MARTIAN GULLIES: MORPHOMETRIC PROPERTIES AND FLOW CHARACTERISTICS.

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Introduction: Although planimetric and some relief and slope measurements have been made of martian gullies based on MOLA topography[*1-3*], the large laser footprint limits accuracy in determination of topographic slopes. High-resolution HiRISE stereo imaging coupled with MOLA topography permit better estimation of slopes and allow estimates of flow velocities and flow volumes based upon gully dimensions.

HiRISE Imaging: As of December, 2007 about 150 HiRISE images have been released targeting the recent gullies formed on crater walls and steep slopes. Of these, about 30 stereo pairs have been collected. We have selected 17 of these stereo pairs to make detailed measurements of gully topography and morphology. Our selection was based upon being able to co-register MOLA tracks to calibrate parallax measurements of topographic slopes.

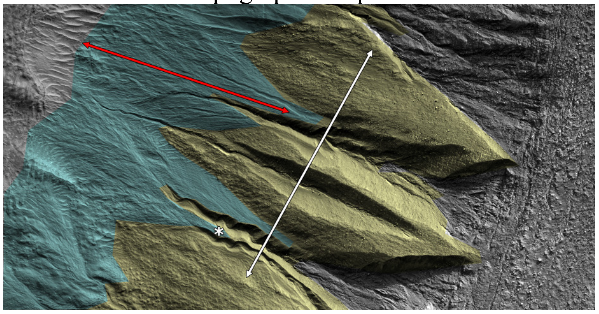

Fig. 1. Gullied crater wall (part of HiRISE PSP 1792-1425). Bottom of slope to left. Image width 1.4 km. Blue: depositional apron; Yellow: thick pasted-on terrain; Red arrow, typical measured apron slope; White arrow: mid-slope; Asterisk: Meandering gullies.

Measurement Procedures: Portions of geometrically-processed released HiRISE images having matching stereo coverage of gullied slopes were extracted at full resolution and imported into Photoshop® as separate layers. Relative elevations were measured by parallax and calibrated by the overall slope relief measured from MOLA tracks. A number of potential stereo pairs were eliminated because MOLA data could not provide accurate relief estimation. A few stereo pairs were included of slopes lacking well-defined gullies but having linear mass-wasting talus slopes. The primary focus of the measurements is the gradient of the depositional aprons and of meandering portions of gullies feeding the aprons(**Fig. 1**).

Apron Slopes: The most informative observations about flow processes in sedimentary systems, including gradients measured here, are usually derived from their deposits. For cohesionless materials emplacement entirely by superficial gravity-driven granular flow generally occurs at the dynamic angle of repose characteristic of disentrainment of grains flowing across the surface. Lower gradients generally imply a transport mechanism with enhanced mobility [*3*], generally implying involvement of a fluid, either intimately mixed with the granular medium in the case of debris flows or as bedload transported at the base of the fluid.

Gradients were measured on 53 footslope aprons (**Fig. 1**). These gradients varied from 7.4° to 34.6°, averaging 15.8°. However, the gradient distribution is bimodal. To refine interpretation of the gradient distribution, a qualitative ranking was made of the characteristics of the mid-slope and aprons of the hosting slope . Mid-slopes (**Fig. 1**) are characterized as category 1 if they are deeply incised by gullies, 2 if shallowly incised, often by numerous parallel rills, and 3 if the slopes are smooth. Aprons are characterized in category 1 if they show fan-like radiation from a feeding gully, have distributary feeders and hummocky depositional morphology, 2 if these features are muted and aprons merge laterally, and 3 if the slope base is smooth at multi-meter scales. Scores for the two criteria are added and plotted against apron gradient.

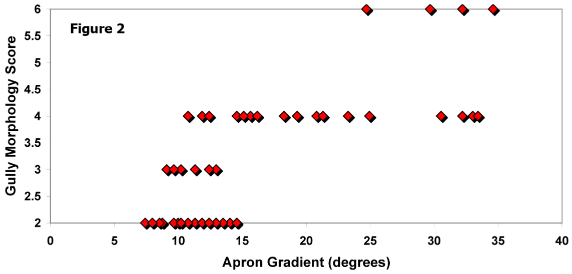

Figure 2 shows that the classic, deeply-incised slopes with well-defined aprons are characterized by apron gradients in the range of 7.5°-15° and thus display transport by flows with enhanced mobility. Smooth, ungullied or slightly rilled slopes typically have gradients that are close to the angle of repose for cohesionless debris.

Flow Velocities and Discharges from Gully Properties: Measurements were made of the wavelength, λ, width, W, and gradient, S, of 23 slightly meandering gullies on 9 HiRISE stereo pairs (**Fig 1**). Wavelengths varied from 16 m to 157 m, averaging 58 m. Gully gradients ranged from 8.7° to 24.2°, averaging 13.8°. Gully width (average 5.7 m, range 1.6 to 12.3 m) is linearly related to meander wavelength: $\lambda = 10.2W$ (R^2=.73), strongly suggesting that the meandering is not an effect of random surface irregularities. For terrestrial rivers both W and λ have been correlated with bankfull discharges, Q, [*4*], providing estimates for the martian gullies averaging about 15.9 and 8.5 m^3/s, respectively. Such estimates should be viewed cautiously due to lack of gravity scaling and extrapolation to channels much smaller and steeper than the terrestrial database.

Another method uses the linearized, depth-averaged theory of flow in meanders proposed by [*5*]. The wavenumber, k, of incipient meandering is given by:

$$k = 2C_f\left(\Gamma^{0.5}-1\right)^{0.5}/D = {2\pi}/{\lambda}\,, \qquad (1)$$

where

$$C_f = V_*^2/V^2\,, \qquad (2)$$

D is flow depth, λ is meander wavelength, V is average velocity, and V_* is shear velocity. Γ is given by:

$$\Gamma = 0.5\,((A+2)+F^2)\,, \qquad (3)$$

where A is related to cross-sectional slope in meander bends and F is Froude Number. If we assume $F\approx2$ then $\Gamma\approx4$ for alluvial channels where $A\approx2$, and $\Gamma\approx3$ for $A\approx0$ (no cross sectional slope). We will assume Γ=4, so that the term $(\Gamma^{0.5}-1)^{0.5}\approx1$. Assuming flow that is steady and uniform downstream,

$$\tau = \rho V_*^2 \simeq \rho g D S\,, \qquad (4)$$

where S is surface slope and g=3.7 m/s^2 on Mars. Substituting and solving for V, we get:

$$V^2 \approx 1.18\,S\,\lambda\,. \qquad (5)$$

Table 1.	V (m/s)	D (m)$^{\&}$	Q (m^3/s)$^{\%}$
Average	3.8	0.71	27.9
Minimum	2.1	0.19	0.62
Maximum	6.7	1.92	198.2

&: Assumes W/D=8 %: $Q=WDV$

Table 1 presents the average, maximum, minimum values of flow velocity based upon eq. (5). Depth and discharge are also estimated based upon typical terrestrial values of channel width/depth ratio (e.g. [*6, 7*]). The estimated velocity, depth, and discharges are similar to observed terrestrial alpine debris flows (e.g.[*8-11*]), suggesting the martian gullies might involve debris flows. Reasonable ranges of the parameters A and F affect estimates of velocities only by a multiplicative factor of up to ±1.2. A caution in making comparisons to terrestrial debris flows is that they are generally triggered by heavy rain, whereas that is almost certainly not the case for flows in Martian gullies. Additional caution to the use of meander wavelength to estimate velocity arises from possible violation of assumptions in [*5*] that gradients are small, viscous forces are small, and mean flow is steady and uniform downstream.

Discussion: Although the various methods used to estimate discharges, depths, and velocities in the gullies are subject to errors and biases, they suggest appreciable discharges (>10 m^3/s), flow depths (~1 m), and flow velocities (~4 m/s). Chutes and their associated hummocky apron deposits terminate abruptly at the base of the associated scarp. This suggests that the flows within chutes and on aprons have a finite yield strength or strongly non-linear rheology, requiring slopes exceeding several degrees, consistent with deposition by debris flows [*12*]. Low levees border many channels flowing across aprons, consistent with debris flows. Multiple flow events were required to form the gullies and aprons [*13*].

Almost all deeply-incised gullies occur on slopes at least partially mantled with superposed deposits that have been referred to as "pasted-on" terrain [*14-18*]. The pasted-on terrain is likely the dominant source of the fine-grained deposits on well-developed aprons (e.g., **Fig. 1**) [*13*]. The particular properties of pasted-on deposits (e.g., fine grain size or volatile content) may contribute to their propensity for debris flow mobilization.

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