ANALELE ŞTIINTIFICE ALE UNIVERSITĂȚII „AL I. CUZA" IAŞI
Tom LVII s. II – c, Geografie 2011

MORPHOLOGICAL AND MORPHOMETRICAL DIFFERENTIATION OF PROCESSES ON CRATER WALLS IN EASTERN UTOPIA PLANITIA, MARS

Radu-Dan Capitan[1], Gordon R. Osinski[1,2], and Marco J. Van De Wiel[1,3]
[1] Centre for Planetary Science and Exploration, University of Western Ontario, London, ON, Canada N6A 5B, (rcapita@uwo.ca)
[2]Dept. of Earth Sciences/Physics and Astronomy, University of Western Ontario, London, ON, Canada N6A 5B7
[3]Dept. of Geography, University of Western Ontario, London, ON, Canada N6A 5C2

Abstract: This study identifies a variety of processes associated with erosional and depositional structures within impact craters in eastern Utopia Planitia, Mars. Differentiation of the morphological characteristics of erosional and depositional structures within five structures suggests that four types of landforms develop on craters walls: debris flows, linear or dendritic channels resembling gullies, head-cut channels, and dry flows. Previous studies have mostly focused on the orientation characteristics of gully-type landforms and the environmental conditions that contributed to their formation. Most of these studies favored the term gully for all "wet" processes affecting crater walls, although debris flows have also recently been described. The full development of these structures shows that the wet-member structures (e.g., temporary channels resembling gullies) and mixed types (e.g., debris flows) evolved under different environmental conditions than that of present-day Mars. Dry flows can form in the current environmental conditions, but their presence near to the wet-member forms and the structural relationships among these wet and dry forms suggest that they formed within the same periods during fluctuations in atmospheric conditions. The morphometrical characteristics of flows on craters walls show that there is a relationship between the accumulation area and slope of processes, which indicate a morphometric threshold between the wet and dry types of erosion; with gully channels developing on low angle colluvial slopes while the debris flows are forming on more abrupt slopes. It is suggested that the most important controlling factors for flow initiation and development on the crater walls are first related to the morphometry of craters walls, and then to water availability and exposure of bedrock within crater walls.

Key words: Mars, gullying, crater wall evolution, Utopia Planitia

1. Introduction

The mechanisms of formation and the environmental conditions required for the development of different types of temporary short channels on Mars – typically collectively referred to as "gullies" in the literature – have been debated since their discovery by Malin and Edgett (2000a). Most models invoke, and are intrinsically linked to, the availability of liquid H_2O on Mars during recent times (e.g., Malin and Edgett, 2000a; Head et al., 2008; Lanza et al., 2010; Levy et al., 2010; Kneissl et al., 2010). Example models include: (1) prolonged snow accumulation in shaded alcoves and melting during the summer periods (Christensen, 2003; Williams et al. 2009; Lanza et al., 2010); (2) glacial ice or permafrost melting during the obliquity cycles in the near past (Soare et al., 2007; Dickson et al., 2007; Dickson and Head, 2009); (3) top-down melting of ice from permafrost or glaciers due to the limited insulation conditions during the present-day atmospheric conditions (Hecht, 2002; Levy et al., 2010); (4) runoff in different climatic conditions (Soare et al., 2007; Heldmann et al., 2007); (5) groundwater release at surface of perched aquifers (Malin and Edgett, 2000; Mellon and Philips, 2001; Heldmann and Mellon, 2004; Dickson et al., 2007); (6) dry flows of eolian deposits (Treiman, 2003); (7) CO_2 release at surface (Hoffman, 2000; Musselwhite et al., 2001; Ishii and Sasaki, 2004). Despite the various potential formation mechanisms, most workers agree that the development of these channels involved a liquid phase with specific insulation conditions. Generally, the generic term describing the erosional and depositional processes affecting crater walls associated with brief water runoff is “gullying” (Carr, 1996; Malin and Edgett, 2000a; Dickson and Head, 2009); although the most recent comparisons with terrestrial counterparts also refer to debris flows (Dickson et al., 2007; Lanza et al., 2010). Here, we show that both mechanisms of formation and terminology to describe such processes can be revisited and better constrained using the morphological indicators and morphometrical characteristics of landforms developed on impact crater walls.

We carried out detailed mapping of landforms in five craters in eastern Utopia Planitia in the northern plains of Mars to evaluate the characteristics of “gullying” processes at a local scale of study (*Fig. 1*).

By focusing on one region, as opposed to a global study, we can remove the possible effect(s) of variances in climate between different regions of Mars. A survey of the landforms developed on the flanks of these craters shows that there are a variety of “gully” morphologies. Careful consideration of the morphological characteristics of the erosional, transportational and depositional structures suggests that distinct “gully” morphologies can be distinguished based on a number of specific form-related criteria that are identified based on visual and altimetric data (*Fig. 2, Table 1*).With respect to orientation characteristics, seen as a contributing factor to the initiation and manifestation of erosional processes (Costard et al. 2002; Balme et al., 2006; Head et al. 2009), we have statistically tested whether the different processes are randomly oriented. We also report statistical nonparametric analyses on several morphometrical characteristics to ascertain whether processes can be differentiated based on the morphometry on both orientation variation and processes differences. Finally, we discuss the morphometrical factors that may have contributed to the development of the different landforms.

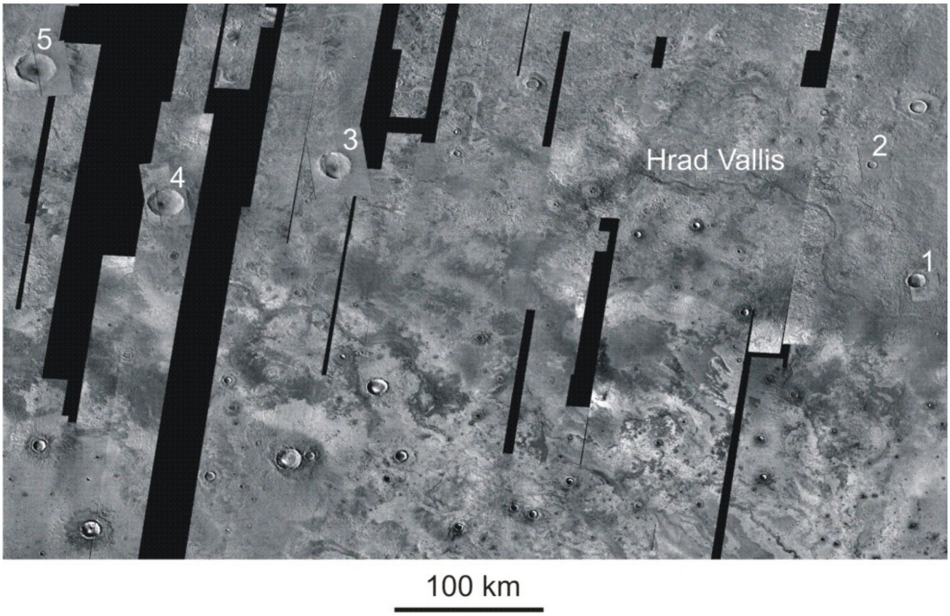


Figure 1. *Regional map of eastern Utopia Planitia in HradVallis region seen on THEMIS infrared mosaic context images.CTX images superposed on THEMIS infrared mosaic* (credit images NASA/THEMIS/JPL). Craters that are considered in this article are numbered on the map.

2. Methods

This study compiled visual and morphometric information using ESRI's ArcGIS software. Visual information from orbital imagery at high resolution was used to differentiate among the types of processes acting on craters walls. Several different layers of raster data were imported and georeferenced (*Fig.1*): MOLA gridded elevation raster, THEMIS (Thermal Emission Imaging System) infrared mosaic data; higher resolution CTX (Mars Reconnaissance Orbiter Context Camera) and HiRISE (High Resolution Imaging Science Experiment) data for each crater was added to permit better description of medium and small scale morphologies. Each dataset was overlain on top of each other georeferenced to an equal area sinusoidal map projection. As an intermediate step between the collection of data and data analysis, a survey of the different types of landforms inside and outside the craters was performed in order to investigate possible genetic inter-linkages among various morphologies. Next, different shapefiles (to describe areal and length characteristics) were created for each type of morphology (alcove, channels and aprons) to describe the morphometry of the analyzed landforms. Linear distances were extracted from CTX and HiRISE images. As such channel and landform lengths reported here represent minimum lengths and are potentially slightly longer due to slope of crater walls. Length of the landforms was measured for each of the landform component from apex to the base along the longest line. Areal data was extracted for alcove along divides and apron along morphologic shape edge. Elevation information data was extracted from MOLA tracks to allow the determination of elevation information for each alcove, channel and apron apex and bottom. The position of each type of landform was also recorded for the eight compass orientations using map-projected CTX images along the gully axes. Finally, after the vector data was collected and attributes computed, they were exported for statistical evaluations in SPSS.

Table 1. Morphological characteristics of the four processes forming short temporary channels on Mars.

Type	Morphological characteristics		
	Alcove	Channel	Apron
Type A	Multiple elongate and heavily eroded alcoves	Linear channels emerging into a collector channel	Simple elongate or triangular fan Developed on colluvial slopes eroded in some cases by rills
Type B	Fan-shaped alcoves Sharp scarps Deep incised channels into alcove area	Multiple linear channels emerging from a broad contributing area Multiple sinuous or straight channels developed on apron Variable width channels Levees	Distant lobes (initial aprons)
Type C	Presence of alcove is not a condition Whereas there are presented they are heavily eroded	Linear discontinuous channels	Lobate or triangular debris apron Steep snouts on apron margins Multiple digitate or triangular fans
Type D	Detachment (“crown”) scarps Lobate or digitate snout developed on steep scarps	Linear valleys Lobate snouts at depositional features Lack of fluvial bed or channels structures	Cuspate and digitate termini Lobes formation on steep slopes

3. Observations

The study sites are located north and west of Hrad Vallis in eastern Utopia Planitia in the northern plains of Mars (Fig. 1). The geologic deposits that cover this area comprise volcanic products on the flank of Elysium Mons and impact crater deposits (Tanaka et al., 2003). We have focused on five arbitrary craters of diverse diameters to evaluate the characteristics of “gullying” processes (Fig. 1). Mapping of inner crater deposits of the three craters shows that surface deposits comprise brecciated deposits of crater rims and colluvial deposits on the flanks of the crater walls.

3.1. Morphological analysis of landforms on crater walls

A detailed survey of the spacecraft images reveals that four types of "gullies" can be distinguished. Below, we describe the landform types with respect to alcove, channel, and apron morphologies (Figure 2, rows A, B, C) and their morphometric characteristics (columns 1,2,3, and 4).

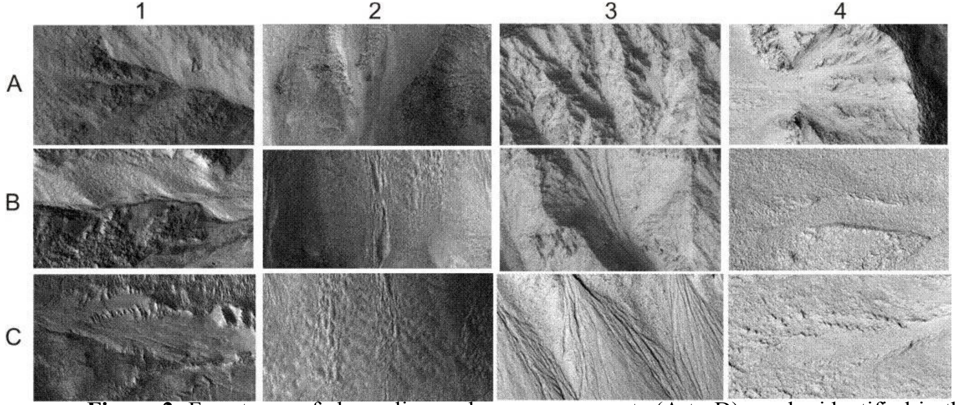


Figure 2. Four types of channeling and mass movements (A to D) can be identified in the study region and can be assimilated in to the current description of Martian gullying. The morphologies shown are parts of the alcoves (1), channels (2), and aprons (3). Images are 300 m wide. Image credit: HiRISE imagery NASA/MRO. HiRISE images: PSP 002266_2190, PSP_006908_2215, ESP_013487_2190 and ESP016283_2215.

Type A: The first type displays elongated alcoves cut by advancing channels along the steepest part of the contributing areas (*Figures 1A, 2*). The channel morphologies best exemplify the differences between Type A and other types of gullies do to their transportational characteristics. These morphologies have well developed linear collectors and tributaries that meander (1B). The fans are elongated, crenulated, and possibly reflect in some cases a transition toward mudflow deposition, or the presence of underground ice, which made possible later mobilization of the alluvial mantle (1C).

Type B: The second morphologic type does not present obvious sculpted alcoves, which are eroded or blanketed (Poesen et al, 1988; Vandaele et. al., 1996), (Fig. 2A). The channels in this case are straight, discontinuous, and deeply incised into the mantled colluvial slope (2B). The depositional areas in the second type of morphologies are convoluted and typically heavily modified by subsequent periglacial processes, indicating the presence of ice in these depositional structures (2C).

Type C: This type presents distinct alcoves and contributing areas and they are sharp and partially dissected by channels. Where a layered crater wall is present, multiple alcoves can be seen to join where a competition for sources of water was possible among concurrent flows (3A). The third type morphologies present single or multiple linear sinuous channels that start within the alcoves or just underneath them (where layering is present, 3B). The third type aprons are triangular, cut by multiple marginal channels, and present sharp edges and convex distal fronts (3C).

Type D: The last type morphologic alcove is sharp and broadly extended, with multiple ramifications due to the presence of layered deposits. The alcove's floor is mantled in most cases by fine colluvial deposits (4A). The fourth type channels are wide and straight. In all cases, this type of channels are visible in the lower parts of the crater walls, below the contributing area, the space between being covered by more recent colluvial deposits (4B The last type of fans are elongated, do not present active channeling on it, but depositional exterior ramifications as they would present resistance from crater bed during the process of formation (4C).

3.2. Morphometrical characteristics of landforms

The morphological characterization of the four different types of landforms provides an additional step to differentiate them. First we analyze the differences between the five craters and then between the different landforms, based on the initial geomorphologic differentiation. The first step to achieving this is to map the location of the four individual types of morphologies (types A to D) seen in CTX images within the five craters *(Fig. 3*).

Figures 3 and 4 show that the overall orientation of the four landforms described above is distinctly different in the five craters. The overall preference is towards south and west facing slopes. In terms of the orientation of landforms within the five craters, debris flow morphologies and head-cut channels preserve this orientation preference, with dry flows morphologies and mature gullies being oriented differently (*Fig. 4*). To test statistically the correlation between the orientation and the process type, we performed a Chi-square test in which the null hypothesis was as follows: there is no preference of process orientation in the case studies area. The alternate hypothesis is that the processes are oriented preferentially. The results show that we have to accept the null hypothesis, with values exceeding the 0.005 level of significance for Chi square distribution (Tables 2, 3; Fig. 4). Moreover, the symmetric test indicates that the type of process is not correlated with orientation (Phi test, Table 3), with less than 20% of the process types being linked with the orientation.

Another goal of our study was to investigate the initial conditions that contributed to process differentiation, specifically the relationship between crater wall morphometry (slope) and length of the different landforms. Our hypothesis was formulated in the initial morphological description; namely, that processes are influenced by the initial crater morphometrical characteristics. Type 4 morphologies are shorter in length and less energetic than the type 3 morphologies. Type 1 landforms concentrate on two distinct trends on steeper slopes than expected initially, while type 2 morphologies occupy the less steep domain, being developed on the pole-facing colluvial deposits.

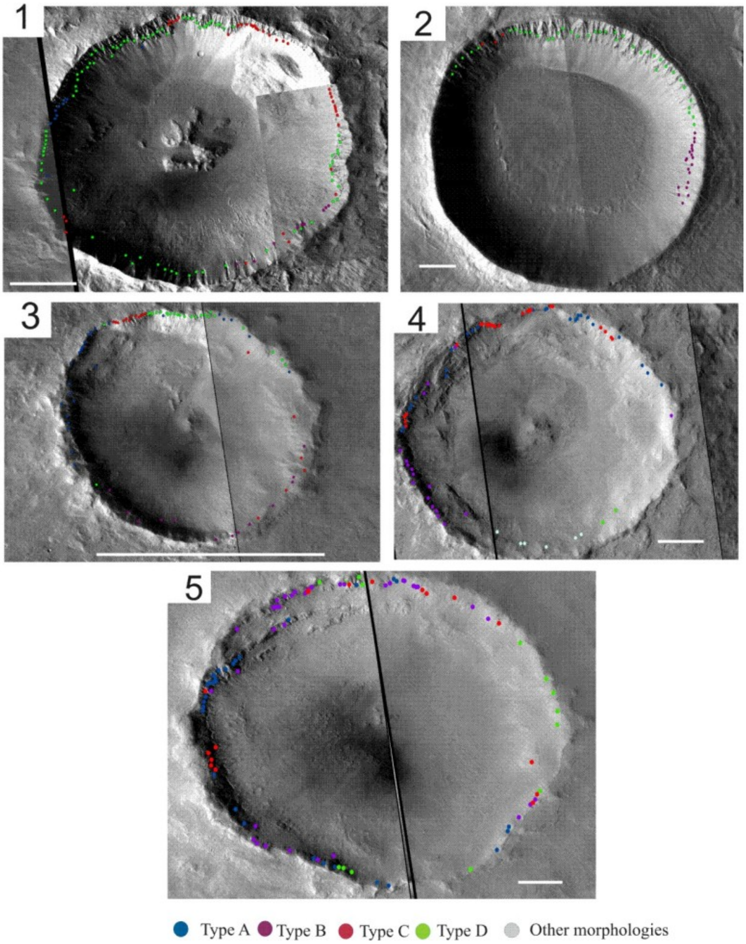


Figure3. Landform distribution on the five craters in western Utopia Planitia. (1) Type 1 morphology; (2) Type 2 morphology; (3) Type 3 morphology; (4) Type 4 morphology; The morphologic characterization is based on the description of the three parts of landforms seen on CTX and HiRise images. Other morphologies are observed and classified distinctly (blue dots). In the second crater case, no processes develop on southern wall, showing that other constraints are necssary for landform development than the orientation. Scale bar is 5 km long, north is up. Image credit: CTX images P02_001910_2215 (crater 1), P03_002266_2188 and B10_013487_2198 CTX image (crater 2), P 15_006908 and P15_007053_2215 (crater 3), P22_009479_2206 and P01_001528_2209 (crater 4) and G02_018960_2236, P16_007396_2237 (crater 5) NASA/JPL.

Table 2. Chi-square test

	Value	Df	Chi-statistics at P=0.005	Asymp. Sig. ((2-sided)
Pearson Chi Square debris flows	55.29133604	7	14.07	.000
Pearson Chi Square dry flows	36.24444444	7	14.07	.000
Pearson Chi Square gullies	21.26681312	7	14.07	.000
Pearson Chi Square head-cut channels	14.92061566	7	14.07	.000
N of Valid Cases	450			

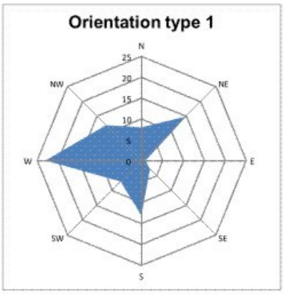
Table 3. Symmetric Measures

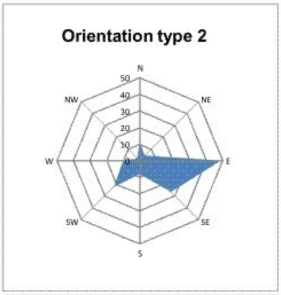
		Value	Approx. Sig.
Nominal by Nominal	Phi (debris flows)	.195	.000
	Phi (dry flows)	.128	
	Phi (gullies)	.075	
	Phi (head-cut channels	.052	

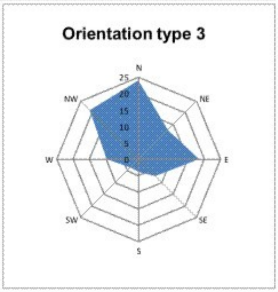
Because we observed that both types A and B are developed on colluvial slopes, we coupled these two types in the morphometrical analysis. Figure 5 shows that the relationships between the two variables exist and that the processes are grouped clearly.

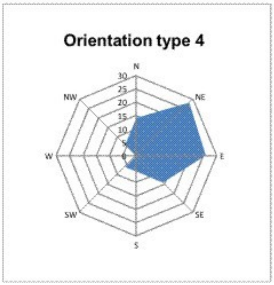
The final morphometrical analysis we carried out investigates whether or not there is a threshold for the initial conditions required for the development of a specific type of process. The literature (Montgomery and Dietrich 1994; Lanza et al,. 2010) provides examples of a threshold in initialization of channeling in debris flows in terrestrial and Martian environments. These previous studies describe a relationship between the area of alcove and the slope of the alcove between the point where the channels start to develop and the hillside top. In these cases the relationship describe an increase of the area necessary for a channel to develop as the slope is less steeper. In our case, because the alcove areas frequently develop on crater walls that present variations in homogeneity (e.g., colluvial or stratified hard-rock deposits) this type of measurement is not applicable.Therefore, we performed another analysis, which investigates the empirically derived curve between alcove area and the slope of the first-order channel (Montgomery and Dietrech, 1989), sorting the data from the less steeper channel slopes with the higher alcove area to the higher steeper channel slopes with the smalles contributing areas. (*Fig. 6*). Our analysis suggests that the less steeper the slope of the channel, the larger the alcove area. An interesting outcome is that there is a clear differentiation among the three phases of erosional modifications.

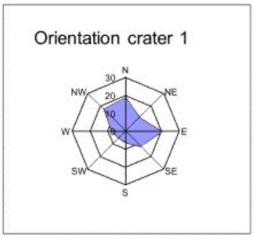
There are clear thresholds, with type A landforms having mostly alcoves less than 0.5 Km^2 and the channel slope being between 4.5° and 10° (0.1 and 0.4 m/100m; Fig.6). Type C morphologies clearly require large alcove areas by comparison to gullies but there is a threshold around 40° above which they are more common. Type D morphologies have less developed alcoves and wider angles of incidence, distinct from gullies and debris flows (*Fig. 6)*.

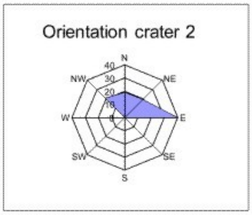

Orientation type 1

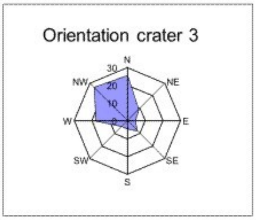

Orientation type 2

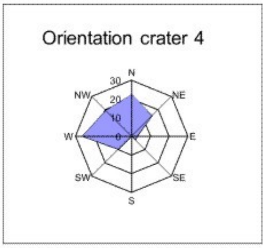

Orientation type 3


Orientation type 4


Orientation crater 1


Orientation crater 2


Orientation crater 3


Orientation crater 4

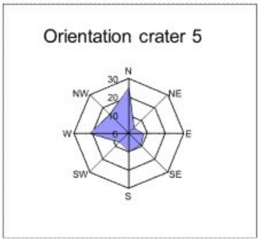

Orientation crater 5

Figure 4: (a) Orientation of overall processes on different craters; (b) orientation of distinct processes within the five Martian craters.

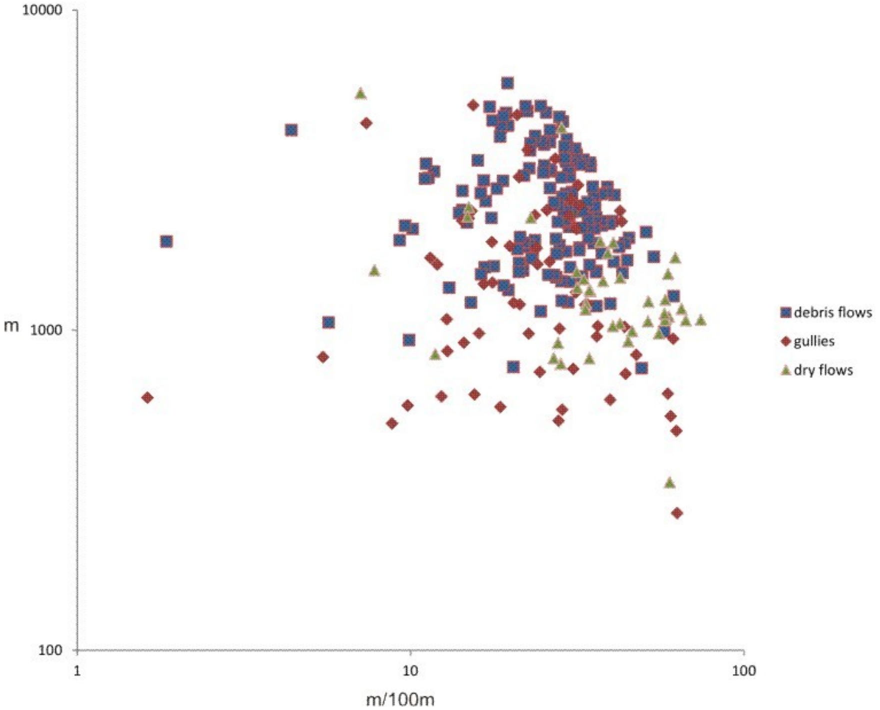


Figure 5: *Relationship between the crater wall length (along the process axis of development) and slope of processes on sampled craters in Utopia Planitia, Mars*.

4. Discussion

4.1. Landform classification

The morphological and morphometrical differences among the four types of landform identified in our study (Table 1) shows that simply describing the variety of morphologies as "gullies" is an oversimplification (Fig. 2). This is important as the different landforms may have very different formation mechanisms and, therefore, different implications for assessing the role of H_2O in their formation. Below, we discuss the origin of each of the type landform types based on their morphological and morphometrical properties and comparisons with terrestrial analogues. We acknowledge that in most terrestrial cases, landforms can be studied as they develop, or can be easily recognized and reconstructed in the field. On Mars, the active processes are rarely observed from orbit (McEwen et al, 2011) and we are faced with observing the similar forms that could be generated by the same type of process. Although caution is advised to interpret their formation and evolution in detailed comparison with terrestrial counterparts, remote sensing datasets reveal sets of observable characteristics that point the interpretation to similar terrestrial morphologies. As such, similarities indicates that the four types of landforms can be interpreted morphologically as gullies (ephemeral channels cut by running water), head-cut channels (channels developed as result of head-cut point migration upwards due to throughflow), debris- flows (channels generated by high concentrated water-sediment mixture) and dry flows (channels formed by rapid movement of materials along preferential pathways on steep slopes) (Kolb et al. 2010). Consequently, based on comparison to terrestrial analogues, we interpret type A as gullies, type B as head-cut channels, type C as debris flows channels, and type D as dry flow channels.

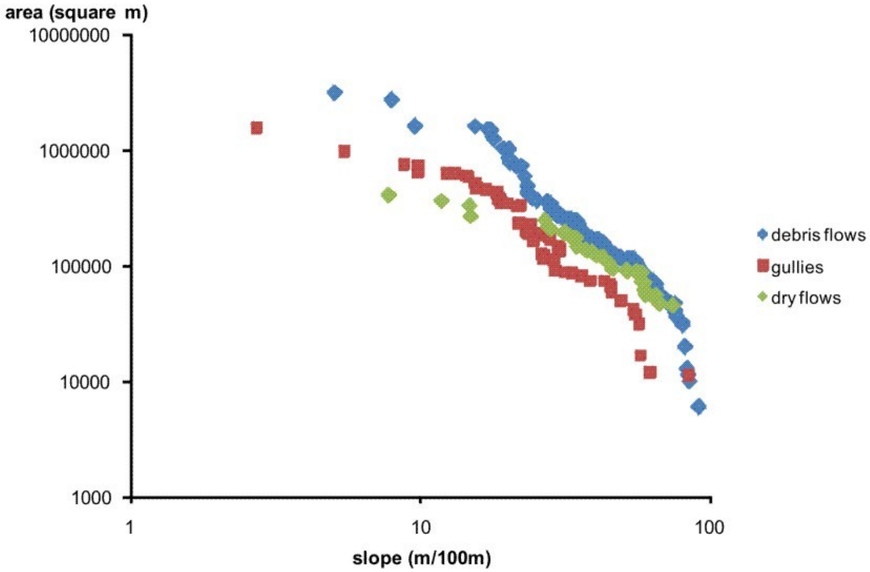


Figure 6 : *Chart indicating the empirically derived curves for the alcove area and first-order channel slope relationship on crater walls in Utopia Planitia for the three types of processes*. The data is measured on the CTX images for the five craters in Utopia Planitia. The relationship indicate thresholds in alcove area between the mixed and wet processes at 0.350 square kilometers, and in the slope of processes at 0.35 m/m (19.29 °). Horizontal scale is logarithmic, the verical scale is semilogarithmic.

Type A – The current literature often generically describes fluvial-driven landforms formed on crater walls on Mars as “gullies” (*Figs. 2, 1A-C)*. These landforms typically comprise an alcove area (that superposes in most cases largely on accumulation or source area), a channel (i.e., the transportation area), and a deposition fan (apron) (Malin and Edgett, 2000a). In terrestrial geomorphological terminology, a gully is a landform created by running water (overland flow) eroding sharply into soil, typically on a hillside (Vandaele et al., 1996; Bull and Kirkby, 1997; Poesen et al. 1998). In terrestrial environments gullies develop mostly on soils cleared of vegetation and evolve mainly due to changes in land use (Valentin et al., 2005). There are several formation characteristics that do not directly apply to Martian gullies, such as the rate of erosion on degraded soils and rate of gully advance due to intensity and duration of seasonal, decadal and multiannual precipitation. A typical terrestrial gully is associated with sheetwash and rill erosion and comprises a main channel, which widens progressively downslope. In the Martian case, particularly in our area of study (*Fig. 2, 1A-C),* gullying typically evolves within craters, along trenches, and on median slopes, being similar in shape to hillside terrestrial gullies, which progressively downcut the hillslopes (Kochel, R.C., et al., 1985; Heldmann et al., 2007). In the Utopia Planitia region, this type of gullying is developed on craters walls covered by debris or colluvial mantles. The landforms comprise a main collector that collects side tributaries (*Fig. 2, 1B*). The accumulation area (also known as an alcove) is, in some cases, well contoured, the transportation area showswell-developed channels, and the accumulation area is lobate shaped. In many cases gullies are accompanied by rilling on each side of the main landform, a characteristic that is common on both planets and which describe a typical runoff process associated with landform formation.

Type B – The second type of landform observed within Martian craters are head-cut channels that have not evolved into mature gullies (*Fig. 2A-C*) (Howard, 1986). This type of intermittent fluvial erosion landform resembles head-cut gully channels on Earth (Poesen et al., 1998). The mechanism of development is related to piping and subsurface flows (white lines indicating head-cutting as frequently seen on terrestrial environments). However, in contrast to gullies on Martian craters, the head-cut channels are wide and discontinuous, and do not present evolved depositional areas. Alcoves are in this case not branched as in gullies.

Type C – Another term attributed to short channels affecting crater walls is "debris flow". As a process, a debris flow is a fast moving, liquefied landslide of unconsolidated, saturated debris that has the appearance of flowing concrete (Iverson, 1997). In the words of Iverson (1997), "debris flows occur when masses of poorly-sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction". Although debris flows are frequently channelized, they represent a transition between mass movement and fluvial processes, although they are commonly classified as mass movements. Despite this common cliché, Iverson (1997) made clear that "debris flows characteristically originate as nearly rigid sediment masses, transformed at least partly as liquefied flows, and then retransform again to nearly rigid deposits", thus implying a flowing phase of movement, capable of scouring a channel. They can precede or postdate fluvial channelization and they can develop on depressional concave flexures of steep hillslopes, and are usually preceded by heave or slumping/sliding of unconsolidated deposits above the alcove. In both cases, the terrestrial processes actively modify the slopes, their rate and frequencies being related to recent climatic conditions (generally during the last several decades), and definitively related to a surplus of water in unconsolidated surficial deposits (Iverson, 1997). In terrestrial environments, they develop on steep mountain areas or along steep canyon walls (Stock and Dietrich, 2006). One subtype of mass movement that is more related to en masse movement of materials is a "debris slide", which is not channelized. Debris flow morphologies develop on steep crater walls, present well defined alcoves areas and distinctive channel(s) flanked by levees, and well defined apron areas on which multiple channels divert (*Figs. 2,3A-C,*) (cf., Lanza et al., 2010).

Type D – The final type of landform that we have identified are dry (granular) flows channels (*Figs. 2, 4A-C,*). As a process, it is a rapid mass movement along preexisting depressional areas, or downside steep areas, such as those on the crater rims that display layered, forming avalanche channeling. Channels are wide and steep and alcove areas are crenulated and eroded away along weaker deposits (cf., Sulivan et al., 2001; Baratoux, et al., 2002; Treiman, 2003; Shinbrot et al., 2004). This type of landform is seen in terrestrial environments (e.g., sand dunes), but is generally associated with processes developed in dry climatological conditions in mountainous areas, and on talus slopes in humid areas (Allen, 1970; Cooke et al., 1993). The landform develops and advances in correlation with diurnal/annual weathering changes and infrequent mobilization of surface deposits due to gravitation.). In the terrestrial counterparts, some of these types of flow are associated with movement of dusty deposits along straight channels in the steep mountains, resembling (dry) avalanche corridors (Shinbrot et al., 2004).

These observations suggest that the range of processes vary from dry energetic processes that could form instantaneously, to long-term fluvial processes that develop in certain pluvial and nivial conditions.

4.2. Controlling factors for flow initiation and development

The only procedure to associate a landform seen in satellite imagery with a process and interpret it is by associating the form with a probable mechanism of formation, based on the interpretation experience of the observer, the existent models and, and comparisons with terrestrial counterparts.

When the distribution of the four major landforms developed on the inner crater walls is analyzed, differences in orientation and development characteristics are clearly present (*Figs. 2* and *3*). The erosional, transportational and depositional characteristics of the four types of landforms suggest that controlling conditions for their initiation and development varied within the same crater. However, comparison of the craters reveals that orientation is not necessarily a major controlling factor that can aid in the differentiation of such processes. For example, some areas of exposed crater walls are not affected by these types of erosion, and in other cases, both the wet and dry end members of the processes we describe (gullying versus dry mass movements) are present on the same crater wall flank, which suggest changing climate conditions from wet to dry. An important outcome is that gullies show three maxima and thus have a preference orientation toward opposite directions; head-cut channels have a dual orientation, neither of which being oriented toward pole or equator facing slopes, but rather on western and eastern flanks of the craters, suggesting diurnal change in melting rather than seasonal one. The most energetic processes (debris flows and dry flows) are oriented toward equatorial and eastern-facing slopes, suggesting seasonal exposure of presumptive aquifers (Fig. 3). However, the analysis is made in our case on more refined slope orientation; therefore, we expect that slight changes in orientation can cause major changes in availability of water at surface or nearby surface deposits.

The morphometric characterization of the relationships between the slope of crater walls and the type of processes developed on them reveals that debris flows occupy the steepest slopes, and gullies develop predominantly on less inclined colluvial slopes.

Table 4. Classification of gully landforms

Type of landforms	Possible mechanism(s) and conditions of formation
Gullies	Increase in flow of surface (or subsurface) water (Valentin et al, 2005). Alternate sedimentary strata Significant increases in sediment yield
Head-cut channels	Concentration of overland and through flow (Poesen et al. 1998, Vandaele et al., 1996).
Debris flows	High pore pressure along pre-existing rupture surface (Iverson, 1997) Unconsolidated materials on hillsides (Lanza, 2010) Steep hillsides promoting gravity induced slope failure (Stock and Dietrich, 2006).
Dry flows	Rapid movement of unconsolidated materials on colluvial or bare slopes (Shinbrot et al., 2004)

Most of the landforms present evident signs of complete development (*Fig. 2*), such as multiple channel development on aprons and deep cut gully channels that both extend over 2 km in most cases. This strongly suggests that pluvial or nivial conditions on the crater walls must have prevailed for an extended (weeks to decades) period of time. In contrast, debris flows can develop over a relative short periods of time (hours to days) during successive phases of aquifer recharge or melting of surface ice deposits. In terms of the origin of fluids required to generate debris flows and gullies, the two possible end member mechanisms of formation that produced these landforms are: (1) infiltration of water in near surface colluvium that produce complex movements of surface deposits associated with debris flows on steeper slopes (Irvin, 1997), and (2) channel formation due to runoff or throughflow on less steeper colluvial slopes, the later in the case of head-cut channeling (Poesen et al., 1998). These conditions are presented in Table 4.

In the case of debris flows, multiple channels diverge on aprons and erode into alcoves, mainly on the sides (*Figs. 2, 3A*). On Earth, there is a phase of runoff during summer periods that contributes to debris development through runoff (Iverson, 1997). On Mars, this mechanism would form fully developed debris flows on the steep slopes of craters. The difference in size among debris flows is important and in some cases multiple processes or multiple phases of the same process develop. Generally, debris flows develop on more abrupt pole facing slopes and mainly associated with the presence of stratified deposits (e.g., Figs. 2, 3A). Head-cut channels are mostly straight, affecting the entire colluvial slope, and develop kilometers down the slope (Fig. 3); whereas gullies develop in networks on the upper part of the slope, sometimes in association with rilling . Conditions to initiate development of multiple scouring channels and downslope movement of materials imply lubrication of upper materials in the alcove area by a major source of water or underground ice.

An important observation is that the two types of runoff processes form on different oriented crater walls: the head-cut channels develop on shallower slopes oriented pole wards, whereas gullies develop on east facing slopes. This asymmetric disposal and slope differences was also recognized by Lanza et al. (2010) for gullies in southern hemisphere between 25 and 46^{o}, and interpreted as a result of variations in underground ice content, such that ice is preferentially preserved on pole facing slopes, which permits ice creep to develop. We consider this as being local situations, exceptions to the rule being obvious and related rather to crater wall morphometry than to insulation properties (Figs. 3 and 4). It is obvious that multiple factors can influence the typology of geomorphic processes that develop on craters walls, e.g., environmental constraints, morphometry of crater walls, colluvial deposits granulometry, etc. Differentiation of the processes based on crater morphometry suggests that the last two factors are more important than orientation. As such, we suggest that bimodal orientation of debris flows on crater walls is related to the morphometric threshold in alcove area and crater wall slope that are larger than the minimum value at these orientations.

Channels resembling gullies or dry flows develop, due to changes in these controlling factors, that either permitted channel development on mantled slopes, or non-availability of water to initiate flow, in the case of dry flows. This can also be related to the succession of wet and dry environmental conditions that enabled or restricted the amount of liquid water on upper deposits. Soare et al. (2007) proposed that intermittent periods of runoff are possible in western Utopia Planitia and argued that regressive erosion of alases is an indicator of atmospheric conditions that favored pluvial conditions, which preceded the actual dry and cold atmospheric conditions of the present day. This is consistent with the results of the present study. Because the distribution of processes around the crater walls is controlled by different factors, and the processes span from the wet member structures to dry ones, we conclude that as the climatic conditions changed and the availability of water reduced, the processes evolved from gullying in the initial most developed phase, to debris flows and finally to dry flows, a final component that can be related to the present-day atmospheric Martian conditions.

At the opposite end of processes that act on Martian crater walls are the dry granular flows that generate dry channels morphologies. Fluvial channeling is absent; instead, the movement of material along wide straight channels involves probably rapid movement of unconsolidated deposits along transportational paths. As a subtype of these processes there are the talus materials that emerge under the stratified crater walls, which present a fan-shaped deposit down the slopes, which represents a common case on the Martian craters (Lanza, 2010).

More extended studies are necessary to clarify the diversity and association of processes on craters walls because it seems that the degree of crater evolution (mantled crater walls versus abrupt ones) and availability of water in source area differ from one crater to another. Moreover, the processes show different stages of evolution within different craters where more evolved channelization occurs on colluvial slopes and brief debris flows on steeper slopes.

4. Conclusions

This study provides an initial step in refining the morphological and morphometrical description of “gully” classification on Mars, using examples from northwestern Utopia region and based on widely used nomenclature from terrestrial studies. The approach used in this paper was to describe, using planetary image description techniques, the morphological differences among the processes that affect the crater walls. Finer description of morphometrical characteristics permitted us to differentiate among four processes that affect the crater walls. Their orientation and morphometric characteristics can be differentiated based on a morphometric basis. Based on morphological characteristics we performed a statistical analysis on the distribution of the processes among the five craters, and orientation of the processes. This showed that orientation is not necessarly the predominant factor that poses conditions for gullying, debris flows or dry granulat flow development. Finally, a relationship between the crater morphometric characteristics and morphometrical characteristics of the processes was illustrated, which suggests that processes are controlled by initial deposition of materials on crater walls and availability of water within contributing area, and not on orientation. It is noted that geographically the distinction is important and the regional trend accepted in literature that gullies evolve mainly with respect to specific orientation (insulation) conditions and related presumtive sources of water (Heldmann et al. 2007) is not entirely applicable at a local scale of study. More extended studies are necessary in the area of study to confirm or infirm that this trend is a regional one or applies only on a very local setting.

The observed morphologic and morphometric evidence of multiple phases of erosion in diverse environments suggests that the source of liquid was differently distributed within the same crater and that the external (environmental) conditions alternated from the wet phase to the dry one in multiple stages in recent times. The observed signs of glacial erosion (Fig. 3, other ladforms on crater walls) and polygonal terrain in the area (Heldmann et al. 2007, Soare et al., 2007; Soare et al. 2007; Levy et al., 2009a) suggest that water reservoirs were present in the area and that the upper deposits may be saturated. Therefore, prior to the current conditions, there was likely a wetter, possible multiphase period when surface and underground aquifers were created by extensive pluvial and nivial conditions, as observed in gullies and rill morphologies. The local scale study presented in this analysis also has the advantage of better constraining the succession of the processes that acted locally, and possible regionally, from glacial-periglacial, to pluvial/ nivial ones and finally to dry and cold conditions that prevail now at this location on Mars. We did not exclude that some of the processes can act during recent or actual times (McEwen et al., 2011), but they would represent in our opinion final stages of a more extensive phases of landform formation in different atmospheric conditions (Schon and Head, 2011).

The local scale analysis of the landforms affecting the crater walls provide also a better understanding of the mechanisms that affected more broadly the sequence of crater modification (at a regional scale of the five craters and possibly within the entire Utopia Planitia area). Water was most probably capable of runoff during an initial stage and then became localized at perched aquifers above debris and head-cut locations thereafter. Finally, mass movements dominated in a dry environment where dry flows developed and mantling processes covered most pre-existent erosional structures in the area of study (Figs. 1 and 2), which is consistent with one or multiple phases of gully and debris erosion during recent obliquity changes (Costard et al. 2002; Madelaine et al., 1997).

References

Allen, J.R.L. (1970), *Physical processes of sedimentation*, London, George Allen and Unwin.,, p.174.

Baratoux, D., N. Mangold, C. et all, (2002), *Evidence of liquid water in recent debris avalanche on Mars*, Geophys. Res. Lett., 29 (7), 60-1, p. 60-4.

Bull, L.J. and Kirkby, M.J. (1997), *Gully processes and modeling*, Progress in Physical Geography, 21 (3), p. 354– 374.

Balme, M. et all., (2006), *Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express* (HRSC/MEX) *and Mars OrbiterCamera/Mars* Global Surveyor (MOC/MGS) data. J. Geophys. Res. **111**, doi:10.1029/2005JE002607. E05001.

Baker, V. R. et al (1992), *Channels and valley networks.*, in Kieffer, H. H., Jakosky B. M., Snyder, C. W., Matthews, M. S. (Eds.), Mars, Univ. of Ariz. Press, Tucson, p.493-522.

Carr, M. H. (1996), *Water on Mars*. Oxford Univ. Press, New York., p.248.

Christensen, P.R., (2003), *Formation of recent martian gullies through melting of extensive water-rich snow deposits*. Nature, 422, p.45-48.

Cooke, R.U., Warren, A., Goudie, A.S., (1993), *Desert Geomorphology*, UCL Press, London, p.526.

Costard, F. M., et all., (2002), *Formation of recent martian debris flows by melting of near-surface ground ice at high obliquity*. Science, 295, p.110–113.

Dickson, J.L., Head, J.W., Kreslavsky, M. (2007). *Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography*. Icarus, 188, p. 315–323.

Dickson, J. L., and Head, J. W. (2009), *The formation and evolution of youthful gullies on Mars: Gullies as the late-stage phase of Mars' most recent ice age*, Icarus, 204, p. 63-86.

Dundas, C.M. et all., (2010), *New and recent gully activity on Mars as seen by HiRISE*: Geophysical Research Letters, 37, p. L07202, doi: 10.1029/2009GL041351.

Hartmann, W. K., Neukum, G. (2001), *Chronology and Evolution of Mars*. Space Sc. Rev. **96,** 1-4, DOI 10.1023/A:1011953424736, 165-194.

Head, J.W., Marchant, D.R. and Kreslavsky, M., (2008),. *Formation of gullies on Mars: Link to recent climate history and insolation microenvironments implicate surface water flow origin*, Proc. Natl. Acad. Sci., 105, p.13258–13263.

Hecht, M.H., (2002), *Metastability of liquid water on Mars*, Icarus, 156, p.373–386.

Heldmann, E.C. et all., (2007), *Observations of martian gullies and constraints on potential formation mechanisms: II. The northern hemisphere*, Icarus, 188, (2), p.324-344.

Heldmann, J. L. and Mellon, M.T. (2004), *Observations of martian gullies and constraints on potential formation mechanisms*, Icarus, 168, (2), p.258-304.

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

Howard, A. D, (1986),.*Groundwater sapping on* Mars and Earth.Proc.,and Field Guide, NASA Groundwater Sapping Conf., A. D. Howard,R. C. Kochel, and H. E. Holt, Eds., National Aeronautics and Space Administration, Flagstaff, Ariz., pp. vi–xiv.

Kochel, R. C., Howard, A. D., and McLane, C. F., (1985), *Channel networks developed by groundwater sapping in fine-grained sediments: Analogs to some Martian valleys,* Models in geomorphology, M. J. Woldenberg, ed., Allen and Unwin, Boston, p.313–341.

Kneissl, T. et all., (2010), *Distribution and orientation of northern-hemisphere gullies on Mars from evaluation of HRSC and MOC-NA data*, Earth Planet. Sci. Lett.

Ishii, T. and Sasaki, S, (2004), *Formation of recent Martian gullies by avalanches of CO_2,*. Lunar and Planet. Sci Conf. 35, Abstract 1556.

Iverson, R.M. (1997), *The physics of debris flows*, Reviews in Geophysics, 35, p.245–296.

Lanza, N.L. et all., (2010),. *Evidence for debris flow gully formation initiated by shallow subsurface water on Mars*, Icarus, 205, p.103–112.

Levy, J.S., Head, J.W., Marchant, D.R., (2009), *Thermal contraction crack polygons on Mars: classification, distribution, and climate implications from HiRISE observations,* J. Geophys. Res. 114, E 01007.

Levy, J.S. et all., (2010), *Identification of gully debris flow deposits in Protonilus Mensae, Mars: Characterization of a water-bearing, energetic gully-forming process*, Earth Planet. Sci. Lett.

Kolb, K.J., McEwen, A.S., Pelletier, J.D., (2010),.*Investigating gully flow emplacement 825 mechanisms using apex slopes*, Icarus 208, p.132-142.

Madeleine, J. et all. (2007),. *Exploring the northern mid-latitude glaciation with a general circulation model.* In: Seventh International Conference on Mars. Abstract 3096.

Malin, M.C. and Edgett, K.S., (2000), *Evidence for recent groundwater seepage and surface runoff on Mars*. Science, 288, p.2330-2334.

Mc.Ewen, A.S. et all. (2011), *Seasonal flows on warm Martian slopes*, Science, 333, p.740-743.

Mellon, M. T., and R. J. Phillips, (2001), *Recent gullies on Mars and the source of liquid water*, J. Geophys. Res. , 106, 23, 165-23,179.

Montgomery, D.R. and Dietrich, W.E, (1989), *Source areas, drainage density, and channel initiation.,* Water Resources Research, 25, 8, p.1907-1918.

Montgomery, D.R. and Dietrich, W.E, (1994), *Landscape dissection and drainage area–*
*slope threshold*s. In: Kirkby, M.J. (Ed.), Process Models and Theoretical Geomorphology. John Wiley & Sons, Chichester, UK., p.221-246.

Musselwhite, D. S., Swindle T. D. and Lunine J. I., (2001), *Liquid CO_2 breakout and the formation of recent small gullies on Mars*. In Lunar and Planetary Science XX, Lunar and Planetary Institute, Houston, Texas, abstract No. 1030.

Nunes, D. C. et all., (2010), *Examination of gully sites on Mars with the shallow radar*, J. Geophys. Res., p. 115.

Poesen, J., Vandaele, K., and van Wesemael, B., (1998)., *Gully erosion, importance and model implications*. In: Boardman, J., Favis-Mortlock, D.T (Eds.), Modelling Soil Erosion, NATO-ASI Series, I-55. Water Springer-Verlag, Berlin, pp. 285–311.

Schon, S.C., Head, J.W., (2011), *Keys to gully formation processes on Mars*: *Relation to climate 983 cycles and sources of meltwater*. Icarus 213, p.428-432.

Shinbrot, T. et all. (2004), *Dry granular flows can generate surface features resembling those seen in Martian gullies*, Proceedings of The National Academy of Sciences, 101(23), p.8542-8546.

Soare, R.J. et all., (2007), *Thermokarst processes and the origin of crater-rim gullies in Utopia and western Elysium Planitia*. Icarus, 191, p.95-112.

Stock J. D. and Dietrich, W.E., (2006), *Erosion of steepland valleys by debris flows*, GSA Bulletin, 118, (9-10), p.1125-1148.

Sullivan, R. et all., (2001), *Mass movement slope streaks imaged by the Mars Orbiter Camera*, J. Geophys. Res., 106(E10), 10.1029/2000JE001296, 23607-23634.

Tanaka, K. L. et all., (2003), *Resurfacing history of the northern plains of Mars based on geologic mapping of Mars Global Surveyor data*, J. Geophys. Res., 108, E4, 8043

Treiman, A. H., (2003), *Geologic settings of Martian gullies:* Implications for their origins, J. Geophys. Res., 108(E4), 8031,doi:10.1029/2002JE001900.

Williams, K.E., Toon O.B., Heldmann J.L. and Mellon, M.T., (2009), *Ancient melting of mid-latitude snowpacks on Mars as a water source for gullies*, Icarus, 200, p.218–425.

Valentin, C., Poesen, J. and Yong L., (2005), *Gully erosion: Impacts, factors and control,* Catena, 63, 31, p.132-153.

Vandaele, K., Poesen, J., Govers, G., Van Wesemael, B., (1996), *Geomorphic threshold conditions for ephemeral gully incision. Geomorphology*, 16: p.161-173.

Received September 11, 2011
Accepted November 24, 2011