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Quantitative analysis of the morphology of martian gullies and insights into their formation

Z. Yue [a], W. Hu [b], B. Liu [a], Y. Liu [a], X. Sun [a], Q. Zhao [a], K. Di [a,*]

[a] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth Chinese Academy of Sciences, Beijing 100101, China
[b] IoT Perception Mine Research Center, China University of Mining and Technology, Xuzhou 221008, China

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ABSTRACT

The process of formation of observed geologically recent gully features on Mars has remained a topic of intense debate since their discovery. In this study, we performed quantitative morphological analysis on certain parameters of gullies from different settings, such as crater walls, terraces, and sand dunes, on the martian surface in addition to the Meteor and Xiuyan craters on the Earth. The morphometric parameters were measured for cross profiles, which were extracted along each gully at certain intervals. Some interesting relationships among the parameters were determined, which could provide us a comprehensive understanding of the morphologies of the gullies'. The results show that strong correlations exist among those parameters, and the gullies are morphometrically similar, except for a scale difference in different geologic settings. The morphometric similarity implies that they were probably formed by some common processes. On the other hand, the morphometric differences indicate that the processes may have played different roles in the formation of the gullies. The formation of gullies on the Earth crater walls was heavily affected by surface flow and slippage, and pre-existing fractures and faults were also very influential in their formation. We propose that gullies in martian crater walls and terraces should have a similar formation mechanism, and they can probably account for most of gullies appearing on crater walls. The morphometric differences between the gullies in sand dunes and other gully types are probably a result of the disparity in lithological settings, which have significant influence on erosion ability even for the same agents.

1. Introduction

Gullies are a type of young phenomenon on the martian surface, and were first found by the Mars Orbiter Camera (MOC) on board the Mars Global Surveyor (MGS) in 2000 (Malin and Edgett, 2000). In the earlier study, most of the gullies were found exposed on crater walls or terraces (Fig. 1A and B), and they can be observed in all types of substrate (layered, massive, shattered, and rubble) (Treiman, 2003). Generally, they are composed of an alcove, a channel, and an apron, although not as distinctly in some areas as in others. The alcove is a theater-shaped wide region originating within the upper one-third of the slope encompassing the gully (Heldmann and Mellon, 2004). In some cases, the alcove may be filled by finer grains with a smoother texture relative to the surrounding material (Arfstrom, 2002), or may be very indistinct. If present, the alcove tapers downward to form the channel, which is often the primary part of many gullies. Channels appear incised into the slope surface, having steep walls with a distinctive V-shaped cross section (Malin and Edgett, 2000). Most of the channels are sinuous probably in response to topographic variations or the instability of certain type of flow (Mangold et al., 2010), and they often become narrower and shallower downslope. In addition, they often appear in polygonally patterned ground where the alcove and channel exist (Levy et al., 2009). Gullies can terminate with depositional aprons of variable sizes, which typically have a triangular shape and broaden downslope. The apron structure is sometimes incised by the channel (Fig. 1), and they can be composed of distinct lobe contacts, indicating that gullies are formed in several stages (e.g., Schon et al., 2009). The latitudinal distribution of such gullies shows the greatest concentration in the mid-latitudes in each hemisphere. In the southern hemisphere, the number of gully systems steadily declines poleward from 30°S with the minimum value occurring between 60°S and 63°S, and then rises again poleward from 63°S (Heldmann and Mellon, 2004). Most gullies in the 30–45°S latitude band occur on slopes below the angle of reposes, and the slopes are generally between

* Corresponding author. Present address: No. 20 Datun Road, Chaoyang District, Beijing 100101, China.
E-mail address: kcdi@irsa.ac.cn (K. Di).

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20° and 30° (Dickson et al., 2007). Heldmann and Mellon (2004) also showed that gully channel length generally decreases as the latitude increases (i.e., toward the South Pole). Gullies can occur on all orientations of slopes, and the poleward preference of gullies at any latitude should not be overemphasized (Heldmann and Mellon, 2004; Balme et al., 2006). In the northern hemisphere, the number of gully systems increases between 30°N and 45°N and then tends to taper off at higher latitudes (Heldmann et al., 2007), or most of the gullies are concentrated in the 30–55°N band (Bridges and Lackner, 2006; Kneissl et al., 2010). In addition, the most impressive feature is that gullies within the 30–35°N band exhibit a transitional morphology between dry and fluid-like features (Bridges and Lackner, 2006). Although gullies can occur in a wide range of latitudes, they are usually concentrated in several preferred locations such as Acidalia Planitia (45°N, 330°E), Utopia Planitia (40°N, 110°E), Dao Vallis (35°S, 30°E), the south polar pits (72°S, ~0°E), and the chaotic terrain north of Terra Sirenum (35°S, 190°E) (Heldmann and Mellon, 2004; Kneissl et al., 2010). The regionally clustered distribution of gullies may show that latitude alone cannot be considered responsible for their global distribution, and additional factors (e.g., elevation, slope, lithology, local climate/weather regime, and/or any combination of these) that vary regionally, may play important roles in determining the origin of gullies (Bleamaster and Crown, 2005).

The other type of unusual gullies on martian surface was reported in late time, mostly appeared on sand dunes, and has relatively longer incised channels (Costard et al., 2002; Mangold et al., 2003; Reiss and Jaumann, 2003). Those dune gullies, also called linear gullies (Dundas et al., 2012), have an unusual form that mostly consist of a long sinuous channel or trough, usually with terminal pits, but with minimal alcoves and depositional aprons (Fig. 1C). (Note that gullies similar to those in crater walls with obvious aprons and alcoves can also appear in sand dunes, and linear gullies also exist in crater walls, if there is sufficient accumulation of soft soil.) Some channels are connected with branching track, as in terrestrial channel networks, over hillslopes; however, few channels are connected together in the lower part. Most of the channels are accompanied by symmetric levees, which are especially visible in the terminal parts of the linear gullies (Mangold et al., 2003). All the linear gullies are located only in several dune fields inside large craters, the latitudinal distribution of which, from 45°S to 55°S, is also consistent with that of gullies in crater walls (Mangold et al., 2003; Reiss and Jaumann, 2003).

Gullies are very young in geologic time because of their fresh-looking appearance and the superposition of only a few impact craters (Malin and Edgett, 2000). Reiss et al. (2004) derived an absolute age of at most 3 Ma; however, they might be younger than 300,000 years from crater counts on overlaid dunes. Schon et al. (2009) studied a single well-developed gully system with secondary craters on one part of its depositional lobes in eastern Promethei Terra (~35°S, 131°E), and dated the gully as ca. 1.25 Ma by tracing back to the primary crater. Linear gullies on sand dunes are probably even younger because of the preservation of fresh-appearing erosion tracks and the absence of craters superposed on the dune surfaces on which they are situated, and estimated age upper limits are in the range of 100–10,000 years with an uncertainty factor of two (Reiss and Jaumann, 2003). However, the two categories of gullies are still active today, which has been verified by repeated observations from High Resolution Imaging Science Experiment (HiRISE) images (Diniega et al., 2010; Reiss et al., 2010). Dundas et al. (2012) summarized the activities of the gullies at 12 sites, focusing on the southern hemisphere, and found that the activities related to linear gullies mostly involved the appearance of meter-scale blocks in the channels and dark flows around the upper alcoves and channels. Gully activities of gullies on crater walls are much more remarkable, including meter-scale channel widening, movement of meter-scale boulders, and deposition of decameter-scale mounds of material (Diniega et al., 2011; Dundas et al., 2012). However, it is significant that most of the activities that are directly related to the gullies themselves occurred in sand dunes or soft soils, and the gullies may be linear or non-linear.

Numerous mechanisms have been proposed for martian gully formation, and earlier hypotheses were mainly inferred from the morphology and martian climatic conditions. These hypotheses can be divided into three broad categories (Schon et al., 2009): entirely dry mechanisms, underground wet mechanisms, and surficial wet mechanisms. The first category mainly refers to dry mass wasting of fine-grained materials (Treiman, 2003), and the numerical flow modeling results by Pelletier et al. (2008) also favor dry granular flows, although the presence of liquid water in these flow events cannot be ruled out. The underground wet mechanisms involve hypotheses on the release of groundwater (Malin and Edgett, 2000; Mellon and Phillips, 2001) and liquid CO_2 (Musselwhite et al., 2001), which could be liquefied at some depth under the overburden pressure. Finally, the surficial wet

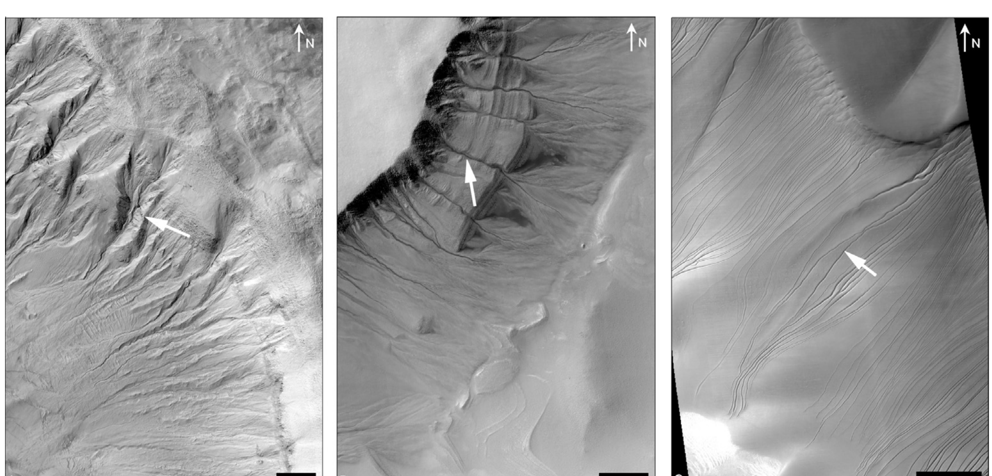

Fig. 1. Examples of martian gullies, indicated by the white arrows pointing respectively to a crater wall (A, HiRISE RED channel, subset of PSP_005943_1380), a terrace (B, HiRISE RED channel, subset of ESP_013585_1115), and sand dunes (C, HiRISE RED channel, subset of PSP_007018_1255).