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Testing the water hypothesis: Quantitative morphological analysis of terrestrial and martian mid-latitude gullies

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ABSTRACT

Although Martian gullies resemble terrestrial counterparts, two conflicting hypotheses exist for their formation still invoke fluvial processes on the one hand or lubricated CO_2 flows on the other. In this work we compared the quantitative morphology of terrestrial gullies, known to have formed by liquid water, and mid-latitude Martian gullies in the Martian southern hemisphere. We also compared these results with measurements of Martian dry ravines adjacent to the gullies. Our results show a similarity between Martian and terrestrial gully formation, supporting the hypothesis that liquid water was involved in their erosion. Our results show dry ravines differ morphologically from gullies, further suggesting fluidised flows as a likely origin of the latter. Variations in the relationships across various terrestrial and Martian gullies indicate the significance of local environmental and geological conditions. Our work supports the idea that Martian gullies may not have been formed by just one single process but may have evolved through a more complex interaction of processes and environment.

1. Introduction

The discovery on Mars of small scale, youthful erosive features resembling terrestrial hillslope gullies suggested the possibility that liquid water existed on the red planet in recent times (Malin and Edgett, 2000; Golombeck et al., 2006; Parkner, 2016). This discovery led to a growing body of work in efforts to determine how, and by what process, gullies on Mars are formed and erode (e.g., Baker et al., 2015). Martian gullies superficially resemble terrestrial features in that they possess V-shaped channels, often with an associated alcove, and V-shaped delta deposits (Malin and Edgett, 2000; Dickson and Head, 2009). Terrestrial hillside gullies possessing these features have been formed by concentrated surface runoff or snowmelt from topographic catchments (Selby, 1991); water seepage from a subsurface aquifer (Soms, 2006; Grasby et al., 2014); or debris flow processes (Selby and Hodder, 2000; Hartmann et al., 2003; Reiss et al., 2009a, 2009b).

Early theories of Martian gully formation suggested origins through groundwater processes (Malin and Edgett, 2000). The inability to identify perched aquifers via subsurface radar analysis (Nunes et al., 2010) and subsequent discovery of gullies in locations inconsistent with subsurface flow and recharge mechanisms, such as on isolated topography, indicated differing explanations (Costard et al., 2002; Schon and Head, 2011, 2012). Research, inspired by studies of the Antarctic Dry valleys and identification of likely water-ice deposits in some gullies has suggested snowmelt (Mellon and Phillips, 2001; Christensen, 2003; Head et al., 2008; Dickson and Head, 2009; Levy, 2014) with pole-facing gullies being influenced by solar heating of accumulated water ice (Mellon and Phillips, 2001). Other research identified many gullies existing within latitude dependent mantle (LDM), where ice mixed with sediment is likely to be found (Kreslavsky and Head, 2002; Dickson and Head, 2009; Araki, 2012; Schon and Head, 2012; Conway and Balme, 2014). Melting of ice could provide the source of liquid water for gully channel erosion (Dickson and Head, 2009; Reiss et al., 2009a, 2009b; Conway et al., 2011a, 2011b; Schon and Head, 2011, 2012).

Because of the difficulty of obtaining sufficient liquid water for gully erosion in the hyperarid Amazonian conditions of Mars, dry mass wasting processes have been suggested, either consisting of landslides of fine-grained material (Treiman, 2003) or frosted granular flows acting in a similar manner to snow avalanches (Hugenholtz, 2008). Nonfluvial proponents have also suggested CO_2-based processes for gully erosion (Hoffman, 2000) based partly on observations of gully alteration during temperature ranges incompatible with melting of water ice (Dundas et al., 2010, 2012, 2015; Raack et al., 2015; Nunez et al., 2016). A possible terrestrial analogue and subsequent morphology for this process was postulated to be pyroclastic flows (Hoffman, 2000). Numerical modelling by Pilorget and Forget (2016) has suggested that atmospheric CO_2 is capable of freezing into gully alcoves during the Martian winter. Later CO_2 sublimation in the Martian spring has been

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hypothesized to form gas-lubricated, fluidized debris flows capable of eroding gully channels over time. This hypothesis is supported by the ability of frozen CO_2 ice to condense, sublimate, and pressurize at latitudes and slope orientations where gullies are observed (Pilorget and Forget, 2016).

Given the difficulty in obtaining liquid water on Mars cited by CO_2 proponents, flume experiments have been conducted in simulated Martian conditions to directly test whether Amazonian Martian fluvial erosion is viable (Conway et al., 2011b; Masse et al., 2016). Part of this research was inspired by the discovery of recurring slope lineae (RSL), thought to be evidence of real-time fluvial activity (e.g., McEwen et al., 2011). Laboratory testing of water behaviour under Martian conditions revealed that the metastability of water was able to cause slope destabilisation and, in some cases, produce a higher degree of erosion and runout when compared to similar amounts of water under terrestrial conditions (Conway et al., 2011b; Masse et al., 2016). Conway et al. (2011b) found that water produced a thin film of ice below the liquid-sediment contact that increased runout distances. Additionally, Masse et al. (2016) postulated that water seeping into erodible material would boil, loosening particle grains that would then flow downhill and cause erosion.

Additional research has identified erosion activity and types that are not consistent with a CO_2-based hypothesis for gully erosion such as sinuous channels, small scale lobes, and transportation of boulders downslope (Stock and Dietrich, 2006; Mangold et al., 2010; Dickson et al., 2015; Vincendon, 2015; Harrison et al., 2016b; Johnsson et al., 2017). Recent work has also indicated complex drainage systems on some gullies (Corrigan et al., 2017; Gulick et al., 2017) and multiple generations of gullies whose activity is consistent with melting of ice within pasted-on material (Harrison et al., 2017). This previous research has suggested that it is unlikely that CO_2 processes could produce such morphology in gullies.

1.1. Previous morphometric research

Unlike terrestrial features, the study of Martian gullies is curtailed to remote sensing methods. No direct field observations are possible, and the period of observations have been limited to the time high-resolution cameras have been in Mars orbit compared with the extended timescales at which most gully processes operate (Barlow, 2008). Limited observations may lead to a heightened risk of equifinality, the concept that differing processes may produce similar morphology, and may lead to incorrect assumptions on the origin and formation of features under study (Schumm, 1988). Although a detailed understanding of the environment surrounding the feature under study, such as its climate and geology, would assist in inferring the history and morphology of gullies, this knowledge is limited, and researchers have had to rely on geomorphic indicators of fluidized or dry flow (e.g., Mangold et al., 2010). Table 1 summarizes morphological characteristics of fluidized flow vs. dry mass wasting found on small-scale features on Earth and inferred for Mars (Lucchitta, 1978; Patton, 1981; Heldmann et al., 2007; Conway et al., 2009; Levy et al., 2010; Mangold et al., 2010; Bourke, 2013; Harrison et al., 2015).

In the absence of direct observations of flowing liquid water, the presence and identification of these characteristics on Martian gullies would greatly assist in inferring the type of erosion (wet or dry) that has acted on the gullies. For example, gullies possessing concave up longitudinal profiles, sinuous channels, and triangular-shaped depositional fans may have been eroded by liquid water, contrasting with linear talus-like dry flows such as those observed on the Moon (Kumar et al., 2013).

Some researchers have suggested limitations in Martian gully morphometric analysis, given the inability for such analysis to distinguish between fluidized or debris flow processes, or possible removal of diagnostic features in depositional aprons (Reiss et al., 2009a; De Haas et al., 2013). Recent work, however, has focused on conducting quantitative analysis on gully morphometrics and comparing them with analogous features on Earth. This was conducted in order to identify trends in morphology and to infer whether Martian gullies erode in a similar way to terrestrial features. Yue et al. (2014) performed statistical analysis of gullies in different geological context such as within crater walls, terraces, sand dunes, and on Earth. These authors were able to identify similar morphological characteristics in gullies in different geological settings, finding that these characteristics were quite similar between Mars and Earth and that gullies were probably formed by the same process (Yue et al., 2014). Comparative analysis of longitudinal profiles of 78 Martian gullies with 24 fluvial and 22 debris flow terrestrial gullies by Conway et al. (2015) identified a clear morphological marker between terrestrial debris flow and fluvial erosive processes. Their work used the exponential curve-equilibrium state that has been found as a common feature of mature fluvial systems (Hack, 1957) compared with a reduction in profile concavity and steepening of the profile that are caused by debris flow systems (Brardioni and Hassan, 2006; Stock and Dietrich, 2006; Mao et al., 2009). The longitudinal profiles of debris flow gullies studied by Conway et al. (2015) were found to be consistently steeper and less concave than fluvial gullies, while the Martian longitudinal profiles showed a slightly greater affinity for fluvial processes (Conway et al., 2015). Thus, gully processes were able to be inferred from geomorphology. Later work by Conway and Balme (2016) used statistical and hydrological analysis in order to identify similarities and differences between gullies on Earth, Mars, and the Moon. This analysis was able to discriminate between dry slopes on Earth and the Moon and those formed by debris flow or fluvial erosion.

In this current work we expand our previous gully research (e.g., Hobbs et al., 2013, 2016) and conduct geomorphological analysis of 68 mid-latitude southern hemisphere Martian gullies. We compare our findings with similar analysis conducted on 51 terrestrial gullies where liquid water is known to be a dominant erosive process to determine how closely Martian gullies conform to terrestrial geomorphic features of fluvial origin.

Many craters hosting mid-latitude gullies also feature alcoves and mass wasted material though lack the incised, V-shaped channel observed in pole-facing gullies (Dickson and Head, 2009; Schon and Head, 2012; Harrison et al., 2016b). These features have also been observed in latitudes closer to the equator where gullies are not observed (Treiman, 2003; Shinbrot et al., 2004). Previous research has used comparative analysis between these features and terrestrial dry debris flows to infer nonfluidized erosion in these areas (Hartmann et al., 2003; Schon and Head, 2012; Diniega et al., 2013). Johnsson et al. (2014) compared talus cones in Puna Vacas, Argentina, with similar features on Mars and found that the equator-facing talus flows exhibited morphology that was consistent with dry granular flow. Further analysis of the morphology of *dry ravines*, the terminology used in Hobbs et al. (2013) to describe such features, will allow additional characterization into the differences between them and pole-facing

Table 1
Comparison of wet vs. dry flow morphology characteristics.

Parameter	Wet flow	Dry flow
Sinuosity	Generation of sinuous channels	Little sinuosity, straight flows or following local topography
Longitudinal profile	Concave (influenced by water)	Linear—slightly concave
Depositional apron	Broadened, triangular shaped with noticeable relief	Narrow, linear streaks gradually tapering downslope. Little topographic relief