PRELIMINARY EVIDENCE FOR A DEBRIS FLOW GULLY SLOPE-AREA RELATIONSHIP ON MARS AND IMPLICATIONS FOR A SOURCE LIQUID.

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Introduction: A variety of martian gully forms have been observed [1]. On Earth, the morphometry of a gully and its drainage basin provides information about the mechanism of its formation. Terrestrial gullies form by a number of mechanisms, most notably through erosion by surface runoff and infiltration-triggered soil slip [2]. Using data from the High Resolution Imaging Science Experiment (HiRISE) camera onboard the Mars Reconnaissance Orbiter (MRO) [3], we have compared morphometric characteristics of terrestrial gullies associated with debris flows with a subset of martian gullies as a preliminary test of the hypothesis that the latter are formed by analogous saturation and failure of the regolith.

The debris flow mechanism and topographic signature: The most common mechanism of terrestrial debris flow initiation is sliding of a relatively thin layer of unconsolidated material that has failed due to saturation with water [4]. Unconsolidated material (regolith) is held on a slope by shear strength, a combination of friction and cohesion. Most importantly, saturation reduces frictional strength because pore pressure counteracts the normal stress holding material on a slope, so that shear failure occurs when a critical saturation point occurs in the regolith. A gully (channel) head is formed at the uppermost point of failure. The slide of saturated regolith transforms into debris flow as it moves downslope. Channel formation by scouring and entrainment of colluvium occurs as the debris flow acquires more material downslope [5], with flow material eventually coming to rest lower on the slope. This process creates an alcove-channel-apron morphology similar to that identified by [1]. On Earth, saturation of regolith typically occurs when precipitation or snowmelt infiltrates and moves downslope as shallow subsurface flow in unconsolidated material over bedrock or another less permeable substrate, and is concentrated in slope hollows by topography. Attainment of the critical pore pressure threshold depends on the relationship between size of the contributing area for subsurface flow and slope gradient; a larger contributing area provides a greater total amount of throughflow, and thus requires a lower gradient for failure [6]. This slope-area signature for debris flow initiation has been used successfully to describe the location of terrestrial debris flow channel heads [e.g. 2, 6-9].

Observations of distinct gully heads in regolith on Mars suggest that some martian gullies may also be created by debris flows triggered by shallow subsurface processes. If this is correct, and the generation of liquid is broadly distributed within the associated slope hollow (alcove), then they should also exhibit a relationship between the contributing areas and slope at the channel head. Specifically, this relationship should hold if melting of shallow subsurface ice within the alcove provides a source of liquid on Mars that causes saturation failure. Here, we apply this approach to a subset of martian gullies associated with debris flow morphologies to provide a preliminary test of this hypothesis.

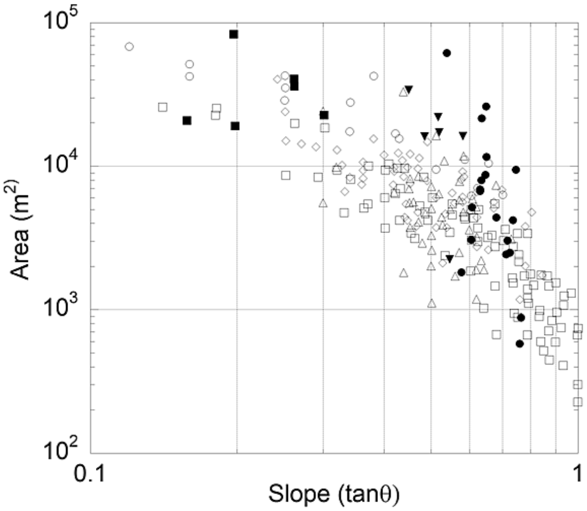

Figure 1. Measured slope-area relationships for martian gullies (filled symbols) and terrestrial gullies (open symbols). Martian gullies were measured in HiRISE images for site 1 (closed circles), site 2 (closed triangles), and site 3 (closed squares) as listed in Table 1. Also shown are the results of terrestrial studies of primarily landslide initiated channels in Tennessee Valley, CA (open diamonds) [7], Coos Bay, OR (open squares) [8], Southern Sierra Nevada, CA (open circles) [8], and San Pedro Ridge, CA (open triangles) [9].

Methods: Stereo image pairs from HiRISE were examined for debris flow erosional and depositional features. In order to examine relatively straightforward slope-area relationships, we selected areas with sharp, well-defined gully heads within first-order basins and limited evidence for multiple flows. In this initial study, thirty-two gullies were measured using stereo image pairs in three locations (Table 1), all on walls of southern hemisphere craters. Three digital elevation models (DEMs) were analyzed in this study; these were constructed from publicly released HiRISE images following the method of [10]. The HiRISE images have a pixel scale of 25-28 cm in non-binned channels, and the resulting DEMs contain elevation postings with 1-meter spacings. Images were overlain on the DEMs in ArcGIS, and measurements of contributing area and slope were made by digitizing regions of interest and extracting values from the DEM. Contributing areas were calculated using the free ArcGIS tool Easy Calculate (5.0). Area was measured using the topography to define the apparent drainage basin in which the gully channel resided, and slope was measured from the head (uppermost part) of the channel to the top of the drainage divide [2, 6, 9]. Only first-order (unbranched) channels were measured.

Results: Figure 1 shows the relationship between contributing area and slope for the study set of martian gullies showing debris flow morphology. In order to place these measurements in context, our data were plotted alongside the results for terrestrial studies of the area-slope relationship for similar channels [6-9]. Our results show that overall, martian gullies measured in this study have a similar area-slope relationship to terrestrial debris flows. As the slope gradient increases, the contributing area decreases for martian gullies. The spread seen in both the terrestrial and martian data in Fig. 1 is expected given the large number of variables that may affect the slope-area relationship, most importantly soil properties such as cohesion, permeability, and frictional strength. Within the individual martian study sites, however, the data spread is relatively small and no clear relationship is evident, in part because of limited topographic variability within each area.

Discussion: Initial results suggest that our hypothesis that recent slope failures in some regions of Mars have been triggered by shallow subsurface flow from a broadly distributed source of liquid in the alcove is tenable, and warrants further investigation. Although debris flows could be mobilized by a release from a subsurface aquifer [11, 12], this mechanism is unlikely to produce any relationship between contributing area and slope gradient, as aquifer discharge is typically localized by fractures or permeability boundaries, rather than broadly distributed. On Earth, infiltration of precipitation or snowmelt is the typical source of near-surface liquid, but liquid precipitation has not been observed on the surface of Mars. While numerous studies [e.g. 13, 14] suggest that the past martian climate may have supported precipitation and liquid water on the surface, the martian gullies appear to be actively forming features [15] and have likely formed in conditions similar to the present. Additionally, the current-day amount of insolation a slope receives appears to have an effect on whether or not a gully will form on that slope [e.g. 1, 16, 17], suggesting that temperature controls the behavior of the source liquid. A potential source that is shallow, broadly distributed, and temperature controlled is near-surface ice, which, when melted, could act much as terrestrial throughflow in the near subsurface. Subsurface ice has been inferred to exist on Mars from surface morphologies [18, 19], thermal modeling [20], global hydrogen abundances detected by the Neutron Spectrometer onboard the Mars Odyssey [21], and radar sounding results from the Shallow Radar (SHARAD) onboard MRO, which are consistent with large ice deposits in the midlatitudes where gullies are generally located [22]. Frost also accumulates annually in gullied areas in the current climate, as seen in various HiRISE images. Polygonal fracturing in several alcoves and surrounding regions in this study also point to the presence of ground ice in gully-bearing regions. Polygonal terrain has been observed associated with gullies previously by [23], who noted that many of these fractures appeared to predate and control the direction of some gully channels. They also note gullies formed by broadly distributed subsurface flow in the Antarctic that are overlain on polygonal permafrost terrain.

In summary, initial results imply that a debris flow formation mechanism for some martian gullies by broadly distributed shallow melting of ice leading to subsurface flow, regolith saturation, and slide failure may be applicable to some regions of Mars. We intend to conduct additional analyses of slope-area relationships for martian gully heads to further test this hypothesis.

Table 1. Observation IDs and locations of HiRISE images

Site	First image	Second image	Lat.	Lon. (E)
1	PSP_004060_1440	PSP_005550_1440	-35.722°	129.428°
2	PSP_001714_1415	PSP_002136_1415	-38.382°	96.804°
3	PSP_003418_1335	PSP_003708_1335	-46.067°	18.819°

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