and parabolic profiles of high alpine surfaces of the Wind River Range, Wyoming, *Geomorphology*, *46*, 35–58, 2002.

Boynton, W. V., et al., Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits, *Science*, *297*, 81–85, 2002.

Caine, N., A model for alpine talus slope development by slush avalanching, *J. Geol.*, *77*, 92–100, 1969.

Carson, M. A., and M. J. Kirkby, *Hillslope Form and Process*, Cambridge, 1972.

Costard, F., F. Forget, N. Mangold, and J. P. Peulvast, Formation of recent Martian debris flows by melting of near-surface ground ice at high obliquity, *Science*, *295*, 110–113, 2002.

Hoffman, N., White Mars: A new model for Mars' surface and atmosphere based on CO_2, *Icarus*, *146*, 326–342, 2000.

Howard, A. D., Tongue ridges and rumpled crater floors in mid-southern-latitude Martian craters, *Proc. Lunar Planet. Sci. Conf.*, *34th*, 1065, 2003.

Kirkby, M. J., Measurement and theory of soil creep, *J. Geol.*, *75*, 359–378, 1967.

Kirkby, M. J., and I. Statham, Surface stone movement and scree formation, *J. Geol.*, *83*, 349–362, 1975.

Klein, S. P., and B. R. White, Dynamic shear of granular material under variable gravity conditions, *AIAA Ann.*, 88–0648, 1988.

Kohl, C. P., M. T. Murrell, G. P. Russ III, and J. R. Arnold, Evidence for the constancy of the solar cosmic ray flux over the past ten million years - Mn-53 and Al-26 measurements, *Proc. Lunar Planet. Sci. Conf.*, *9th*, 2299–2310, 1978.

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

McKean, J. A., W. E. Dietrich, R. C. Finkel, J. R. Southon, and M. W. Caffee, Quantification of soil production and downslope creep rates from cosmogenic ^{10}Be accumulations on a hillslope profile, *Geology*, *21*, 343–346, 1993.

Mellon, M. T., and B. M. Jakosky, Geographic variations in the thermal and diffusive stability of ground ice on Mars, *J. Geophys. Res.*, *98*, 3345–3364, 1993.

Mellon, M. T., and B. M. Jakosky, The distribution and behavior of Martian ground ice during past and present epochs, *J. Geophys. Res.*, *100*, 11,781–11,799, 1995.

Mellon, M. T., and R. J. Phillips, Recent gullies on Mars and the source of liquid water, *J. Geophys. Res.*, *106*, 23,165–23,180, 2001.

Mitrofanov, I., et al., Maps of subsurface hydrogen from the High Energy Neutron Detector, Mars Odyssey, *Science*, *297*, 78–81, 2002.

Moore, H. J., and B. M. Jakosky, Viking landing sites, remote-sensing observations, and physical properties of Martian surface materials, *Icarus*, *81*, 164–184, 1989.

Musselwhite, D. S., T. D. Swindle, and J. I. Lunine, Liquid CO_2 breakout and the formation of recent small gullies on Mars, *Geophys. Res. Lett.*, *28*, 1283–1285, 2001.

Mustard, J. F., C. D. Cooper, and M. K. Rifkin, Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice, *Nature*, *412*, 411–414, 2001.

Nishiizumi, K., C. P. Kohl, J. R. Arnold, J. Klein, D. Fink, and R. Middleton, Cosmic ray produced ^{10}Be and ^{26}Al in Antarctic rocks: Exposure and erosion history, *Earth Planet. Sci. Lett.*, *104*, 440–454, 1991.

Rapp, A., Recent development of mountain slopes in Kärkevagge and surroundings, northern Scandinavia, *Geografiska Ann.*, *42*, 65–200, 1960.

Sauchyn, D. J., Particle size and shape variation on alpine debris fans, Canadian Rocky Mountains, *Phys. Geog.*, *7*, 191–217, 1986.

Schultz, P. H., and D. E. Gault, Seismically induced modification of lunar surface features, *Proc. Lunar Sci. Conf.*, *6th*, 2845–2862, 1975.

Seibert, N. M., and J. S. Kargel, Small-scale Martian polygonal terrain: Implications for liquid surface water, *Geophys. Res. Lett.*, *28*, 899–902, 2001.

Squyres, S. W., and M. H. Carr, Geomorphic evidence for the distribution of ground ice on Mars, *Science*, *231*, 249–252, 1986.

Stewart, S. T., and F. Nimmo, Surface runoff features on Mars: Testing the carbon dioxide formation hypothesis, *J. Geophys.*, *107*, doi:10.1029/2000JE001465, 2002.

Van Burkalow, A., Angle of repose and angle of sliding friction: An experimental study, *Geol. Soc. Am. Bull.*, *56*, 669–707, 1945.

Van Gassen, W., and D. M. Cruden, Momentum transfer and friction in the debris of rock avalanches, *Can. Geotech. J.*, *26*, 623–628, 1989.

Whitehouse, I. E., and M. J. McSaveney, Diachronous talus surfaces in the Southern Alps, New Zealand, and their implications to talus accumulation, *Arc. Alp. Res.*, *15*, 53–64, 1983.

Zuber, M. T., et al., Observations of the north polar region on Mars from the Mars Orbiter Laser Altimeter, *Science*, *282*, 2053–2060, 1998.

W. Dietrich and J. T. Perron, Department of Earth and Planetary Science, University of California, 307 McCone Hall, Berkeley, CA 94720, USA.

A. Howard, Department of Environmental Sciences, University of Virginia, 291 McCormick Rd., Charlottesville, VA 22904, USA.

J. McKean and J. Pettinga, Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.