Stability of rock slopes in Valles Marineris, Mars

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[1] New slope measurements from the Mars Orbiter Laser Altimeter (MOLA), in conjunction with the Rock Mass Rating system (RMR), permit inversions of slope height and angle from wallrock and interior deposits within Valles Marineris troughs for strength and lithology. Wallrock (50 < RMR < 65) is stronger than interior deposits (30 < RMR < 55). These values are consistent with layered igneous rock beneath wallrock slopes, with interior deposits consistent with partially indurated sedimentary or volcaniclastic rocks. Larger volumes of landslide debris relative to terrestrial slides are related to the reduced Martian gravity. Seismicity along trough-bounding normal faults likely triggered the landslides in the adjacent wallrock. The weaker interior deposits are located sufficiently far from a border fault (and on its hangingwall) to have remained stable during the seismogenic faulting in Valles Marineris. *INDEX TERMS:* 5460 Planetology: Solid Surface Planets: Physical properties of materials; 6225 Planetology: Solar System Objects: Mars; 7221 Seismology: Paleoseismology; 8040 Structural Geology: Remote sensing. **Citation:** Schultz, R. A., Stability of rock slopes in Valles Marineris, Mars, *Geophys. Res. Lett.*, *29*(19), 1932, doi:10.1029/2002GL015728, 2002.

1. Introduction

[2] Slope instability is a process identified on nearly every planetary surface in the solar system. Landslides are found on Venus, the Moon, Mars, and Io. Lobate debris flows have been identified within impact craters on Callisto and in parts of the interior deposits in Valles Marineris on Mars. These failures of rock slopes contrast with simple downslope transport of surficial regolith, analogous to soil slips, that have recently been observed on Mars [*Sullivan et al.*, 2001] and that do not involve deeper (rock) layers.

[3] The Martian landslides are characterized by spectacular ampitheater-shaped depletion zones ("alcoves"), where the slide mass originated, and prominent flow lobes containing the long-runout debris [e.g., *Lucchitta*, 1978; *Cruden and Varnes*, 1996; *IAEG Commission on Landslides*, 1990]. In cross section the depletion zones are curved, with lower terminations at or near the adjacent normal fault trace [e.g., *Lucchitta*, 1978; *Schultz*, 1997; *Peulvast et al.*, 2001], suggesting circular failure of mechanically homogeneous slope rocks (i.e., no planar zones of substantially weaker strata) and rotational sliding along a curved basal slip surface [*Cruden and Varnes*, 1996; *IAEG Commission on Landslides*, 1990; *Muller and Martel*, 2000].

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[4] *Clow et al.* [1988] previously modeled wallrock slope stability in Valles Marineris. Their best result, for a depletion zone (slide alcove) in Ius Chasma, yielded values of cohesion and friction angle of C_0 = 0.4 MPa and ϕ = 20°, respectively. The strength values were considered too low for typical rocktypes, suggesting that weathering or hydrothermal alteration of wallrock was necessary to reduce the normally much larger intact-rock strengths. Similarly, impact-crater ejecta breccias and highly fractured basement rocks were, at the time, thought to underlie wallrock slopes [*Lucchitta et al.*, 1992]. However, recent observations of fine-scale layering in wallrock of Coprates Chasma by *McEwen et al.* [1999] now suggest that wallrock is underlain by a continuous sequence of thinly bedded layered rocks to depths of >8 km. Reassessment of the Ius Chasma slope using MOLA data [*Caruso*, 2002] reduces the height from 6 to 4 km and the angle from 46° to 29°, consistent with a stronger rocktype such as basalt (see below). We also incorporate concepts of rock-mass strength (not utilized or available before) that are more appropriate for relating large Martian slopes to rock strength at these scales.

2. Analysis

[5] Rotational slope failure is commonly modeled by standard limit-equilibrium analysis methods of slope stability, such as the Bishop or Janbu methods (either of which give comparable results) [*Cruden and Varnes*, 1996; *Kumar*, 2000]. The analysis requires values of either slope geometry (height and angle) or rock-mass strength properties.

[6] Slope height and angle are extracted from MOLA profiles of representative sections of wallrock (from both depletion zones ["failed wallrock"] and unfailed spur-and-gully topography) and interior deposits (Figure 1). Care was taken to measure representative profiles that lack discernable thicknesses of eolian or other mantling materials.

[7] The stability of Martian slopes is calculated by using the method of slices [e.g., *Cernica*, 1995, pp. 302–311], as implemented in the XSTABL software package [*Sharma*, 1994]. The two-dimensional slope (with along-strike dimensions $\gg$ height) is divided numerically into individual vertical slices, for which individual factors of safety (ratio of driving forces to resisting forces) are calculated. Resulting factors of safety for each slice are summed and averaged to estimate the stability of the slope. Driving forces include gravity loading, changes in pore-fluid pressure, physical or chemical weathering, and seismically induced ground accelerations [*Hoek and Bray*, 1981; *Norrish and Wyllie*, 1996]. Resisting forces are given by the rock-mass strength (cohesion and friction) [*Hoek and Bray*, 1981]. Reduced Martian gravity is considered by reducing rock density by a corre-

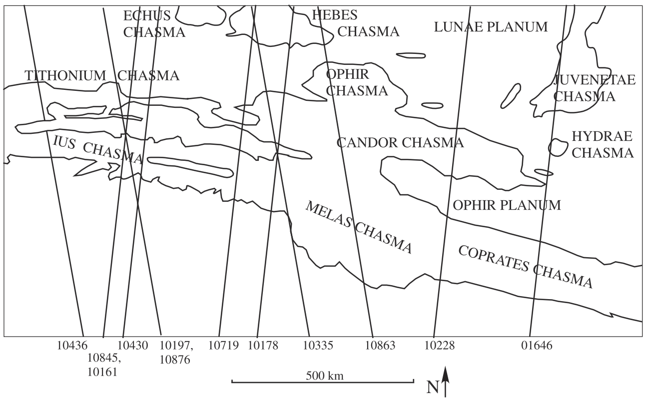

Figure 1. Location of MOLA tracks across Valles Marineris troughs indicating locations of measured slopes (after *Caruso* [2002]).

sponding amount ($\rho_{Mars}/\rho_{Earth} = g_{Mars}/g_{Earth}$) which is permissible for static or seismic loading of the dry (anhydrous) slopes inferred in this study. Representative (unreduced) dry densities of 2900 and 2500 kg m^{-3} were chosen for wallrock and interior deposits, respectively. For failed slopes, the best match between predicted shapes of the basal slip surface and observed topography, obtained by iteratively searching through C_0-ϕ space, indicates the strength of the slope during failure. For unfailed slopes, the predicted strength parameters are upper limits to the likely slope strengths [e.g., *Somnez et al.*, 1998].

[8] Factors of safety, and therefore the implied rock-mass strengths, obtained from XSTABL likely approximate the actual field values. Explicit modeling of progressive rotational slope failures [*Muller and Martel*, 2000; *Lechman and Griffiths*, 2000] and more general solutions to the stability problem [*Beikae*, 2000] suggest that XSTABL values are too large by several tens of percent. On the other hand, large Martian depletion zones may be better treated as three-dimensional failures, with ampitheater widths W of 10–20 km (in northern Candor Chasma) and heights H of 4–8 km, for W/H = 1–5. *Arellano and Stark* [2000] show that two-dimensional strengths are underpredicted by >20% for W/H < 4. The uncertainties in the XSTABL analysis are probably in the range of ± 20–30%.

[9] We obtain admissible ranges of rock-mass properties for both sets of Martian slopes by defining cohesion and friction pairs for representative rock masses using the Rock Mass Rating (RMR) system [e.g., *Bieniawski*, 1993] with the nonlinear Hoek-Brown strength criterion [e.g., *Schultz*, 1996; *Hoek*, 1998; *Dawson et al.*, 2000]. We represent intact crystalline rock with RMR = 100, unconfined compressive strength σ_c = 300 MPa, and Hoek-Brown parameter m_i = 33; bedded lava flows, RMR = 75, σ_c = 200 MPa, and m_i = 22; sedimentary rock, RMR = 50, σ_c = 100 MPa, and m_i = 8; and soft rock/strong soil, RMR = 25, σ_c = 50 MPa, and m_i = 2. C_0 and ϕ calculated from these values [e.g., *Bieniawski*, 1993; *Schultz*, 1996] are then used as inputs to predict the strength of Martian slopes consistent with these strength properties. The resulting curves of slope strength (Figure 2), when compared to measured slope height and width from MOLA data, bracket values for the strength of Martian slopes.

3. Results and Implications

[10] Wallrock spans a wide range of heights at relatively shallow slope angles. As a result, neither height nor slope angle alone determines the slope stability, and both must be considered when discussing or modeling slope strength. Mechanical modeling of the frictional strength of dry rock masses scaled to the lower Martian gravity demonstrates that slope dimensions (height and angle) scale inversely with planetary surface gravity [*Caruso*, 2002]. This implies that larger slopes on Mars are stable relative to terrestrial ones (of the same dimensions) and that correspondingly larger volumes are mobilized into landslides when Martian slopes fail, leading to correspondingly larger volumes of landslide deposits [*McEwen*, 1989; *Dade and Huppert*, 1998].

[11] Layered wallrock exposed in Valles Marineris is eroded into slopes of 10–30° with heights between 1 and 8 km (Figure 2). Landslides that nucleated in wallrock left headscarp alcoves with slopes of 25–30° and heights of 1–5 km. Interior deposits within the troughs have slopes of 10–20° and heights of 1–5 km. Inspection of Figure 2 suggests that the strength of wallrock is given approximately by 50 < RMR < 65 (corresponding to cohesion C_0 of ∼0.1–0.2 MPa and friction angle ϕ of ∼14–25°) and that of interior deposits by 30 < RMR < 55 (corresponding to cohesion C_0 of ∼0.05–0.12 MPa and friction angle ϕ of ∼5–18°). Both wallrock and interior deposits are considerably stronger than Martian soils [*Rover Team*, 1997], and slopes in both materials are stable against failure due to gravity alone.

[12] All slopes are weaker than any intact rock (RMR 100), requiring fracturing, weathering, and/or pore-fluid pressure. Of these, fracturing is the most likely and common strength-reducing factor in rock masses larger than cm in size [e.g., *Bieniawski*, 1993; *Schultz*, 1996]. On the scale of the entire slope, the strength properties of wallrock appear remarkably homogeneous (including the uppermost kms of layered strata), as implied by vertically uniform erosional patterns within the section [e.g., *Blasius et al.*, 1977]. MOC images of wallrock show, however, that individual layers are closely jointed. On the other hand, interior deposits weather out as massive or layered sequences of nearly comparable strength [e.g., *Nedell et al.*, 1987; *Malin and Edgett*, 2000], with a lesser degree of fracturing of these

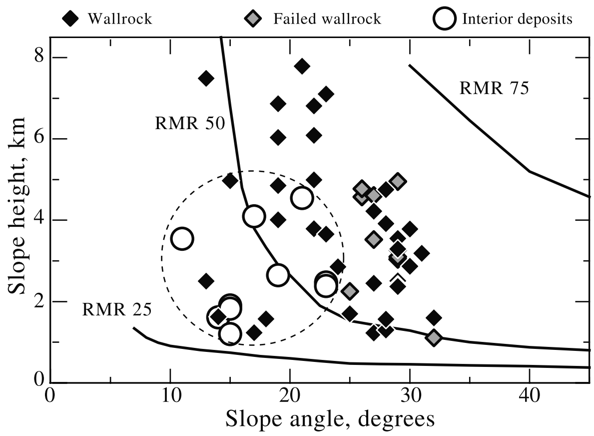

Figure 2. Slope heights and angles in Valles Marineris compared to predicted strengths of rock slopes.

materials at the scale of individual beds. Given scant evidence for significant pore fluids draining from either slope-forming material, however (justifying modeling both slope types as predominantly dry), and the inverse correlation between visible fracturing and strength, the differences in RMR likely reflect lithologic contrasts between these materials. If water ice, or other solid volatile phases, were present in either rock mass [e.g., *Lucchitta*, 1978; *Lucchitta et al.*, 1992; *Peulvast et al.*, 2001], they would have been contained primarily within the fractures, leading potentially to a modest (i.e., <10%) additional reduction in RMR.

[13] The strength characteristics of wallrock are consistent with a variety of rocktypes at the field scale, including basalt (assuming that columnar joint networks are explicitly incorporated into its rock-mass strength). Spectral observations of wallrock from the Thermal Emission Spectrometer also suggest basaltic compositions for these materials [*Bandfield et al.*, 2000]. Fresh basaltic rock masses, with rough columnar joint surfaces and minimal groundwater, have RMR ~75, whereas older, altered basaltic rock masses with wet clayey gouge in the joints have RMR ~45 [*Schultz*, 1995]. The RMR values from Martian wallrock are consistent with the range of terrestrial basaltic rock masses.

[14] Interior deposits are generally weaker (smaller values of both cohesion and friction angle) than wallrock (Figure 2). Rocktypes at the field scale that are consistent with these strength values include the softer sedimentary rocks such as shale, siltstone, mudstone, sandstone, limestone, breccia, and nonwelded tuff [e.g., *Lin et al.*, 1993; *Somnez et al.*, 1998]. With the exception of limestone, any of these rocktypes would be consistent with both the strength (Figure 2) and morphologic [e.g., *Nedell et al.*, 1987; *Lucchitta*, 1990; *Chapman and Tanaka*, 2001] characteristics of interior deposits. Massive (i.e., unfractured) igneous, metamorphic, or hard sedimentary rocks are not consistent with either class of constraint. On the other hand, fracturing and/or pore water appear indicated by the erosional and strength properties of these (softer) materials.

[15] Curiously, no landslides have been identified in the interior deposits [*Lucchitta*, 1987; *Nedell et al.*, 1987], although several occurrences of debris or earth flows [*Cruden and Varnes*, 1996] have been reported. As reviewed by *Chapman and Tanaka* [2001], a stack of flows emanating without significant headscarps or slide planes has been identified in the interior deposits of eastern Candor Chasma. These flows resemble mud or debris flows that were mobilized by limited amounts of fluid [*Schultz*, 1997] and which flowed over short distances. Similar-appearing flows in other troughs (western and central Candor Chasma, Ophir Chasma) may have nucleated by removal and flow of a volatile-rich lower massive unit. The occurrence of moisture and pore-fluid pressure would further reduce the strength of interior deposits relative to wallrock from the values inferred here. However, these materials remained stable to catastrophic slope mobilization (into landslides) despite failure of the stronger wallrock. This paradox motivated the slope stability investigation.

[16] The landslides in Valles Marineris wallrock occur adjacent to prominent normal-fault scarps that bound the troughs [e.g., *Witbeck et al.*, 1991; *Lucchitta et al.*, 1992; *Schultz*, 1997]. Landslides were nucleated upslope of the faults (i.e., in their footwalls), similar to the positions of seismically triggered landslides on Earth [*Jibson*, 1996]. Seismic slip propagating up from depth along a normal fault produces enhanced ground accelerations in the footwall, leading to landslide triggering for sufficiently strong seismic events [e.g., *Wieczorek*, 1996]. Preliminary calculations [*Caruso*, 2002] suggest that a surface magnitude 3.6 Marsquake, consistent with fault lengths [*Wells and Coppersmith*, 1994] observed in northern Ophir Chasma, could induce ground accelerations of 0.25 m s^{-2} (or 0.07 g_{Mars}) within a distance of 10 km from the fault, sufficient to trigger landslide failure of the dry wallrock (Figure 3). Indeed, seismic triggering is suggested morphologically from the penetration of depletion zone down to the fault, whereas simple gravity-driven slope failure would produce depletion zones only on the upper reaches of the slope (Figure 3). Given the absence of other driving forces such as pore-pressure transients (e.g., rainfall or snowmelt) [e.g., *Wieczorek*, 1996], seismic slip along the subjacent Martian trough-bounding normal faults is considered the most plausible mechanism for triggering landslides in wallrock.

[17] Mesas of interior deposits do not overlie the trough-bounding normal faults, but instead occur tens of km away in trough interiors [e.g., *Witbeck et al.*, 1991]. Seismic shaking decreases in its intensity linearly with distance from the source fault [*Wilson and Keefer*, 1985]. The lack of landslides in the weaker interior deposits implies that seismic activity along the Valles Marineris trough-bonding faults was sufficiently small in magnitude, and sufficiently far away (e.g., tens of km), for interior deposits to have remained stable under the attenuated seismic shaking.

4. Conclusions

[18] Valles Marineris wallrock is stronger than interior deposits, yet only the stronger wallrock has failed by landslides. The occurrence of landslide alcoves down to normal-fault scarps, in conjunction with slope-stability modeling, suggests that the landslides were triggered by seismic accelerations from the subjacent trough-bounding fault. Attenuation of seismic energy with distance from the fault likely prevented the weaker interior deposits from failing

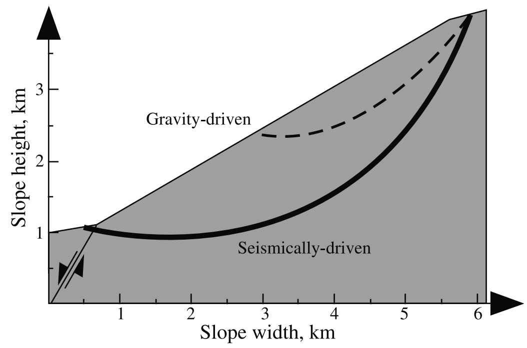

Figure 3. Representative failure surfaces (landslide alcoves) predicted for dry wallrock. Dashed (upper) curve, failure due to gravity alone; bold (lower) curve, failure due to gravity plus near-field seismic ground acceleration due to slip along adjacent normal fault (arrow). Note that slopes in wallrock and interior deposits are both stable against gravity-driven failure.

and generating landslides. These results imply that Martian trough-bounding normal faults in Valles Marineris, and perhaps elsewhere on Mars, were seismogenic when they were active.

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