地学雑誌 Journal of Geography (Chigaku Zasshi) 125(1) 155–161 2016 doi:10.5026/jgeography.125.155

Gullies on Mars: A Review

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[Received 4 August, 2015; Accepted 5 November, 2015]

Abstract

Gullies were not only investigated for scientific endeavor, but also were prime targets for the search for presence of water and life on Mars, as habitats might have or are existing. Gullies on Mars were first identified in the milestone paper by Malin and Edgett in 2000. Since then more than 174 papers were published on Martian gullies. A typical gully consists of an upper theatre-shaped alcove that tapers downslope to converge on a channel that extends further downslope to terminate in a triangular apron of deposited material. A number of processes were proposed for gully formation. These include liquid-induced processes, such as overland flow, headward sapping, debris flow, and other wet mass movements. The formation of liquid is attributed to groundwater sapping, to supply from deep subsurface aquifers by cryovolcanic processes, to melting of snow or melting of ground ice from surficial to shallow depths. Liquid-free mass movements, such as dry granular flows and dry ice outbreak, are also invoked as formation processes. Supporting and opposing morphologic evidence is shortly discussed. Tens of thousands of individual gullies were identified on Mars, which are concentrated on mid- to high-latitudes in both hemispheres. Gullies might have been active from 3 Ma ago to present. Future research may learn lessons from terrestrial gully research. On Earth, linear gullies may gradually develop oversteepened sidewalls, which in turn initiate deep-seated mass movements. Such systems are named gully complexes. Gullying can also be induced by sliding. Such landforms were termed slide complexes. These process sequences may occur also on Mars. In future investigations, identification of such complexes on Mars requires a focus on phases of incision and infilling to elucidate gully evolution.

Key words: gully, gully erosion, gully distribution, gully age, Mars

I. Introduction

Since the first recognition of the fluvial history of Mars in the 1970s, scientists developed hypothesis on the existence of gullies on Mars (Pieri, 1976; Craddock and Maxwell, 1993). Gullies were not only investigated for scientific endeavor, but also were prime targets for the search for presence of water and life on Mars (Gilmore and Phillips, 2002), because liquid water was assumed necessary in their formation. Though habitats could have existed on Mars from 4.1 Ga to the present-day, they are or were uninhabited (Cockell *et al*., 2012).

While valleys on Mars with widths from < 1 km to 10 km and lengths from < 5 km to about 100 km were detected in the early 1980s (Baker *et al*., 1993), more recent studies have extensively identified smaller scale gully channels typically 5–40 m wide and 100–500 m long (Heldmann *et al*., 2014) reaching a maximum length of 15.4 km (Aston *et al*., 2011). A typical gully on Mars is shown in Fig. 1. These hillslope landforms of much smaller size than valleys were first identified in Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) images in 1999 with 2 to 8 meter/pixel resolution (Malin and Edgett, 2000).

The milestone paper of Malin and Edgett (2000) preceded 174 articles on gullies on Mars,

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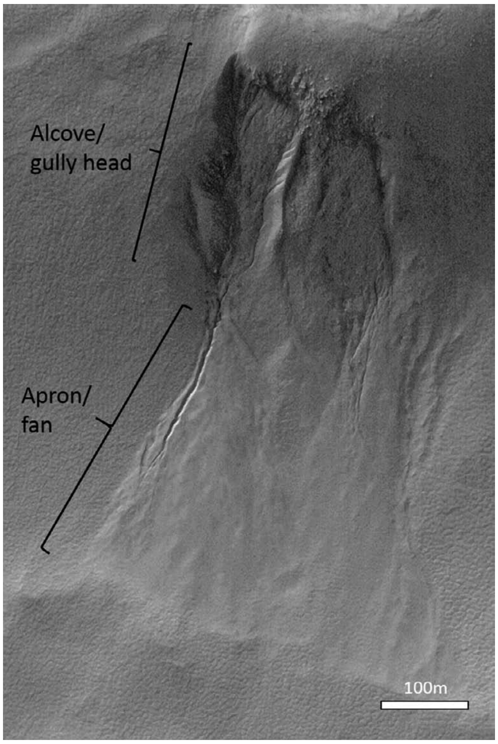

Fig. 1 A typical Martian gully with an alcove and apron. The term alcove and apron are used for gullies on Mars, while gully head and fan are used for gullies on Earth. Image credit: NASA/JPL/Malin Space Science Systems.

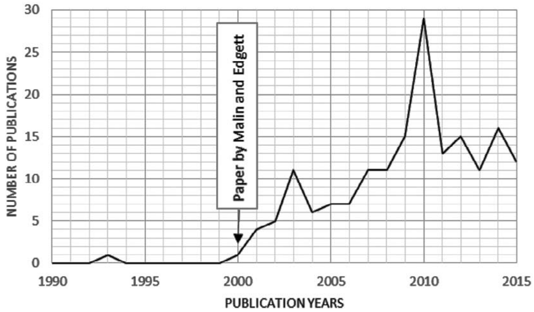

Fig. 2 Number of published papers on gullies on Mars.

as identified by a literature search on the topics "gully" and "Mars" in July 2015 using the search engine Web of Science. Their article was cited 616 times by July 2015. After their publication a rapid increase in paper output reached 29 published papers in 2010 which included 3 articles in a special issue on Mars of the journal *Icarus*. Since then an average of 13.4 papers per years is published until July 2015 (Fig. 2). The aim of this review paper is to concisely summarize what Martian gullies are, to describe the processes shaping these landforms, to review their ages and locations, and to point to lessons from terrestrial gully research for future Martian gully research.

II. What is a gully on Mars ?

Surface features on Mars, which visually resemble terrestrial gullies, are also named gullies. They typically consist of an upper theatre-shaped alcove which tapers downslope to converge on a channel that extends further downslope to terminate in a triangular apron of deposited material (Malin and Edgett, 2000). For terrestrial gullies, the alcove is called gully head, and the apron is termed gully fan (Fig. 1).

Aston *et al*. (2011) propose a gully classification based on incised material type: mantle material only and mantle material as well as bedrock. Immature mantle gullies exhibit no separate alcove, while matured gullies develop a V-shaped alcove. Immature gullies, which cut into mantle and bedrock, do not reach the slope line, whereas mature gullies in this category reach the slope line and cut backwards. Longitudinal profiles of gullies on Mars resemble those of terrestrial gullies formed by either water erosion or debris flow, with slightly more affinity to water erosion. Gullies on Mars can only be weakly separated from gullies on Earth. Water incised gullies on Mars are separated from terrestrial fluvial gullies by curvature parameters and from terrestrial debris flow gullies by slope parameters (Conway *et al*., 2015).

The term gully for Martian gullies refers to a morphologic feature and does not involve a specific genetic process (Lanza *et al*., 2010). On Earth, there is a genetic relationship between form and process. This does not apply to the current usage of the term gully on Mars, as a number of processes are invoked to produce the landform. Carr (2012), for example, describes Martian gullies as seemingly water-worn, whereas Bargery *et al*. (2011) emphasize that Martian gullies are masswasting landforms which have a fluvial-like form. These processes are discussed in the next section.

III. Which processes shape gullies on Mars ?

Since the discovery of gullies on Mars, a variety of processes has been proposed to explain diverse form observations. These processes can be divided into two categories:

1) Liquid-induced processes

Malin and Edgett (2000) explained the formation of gullies on Mars by a combination of water-induced processes, including overland flow, headward sapping, debris flow, and other mass movements. Morphologic evidences are that a) alcoves are often associated with distinct layers within a cliff interpreted as the sapping zone where undermining and collapse occur, b) channels display characteristics of fluid flow, including sinuous paths, branched or anastomotic reaches, levees, streamlining, super-elevated banking, and incision, and c) aprons show patterns in morphology that mimic those seen on terrestrial alluvial fans, including a filigree of distally diverging medial to marginal lineations and channels, lobate margins, and distal thinning.

Other studies suggest different sources of liquid water, because observations of gullies originating from isolated peaks and dune crests question sapping as a fluid supplying process (Costard *et al*., 2002). Gaidos (2001) proposes liquid supply from deep subsurface aquifers by cryovolcanic processes. The formation of liquid water causing gully erosion was also attributed to melting of ground ice at shallow depths by normal geothermal heating (Mellon and Phillips, 2001), melting of snow or surficial ice during periods of higher obliquity (e.g., Christensen, 2003; Head *et al*., 2008; Williams *et al*., 2008; de Haas *et al*., 2015), or melting of near-surface ground ice at high obliquity (Costard *et al*., 2002).

2) Liquid-free processes

Liquid-free mass movements, such as dry granular flows, were often proposed as erosion processes, because surface temperatures seldom approach the melting point of water at mid latitudes (e.g., Treiman, 2003; Shinbrot *et al*., 2004). Shinbrot *et al*. (2004) show that reduced gravity has the effect of prolonging fluidization of particle flows by decreasing particle settling speeds as compared with debris flow speeds. Some, although perhaps not all, morphological features of liquid-erosional flows can be produced by dry granular materials when individual particle settling is slower than characteristic debris flow speeds (Shinbrot *et al*., 2004). Treiman (2003) proposes that gullies are produced by dry flows of eolian material. This is supported by the observation that the deposit is in general fine granular material with grain sizes ranging from dust to sand. Identifiable boulders are uncommon in the debris deposit, which questions liquid-induced processes that are capable to transport large grain sizes.

Gully erosion could also occur as the rapid release of the liquid CO_2 with entrainment of rock and clathrate-hydrate ice produces a density flow analogous to a terrestrial nue ardente (Musselwhite *et al*., 2001; Cedillo-Flores *et al*., 2011).

It has been difficult to differentiate between hypotheses for liquid-free and liquid-induced processes and to test their validity using past observations (e.g., Pelletier *et al*., 2008). Morphologic evidences such as braided channels, terraces and erosional channels occurring on slopes of less than 20° (McEwen *et al*., 2007) are consistent with liquid-induced processes. Numerical simulations by Mangold *et al*. (2010) indicate that sinuous gullies are better reproduced by liquid-water-bearing debris flows with yield strength of 100–2200 Pa, velocities of 1.1–3.3 m s^{-1}, and viscosities from 40 to 1040 Pa s for 3600 analyzed gully channels. But still, the lack of identifiable boulders poses major questions on liquid-induced interpretations.

To reduce inconsistencies Harrison *et al*. (2015) do not consider alcove-apron systems lacking incised channels as gullies but classify those as mass movements, because the terrestrial definition of a gully requires incised channel morphology. This refined definition implies differences in formation processes and distribution of gullies.

IV. Where do gullies typically occur ?

The distribution of gullies on Mars has been mapped on images of MOC narrow-angle with

18 m pixel resolution with < 1% coverage of the planet or Mars Express High Resolution Stereo Camera (HRSC) with a lower resolution of 12.5–50 m pixel (Malin and Edgett, 2000; Costard *et al*., 2002; Heldmann and Mellon, 2004; Balme *et al*., 2006; Dickson *et al*., 2007; Heldmann *et al*., 2007; Kneissl *et al*., 2010). However, Kneissl *et al*. (2010) state that 42% of the gullies imaged with MOC narrow-angle could not be detected by HRSC in their study due to small size of gullies at this pixel resolution, poor atmospheric conditions or unfavourable illumination angles at the time of image acquisition. The most recent, unprecedented documentation by Harrison *et al*. (2015), using more than 54,000 images from the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) covering 85% of the Martian surface at a resolution of 6 m/pixel, resolve the problems mentioned above. Tens of thousands of individual gullies were identified, which are confined to the Martian mid- to high-latitudes (30–80 degrees) in both hemispheres. Dickson *et al*. (2007) found that gullies occur at elevations between −5000 m to +3000 m, whereas Harrison *et al*. (2015) specify the altitude range from −7500 m to +5700 m, with a strong preference from −500 m to +2500 m. Gullies are hosted on a variety of landforms with all ages and origins (Malin and Edgett, 2000; Treiman, 2003; Dundas *et al*., 2012): volcanic plains and constructs, craters terrain, chaotic terrain, polygonal patterned ground, and sedimentary deposits such as dunes. Their predominant orientation with increasing latitude, from poleward-facing to equator-facing preference, next to their locations indicate that climate, insolation, and thermal properties of the substrate play the key factors in gully formation on Mars (Harrison *et al*., 2015).

V. Are gullies old landforms?

Gullies have been active in the last 3–1.25 Ma (Reiss *et al*., 2004; Schon *et al*., 2009). Gullies are not catastrophic landforms that formed in single events (Schon *et al*., 2009). They may have developed in multiple phases of erosion (Aston *et al*., 2011). Other studies emphasize very young ages of gullies produced by water incision on decadal scale (Malin *et al*., 2006). Also seasonal present-day activity was evidenced by new deposits at the terminus of the gully channel and on the gully apron (Dundas *et al*., 2012; Raack *et al*., 2015) (Fig. 3).

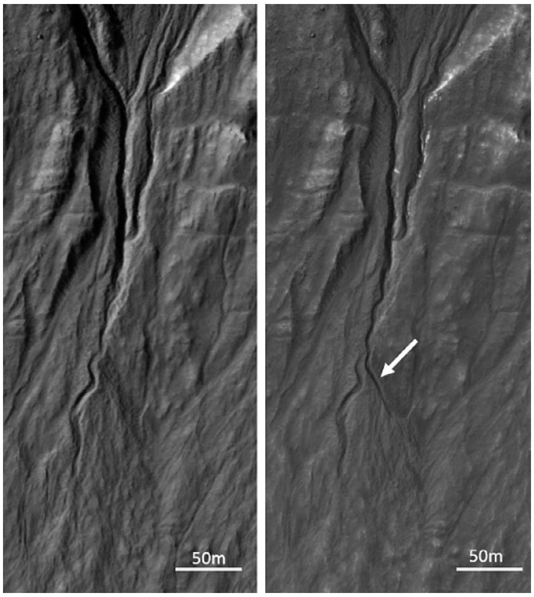

Fig. 3 Development of a new channel on Mars between 5 November 2010 and 25 May 2013 in Terra Sirenum, Mars. The new channel is indicated by an arrow (Dundas, 2014). Image Credit: NASA/JPL/University of Arizona.

VI. Lessons from terrestrial gully research?

Initiation of gullies is attributed to melting of snow or near-surface ground with multiple types of mass movement acting in gullies on Mars today. Gullies on Earth develop by the action of a number of processes after channel formation, ranging from water erosion to wet debris flows to dry rockfalls (Harrison *et al*., 2015). In erosion prone regions on Earth, such as the East Coast on the North Island of New Zealand, next to debris flows also deep seated landslides in gullies have been evidenced (Betts *et al*., 2003). In this region the term "gully complex" has been developed for systems where incipient, linear gullies gradually develop oversteepened sidewalls, which in turn initiate deep-seated mass movements. The larger amphitheater-like gully complexes make up virtually their entire catchment and contribute a major part of sediment production compared to gully erosion (DeRose *et al*., 1998; Parkner *et al*., 2006). A similar process sequence was described for Martian gullies by Aston *et al*. (2011), as immature mantle gullies exhibit no separate alcove, while matured gullies develop a V-shaped alcove characterized by mass movements (Malin and Edgett, 2000). These matured gullies could also be named gully complexes as their terrestrial analogies. Gullying can also be induced by sliding. Such landforms were termed slide complexes (Parkner *et al*., 2007). Such process sequences may also occur on Mars. To identify those sequences detailed investigations on phases of incision and infilling on different time scales are necessary. On Earth, such incision and infilling has been shown for time scales over few years (Fuller and Marden, 2011) to historical time scales (Vanwalleghem *et al*., 2006). Future research may learn such lessons from terrestrial gully erosion research to elucidate gully evolution on Mars.

Acknowledgments

This publication was partly supported by the Grants-in-Aid for Scientific Research (25560143) from the Japan Society for the Promotion of Science. The author would like to thank the two reviewers for their valuable hints and questions.

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火星のガリー ―研究の動向―

トーマス・パークナー*

火星のガリーは科学研究の対象であるだけでなく，水や生命の存在を探査するための対象でもある。火星のガリーは Malin and Egett（2000）による記念碑的な論文で最初に認定され，以来 174 編以上の論文が出版されてきた。典型的なガリーは劇場形の源頭部に端を発し，下方に向かって狭まった流路となり，三角形の堆積地形で終わる。ガリー形成には多くのプロセスが提唱されている。液体による侵食プロセスとして，地表流，谷頭侵食，土石流や他の湿潤性斜面移動などがある。液体の起源としては，地下水の滲出，地下深部の帯水層，融雪，表層ないし深層の地下氷の融解などが指摘されている。液体を必要としない成因として，乾燥粒子流やドライアイス崩壊説もある。それらの説を支持する，または反証となる形態的証拠について論評を加えた。火星では数万個のガリーが認定されているが，それらは両半球の中・高緯度に集中する。ガリーは 3 Ma 以降も活動した可能性がある。今後の研究では地球上での研究が参考になるだろう。地球では，線状のガリーは次第に過傾斜の側壁をもつようになり，その後，深層崩壊を引き起こすこともある。これはガリー複合体と呼ばれる。ガリー形成は地すべりによっても起こり，この場合は地すべり複合体と称される。このような一連のプロセスは火星でも起こりうる。将来の探査では，ガリーの発達過程を解明するために，侵食相と堆積相に焦点をあてて，これらの複合体の認定することが望まれる。

キーワード：ガリー，ガリー侵食，ガリー分布，ガリーの年代，火星

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