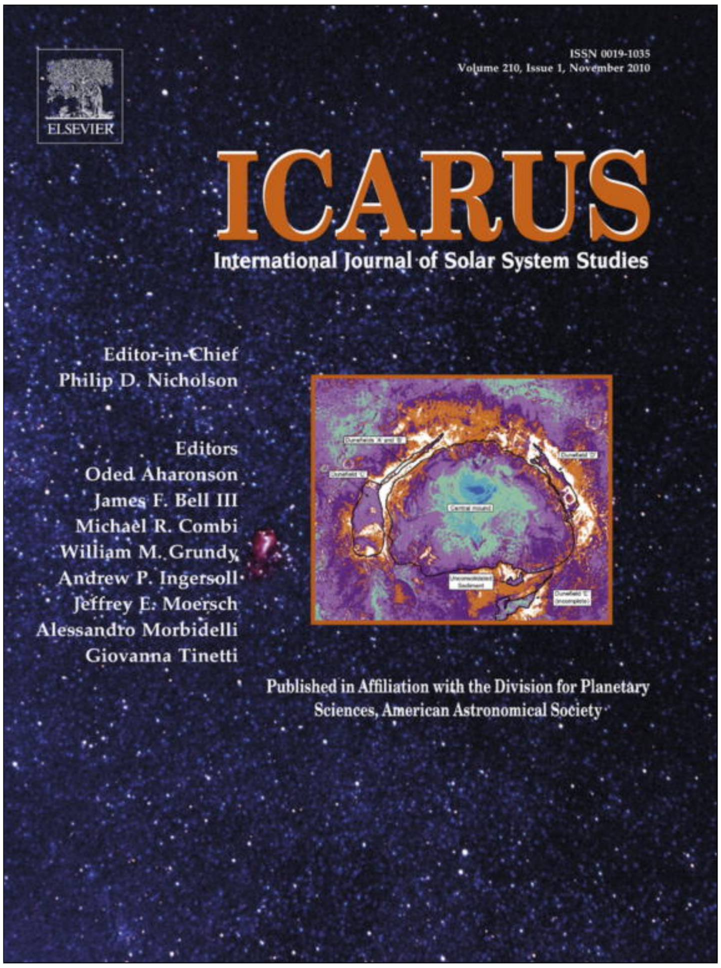

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Evaporation effects on the formation of martian gullies

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ABSTRACT

In order to investigate the formation of martian gullies and the stability of fluids on Mars, we examined about 120 gully images. Twelve HiRISE images contained a sufficient number of Transverse Aeolian Ridges (TARs) associated with the gullies to make the following measurements: overall gully length, length of the alcove, channel and apron, and we also measured the frequency of nearby TARs. Six of the 12 images examined showed a statistically significant negative correlation between overall gully length (alcove, channel and apron length) and TAR frequency. Previous experimental work from our group has shown that at temperatures below ~200 K, evaporation rate increases by about an order of magnitude as wind speed increases from 0 to ~15 m/s. Thus the negative correlations we observe between gully length and dune frequency can be explained by formation at temperatures below ~200 K where wind speed/evaporation is a factor governing gully length. In these cases evaporation of the fluid carving the gully was a constraint on their dimensions. Cases where there is no correlation between gully length and TAR frequency, can be explained by formation at temperatures >200 K. The temperatures are consistent with Global Circulation Model and Thermal Emission Spectrometer (TES) data for these latitudes. The temperatures suggested by these trends are consistent with the fluid responsible for gully formation being a strong brine, such as $Fe_2(SO_4)_3$ which has a eutectic temperature of ~200 K. We also find that formation timescales for gullies are 10^5–10^6 years.

1. Introduction

Gully features were first observed in the images taken by the Mars Global Surveyor (MGS) Mars Orbital Camera (MOC) in a diversity of landform and landscape settings (Malin and Edgett, 2000). The gullies are not distributed uniformly over the entire planet, but tend to occur at mid-latitudes (Heldmann and Mellon, 2004). Recently acquired imagery by the High Resolution Imaging Science Experiment (HiRISE) on Mars Reconnaissance Orbiter (MRO) supports the conclusion that the gullies were formed by fluvial erosion (McEwen et al., 2007), but the source and composition of this fluid is unclear. The gullies consist of three morphological elements, the alcove, the main and secondary channels, and the terminal depositional apron, although the alcove is not present in all cases (Malin and Edgett, 2000). The superposition of the gully aprons over aeolian features, i.e. TARs, suggests that the gullies are relatively young since TARs are dynamic and intrinsically unstable and clearly not associated with the ancient fluvial episodes widespread in the northern uplands. Gully features are usually interpreted in terms of erosion by surface runoff and their length is usually assumed to be largely governed by loss of water due to seepage into the regolith (Mellon and Phillips, 2001; Malin and Edgett, 2000; Carr, 2006).

There are limited measurements of martian surface winds. Average wind velocity data for the Viking sites range from 5 to 10 m s^{-1} (Hess et al., 1977), with the occasional gusts to 25–30 m s^{-1} during dust devil episodes and local dust storms (Ryan et al., 1981). The Pathfinder windsock experiment measured wind speeds of 6.94–9.68 m s^{-1} (Schofield et al., 1997; Sullivan et al., 2000).

A General Circulation Model (GCM) can be also used to infer surface wind speeds where direct measurements are not available (Zent et al., 1993; Rafkin et al., 2001). Information on wind speed and direction can also be obtained through observations of upper atmosphere clouds from orbiting spacecraft (Wang and Ingersoll, 2003) and the Hubble Space Telescope (Kaydash et al., 2006; Mischna et al., 1998). Such observations agree well with the GCM predictions (Murphy et al., 1990).

Gullies are often associated with aeolian forms including Transverse Aeolian Ridges (TARs) on Mars, with the gully aprons frequently overlaying the TARs (Malin and Edgett, 2000; Reiss et al., 2004; Costard et al., 2002). Aeolian Ridges and the many factors that determine their morphology have been formulated by Bagnold (1941) and their formation under martian conditions has been discussed by Greeley and Iversen (1985), and more recently by

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Edgett (2002), Byrne and Murray (2002), Greeley et al. (2002), Fenton (2005), Fenton et al. (2005) and Bourke et al. (2010).

The nature and origin of aeolian forms on Mars has received considerable attention in the literature with much of the recent work being summarized in Carr (2006) and Bourke et al. (2010). Dune and ripple forms are the result of interactions between granular materials (of varying size and abundance) and flow shear. The form reflects the characteristics of the sediment (primarily grain size), and the surface wind regime, especially directional variability. In the terrestrial context, vegetation may play an important role. As the form increases in height into the boundary layer the primary airflow is modified by local wind speed, shear stress, and turbulence, which creates secondary flow circulation especially in the lee of the dune forms (Pye and Tsoar, 1990; Lancaster, 1995; Livingstone and Warren, 1996; Smith and Goodrich, 2005). Transverse Aeolian Ridges occur in self-organized patterns that develop over time in response to the nature of sand surfaces and the wind regime. What results is a hierarchy of forms ranging in size from wind ripples to granular ripples to mega ripples and eventually into dunes, which are widespread on Mars (Carr, 2006; Balme et al., 2008; Zimbelman, 2010). For some part of the size range of these features, most notably the ripples and megaripples, the principle controls on the spacing of these forms are sand size and wind speed (Bagnold, 1941; Sharp, 1963; Seppälä and Linde, 1978; Lancaster, 1995, 2009; Bourke et al., 2010). While there is no universal agreement on the origin of TARs, there is general consensus that TARs are predominantly ripple forms. As such, our assumption that there is a direct relationship between TAR spacing and wind velocity is valid.

Preliminary work by Sears et al. (2005) suggested the possibility of a relationship between gully length and TAR frequency in one particular MOC image. (Sears et al., 2005, contains a mistake, it should say gully length decreases as TAR frequency increases as indicated in their Fig. 3). TAR frequency is the reciprocal of the TAR wavelength, the wavelength being the distance between successive TAR crests (Breed and Grow, 1979). On these initial observations, we hypothesize that TAR geometry, specifically TAR frequency, can be used as a meaningful indicator of periods of increased aridity and associated evaporation. As aridity (evaporation) increases overall gully length will decrease as available fluids for erosion and sediment transport progressively evaporate. Experiments by Chittenden et al. (2008) determined the linear increase in the evaporation rate of water (from about $\sim 0.7\ \mathrm{mm\ h^{-1}}$ to $\sim 1.0\ \mathrm{mm\ h^{-1}}$) as wind speed increases from zero to $\sim 12\ \mathrm{m\ s^{-1}}$ at $-15\ ^{\circ}\mathrm{C}$. The dependence of evaporation on wind speed is not strong, and temperature plays a more important role in determining evaporation rates. However, at lower temperatures the Chittenden et al. (2008) data show a relationship between evaporation rate and wind speed.

This study explores the possible relationship between the gully length and frequency of adjacent TARs using HiRISE images in which the two forms co-occur and thus the relationship between gully length and evaporation rate. If there is a gradient in wind speed across a TAR field, then one might expect a relationship between gully length and TAR frequency. Where such gradients fail to occur and ambient temperatures are in a range where wind speed does not affect evaporation rate, we propose that it is reasonable to expect that no relationship between gully length and TAR frequency will be found. The existence of such relationships has implications for the stability and distribution of fluids on Mars as well as evidence that evaporating fluids formed these gullies.

2. Methods

Twelve HiRISE images with 0.25 m and 0.5 m resolutions containing 11 craters with gullies and TARs from the martian mid-latitudes and varying longitudes were examined (Table 1). Images were chosen so as to ensure that gullies and TARs in close proximity were clearly identifiable and that the image contained at least five gullies suitable for morphometric measurements. The geographical distribution of the images is shown in Fig. 1 and images of the field studies are shown in Fig. 2. Since TARs are more prevalent in craters and since craters are more numerous in the southern hemisphere (Hayward et al., 2007), all but one of the images is located inside a crater and only four of the images are from the northern hemisphere.

Our data were obtained using ENVI image processing software. Processed images that have been radiometrically calibrated, stitched, and geometrically projected were used. The alcove, channel, apron, and overall gully lengths were measured for each of 72 gullies, and the frequency of TARs at the base of each gully were measured. An example of our measurement process is shown in Fig. 3. Each data point represents a gully and the TAR frequency, as determined by averaging data for the nearest four TARs. Linear regression analysis of gully parameters and TAR frequency was conducted to determine the strength and direction of the relationships, and Pearson product moment correlation coefficients were calculated.

3. Results

Plots of gully length against TAR frequency are shown in Fig. 4. Statistically significant negative correlations of overall gully length and TAR frequency were not found in six cases (Fig. 4a–f). These cases apply to the six study areas shown in Fig. 2a–f, respectively. On the other hand, in six cases (Fig. 4g–l), which are the areas shown in Fig. 2g–l, did show statistically significant correlations (Table 2). Significance levels are greater than 0.05 for four of the six cases and in excess of 0.15 level for the remaining two.

Table 2 also lists statistics for the individual components, alcove, channel and apron length vs. TAR frequency. There are very few significant correlations in these data. For the field areas in which overall gully length correlates with TAR wavelength, individual gully components for this group of gullies generally fail to show significant correlations. However, for apron length vs. TAR frequency significant correlations are observed for four cases Fig. 2g and j–l. A significant correlation is also observed for one channel segment length and TAR frequency, namely Fig. 2i.

For the field areas in which overall gully length does not correlate with TAR wavelength, there is a lack of significant correlations between gully components and TAR frequency. However, three exceptions to this are observed. Two apron length measurements significantly correlate with TAR frequency (Fig. 2b and d) and one channel length and TAR frequency are significantly correlated (Fig. 2d). Gully length reflects the entire distance when fluids are present; the alcove length, channel length and apron length reflect more complicated processes, like rock texture. Our experimental simulations show similar behavior (Coleman et al., 2008, 2009).

4. Discussion

Our discussion considers the factors that control TAR frequency and gully length, and the possible processes that might lead to correlations between them. We then discuss quantitative aspects of evaporation and wind speed, and any geographical controls on our observations. Finally, we consider the implications of these results for the temperature and composition of fluids responsible for the gullies, and finally the timescale for gully formation.

4.1. Factors that control gully length and TAR frequency

We are not so much interested in the factors that affect gully length and TAR frequency, but, rather, how these factors could

Table 1
HiRISE images analyzed and their location and acquisition time and date.

Figs. 2 and 3	Image	Location	Acquisition date	Local Mars time	Latitude	Longitude (East)
a	PSP_002330_1385	Crater	January 24, 2007	3:50 PM	41.1N	201.4
b	PSP_002114_2300	Crater	January 8, 2007	3:22 PM	49.5N	325.2
c	PSP_006794_2200	Crater	January 7, 2008	2:25 PM	39.7N	356.9
d	PSP_006922_2120	Crater	January 17, 2008	2:29 PM	31.9N	102.5
e	PSP_003662_1410	Crater	May 8, 2007	3:33 PM	38.9S	196.2
f	PSP_001908_1405	Crater	December 23, 2006	3:47 PM	39.3S	202.8
g	PSP_004176_1405	Crater	June 17, 2007	3:06 PM	39.4S	202.7
h	PSP_006866_1375	Crater	January 13, 2008	2:46 PM	42.2S	202.0
i	PSP_006888_1410	Crater	January 15, 2008	2:42 PM	38.5S	319.8
j	PSP_005648_1405	Crater	October 10, 2007	2:21 PM	39.2S	336.0
k	PSP_006922_2120	Crater	March 23, 2008	3:08 PM	37.6S	329.4
l	PSP_006791_1415	Valley	January 7, 2008	2:41 PM	38.1S	88.6

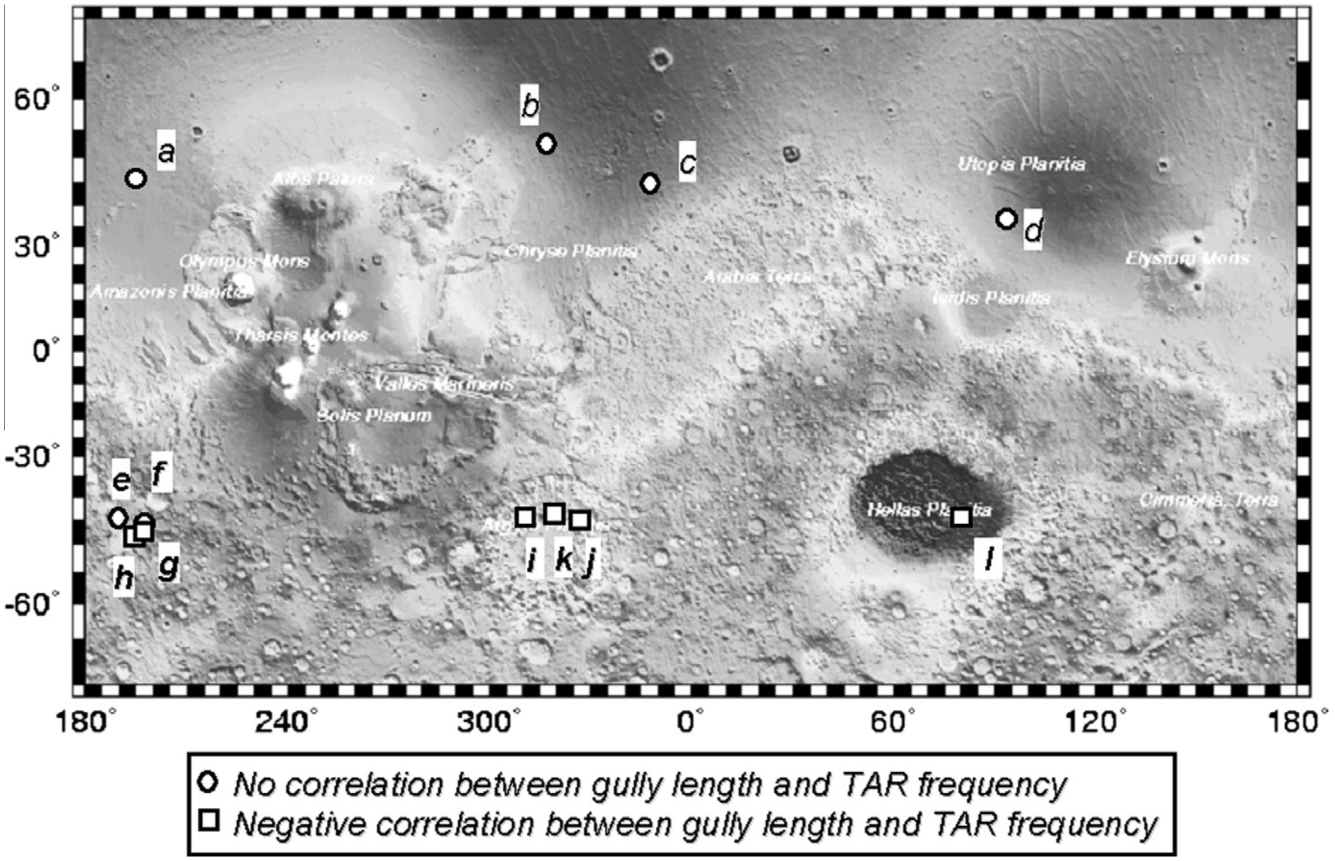

Fig. 1. Topographic shaded relief map of Mars derived from MOLA and other imagery with the locations of the study fields used for the present study; the lower case letters by each site referring to column in Table 1 and images in Figs. 2 and 3. The symbols identify the nature of the correlation between gully length and TAR frequency at each site. All the northern lowland sites and two of the southern highland sites display no correlation, whereas all of the sites displaying a negative correlation are in the southern highlands.

work to produce a negative correlation between gully length and TAR frequency.

We begin by recognizing the six factors that we believe fundamentally control gully length, and then discuss eight factors that fundamentally affect TAR frequency, and finally identify those that could explain correlations (Table 3). Factors that determine gully length are identified from a combination of existing literature on the origin of gullies and debris flow channels, our own flume experimentation, and considerations from first principles. (1) As fluid viscosity increases there is a negative response in gully length as the shear stress of the moving fluid is decreased as load capacity is reached (Knighton, 1998). (2) As fluid velocity increases and shear stress increases there is a positive response of gully length (Howard, 1999, 2009). (3) As discharge increases there is an increase in shear stress and as a result there is a positive response on the part of gully length (Knighton, 1998). (4) From first principles, it is reasonable to expect that as the friability of rock or regolith increases the greater will be the tendency to form gullies and the longer those gullies would appear. (5) Similarly, we can assume that as infiltration increases and discharge and velocity decrease there is a negative response in gully length as critical shear stress drops below threshold values for erosion and transportation (Knighton, 1998). (6) Finally, we assume that while evaporation of fluids in terrestrial gullies and debris flow channels is not a significant factor, in the Martian context, where liquids are close to their eutectic for short dura-

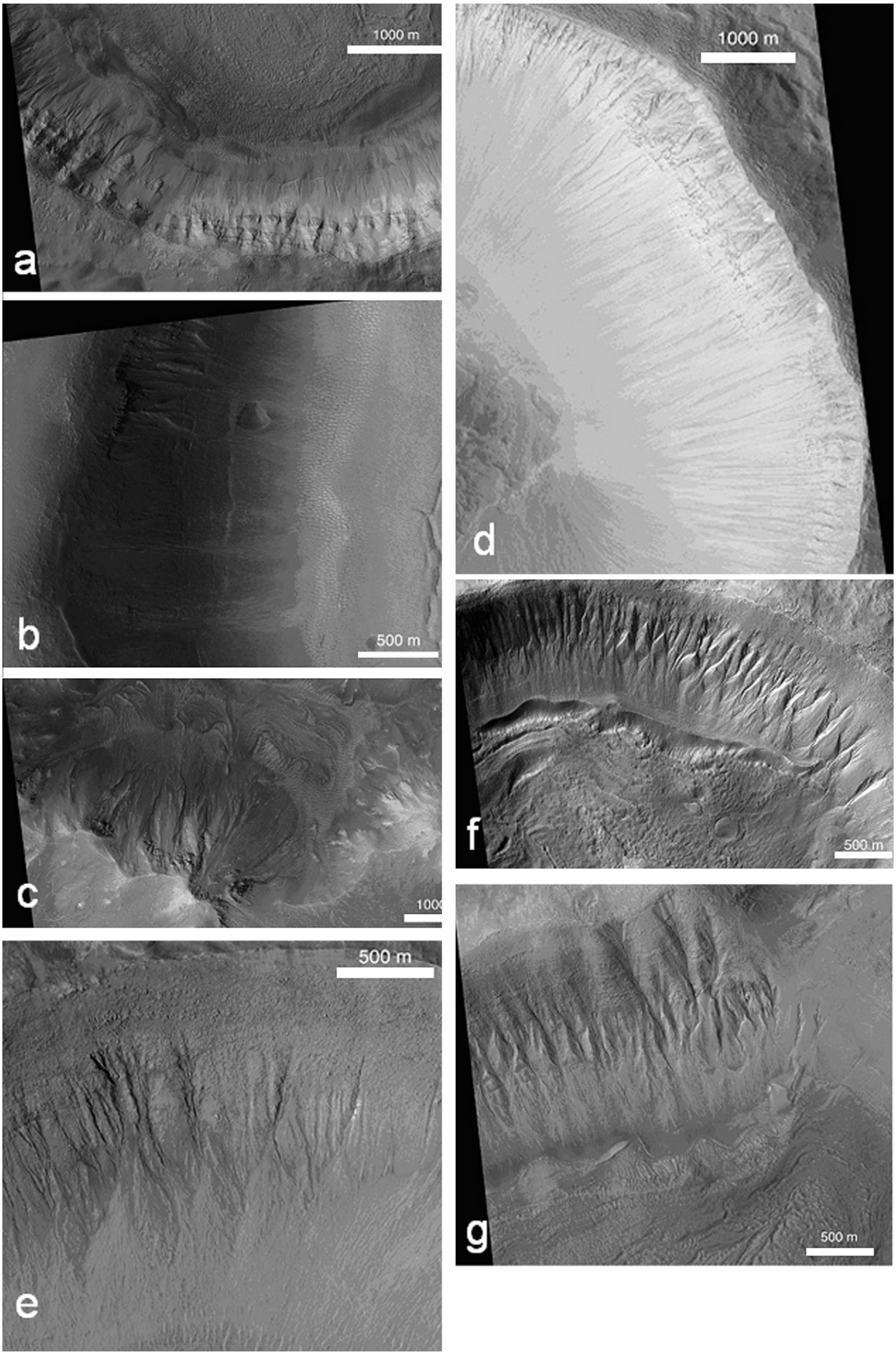

Fig. 2. HiRISE images of the study fields used in the present paper. Fields showing both gullies and TARs whose lengths and frequencies, respectively, could be measured were selected. The fields are within the following images (a) PSP_002330_1385, (b) PSP_002114_2300, (c) PSP_006794_2200, (d) PSP_006922_2120, (e) PSP_003662_1410, (f) PSP_001908_1405, (g) PSP_004176_1405, (h) PSP_006866_1375, (i) PSP_006888_1410, (j) PSP_005648_1405, (k) PSP_006922_2120, and (l) PSP_006791_1415. Locations are listed in Table 1.

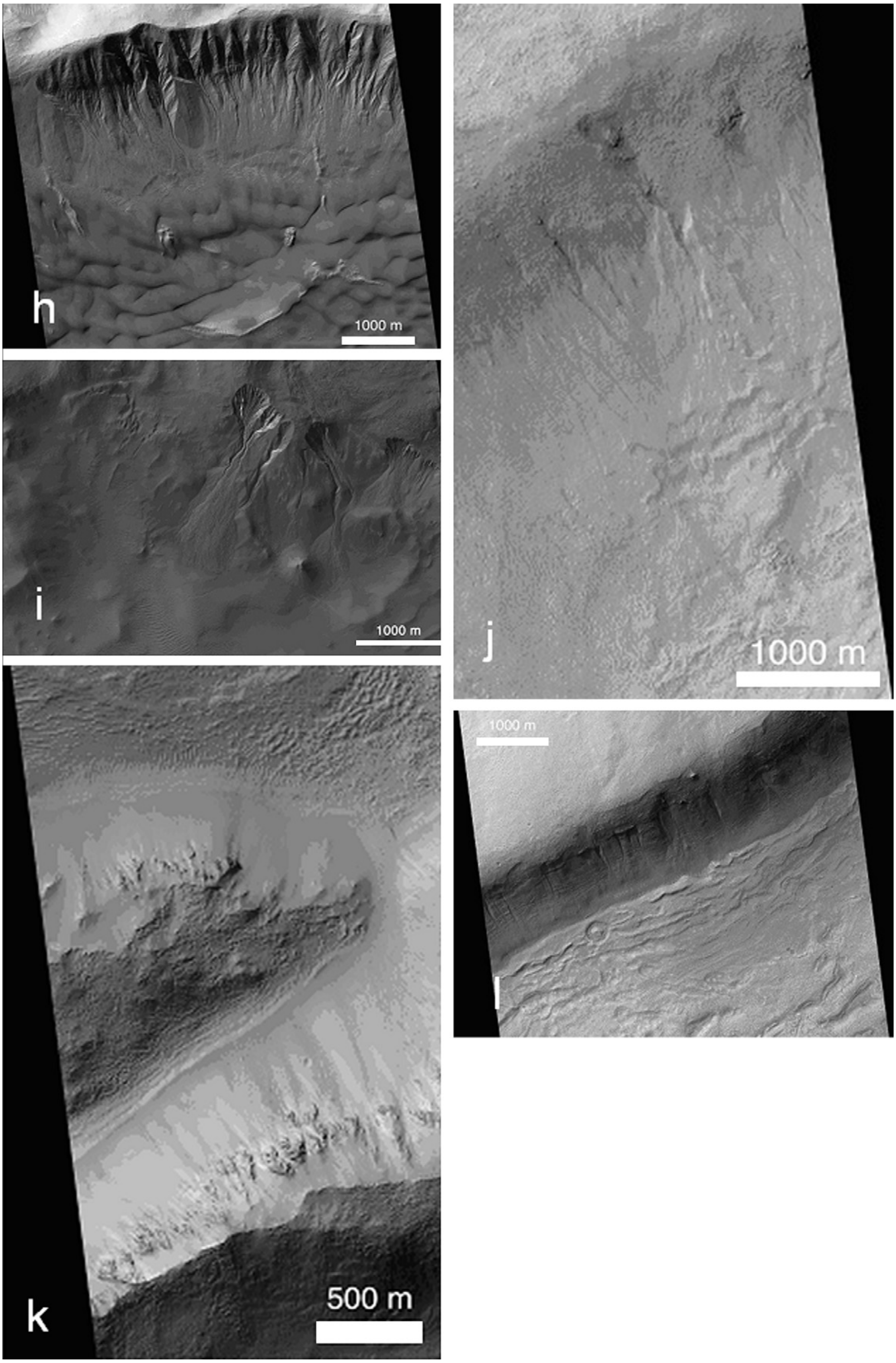

Fig. 2 (*continued*)

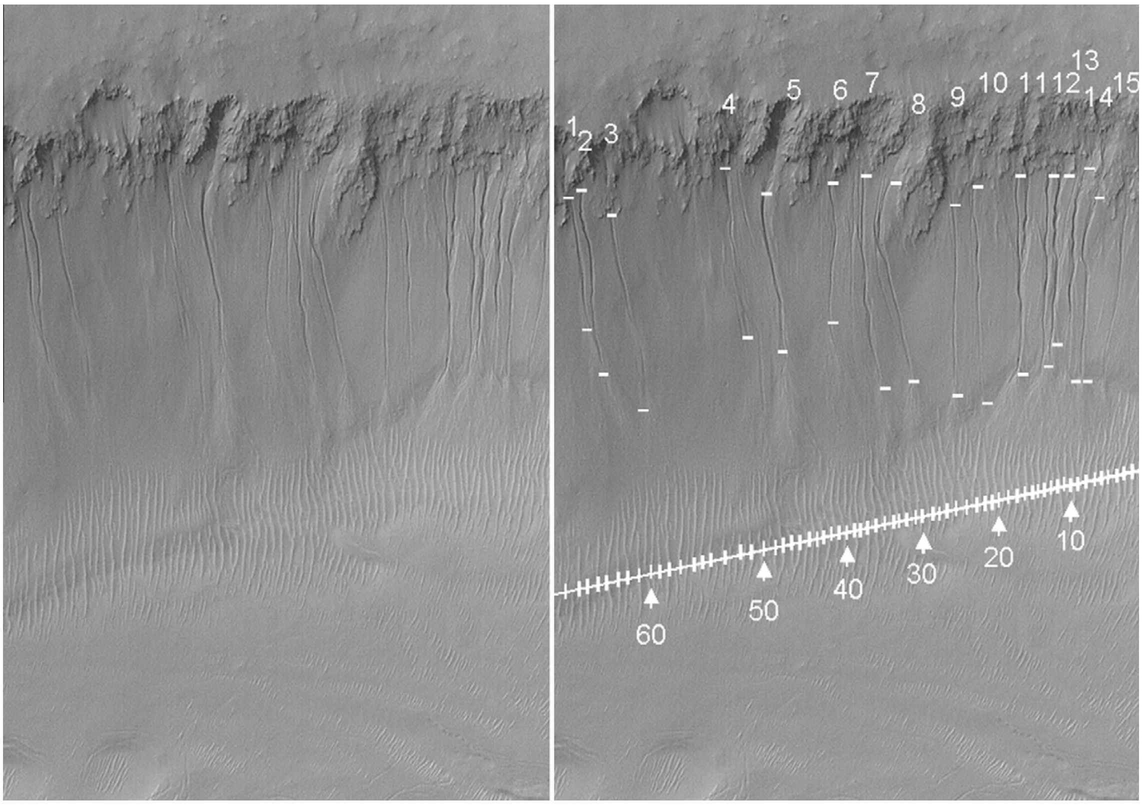

Fig. 3. Fourteen gully features in the south-facing walls of Nirgal Vallis (29.7°S, 38.6°W) on Mars in a region ~2.3 km wide by ~2.8 km long imaged by the Mars Global Surveyor indicating the method of measurement. The gullies have deposited a fine-grained apron of sediment onto TAR fields at the bottom of the valley.

tions, evaporation becomes a more significant factor (Chevrier and Altheide, 2008).

Factors potentially affecting TAR spacing are identified from the geomorphic and physics literature related to TAR formation (Bagnold, 1941; Sharp, 1963; Lancaster, 1995; Zimbelman, 2010; Balme et al., 2008; Bourke et al., 2010). We have identified eight factors (Table 3). (1) Sediment supply is one of the crucial factors in TAR formation, but TAR spacing however displays great variability (Lancaster, 1995). However, sediment supply is not expected to affect the TAR frequency in a systematic way. (2) Wind speed has been shown by Bagnold (1941) to display a positive relationship with ripple spacing and (3) we also assume that with increasing gustiness TAR spacing also increases. (4) Studies by Wilson (1972) found a strong relationship between dune spacing and grain size of the coarsest 20th percentile of dune crest sands, which subsequently became widely incorporated into the geomorphological literature. However, subsequent studies from a wide variety of locations suggests otherwise (Lancaster, 1988; Wasson and Hyde, 1986; Thomas, 1988). (5) Particle shape appears to have some bearing on sediment flux (Williams, 1964), but even here there are conflicting observations. Grain shape appears to have no relationship with the spacing of aeolian forms (Lancaster, 1995). While desert sands are normally dry, they are at times wet following rare rainfall precipitation events and they are at relatively shallow depths below the surface (Lancaster, 1995). (6) Moisture content affects sand transport rates by increasing the threshold velocity needed to move the sand, but as shear velocities increase the effect is diminished. Overall moisture content has little or no effect on spacing. (7) Atmospheric pressure and (8) temperature have no impact on TAR spacing. TARs are extensively developed from the tropics to the poles but are especially concentrated in the middle latitudes where sand is available to be moved. TARs across these areas of very different temperature and pressure have all ranges of TAR spacing and therefore this shows that temperature and pressure have no impact on spacing.

4.2. Relationship between gully length and TAR frequency, and their formational factors

Table 3 summarizes our views on how the correlations between gully length and TAR frequency are best explained. The columns identify the factors that affect gully length, fluid viscosity, flow velocity, total fluid discharge, rock friability, infiltration and evaporation. Under the column headings, in highlighted cells, is an indication of the nature of the relationship between these factors and gully length. For example, there is a negative relationship between gully length and fluid viscosity. The left column lists the factors that affect TAR frequency, and in the second column, highlighted, indicates the nature of the relationship between these factors and TAR frequency. For example, there is no relationship between sediment supply and TAR frequency while there is a positive relationship between wind speed and TAR frequency. The inner columns, columns three to eight, indicate whether a given combination of gully (horizontal) and TAR (vertical) factors would produce a correlation between the two factors.

Fluid viscosity is a function of fluid temperature, chemistry, and suspended sediment load and, as such, as sediment supply increases there is an increase in viscosity (Richards, 1982; Chevrier et al., 2009). However, sediment load bears no relationship to TAR frequency. There is a relationship between sediment size and viscosity with suspended load in the fluid being the dominant size influence. As suspended load increases viscosity increases (Richards, 1982). There is no relationship between sediment size and TAR frequency. No relationship exists between fluid viscosity and wind speed and gustiness or with sediment shape or moisture, atmospheric temperature of pressure.

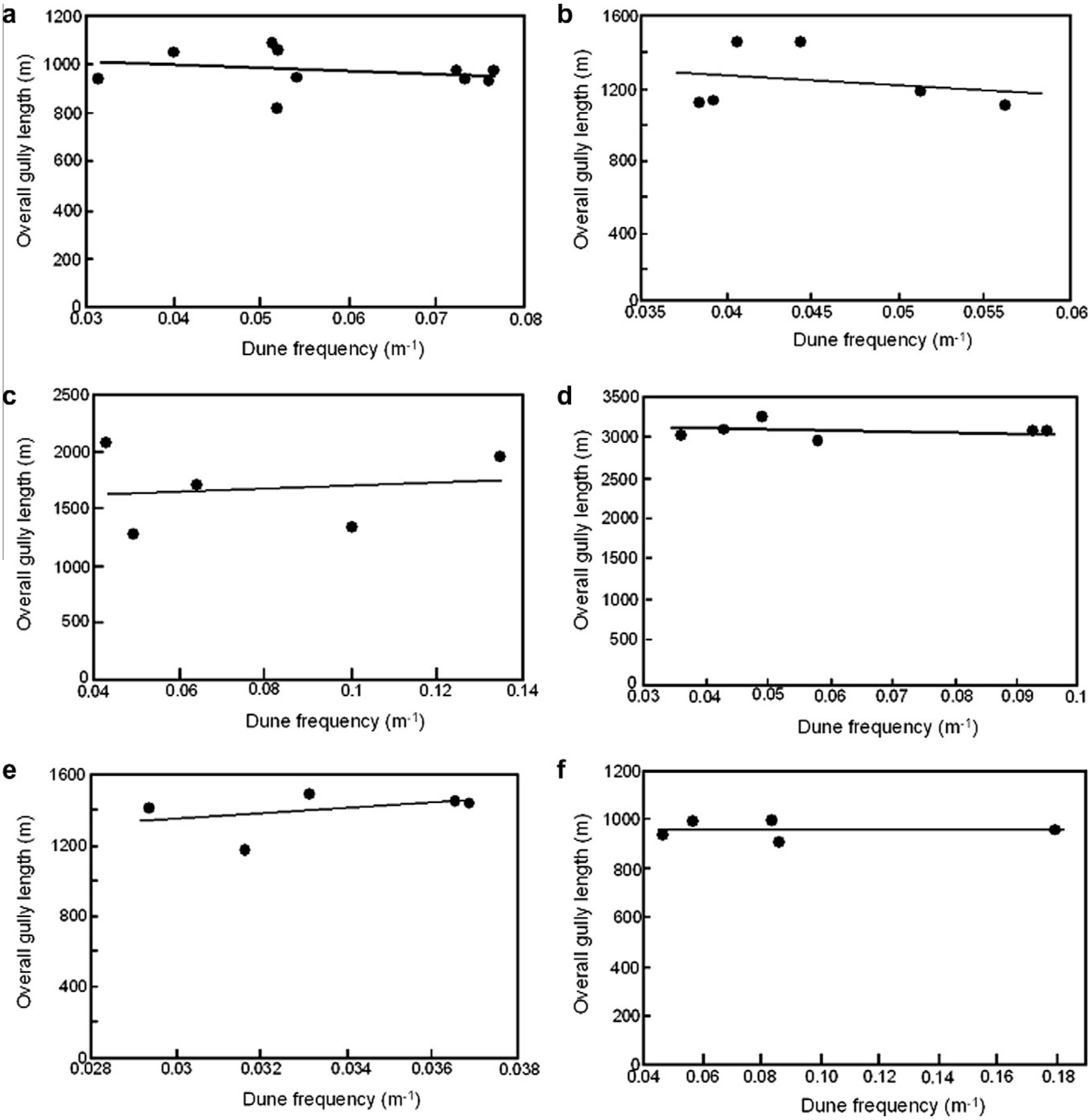

Fig. 4. Plots of overall gully length vs. TAR frequency for the 12 study areas in the present work (Fig. 2) with regression lines indicated. Each data point represents one gully. Of the 12 study areas, six (Fig. 4a–f) show no correlation consistent with evaporation not being a limiting factor in determining the length of the gullies at that location while six (Fig. 4g–l) show negative correlations consistent with evaporation playing a part in controlling gully length.

Fluid velocity is defined by the Chezy and Manning equations (Richards, 1982) and is fundamentally a relationship between hydraulic radius and slope. Therefore fluid velocity is unrelated to any of the TAR frequency factors.

Similarly fluid discharge is defined by the continuity equation and as such is a function of channel width, depth, and velocity. Again there is no relationship between discharge and any of the TAR frequency factors.

Rock friability is related to the nature of the substrate whether it is bedrock or regolith. It is fundamentally a material property factor related to ease of crumbling and as such is unrelated to any of the factors affecting TAR spacing or gully length. It does affect the ease with which erosion occurs but not the transport of sediment either by wind or a viscous fluid. Rock friability is unrelated to TAR frequency.

Infiltration is affected by sediment size and sediment shape (Beven and Germann, 1982) and also by sediment moisture, but is unaffected by atmospheric parameters such as wind speed and gustiness, atmospheric pressure and temperature. With the exception of wind speed and gustiness, none of the other parameters affect the TAR frequency.

Evaporation is related fundamentally to atmospheric temperature. As temperature increases, rates of evaporation also increase. In addition it is also related to wind speed and gustiness

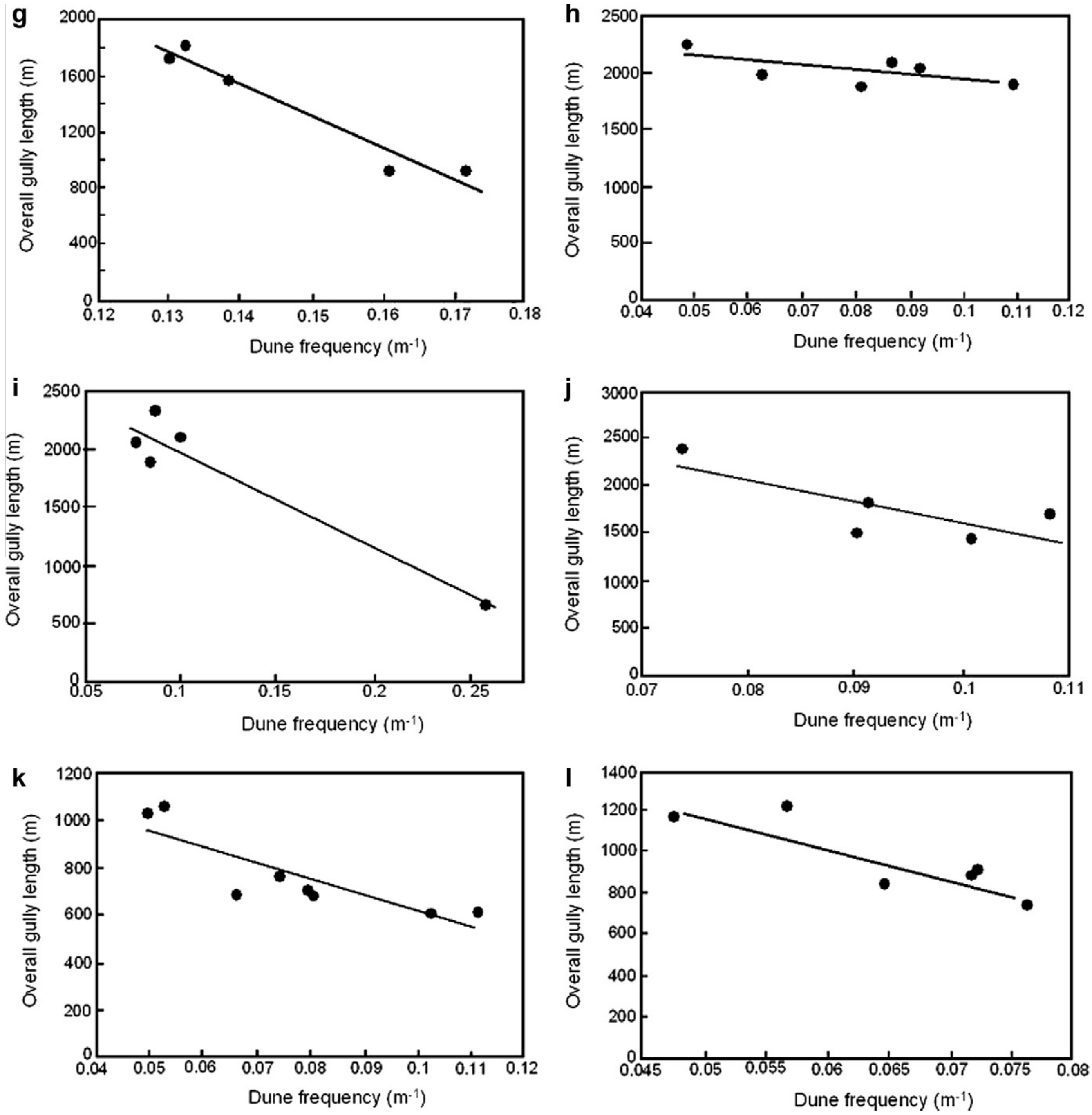

Fig. 4 (*continued*)

(Chattopadhyary and Hulme, 1997). As wind speed and gustiness increases so does the rate of evaporation. However evaporation is unrelated to other TAR frequency factors.

Thus for example, fluid viscosity and sediment supply fail to produce a correlation. On the other hand, evaporation and wind speed produce a correlation and this situation is indicated as a highlighted "YES" box in the table. Similarly, wind gustiness and evaporation would explain a correlation between gully length and TAR frequency. No other combination of gully and TAR-producing factors produce a straightforward explanation for the observed correlations between gully length and TAR frequency. We conclude that evaporation is constraining gully length and this is dependent on wind speed and gustiness, which also control TAR frequency.

4.3. Quantitative aspects of evaporation and wind speed

Chittenden et al. (2008) concluded on the basis of their experiments that both free and forced convection (mixed convection) were important in determining evaporation rates under martian conditions. Heat transfer models for mixed convection indicate that the transfer rate is equal to a free convection term (that is a buoyancy driven process in which the lighter water molecules rise above the heavier carbon dioxide molecules, with zero wind velocity) plus a forced convection term in which evaporation is linearly proportional to wind velocity. The nondimensional numbers describing the physics of heat and mass transfer are equivalent: the Sherwood number in mass transfer is equivalent to the Nusselt number in heat transfer while the Schmidt number in mass trans-

Table 2
Statistical data for gully parameters and TAR frequencies.[a]

Fig. 2	No. of gullies	*L* vs. *f*		*A* vs. *f*		*C* vs. *f*		*Ap* vs. *f*	
		R^2	Sig. level (*p*-value)	R^2	Sig. level (*p*-value)	R^2	Sig. level (*p*-value)	R^2	Sig. level (*p*-value)
No correlations (Fig. 2, part 1)									
a	10	0.03	0.64471	0.06	0.49723	0.06	0.44759	0.04	0.59955
b	6	0.05	0.67162	0.31	0.2509	0.45	0.21185	0.58	0.07914
c	5	0.01	0.88793	0.16	0.73767	0.00	0.92456	0.12	0.56904
d	6	0.03	0.75698	0.33	0.23068	0.61	0.06631	0.85	0.00837
e	5	0.14	0.52831	0.92	0.18635	0.00	0.98394	0.16	0.50177
f	5	0.00	0.93684	0.13	0.54493	0.15	0.52638	0.09	0.61818
Inverse correlations (Fig. 2, part 2)									
g	5	0.94	0.00591	0.10	0.7911	0.48	0.19178	0.54	0.15475
h	6	0.42	0.1610	0.03	0.73241	0.15	0.44097	0.00	0.93632
i	5	0.92	0.00984	0.02	0.85479	0.74	0.06233	0.24	0.40646
j	5	0.55	0.1506	0.16	0.58356	0.17	0.50784	0.51	0.17626
k	9	0.76	0.00225	0.41	0.06499	0.13	0.33234	0.69	0.00586
l	7	0.69	0.02015	0.06	0.64073	0.20	0.31872	0.89	0.00148

L, total gully length; *A*, alcove length; *C*, channel length; *Ap*, apron length; *f*, TAR frequency.

[a] Entries that are shaded are significant at the 0.05 (95%) level or better, values with darker shading are significant at the ~0.15 (85%) level.

Table 3
Factors potentially governing gully length and TAR frequency with relationships indicated that could give rise to our observed TAR frequency–gully length correlations.

	Relationships	Gully length factors					
		Fluid viscosity	Fluid flow velocity	Fluid discharge	Rock friability	Infiltration	Evaporation
		Neg.	Pos.	Pos.	Pos.	Neg.	Neg.
TAR frequency factors							
Sediment supply	None	No	No	No	No	No	No
Wind speed	Pos.	No	No	No	No	No	Yes
Wind gusts	Pos.	No	No	No	No	No	Yes
Particle size	None	No	No	No	No	No	No
Particle shape	None	No	No	No	No	No	No
Sediment moisture	None	No	No	No	No	No	No
Atmospheric pressure	None	No	No	No	No	No	No
Atmospheric temperature	None	No	No	No	No	No	No

fer is equivalent to the Prandtl number in heat transfer (Jakob, 1949). Based on these similarities, coefficients determined from the data, and the experimental data's linear dependency the evaporation rate (E_s) is described by the equation (Chittenden et al., 2008, without the erroneous ρ_{atm}/ρ_{ice}):

$$E_s = \Delta\eta(D/\nu)^{2/3}[0.17(D\Delta\rho g/\rho)^{1/3} + 1.23 \times 10^{-3}\ \mathrm{V}] \qquad (1)$$

where $\Delta\eta$ is relative water vapor density difference, D is inter-diffusion coefficient of H_2O and CO_2 ($\mathrm{m^2\ s^{-1}}$), ν is kinematic viscosity ($\mathrm{m^2\ s^{-1}}$), $\Delta\rho/\rho$ is relative gas ($CO_2 + H_2O$) density difference, g is gravity constant ($\mathrm{m\ s^{-2}}$), and V is wind velocity ($\mathrm{m\ s^{-1}}$).

Fig. 5 shows the results of solving Eq. (1) and allows the determination of the evaporation rate at various temperatures and wind speeds. Two points should be stressed. First, that temperature played a major role in determining evaporation rates. Second, that it is only at very low temperatures that the evaporation rate depends on wind speed. Increasing the wind speed from 0 to 14 $\mathrm{m\ s^{-1}}$ causes evaporation rate to increase by a factor of 1.5 at 268 K, but at 170 K the same increase in wind velocity causes a factor of 100 increase in evaporation rate. Thus, given the observed negative correlations between gully length and TAR frequency and with evaporation being a limiting factor for the former, then we predict that at such locations on Mars the gullies formed at low temperatures where wind speed is a controlling factor, with the slope of the correlation being temperature dependent, being steeper for gullies forming at low temperature than gullies forming at high temperature. Of course, the formation of gullies at temperatures much below 273 K requires that the gullies were formed from strong brine solutions and these are discussed below.

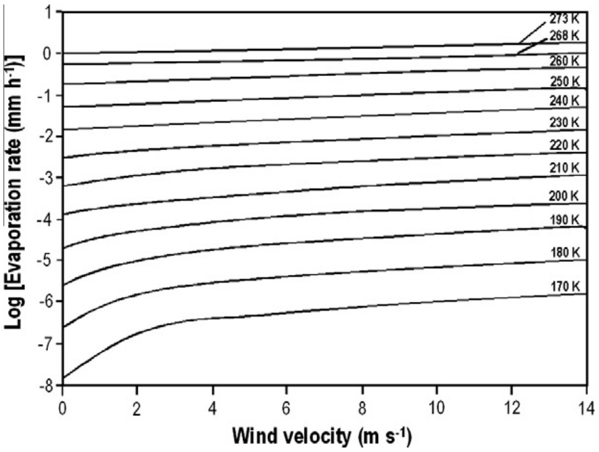

Fig. 5. Plot of evaporation rate against wind speed for a variety of temperatures based on laboratory experiments and theoretical treatments (Chittenden et al., 2008). Temperature is a very strong control on evaporation rate, and the effect of wind is minimal at temperatures around the freezing point of pure water. However, at temperatures below, say ~200 K, there is a strong dependence of evaporation rate on wind velocity so that by 170 K there is almost a factor of 100 difference in evaporation in the absence of wind and in the presence of 14 $\mathrm{m\ s^{-1}}$ winds.

The data shown in Fig. 4g–l display these inverse relationships between gully length and TAR frequency. On the other hand, the data shown in Fig. 4a–f show no relationship between gully length and TAR frequency, which would be consistent with evaporation not being an important factor in controlling gully formation and thus these gullies formed at higher temperatures, say >200 K. The average northern mid-summer temperature from GCM and TES data at $-35°$S is $\sim$210 K (Haberle et al., 2001), so fluctuations of the sort are reasonable. We note the fact that 3e and 3f (consistent with gullies forming at a higher temperature) and 3g and 3h (consistent with gullies forming at a lower temperature) are located very near one another and this is discussed below.

4.4. Comparisons with geography

Shown in Fig. 1 are locations of our study sites and a symbol indicating whether there is a correlation between gully length and TAR frequency. The regions in which we observed a significant inverse correlation are predominately in the southern hemisphere. Six of the eight sites in the southern uplands display a negative correlation, while all four of the sites in the northern lowlands show no correlation. This suggests a significant difference in the local environments of the two hemispheres, either the local or seasonal temperatures are systematically lower in the highlands and/or there are major differences in the wind characteristics associated with the more complex topography of the uplands. We suggest it is the topographic complexity of crater interiors (where most gully-TAR associations occur) that results in a variety of wind speeds and enables us to see correlations between gully length and TAR wavelength in the southern uplands. It seems that in order to obtain the present correlations, that to a first approximation wind speeds at a given location on the crater rim (where the gullies form) are similar to those at the base of the crater wall where the TAR form. It is possible that such geographically close areas have such different temperatures because of even subtle differences in age, albedo, aspect, elevation, and thermal properties of the regolith.

4.5. Implications of temperature on composition of fluid

Our observed correlations probably indicate that the ambient temperatures during gully formation differ at the various sites. It is almost certain that these gullies were not formed under current Mars conditions and any comparisons with present conditions are not necessarily meaningful. In fact, our results provide only a clue as to the temperatures of gully formation.

Since much of the martian surface is below 273 K, the fluids that formed these gullies were not pure water. Salt-rich solutions, brines, can remain liquid down to 223 K. Brines composed of NaCl and $CaCl_2$ have been suggested on Mars (Brass, 1980; Knauth and Burt, 2002; Sears and Chittenden, 2005). The chloride bearing minerals on the martian surface have been localized in Noachian deposits in the southern hemisphere (Osterloo et al., 2008). Large evaporitic deposits of magnesium and calcium sulfates have been detected in numerous locations (Gendrin et al., 2005), but Mg and Ca-sulfates have high eutectic points, around 270 K (Kargel, 1991). On the other hand, ferric sulfates can have eutectics as low as 175–205 K (Chevrier and Altheide, 2008). Abundant jarosite ($KFe_3(SO_4)_2(OH)_6$) has been found in Meridiani Planum (Klingelhöfer et al., 2004) and some soils in Gusev Crater contain up to 30% pure ferric sulfates (Johnson et al., 2007; Lane et al., 2008). These fluids have evaporation rates under martian conditions that are strongly dependent on temperature and they would remain liquid at temperatures low enough for wind speed to affect evaporation rates (Fig. 5; Sears and Chittenden, 2005; Chevrier and Altheide, 2008).

Thus the negative correlations we observe in the gullies of the southern uplands that are consistent with formation at low temperatures imply that the fluids were low temperature eutectics analogous to ferric sulfate.

4.6. Interplay between evaporation rate and gully formation timescales

While changes in albedo within gullies have been observed on mission timescales (Malin et al., 2006), gully formation has not been observed on these timescales. Some authors do suggest the gullies are modern, since they overlay contemporary TARs (Costard et al., 2002; Védie et al., 2008), while other authors have suggested that they may date from 300,000 to 3,000,000 years (Reiss et al., 2004). On the assumption that, at the low temperatures where evaporation is dependent on wind speed, say $\sim$200 K, evaporation rates are $\sim10^{-4}$ mm/h and that gullies are typically 5 m deep, the lifetime for complete evaporation of an aqueous solution is $\sim$5700 years. However, in view of the high dependency of evaporation on temperature, variations in topography, the effect of infiltration, and decrease in water activity due to the presence of solutes, there is probably an order of magnitude uncertainty either way in this value. At lower temperatures (180 K and 160 K), the calculated timescales are $\sim$57,000 and $\sim$285,000 years. These timescales seem reasonable in view of most ideas concerning the age of the gullies.

5. Conclusions

We examined HiRISE images of gullies and TARs, measuring total gully length, the length of the alcove, channel and apron, and the frequency of adjacent TARs. Most of these images are found in southern hemisphere craters, but this may just be a bias based on the locations of TARs on the martian surface. We found an inverse correlation between gully length and TAR frequency in six of the 12 images examined. The negative correlations we observe between gully length TAR frequency can be explained by formation temperatures <200 K, where wind speed/evaporation is a factor governing gully length. The evaporation–wind equation (Eq. (1)) indicates that higher wind speeds will increase evaporation rates, and that at lower temperatures there are wider variations in the evaporation rate. Craters do affect the speeds and directions of the wind across the slopes and 11 of the 12 images were in craters. The connection between gully length and TAR frequency and the factors that could give rise to this further indicates that an evaporating brine fluid formed the gully features. Finally, with evaporation rates being a controlling factor in the lengths of the gullies, then the formation timescales of these gullies must be on the tens to hundreds of thousands of years timescale.

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