GLOBAL SYNTHESIS OF MARS GULLY OBSERVATIONS: EVIDENCE FOR CLIMATE-CONTROLLED FORMATION FROM MORPHOLOGY, DISTRIBUTION, TOPOGRAPHY, AND TERRESTRIAL ANALOGS.

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Introduction: Gullies on Mars have generally been treated as anomalously young water-carved features found in the mid-to-high latitudes in both hemispheres [1]. While recently obtained sub-meter-scale imagery from HiRISE supports the general concept of fluvial erosion of gullies [2], the source for the water is still debated. Two end-members have emerged: 1) Sudden release of a confined aquifer at several hundred meters depth [1, 3-6] and 2) Accumulation and melting of surface/near-subsurface snow and ice, controlled by variations in orbital parameters [7-13].

The local and global distribution of gullies has been brought into greater focus since their initial discovery [1]. In addition to being latitude-dependent [1], gullies are only observed within distinct elevation windows [4,12], only at preferred orientations depending on latitude [4,11-12,14], and only on steep slopes [12]. Here, we synthesize these observations and incorporate new HiRISE observations of gullies and recent field work from similar features in the Antarctic Dry Valleys.

Lateral and Vertical Distribution: On Mars, gullies are found at mid-to-high latitudes [1] in the same vicinity as climate-related deposits such as dissected terrain [15], pasted-on terrain [10], viscous flow features [16], polygonally patterned ground [17], and concentric crater fill [18]. The lack of gullies within 30° of the equator in either hemisphere immediately suggests a climatic component to their formation [13], and their association with other atmospherically-derived latitude-dependent deposits argues that they are a component of recent climate change on Mars [13,19]. We have analyzed in detail the local and regional topographic properties of gullies and observed additional trends indicative of climate control on gully formation.

Slopes. Steep slopes (> 20°) are essential for gully formation on Mars [12]. Previous analyses using interpolated MOLA gridded data [4] (463 m/px) showed that gullies form on surfaces with a mean slope of 21°. Our analysis [12], using MOLA track data (300 m between shots) on North-South trending gullies, showed that the mean slope value is 26.5°, with only 13% of gullies occurring on slopes below 21°. Steep slopes at preferred orientations are conducive to protecting surface deposits of ice/snow that would sublimate if exposed to direct solar insolation [7]. Gullies carved by the release of groundwater, however, should occur at all slopes. The clustered nature of gullies in the southern hemisphere [12] (eastern margin of Hellas, circum-Argyre, Newton Crater and westward) correlates strongly with regions mapped to be topographically rough in multiple independent analyses of MOLA global data [20,21].

An argument proposed against the surface snowmelt model is that a more uniform distribution of gullies would be expected if the surface volatiles were atmospherically derived [6,22]. Specifically, Hale Crater, which shows an abundance of gullies, has been compared to nearby Bond Crater, which shows no evidence for gullies [22]. While the craters are of comparable size and are found at similar elevations, there is a vast disparity in slopes along their respective crater walls and central peaks. Hale Crater is a relatively young crater with few superposed craters on its floor, and its walls are still steep (>30°). Bond Crater, however, is considerably older and the walls have been heavily degraded (slopes < 20°), so that gully formation would not be expected on any of its walls. This is consistent with analysis of HRSC data [23].

It has recently been proposed that the gullies within Hale may be a product of the impact event itself, based upon other young channels associated with the ejecta blanket and similar features observed in and around Mojave Crater (7.6°N, 327.4°E) [2]. In this scenario, heat from the impact alters the immediate climate around the crater and facilitates the melting of surface snow/ice such that channels could form. While this is plausible in the case of Hale, it is insufficient to explain mid-latitude gullies as a whole, which are found on non-impact structures such as valley walls, dunes, and along the flanks of mesas, buttes, and massifs [11,12]

Elevation. Gullies are found at elevations up to 3089 m in the southern hemisphere, but not above that [12]. The climate of Mars hovers around the triple point of water, and surface deposits of ice/snow are more likely to sublimate than melt at higher elevation. Groundwater beneath a ~200 m layer should be less affected by local pressure conditions, although providing a source for groundwater at such a high elevation is difficult [12].

Gullies also do not occur at extremely *low* elevations in the southern hemisphere. Our study [12] revealed that gullies do not occur below -5177 m. Both the groundwater model and the surface-melting models would predict an *increase* of gully frequency at lower elevations due to groundwater availability and atmospheric pressures more conducive to accumulation and melting of volatiles. This contradiction is accounted for in the snowmelt model by the lack of steep slopes on the heavily modified floor of the Hellas impact basin [20,21], which is one of the smoothest terrains in the southern hemisphere and accounts for all of the terrain below ~-5000 m in the southern hemisphere. Groundwater should not be affected by the lack of steep slopes. Upon release, groundwater would be stable for long periods on the surface at the highest pressures on the surface of Mars, yet gullies are not observed on the floor of Hellas.

Orientation. Multiple independent studies [1,4,11-12,14] have documented orientation preferences for gullies, particularly in the southern hemisphere, where the sample set is largest. These studies all confirm that gullies between 30°-45°S are *poleward* facing. Further analyses have shown a latidude dependence at local [14] and hemispheric [4,11] scales: at higher latitudes, gullies trend more equatorward. Before statistically significant data were returned by MGS, Hecht [7] predicted this type of orientation preference: gullies should occur on steep, sheltered walls in the mid-high latitudes of Mars where ice is most likely to accumulate. This was consistent with the discovery of other mid-high latitude surface features that indicated an extensive ice depositional history related to recent climate change on Mars [13,15]. Like latitude and elevation, orientation preference is a climate signal: at mid-latitudes (30°-45°), equatorward slopes are exposed to sufficient solar insolation so that surface ice/snow will rapidly sublimate. Poleward slopes, however, are protected and ice/snow will accumulate and potentially melt at increased obliquity. At higher latitudes (>45°), temperatures are low enough to prevent surface volatiles from sublimating at low pressures. An increase in obliquity would raise both the atmospheric pressure and the surface temperature at higher latitudes, such that surface ice/snow would melt instead of sublimating [7,8].

Morphology. Upon their discovery, it was observed that gullies on Mars appear to be sourced from beneath layers of bedrock several hundred meters thick [1]. While this correlation exists in some instances, the majority of gullies show no association with bedrock layering [12]. Gully alcoves are frequently found at the crest of raised crater rims [12], and gullies themselves have been observed on other isolated topographic highs such as central peaks, mesas, and dunes [11-12,24], where confined aquifers are not likely to exist.

HiRISE data have revealed further details concerning the formation and evolution of gullies. Diagnostic fluvial bedforms such as meanders, point bars, and streamlined islands have been observed [2]. HiRISE has confirmed MOC observations that flow through gullies has been episodic, as multiple instances of channels cutting fans have been observed [19]. Channels cutting through alcoves show that alcove formation is not simply a process of undercutting and collapse. And finally, gullies have been observed at higher latitudes having a strong correlation with polygonally patterned ground [17], suggesting that the two processes are related in these locations.

Terrestrial Analogs. Terrestrial analogs for gullies on Mars have been found in the Canadian Arctic [25], Greenland [8], and Iceland [9], all showing evidence for surface/near-surface melting of snow/ice. We have recently completed a field investigation of gullies in the south fork of Upper Wright Valley in the Antarctic Dry Valleys (ADV), a hyper-arid polar desert that shares many of the same landforms observed on Mars [26]. As on Mars, gullies in the ADV occur at lower elevations, on steep slopes, and their occurrence is highly dependent on orientation and solar insolation [27,28].

Gullies in Wright Valley are presently being modified by the melting of surface snowpacks that accumulate during austral winter [27]. Despite the low precipiation in the ADV [26,28], snow that does fall in the winter is transported by the intense winds in the valley and accumulates in topographic traps such as channel floors and gully alcoves. These deposits then melt during peak summer insolation periods. No evidence for groundwater release was observed. Gullies in the ADV emphasize the importance of microclimates with regard to gully formation [26]. The critical component of gully formation in the ADV and on Mars are the same: steep slopes and orientation angles that allow for both the accumulation and melting of surface snow/ice deposits.

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