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Workshop on

Martian Gullies: Theories and Tests

February 4–5, 2008 • Houston, Texas

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Preface

This volume contains abstracts that have been accepted for presentation at the Workshop on Martian Gullies: Theories and Tests, February 4–5, 2008, Houston, Texas.

Administration and publications support for this meeting were provided by the staff of the Publications and Program Services Department at the Lunar and Planetary Institute.

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Tuesday, February 5, 2008
FRAMING THE WORKSHOP: TESTS OF GULLY ORIGINS
1:30 p.m. Lecture Hall

Moderator: **A. H. Treiman**

1:30 p.m. Reprise: What is a Gully?

1:45 p.m. Moderated Discussion: Testing Theories

3:00 p.m. Break into Groups, Write about Tests for White Paper

The Water Cycling and Secondary Ice-Salt Structures in the Gullies and Crater on Mars

Pedram Aftabi, Geological Survey of Iran, PO Box 13185-1494, Tehran, Iran;Ped_Aftabi@yahoo.com

Our understanding of Martian gullies could be important in the design of Mars spacecraft missions, and landing sites. The water-ice exploration on Mars is an enigmatic and questionable works, because the H2O ice is minimum in that planet in compare to CO2 ice [1, 2]. Sulfate salt formation in the regolith [3, 4] can be a major sink for H_2O. The salt is as old as the Solar System, so the water trapped inside the salt is also ancient. There appears to be a global crust of salt enriched materials on the surface of Mars, probably in the form of Sulphate salts, NaCl, (Mg, Ca) CO3 [3] and jarosite or epsomite MgSO4.7H2O [4]. Most salt contains at least some H_2O as hydrous minerals and as fluid inclusions, either intracrystalline or intercrystalline [5], and the ice can be dirty with low amount of water content [6, 7].

The possibility of acidic brines in the planet Mars suggest better understanding of salt and ice mixtures on Mars planet. Malin& Edgett[8]made the initial announcement of the discovery of Martian gullies in Mars Global Surveyor MOC images[23]. Christensen[9]proposes a different model in which melting of an overlying snow pack provides the source of water to erode gullies. Geothermal heated ground ice has also been invoked as source water forming the gullies[10]. Perhaps the gullies formed during warmer periods. Salts have the potential to significantly lower the freezing point of water[11]. The gullies formed by debris flows initiated by ground water saturation and/or by drainage of water from cliffs higher on the slopes[8,12,and 13].The salt of the brine rapidly deposit on the surface of new channel with white color as secondary salt by rapid evaporation. The brines hypothesis is strengthened by studies of Martian meteorites that show the rocks with salt minerals halite, anhydrite [14]. The water source from shallow aquifers (perhaps 200 to 300 meters beneath surface) contains 35wt% to 100wt% water-ice buried beneath a shallow layer of ice-free material[15]. The groundwater seepage from shallow aquifers and subsequent surface runoff [16] formed the gullies. The new experiments by author suggest that chloride salt never freeze to ice shell but epsomite salt lower the freezing point very little, and formed ice shells(Fig3 j). Water is constantly in motion, called water cycling [17]. The liquid water of icy plates transported to the salt or salt-ice mixture and flow as rivers over the slopes of craters(Fig1) or other big cavities as gullies both on Martian moons[6,7]and mars planet[8,16). This cycle is through the high pressure area to low pressure areas during climatic and structural changes[11,6,7].Viscous fluids flow down pressure gradients under the influence of boundary conditions[18,19,20]. Channels(Fig1), of course, are the most striking features of the gully systems; they generally begin deep and broad at a specific exposed rock layer, and then taper down slope. Another source of energy for melted water brine is changes in the internal and external heat. The heat can be converted to motion by internal convection [21, 22, and 18]. The experiments by author(Fig2) suggest that the salt and ice mixture in bottom of an ice sheet are the first freezing crystals in the bottom and the last in top of the ice sheet, but the flowing brine every time generated different sheets of ice salt mixture on top. The fast evaporation of ice in the ice salt mixture of the top layer leads to forming a thin sheet of salt (epsomite) on top of the ice sheet(Figs 3 a to i). .In Martian position the salt or salt-ice mixture of the cut off layer(exposed in craters)may act as a cap for ice but transported the brine to the low pressure areas as new gullies(Fig1m). The water and sand generated a sandstone with ice cement when frizzed [6, 7].After every 24 hours generated 1 mm soil in the small scale model [6, 7].In other experiments with epsomite brine and sand the sandstone with salt and ice cement generated soil very slow with rate of 0.5 mm after every 96 hours (see Fig 3c) and act as barrier for ice evaporation. At some point, the barrier became too thin and extruded the liquid under pressure(Figs 1 g to m) . It breaks through the surface into the atmosphere, where it evaporates quickly due to the sudden drop in pressure(Figs 3k,l). However the liquids in other Duricrust barriers flow under pressure and flow out and down slop in the crater slopes. The duricrust mostly consist of epsomite salt and ice mixture with high amount of soil and old dust which is enriched of water(Figs 1m &3d-g). The gullies are very young and may currently be forming(Fig1) on Mars because in authors experiments gullies formed very fast(in few seconds) by change in the atmosphere temperature in small scale ice models(Figs 3k,l). These rivers later filled by deposits (by storms or wind)and covered the secondary salt(Fig1m) . A series of concentric ,radial and polygonal structures formed in the map view of craters and gullies (Figs 1 a to f), because of stages of icing and deicing periods, evaporation of brine, viscous flows of rising ice(Fig2),and thermal changes. The rise of the ice after impact is an important factor in water cycling on Mars(subscribed and Fig2 here)which helped to gullies formation by Martian water cycling in the slopes(subscribed). The experiments here showed that the convectional movements of brines by temperature changes is more penetrative around the craters and gullies(Fig1) because the salt deposits are very conductive for melting but they are barrier for rapid evaporation of ice(Figs2 b,c). Evidences of water brine cycling distinguished with separation of a white circular secondary salt rim around the craters by author’s photo geology studies on NASA's pictures(in prep.).The Polygonal fractures in salt generated polygonal dry rivers (Figs4a, c) and polygonal rising brine flow (Fig4 b, f).The polygonal features generated brine evaporation and formed salt walls (Figs 4b, f) which surrounded high content salt brine (Fig4).The secondary salt and teepee structures on Earth is a key for Martian secondary structures in gullies and craters (Figs 4 &1).

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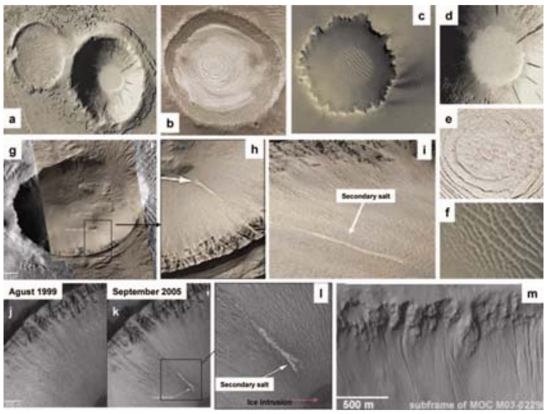

Fig1-a,b,c)Different craters on Mars with radial, concentric and polygonal features(consist fractures). a&d) is Martes Valles Double Crater,show a double crater with radial fractures and probable a Martian cusp ice rise through the crater center. b&e)Sediment Filled Crater with concentric structural morphological lines suggest that the conical passive ice pillow spread sideway below the surface deposits. c&f)Victoria Crater suggest evaporation of brine in the middle of crater where the ice rise as a passive pillow(subscribed).All these morphological and structural features suggest water cycling on Mars g,h&i)A mosaic of MOC images using HiRISE color data and overlain on THEMIS) image V16997005, show evidences of water flow and secondary salt deposition. The scale bar is 1km.Part of the evidence showed in different views on h&i. j&k)Picture no MOC2-1619 Show new Gully deposit in a Crater in the Centauri Montes Region on Mars between Aug.1999 to Sep.2006(7 years). Show that the gullies may be so young that some of them could still be active today. m)The groundwater seepage from shallow aquifers and subsequent surface runoff(After [8,16];see www.NASA.Gov).

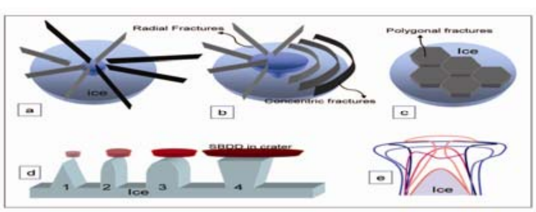

Fig2-Radial and concentric and polygonal fractures and rising ice after impact see analogue models by Aftabi which subscribed or published in LPI.

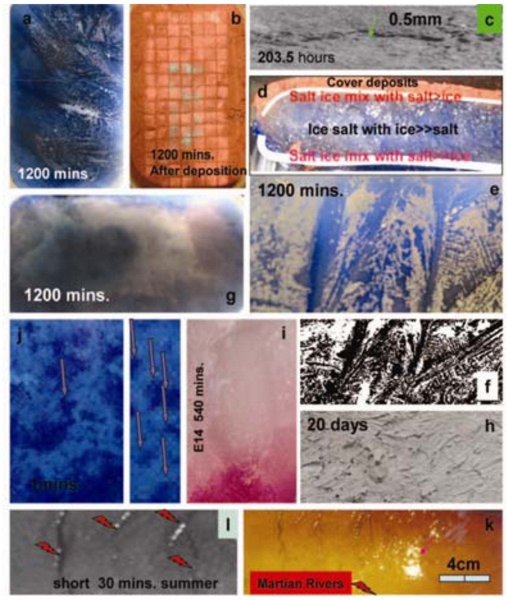

Fig3-Aouthor’s experiments: brine with low to medium amount of epsomite(25 m/l) salt generated ice sheet with blue color(a) and thin sheet of salt on top in white color(e,f) and salt ice mix with high amount of salt with white to purple color in bottom(g).The sheet(b,d)covered by sand. The brine penetrated to sand and made sandstone with epsomite and ice cement. The sandstone cover acted as cap lower the evaporation of ice(c).An ice shell with epsomite generated pinched crust of salt with polygonal, radial and concentric fractures(h).High amount of epsomite(>75m/l)showed similar manner which most of the salt deposited as dark pink but the brine penetrated to top and formed thin sheet of epsomite salt on top. The brine with high amount of halite never frizzed but ice-salt crystals formed after few seconds and deposited in the base(j).The ice sheet with topographic changes generated dry rivers in model, because the brine evaporated very fast in few seconds at -27 degrees.

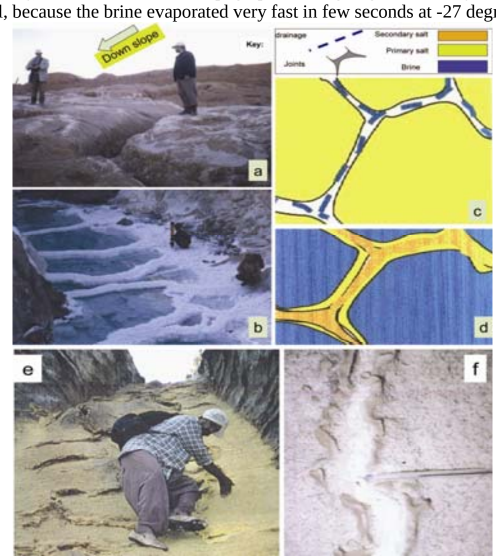

Fig4-Polygonal fractures in salt on Earth(in Iran)generated polygonal dry rivers(a,c) and polygonal rising brine flow (b,f).The polygonal features generated brine evaporation and formed salt walls(b,f)which surrounded high content salt brine(b)Every time the brine intruded the middle of crack(f) from as a flowing material beneath the salt sheet and intruded into fractures mainly down slope(e) like brine flow down slope in crater walls. The salt and ice define pseudo stratigraphy. Blue is brine and yellow is salt.

CORRELATION OF REGIONAL TOPOGRAPHY AND MARTIAN GULLY ORIENTATION. T. L. Allen[1], M. B. Wilhelm[2], J. L. Heldmann[3], and S. J. Allen[4], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035. Trinity.L.Allen@gmail.com, [2]NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035. mbwilhelm47@yahoo.com, [3]NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035. Jennifer.L.Heldmann@nasa.gov, [4]NASA Ames Research Center.

Introduction: Liquid water emanating from a subsurface aquifer has been proposed as a possible explanation for the formation of gully features on Mars [1, 2]. In this scenario, a correlation may be expected between the location of gullies and the location of regionally downward sloping terrain due to the resultant hydraulic gradient, which would slope downward causing water in an aquifer to move towards the gully site. A comprehensive survey of gully orientation angles and the corresponding regional topographic trends is presented here to further test the shallow aquifer model.

Methodology: We searched all Mars Orbiter Camera (MOC) narrow angle images in latitudes known to contain gullies, approximately 30°-75° in both the northern and southern hemispheres, from mission phases AB1 through S10. Gullies were identified primarily by the presence of a distinct, v-shaped channel emanating from the base of a theater shaped alcove. Gullies located on Hale crater, central peaks, and dunes were omitted due to significant morphological differences from classical gullies found on most crater, trough, and pit walls [3].

Only gullies found on crater walls were used for this study though classical gullies were also found on trough and pit walls. Craters with significant coverage were used for orientation angle measurements while only craters with full coverage were used for regional topography analysis. Significant coverage is defined as imagery data spanning at least 100° of orientation along a crater wall or a cross-sectional image showing a portion of both the north and south facing walls.

In order to analyze the possible bias for poleward facing slopes during the imaging process, the angular extent of MOC narrow angle image coverage for each of the craters was recorded.

To determine the locations of gullies and gully systems we measured the orientation angles of up to twelve individual gully channels in each map projected MOC narrow angle image. Repeated measurements of the same gully were avoided where possible by discarding repeated MOC images and visual inspection of overlapping images.

Elevation contour plots of the region imaged by the MOC wide angle image corresponding to the narrow angle image of interest were created using MOLA gridded data at 128 pixels per degree for each of the fully covered, southern hemisphere craters. These plots were used to determine where the regional topology slopes towards the crater of interest. Small scale, local features were ignored initially in favor of large scale regional trends.

Results/Analysis: A total of 1790 images containing gullies were found. The exclusion of gullies in Hale crater, central peaks, and dunes and the requirement of significant coverage narrowed the initial set of 1790 images down to 1207 images. Of these 1207, 170 images are in the northern hemisphere and 1037 are in the southern hemisphere. There are 535 individual craters containing gullies, which account for 757 individual images. The remaining images represent gullies in troughs, pits, and chaotic terrain. Of the 535 craters containing gullies, 424 are in the southern hemisphere, and 49 of these can be seen in their entirety using only the MOC narrow angle images in our data set.

Slope Coverage: There is no significant poleward coverage bias in either the northern or southern hemispheres. There are, however, more north/south images than east/west images in the northern hemisphere. These results can be seen in figs. 1a and 2a.

Gully Orientations: Gullies are found at all orientations on the walls of craters, troughs, and pits. However, there appear to be more gullies oriented towards the pole in the southern hemisphere, as indicated in fig. 1b. The corresponding northern hemisphere data is shown in fig. 2b and reveals that there is no apparent poleward preference in the northern hemisphere. There is a conspicuous decrease in the number of east/west facing gullies in the north, but this could be the result of imaging bias as there are fewer east/west facing images. These results are in agreement with previous works concerning possible poleward biases though there is no previous mention of fewer east/west facing gullies in the northern hemisphere [4, 5, 6].

Regional Topography: For the 49 craters analyzed, approximately 70% show a significant correlation between the location of gullies and the location of regionally downward sloping topography. Of these, approximately 50% are perfectly correlated with all of the gullies lying in locations where the regional topography is sloping towards the crater. The angular extent and orientation of the regional down sloping topography relative to each crater is shown along with the gully orientation data in fig. 3.

Preliminary data suggest that down slope topography due to localized features could lead to full correlation between gully locations and down slope topography for the 30% of images that currently do not show correlation with regional down slope topography. This could indicate that local topological features, when present, play a larger role in gully formation than regional trends.

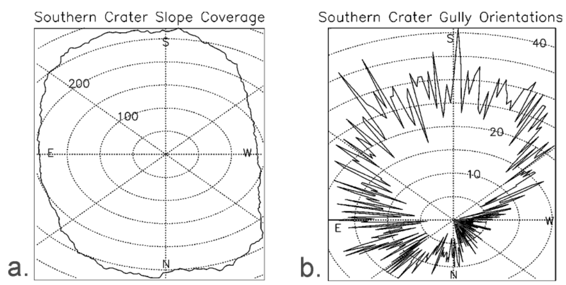

Figure 1: a) Number of gullies at each orientation angle in the southern hemisphere. b) Number of images showing each orientation angle. Note that 90° indicates a poleward facing gully or slope and all values have been rounded to the nearest degree.

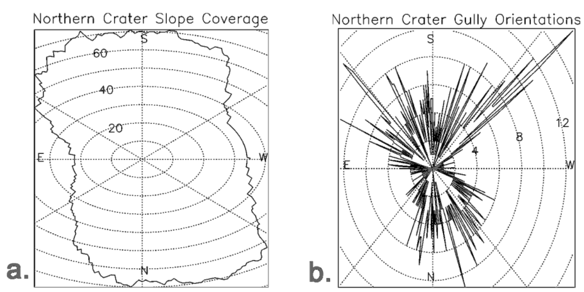

Figure 2: a) Number of gullies at each orientation angle in the northern hemisphere. b) Number of images showing each orientation angle. Note that 270° indicates a poleward facing gully or slope and that all values have been rounded to the nearest degree.

Conclusions: There does appear to be a poleward preference in orientation for southern hemisphere gullies that is not caused by imaging bias. A poleward preference is not seen in the northern hemisphere, however, and gullies can be found on all slope orientations in both hemispheres. This suggests that insolation may not be the driving factor behind gully orientation. Gully orientation may instead be linked to regional topography, as suggested by the 70% correlation between regional down slope topography and gully location.

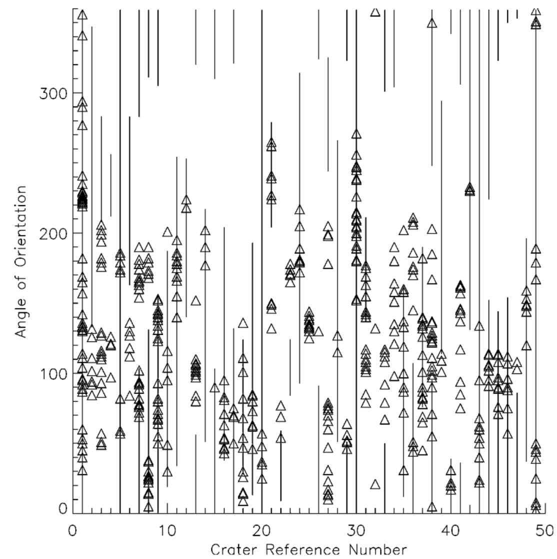

Figure 3: The angles for which surrounding topography slopes towards the crater (lines) as well as the orientation angle measurements for the individual gullies in that crater (triangles).

The possible link between gully location and regional topography could help explain the mechanism for water flow in a subsurface aquifer since the hydraulic gradient is affected by topography on a regional scale. Thus a correlation between down slope gradient and the location of gullies suggests that water, if present in a subsurface aquifer, may flow towards the locations where gullies are found. If this water reaches the crater wall it could breach the surface to form gullies.

Further work: Along with further investigation of the effects of small localized features, the research will also be extended to include regional topography and hydraulic gradient analysis for all imaged features, including both northern and southern hemisphere craters, troughs, and pits. Modeling of subsurface water flow and seepage forces will also be used to test the theory that water may be originating underground and flowing towards the locations where gullies are observed on the martian surface.

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DEGRADATION OF MID-LATITUDE CRATERS ON MARS: GULLIES, ARCUATE RIDGES, AND SMALL FLOW LOBES. Daniel C. Berman, David A. Crown, and Leslie F. Bleamaster III, Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ, 85719, bermandc@psi.edu.

Introduction: The degradation of craters in ice-rich environments is key to understanding the geologic history of the terrain surrounding the crater, as well as the source of the ice (i.e. ground ice or emplaced from the atmosphere as an ice-rich mantle [1-3]). Features such as arcuate ridges, gullies, and small flow lobes found on crater walls and floors can be used to understand the styles of emplacement, abundance, and distribution of the ice. Arcuate ridges and gullies are mainly found in small craters (~2-30 km in diameter); the orientation of these features on crater walls has been found to be dependent on latitude, suggesting that their formation is related to climatic changes driven by obliquity cycles [1-7]. In larger craters (~30-100 km in diameter), potentially ice-rich flow lobes are typically found on pole-facing walls, along with a suite of other degradational morphologies indicative of ice-driven modification processes. Through a series of studies, we have examined small (2-30km diameter) and large (>20km diameter) craters in detail, noting the potential water/ice-rich morphologies present and assessing their relationships to latitude and crater diameter.

Crater Morphologies: ArcGIS was used to integrate available datasets (including Viking Orbiter MDIM 2.1 and THEMIS IR mosaics, MOLA 128 pixel/degree DEM, MOC images, and all available THEMIS VIS images) to complete surveys of three study regions, one to examine small craters, and two for larger craters. Every crater in the specified size range for each region, as identified in the Barlow martian crater database [8], has been studied in detail for evidence of gullies and other morphological indicators of ice-rich deposits or fluvial erosion. For the smaller craters, MOC images were used to analyze crater morphologies; for the larger craters, THEMIS VIS images were used. The geomorphic characteristics of each crater were noted to determine relationships between the observed features and factors such as crater diameter, latitude, and wall slopes.

Craters containing gullies also commonly exhibit other features consistent with the presence or flow of water or ice, including arcuate ridges, small flow lobes, valley networks (sometimes with valley floors covered by potentially ice-rich material), narrow runoff channels, pitted and/or lineated floor deposits, debris flows, and lobate ejecta.

Surveys: Three study areas have been selected to examine crater degradational morphologies: one in the northern mid-latitudes in Arabia Terra along the dichotomy boundary (30º-55º N, 0º-40º E), one in the southern mid-latitudes in the highlands east of Hellas Basin (30º-60º S, 110º-150º E), and one in the southern mid-latitudes in the region of Newton Basin (30°-60° S, 180°-240° E). Large craters were surveyed in the Arabia and Hellas regions, whereas small craters were surveyed in the Newton Basin region. Out of 400 craters in the southern study region, as identified by [8], 121 had sufficient image coverage in THEMIS VIS images for more detailed examination. In the northern study region, 116 craters out of 197 were examined. In the Newton Basin region, 225 craters were examined with sufficient MOC coverage, 188 of which had gullies on some portion of their walls.

A distinct relationship between orientation and latitude has been found for gullies, arcuate ridges and lobate flow features in the three regions. In the Newton Basin region, all of the craters with gullies only on the pole-facing walls were found north of ~44° S, whereas all the craters with only equator-facing gullies were found south of ~44° S. Arcuate ridges also exhibited a similar latitude dependence, with craters with only equator-facing ridges being found only south of 44° S. This relationship also exists in the Hellas and Arabia regions, although a smaller number of gullies and arcuate ridges were found in the larger craters.

A multitude of lobate flow features have been found on the walls of large craters throughout both the Hellas and Arabia regions, typically on the pole-facing side. Nearly all of the lobes are on pole-facing walls, and all of the pole-facing lobes are found below 45º. We have found three craters with lobes on an equator-facing wall, two in the southern study region, and one in the northern region. These craters are found south of 50º in the southern region, and north of 45º in the northern region.

Discussion: A suite of distinct morphologic features is found to be characteristic of mid-latitude craters. These features (e.g., gullies, arcuate ridges, lobate flows, narrow channels, wider valleys, filled and unfilled alcoves, mantling deposits, and debris flows) appear to be related to the deposition and/or accumulation of ice with subsequent erosion due to mobilization of this ice. Which features develop in a crater is a function of latitude, crater diameter, crater wall slope, and crater rim topography. Gullies and arcuate ridges are common in mid-latitude craters smaller than 20 km in diameter. Lobate flows are common in mid-latitude craters larger than 20 km in diameter and are mostly pole-facing in orientation at lower latitudes, and equator-facing at higher latitudes, similar to the relationship between gully latitude and orientation [4]. These interrelationships suggest a dependence on total solar insolation. Cycles of deposition and re-distribution of ice [6, 7, 9] due to obliquity variations [5] are the likely formation mechanism for the observed features.

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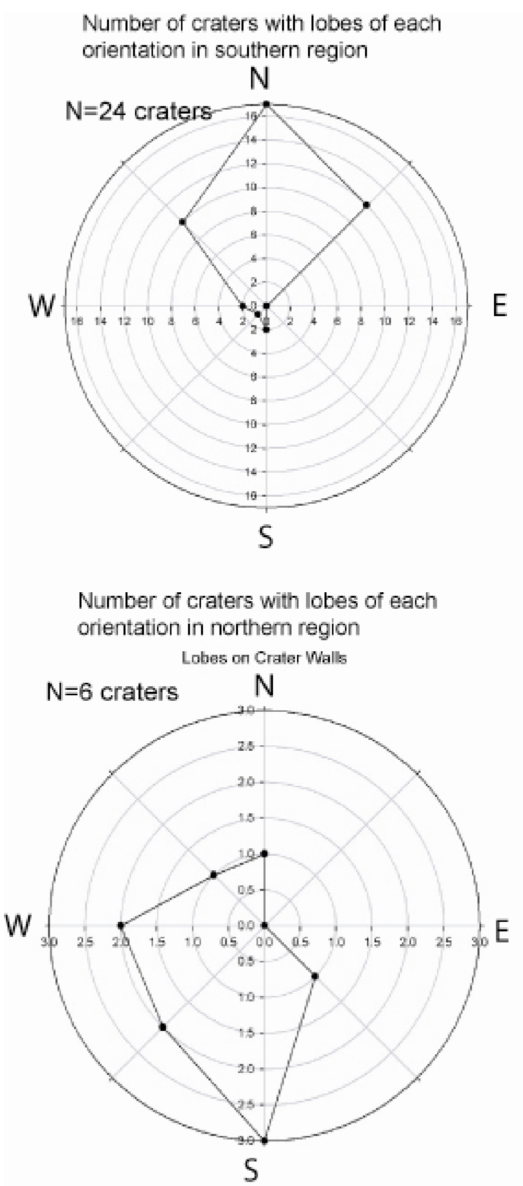

Figure 1. Number of craters with lobes on each of 8 cardinal direction crater walls in the southern and northern regions.

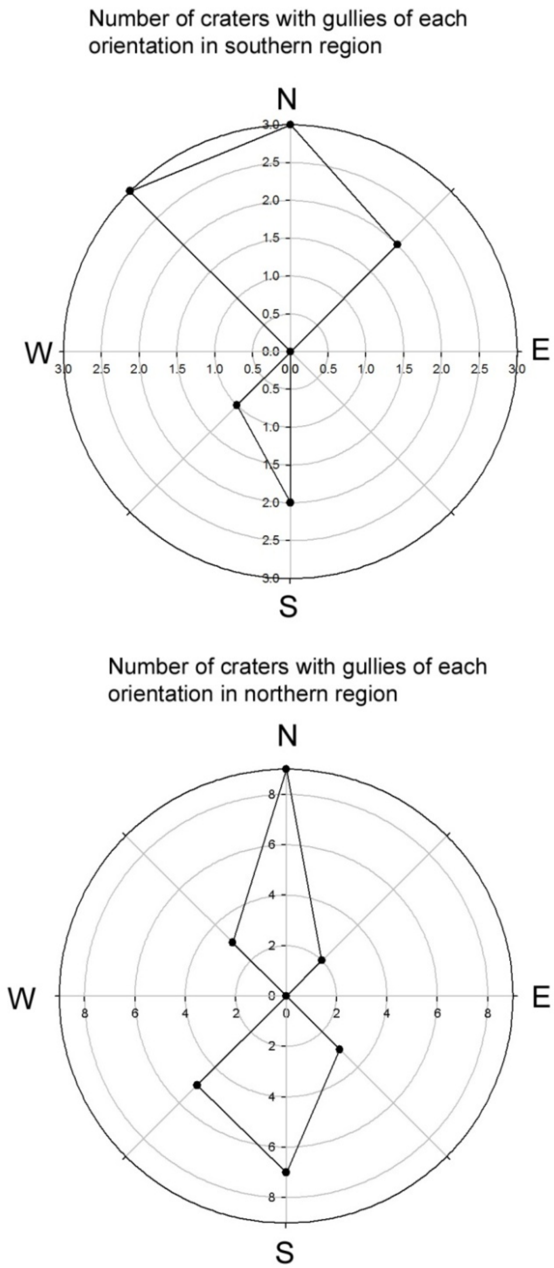

Fig. 2. Number of craters with gullies on each of 8 cardinal direction crater walls in the southern and northern study regions.

MARS GULLY ANALOGS IN ICELAND: EVIDENCE FOR SEASONAL AND ANNUAL VARIATIONS.

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Introduction: When in 2006 Malin et al. [1] reported images showing higher-albedo deposits in gullies that had lacked them in photographs taken 4-5 years previously, the controversy over the formation mechanisms for the gullies did not abate [2-7]. These images did, however, provide strong evidence for some contemporary activity of the gullies, in addition to underlining the following pressing questions: (i) What is the rate of Martian gully formation, (ii) is gully formation episodic or continuous, (iii) is gully formation fast or slow, (iv) how has the rate of gully formation changed over time, and (v) what factors govern the rate and morphology of gully formation?

Previous workers have reported the existence of Mars gully analogs on Earth, in particular in Greenland [7], Iceland [8] and Antarctica [9,10]. However, many of these studies have been limited in scope or duration. Here, we will present the preliminary findings from a longer-term study of Icelandic Mars gully analogs (September 2007 to June 2008), with a goal of identifying clues to the formation mechanisms for a range of gully morphologies, along with rates of gully formation and degradation.

Methodology: In order to assess the seasonal alterations in Icelandic gullies, we have established a network of 11 gully sites. The sites encircle the island. The more accessible sites near to Reykjavik are visited on a monthly basis, whereas the more remote sites are monitored on a seasonal basis. We also installed two electronic temperature sensors, one on Ármannsfell, a 766-meter high mountain ~50 km northeast of Reykjavik, and one on Langahlið, a 527-meter high slope ~20 km south of Reykjavik. Both sites are Upper Pleistocene hyaloclastite formed by subglacial volcanism. As shown in Figure 2, the sensors were placed in the bottom of the gullies near the debris aprons to catch any top-to-bottom flow; the Ármannsfell sensor rests on bedrock. The *Starmon* sensors have an accuracy of ±0.05°C and they take a temperature reading every minute. Any snowmelt events resulting in top-to-bottom flow should appear as periods of constant near-freezing temperature.

These field approaches will be supplemented by analysis of aerial photographs, which we hope to have completed by Spring 2008. These photographs promise additional insights into rates of gully formation, stages of activity and dysfunction, and areal distribution. Complete coverage of Iceland is available at intervals of roughly 10 years, from the 1940s onwards.

Observations and Discussion: The fall of 2007 has been anomalously wet in Iceland. Rainfall equivalent precipitation in September in Reykjavik reached 163 mm and 175 mm in October, roughly double the 1961-1990 averages. These conditions, by increasing the available water inventory, should increase any water-related gully activity.

Insights from Field Observations. The scale and morphology of many Icelandic gullies are extremely similar to Martian examples. Channels originate in deep alcoves in blocky escarpments or shallow alcoves that collect snow in winter, and terminate in digitate debris aprons (see Figure 1). Gully systems range from several hundred meters to a kilometer in length, which is comparable to gully sizes on Mars [2]. Multiple terminal deposits and braided channels and debris aprons suggest several discrete episodes of flow. Unlike on Mars [4], older, degraded, and inactive gullies are

Figure 1 (top). *A gully in the Tindastóll range in northern Iceland. Note the snow-filled alcove and channel, the levees, and the debris apron in the foreground.* **Figure 2.** *A temperature sensor deployed on bedrock on the floor of a gully on Ármannsfell.*

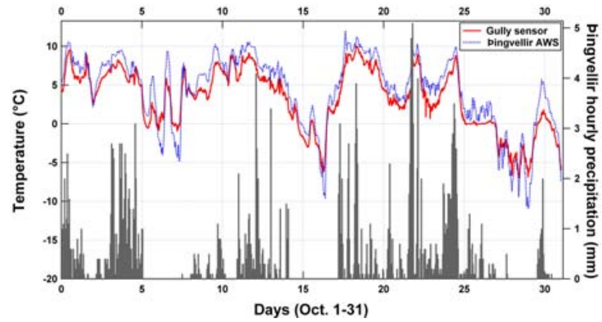
clearly present in Iceland. Vegetation is one valuable indicator of dormancy that is unavailable to us on Mars. As Figure 1 shows, substantial volumes of wind-blown snow (1-2 meters depth) collect in gully channels, even when nearby slopes are snow-free.

Initial investigations of Icelandic gullies did not focus on snow-related features, as snowmelt phenomena were considered unviable on Mars [8]. Recently, theories of high-obliquity Martian snow deposition and melt [4,5] have been proposed as explanations of the Martian gullies. Opponents suggest that the production of significant volumes of runoff from snow would be difficult on Mars [6]. Snowmelt gullies appear to be plentiful in Iceland; they tend to originate upslope in a shallow concavity, often with braided depressions feeding into a central channel without levees. Similar morphologies also exist on Mars [2]. Further investigation of morphologies associated with snowmelt in terrestrial analogs may shed light on whether there is evidence for a similar process on Mars.

Hartmann et al. [8] found that evidence from Icelandic gullies agreed with Costard et al.´s [7] hypothesis of obliquity-induced melting of ground ice and consequent debris flow. We suggest that the prevalence of two distinct morphologies in Iceland—debris flow gullies and snowmelt gullies—may also be the case on Mars. Martian microclimates [10] might have allowed snow to exist on some slopes and ground ice to melt on others simultaneously during the last high-obliquity period; this is consistent with the wide variety of gully forms observed on Mars.

Insights from Temperature Measurements. Initial monitoring of the Ármannsfell gully during the months of October and November captured one anomaly with the characteristics we predicted for a snowmelt event, as described above. Beginning October 26th around 1 a.m. and continuing until October 27th around 10 p.m., the temperature flatlined at 0ºC, with only a few small excursions, no greater than ±0.4ºC. Although the Þingvellir weather station (~4 km away) also recorded air temperatures near freezing during this period, the temperatures at the weather station show greater variability. As Figure 3A shows, the stable temperature during this time period resembles no other section of the temperature profile between September 30 and November 5. The likelihood that such an anomaly would occur at exactly 0ºC by coincidence seems extremely low. We conclude that this section of the temperature profile represents a likely period of snowmelt flow in the gully, with flow reaching at least to the apex of the debris apron where the sensor was located.

The three days preceding October 26 were unusually warm, with heavy precipitation (Figure 3A). Precipitation on the day preceding the anomaly was



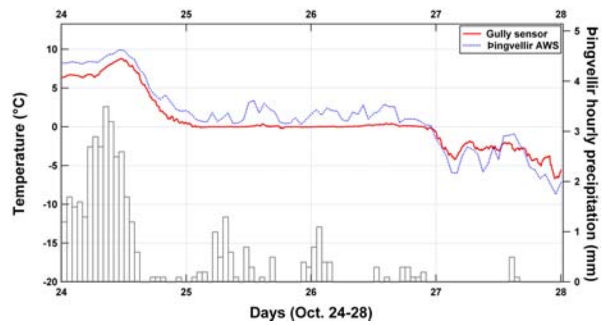


Figure 3A (top). *October temperature measurements from a sensor at Ármannsfell (elev. ~400 m) along with hourly precipitation (gray bars) and temperature at the nearby Þingvellir weather station.* **Figure 3B.** *An enlargement of a period of potential gully flow.*

especially heavy. We hypothesize that a combination of a warm air mass passing through the area and heavy rain may have triggered snowmelt in the alcove and channel, leading to runoff in the gully. Results from several seasons of monitoring should provide a more complete picture of the conditions and frequency of gully activity.

Acknowledgments: The authors thank William K. Hartmann, Trausti Jónsson and Oddur Sigurðsson for sharing their expertise. B. Black is especially grateful to the Fulbright Iceland-United States Educational Commission and to the National Energy Authority of Iceland for their support.

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SLOPE STREAK EMPLACEMENT IN THE DISRUPTED TERRAIN OF OLYPMUS MONS AUREOLES.
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Introduction: Variable-resolution imaging and topographic datasets have revealed new detail on the Martian surface [1,2], raising questions about active geomorphic processes. Evidence for slope streak emplacement between repeat MOC and HiRSIE images indicate that processes responsible for their formation operate in the current environmental conditions. They are therefore some of the youngest geomorphic features on Mars and their signature is thought to fade over time [3]. However, like gullies [4], the emplacement of these streaks has never been observed, and their origin remains controversial. Proposed emplacement mechanisms include dry dust avalanches [5, 6, 7, 8], wet debris flow [9, 10], liquid water flow and liquid CO_2 flow [12].

The aureoles that surround Olympus Mons contain one of the two major global concentrations of slope streaks. Image and topography datasets of the auroles from the last decade of Mars missions have been combined into a common projection and co-ordinate system. These constitue the products for the creation of a new geomorphic map. Aureole units show topographic variability suggestive of either multiple deposits resulting from the same failure or that there were multiple failures each of which can be considered to be a separate event. Slope streaks occur on all aureole units suggesting either that they are all relatively recent or that their emplacement can be related to time since the individual aureole events were emplaced. The properties of slope streaks within aureoles have been quantified and used to determine if they differ from those reported on escarpments, impact craters and alos to test models for streak emplacement.

Approach: Data from MOLA, MOC, THEMIS, HRSC and HiRISE have been used to 1) determine the extent of slope streaks in aureole units, 2) characterize the dimensions of slope streaks, 3) determine topographic variability, and 4) describe the geomorphology of the area. From these an improved characterization of streaks in aureoles is being obtained. This in turn, enables comparison with those reported on escarpments, impact craters and other geographic locations.

Topography and image data were related in a geographic information system (GIS) environment. For MOLA topography a cylindrical equal area projection was assigned along with a user defined datum derived from the gridded 128 pixels/degree data. Derivative products created included shaded relief, slope gradient maps, contours and profiles. THEMIS visible images were mosaiced and assigned the same datum and projection as the MOLA DEM. These datasets were used to map the geomorphology of the aureole units.

Streak Characteristics: The morphologies and morphometrics of over 300 streaks were examined in MOC (~1.4 m/pixel) and HiRISE (~30 cm/pixel) images plus MOLA topography. Slope streaks have dark to bright albedo features on Martian slopes (Figure 1). Each streak was assigned an albedo ranking of 1-3, with 3 being the darkest. It was found that if two streaks ranked 1 overlap they become briefly indistinguishable while in situations where streaks ranked either 2 or 3 overlap, 3 overlays 2. Morphologically, a streak was described as ‘complex’ if it has more than one flow source, or overlaps with another (e.g. a, b in Fig 1). Streaks that are not complex are described as ‘simple’ (e.g. f in Fig. 1). In their distal regions (Box B in Fig 1) streak were found to be: 1) wide, usually digitate (more often in larger streaks), and 2) narrow where beyond a point of maximum width the deposit narrows (more often in smaller streaks).

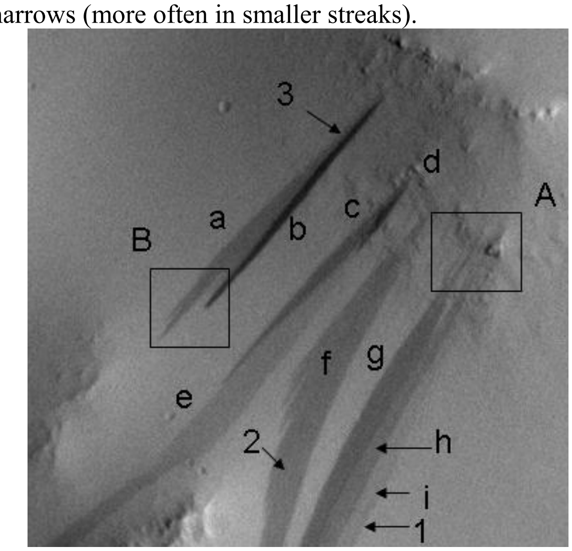

Figure 1. Examples of albedo variations 1-3, complex and simple streaks, source areas (box A) and digitate plus lobate distal margins (Box B). From MOC2-1621-b.

Lengths and widths measurements were conducted in ArcMap and also in NIH Image software. The length was measured along the center of a streak’s width. For digitate streaks, length was measured to the that which extended furthest downslope. Width measurements were made on streaks wider than ~5 pixels. Streaks commonly start and end only 1 pixel wide. For smaller streaks (and for complex streaks where width measurements are difficult), one representative width measurement was obtained at the widest part. In MOC images, determining true versus pixel width is difficult. Areas of sufficiently large 'simple' streaks were measured. Where possible, the angle of spread from proximal to the distal zone was also measured. Analysis of HiRISE images reveals that the size class with the greatest percentage of streaks is <100 m in length and <10 m in width, compared with the 100-200 m in length and 10-20 m in width noted from MOC images [14]. Many small streaks visible in HiRISE images are not resolved in MOC images (Figure 2).

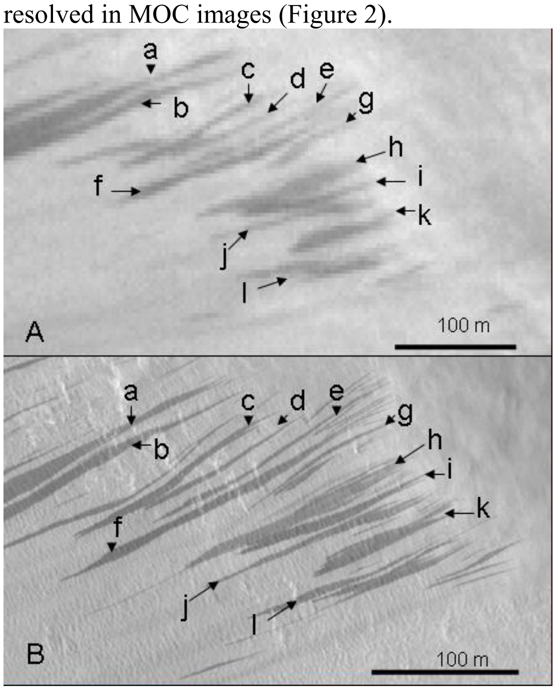

Figure 2. Two views of a slope in Acheron Fossae. A. MOC S13-01131. B. HiRISE PSP_001656-2175.

Slope angles and heights were calculated from MOLA data using 1) raw PEDR files but with elevation profile paths limited to MOLA orbit tracks, 2) MEGDRs in which evelation profiles can be taken along any path but data are interpolated. Streaks tend to occur on slopes with gradients of 10-24° and ranging from ~100 m to ~1100 m in height. It is anticipated that HRSC DEM's will refine these measurements.

Discussion: Dimensional analysis of over 150 streaks at sites on escarpments, craters and aureole units reveals no evidence that those in aureole units can be distinguished from those found elsewhere (Figure 3). Streaks in aureole units can therefore be used to test models of emplacement [5-11]. The aureoles are considered to have originated from Olympus Mons as a result of flank failure [12]. Streaks are found oriented in all cardinal directions on aureole blocks. The disrupted nature of the aureoles with bedding planes at multiple angles is problematic to emplacement models that invoke aquifers, a perched water table or seepage along bedding [e.g. 7]. This suggests that the factors contributing to streak formation appear not to be unique. Can the ubiquitous presence of dust, sand, wind, and gravity along with time explain slope streaks?

Data for Martian streaks are similar to dimensional and morphologic characteristics of naturally occurring gravity and wind-driven dry granular flows on terrestrial sand dunes. The term flow is used to describe a mass of clasts moving downslope in a coherent manner with individual clasts sliding, rolling and saltating. On sand faces, wind has been observed to preferentially deposits sand in hollows on the slope resulting in periodic failing of piles. Resulting flows (lobes or sheets) can form channels near the proximal zone, maintain relatively uniform widths, have a darker albedo than the surroundings that fades with time, can block each other and overlay older flows, can be triggered mid-slope, follow local topography and can anastomize or digitate in the distal region. Multiple flows can form a single larger aprons. Rocks of pebble size and larger can trigger flows and can be 'rafted' on them. Flow speeds (~ 10 cm/sec) are likely less than for gravity-driven dry granular flows on Mars (possibly 1-10 m/sec). Critical to mobility is the size, sphericity and angularity of individual clasts. Analysis of the size distribution of sands observed to flow naturally shows they have the highest weight percent in the 2 Φ (medium) and 3 Φ (fine) class [13]. Those that flow are dinstinguished from those that do not by havinig a high proportion of clasts subrounded to well rounded and with high sphericity. This occurs as a result of physical and chemical weathering. This result indicates that if streaks on Mars are formed by gravity and wind-driven dry granular flows then individual clasts are likely to be rounded with high sphericity. The key factor for clasts on Mars may be the tens to hundreds of million years they are exposed to physical and chemical weathering. This can be tested in the future by in-situ sampling of Martian streaks to examine size, sphericity and angularity.

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MARTIAN GULLIES AND SALTY SIDEWALKS. D. M. Burt[1], L. P. Knauth[2], AND K. H. Wohletz[3] [1]School of Earth and Space Exploration, Arizona State Univ., Box 871404, Tempe, AZ 85287-1404, dmburt@asu.edu, [2]School of Earth and Space Exploration, Arizona State Univ., Box 871404, Tempe, AZ 85287-1404, knauth@asu.edu, [3]Los Alamos National Laboratory, Los Alamos, NM 87545, wohletz@lanl.gov.

Introduction: Martian orbital imaging provides strong evidence for active impact cratering and active fluid flow in gullies [1,2]. Impact cratering and gully flow might appear to be unrelated. We describe a model that relates them, if cratering has excavated chloride salts (directly, or via flash-evaporation of brine or condensation of salt vapor) from beneath ground ice [3]. Tossing salts on ice could cause some ice to melt. Because martian ground ice, except at the poles, lies beneath the surface, slow brine drip caused by frost condensation on excavated salts is inferred (a circum-polar moisture trap). The analogy "snowing on a salty sidewalk can cause melting" illustrates the basic principle. This hypothesis is an earlier melting idea [4] inverted (flipped over) by impact cratering.

Previous investigators [5] have noted that chloride brines, but not sulfate brines (whose freezing point depression is less than 5 C), remain liquid at temperatures over 50 C colder than otherwise (i.e., at temperatures approximating the mean Martian surface temperature of 220 K). However, sulfates, not chlorides, appear to dominate the Martian surface. Our chloride leaching hypothesis accounts for this observation, without invoking sulfuric acid as antifreeze, because acid in contact with basaltic regolith should be unstable [6].

Young Gully Formation: The recent gullies occur in both hemispheres of Mars, at mainly intermediate and some polar latitudes, and (in any given area) commonly concentrated on slopes facing in the same direction [e.g., 1]. Most occur in the walls of old impact craters (an obvious connection to impacts) although they also occur in other slopes. Commonly many gullies originate in the same horizon, generally at a slight break in slope, with the more resistant, blocky layer above having collapsed, forming alcoves. The quantity of aqueous fluid (if any) involved in gully formation appears to have been relatively small, because gullies die out in a distributary debris apron.

Many explanations have been offered for the gullies [7], ranging from ground water (from a shallow or deep aquifer), probably breaking through an ice plug, to surficial snow or ice melting from beneath a cover of dust, to brine melting along an ice-salt interface [4], to explosive CO_2 escape, to wet or dry debris flows [8], and probably others. The latitudinal and directional restriction suggests tight climate constraints (not too hot and not too cold). The variable orbital tilt of Mars and consequent sun angle and climate variability feature in some hypotheses. The extremely low atmospheric pressures and cold temperatures on Mars are problems for any model involving unstable liquid water. Geothermal heating of subsurface aquifers and local solar heating of dark surfaces could warm temperatures, however. Low pressure can be alleviated by dissolving soluble salts [3], which lowers vapor pressures and freezing temperatures, stabilizing liquid water with regard to both freezing and boiling. Also, a flowing mass of even unstable pure liquid water might form a gully before it boiled and froze (then sublimed).

Possible Salt Residues. The very light tone of present-day gully residues [1] suggests surface salts remaining after brine evaporation. (Light-toned dust or mud is another explanation [1,2].) Surface frost is presumably not the cause, because the features have persisted over months or years [1,2]. The lack of light-toned residues on most older gullies suggests that the salt coating (or other cause) is temporary, and has gradually disappeared or become hidden by dust. Many salts absorb enough moisture from the atmosphere to become sticky and attract dust. Deliquescent salts such as $CaCl_2$ can absorb sufficient moisture to liquify and drip into the subsurface. Frost deposited on a variety of salts could melt to brine, yielding the same result. By the same process on a larger scale, according to our model, impact-excavated salts in the circum-polar region could cold-trap moisture or frost that then drips into the subsurface as brine, much as the poles themselves cold-trap ice. Slow brine drip provides a possible source for the small quantities of ground water that presumably formed recent gullies [1,7], and explains their bright, temporary residue. The lack of hydrated sulfate salts detected via near-IR spectra [2] of these deposits does not rule out chloride salts. Sulfate salts would not be expected owing to their extremely poor freezing point depression [5].

Primary Layering and Impact Excavation: If an ancient Martian hydrosphere froze, then ice, brine, and salts should have become segregated by density in the regolith, in that order [3]. Sulfates, being less soluble and far less able to depress freezing points than chlorides [5], would crystallize early. Continued freezing (fractional crystallization), especially near the poles, plus ion exchange of Na-rich brines with the Ca-rich basaltic regolith, would drive brines to compositions rich in salts exhibiting the most freezing-point depression (mainly $CaCl_2$) [3]. If brines finally froze completely (at temperatures probably below -55 C), the interface between upper ice and lower salt would be enriched in $CaCl_2$ plus trace components such as Br, Li, and Zn. Ice sublimation would make the permafrost layer near the equator deeper and thinner. Lateral brine escape, local magmatic heating, or impact excavation could have perturbed this pattern in many areas [4]. Impact excavation of salts is of major interest, because Mars (in common with the Moon and Earth) appears to have been largely resurfaced by impacts about 3.8 billion years ago (when Mars finished losing most of its atmosphere and the surface freeze-dried to close to its present state), and impacting continues today.

Eutectic Melting and Salt Leaching: If salt grains are thrown on ice, ice will melt, unless the temperature lies below the eutectic temperature (the lowest possible melting temperature for a given mixture – always lower for a complex salt mixture than for individual salts). Ignoring waters of hydration, the salt-ice eutectic temperature for NaCl salt is about -21 C, for $CaCl_2$ salt, about -50 C; and for a NaCl-$CaCl_2$ mix, -52 C (with little pressure effect, because all phases are condensed). Obviously, multi-salt eutectic melting is dominated by the salt exhibiting the most freezing point depression ($CaCl_2$). Other common salts behave like NaCl (i.e., they play a secondary role), inasmuch as they likewise exhibit much less freezing point depression than $CaCl_2$ (although at -34 C, $MgCl_2$ comes close, and its eutectic with $CaCl_2$ is -55 C).

On ancient Mars, impacts probably excavated and distributed a wide variety of salts across the surface, but ground ice, even in the past, may have been too deeply buried to react directly with those salts, at least away from the poles. Therefore, the only means of getting those salts back underground, once the ejecta had cooled, would have been to expose the surface salts to frost or snow, including frost arising from deep permafrost sublimation (i.e., from below). On dry, cold Mars, such frost leaching, whether from above or below, would be slow, especially in equatorial regions. On exposure to frost, impact-excavated chlorides (especially $CaCl_2$) should leach first, owing to their greater solubility and much greater freezing point depression compared to sulfates. Selective leaching of impact-excavated chlorides provides one explanation for why the present-day Martian surface is apparently enriched in sulfates vs. chlorides, and for crystal-shaped cavities imaged by the Opportunity rover [9]. Also, measured high Br/Cl ratios might indicate fractional crystallization of chlorides during brine freezing prior to their excavation and leaching [9]. Selective leaching may also explain why active gullies are now a rare, limited feature (few appropriate chloride salts remain near the surface in most places), and contribute to why they are absent from equatorial regions (insufficient surface frost, plus too deep a permafrost layer). Local chloride deposits, as recently inferred [10], might therefore persist in equatorial regions, especially if they were Na-rich. By this hypothesis, an impact that excavated many chlorides could temporarily rejuvenate gully formation, at least in the right climate zone, with wind transport extending the effect. Sporadic impact excavation of chlorides (or gradual climate change) would assist in maintaining at least some gully flow.

Impact Inversion of Layering: Climate constraints are possibly thus explained, but not the tendency of many gullies to originate at about the same horizon. An impermeable layer is required, such as a lava flow or a layer rendered impermeable by, e.g., ice cement. In this regard, impact cratering should invert primary layering by ejecting deep salts on top of impermeable permafrost, thereby possibly provoking future gully formation along that impermeable horizon in the walls of the crater. Also, salts should provide a more durable rock cement than subliming ice, thereby possibly explaining why many gullies emerge from collapsing alcoves. Add positive feedback for eutectic overshoot in heterogeneous mixtures (autocatalysis of melting once some brine has actually formed), or time for the brine to get salty enough to melt its way through an ice plug, and the apparently infrequent and episodic nature of brine release to young gullies might be explained. Finally, any large accumulation of eutectic brine puddled on permafrost away from a slope should melt straight down (while freezing on top), and thus disappear in place – a possible explanation for why only relatively small amounts of fluid, near slopes, appear to be involved in gully formation.

Similar eutectic phenomena may have contributed to other aqueous flow phenomena on Mars, including outwash channels and drainage networks. Dissolved chloride salts thus permit an ancient martian climate as cold as (but probably wetter than) today's.

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MARTIAN GULLIES CREATED BY FLUIDIZATION OF DRY MATERIAL. Y. Cedillo-Flores[1, 2], H. J. Durand-Manterola[1], and R. A. Craddock [3] . Departamento de Física Espacial, Instituto de Geofísica, Universidad Nacional Autonoma de Mexico. UNAM. Coyoacan C.P 04510. D.F. Mexico[1]. (yolanda@soho.igeofcu.unam.mx), (hdurand_manterola@yahoo.com). Posgrado de Geografía, Facultad de Filosofía y Letras, Universidad Nacional Autonoma de Mexico. Circuito Interior. Ciudad Universitaria s/n. C.P 04510. D.F. Mexico[2]. Smithsonian Institution. Nacional Air and Space Museum. Room 3762. 6 th Street and Independence Avenue SW. Washington D.C. 20560-0315 [3] (craddockb@si.edu).

Introduction: Since the discovery of the Martian Gullies [1] several different theories try to explain their origin. However the formation of these features remains poorly understood, and distinctive morphologic variations exist that have often been ignored. The models based on the water, are somewhat controversial since the location of the gullies also appears in regions of very low temperature like so that the water in liquid state has taken part.

Here we present a new model and the experimental results that attempt to create Martian gullies through gaseous fluidization of CO_2 using mixtures of dry granular material and CO_2 ice.

Descrption of the model. Our model suggests this mechanism for the formation of these gullies:

On Mars flows of dry material mixed with dry ice may result from the accumulation of CO_2 ice and dust on slopes during the winter. Increases in temperatures during the spring may cause the CO_2 ice to sublime initiating slope failure and mass-wasting.

Based on our experimental data and observations, we suggest that the formation of at least some gullies may be analagous to pyroclastic flows but colds.

Experiments. Our objectives when making the experiments in laboratory were to produce the fluidization of the sand by gas and to try to reproduce structures type gullies. We constructed a slope with volcanic dry sand. Tubes of 6 mm of diameter perforated in their surface each 9 mm were buried to 4 cm of depth parallel to the surface of the slope.

By these tubes was injected air that bubbled in the sand, allowing that this fluidize and flow like a liquid by the slope (Fig. 1). The air in the laboratory is the substitute of the gaseous CO_2 that is coming off when the carbonic ice being sublimated in Mars. The structures that formed in the laboratory are comparable with the Martian gullies (Fig. 2).

Methodology. Using Mars Orbiter Camera (MOC), Thermal Emission Imaging System (THEMIS) and High Resolution Imaging Science Experiment (HiRise) 28 images and data, we identified 12 gullies with morphologic characteristis similar to those produced from our experiments. These gullies range occur at mid-latitude regions (33° to -71°) and at a range of elevations (-4800 to 2700 meters).

Fig. 1 A gully created by fluidization of dry material. Of the results of this experiment it can be observed that the fluidization produces sliding of the sand.

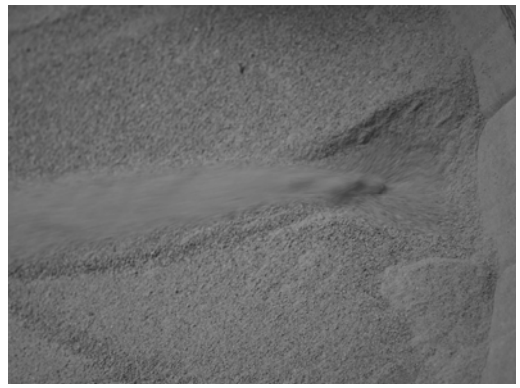
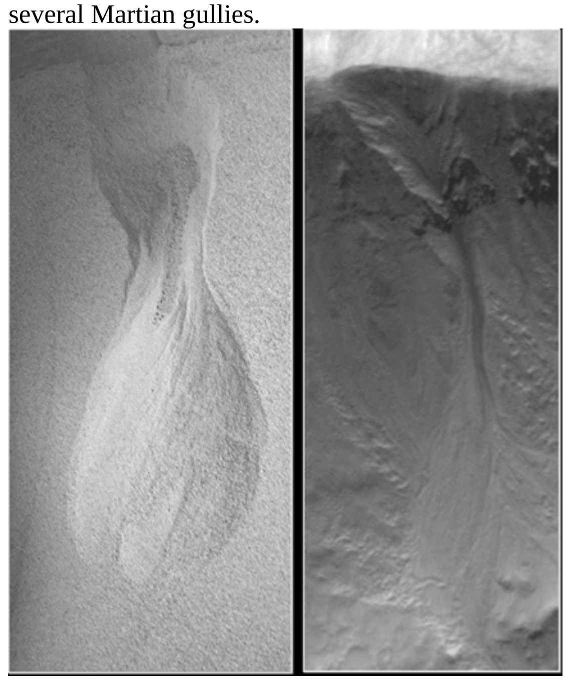


Fig. 2

Comparing the experimental gullies (left) with some Martian gullies (right), several similarities like narrow and winding channels, wide alcoves, wide, narrow and lobate aprons are appraised, similar to which exhibits several Martian gullies.



The different elevation and latitudes in which we found gullies suggest that their existence can be explain by our model.

Discussion: If it existed liquid water on the Martian surface, it had occurred in a very old geologic stage and nevertheless the gullies seem to be young. This appearance is due to the almost absence of small superposed craters of impact in the channels and the cones of detritus and by the comparison of these characteristics with the rest of the Martian surface. Those very old gullies possibly formed by stages during different cycles of high obliquity, between 10^5 to 10^6 years [1] to variations from 15º from 35º when the melted water ice was transported towards the poles.

The gullies later to the dense atmosphere stage had to form by other processes, without intervention of some liquid. The type of morphology periglacial that is observed in numerous regions with gullies suggests frost weathering processes gave rise to the formation of eroded slopes that would represent the first stages of the formation of the gullies. Our model explains better the formation of gullies to different latitudes and in different lands and different directions since the formation processes are external and are adapted to the present conditions of the planet. The existence of gullies without intervention of a liquid is possible since recently the discovery of gullies in the Moon was reported, [2] where the nonexistence of some liquid in its surface is evident due to the extreme conditions of the satellite.

Conclusions. Our scenario allows the formation of gullies in recent times and to a more extensive rank of latitude of what predict the models that require the liquid water presence. By our experimental results we concluded that the fluidized sand by CO_2 is a feasible mechanism to form the gullies in diverse geologic and latitudinal settings and to any altitude.

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LIQUID WATER AND FERRIC SULPHATE ON MARS. V.F. Chevrier[1] and T.S. Altheide[1], [1]W.M. Keck Laboratory for Space Simulation, Arkansas Center for Space and Planetary Science, MUSE 202, University of Arkansas, Fayetteville, AR, 72701, vchevrie@uark.edu, talthei@uark.edu.

Introduction: Numerous geomorphologic features are seen on the martian surface which indicate fluvial activity, both ancient and recent [1,2]. In addition, abundant hydrated minerals have been found across Mars, suggesting a wet past [3,4]. However, given the conditions existing at the surface,liquid water should not have been stable on Mars for any significant period of time.

Yet this only holds true for pure liquid water. Brines involving chlorides would allow liquid water to exist for much longer periods under the harsh surface conditions [5,6]. Concentrated halide solutions involve may remain liquid down to around -50°C, which is approximately the average temperature on Mars. But unlike the surface of Earth, chlorides and other halogens are quite scare on Mars, making such solutions unlikely to have existed in sufficient quantities to cause the observed structures.

The opposite holds true for sulphate minerals. Magnesium sulphates, such as kieserite, are abundant in the martian soils [7]. Other sulphates, including gypsum, have also been found primarily in equatorial regions and in the northern polar regions [8]. However, these minerals are not extremely soluble and can only lower the freezing point of water by less than 5 K [9]. Thus, these solutions are not liquid at temperatures appropriate to Mars.

We suggest that ferric sulphates are an important component in martian fluids. Both iron and sulphate are found in abundance on Mars, so solutions of ferric sulphate should not be rare over geologic history. Indeed, jarosite has been detected in Meridiani Planum [10], and other ferric sulphates have been found in concentrations of up to 30% by weight in some soils in Gusev Crater [11].

Here, we present data demonstrating the stability of ferric sulphate solutions under simulated martian conditions.

Materials and Methods: The following solutions were made using DI water and dried ferric sulphate ($Fe_2(SO_4)_3$): 30, 35, 40, 45, 50, 55, and 60 wt%. Ferric sulphate n-hydrate was dried in an oven for 48 – 72 hours at 110°C under a total pressure of 0.04 bars. The dried sulphate was analyzed using XRD to confirm nature of original phase (composed of amorphous $Fe_2(SO4)_3$, rhomboclase, mikasaite and coquimbite). Weight loss measurements at 400ºC showed that the originally dried ferric sulphate contained ~15 wt% H_2O, and this was allowed for in calculating concentrations of solutions made from the salt.

The evaporation rate of each solution was measured in our Mars Simulation Chamber, where it was exposed to 7 mbar of CO_2 for 0.5 to 3 hours. The average temperature of the atmosphere inside the chamber was 264K. The temperature of each solution tested ranged from 274 to 257K. Humidity inside the chamber was kept from around 1% by carefully injecting CO_2 and pumping. The density of each solution was also determined.

Samples were observed over a range of low temperatures in an attempt to observe any potential crystallization. For the 50 and 60 wt% solutions, CO_2 ice and liquid nitrogen were used to achieve temperatures of 195K and lower.

Results: The evaporation rate for each ferric sulphate solution was determined from the mass loss at low pressure (Fig. 1). Two observations can be noted from these experimental data: first, the evaporation rate strongly decreases at lower temperature. This has been demonstrated under similar conditions for brine solutions of NaCl and $CaCl_2$ [6]. Second, we observe that increasing concentrations decrease the evaporation rate at constant temperature. The 60 wt% concentration demonstrated an evaporation rate 20 times slower than that of pure liquid water at the same temperature.

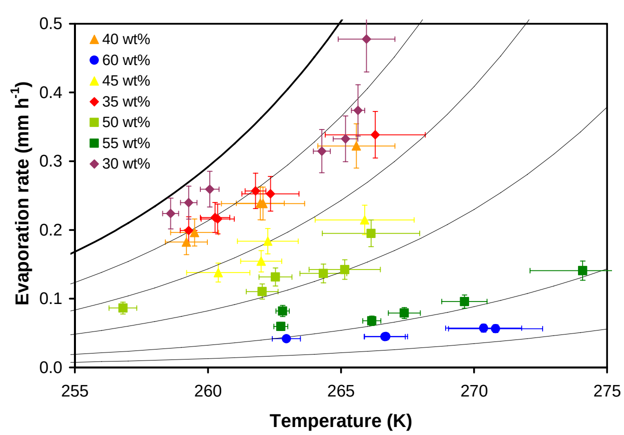

Figure 1: Evaporation rate of ferric sulphate solutions as a function of the sample temperature for various concentrations: 30, 35, 40, 45, 50,, 55 and 60 wt %. The top black line indicates the evaporation rate of pure water calculated using Ingersoll (1970) equation.

The observed eutectic seems to be around 201K for an initial concentratioin of 65 wt% (or 55.3 wt% $Fe_2(SO_4)_3$). When exposed to very low temperatures, these solutions exhibited a strong increase in viscosity with decreasing temperature. This effect was particularly obvious for high concentrations (above 50 wt%) [12].

Discussion: It has been shown before through experiments and theory that the saturation vapor pressure controls the diffusion of water molecules in the CO_2 atmosphere [6,13]. However, in the case of strongly concentrated solutions, the saturation pressure is affected by the lower water activity resulting from interactions between water and ions in the solution. Using our evaporation data we determined the corresponding water activity in the solution (Fig, 2). As expected the activity strongly decreases with increasing $Fe_2(SO_4)_3$ concentrations.

The Pitzer ion interaction model for the $Fe_2(SO_4)_3$-H_2SO_4-H_2O system was used as an independent model to recalculate the water activity [14,15] at very high ionic concentration. The results show that the Pitzer model perfectly fits our data within the error bars (Fig. 2), confirming our approach to the evaporation process and the validity of the Pitzer model at very high concentration.

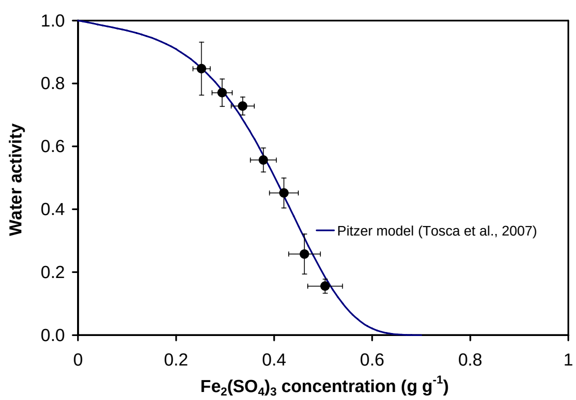

Figure 2: The Pitzer model applied to our kinetic evaporation data. The data fit the model within the margins of error.

The data obtained from each simulation run was used to build a three dimensional model detailing the relationship between concentration and temperature of solution, and the resulting evaporation rate (Figure 3). From this model we were able to determine that at temperatures ranging from 190 – 210 K, a one meter deep pond of 60 wt % ferric sulphate solution would last more than 300,000 years.

Conclusions: Depending on the concentration of these solutions, a freely flowing liquid is still achieved at temperatures dominating the surface of Mars today. The very low evaporation rates of these solutions at such temperatures and concentrations make them perennial at geologic times. We suggest that such solutions should have formed quite easily, and subsequently, may be responsible for formation of liquid-related geomorphologic features on the surface today.

The flow characteristics of these solutions need to be determined in order to access their potential in forming features like gullies. This may be especially relevant to northern latitudes from 30° to 60°, where extensive gully formations are found, where the temperature range allows liquid ferric sulphate solutions to exist and where these solutions would remain quite stable for geologically relevant periods of time.

Reflectance measurements of the viscous states of these solutions at low temperatures should be investigated to determine if indeed they exhibit any spectral properties. This knowledge would be most important for determining the presence of these ferric sulphates within areas demonstrating fluid activity.

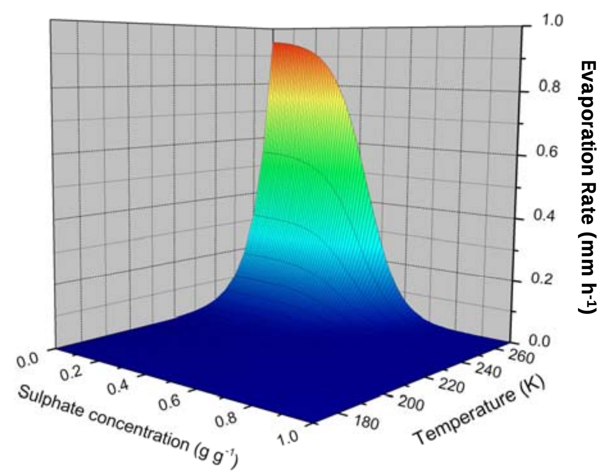

Figure 3: Three dimensional model of ferric sulphate stability under martian surface conditions. Dark blue areas represent most stable conditions.

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ICELANDIC DEBRIS FLOWS AND THEIR RELATIONSHIP TO MARTIAN GULLIES.
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Introduction: Martian gullies and Icelandic debris flow gullies show remarkable similarities in terms of morphology (e.g. both display the alcove – channel – debris apron structure) and in terms of scale (**fig 1**). The aim of this project is to assess whether there is a link between their formation processes through the use of detailed morphological analysis.

A debris flow, by definition, requires fluid [1]: *"Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down slopes in response to gravitational attraction. Both solid and fluid forces vitally influence the motion"*. In Iceland the debris flows are initiated by over-steepening and over-saturation of the regolith mantle, with the source of the water being from snowmelt or storm events [2]. The Icelandic flows occur on regolith mantled slopes of 25-30º on the sides of fjords that are cut into basaltic bedrock: a good analogue for Martian gullies [3].

The gullies above the town of Ísafjörður in the Westfjords region of Iceland provide a unique opportunity to study recent debris flows because the debris flow frequency is unusually high (the minimum return time between large flows is 4 years [2]). On other slopes in Iceland debris flows are much less frequent and/or smaller because they are supply limited, so the regolith on the slopes must reach a certain thickness and steepness before it can slide. By studying very fresh debris flows the influence of post-depositional reworking is minimized.

Approach: A detailed GPS survey was performed of five debris flows located above the town of Ísafjörður and one located in an adjacent valley. An air survey comprising of air photography (at better than 25cm/pixel) and LiDAR (at 1.0-1.5m posting) was commissioned and the data is pending. These data and additional field observations can be compared to datasets from Mars, such as imaging data from HiRise and MOC NA and digital elevation models derived from HiRise stereo-photogrammetry. From a database of MOC NA images [3] the alcove, channel and debris apron have been mapped. The same has been done for with available air photography in Iceland (Westfjords, Eastfjords and north of Akureyri).

Results: Debris flows above Ísafjörður have a typical distinctive morphology, with large (up to 5m high) convex levées and a channel that is irregular in cross section. They are from 200 to 1000 metres long and several metres to tens of metres wide. The deposits of the smallest flow (200m long) have a calculated volume of 143m^3 and those of a medium flow (700m long) of 11600 m^3 (**fig.2**). Sixty-two gullies from across Iceland were mapped, independent of dominant process. The channels have lengths between 209m and 1426m and a sinuosity between 1.0 and 1.2. The alcoves have an area of between 628m^2 and 0.4x10^{6}m^2 (mean 44184m^2).

From preliminary analysis of 71 gullies in three areas (North of Argyre Planitia, Noachis Terra and Terra Sirenum) gully channels on Mars have lengths between 123m and 3256m and they have a sinuosity between 1.0 and 1.1. The alcoves have an area of between 231m^2 and 2.6x10^{6}m^2 (mean 0.5x10^{6}m^2). During observations it has been noted that some of the channels and debris aprons display levées.

Discussion: Initial results suggest that debris flow could be an important factor in the formation of Martian gullies. Gullies in Iceland and on Mars have similarity of scale, in terms of length and alcove size (although the maximum alcove size on Mars is larger). There is also similarity in terms of form, as the sinuosity is very similar. Ongoing work including producing elevation models from HiRise will enable more detailed morphological analysis to assess specific debris flow traits. Erosion and deposition maps like **fig.2** can be made from these elevation models.

The Icelandic debris flow in **fig.2** shows that the slope is an important controlling factor on deposition and erosion patterns. The main erosional part of the channel ceases at 32° and the mixed area of erosion and major deposition ceases at 23°. There is little deposition at lower slope angles as the debris flow has exhausted its material (this is a relatively small flow for Ísafjörður). The flow continues on slopes as low as 8°. The flow does not necessarily follow the line of greatest slope, the breakout on the right of the diagram is following the most optimal path, but the levées have blocked further flow.

Conclusion: The assessment of the 3D shape of the Martian channels, including long sections and cross sections, will be able to tell us the contribution of debris flow to these channels. This analysis is pending photostereogrammetry. By using the same techniques used for terrestrial debris flows the erosion and deposition patterns can be assessed in a manner similar to that demonstrated in **fig.2**. Due to the abundant regolith on Mars any debris flow would be limited by the frequency and intensity of events that supply water, like those in Ísafjörður. The physics of debris flows are not well understood, but the morphology is unique [1,5]. Debris flow does not occur if there is too much or too little water, so the assessment of debris flow morphology on Mars will provide a strong constraint on the water content of flows in Martian gullies.

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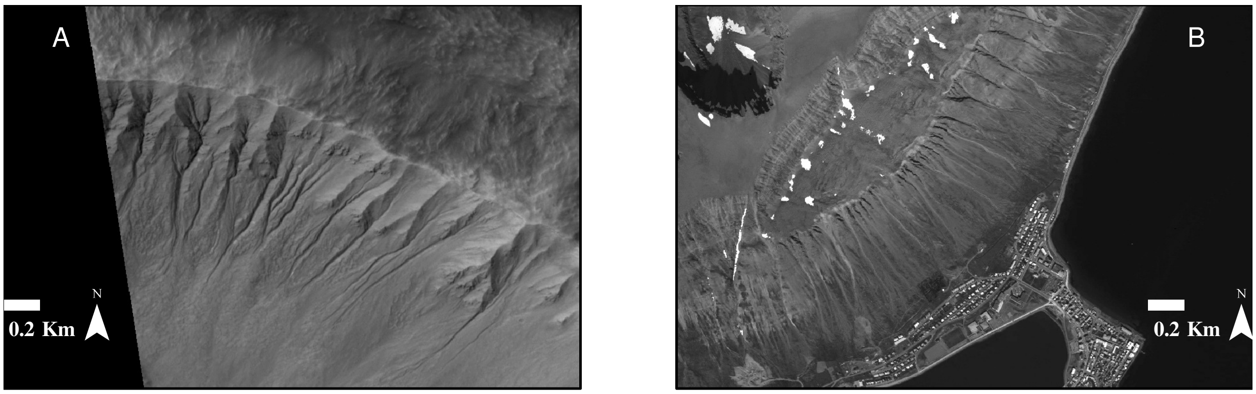

Figure 1: Scale and orientation the same for both; (A) MOC-NA number E1401935 and (B) Air Photograph of Gullies above Ísafjörður N1394, ©LMÍ 1994

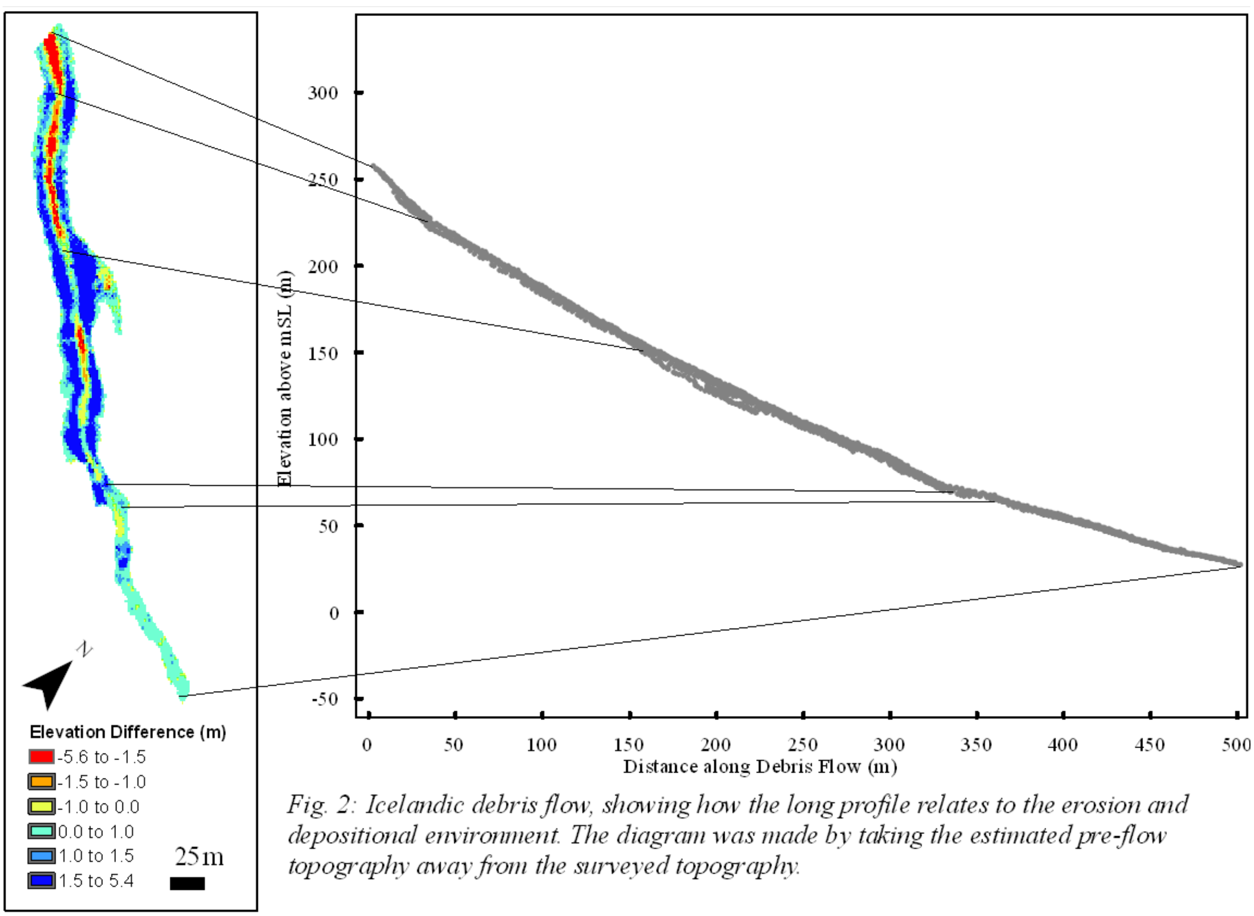

Fig. 2: Icelandic debris flow, showing how the long profile relates to the erosion and depositional environment. The diagram was made by taking the estimated pre-flow topography away from the surveyed topography.

BOUNDARY LAYER MODELS OF MARTIAN HYDROTHERMAL SYSTEMS. Kathleen Craft[1], Robert Lowell[2] and Erin Kraal[2], [1]311 Ferst Drive, School of Earth and Atmospheric Sciences, Georgia Tech, Atlanta, GA 30332-0340, kcraft@gatech.edu, [2]4044 Derring Hall (0420), Department of Geosciences, Virginia Tech, Blacksburg, VA 24061, rlowell@vt.edu and ekraal@vt.edu.

Introduction: Many geomorphic features on the surface of Mars, such as gullies, fans, paleolakes, outflow channels, and deltas, were likely caused by flowing water; however, the source of that water is disputed. One possible water source is a hydrothermal system driven by a magma intrusion. We investigated such hydrothermal systems by first developing analytical, steady state, two-dimensional, thermal boundary layer models in order to determine the mass and heat fluxes near the quasi-vertical boundaries of magma intrusions with heights ranging from 1 to 10 km. We analyzed the effects of various permeabilities and intrusion dimensions on the heat and mass fluxes generated by hydrothermal flow.

Results from our simulation showed, for example, that a 100 km long dike with a depth of ~ 5 km injected into a highly permeable rock would produce ~10^{19} J/yr of heat and transport ~10 km^3/yr of fluid. This and additional mass flux results were compared with hydrographs estimating the volumes of fluid outflow and durations of flow needed to form various observed geomorphic features. The hydrograph comparisons indicate that flow from such hydrothermal systems could be responsible for some fluvial features on Mars including gullies and stepped fans. The relatively small flow volumes, however, suggest it is unlikely that the larger features were formed directly by out flowing hydrothermal fluids. Another possibility though, is that additional fluid may be provided by the melting of subsurface ice as a result of hydrothermal heat transport.

The possibility of ice-melt providing additional water to the hydrothermal system along with other considerations are being modeled in improved numerical, time-dependent simulations using a NaCl-H_2O, two-phase, control-volume code called FISHES that was developed at Georgia Tech. These capabilities simulate more realistic physical behavior including the formation of saline brine and the transport of high enthalpy heat and fluid during the early stages of hydrothermal flow when the melting of subsurface ice might be most efficient. Moreover, since brines are more stable than ordinary water under Martian low pressure and temperature conditions, estimates of the volumes of brine produced during hydrothermal circulation may have important implications for subsequent water storage in the Martian crust.

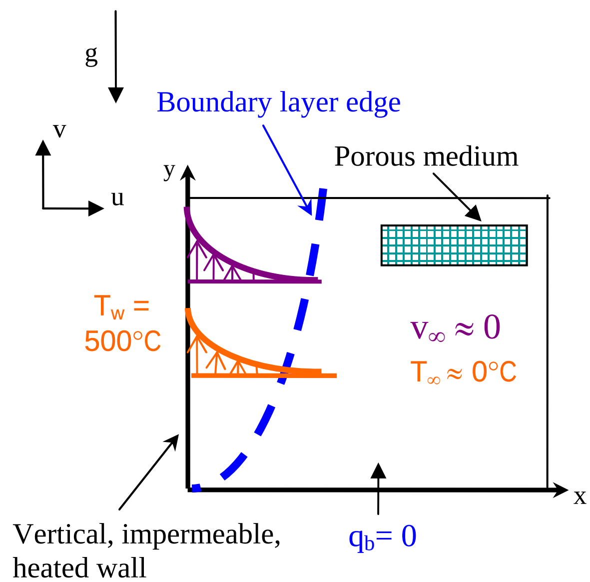

Figure 1. Sketch of model area, boundary conditions and resuling boundary layer. Variable definitions: *u*: horizontal velocity, *v*: vertical velocity, *g*: gravitational acceleration, *x*: horizontal positions, *y*: vertical position, q_b= heat flux, *T*: fluid temperature, T_w fluid temperature at chamber wall, and T_∞ & v_∞ : fluid temperature and vertical velocity respectively, at an infinite distance from chamber wall

GULLIES IN THE EASTERN HELLAS REGION OF MARS. D.A. Crown, L.F. Bleamaster III, and D.C. Berman, Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719, crown@psi.edu.

Introduction. The eastern Hellas region of Mars is characterized by an extensive history of volatile-driven activity, although the style, spatial extent, and magnitude have varied considerably over time [1-5]. Highland volcanoes and cratered terrains dissected by fluvial valleys, extensive sedimentary plains, and the prominent canyons of Dao/Niger, Harmakhis, and Reull Vallis illustrate the widespread and then more localized influence of volatiles, potentially associated with climate change. The regional geology of E Hellas is overprinted with a suite of geologically recent features indicative of contained ice, melting of ice, or its release to the atmosphere. These include lobate debris aprons [e.g., 6] and lineated valley fill, noted as geomorphic indicators of ground ice in analyses of Viking images, as well as ice cemented soils [7], characteristic of the Martian mid-latitudes, and numerous gullies and small flow lobes [8-10]. Gullies in the E Hellas region are found along the walls of the circum-Hellas canyons and along the interior rims of impact craters. The present investigation synthesizes a series of independent analyses of gullies in E Hellas to address their occurrence and potential modes of formation.

Promethei Terra/Eastern Hellas Crater Survey. Part of the E Hellas region (30-60°S, 110-150°E) is being examined (along with other mid-latitude zones [11-12, Berman et al., this issue]) in order to assess the distribution and nature of a suite of degradation features known to be concentrated on crater rims, including gullies, arcuate ridges, and small flow lobes. Numerous, well-developed gully systems are evident on the walls of craters in this region. Gullies and arcuate ridges tend to be found on the walls of craters ~2-30 km in diameter, with small flow lobes found in clusters on the walls of some craters with diameters > 20 km. As in other regions, Berman et al. [11-12] have found gullies, arcuate ridges, and flow lobes on both pole- and equator-facing crater walls, with pole-facing orientations typically between 30 and ~45° latitude and equator-facing orientations typically between ~45 and 60° latitude. These variations have been attributed to cycles of ice deposition, sublimation, and erosion by ice-rich mass wasting and melting of ice. In some cases, pitted and lineated deposits were found to slope away from the base of a gullied crater wall across the crater floor. This work suggests that the occurrence and/or preservation of ice-rich geologic landforms is significantly influenced by insolation history.

Gullies Associated with Dao and Harmakhis Valles. Dao and Harmakhis Valles are parallel canyon systems extending for a combined length of > 2400 km; each extends from ~30 to 45°S and exhibits 5 km of relief from head to terminus. Dao Vallis was described in the initial report on Martian gullies [8] as a location with a significant population and where filled alcoves were common [8, 13]. The vertical distribution of gullies along Dao Vallis was also cited as evidence in support of gully formation involving subsurface aquifers [14]. Relationships between ice-rich mantling deposits, gullies, and viscous flows along Dao Vallis have also previously been noted [9, 13].

Evaluation of MOC narrow-angle images has allowed a systematic characterization of the walls of Dao and Harmakhis Valles [10]. Vallis wall morphology was classified on the basis of the presence and preservation of mantling deposits and occurrence of gullies into the following three types: exposed, mantled, and incised. Gullies are exposed by the removal of semi-competent mantling deposits. Observations suggest a sequence of progressive development from mantled walls to incised mantle and, with further degradation, to walls that display exposed gullies. Analysis of latitude, elevation, and wall orientation for 420 representative sites along vallis walls shows preferential spatial clustering of end-member morphologies: exposed gullies are favored at lower latitude, higher elevation, and on east facing walls, and mantled walls are favored at higher latitude, lower elevation, and on south and southwest facing walls. The observed morphologies and spatial patterns are consistent with the hypothesis that gullies emerge from beneath an ice-rich mantle that is degrading in response to local variations in total solar insolation. These results do not directly address the mechanism of volatile accumulation nor the specific gully formation process, but do suggest that the ice-rich mantling deposits are directly linked to gully formation [see also 15-16], either as 1) the source of volatiles that carve gulles or 2) an insulating layer that allows volatiles to accumulate and act as an erosional agent prior to evaporating or refreezing.

Contemporary Gully Activity in Centauri/Hellas Montes. The discovery of abundant, geologically recent gullies has been a major contribution of the MGS mission [8], and the recent evidence for surface changes along two gullies is especially intriguing, given the interpretation of contemporary flow of liquid water [17]. Comparison of MOC images taken in 1999 and in 2004/2005 shows a new light-toned deposit on the SE wall of an ~10 km diameter crater between Centauri and Hellas Montes (near 38.7°S, 263.3°W) in Promethei Terra. This deposit has digitate lateral and distal margins that appear to have been influenced by small topographic obstacles on the crater wall. Malin et al. [17] attributed the observed morphology to short duration, highly fluid flows of a mixture of water and debris, perhaps triggered by failure of ice-rich rock dams on the crater wall. The light tone was interpreted to be due to frost, fine-grained sediment, or salts.

The crater exhibiting evidence for contemporary activity is located south of a degraded, rugged highland massif in western Promethei Terra and north of Reull Vallis. Global and regional geologic mapping studies characterize this area as variably degraded highland terrain of the Hellas rim [5, 18-19]. Detailed mapping studies of eastern Hellas [1-3, 20] define the unit containing the crater as pitted plains material, with numerous exposures of younger lobate debris aprons nearby, including the prominent elongate "tongue-shaped" apron featured in studies of volatile-rich mass-wasting on Mars [e.g., 6, 21-23]. Pitted plains were observed to fill low-lying regions of the highlands and were interpreted to be water- or ice-rich deposits resulting from coalescence of debris aprons [2-3, 20]. Pits were attributed to removal of volatiles.

The crater has interesting morphologic attributes reflecting its geologic setting and history [24]. It has a well-defined rim with the exception of its NE margin. High-resolution images do not show a distinct ejecta blanket [23] but rather pitted, lineated, and possible deformation textures typically associated with debris aprons [6, 22-23] are observed, particularly to the E and N. To the S, subdued topography consistent with a former lobate ejecta blanket is apparent. Scarps stepping down away from the crater rim indicate significant erosion; layered, smooth deposits confined to local depressions suggest burial by and extensive degradation of surface mantling deposits.

The relief of the crater rim (except to the NE) and exposure of rocky outcrops along the S and SE interior rims suggest that the crater formed in highland bedrock. The crater is inundated by ice-rich debris flows from the N. We interpret the topographic and morphologic characteristics to be due to collapse of the NE crater rim and flow of ice-rich debris into the crater interior. The hummocky nature of the floor is consistent with collapse and infilling. Destabilization of the NE rim likely continued, as rocky outcrops are absent here and the present scarp defining the crater wall cuts ridges that characterize the debris apron surface.

The crater walls, floor, and small topographic depressions in the surrounding surfaces suggest the presence of partly degraded mantling deposits. The north crater wall contains gullies incised into mantling deposits; several filled alcoves are observed. On the NE rim, gullies appear to have redistributed debris apron materials along the crater rim slope. The SE crater wall exhibits faint narrow, shallow lineations, or poorly developed gullies, extending from rocky rim materials. The characteristics of the N (pole-facing) and SE (equator-facing) walls are consistent with observations of the NW and SE walls of Dao and Harmakhis Valles [10]. The highly digitate nature of the light-toned deposit in this crater reflects the subdued south crater wall topography and lack of confinement by a well-incised gully channel.

In considering implications of contemporary gully activity at this site for understanding gully volatile sources, it is important to note that the surface containing the gullied crater is geologically young (i.e., Amazonian) and thought to be ice-rich. Ice may have been emplaced by geologically recent flow of ice/rock mixtures (i.e., debris-covered glaciers, rock glaciers, or ice-rich mass movements), thus obscuring the ultimate source (ground vs. atmosphere) and timing of initial deposition of the volatiles. Given typical debris apron thicknesses of 100-300 meters at their fronts, ice may be abundant in the subsurface down to at least these depths. Even younger ice-rich mantling deposits may be an additional source of volatiles for the gullies in this crater. The diverse evidence for abundant volatile-rich materials near and at the surface suggests that this is not an unlikely location for contemporary activity.

Implications. In E Hellas, gullies occur in a variety of different geologic settings at different latitudes, elevations, and orientations; they dissect different geologic materials. They appear to be the most recent manifestation of an extensive history of volatile-driven erosion. There is a clear spatial correlation with mid-latitude mantling deposits, suggesting significant influence of insolation history. Further study is required to determine the amounts of water needed, water flow history, and the ultimate source of the water.

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GLOBAL SYNTHESIS OF MARS GULLY OBSERVATIONS: EVIDENCE FOR TOP-DOWN FORMATION FROM MORPHOLOGY, DISTRIBUTION, TOPOGRAPHY, AND ANALOGS FROM THE ANTARCTIC DRY VALLEYS. J. L. Dickson[1] and J. W. Head[1], [1]Brown University, Dept. Geo. Sci., Providence, RI, 02912 (jdickson@brown.edu).

Introduction: Since their discovery in Mars Global Surveyor (MGS) data [1], gullies on Mars have generally been treated as anomalously young water-carved features found in the mid-to-high latitudes in each hemisphere. 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 heavily 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 snowpacks, controlled by variations in orbital parameters [7-13].

With the acquisition of new data from Mars Odyssey (MO), Mars Express (MEX) and the Mars Reconnaisaince Orbiter (MRO), the local and global distribution of gullies has been brought into greater focus. 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]. In this contribution 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 more trends indicative of climate control on gully formation.

Slopes. Steep slopes (> 20°) are essential for gully formation on Mars. Previous analyses using 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].

Elevation. Global MOLA data reveal a distinct topographic ceiling for gully formation. 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, and surface deposits of ice/snow are more likely to sublimate at lower atmospheric pressures. Groundwater beneath a superposing ~200 m layer should be less affected by local pressure conditions, though 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 density at lower elevations due to groundwater availability and atmospheric pressures more conducive to accumulation and melting of volatiles. This contradiction is explained by the snowmelt model due to 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. 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 dominantly *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 (if they have been formed by surface melting) 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 clear 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 [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 is true 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 unlikely to be present.

HiRISE data have revealed further details concerning the formation and evolution of gullies. Diagnostic fluvial bedforms such as meanders, pointbars, and streamlined islands have been observed [2]. HiRISE has confirmed 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]. 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 are 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 components to gully formation in the ADV and on Mars are the same: steep slopes, low elevation, and orientation angles that allow for both the accumulation and melting of surface snow/ice deposits.

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SIMULATION EXPERIMENTS OF MARS' GULLIES. J. Dixon[1,2], K. A. Coleman[1], K. L. Howe [3], L. A. Roe[1,4], V. Chevrier[1]. [1]W.M. Keck Laboratory for Space Simulations, Arkansas Center for Space and Planetary Science, MUSE 202, Fayetteville, Arkansas, USA < ksacolem@uark.edu>, [2]Dept. of Geological Sciences, 113 Ozark hall, University of Arkansas, Fayetteville, Arkansas, USA, [3]State University of New York at Geneseo, [4]Dept. of Mechanical Engineering, University of Arkansas, Fayetteville, AR, USA.

Introduction: Gullies are widespread on slopes on the surface of Mars [1] and have been investigated by numerous workers [2-4], yet their origins remain elusive [5-9]. In an attempt to pursue the potential of a water-based origin for these forms, we undertook a series of flume experiments at Earth surface temperatures and pressures. Our objectives are to produce forms that resemble those most commonly observed on Mars, documenting their morphometric characteristics, and identifying any statistically significant relationships between form and controlling factors of slope and flow rate. These gully experiments will be used to verify numerical models developed by Ulrich et al. (meeting) [10], which will be used to scale the simulations to martian conditions and gully sizes.

Methods: Our experiments were conducted in a 1m x 1.5m flume filled with medium grain size sand. The sand was given a 10° - 30° range of slope angles, corresponding to the range for gullies on Mars [4]. Water with a constant head fed onto the slopes through 5 mm tubing just below the surface at the top of the slope. Gullies were produced at three slopes with four flow rates at each slope angle.

Camera and light mounting arms were attached to the flume so that a Canon Power Shot A710IS camera could record each gully from multiple viewing and lighting angles. A 15 cm ruler and label identifying run number and run conditions was included in the photograph. Eighteen morphometric parameters were identified and measured on each gully on which they occurred. These were width, depth, and length of the alcove, channel and apron. As on Mars, not all gullies exhibited all of these morphometric elements [1].

Results and Discussion: Two principal gully forms were successfully reproduced: shorter gullies (Fig. 1a) and long/narrow gullies (Fig. 1b). The gullies in our experiments displayed development of the fundamental morphological components observed on Mars: alcove, channel, and apron [1] and low flow gullies displayed a prominent steep apron toe slope (Fig, 1a) while higher flow gullies did not.

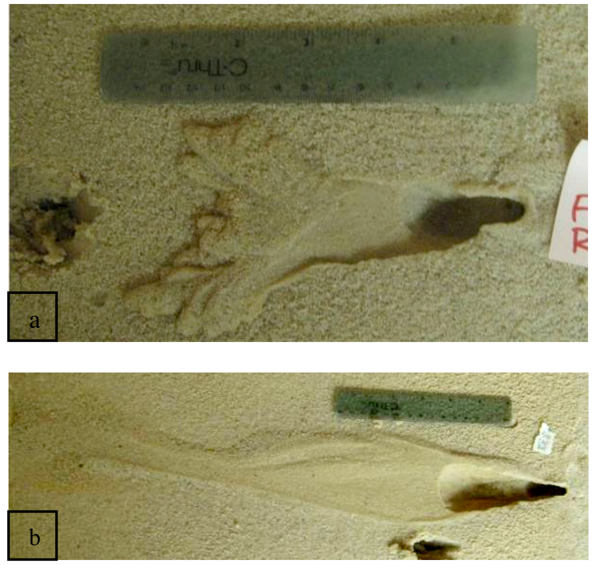

Figure 1 Gully forms produced in our experimental flume. a) A short gully produced at a low flow rate (445 ml/min) on a higher slope (30°). b) A longer gully form produced at a higher flow rate (1265 ml/min) on a lower slope (10°). Note the 15 cm ruler for scale.

Our initial experiments demonstrate that gullies with morphologies that resemble those of Mars can be produced by running water within an experimental flume and that it is possible to quantitatively identify controlling factors on gully morphology at earth temperatures and pressures.

Statistically significant relationships were found between flow rate and form. At lower flow rates, gullies were shorter while those produced at higher flow rates were comparatively longer (Fig. 2).This relationship occurs because increasing flow rate causes more fluid to flow through the gully in a give period of time. Incomplete drying of the sand between runs seems to be related to the two outliers above 40 cm in the middle two flow rates because decreased infiltration causes more liquid to remain in the gully.

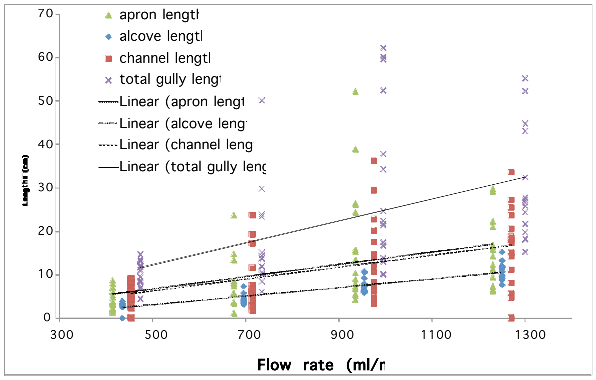

Fig. 2 Increasing flow correlates with increasing lengths of each gully component. Flow rates have been slightly staggered from their true values of 445, 705, 965, 1260 ml/min for clarity. Outliers above 40 cm are probably caused by saturation of the subsurface.

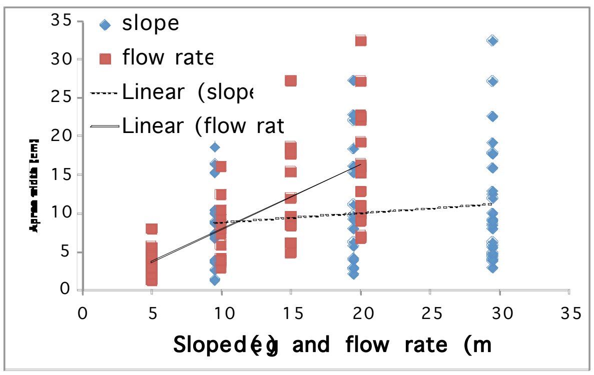

Fig. 3 As flow rate increases the width of the gully apron increases, but as slope angle increases this width does not show the same increase.

Flow rate was found to be correlated with apron width (Fig. 3). Increasing apron widths occurred with increasing flow rate. This relationship occurs because with higher flow more sediment is moved through the gully and subsequently deposited in a larger apron. We would expect this general trend to apply on other planetary surfaces.

Statistically significant relationships were found between slope and form. At lower slope, gullies are comparatively longer than at high slopes. As slope angle increases, gully length parameters decrease. For gullies on 10° slopes, the average length-width ratio is 10.39 while on 20° slopes the average is 8.45 and on 30° slopes it is 5.96. This relationship occurs because as slope angle increases, the amount of accommodation space increases. As sediments collect, the velocity of the flow will decrease so sediments are dropped creating a wide, thick apron (Fig. 3 and 4) and preventing elongation of the gully in a manner similar to the distributary mouth bar on a delta. Other parameters show no relation to slope or flow rate.

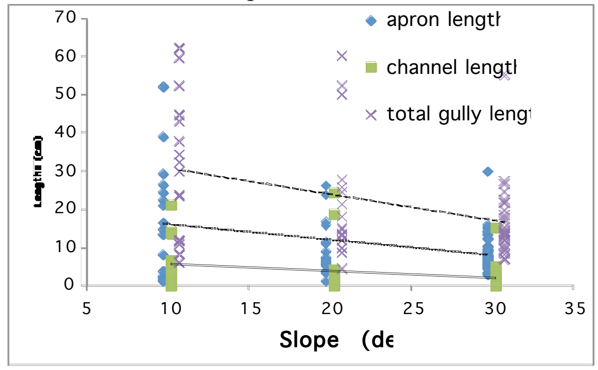

Fig. 4 Increasing slope angle correlates with decreasing length of gully components and the total gully length. Slopes have been staggered slightly from their true values of 10, 20, 30 degrees for clarity.

Conclusion: Forms similar to those observed on Mars can be created by running water in the laboratory flume under terresterial conditions. Morphometric parameters can be measured and permit identification of controlling factors. Experimental simulation of martian gullies appears possible with proper scaling of experimental parameters. Although flume gully parameters are not directly scalable to Mars, they will be used to verify the results of numerical models that will be used to develop dimensionless parameters for the flows. These scalable parameters will be used to develop the next round of flume experiments, to be performed in our Mars Environmental Chamber, with outputs that can be scaled to the gullies on Mars.

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STUDY OF GULLY-EXPOSED SITES ON MARS BY OMEGA IMAGES. Chaojun Fan[1], Dirk Schulze-Makuch[1] and Hongjie Xie[2], [1]SEES, Washington State University, Pullman, WA 99164, USA, cfan1@wsu.edu, dirksm@wsu.edu, [2]LRSG, University of Texas at San Antonio, San Antonio, TX 78249, USA, Hongjie.Xie@utsa.edu

Introduction: Gully features were first observed by Malin and Edgett [1] on Mars Orbiter Camera (MOC) images and in detail examined by Heldtmann et al. [2]. Two categories of mechanisms of gully formation were proposed: liquid water related and non-liquid water related. The mechanisms of these features have been discussed primarily based on geomorphology and fluid mechanics. Here, we examined four selected gully sites using Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA) imagery. Our hypothesis is that if liquid water has been the fluid agent, then we should be able to detect a stronger water signature by using hyperspectral images.

Methods: We analyzed hyperspectra of OMEGA images and measured the absorption band depths (ABD) of water on a pixel scale (Fig 1), and interpreted the abundances of water components in the surface soils and rocks at the gully-exposed sites and its surrounding areas. We assumed that the water's ABD is proportional to the abundance of water-related materials by which the absorption is produced. This is generally true for a small area where the environmental effects are the same and the affect of grain size is limited [3]. In our study, we focused our analysis on absorption features of wavelengths ranging from 0.97 to 2.55 µm with a total of 114 channels of OMEGA images. In this wavelength range the presence of H_2O and/or OH can cause a number of absorptions. Isolated water molecules have 0.942, 1.135, 1.379, 1.454, and ~1.875 µm absorption bands [4]. The overtones of OH stretching vibration are near 1.40 and 0.95 µm [5]. In water ice, the overtones and combination bands are shifted to 1.04, 1.25, 1.50-1.66 and 1.96-2.05 µm [5]. Combination vibrations involving the OH stretch and metal-O-H bend cause absorptions at 2–2.5 µm [6].

Investigation of selected sites: Four gully-exposed sites have been investigated in the study (Fig. 2).

1. Terra Sirenum (36.5ºS/161.8ºW). Gullies observed at 36.5ºS/161.8ºW match the pixel X: 106/Y: 139 of the OMEGA image Orb1408_5. One pixel in the OMEGA image is about the same size as the crater itself. The target pixel and its 5 surrounding rings of pixels were selected as regions of interest. Ten absorption bands were observed and examined, among them water- related bands are at 1.04, 1.40, 1.50, 1.80, 1.87, 1.91, 2.04 and 2.18 µm. Our measurements indicate that in the target pixel the ABDs of water-related bands are larger or equal to those of its adjacent pixel rings except in the atmospheric water vapour band (1.87 µm). The variations from the target pixel to the adjacent pixel rings are 14.3%, 10%, 33.3%, 3.4%, 10%, and 8.3%, for the 1.04, 1.50, 1.80, 1.91, 2.04 and 2.18 µm bands, respectively. The variations are 33.3% from the target pixel to the 2nd and 60% to the 4th pixel ring for the 1.40 µm band. At 1.04, 1.40 and 2.04 µm the ABDs decrease as the distances increase from the target site, with a correlation coefficient of 0.85, 0.94 and 0.82, respectively.

2. A high southern latitude site (70.8ºS/355.8ºW). Gullies observed at 70.8°S/355.8°W matches the pixel X:80/Y:304 in OMEGA image orb1899_2. Like the first site, the ABDs of water-related bands are the greatest at the target site and 15.2%, 11.4%, 15.6%, 9.5% and 2.9% greater than the adjacent ring for the 1.21, 2.04, 2.18, 2.29 and 2.34 µm bands. They decrease gradually away from the target site with correlation coefficients within 0.84 to 0.94. The ABD of water vapour (1.87 µm) was also significant at the target site and decreased with a high correlation coefficient (0.94) to the surrounding areas. More water vapour likely accumulated in the atmosphere above the target site due to sublimation because the image was taken in the spring time of the southern hemisphere.

3. Sirenum Fossae region (38.5ºS/171.3ºW). Gullies observed at 38.5°S/171.3°W match two pixels X:71-72/Y:1 in OMEGA image orb1441_5. The absorptions of eleven bands were examined, among them the water-related absorption bands at 1.21, 1.34, 1.41, 1.50, 1.80, 1.87, 1.91, 2.04 and 2.18 µm. The ABDs of water at the target site are equal to or greater than the adjacent pixel ring except the absorption of atmospheric water at 1.87 µm. For example, the ABD of the 1.41 µm band at the target site is 23% greater than the adjacent pixel ring. The ABDs at 1.41, 1.50, 1.80 and 2.18 µm decrease from the target site to the outlying pixel rings with correlation coefficients of 0.82 to 0.89.

4. Upper Dao Vallis (33.1ºS/266.8ºW). Alcoves observed at 33.1ºS/266.8ºW match four pixels X: 125-126/Y:33-34 in the OMEGA image orb1464_4. The ABDs of water are greater at the target site than the surrounding pixel rings among ten absorptions examined. The ABDs of 1.04, 1.41, 1.51, and 2.04 µm show spatial variations with correlation coefficients above 0.9.

Discussion: The ABD at ~1.91 µm was the most obvious among the absorptions of water-related bands and its depths was about 3% greater at the target sites than the adjacent areas for three investigated sites. The

ABD at 1.80 µm was 33.3% greater at the target site than the adjacent areas at one site and showed a higher correlation (0.884) with respect to the target site at another site. Absorption at 1.80 um is not significantly overlapped by bands from other common minerals [6], thus it is a good diagnostic absorption for water. The absorptions at the ~1.40 µm were the largest at the target sites and decreased to the surrounding areas for three investigated sites with correlation coefficients of 0.82–0.94. The ABDs of water ice at the 1.04, ~1.50 and ~2.04 µm were all greater at the target sites than the surrounding areas with correlation coefficients for most investigated sites between 0.82 and 0.97, except one site for each band. The absorption of 1.50 µm is thought as the best band to monitor water ice on the Martian surface with OMEGA [7]. The ABD at 2.18 µm was the greatest at the target sites and about 6.3–13.3% greater than the surrounding areas for three investigated sites. The ABDs at 1.21, 2.18, 2.29 and 2.34 µm were about 2.9–15.6% greater at the target site than the adjacent rings as investigated at the site of 70.8ºS/355.8ºW. They showed high correlation (correlation coefficient of 0.84–0.93). The accumulation of water at the gully-exposed sites implies that liquid water was once likely more active at the site than its surrounding regions because the liquid water movement near the subsurface would freeze in the pore space of loose materials or incorporate water into minerals by chemical alterations.

Conclusion: The depth of the water related absorption bands was observed to be greater at the gully-exposed site than in its surrounding areas, thus supporting the conclusion that the formation of gullies has involved processes associated with liquid water. Subtle variations of ABDs, especially their trends provide insights in identifying small differences of materials with very similar reflectance spectra due to the sensitivity of imaging spectroscopy to material composition and structure. Further study of hyperspectral images is desirable with higher spatial and spectral resolutions (e.g. CRISM) for better understanding of the water occurrence at gully sites.

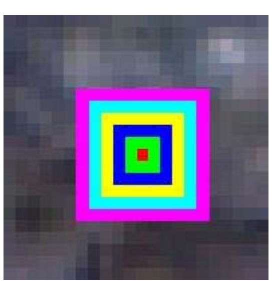

Fig. 1 Schematic location of a gully-exposed site as a pixel in the center (red) and its surrounding areas as pixel rings (the 1^{st}, green to the 5^{th}, magenta) in an OMEGA image.

Acknowledgement: We thank the ESA/OMEGA and MGS/MOC teams for making available the OMEGA and the MOC images.

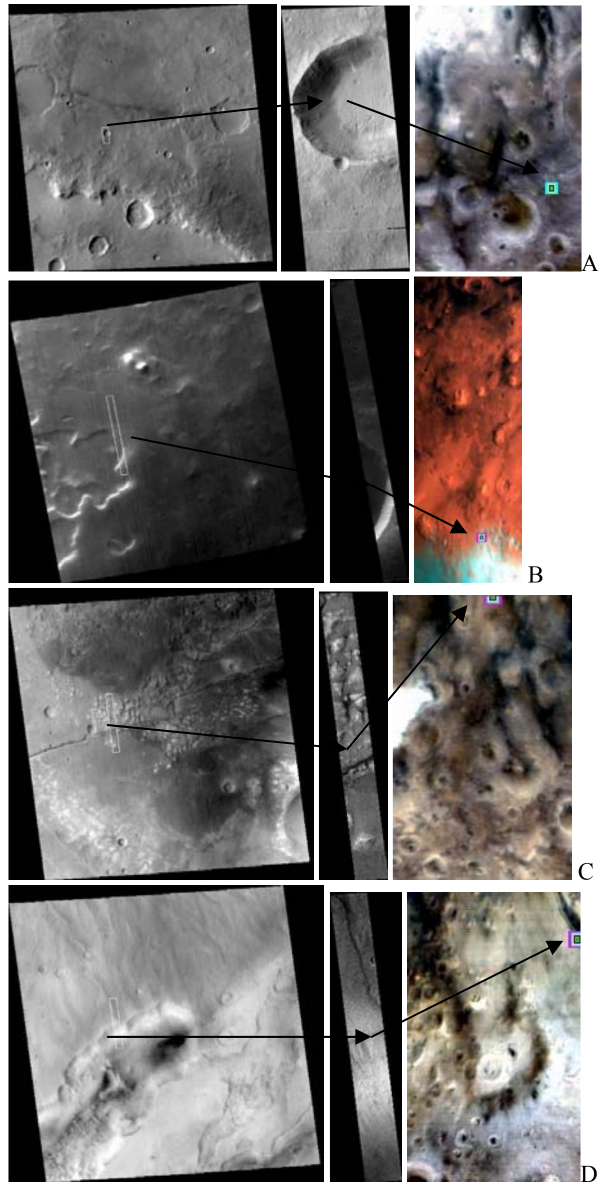

Fig. 2 MOC wide- (left) and narrow- (middle) angle images and OMEGA image (right) of investigated sites. Scale: ~ 10 km (left) : ~2.0 km (middle) : ~ 100 km (right). A) S05-01464, S05-01463, and orb0140_5; B) M03-02709, M03-02710, and orb1899_2; C) M07-02910, M07-02909, and orb1441_5; D) M11-01620, M11-01601, and orb1464_4.

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GULLIES AS A SOURCE OF AEOLIAN SAND IN THE SOUTHERN MIDLATITUDES. L. K. Fenton, Carl Sagan Center, NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035, lfenton@carlsagancenter.org.

Introduction: Although gullies are common features in the midlatitudes of Mars [e.g., 1-3], it is not yet clear how the sediments they mobilize contribute to the sedimentary processes that shape the martian landscape. Sand dunes are widely distributed across the southern highlands [e.g., 4], suggesting that at least one significant source of aeolian sand is/was present. This work investigates gullies as a potential source of aeolian materials, particularly the dark mafic sand that comprises the many dune fields in the southern midlatitudes of Mars.

Background: Aeolian sand sources are regions from which sand-size grains (0.625 µm – 2 mm) are created (or made available by erosion) and exposed to a wind regime strong enough to saltate the grains. On Earth, most such sand is formed by weathering and erosion of crustal rocks (mostly quartz and feldspar) [e.g., 5]. Most sand is formed and concentrated by moving water (thus its prevalence along beaches, riverbeds, and lakebeds) [5], but other major formation processes include erosion of old sandstones (some of which are themselves former dunes), glacial scour, chemical precipitation (forming carbonate or gypsum sands), and volcanic ash.

Establishing the source regions of martian sand is an integral part of understanding the sedimentary history of that planet. Sand sources on Mars are not as well understood as those on Earth, but they appear to consist of layered materials that are eroding away and exposing sand (among other materials) to the wind [e.g., 6-9]. The processes forming and exposing these materials are not well constrained, but it is possible that moving water has played a role in producing and mobilizing sand on Mars. In a study of dune fields in Noachis Terra, a region in the southern midlatitudes ranging from 0º-60º E, 30º-65º S, [8] concluded that the only identifiable aeolian sand source was gullies (see Figure 1), although it is possible that in the past other erosional processes (now defunct, or with exhausted source regions) have made sand available for transport by the wind. The presence of sand on gully deposits is supported by the discovery of springtime defrosting spots on gullies, which are most commonly observed on dunes (indeed, these defrosting spots may be diagnostic of sand) [10].

Method: Starting with the distribution of gullies in the southern hemisphere [2, 11], all identified gullies were compared with the positions of known dune fields [4]. Because many small dune fields were not identified in a global-scale study [4], MOC narrow angle and THEMIS VIS images near each identified gully (or gully system) were inspected for dunes. In many cases, dunes and dune fields were not identified near the gullies, but accumulations of dark sand were present (e.g., Figure 2). Such accumulations were not included in the list of gullies near dune fields, although the presence of the dark sand does indicate some amount of local aeolian activity.

Results: Figure 3 shows the distribution of Heldmann et al.'s gullies. Gullies with nearby dunes are shown in yellow; all other gullies are shown in red. Of the 1037 gullies/gully systems identified in the southern hemisphere, 289 (28%) are located in the immediate vicinity of a dune field. Many dune fields (not shown) do not appear to be associated with gullies.

Discussion: To first order, it does not appear that locations with gullies necessarily correspond to locations with dune fields (although the examples of images including both are suggestive of this). However, the distribution of MOC images (which were used to identify gullies [2, 11]) is nonuniform over the martian surface. Crater walls were imaged less often than crater interiors, and it is on crater walls where gullies appear to be most concentrated. It is possible that with further coverage by CTX and HiRISE, a closer correspondence between gullies and dunes may be established.

In addition, aeolian sand is nearly ubiquitous in small quantities in many regions on Mars. It is possible that gullies are responsible for eroding much of this sand, but that the supply is not great enough (or perhaps the wind is not strong enough) in all places to produce sand dunes.

Dark dunes are present across much of the martian surface. Because they are more widespread than gullies, it is clear that gullies cannot be a major source of dune sand on a global scale. Although a correlation cannot be established with available data, it is likely that gullies provide at least a minor component of the sand that composes aeolian sand dunes in the southern midlatitudes.

References: [1] Malin, M. C. and Edgett, K. S. (2000) *Science, 288,* 2330-2335. [2] Heldmann J. L. et al. (2007) *Icarus, 188,* 324-344. [3] Balme, M. (2006) *JGR,* 111, E05001, doi:10.1029/2005JE002607. [4] Hayward, R. K. et al., *JGR 112,* doi:10.1029/2007JE002943, in press. [5] Pye, K. and Tsoar, H. (1990) *Aeolian Sand and Sand Dunes,* 396 pp. [6] Ruff, S. W. et al. (2001), *JGR, 106*(E10), 23,921-23,927. [7] Byrne and Murray (2002) [8] Fenton, L. K. (2005) *JGR, 110,* E11004, doi:10.1029/2005JE002436. [9] Fergason, R. L. et al. (2006), *JGR, 111,* E12004, doi:10.1029/2006JE002735. [10]

Bridges, N. et al. (2001), *LPSC XXXII*, Abst. #2126. [11] Heldmann, J. L. (2004), *Icarus* *168,* 285-304.

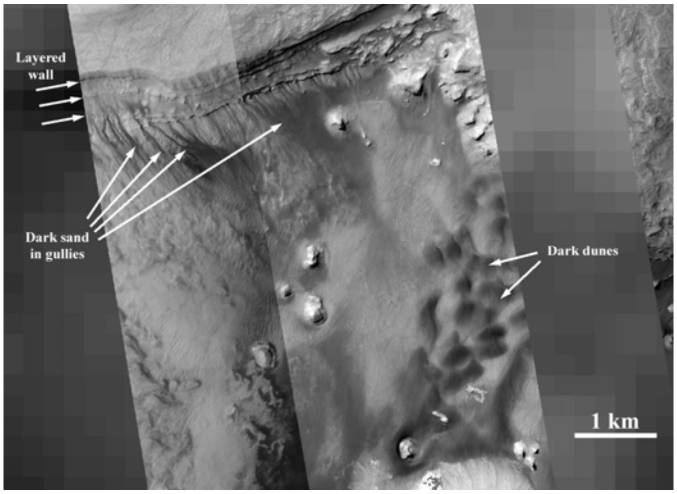

Figure 1. MOC images E11/00389 and R14/01181, showing gullies containing dark sand that likely contributes to aeolian sand dunes at the base of the cliff.

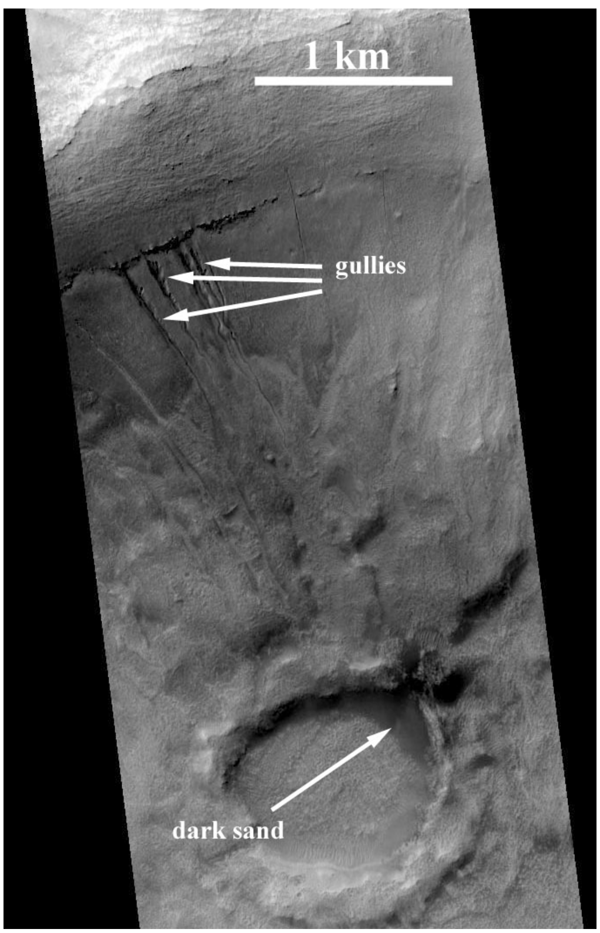

Figure 2. Gullies and dark sand (MOC image R16/01269). Even though no dunes are present, dark sand has still accumulated at the base of the cliff.

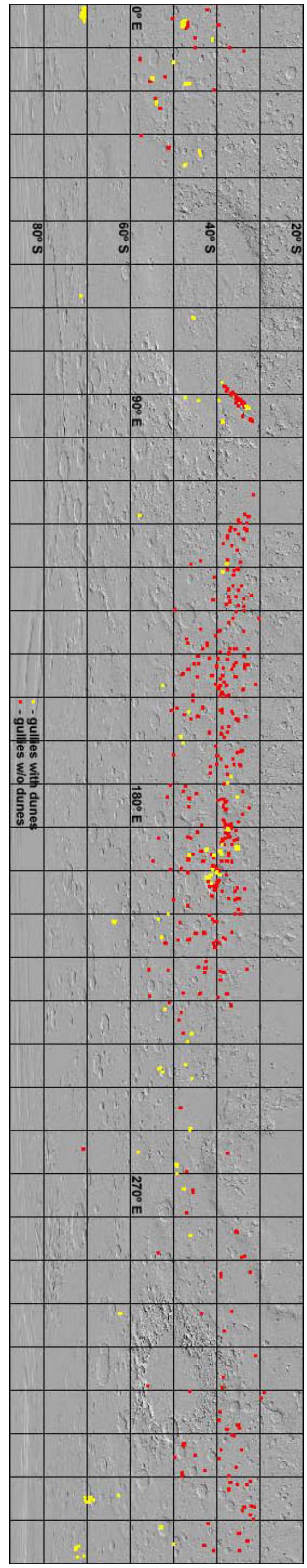

Figure 3. Distribution of gullies/gully systems in the southern hemisphere, showing those that may be associated with dune fields.

FORMATION OF GULLIES BY LOCAL MELTING OF WATER ICE: CLUES FROM CLIMATE MODELLING.

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Introduction: Using a numerical Global Climate Model designed to simulate Mars water cycle (water vapor, clouds, surface ice) and local models able to represent the local conditions on slopes, we study the environment in Mars gullies locations, and investigate possible purely climatic scenarios that could have lead to local melting of water ice and the formation of debris flows in recent Mars history. We also first review how recent climate changes may have transported and accumulate large amount of ice in various locations on Mars, in particular where gullies are now observed.

Recent climate changes and ice depositions.

At present, Mars is a relatively dry planet on which even surface water ice is not stable (for more than a few days) outside the Polar Regions.

However, geologically recent glacier-like landforms have been identified in the tropics and mid-latitudes of Mars, and an ice-rich mantling seems to cover both hemisphere above 60°latitude. In the past few years, we have used the LMD Global Climate Model initially designed to simulate Mars current climate [1] and the details of the present-day Mars water cycle [2] to simulate how such large amount of ice could have been transported and accumulated by the current Mars Climate System.

We first found that at high obliquity (e.g. 45°), the model predicts the accumulation of ice and the formation of glaciers on the western flanks of the great Tharsis volcanoes if the current northern polar cap remains a source of water, and in eastern Hellas if a water ice polar cap is assumed to be present at the southern pole [3] This is precisely where the most characteristic Glacier-like features have been discovered. Eastern Hellas is also the locations of many gullies.

Using the same model, we also discovered that when Mars returns to lower obliquity conditions, the low and mid-latitude glaciers becomes unstable, partially sublimes and tend to accumulate in both hemisphere above 60° [4] if the atmosphere is assumed to be clear. With a more dusty atmosphere (which is likely at high obliquity) the models favors the formation of ice accumulation in the mid Martian latitudes [5]. The exact location of the accumulation strongly depends on the eccentricity and season of perihelion (Figure 1).

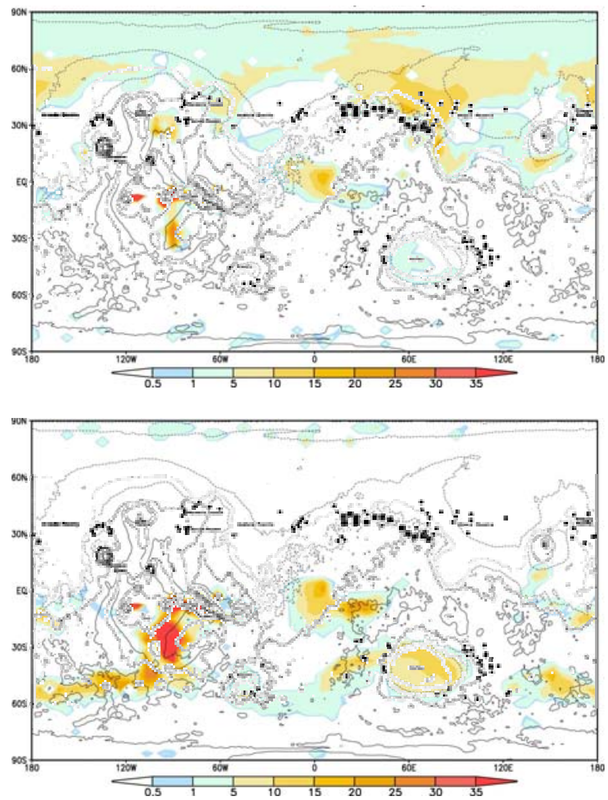

Figure 1. Examples of ice deposition (mm/year) assuming a dusty atmosphere (dust opacity =2.5), an obliquity of 35°, and remnant glaciers in the Tharsis region. Depending of the season of perihelion, ice will tend to accumulate in the northern mid-latitudes (Top : Ls(perihelion)=270°) or in the southern mid-latitudes (Bottom Ls(perihelion)=90°). The black squares illustrate the locations of lobate debris aprons mapped by Squyres [6]

Global climate simulations and gullies

Our "past climate" simulations can be used to better understand the kind of environment that could have led to the formation of gullies in the recent Mars history. In particular, we show that the climate conditions (temperature, water vapor, stability of surface and near-surface ice) were much more favorable to local melting of water when the obliquity was higher than 30°, than on present-day Mars.

Local climate simulations and gullies

On Mars, the local surface and subsurface environment strongly varies with the surface slope and its orientation. In a previous work [7] we showed that the only places on Mars where the daily mean temperature has been above the melting point of water during the past obliquity cycles are the mid and high latitudes above 30°, especially on pole ward-facing slopes, except in the polar region where warm temperatures are found on both southward and northward facing slopes. The corresponding thermal wave could have melted the ground ice over several tens of centimetres (the fact that poleward-facing slopes receive more sunlight and get warmer at high obliquity in the summer is due to the pole being tilted toward the sun). This preferential orientation and the latitudinal distribution of the warmest near-surface temperature coincide with the location of the observed Martian gullies, suggesting a link between near-surface warming and debris flows.

It must be noted that, even though the poleward facing slopes can get very warm around summer solstice at high obliquity, they remain colder on a yearly average than any other exposition. For instance, at 35° obliquity, a 30° poleward slope receives about 100 W m^{-2} along the year, compared to almost 150 W m^{-2} on a flat surface. When studying other aspect of the climate system like the CO2 cycle and the water ice cycle, this means that both CO2 ice and water ice tends to be more stable on such slopes. This strongly favours the formation of gullies. For instance, around summer solstice, any ground or ice layer which is progressively warmed toward 0°C tends to sublime or lose its water trapped in its pores through the diffusion of H2O molecules into the atmosphere. However, on poleward-facing slopes, the seasonal CO2 ice layer accumulated during fall and winter maintains the surface at the low CO2 frost point temperature until late spring (see Fig. 3 in [7]). These slopes are covered by seasonal CO2 ice later in the season than other slopes, and get free of ice only in summer when the solar flux is already strong. The disappearance of CO2 ice allows a sudden warming of the surface and of the near subsurface which reach 0°C in a few days. If any water ice is present on the surface or in the soil, it have less time to completely sublime or diffuse out of the ground, especially since the atmosphere water content is then near its peak (diffusion primarily depends on the ground – atmosphere water density gradient). In addition, poleward slopes act as cold trap for the water ice sublimed for nearby area, and this also favour the accumulation of ice before they get warm.

On this basis, and since Mars at high obliquity sometime corresponded to an environment favorable to surface ice and/or near-surface ice, Mars gullies could have resulted from the melting of the ice at high obliquity. Figure 2 presents a summary of the environmental conditions on poleward facing slope at high obliquity that may have enable the formation of gullies.

To better understand this scenario, we have develloped a high resolution 3D meso-scale model [8] which can be imbeded in our Global climate model and which includes all the physical parameterisation needed to simulate the behaviour of surface and subsurface ice in a small crater at high obliquity, for instance. We plan to present preliminary results of such simulations.

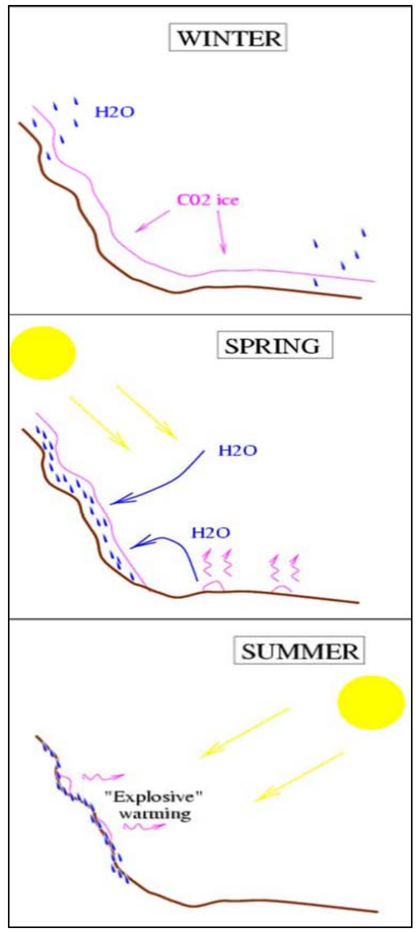

Figure 2: Schematic drawing of the environmental conditions on poleward facing slopes at mid latitude when Mars obliquity is higher than 30° which are thought to favour the formation of gullies.

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MORPHOLOGIC DIVERSITY OF GULLY SYSTEMS ON MARS: NEW INSIGHTS INTO THEIR FORMATION FROM HIRISE. Virginia C. Gulick[1] and the HiRISE Science team, [1]NASA Ames/SETI Institute, NASA Ames Research Center, MS 239-20, Moffett Field, CA 94035; *email: Virginia.C.Gulick@nasa.gov.*

Introduction: As of late November 2007, HiRISE has returned over 4,200 images of the surface of Mars, including nearly 600 images of gullied locations. The HiRISE images (with resolution as high as 25 cm/pixel) provide an opportunity to test the current MOC-derived understanding of gully provenance and various suggested formation mechanisms.

Gullies imaged by HiRISE exhibit a great deal of morphological diversity. Lengths range from several tens of meters to several kilometers; widths range from several tens of meters down to the HiRISE resolution. Some gullies form tributaries that coalesce into networks, while others exhibit the canonical single source alcove, incised middle reach and terminal debris fan deposits. Some gully sources blend in gradually with the surrounding uplands, while others start full-borne from blunt, theater heads. Gully systems displaying different morphologic patterns can be located physically adjacent to each other. The most morphologically complex gully systems exhibit point bars, cut banks, undercutting of walls and source regions, erosion into underlying surfaces, braided and anastomosing reaches, multiple terraces located along gully margins, and erosion and deposition of materials along the gully and overlapping adjacent systems. This complex suite of morphological features suggests a fluvial origin [1].

Some gully-like systems, such as those located on high-latitude dunes (Figure 1) [2], lack key morphological indicators and are little more than sets of parallel troughs without apparent debris fans. Others have distinct source regions and debris fans, but lack incised middle reaches. These particular features are located on steep slopes, such as the inner walls of several volcano calderas, as well as on some crater, valley and canyon walls and may be more akin to debris chutes where material is transported down steep slopes mostly by gravity alone. We conclude from these observations that there may be a continuum of processes involved in the formation of gullies and gully-like forms, ranging from fluvial erosion to mass movement processes including dry flows and slides and possibly involving seasonally active processes.

HiRISE imaging also shows that gullies in a single locale may emerge at a variety of elevations and may display strikingly different morphologies. For example, miniature gully systems, some less than a kilometer long, are found along a crater wall in the Terra Sirenum region. These small gullies are adjacent to larger ones and exhibit typical gully morphologic characteristics, however they emerge much further downslope than their nearby counterparts. In another example, along a crater wall in the Terra Cimmeria region, adjacent gully systems emerge from source regions at a variety of elevations. Some gullies have characteristics typically associated with runoff-dominated fluvial processes while others have characteristics of terrestrial sapping-dominated fluvial systems. Systems adjacent to these areas have transitional morphologies [3].

Other intriguing gully systems are located on some pristine, mid-sized impact craters (e.g., Mojave [4]). Figure 2 shows well-developed and integrated “gully” systems heavily dissecting the eastern rim region of Mojave crater. In figure 3, pristine gullies have eroded both sides of the rim of Hale Crater, flowing in opposite directions. In one location, only a narrow ridge separates eastward and westward oriented gullies. Associations such as these may challenge any single gully formation mechanism.

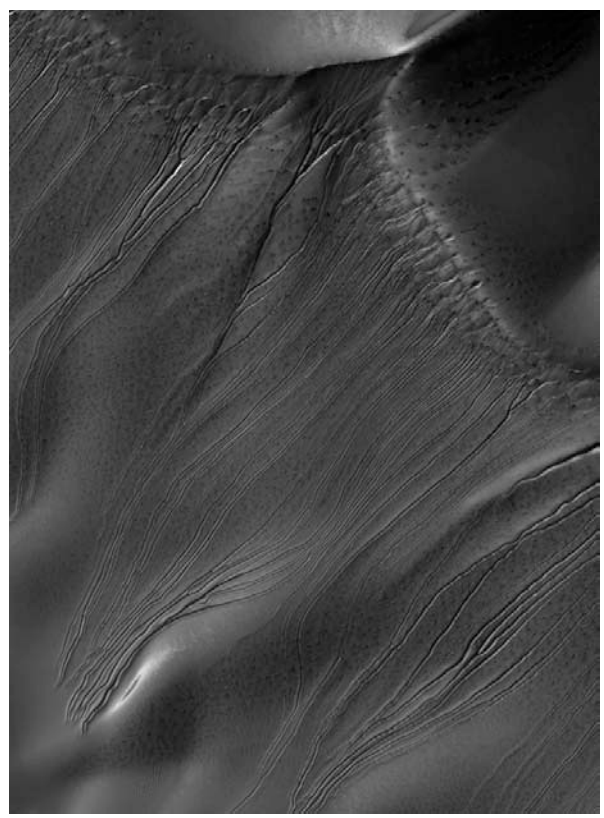

Figure 1: HiRISE image PSP_001440_1255. Sets of trough gullies on Russell Crater dunes. Gullies source at the dune crest, some originate from alcoves, while others appear to coalesce forming tributaries in the upper reaches. Middle and lower reaches form incised parallel troughs that termi-

nate abruptly leaving little or no distal debris deposits.

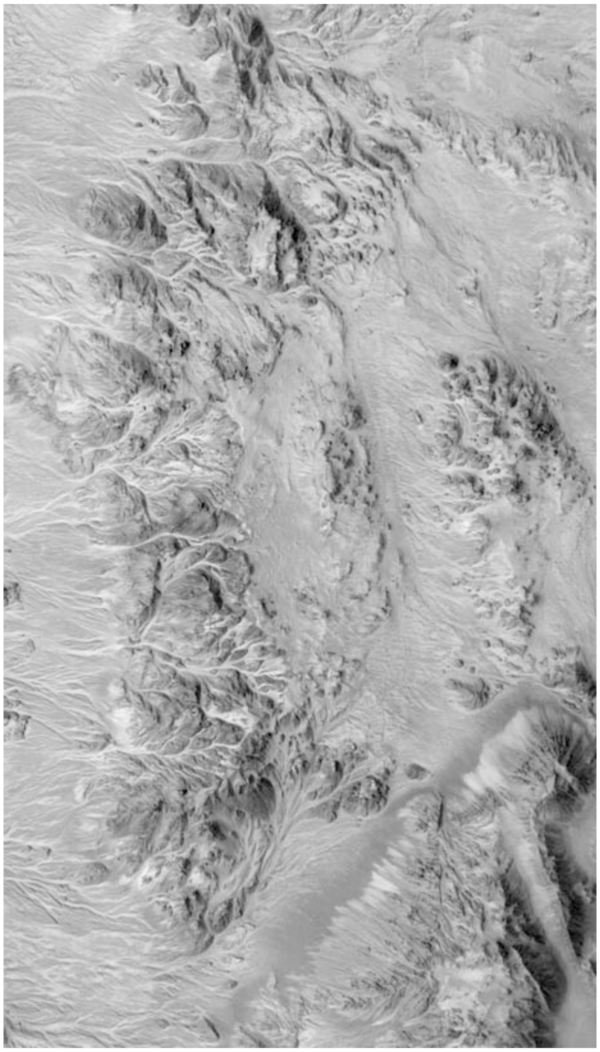

Figure 2: Portion of HiRISE image PSP_005714_1875. Eastern rim region of Mojave crater is extensively dissected by integrated "gully" systems.

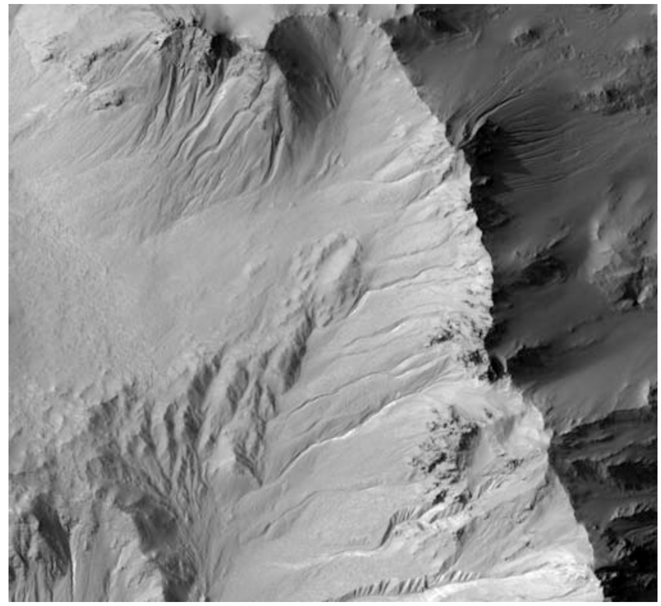

Figure 3: Portion of HiRISE image: PSP_002932_1445. Gullies along the northeastern rim of Hale crater. Gullies formed on both sides of the ridge and at different orientations. Note bright deposits along some gullies.

References: [1] V.C. Gulick et al., 2007, LPSC XXXVIII, abstract # 2300. [2] C.J. Hansen et al., 2007, 7th Mars Conf., abstract # 3364. [3] V.C. Gulick et al., 2007, 7th Mars Conf. abstract # 3371. [4] L.L. Tornabene et al. 2007, 7th Mars Conf., abstract # 3288.

FORMATION OF GULLLIES ON MARS: LINK TO RECENT CLIMATE HISTORY IMPLICATES SURFACE WATER FLOW ORIGIN. James W. Head[1] and David R. Marchant[2]. [1]Department of Geological Sciences, Brown University, Providence, RI 02912 USA (james_head@brown.edu); [2]Department of Earth Sciences, Boston University, Boston, MA 02215 USA (marchant@bu.edu).

Summary: The geological record of an impact crater interior microenvironment typical of the mid-latitudes of Mars shows that formation of gullies immediately followed a recent period of mid-latitude glaciation. Geological evidence indicates that in the recent past, sufficient snow and ice accumulated on the crater wall to cause glacial flow and filling of the crater floor with debris-covered glaciers. As the period of glaciation waned, debris-covered glaciers ceased flowing, accumulation zones lost ice, and newly exposed wall alcoves became the locus of snow/frost deposition, entrapment, and preservation. During the warming trend toward the end of glaciation, melting of residual snow and ice in alcoves formed fluvial channels and sedimentary fans.

Background: Because the current temperature-pressure regime is below the triple point, it came as a major surprise when Malin and Edgett [1] reported the discovery of young features apparently carved by running water. Termed gullies, these consist of an alcove, channel and fan (Fig. 1a). These observations generated a host of alternative explanations for the gullies, including (summarized in [2]): 1) bottom up liquid sources, such as the release of subsurface groundwater or subsurface liquid CO_2, perhaps aided by geothermal activity; 2) top-down water sources, such as the accumulation and melting of surface snowpacks, or melting of near-surface ground ice; and 3) dry granular flow. Here we assess the stratigraphic relationships in a crater interior typical of many gully occurrences. These data provide evidence that gully formation is linked to glaciation and to recent climate change that provided conditions for snow/ice accumulation and top-down melting.

Observations: The latitudinal dependence of gullies shows a distinct concentration in 30-50° latitude bands [3], and a significant number form on impact crater interior walls [4]. For this reason, we chose to analyze in detail the geology of a crater interior in the ~40° latitude range in order to assess geomorphic features and stratigraphic relationships associated with gullies. A 10.5 km-diameter crater (-155.3E, 40.1° S) displays well developed gullies (Fig. 1a) and a very asymmetric wall and floor topography (Fig. 2). Crater floor morphology shows multiple lobate depressions along the base of the northern wall directly upslope of multiple parallel lobate flow textures on the floor; these in turn merge and converge toward two major southern floor lobes (Fig. 2a-b). The characteristics of the surface morphology and the array of geomorphic features implicate snow and ice in the crater modification. The surface texture of the floor lobes is very similar to that of older mid-latitude lobate debris aprons, lineated valley fill, and concentric crater fill, all interpreted to involve a significant amount of ice in their formation [e.g., 5]. The topography and surface morphology are very similar to deposits at the dichotomy boundary interpreted to be debris-covered glaciers in valley systems [e.g., 6]. Lobe-shaped spatulate depressions along the northern base of the crater wall (Fig. 3a,b) are similar to remnant features interpreted to be due to flow of glacial ice in other craters at this latitude. Furthermore, a change in climate between the time that the broad floor lobes were emplaced and today is indicated by the fact that the multiple lobe-shaped spatulate features are now depressions, interpreted to mean that the previously existing snow and glacial ice have sublimated, and the glaciers beheaded. Further evidence for climate change is seen from superposition relationships at high resolution along the northern crater wall (Fig. 3a,b). Gullies are superposed on, and postdate, the period of active ice lobe formation. The crater interior maps show that gullies (Fig. 1a) occur in the regions that would have been the accumulation zones for ice flowing into the lobate spatulate depressions. Superposition relationships show that the gully distal fans embay the base of the slope and the lobate spatulate depressions, indicating a younger age (Fig. 3b-d). Broad alcoves high on the crater wall contain channels in their interiors that exit the alcoves, extend downslope, and terminate in a distal fan along the base of the wall slope in the interiors of the lobate depressions. The very close stratigraphic relationships between the gullies and the lobate depressions (Fig. 3a-b) strongly suggest a genetic relationship related to the waning stages of the glaciation that marks the modification of the crater floor. We interpret the sequence of events on the floor and wall as follows: 1) accumulation of snow and ice on the wall to sufficient thickness to cause flow; 2) formation of debris-covered glaciers to produce the major floor lobes; 3) decrease in snow and ice accumulation on the crater walls to cause recession of ice lobes, ultimately leaving the beheaded lobate spatulate depressions; 4) formation of gullies on the crater walls and distal fans in the empty spatulate depressions (Fig. 4).

There is clear evidence that activity in the gully fans was episodic (Fig. 3b-d). Early distal fans are deformed by a pervasive series of closely-spaced fractures that are generally parallel to the base of the slope. Later fans are clearly superposed on both the earlier fans, and on their deformed bases (Fig. 3c-d). The most recent fans consist of anastomosing distributary channels on the fan surface and distal channel deposits.

What are the sources of the fluid causing the gully erosion? We interpret the trends in the stratigraphic relationships in the crater to mean that climatic conditions changed from those favoring significant glaciation, to those favoring progressively less snow and ice accumulation, ultimately leading to conditions in which there was patchy seasonal snow and ice on the northern crater walls. Such accumulation would concentrate snow and ice specifically in the topographic traps of the alcoves, where shielding would further favor perennial ice retention. For example, a long-term warming trend might cause such an evolution in glaciation and ice retention, with the latter phases conducive to seasonal heating and melting of snow/ice accumulated in the alcoves to cause water flow and formation of gully channels and fans. What are the causes of the observed trends? The latitude dependence of gully occurrences, the similarity of their occurrences with those of viscous flow features here and elsewhere on Mars [3], and their general relationship to a widely distributed latitude-dependent young mantling deposit [e.g.., 7], strongly suggest a link to climate change and variations in the astronomical parameters that drive climate change. Specifically, recent astronomical parameter solutions for the last 20 million years [8] show that obliquity has been progressively decreasing in average magnitude and amplitude over that time. Such changes would tend to make the mid-latitudes progressively warmer up to the present time, when water ice is generally not stable in the uppermost part of the regolith at these latitudes. Thus, we interpret gullies to have formed in the waning stages of this glaciation when warming conditions were such that patches of snow and ice in gully alcoves could seasonally melt and form fluvial channels and fans [9; Fig. 16]. Current Mars conditions may be too cold and dry for top-down melting to occur in these microenvironments, but accumulation and melting of wind-blown snow and ice may permit the mechanism to operate on Mars relatively recently.

References: [1] M. Malin & K. Edgett, *Science* 288, 2330, 2000; [2] MEPAG SR-SAG, *Astrobiology* 6, 677, 2006; [3] R. Milliken et al., *JGR*, doi: 10.1029/2002JE002005, 2003; [4] D. Berman et al., *Icarus* 178, 465, 2005; [5] S. Squyres & M. Carr, *Science* 231, 249, 1986; [6] J. Head et al., *EPSL* 241, 663, 2006; [7] Head, J. et al., *Nature* 426, 797, 2003; [8] Laskar J. et. al. *Icarus* 170, 343, 2004; [9] G. Morgan et al., this volume.

Fig. 1. Gullies (alcoves, channels and fans). (a) On crater interior wall; (b) Wright Valley, McMurdo Dry Valleys, Antarctica. Wind-blown snow in alcoves and channels melts during austral summer causing fluvial activity [10].

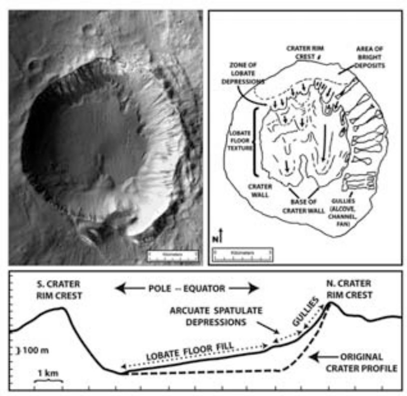

Fig. 2. Impact crater (-155.3E, 40.1S). (a) CTX p02_001842_1397_xi_40S155W. (b) Sketch map showing main geologic features. (c) Asymmetrical crater profile shows that crater has been modified from initial morphology. MOLA profile 15161.

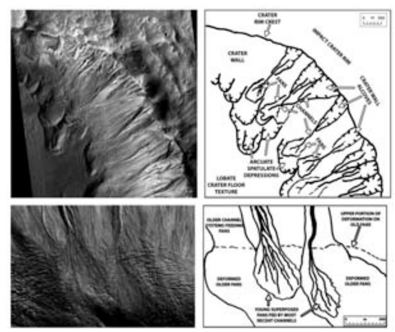

Fig. 3. Detailed relationships of geomorphic features in the crater interior. (a, b) Gullies forming on upper wall emplace fans that are clearly superposed on the central parts of the arcuate spatulate depressions. (c,d) Deformed gully channel and fan deposits form fractures and terraces at base of slope along the crater wall. The most recent channels and fans clearly postdate the fractures. HiRISE PSP-001842_1395.

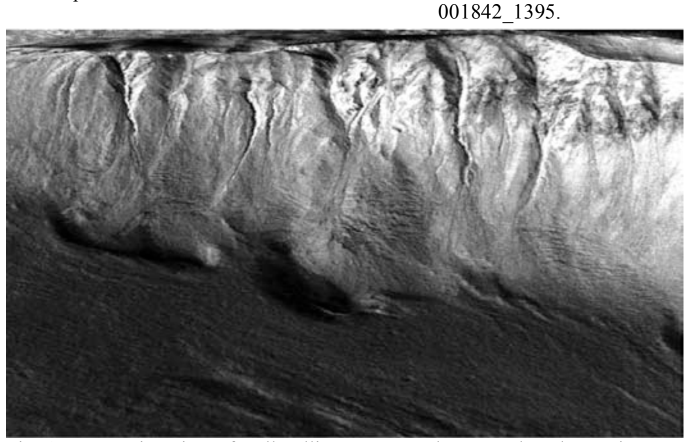

Fig. 4. Perspective view of wall gullies superposed on spatulate depressions.

ATACAMA DESERT MUDFLOW AS AN ANALOG FOR RECENT GULLY ACTIVITY ON MARS. J.L. Heldmann[1], C. Conley[1, 2], A.J. Brown[3], L. Fletcher[1], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035 USA Jennifer.L.Heldmann@nasa.gov, [2]NASA Headquarters, Washington, DC, 20546 [3]SETI Institute, Mountain View, CA 94043.

Introduction: Evidence of recent gully activity on Mars has been reported based on the formation of new light-toned deposits that have occurred in the past decade [1]. The nature of these deposits (Figure 1a) remains enigmatic but their association with the Mars gully features may suggest that liquid water played a role in their formation since the gullies themselves most likely formed via liquid water activity. Here we discuss light-toned mudflow deposits associated with gullies in the Atacama Desert, Chile (Figure 1b), which share similar morphologic and spectral signatures as the new Mars deposits. We suggest that, similar to the Atacama deposit, the Mars gully deposits may be remnant mudflows.

Recent Gully Activity on Mars: Malin et al. [1] recently reported the discovery of gully activity occurring within two separate gully systems within the past decade. Light-toned deposits were discovered in gullies in both the Terra Sirenum and Centauri Montes regions on Mars using the Mars Orbiter Camera (MOC) aboard the Mars Global Surveyor spacecraft (Figure 1a). The Terra Sirenum gully showed evidence of new light toned deposit which formed sometime between December 2001 and April 2005. The new deposit is ≤20% brighter than the surrounding region [1]. The Centauri Montes gully showed evidence of a new light toned deposit which was formed sometime between August 1999 and February 2004 and shares similar brightness values with the Terra Sirenum deposit [1].

The deposits in both regions are morphologically similar. The new deposits show long digitate distal and marginal branches, divert around obstacles, and have relatively low relief [1]. The material also flows slowly as it can't run over the top of obstacles. Malin et al. [1] interpret these observations as indicative of the action of a very fluid material that thins while flowing and can bud into multiple branches.

Recent HiRISE imagery covers both the Centarui Montes and Terra Sirenum sites. Even in the HiRISE images no smaller scale structure is visible within the deposits themselves. Also, neither of the new gully sites shows any discernable changes of these new light-toned deposits when compared with the earlier MOC imagery.

In addition, spectral data associated with the Mars gullies shows that in general the gully deposits are spectrally indistinct from the surrounding terrain [2]. CRISM is a visible-near infrared imaging spectrometer which takes measurements at 544 wavelengths from 0.36-3.92 microns at 15-19 meters/pixel. CRISM data suggests that gully sites are not associated with hydrated minerals [2].

The precise formation mechanism for these new deposits remains enigmatic. Malin et al. [1] suggest that the deposits are the result of fluvial activity and the observed residues may be created by a water-bearing fluid. If the new deposits are indeed formed from water activity then they may contain ice and/or frost but due to the instability of these materials on the martian surface then the deposits can retain their light tone only through replenishment of the water-based content [1]. Alternatively, the deposits could be the result of salt deposition or deposition of fine-grained sediments [1].

Atacama Gully Mudflow Deposit: The deposit in Figure 2 was imaged in a pre-existing gully in the Atacama Desert in June 2005. The Atacama deposit shows very low relief and only exists as a thin veneer over the desert surface. The deposit shows multiple flow lobes along the terminus. In Figure 2a the deposit appears as a relatively smooth feature but Figure 2b shows a close-up view of the same deposit which reveals that the deposit is actually composed of disjointed and warped pieces of cracked mud. Small-scale relief is evident in this image on the order of several centimeters.

This deposit was formed as a result of a rain event in the Atacama that occurred approximately one month prior to when these images were taken. The deposit is the result of a slurry of mud (soil and water mixture) which flowed downslope. The fluidized mixture then became desiccated in the extremely dry Atacama Desert environment and formed the cracked mud surface shown in Figure 2b. The deposit is composed of the same material as the surrounding terrain since the cracked mudflow is the remnant of soil and dust fluvially transported downslope.

Visible to near infrared (0.4-2.5 microns) reflectance spectra of both the light-toned mudflow deposit and the surrounding terrain were obtained using an ASD FieldSpec Pro (Figure 3). The samples of the mudflow deposit and the surrounding, undisturbed terrain are spectrally similar, requiring only a scaling factor in reflectance to explain the differences. This could be accomplished by a change in grain size or porosity of the two samples. This suggests that the two samples are composed of the same minerals. This interpretation is consistent with the formation mechanism of the mudflow deposit since the light-toned material in Figures 2a and 2b is simply material that has been lubricated by liquid water and flowed downslope to eventually dessicate into a cracked mud deposit on the desert surface.

The Atacama spectra show bands at 1.4 and 1.9 microns indicative of hydroxyl, bound, or unbound water and a weak band at 2.2 microns suggestive of an Al-rich clay. Since these bands are evident in both the mudflow and surrounding terrain samples, the presence of water is most likely due to the presence of small amounts of water found in the Atacama at this field site (primarily due to rain and fog events) and/or the fact that these samples have been exposed to a humid California environment for several years prior to this spectral analysis.

Discussion and Conclusions: The new light-toned deposits seen in association with gullies on Mars in Terra Sirenum and Centauri Montes show striking similarities in morphology with the new Atacama Desert gully deposit. The deposits on Earth and Mars are both thin deposits that are more light-toned that the surrounding terrain. The martian and terrestrial deposits both show digitate flow lobes particularly near the terminus of the deposit. Deposits on both planets also have formed in conjunction with pre-existing gully features. In addition to these geomorphic similarities, all of these features have formed in arid desert environments. Due to these myriad similarities, we believe the Atacama gully deposit is an excellent terrestrial analog for the martian deposits.

Similar to the Atacama deposit, the martian deposits were most likely formed by the action of liquid water. Similar to the Atacama case, the martian deposits were most likely formed by a soil and water fluidized slurry which flowed downslope. Due to the ambient environmental conditions on Mars, the liquid water within this slurry will evaporate and the mud-like deposit will become desiccated. As the deposit dries, the deposits will develop cracks to form a similar mud cracked appearance as shown in Figure 2b. The individual mudcracks are not visible in the Mars images likely because the camera resolution is not sufficient to resolve these small features. Instead, the martian deposits appear as relatively smooth terrains (Figure 1), just as the Atacama deposit appears as a relatively smooth deposit when viewed from a further distance with decreased resolution (Figure 2a).

Because the light-toned deposit is composed of regolith and dust material that has been transported downslope, the spectral signature shows the same composition as the adjacent terrain as shown in Figure 3. Also, because the deposit is composed of desiccated surface material, the deposit should not change in albedo, size, or shape over time, which is also consistent with the observations to date (no detectable changes have been observed for either of the martian deposits since they were first discovered). A dried mudflow provides a simpler explanation for this observation than the requirement for replenishment of ice if the deposit is composed of snow, ice, or frost. To date, no spectral signatures of water ice or hydrated minerals have been detected in association with gullies on Mars [2] which indicates that likely there is not water ice/frost at the surface of these deposits.

References: [1] Malin et al. (2006) Science 314, 1573-1577. [2] Murchie, S. (2007). GSA Annual Meeting, Paper No. 60-2.

Acknowledgements: The authors would like to thank Dr. Janice Bishop for use of the ASD FieldSpec Pro spectrometer at the SETI Institute.

Figure 1a (left). New light-toned gully deposit on Mars [1]. Image courtesy of Malin Space Science Systems. Figure 1b (right). Aerial view of Atacama Desert mudflows (Google Maps).

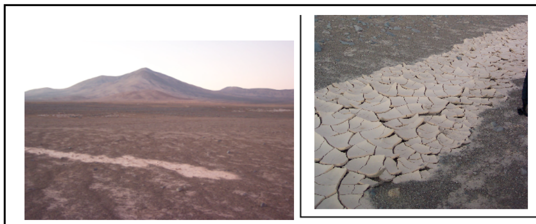

Figure 2a (left). Atacama mudflow deposit.
Figure 2b (right). Close-up view of mudcracks within mudflow deposit.

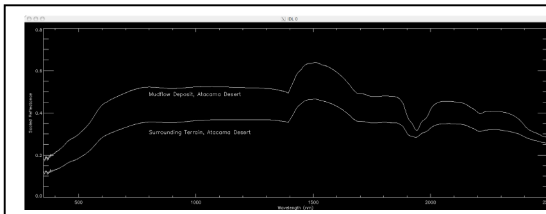

Figure 3. Atacama desert sample spectra of mudflow deposit (top spectra) and surrounding terrain (bottom spectra).

MARTIAN GULLIES: VARIETY OF SETTINGS AND IMPLICATIONS FOR FORMATION PROCESSES. J.L. Heldmann[1] , K.S. Edgett[2], O.B. Toon[3], and M.T. Mellon[4], [1]NASA Ames Research Center, MS 245-3 Moffett Field, CA 94035, Jennifer.Heldmann@nasa.gov, [2]Malin Space Science Systems, San Diego, CA [3]University of Colorado, Program in Atmospheric and Oceanic Sciences & Laboratory for Atmospheric and Space Physics, Boulder, CO [4]University of Colorado, Laboratory for Atmospheric and Space Physics, Boulder, CO

Introduction: Middle- and high-latitude, kilometer-scale, geologically young gullies were first recognized on Mars in images from Mars Global Surveyor [1]. One of the models for their formation is seepage and surface runoff of liquid water escaping from a shallow, subsurface aquifer (often, it is forgotten that the model is more complex than this—undermining and collapse contribute to alcove formation, and mass movement and eolian processes continue to modify the landforms to this day). However, some middle- and high-latitude gullies occur on slopes that do not seem to have characteristics that fit the groundwater model; these have been noted by some researchers as features that falsify the groundwater model and instead favor other models, including melting of snowpacks and mass movement involving no contribution from a liquid or gas lubricant. These other gully forms occur on eolian dune slip faces, crater central peaks, and isolated mountains and massifs. However, these gullies and gully-like features are geomorphically distinct from the more common, typical gullies that occur on the walls of craters, valleys, troughs, and pits. Hence, here we describe and classify the range of gully features according to differences in morphology, geographic distribution, and geologic setting. Each class of features might have formed by different processes.

Gully Classes and Settings: All four gully classes described here (CL, SD, CP, IP) occur at middle to high latitudes in both Martian hemispheres [1, 2, 3].

Classic Features (Type CL). Classic, or type CL gullies form on the walls and slopes of craters, troughs, channels, pits, and other depressions which have an overlying, relatively flat plateau upslope from the gully alcove [2, 4]. Generally, Type CL gully morphology can be divided into three parts: alcove, channel, and apron. The central, identifying attribute of any Martian gully is its channel, but in many cases it is the mutiple lobed nature of the apron deposits that suggests debris flows rather than dry mass movements contributed to their genesis. Some gullies have an alcove that formed on the slope above the channel and the majority of gullies have an apron of debris located where the channel reached the bottom of the slope. However, not all gullies have all three geomorphic segments, especially alcoves [1].

A quantitative study of gully characteristics based on MOC, MOLA and TES data suggests that the gullies were formed by the release of liquid water from a shallow (several 100 m deep) subsurface aquifer [2]. A shallow aquifer can occur where competent rock layers trap water below ground while maintaining an overlying dry and thermally insulating soil layer. The dry, insulating overburden allows geothermal heat to maintain liquid water at only a few hundred meters depth. Indeed, the depth to the typical channel head is positively correlated with the depth of the 273 K isotherm when using an overburden thermal conductivity value measured by the MGS TES [2].

Sand Dune Features (Type SD). Gully-like forms were also found on sand dune slip faces [5, 6, 7]. Dune gullies are extremely rare and most commonly found on dunes in just a few of the mid-latitude dune fields in craters of Noachis Terra. All dune gullies occur on slopes that face generally poleward; equatorward-facing slip faces on the same dune as a gully will exhibit slip face avalanches, suggesting that the dune gullies, too, result from slip face avalanching, but with some added attribute that forms a channel in the avalanche deposit. Two distinct types of gully-like dune features exist on Mars. These two classes are distinguished by their unique morphologic qualities.

The uppermost portion of the first, type SD1, is characterized by a lack of well-developed alcoves. Instead of channels emanating from an eroded, theater-shaped depression, channels commence from the top or near the top of a slip face. In a few cases there is an extremely small (less than 10 m long) eroded depression at the top of the channel. The Type SD1 channels typically begin at the top of the sand dune and run essentially parallel down the length of the slope. Type SD1 channels are commonly leveed and there is almost always a lack of an apron at the base of the slope.

The second, type SD2 features, are also found on sand dunes and are also rare and most commonly found in Noachis Terra. The type SD2 features are complex with varying alcove morphologies in adjacent structures. One feature has a small alcove (< 7 m in length) which is located at the top of the sand dune. The adjacent Type SD2 feature lacks such a well-developed alcove. Instead, the channel-like structure seems to emanate from the dune crest, although the channel does appear slightly widened at the uppermost reaches near the dune crest, reaching a maximum width of nearly 3 m at its widest point.

Type SD1 features might form from erosion due to ice which condenses from the atmosphere and forms at the crest of a dune, tumbles downhill, and then eventually sublimates away into the atmosphere. The ice could be knocked loose as it starts to sublimate and/or melt away, causing undercutting and a removal of the support structure for the ice itself. Alternatively, ice-cemented sand from the near-surface of the dune might serve as an erosional agent. Some HiRISE images of gullies on dunes in Russell Crater suggest the presence of subsurface ice. If blocks of ice-cemented sand were destabilized near the dune crest due to small amounts of melt then this material could likewise serve to erode the Type SD1 channel features. By contrast, Type SD2 features most likely formed from dry mass movement down the slip face of an indurated dune [8, 9].

Central Peak Features (Type CP). Type CP features form on crater central peaks. The heads of these Type CP features do not begin at a consistent depth beneath the overlying ridge, and are typically not associated with cohesive strata layers. Alcove depressions are generally absent or much less prominent than the alcoves of Type CL. Debris aprons can be found on Type CP features but are sometimes absent. In cases where Type CP features lack aprons, there is no evidence for a change between erosion within the channels to deposition within an apron. The substrate underlying Type CP channels is also distinct from that observed for Type CL gullies. Type CP features on central peaks often have a wide (at least 3 km based on the MOC narrow angle imaging scales) swath of smoother material crosscut by channel-like features.

The formation of Type CP features may thus be connected to the formation of the crater central peaks. Sometimes the central peak is composed of more resistant rock strata located below the surface [10, 11], and such a layer could have served as an aquiclude for a deep reservoir if water was present at depth on Mars. Other potential water source~~s~~ to feed these gully features includes water within the permafrost and/or adsorbed water within the soil which can be heated and mobilized from the impact event [12, 13]. Perhaps the fracturing of the rock beneath the crater allows for a connection between a pre-existing deep water reservoir and the surface expression of the central peak. Deformed strata below a crater are uplifted towards the crater center [10, 14] and so the central peak would be an obvious outflow site for released subsurface water.

Isolated Peak Features (Type IP). Type IP features are found on isolated peaks, mountains, and massifs. The majority of Type IP features are located on the mountains that rim the Argyre Basin.

The morphology of the Type IP features is similar to the morphology of the Type CL features. In general, the Type IP features exhibit an alcove, channel, and depositional apron features. However, Type IP features exhibit a larger range in alcove depths even among features that are adjacent compared to Type CL features. In addition, Type IP features tend to have fewer individual features clustered together compared to Type CL features.

The formation mechanism of the Type IP features is unknown. We offer several scenarios that are consistent with the observations. The responsible fluid, assuming a liquid is involved at all, could emanate from the subsurface and fractures and faults in the rock (remember, the majority of these are on the eroded, mountainous remains of the Argyre impact basin) may provide a natural mechanism for transporting to the surface in these regions. We note, however, that since the alcove depths are not as consistent within a system compared with the Type CL features, the subsurface must be comparatively more complex to control the observed variation in outlet locations. Also, because Type IP features typically have fewer individual gully-like features clustered in one locale compared with the Type CL gullies, less water may be available from the source to feed and carve these features. Therefore if the water feeding the Type IP features is stored underground in and/or around the massifs, the physical size of available space to store the water is less for the Type IP features compared with the Type CL gullies.

Conclusions: Type CL gullies on Mars are found on a variety of terrain types (crater walls, valley walls, graben, etc.) and despite this diversity in geologic setting exhibit remarkable similarities in morphology and physical dimensions. These gullies might have been formed by release of water from the subsurface [1, 2, 15]. Gullies on eolian dunes, crater central peaks, and isolated massifs have been used by others to suggest that the groundwater hypothesis is falsified. However, such features are geomorphically distinct from Type CL gullies and cannot with confidence be used to rule out the subsurface aquifer hypothesis.

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MARTIAN GULLIES: SOURCE MATERIALS, FLOW PROPERTIES, AND TERRESTRIAL ANALOGS. A. D. Howard[1], J. M. Moore[2], W. E. Dietrich[3], and T. Perron[4], [1]Dept. Environmental Sciences, University of Virgina, P.O. Box 400123, Charlottesville, VA, 22904-4123 (ah6p@virgina.edu). [2]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000. [3]Dept. Earth and Planetary Science, Univ. or California, Berkeley, CA 94720-4767. [4]Dept, Earth & Planetary Sciences, Harvard University, 20 Oxford St., Cabridge, MA 02138.

Introduction: Because of the evident youth of the Martian gully systems and the obvious occurrence of channelized flows in their origin, a lively discussion has resulted concerning the source and nature of the fluid flows, the source and composition of the materials being transported, and the prevailing climatic environments during their formation. We report here on our analysis of gully geomorphology and preliminary estimates of flow rates and flow volumes involved in gully formation. Our observations and estimates are based largely on released HiRISE images. We highlight several preliminary conclusions.

Gully Geomorphology: A wide range of geologically recent erosional and depositional features occur on steep Martian slopes in fresh craters and on tectonic scarps. At one end of the spectrum are talus slopes that result from debris avalanching with little channelization. We limit our discussion and conclusions, however, to the widely-investigated "typical" gully systems involving well-defined source alcoves, channels or chutes (we prefer the latter term as being less process-specific), and associated depositional aprons.

Association of gullies and pasted-on terrain. Almost all typical gullies occur on slopes at least partially mantled with superposed deposits that have been referred to as "pasted-on" terrain [*1-5*]. Small gullies are often incised solely within the mantle. Larger gullies incise through the mantle, exposing scarp or crater wallrock. The sidewalls of deeper chutes and channels are generally within the mantle.

Grain size characteristics of aprons and alcove walls. HiRISE images of the depositional aprons generally reveal only a small component of boulders coarse enough to be resolved (~1 m). This paucity of coarse boulders also characterizes the pasted-on terrain (although a few boulders can be present which may have been derived from occasional rockfalls from superjacent wallrock). By contrast, wallrock exposed in alcoves commonly displays abundant multi-meter scale boulders. The combination of these two observations leads to a working hypothesis: ***Typical gullies primarily erode within pasted-on terrain.*** A correlary to to this is that erosion rates within alcoves diminish as wallrock becomes exposed. Many large alcoves are associated with very small indentations in their associated wallrock. Formation of deeper wallrock indentations may have required multiple episodes of alternating deposition and erosion of pasted on terrain.

Flow history from chute and apron features. Aprons clearly record multiple flow events separated by appreciable intervening periods of inactivity. The freshest-appearing chutes generally narrow and shallow at their distal ends, transitioning into well-defined hummocky deposits on limited portions of the apron. Portions of aprons that are not currently connected to chute feeders are generally smoother in appearances, suggesting modification by deposition, ablation, or creep subsequent to deposition. In addition, numerous chutes disconnected from source alcoves, degraded chutes, terraces along chutes, and apron-head trenching indicate multiple flow events and evolving boundary or environmental conditions. Thus we conclude that ***formation of alcoves, chutes, and aprons requires dozens or perhaps hundreds of flow events***.

Flow properties from chute and apron morphology. Chutes and their associated hummocky deposits terminate abruptly at the base of the associated scarp. We have observed no indisputable channel or depositional features extending from the alcoves any appreciable distance onto crater floors or across plains at the base of scarps. This suggests that the ***flows within chutes and on aprons have limited mobility, requiring slopes exceeding several degrees***. Although some chutes exhibit indistinct, broad levees, the tall, narrow levees characteristic of water-rich terrestrial debris flows are rare or absent. Similarly, although aprons display hummocky topography, narrow raised terminal lobes are rare. Chute floors are typically 1-10 m in width at floor level, and low, lenticular bedforms suggest flows may have on occasion occupied the entire gully width. This suggests that the c***hutes and aprons form through short duration flows of appreciable magnitude (e.g. debris flows) rather than long-duration flows of low discharge.***

Estimates of Flow Velocities and Discharges. A variety of methods can be utilized to estimate flow properties through the chutes. Most require assumptions be made concerning flow depths, flow widths, and or boundary roughness. Some gullies exhibit low-sinuosity meandering, which suggests making flow estimation using the linearized, depth-averaged theory of flow in meanders proposed by [*6*]. The wavenumber, *k*, of incipient meandering is given by:

$$k = 2C_f\left(\Gamma^{0.5}-1\right)^{0.5}/D = 2\pi/\lambda\,, \qquad (1)$$

where

$$C_f = V_*^2/V^2\,, \qquad (2)$$

D is flow depth, λ is meander wavelength, V is average velocity, and V_* is shear velocity. Γ is given by:

$$\Gamma = 0.5\,((A+2)+F^2)\,, \qquad (3)$$

where A is related to cross-sectional slope in meander bends and F is Froude Number. If we assume F≈1, then Γ≈1.6 for alluvial channels where A≈3, and Γ≈ 1.2 for A≈0 (no cross sectional slope). We will assume Γ=1.4, so that the term $(\Gamma^{0.5}-1)^{0.5}\approx 0.4$. Assuming steady flow,

$$\tau = \rho V_*^2 \simeq \rho g D S\,, \qquad (4)$$

where S is surface slope and g=3.7 m/s^2 on Mars. Substituting and solving for V, we get:

$$V^2 \approx 0.47\,S\,\lambda\,. \qquad (5)$$

Gradients in chutes are uncertain, although we are presently using HiRISE stereo image pairs to make improved estimates. We will assume extremes of 10º (S=.18) and 30º (S=.58): Using (5) we arrive at the following estimates:

HiRISE Image	λ (m)	*V* (*S*=.18) (m/s)	*V* (*S*=.58) (m/s)	*W* (m)#
1908_1405	13.6	1.1	1.9	1.36
1684_1410	14.3	1.1	2.0	1.43
4310_1445	37.8	1.8	3.2	3.78
2884_1395	99	2.9	5.2	9.9

Assumes channel width,W=λ/10. Direct measurements were close to estimated values.

Assuming a width-depth ratio of 10 provides corresponding discharge estimates between 0.2 to 50 m^3/s. These estimates assume turbulent liquid flow and the estimates may not be appropriate if flows are laminar or are dense debris flows with or without a fluid matrix. In any case, the estimated flow widths, depths, discharges, and velocities are consistent with our geomorphic observation that flows are of large magnitude and short duration.

Terrestrial Analogs. We have investigated a number of potential terrestrial analogs to the “typical” Martian gully systems in Iceland, New Zealand, the southwestern U.S. and the Atacama Desert. Chutes and aprons on the terrestrial sites exhibit a range of flow mobilities and morphometric features, which, at the less mobile end of the spectrum, are very similar to Martian gullies. Most of the terrestrial examples involve water in the transport and deposition of debris. A major difference between almost all terrestrial analogs and Mars is the important direct role that precipitation plays in triggering the flows, eroding chutes and depositing debris. Heavy rains create “firehose” effects at the base of cliffs in triggering debris flows in talus. Rains cause rapid snowmelt and slope saturation. The more mobile end of terrestrial gully systems are poor Martian analogs because of the direct role of precipitation, generally manifested by debris flows that are characterized by narrow, tall natural levees and flows that extend beyond the toe of the depositional apron.

Implications for Gully Formation Scenarios. A major problem with regard to unique determination of the materials, processes, and environmental controls on Martian gully formation is the steepness of the terrain on which they occur. Little increase in shear forces or decrease in material strength is required to trigger and maintain flows. Our observations place some constraints on formation scenarios and favor or disfavor some scenarios, but do not provide a definitive answer. The observation that gullies primarily erode pasted-on terrain disfavors a groundwater source of transporting fluids. The observation that gullies form by multiple flows that involve appreciable volumes of transported material does not support erosion by slow release of groundwater or direct erosion by snowmelt. However, large slope failures and flows might be triggered by slow buildup of hydrostatic pressures (perhaps at the interface between wallrock and pasted-on terrain) or decrease in slope strength from melting of surface materials.

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DISTRIBUTION, ORIENTATION AND RELATIVE AGE CLASSIFICATION OF NORTHERN HEMISPHERIC GULLIES ON MARS USING HRSC AND MOC DATA.

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Introduction: Gullies show morphologic features that indicate the presence of a flowing liquid in the forming process [1]. However, the current climate in the northern hemisphere does not allow the existence of liquid water over long periods of time. Therefore, the exploration of gullies is a valuable key in order to understand the youngest climatic history of Mars. We evaluated HRSC and MOC data covering the northern hemisphere to analyse distribution and orientation of gullied slopes. MOC data additionally allowed a morphologic age classification of gullies.

HRSC data: Images of the High Resolution Stereo Camera (HRSC) with a resolution of up to 10 m/pixel [2] cover wide parts of the northern hemisphere. For this reason it is possible to measure the orientation of identified gullies representatively. In 50 of 230 evaluated HRSC images north of 30°N (orbits 32-1644) we identified approximately 2300 gullies (Fig. 1). High densities of occurrences are found between 35°N and 60°N. The preferred flow direction of all analysed gullies is southeast. However, the analysis of gullies on crater walls is more representative, because impact craters are at first order circular features. They have a point symmetry and there is a uniform azimuthally distribution of slopes, which is ideal when investigating the influence of insolation on the distribution and development of landforms. Approximately 1500 of all identified gullies are situated on crater walls and their orientation changes with respect to latitude (Fig. 3). Between 30°N and 40°N gullies occur at poleward facing slopes and between 40°N and 60°N at all slope directions.

MOC data: Images of the Mars Orbiter Camera (MOC) cover small areas of the northern hemisphere, but with a much higher resolution when compared to HRSC data (up to 1.4 m/pixel [3]). MOC-NA images taken during sub-phases AB – S04 covering the northern hemisphere were evaluated. In approximately 320 of ~35,000 MOC images (0°N - 90°N) ~3200 gullies were detected (Fig. 2). High densities of occurrences of gullies are found between 30°N and 55°N. Just like HRSC evaluation it is more representative to analyse only the orientation of gullies located on impact crater walls. ~2600 of all identified gullies on MOC images are positioned on crater walls. Similar to HRSC results, orientation of gullies changes with latitude (Fig. 3). Between 30°N and 40°N most of the gullies are situated on poleward facing slopes. North of 40°N the gullies occur usually on slopes facing towards the equator.

Analysis of orientation data: For a better interpretation of gully orientation, results of HRSC and MOC surveys were merged. That way a higher number of gullies for the statistical analysis of orientation is obtained and the influences of different illumination conditions and resolutions of the two camera instruments were minimized. Orientation of all detected gullies changes with latitude. Between 30°N and 40°N most of the gullies occur on poleward facing slopes. North of 40°N the gullies occur usually on slopes facing towards the equator (Fig. 3).

Age classification: The higher resolution of MOC images allows a relative age classification based on the morphology of gullies. Differences in orientation and distribution could indicate different climatic forming conditions. We classified the gullies into pristine, degraded and cratered gullies [4]. Pristine gullies show sharp edges and are not covered by dust. They overlay small dunes or young features like polygonal patterns. Degraded gullies are affected by erosion or sedimentation. For instance, they can be covered or filled by dust. Gully aprons can also be eroded partially. Another indicator for this class are cracks, which cut the channels or aprons. Cratered gullies exhibit impact craters on alcoves, channels or aprons. Superimposed craters indicate that these gullies are older than pristine gullies. Additionally, cratered gullies show similar erosion and sedimentation features like degraded gullies. It is possible, that potential impact craters are covered or wiped out by erosion. Therefore, it is possible that degraded and cratered gullies belong to the same class. Approximately 2700 of ~3200 individual gullies were classified. ~2200 of them are positioned at impact crater walls. In contrast to the southern hemisphere [4], there is no difference between the latitudinal orientations of younger and older gullies, which may indicate equal or similar climatic conditions for their formation.

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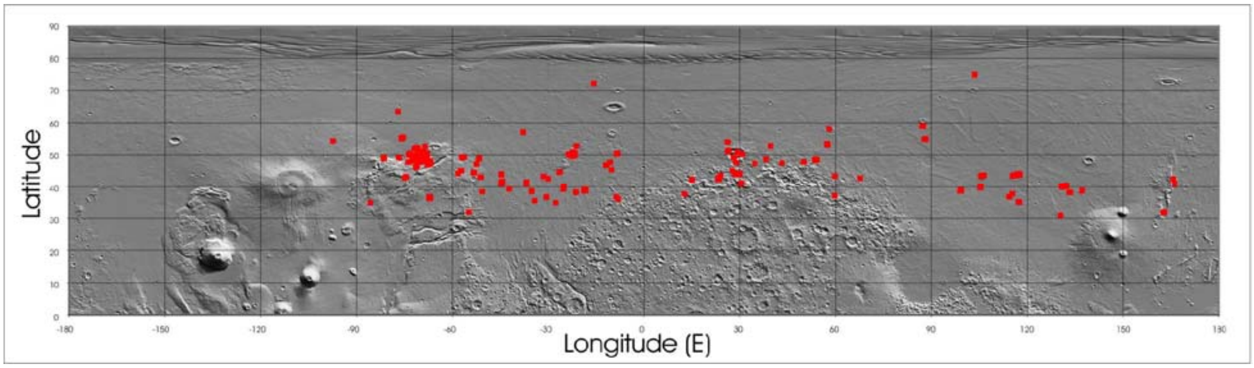


Figure 1: Distribution of gullies found in HRSC survey in the northern hemisphere.

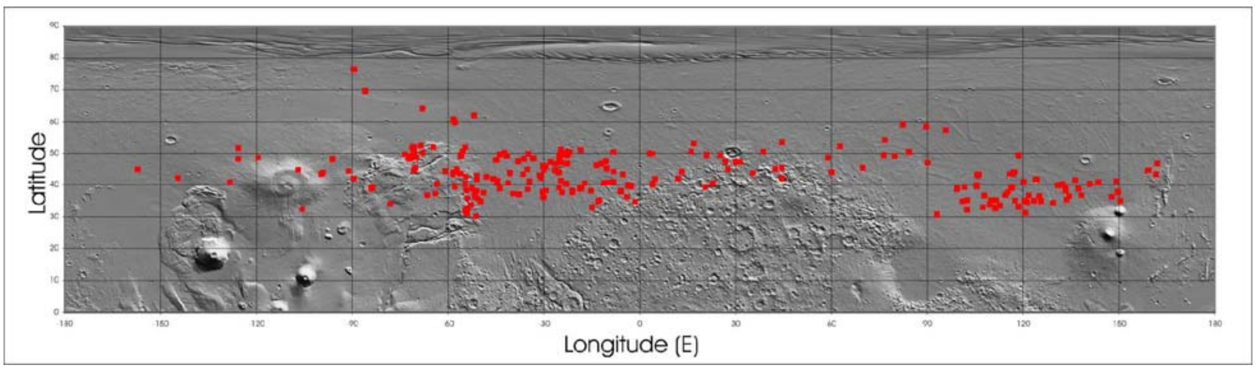


Figure 2: Distribution of gullies found in MOC survey in the northern hemisphere.

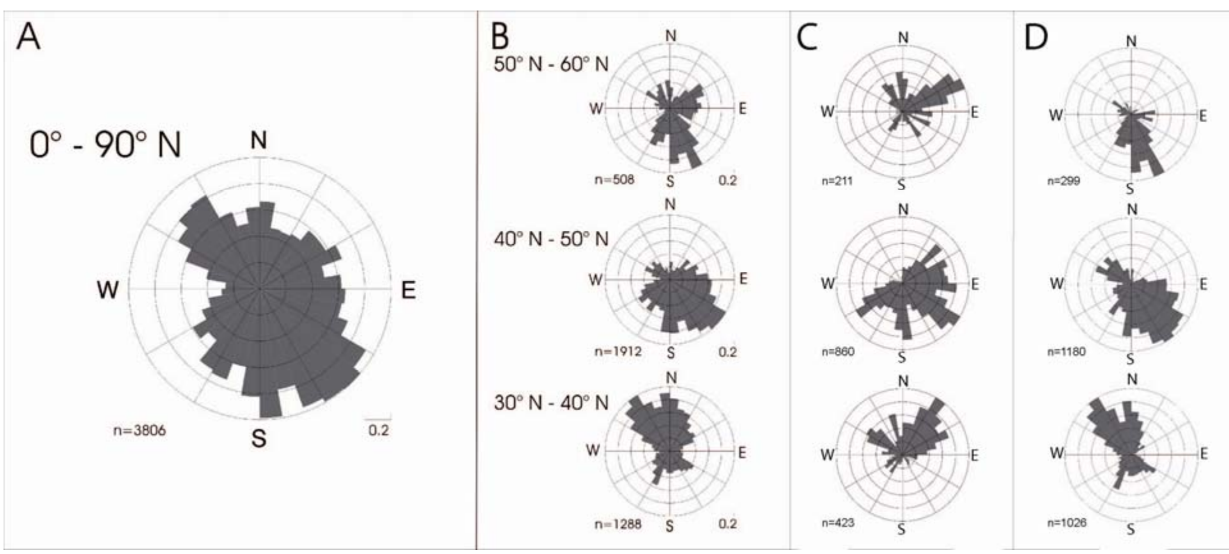


Figure 3: Orientation of craterwall gullies from HRSC and MOC surveys: (A) Orientation of all craterwall gullies in the northern hemisphere. (B) Orientation of all craterwall gullies sorted by latitude. (C) Orientation of craterwall gullies from HRSC survey sorted by latitude. (D) Orientation of craterwall gullies from MOC survey sorted by latitude. In B, C and D only data between 30°- 60°N is displayed because of the low number of craterwall gullies outside this band.

MODELING BRIGHT GULLY DEPOSITS' FORMATION IN HALE CRATER. K. J. Kolb[1], O. Aharonson[2], J. D. Pelletier[1], A. S. McEwen[1], and the HiRISE Science Team, [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721; kkolb@LPL.arizona.edu, [2]Division of Geological and Planetary Sciences, California Institute of Technology, MC 150-21, Pasadena, CA 91125.

Introduction: Hale Crater, a late Hesperian / early Amazonian [1] 120 km x 150 km impact crater, hosts a large number of gullies with a variety of orientations. Gully distributions and orientations have strong implications for distinguishing between gully formation theories, which frequently depend on insolation or a local aquifer. Several of the gullies exhibit bright deposits that are unmodified at the scale, 0.26 - 0.31 cm/pixel, of images acquired by the High Resolution Imaging Science Experiment (HiRISE) aboard the Mars Reconnaissance Orbiter (MRO). Two recently formed bright gully deposits (BGDs) imaged by the Mars Orbiter Camera (MOC) at other locations were initially interpreted as evidence for water on the surface in recent years [2]. One of these BGDs was modeled by Pelletier et al. [3] who found that, although water could not be ruled out in the formation of the studied BGD, dry flow was sufficient. Whether the bright gully deposits' formation involves liquid water is an important question because they have the potential to mark sites of recent liquid water on the martian surface.

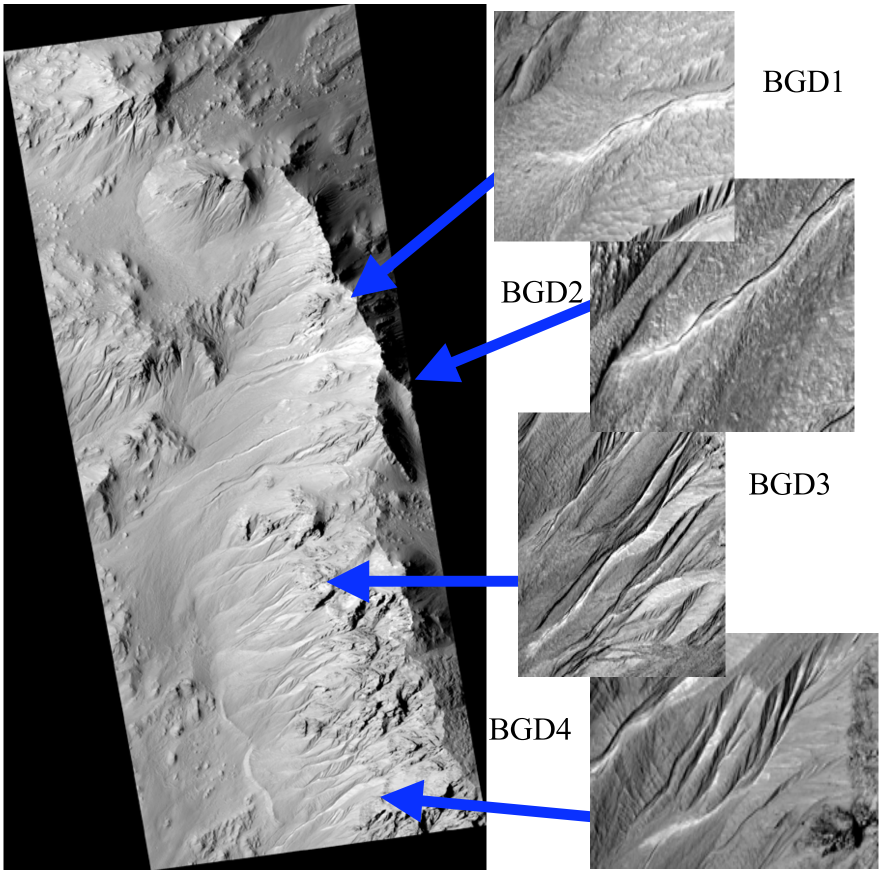
HiRISE has imaged several other unmodified BGDs around Mars, most of which occur in fresh craters on steep slopes averaging 26-35° [4]. The average slopes along the east rim of Hale Crater are closer to 19-20°, and four BGDs are located there as seen in HiRISE images (Fig. 1). Average slope values do not account for the concave crater slope profiles seen in visible imagery, but it is assumed the slopes with a lower average slope value will also be generally shallower upslope than slopes with a high average slope value. Due to the lower average slopes, it is suggested that the Hale BGDs are viable candidates for deposits that required some sort of fluidization, such as saturation by liquid water, to form. We produced a Digital Elevation Model (DEM) and will model the BGDs to determine their best-fit flow parameters.

Observations: MOC and HiRISE have imaged the east rim of Hale Crater multiple times. The BGDs seen in the HiRISE stereo pair include four obvious (Fig. 1) and three faint, all of which stand out in RBG color images as being redder than surrounding, typically blue, gully deposits (Fig. 2). All of the BGDs seen in the HiRISE stereo pair are present in MOC R0702277, the earliest (2003) high-resolution image of this region. No visible changes in shape have been detected, as would be expected if the bright deposits are water frost [5]. Several of the MOC images have a low signal-to-noise ratio, which hampers detecting changes in tone but not necessarily overall shape. We believe that the bright deposits are bright because they contain bright or fine-grained material that was transported. There is obvious bright material upslope of the BGDs, which appears to be pervasive throughout the crater.

Gullies in Hale Crater emanate from isolated mounds and terraces, the central peak, and the rim. The gullies in Hale Crater exhibit many fluvial characteristics. Their channels often meander and have terraces indicative of past flow levels, while some contain streamlined islands. Several channels have resolvable boulders (~1-2 m) that may have been preferentially left behind as a flow transported smaller particles. Because of the possibility that the BGDs are formed by dry mass wasting processes, the BGDs are seen as possible recent activity within gullies rather than marking actual gully formation. Although there are no previous images without the BGDs here, there is good evidence that their channels existed before they formed. For example, BGD 4 (Fig. 2) forms midslope and does not flow through the entire channel.

All of the Hale BGDs reside in gullies that have fluvial characteristics and that are fairly well developed. This is different from other BGDs around Mars, which typically are located in pristine gullies with narrow and shallow channels [6]. The BGDs stand out in false color images (Fig. 2), but their host gullies are not obviously unique in grayscale images. It can be noted that, overall, gullies in Hale show little modification. Like most other BGDs around Mars, the Hale BGDs lie below eroded outcrops that contain noticeably bright material, the likely source material of the deposits.

Methods: As this abstract is being written, we just completed a high-resolution DEM (10 m/post, to be improved to 1 m/post) of a portion of Hale Crater using the commercial stereo software package SOCET SET (® BAE Systems) [7] and the HiRISE stereo pair PSP_002932_1445 and PSP_003209_1445 (both 25 cm/pixel) processed using ISIS (Integrated Software for Imagers and Spectrometers) [8]. High-resolution topography is essential for modeling flows in gullies because their scale (typically 10s to 100s of meters wide) is much smaller than available topography from the Mars Orbiter Laser Altimeter (MOLA), which has spot diameters of ~168 m and along-track spacing of ~300 m [9].



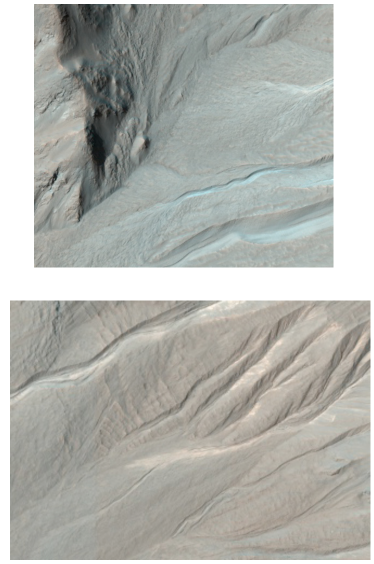


Figure 2. RGB false color image PSP_003209_1445. Not map projected. Rotated so that north is roughly up. Left (~1050 m across) shows redder color of BGD1 compared to an ordinary (blue) debris apron. Right (~800 m across) shows BGD4 forming midslope.

Figure 1. HiRISE PSP_003209_1445, ~5 km across. North is up with illumination from the upper left. Blue arrows mark the alcoves of the gullies with bright deposits.

We will follow the modeling methods of Pelletier et al. [3], which are briefly described here, to model the four obvious BGDs in Fig 1. We model the flows with FLO-2D [10], a 2D finite-difference code that solves the dynamic wave momentum equation and models open channel flow quantifying fluid drag with a Manning roughness or a Bingham rheology. We use 1D kinematic modeling to determine the viscosity and yield stress of a dry granular flow, for a given average particle size, flow thickness, flow density, and particle density, that would occur where each of the BGDs is found along the slopes. These parameters are input into FLO-2D to mimic a dry granular flow. Output of the models includes flow paths, depths, and velocities. We compare the flow paths and resulting deposit morphology to the actual BGDs and determine if the best-fit flow parameters are more indicative of a dry granular flow or a fluid flow. We cannot distinguish between wet and dry debris flows because of the similarities in flow parameters found in terrestrial settings [3], but we can distinguish between a debris flow and a fluid carrying sediment.

Future Work: To extend this work, we will look at slopes in other regions of Hale that do and do not have BGDs and bright material upslope to examine why the BGDs form where they do and to characterize slopes that are conducive to BGD formation, keeping in mind implications for near-surface liquid water.

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SLOPE STEEPNESS OF CHANNELS AND APRONS: IMPLICATIONS FOR ORIGIN OF MARTIAN GULLIES. ***M. A. Kreslavsky***[1] [1]Earth and Planetary Sciences, University of California - Santa Cruz, 1156 High Street, Santa Cruz, CA, 95064, USA; mkreslav@ucsc.edu.

Introduction: Flow of liquid water has been thought responsible for formation of geologically recent gullies on Mars [1], although a number of other potential mechanisms of their formation were proposed, including dry mass wasting and gas density flow. Features classified as gullies contains three morphological elements: erosional alcove, sinuous channel, and depositional apron.

Recent HiRISE images [2] show gullies in remarkable detail and provide an optimal resolution for study of gully morphology. Initial assessment of HiRISE images [3] has given unambiguous evidence of fluvial modification of geologically recent mid-latitude gullies. HiRISE images show that many slope features of uncertain origin (for example, those conservatively referred as "chutes" in high-latitude craters [4]) are gullies with meandering channels, which suggests fluvial origin. Thus, HiRISE observations widely extend geographical occurrence of gullies. More detailed analysis of gully morphology shows that formation of many gullies contains many stages and the most recent episodes of channels incision and sediment deposition on the aprons are separated from previous episodes by formation of ripples, polygonal crack systems, etc.

For terrestrial alluvial fans, the slope of the fan surface is known to be determined by sediment content in the fan-forming water. Hence, slope steepness of aprons and channels can give insight into process of gully formation. Here I report on new accurate slope measurements in gullies.

Slope measurements: To measure slope steepness of gully elements I used stereo imaging with HiRISE. Some HiRISE observations were planned to obtain stereo pairs, when the same scene is viewed from different directions (Fig. 1). Difference of apparent positions of the same objects at two images due to the parallactic shift can be used to reconstruct topography of the scene [5]. I do not perform complete reconstruction of topography. Instead, I measure parallactic shifts and calculate elevation differences and slopes between carefully selected points in the image. For gullies, HiRISE images usually contain a lot of well-recognizable tiny (sub-meter-size) objects (mostly boulders, but also some others), that can be identified in the pairs of images with pixel-scale accuracy. I select such objects and identify their positions. The vector difference between object-to-object vectors in the two images is a parallax vector (Fig. 1) Ideally, its direction is defined by a pair of directions from the scene to the imager, and its length is proportional to the elevation difference between the objects. In reality, the direction of measured parallax is slightly different due to the minor misidentification of the points and random errors. The projection of the measured parallax vector on the ideal direction gives an estimate of the elevation difference, and the residual can be used to assess possible errors and filter out obvious faults in the object identification. Analysis of the residuals shows that the typical precision of elevation difference measurements is about a meter.

This simplified approach has the following essential advantages for the particular task of gully slope measurements in comparison to complete semiautomatic topography reconstruction. (1) Specifically for gully images, there are some essential difficulties in the topography reconstruction. Steep relief of gullied slopes causes significant area of geometric shadows in the images; shadow edges do not coincide exactly at two images making a pair, because the images were taken in somewhat different seasons and local times. These shifted edges of shadows pose significant problem to automated topography reconstruction. Small-scale features (like boulders) look differently when they are directly illuminated by the sun (and have their own geometric shadows) or when they are located in geometric shadow and diffusely illuminated by the sky. Some images contain varying amount of seasonal frost, which makes semiautomatic topography reconstruction impossible. (2) Manual pick of matching points give certainty in attributing steepness to particular parts of slopes. (3) Local slope calculations are more tolerant to imperfection of geometry knowledge (e.g., spacecraft orbit knowledge).

Fig. 2 shows one example of slope measurements in a gully.

Preliminary results: Gullies show noticeable diversity in slope steepnmess. However, given a huge diversity of their morphologies, the slope steepness shows surprising similarity among gullies studied so far. All alcoves (e.g., 32° in Fig. 2) are steep, steeper than 25°, often, steeper than 30°. This agrees with observations reported in [6] with a much less accurate technique for a much larger set of gullies.

Slopes of deposited material are systematically gentler than slopes of corresponding alcoves, which is naturally explained by transition from erosional to depositional regime in the gully-forming flow. Upper parts of the deposits incised by narrow channels (22°

in Fig. 2) are steeper than aprons themselves (18° and 14° in Fig. 2). Distal parts of the aprons (14° in Fig. 2) are gentler than proximal parts (18° in Fig. 2). All these relationships are very typical for terrestrial alluvial fans. The apron slopes (usually steeper than 10°) are rather steep in the scale of terrestrial alluvial fans; usually, distal parts of the alluvial fans in arid areas on the Earth are significantly gentler. This says that total amount of fluid that flowed through the gully was limited, and sediment load was high. The latter demands the presence of friable material in the alcoves and is consistent with steep slopes of the alcoves.

This work is in progress. With more HiRISE stereo pairs accrued and released, and with the larger number of slopes measured, it hopefully will be possible to correlate slope steepness against morphology, latitude, orientation, geological settings, etc. More detailed comparison with terrestrial situation with consideration of scaling due to gravity difference it hopefully will be possible to obtain quantitative constraints on the fluid and sediment load.

Conclusions.

1. Manual slope measurements with HiRISE images provide useful information

2. Formation of gullies occurred in a number of steps, rather than in a single event.

3. Relatively steep gully aprons are consistent with gully-forming fluid with high sediment content and total modest amount of the fluid.

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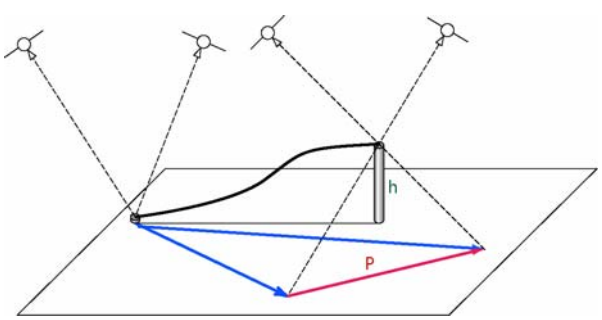

Fig. 1. Scheme of parallax measurement: h, the elevation difference between two points; p, parallax vector.

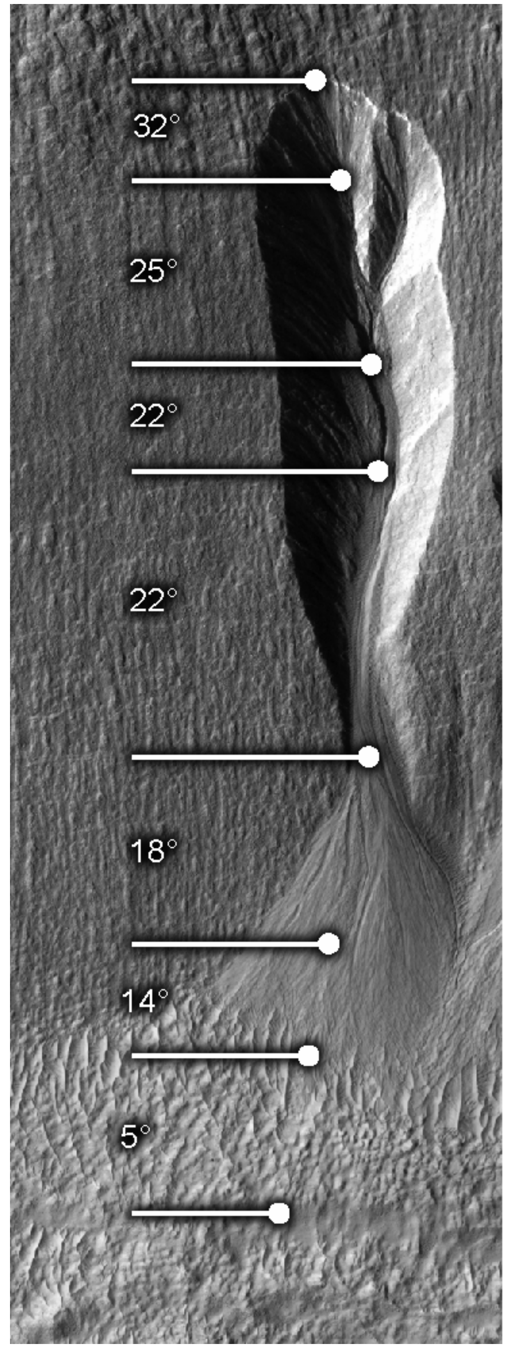

Fig. 2 Example of slope measurements from parallax shifts. Stereo pair PSP_002514_1420 - PSP_002659_1420 (shown in the figure) was used. Location is 37.8°S 217.9°E.

STRUCTURAL AND LITHOLOGIC CONTROLS OF GULLY FORMATION ON THE INNER WALL OF METEOR CRATER, ARIZONA: IMPLICATION FOR THE ORIGIN OF MARS GULLIES, P. Senthil Kumar[1,2], James W. Head[2] and David A. Kring[3], [1]National Geophysical Research Institute, Hyderabad 500007, India, senthilngri@yahoo.com; [2]Department of Geological Sciences, Brown University, Providence, RI 02912, USA, james_head@brown.edu; [3]Lunar and Planetary Institute, Center for Advanced Space Studies, Houston, TX 77058-1113, USA, kring@lpi.usra.edu.

Introduction: One of the compelling pieces of evidence for the presence of liquid water on Mars is the geomorphic expression of gullies, which are formed on the inner walls of impact craters and on the other steep slopes. For example, Malin and Edgett [1,2] initially described a class of young features on Mars that they termed gullies, consisting of an alcove, a channel and a fan (Fig. 1). Restricted to middle and high latitude locations, these features were interpreted to have originated through processes related to the presence of liquid water through groundwater discharge and in some cases by the surface runoff; the potential presence of liquid water on the surface of Mars currently or in the very recent geological past, when liquid water is metastable [3], generated a host of alternative explanations for the gullies [see summary in 4]. Detailed analysis of the conditions under which H_2O could flow as a liquid in the current Mars environment shows a range of conditions under which gully-forming activity is possible [3,5]. Recent observations of changes in gullies, interpreted to mean that a few gullies are currently active [6], have intensified this discussion. Terrestrial analogs to martian environments may provide insight into the processes operating on Mars. For example, the nature of perennial saline springs forming channels on Axel Heiberg Island in the Canadian High Arctic has been used to support the argument that martian gullies formed from subsurface groundwater springs [7], and field studies in the Antarctic Dry Valleys (ADV), a hyperarid polar desert analog for Mars [8-11], have provided ample evidences for top-down melting of annual and perennial snow and ice. However, the geologic factors, which control the distribution of gullies on the crater inner wall, are still poorly understood. Terrestrial simple impact craters emplaced on sedimentary rocks are potential analogues to Mars throwing light on the gully distribution. We chose to study the Meteor Crater, which shows a spectacular development of gullies on its inner wall (Fig. 1).

Meteor Crater: Meteor Crater is a ~1.2 km wide and ~180 m deep bowl shaped impact crater formed as a result of the impact of Canyon Diablo meteorite onto the southern Colorado plateau in north central Arizona [12,13]. The crater was excavated on the >1 km thick flat-lying sedimentary rock layers resting on the crystalline basement. Like many impact craters, it shows a spectacular development of centripetal drainage pattern in response to rainwater precipitation, snow melting and groundwater discharge. Like martian gullies, the drainage system is composed of alcove, channel and fan. These gully systems are radially arranged on the inner wall of the crater. We examine these gully features as well as the entire crater wall to understand how the geologic factors such as lithology and deformation features (fractures and faults) control the location and geometry of the gullies. We argue that the understanding from Meteor Crater can well be extended to gully formation in the craters of other planetary bodies (e.g., Mars), where liquid water may play an important role in the landscape evolution.

Gully distribution: The gully distribution in Meteor Crater has the following characteristics (Fig. 1): (1) some gullies originate from the rim crest; (2) most gullies originate from the middle wall, at the contact of Kaibab dolomite beds and Coconino sandstones with deep incision in the Coconino sandstones, (3) the gullies are located along the tear faults, (4) the gullies are located along the radial fractures, (5) channels are developed in the talus deposits, (6) alluvial fans occur along the periphery of the crater floor, (7) caves are formed at the base of the Kaibab limestone-Toroweap sandstone contact.

The controlling factors: The gully location on the crater wall is principally controlled by the position of radial fractures and tear faults. Recently, we have carried out an extensive structural geological mapping in and around the Meteor Crater that point to the existence of fracture networks in and around the crater [14]. Particularly, the crater wall has a dense network of impact-related fracture systems and faults. The regionally occurring fracture-fault networks (pre-impact weakness planes in the target rocks) can be efficient zones of groundwater recharge, where the surface water can percolate. The clastic sedimentary rocks (e.g., sandstones) of the Moenkopi and Coconino Formations, which are exposed on the crater wall, are the most efficient aquifer systems in this region. The fractures/faults exposed on the crater wall are the favorable locations where surface runoff can preferentially flow causing the degradation. Also, these are the favorable locations for groundwater flow, which can be discharged on the crater walls in the form of springs. As the present-day climate in and around Meteor Crater is arid characterized by scanty rainfall and smaller quantities of snow fall during winter, the gully geomorphic features are less likely to have formed by the present climate system. Also, the present-day groundwater level is below the crater floor, and therefore, cannot form the springs on the crater wall. Therefore, we need to understand the role of past climate, particularly, during the Pleistocene period, when the crater was excavated, at ~ 50000 years ago. Climate reconstructions (e.g., [15]) suggest that, at the time of impact, the regions around Meteor Crater were wetter and that continued for long time, probably up to ~11000 years ago (see for discussion [16]). Late Pleistocene outburst flooding has been reported elsewhere in this region [17]. Consequently, the groundwater level in Meteor Crater could have been at a shallower level (~30 to 45 m) than today [12,13]. The ~30 m thick lake sediments provide significant evidence in support of the past pluvial climate, groundwater conditions and the existence of springs on the crater wall. Caves exposed on the Toroweap-Kaibab contact may point to percolation of surface runoff and selective discharge through the fractures on the crater wall. In addition, the structural uplift and shock compression at the time of impact might also have elevated the groundwater level around the crater, allowing the transient groundwater discharge forming the springs. Shoemaker and Keiffer [18] also observed an ancient soil profile developed on talus in the crater wall that may point to a higher water table, rain fall and groundwater discharge. The gully features are preferentially the sites of groundwater discharge that flowed along them. Fractures and faults must have enhanced this process.

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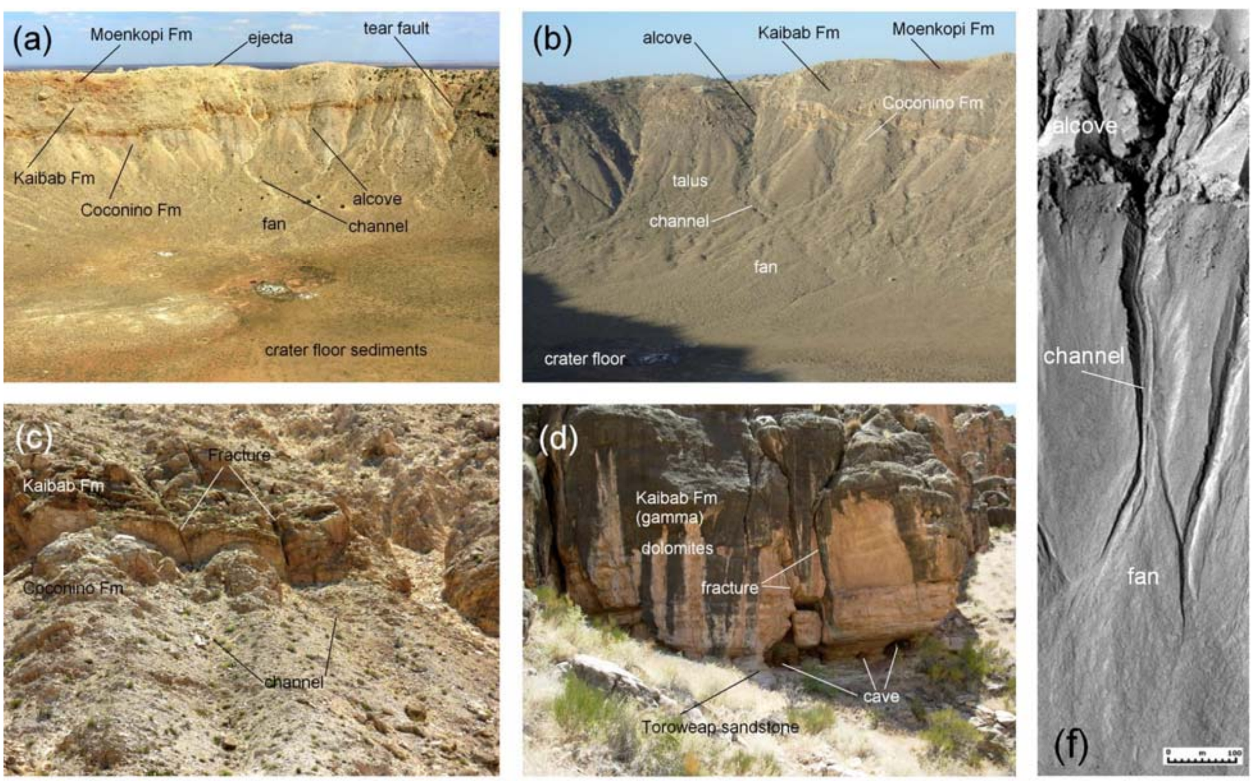

Fig. 1. (a) Southeastern inner wall of Meteor Crater showing spectacular development of gullies. Note that some gullies are originated from the crater rim, while others are from the middle wall, where lithology changes from dolomite to sandstone, (b) gully network on the southwestern wall showing the typical alcove-channel-fan morphology, (c) gully originates where the radial fractures are exposed on the bedrock, (d) a possible example for groundwater discharge: formation of caves at the contact of Kaibab dolomites and Toroweap sandstones, (e) an example for martian gully showing the alcove, channel and fan.

TESTING A DEBRIS FLOW SOURCE AREA AND INITIATION HYPOTHESIS FOR SIMPLE 'CLASSIC' MARTIAN GULLIES. N. L. Lanza[1,2], G. Meyer[1], H. Newsom[2], R. Wiens[3], and C. Okubo[4], [1]Earth and Planetary Sciences, MSC03 2050, 1 University of New Mexico, Albuquerque, NM 87131 (nlanza@unm.edu), [2]Institute of Meteoritics, University of New Mexico, Albuquerque, NM, [3]Los Alamos National Laboratory, Los Alamos, NM, [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.

Introduction: On Earth, gullies indicate the presence of liquid water. Terrestrial gullies form by a number of different mechanisms, most notably through runoff-dominated surface erosion and infiltration-triggered slip [1]. However, the temperature-pressure environment on Mars today does not allow for liquid water precipitation, nor is liquid water stable on the surface for any significant time periods. Thus, the presence of geologically modern gullies on the martian surface presents an interesting problem.

Here, we examine characteristics of terrestrial flow features and compare these to martian gullies. We find that many martian gullies share many key characteristics with debris flow erosional and depositional features. If martian gullies are formed by a debris flow mechanism, and liquid water causes initiation of of the flow by melting of a near-surface layer that broadly underlies slopes (causing saturation, increased pore pressure, and decreased shear strength), then gully head locations should exhibit the same contributing area-slope relationship found for terrestrial debris flow [2]. We are currently examining gullies in a limited study area with well-defined channel heads, limited evidence for multiple flows (e.g. small fans below the gullies) and relatively simple associated alcove regions. Initial results are forthcoming. If a consisitent area-slope relationship is found for these martian gullies, it will provide strong evidence for gully formation as the result of saturation of surface materials by a liquid generated by melting of a near-surface layer.

Why debris flow?: There are several mechanisms of formation for gullies on Earth, and clues about the initiation mechanism can be found in the morphology of the final form. Malin and Edgett [3] identified three main components of gullies: an alcove, a channel, and a debris apron. On Earth, the alcove-channel-apron morphology is often associated with debris flows [4, 5]. The major evidence for debris flow is the presence of a well-defined, leveed channel [5]. An alcove near the top of the channel is also expected, resulting from the loss of material during flow initiation, and may continue to develop over numerous successive events. A debris apron or fan may also occur near the bottom of the slope when debris flow materials cease to flow. In terrestrial debris flows, the formation of the channel is due primarily to scouring of the slope as the debris flow moves past and acquires more slope material [6]. Both Costard et al. [7] and Mangold et al. [8] have also noted the resemblance of feature associated with martian gullies to terrestrial debris flow features.

A debris flow begins as a slide of rigid material, which occurs when the material becomes saturated. This material surges downslope in response to gravity, and more than one surge may occur during a single event. Debris flows can have peak velocities of 10 m/s [9] and can flow distances in the kilometer range [10]. Observations of debris flows show that the material appears to become fluid as it flows along the slope, and becomes rigid again as it is deposited [9]. It has commonly been thought that the solid and liquid fractions of the flow act as one fluid material. Pierson and Costa [11] examined the rheologic response of different sediment-water mixtures, and determined that debris flow is a non-Newtonian fluid that exhibits plastic flow behavior. Iverson [9], however, points out that it is difficult to explain the behavior of debris flow with a single rheology. Instead, he suggests that the interaction between the solid and fluid components leads to the observed behavior, which points to an ever-changing rheology as the flow develops.

It is important to note that the name 'gully' indicates a steep-walled incised channel, but does not imply a specific flow process that caused the erosion. On Earth, gullying is an erosional process that often results from surface runoff produced by precipitation [12]. Debris flow is a mass wasting process that may also cause gully erosion.

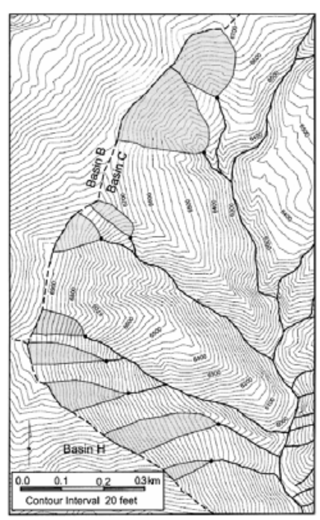

Figure 1. Example of mapping upslope contributing areas to debris flows initiation locations. Solid circles mark initiation locations, and black lines are the flow paths. Shaded polygons denote the contributing area. From Cannon, et al. [1].

The topographic signature of debris flow: Montgomery and Dietrich [2] examined the starting locations of channels in relation to the slopes above the channel, and found a relationship between the drainage area and the slope gradient, with slope decreasing as the drainage area increases. The drainage area is an area above the channel head that focuses shallow subsurface throughflow liquid into slope concavities. On Earth, this liquid is often surface runoff from rainfall. On Mars it is much more likely to be from a subsurface source. However, in both cases liquid is likely to move downslope through the regolith as throughflow. [2] suggest that channels will begin at the first point downslope where there is a large enough source area to support them, i.e. failure occurs at the point on the slope where the slope materials are saturated to a critical depth (and thus a critical pore pressure to induce failure), which requires a minimum amount of water from upslope.

The source area is defined as the region from the top of the drainage divide downslope to the point of initiation at the top of the channel (Figure 1) [1, 2]. The area-slope relationship described by [2] is the relationship between the source area and the gradient of that slope area. As the slope becomes steeper, failure presumably becomes more likely given the increase in shear stress. In addition, throughflow is also concentrated more quickly on steep slopes. This idea is seen in theoretical calculations by Montgomery and Foufoula-Georgiou [13], which show that smaller source areas are needed to initiate channels on steeper slopes. Figure 2 shows the relationship between contributing area and slope for 84 debris flows at Storm King Mountain, CO.

It should be possible to measure this area-slope relationship on Mars using image and topography data sets. If the area-slope relationship holds for martian gullies that have distinct channel heads and are not complicated by many subsequent dry mass failures above the oversteepened channel head, it will point to a liquid agent of formation and potentially a debris flow mechanism.

Implications: If the area-source relationship holds for martian gullies, then the source region of liquid is likely to be distributed broadly over slopes in the near-surface regolith. Past work suggests that liquid water is the most likely agent of formation due to the temperature-pressure environment on Mars. Proposed sources of water include near-surface ice [7], snowmelt [14], and aquifers [15, 16, 17]. While ice may be deposited at and stable in the near-surface at the gully locations at higher obliquities, models do not predict either its abundance or long-term presence today (e.g. [18]). In addition, it is unclear how water from snowmelt would be stable long enough to saturate the slope material. However, both near-surface ice and snowmelt remain good candidates for saturation of slope materials given that they operate at the surface. Aquifers are much less likely to cause saturation distributed broadly over slopes near the surface due to the fact that they are predicted to be stable at greater depths from the surface and discharge along discrete, low-permeability horizons or at footslopes [17]. Regardless, if the gullies are found to be recent debris flows on Mars, this will necessitate a reevaluation of the current models of water stability at the surface.

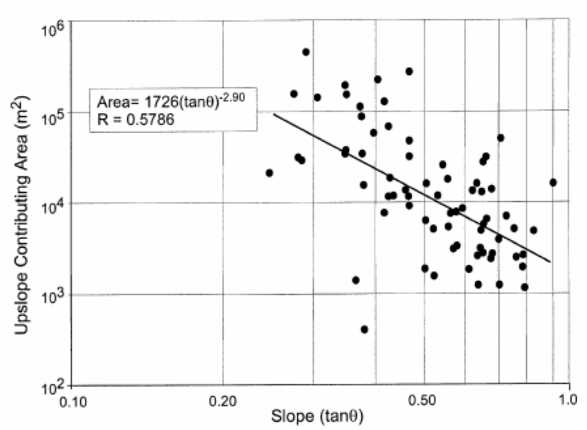

Figure 2. Upslope contributing area as a function of its average gradient. From Cannon et al. [1].

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LATE-STAGE GULLY MODIFICATION ON MARS: POLYGONALLY-PATTERNED GROUND, PERMAFROST, AND GULLY WATER SOURCES. J. S. Levy[1], J. W. Head[1], D. R. Marchant[2], J. L. Dickson[1], and G. A. Mogan[1], [1]Brown University Department of Geological Sciences, 324 Brook Street, Box 1846, Providence, RI, 02912, joseph_levy@brown.edu, [2]Boston University Department of Earth Science, 675 Commonwealth Avenue, Boston, MA, 02215.

Introduction: Gullies on Mars are a class of young features, initially interpreted to have formed by surficial flow of released groundwater [1, 2], and which may still be active [3]. Alternative hypotheses for the origin of gully-carving fluids include melting of dust-rich snow deposits [4], melting of atmospherically emplaced ice [5], and melting of ice-rich permafrost terrains at high obliquities [6]. Recent fieldwork in the Antarctic Dry Valleys (ADV) has reported on the top-down melting of snow as the primary source for water currently flowing through gully channels and hyporheic zones [7-10]. Analysis of composite-wedge polygons in the gullied terrain indicates that polygonally patterned ground enhances local the accumulation of windblown snow (and thus, increases the amount of meltwater in the gully systems), assists in the transport of gully-related meltwater (by altering the local ice-cement table topography to concentrate channelized flow), and mediates in the storage of gully meltwater (in the distal hyporheic zone) [11]. Further, polygons were shown to have pre-dated the gullies studied, and to have remained active during the entire process of gully formation, implying the continuous presence of an impermeable permafrost layer beneath the gullies throughout their evolution [11]. These observations provide a baseline for analyzing gully-polygon interactions on Mars, and suggest that analysis of surface permafrost features can be used to infer the state of the shallow subsurface in martian gullied terrains.

Gully-Polygon Interactions on Mars: A survey of HiRISE images of the martian surface from the primary science phase, spanning 30°-80° north and south latitude was conducted. Of the 537 images studied, 118 feature gullies, and 70 feature gullies in conjunction with polygons. Analysis of gully-polygon suites reveals the presence of several analogous landforms between ADV and martian gully-polygon systems.

Alcove Polygons. As in the ADV, polygons are common in gully alcoves [11] (Fig. 1). Polygons in gully alcoves are commonly outlined by bright deposits which are present preferentially in polygon troughs.

Annexed Polygon Troughs. In ADV gully systems, active and abandoned gully channels show evidence of the diversion of gully-channel water flow into previously incised polygon troughs—a process referred to as polygon trough annexation [11]. In inactive annexed polygon troughs, gully-channel fluvial deposits are present above composite polygon wedge structures [11]. Annexation widens and deepens polygon troughs, and results in less angular trough intersection angles [11]. Although active fluvial processes were not observed in the 537 HiRISE images studied (with the possible exception of [3]), several features were observed which were 1) continuous and sub-linear 2) present on polygonally patterned surfaces in widened and curved polygon troughs, and 3) had a texture similar to gully-fan surface textures (Fig. 2). These features are interpreted as being analogous to terrestrial annexed polygon troughs.

Fan Overprinting and Dissection. Gully-fan deposits in the ADV overprint and embay composite-wedge polygons and are dissected by a network of continuously expanding polygon cracks [11]. Several gully fans observed in HiRISE images embay polygonally patterned ground on gullied slopes (Fig. 3). Further, polygon troughs contiguous with the surrounding trough network are expressed through some gully fan surfaces (Fig. 3). Generally, such fan surfaces are of small spatial extent (>50% the surface area of the associated gully alcove), and have subdued topography (no extensive relief is present between fan surfaces and off-fan surfaces).

Gully-Polygon Stratigraphy and Implications: Taken together, these observations of gully-polygon suites on Mars suggest the following stratigraphic and temporal relationships between gullies and polygons: 1) polygons post-date alcove excavation in some gullies, making polygons the youngest landscape element present; 2) polygon troughs have been annexed by some gully channels, indicating channel formation in a polygonally patterned surface; and 3) fan embayment and dissection implies that gully fan deposits formed on a polygonally patterned surface which has undergone continuous thermal contraction cracking during fan aggradation. Polygon-gully stratigraphic relationships suggest that these martian gullies have formed and evolved on slopes underlain by continuous shallow permafrost during the most recent period of gully activity. No evidence of catastrophic water release was observed. These lines of evidence suggest an atmospherically emplaced, top-down source for gully volatiles involved in the most recent stage of martian gully evolution. Polygon and permafrost enhancement of gully processes analogous to those observed in the

ADV is consistent with cold, ice-depositional climate conditions modeled to have prevailed at gully-polygon sites during the last ~5-10 My [12].

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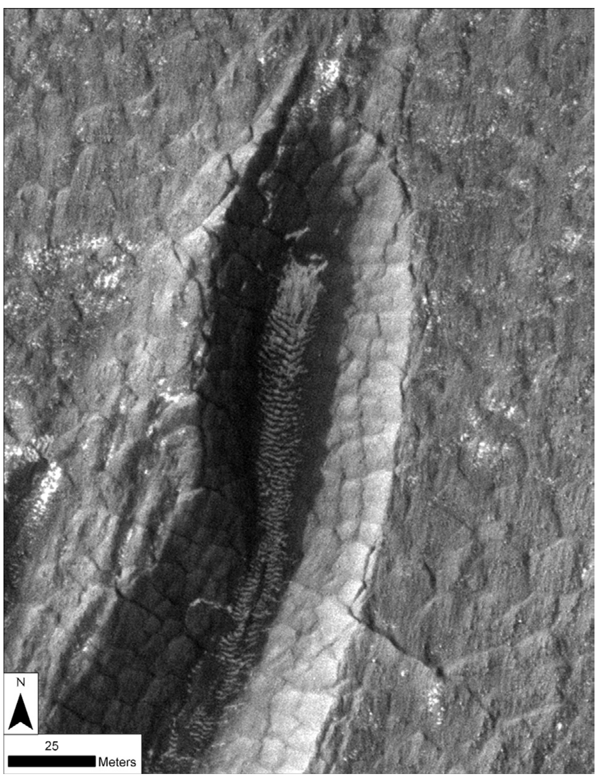

Figure 1. Alcove of gully in PSP_001882_1410 (38.7 S, 194.0 E, Ls = 153.7: southern winter). The origin of bright material preferentially present in polygon troughs remains an active area of inquiry. Illumination from left.

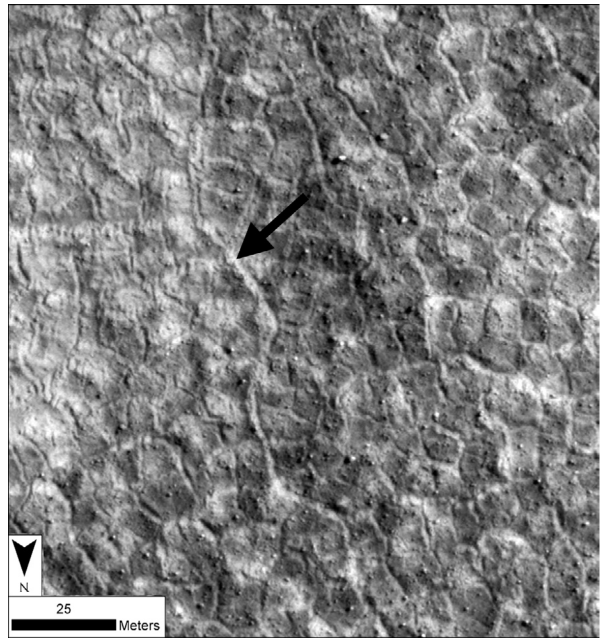

Figure 2. Annexed polygon troughs in PSP_001846_2390 (58.7 N, 82.4 E, Ls = 152.2: northern summer) indicated by arrow. Bright material in sinuous polygon troughs has a similar texture to nearby fan deposits. Illumination from right.

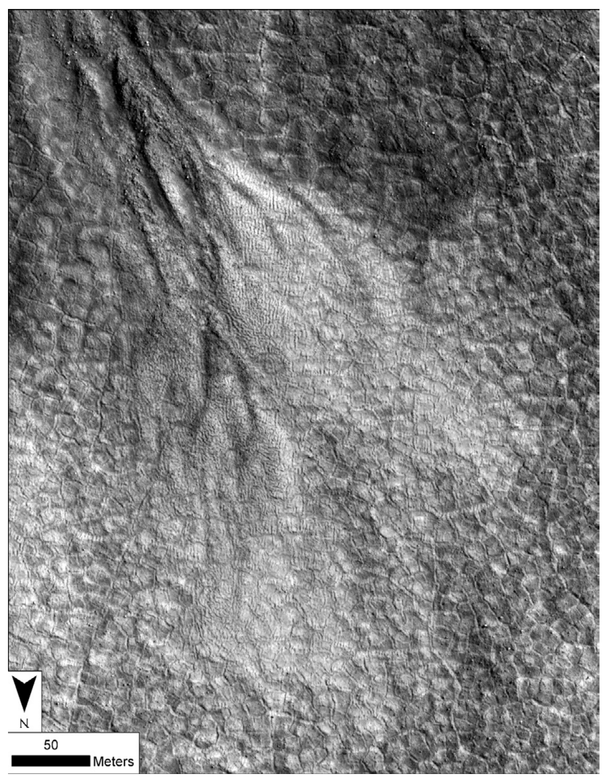

Figure 3. Gully fan deposits in PSP_001846_2390 in contact with polygonally patterned ground. Fan deposits embay some polygons, and fill some polygon troughs. The underlying polygon network is visible through the fan, suggesting continued dissection of the fan surface.

On the mobility of large Martian landslides. A. Lucas[1,2], A. Mangeney[1], D. Mège[2], Bouchut, F[3]. 1 - Institut de Physique du Globe de paris, UMR CNRS 7154, Université Paris Denis Diderot, France. 2 - Laboratoire de Planétologie et de Géodynamique, UMR CNRS 6112, Université de Nantes, France. 3 – Département de Mathématiques et Applications, Ecole Normale Supérieur, UMR-CNRS 5881, Paris, France. (lucas@ipgp.fr).

Abstract:

A new landslide mobility parameter that takes the friction angle into account can shed new light into the dynamics of large Martian landslides.

Introduction:

Landslide morphologies have been identified on Mars [1-2]. Some similarities between experiments on dry granular spreading and Large Martian Landslides (LML) convey to conlude on dry conditions [3]. However, normalized runout on Mars is twice as large as those observed in laboratory. Numerical simulations on theoretical 2D and real 3D topographies reconstructed from remote sensing data show that slope effects significantly reduce the discrepancy between experimental results and Martian observations [4]. However, topography effects are not strong enough to explain the high mobility of Martian landslides, which requires a very small friction angle ($\delta < 10°$), much smaller than required in dry granular spreading simulations ($\delta = 32°$) [4].

As a result, physical processes such as air cushioning or lubrication by a fluid phase should play a key role in the dynamics of Martian landslides.

We investigate landslide mechanics using a new mobility parameter [4] that makes it possible to characterize the flow dynamics regardless of the geometry of the released mass and of the underlying topography.

Morphometric parameters of LML:

Quantin et al. [5] have performed a systematic geomorphology analysis of VM landslides using THEMIS, MOC and MOLA data sets. More recently, Lajeunesse et al. [3] have performed a morphometric analysis of these landslides. From these studies, some landslide morphometric parameters can be defined (fig. 1).

Morphometric Survey:

From THEMIS, MOLA and MOC data available from PDS [6], we performed a morphometric survey using these parameters on five large Maritan landslides (fig. 2).

Mobility of Martian landslides:

The classical mobility is defined as:

$$m_e = \frac{\Delta L}{H},$$

It is volume-dependant. We define instead a new mobility parameter m'_e, which reads [4]:

$$m'_e = \frac{1}{\tan\delta} = \frac{1}{\tan\theta + \alpha\frac{H_i}{\Delta L}},$$

where θ is the bottom slope, and $\alpha = 1.24$ a dimensionless parameter introduced by [7]. The mobility parameter is independent of the initial landslide volume, its aspect ratio, and the underlying topography. This mobility m'_e is thus a function of the friction angle δ. We calculate m'_e for the following landslides:

Landslides	**Mobility (m'_e)**	**δ (°)**
Ophir	5.8	9.8
Candor	5.6	9.9
Ganges	6	9.4
Coprates	7.7	7.3
Melas	6.9	8.1

Tab 1 – Mobility $m'e$ and angle of friction δ calculated for a few landslides on Mars.

Mobility m'_e is useful for numerical simulations of Large Martian Landslides. Based on thin-layer approximation model, we performed a series a simulations of large Martian landslides in which the topography is taken into account [4,8].

Results and discussion:

Calculation of the mobility (m'_e) for the 5 Valles Marineris landslides studied give a similar angle of friction. This result is consistent with the similar geological context of these landslides, and the presumed similar composition of the slided material involved.This indicates that the mobility parameter we used is makes sense and provides a good effective friction estimate.

The friction angle values do not allow us to conclude as to the presence or not of a liquid phase in the dynamics of the large Martian landslides. We will discuss the implications of the use of this new mobility parameter for large Martian landslide numerical modeling, following the path opened by an earlier Ophir Chasma landslide study [4].

References:

[1] Lucchitta, *JGR*, 1979; [2] McEwen, *Geology*, 1989; [3] Lajeunesse et al., *GRL*, 2006; [4] Lucas and Mangeney, *GRL*, 2007; [5] Quantin et al., *PSS*, 2004; [6] *http://pds-geosciences.wustl.edu*; [7] Lube et al., *J. Fluid Mech*, 2004 ; [8] Mangeney et al., *JGR*, 200

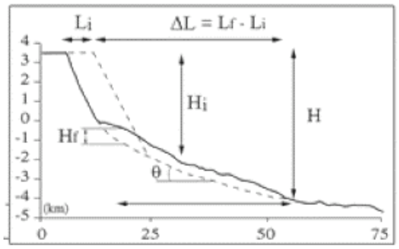

Fig 1 – Morphometrics parameters used in this study. L_i is the initial mass length, H_i is the initial mass height, ΔL is the final runout, H is the total height (topographic slope is taken into account), θ is the slope, and H_f is the final deposit thickness (modified after [4]).

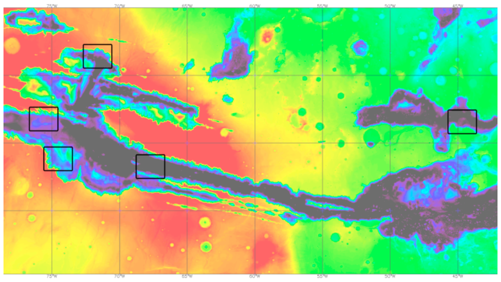

Fig 2 – Valles Marineris Map. The 5 studied landslides are in the 4 black squares.

New Methodology for Initial Volume Estimation of Martian Landslides from DTM and Imagery.

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Abstract: We propose a new method for the reconstruction of slided materials in large Martian landslides, and we take the large Coprates Chasma landslide as an example.

Introduction: Large Martian Landslides (LML) were studied by many authors [1-3]. Studying these landslides contribute to an understanding of the dynamics of the landscapes and is expected to provide insight into the climatic conditions during emplacement at Amazonian Time [4] due to the possible presence of groundwater in liquid or solid phases.

Many studies highlight a much higher mobility of Large Martian Landslides compared to terrestrial cases [1,2,5] (*see also Lucas at al., workshop on Martian Gullies, 2008*). A few parameters allow us to characterize the dynamic of those catastrophic events such as runout, velocity, surface area of deposits, and the volume involved in mass spreading. In order to understand the behavior of Large Martian Landslides, numerical simulations have been performed in [5]. A major problem when simulating real flows is the reconstruction of the pre-event DTM (Digital Topographic Model). Initial mass volume and bottom topography reconstruction are thus needed so as to reproduce the observed final deposits in the simulations.

Sato et al. [7] have already proposed a LML volume measurement method. We focus here on a method developed for numerical simulations [5].

Data used: Using infrared and panchromatic imagery from from THEMIS, HRSC, MOC, andMOLA DTM,we compile data in ENVI®. Correct deposit identification deposits is a key element in our approach. Thermal IR data obtained by THEMIS during night time make it possible to distinguish between the deposits and the surroundings.

DTM processing:

Two steps are needed in the topography reconstruction.

1. After deposit identification on the images, the Region Of Interest (ROI) is used as a mask in the DTM altimetric grid. Deposit thickness within the ROI is removed using a vectorial mapping software (e.g. Didger®). In several cases on Mars (e.g. Coprates Chasma), the deposits are made of a faulted area overhanging debris aprons [3] (fig. 1). The floor topography below the faulted domain is not well constrained. We perfomed here two reconstructions using two floor topographic slopes.

This removal generates dispersion of the altimetric information in the initial grid. The altimetric grid is then rebuilt by kriging [8], defined by the equation:

$$Z^*(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i),$$

where the estimation of $Z^*(x_0)$ is calculated for $x = x_i$ at x_0 (where x_0 are known points) of the plane starting from known values; λ_i is the ponderation coefficient in $x = x_i$. Kriging is appropriate because it takes both the geographical position and variability of the data into account. This interpolation method of interpolation minimizes the errors if information is not spacially regular. The new altimetric grid obtained by this method has the same spacial resolution as MOLA.

2. The second step is reconstruciton of the initial landslide volume. At first order, we interpolate the wallslope using the each edge of the scarp. Afterwards, we perform a topography modeling so as to get the second order of the wallslope shape. The morphometric features are determined by calculating the slope and the curvature of the surface using ENVI® (fig. 2). This step allows us to determine the initial wallslope geomorphology. Our calculation of the missing spur-and-gully volume does not exceed 3% of the total ridge's volume at MOLA resolution (*Further work is in progress using a HRSC DTM. More significant volume is expected due to the better spatial DTM resolution*).

Finally, reconstruction of the initial slided volume is done using the same vectorial method as that used for floor topography retrieval (fig. 3).

Discussion: Volume estimates for Large Martian Landslides have been previously calculated by [3,7] using the same data. Similar to *Sato et al.* [7], our volume estimates are based on floor topography reconstruction, whereas *Quantin et al.* [3] proposed a simple estimate from MOLA data. Nevertheless, we find a volume similar to the volume found in [3], and more importantly, our volume balance has the same sign with [7] (table 1). Moreover, our calculations differ from [7] in the interpolation algorithm used. Whereas *Sato et al*. [7] obtain non physical oscillations in their

DTM (fig. 4-a), the algorithm we use gives a non undulated, more realistic DTM (fig. 4-b), a constraint that we initially imposed because of the requirement of having a smooth topography for subsequent landslide development simulation.

Coprates Landslides:	[3]	[7]	Topo-1	Topo-2
Initial Vol. (km^3)	500	249	300	300
Final Vol. (km^3)	346	472	390	410
Vol. Balance: (Vf-Vi)/Vi	-0.31	0.90	0.30	0.36

Table 1 – Volume estimates for Coprates Chasma landslide in the litterature and in our study. Topo 1 is steeper than Topo 2.

Conclusion: Despite floor topography unknowns, our results are in broad agreement with [7]. In addition, as we mentioned below, our method of reconstruction is suitable to 3D numerical simulations due to an optimal geostatistic algorithm.

Our method may be applied on more recent datasets such as HRSC and HiRISE DTMs, an evolution that is currently in progress.

Finally, given that the intial geometry of VM is a graben structure [9], Our methodology is applicable to estimate the mass wasted by weathering processes.

References: [1] Lucchitta, *JGR*, 1979; [2] McEwen, *Geology*, 1989; [3] Quantin et al., *PSS*, 2004; [4] Quantin et al., *Icarus*, 2004; [5] Lucas and Mangeney, *GRL*, 2007; [6] Lucas and Mangeney, *1st EPSC*, 2006; [7] Sato et al., *7th Int. Conf. Mars*, 2007; [8] Stein et al., Springer ed. 2002; [9] Mège et al., 1996.

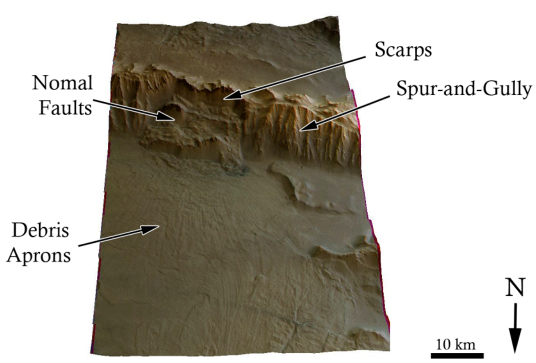


FIG. 1 – HRSC image in Coprates Chasma (12°S, 67°W). Spur-and-Gully features are not present at landslide Scarps. The equivalent missing volume is 3% on MOLA DTM.

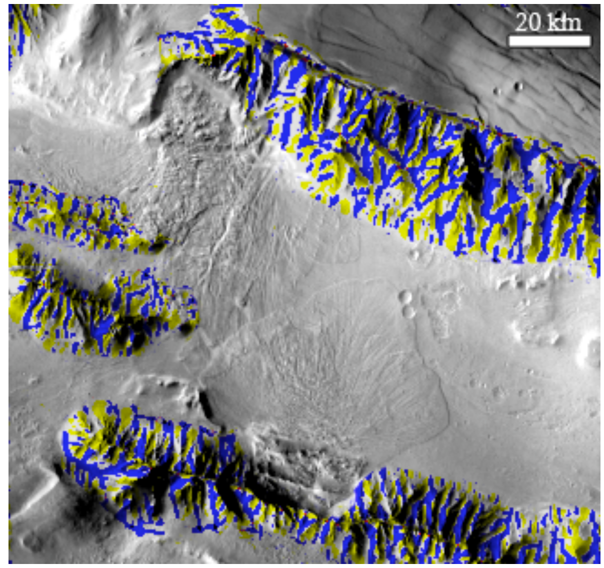


FIG. 2 – Topographic features from modeling (see DTM processes section) over IR-THEMIS mosaic. Yellow areas are spur, blues areas are gullies. Spurs have a convex cross-section and convex longitudinal curvature while gullies have concave curvatures. Mean spur-and-gully morphology wavelength is ~4km in this region.

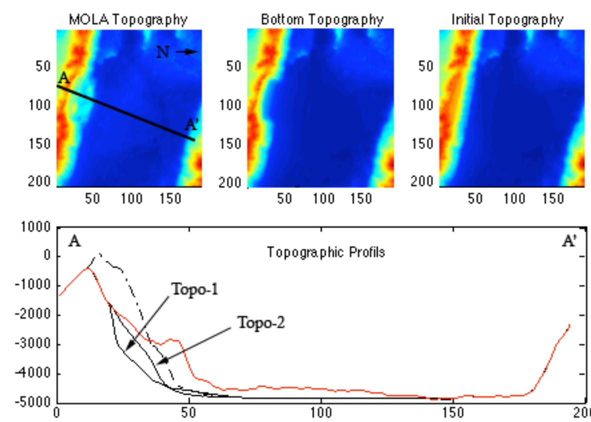


FIG. 3 – (Top) Respectively, MOLA, bottom (floor) and intial topographies. (Bottom) Topographic profiles along the black line. MOLA is in red, initial topography is dashed-dotted , bottom topography is in black.

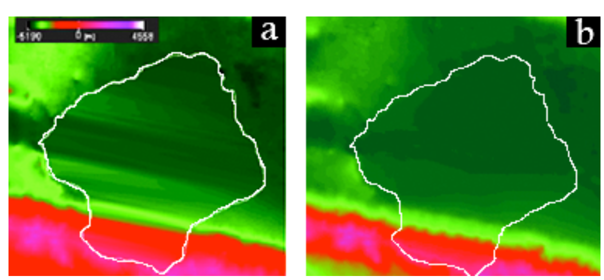


FIG. 4 – (a) Topography reconstruction from [7]. (b) Our reconstruction with the same color chart.

NUMERICAL MODELING OF SELF-CHANNELING GRANULAR FLOWS AND OF THEIR LEVEE-CHANNEL DEPOSITS. A. Mangeney[1], F. Bouchut[2], N. Thomas[3], and N. Mangold[4], [1]IPGP, CNRS, Université Denis Diderot, 4 Place Jussieu, 75005 Paris, France, mangeney@ipgp.jussieu.fr, [2]Département de Mathématiques et Applications, ENS, CNRS, 45 rue d'Ulm, 75005 Paris, France, francois.bouchut@ens.fr, [3]IUSTI-CNRS, 5 rue E. Fermi, Technopole de Chateau-Gombert, 13453 Marseille, France, nathalie.thomas@polytech.univ-mrs.fr, [4]Laboratoire IDES-Orsay, CNRS, Bat 509, 91405 Orsay, France, nicolas.mangold@u-psud.fr.

Introduction: When not laterally confined in valleys, gravitational flows on Earth and on Mars such as pyroclastic flows or gullies create their own channel along the slope by selecting a given flowing width. Furthermore, the lobe-shaped deposits display a very specific morphology with high parallel lateral levees. Such channeled flows leaving a levee-channel morphology in deposits on the slope are observed in very different environments (aerial, submarine) and for flows involving completely different materials [1-3].

This morphology observed on Mars was first interpreted as indicating the presence of water during emplacement [4]. Similarly, assuming a Bingham rheology, *Mangold et al*. [1] deduced from the analysis of levees that the observed gullies over large Martian dunes involve flows with a significant proportion of fluids. These flows occur on slopes of only 10° over length >1 km, values at which dry flows are unlikely. On the other hand, *Treiman and Louge* [2] refer to dry flows to explain the levee-channel morphology of Martian gullies; this possibility is especially pertinent for gullies located on steep hillslopes (>20-25°).

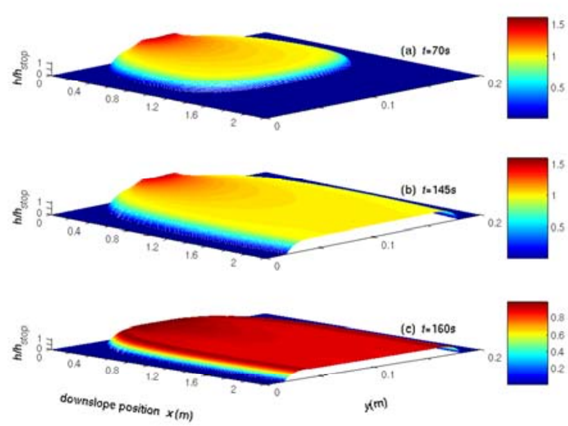
The first question is as to whether the presence of water is a necessary condition for the formation of the levee-channel morphology and how do these levees form. Laboratory experiments show that self-channeling lobes and levee-channel deposits can be obtained using dry granular flows when the slope higher than 20° [5]. In these experiments, particle segregation features are observed to enhance the levee-channel morphology of the deposits. Is it possible to reproduce this morphology without any segregation processes, a situation hardly achieved experimentally ?

Field measurements have been performed on such deposits, but it was not clear as to what extent these measurements provide information on the mechanical properties and dynamics of the flow during emplacement. Which geomorphologic features (such as width or thickness of the channel or levees) are almost independent with respect to time and the distance from the supply and therefore pertinent to characterize the flow?

The aim of this work is to shed light on these questions using a simple depth-averaged model based on Saint-Venant equations and Coulomb type friction. *Mangeney et al*. [6] show that numerical simulations successfully reproduce the self-channeling of the granular lobe and the levee-channel morphology in the deposits without having to take into account mixture concepts or polydispersity. Numerical results suggest that the quasi-static shoulders bordering the flow are created behind the front of the granular material by the rotation of the velocity field due to the balance between gravity, the pressure gradient and friction. Numerical simulations show that measurement of the width and thickness of the central channel morphology in deposits in the field provides an estimate of the velocity and thickness during emplacement.

Shallow granular flows model: Depth-averaged continuum models have been shown to reproduce the basic behavior of the flow on sloping topography under experimental or natural conditions [7-10]. These models are based on the long wave approximation, which is appropriate for granular flows over inclined topography given that the characteristic length in the flow direction is much larger than the avalanche thickness, thereby satisfying the hydrostatic assumption. Using these approximations, the model describes the balance between inertia, gravity, pressure gradients and friction forces acting on the depth-averaged media [6].

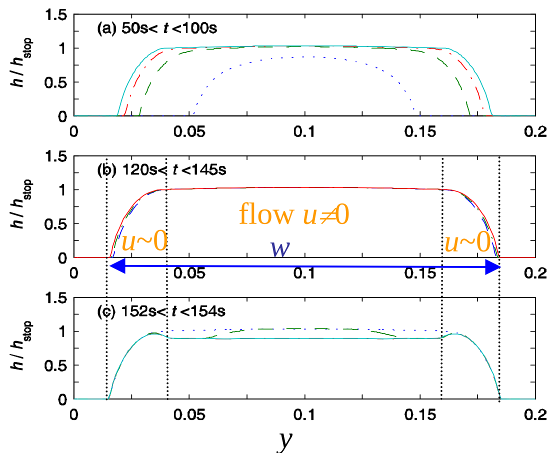
Figure 1: Numerical simulation showing (a), (b) the creation of a self-channeling flow and (c) the formation of levee-channel morphology.



The appropriate flow law to describe dissipation in dry granular flows is still under debate. An empirical parametrization of the friction law suggested by experiments on granular flows over inclined plane is used here [11]. Basically, the idea is that the friction coefficient involved in the classical Coulomb friction law increases with decreasing thickness and increasing velocity. The thickness h_{stop} left on an inclined plane by a steady granular flows when the supply is cut is an empirical parameter of the firction law [11].

We set the initial and boundary conditions in the range of the experiments performed in [5]: at the upper boundary, corresponding to the top of the inclined plane, a flux $Q_0=hu=2.10^{-4}$ m^{2}s^{-1} of granular material is imposed through a width w_0=4 cm generating a granular lobe flowing over a plane with inclination angle θ=25°. The numerical domain is L_x=2.2 m long and L_y=20 cm wide. The supply is stopped at t_s=145 s and the total simulation lasts 160 s. At t=130 s the front has already left the plane, leaving behind a flow quasi-uniform in the downslope direction for $x \geq 1.2$ m (Figure 1c).

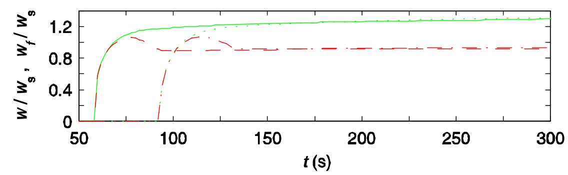
Figure 2: Normalized transverse profiles $h(y)/h_{stop}$ at x=1.2 m, during the flow of the granular lobe, (a) and (b) under constant supply and (c) during the draining phase. The different lines correspond to different



times.

Formation of Channel and Levees: The building of shoulders channeling the flow and the appearance of levee-channel morphology in the deposits have been simulated numerically for the first time (Figure 1) [6]. The main achievement of these simulations is to show that neither mixture concepts nor polydispersity are required to explain self-channeling flows and levee formation. The numerical simulation shows the same evolution as in the experiments. The transverse profiles of the mass thickness obtained at a given downslope position are in very good qualitative agreement with the experimental observations [5, 6]: the front of the flow arrives at the chosen distance and the thickness and width of the cross-section increase until an almost stable profile is reached (Figure 2a). The profiles are then globally stable with time although the width of the flow slightly increases (Figure 2b, 3). When looking at the downslope velocity, two static shoulders occur at the left and right lateral borders of the flow. Finally, as the supply stops, the central part is drained by the downward flow and the thickness between the shoulders decreases (Figure 2c).

Figure 3: Change with time of the total width of the lobe $w(t)/w_s$ (solid gray lines) and of the flowing width



$w_f(x)/w_s$ (dashed lines) at x=1.2 m.

Numerical results provide a possible explanation of the self-channeling process indicating that the shoulders are created behind the front. The fact that the front reaches a steady velocity and shape along the plane seems to be responsible of the width chosen by the flow. In the simplified model used here, the formation of shoulders channeling the flow is shown to result from the balance between a friction force with a friction coefficient depending on the thickness of the flow and the driving forces due to gravity and surface slope.

Pertinent morphological parameters : The total width w of the lobe is shown to increase slightly as a function of time. On the contrary, the width of the flowing channel w_f (where the dowslope velocity is higher than a given threshold) has been proved to be almost constant in time and space. The width of the central channel on the deposit w_c almost corresponds to w_f and therefore provides a pertinent parameter for field measurements. Furthermore, the thickness in the central channel of the deposit h_c almost corresponds to the thickness h_{stop}. Scaling laws show that measurements of these parameters give insight into the dynamics of the flow during emplacement [6]. A next step in that work would be to measure the microtopography of Martian leveed gullies to test these parameters to better determine the relative importance of wet and dry flows in gullies formation.

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CURRENT GULLIES ACTIVITY: DRY AVALANCHES OBSERVED OVER SEASONAL FROST AS SEEN ON HIRISE IMAGES N. Mangold[1], D. Baratoux[2], F. Costard[1], and F. Forget[3]. [1]Lab. IDES-CNRS, bât. 509, CNRS and Université Paris-Sud, 91405 ORSAY, France, [2]OMP, Toulouse, France [3]LMD, Jussieu, Paris, France Contact: nicolas.mangold@u-psud.fr

Introduction: Recent gullies on Mars are observed on the wallslopes of the mid latitude regions with a preferential orientations on poleward facing slopes. They might sign the presence of fluid flows, likely involving liquid water, in a recent past, or even currently as shown by the recent gullies activity [1]. The high resolution images HiRise improve by ten times the MOC resolution allowing us to look in detail to the characteristics of these landforms. Here, we report the observation of streaks, formed over seasonal frost, that might sign a current activity of mass wasting inside gullies alcove. The streaks shapes appear as typical of granular flows, different from viscous or liquid flows involving liquid water. The role of CO_2 defrosting is likely important to trigger the observed mass wasting.

Observations: *Current activity from streaks over seasonal frost:* This study is based on the HiRise image number PSP1684_1410. This image was obtained at Ls=145° and it is located 38.9°S, 196E. The image shows some recent gullies that erode inside the wallslopes of a fresh impact crater. A close-up on the alcoves is possible thanks to the very good spatial resolution of the instrument (Fig. 1). Alcoves are mainly in shadows due to the late afternoon insolation, but the scattered light is sufficient to improve the contrast. Frost, visible by the very bright tone, is locally present on the image, especially inside the gullied alcoves and on the steepest part of the wallslopes. Some eolian ripples, visible from their partial frost cover are present on the hillslopes outside gullies alcove. Our key observation consists of the presence of new streaks formed over the frost blanket. These streaks are visible from their lower albedo in a strong contrast with the surrounding frost layers (arrows on figure 1 and figure 2). Streaks could be highlighted because of frost properties: Frost can be locally transparent inducing specific landforms. In our case, the albedo contrast is very strong, making unlikely that the frost is transparent only over the streaks, being opaque in the surrounding.

Defrosting at different rate can occur depending on the underlying material as it is visible for sand dunes on MOC images. In that case, the streaks would be visible from their difference of grain size or induration compared to the surrounding material. However, if streaks were visible from a difference of sublimation we would see streaks partially defrosted, with patches along the slope not defrosted. Yet we observe only streaks well defined from their begin to their end without any indications of a possible effect of differential sublimation with the surroundings.

In previous observations at MOC scale, we can observe that high latitude landforms are sometimes visible from the relative presence of frost due to difference of insolation angle as a frost trap or differential sublimation, as in the case of polygonal cracks. Differential sublimation effects exists on the studied image by highlighting the eolian ripples around alcoves. However, at the difference of ripples, the streaks inside alcove occurs in locations where the frost is still continuous whatever the local insolation angle. There is no indication that the streaks present a strong topography that could explain a relative frost sublimation here. If formed by a frost trap effect, we would expect variations of frost inside streaks depending on their position in the alcove.

In summary, these observations are much easier to explain if these streaks are superimposed on the frost, or removed the frost. This interpretation is important because it demonstrates that these streaks formed as recently as the frost cover, thus within the last two martian months before the image was taken.

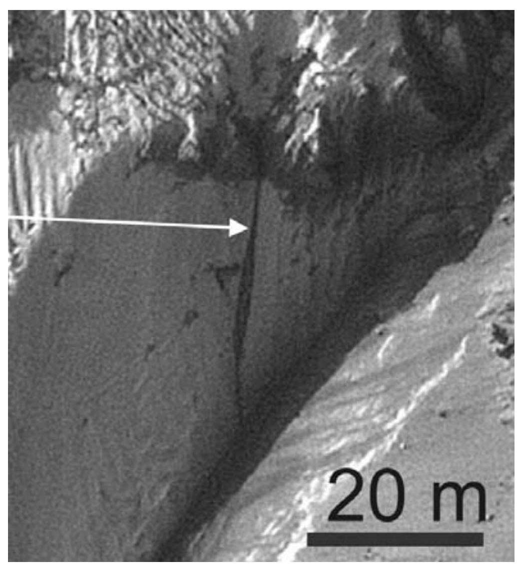

Fig. 1: Close-up on HiRise image PSP1684_1410. Dark streaks are observed over the frost blanket. Notice other streaks visible by a slight albedo difference are visible on the defrosted side of the gully, represent similar type of landforms less visible after the terrain is defrosted.

Shape of the streaks: Dry or wet flows?: The shape of these streaks can be analysed to evaluate the origin of these streaks from liquid, viscous or dry flows. The overall shape is typical of mass wasting activity due to gravity effects on steep slopes (>15°). They are typically 1-2 m large for a few tens of meters long. In general, the streaks are elongated and go straight downslope. They are often narrow close to the source area and sometimes become wider during the flow. Most of these characteristics are typical of small dry avalanches. Viscous flows involving liquid water mixed with rocks have usually larger size (5-20 m) and visible levees at this scale. Liquid flows are also different from what we observe. Streaks sometimes join together but they are not ramified as we would expect for fluvial processes. Thus, we favor a formation by dry avalanche for most flows present.

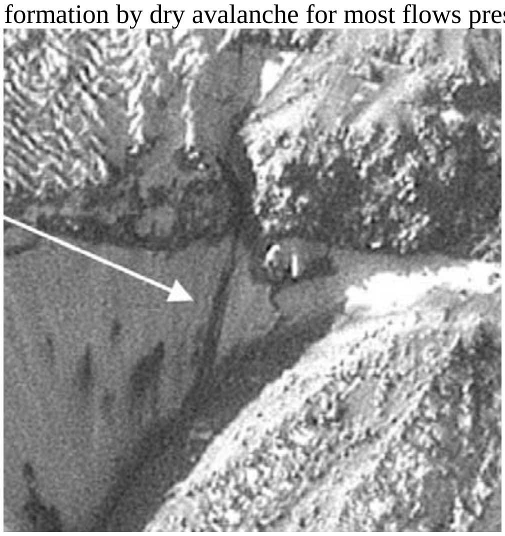

Fig. 2: Close-up on same HiRise image over other alcoves showing other streaks.

Fig. 3: The white arrow indicates a large dark strek with several smaller streaks branching on it.

Many source areas are observed in locations where the frost is still homogeneously present. Close to source areas, dark dots with surrounding gray aureola are observed inside the frost area (Fig. 2). These features are typical of defrosting areas as observed on MOC images taken at springtime: The sublimation of the frost begins at one point and then diffuses around this point. This observation suggests that the defrosting might help to create the initiation of the flow, which then is a consequence of the defrosting effects.

Discussion : Our study then questions if the overall gullies activity is related to this unique current process, or if another process involving liquid water is still required. Indeed, dry processes have been proposed to explain the formation of gullies [2], especially because the presence of levees, alcoves, debris fans are features that can form under pure dry sliding and not only after viscous flows involving a volatile. However, the newly formed streaks are very small, with about 1 meter large and a few tens of meters long, compared to the main channels observed with few tens of meters large and hundreds of meters long. The dry debris flows do not display any levees and they are restricted to the alcove: none of them seems to continue on the apron. Their seems to be more limited and of a different overall shape than the large channelized flows observed

In conclusion, the observed debris flows are likely small avalanches that are dry. They form currently as a consequence of the defrosting by destabilization of the debris aprons material. They contribute to the backward erosion of the gullies alcove and to the accumulation of large amount of debris that might help any further mass wasting process. We exclude liquid water as being responsible of the current gullies activity due to lack of adequate thermodynamic conditions. Nevertheless, liquid water is not excluded for a past activity that created the large channelled flows. The role of CO_2 and the possibility of CO_2 driven flows should be re-emphasized to better understand the relation between the triggering process and the flow itself to know if viscous flows can be generated by CO_2 vapor only as previously proposed [3]. These observations also reinforce the role of insolation and atmospheric conditions in the formation of gullies as mass wasting process rather than process related to subsurface activity.

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LEVEE-CHANNEL DEPOSITS IN DRY OR WET DEBRIS FLOWS: A TOOL TO UNDERSTAND GULLIES FORMATION. N. Mangold[1], A. Mangeney[2], F. Bouchut[3], [1]Laboratoire IDES-Orsay, CNRS, Bat 509, 91405 Orsay, France, nicolas.mangold@u-psud.fr., [2]IPGP, CNRS, Université Denis Diderot, 4 Place Jussieu, 75005 Paris, France, mangeney@ipgp.jussieu.fr, [3]Département de Mathématiques et Applications, ENS, CNRS, 45 rue d'Ulm, 75005 Paris, France, francois.bouchut@ens.fr

Introduction: Recent gullies on Mars are observed on the wallslopes of the mid-latitude regions. They might sign the presence of fluid flows, likely involving liquid water, in a recent past [1]. However, authors have shown that dry flows might be an alternative to the formation of Martian gullies [e.g.2]. Levees are frequently present together Martian gullies independently of their location (dunes, crater wallslopes, isolated hillslopes) [1,3,4]. Levees morphometry is different in a dry or a wet flow therefore enabling us to measure Martian levees and to compare which case fits best. The high resolution images HiRISE allow us to look in detail to levees characteristics and measure their size using photoclinometry. Despite levees are not ubiquitously observed together gullies, many leveed channels have been identified on several images of gullies with HiRISE (Fig. 1, Fig. 2). Thus, the aim of this work is to identify critical parameters that discriminate the processes of the levees formation and test them on Mars from levees observations on HiRISE images.

Physical basis for levees morphometry: Terrestrial wet debris flows are often modeled using the Bingham fluid properties [5]. A Bingham plastic material has a linear relation between the strain rate and the stress but with a finite yield strength [4, 5]. This means that it does not deform until a critical shear stress is reached, after which it deforms as a Newtonian fluid (linear relation). The occurrence of the critical shear stress is the main reason of the presence of lateral deposits: As the flow gets thinner near the lateral shoulders of the channel, the gravity force which is proportional to the thickness of the flow gets smaller. As a result, the driving forces are not strong enough for the material to exceed the critical shear stress, thus leading to the formation of lateral levees.

For granular flows, laboratory experiments show that self-channeling lobes and levee-channel deposits can be obtained when the slope higher than 20° [e.g. 6]. The appropriate flow law to describe dissipation in dry granular flows is still under debate. An empirical parameterization of the friction law has been suggested in the recent years [7]. This theory shows that the friction coefficient involved in the classical Coulomb friction law increases with decreasing thickness and increasing velocity. The thickness h_{stop} left on an inclined plane by a steady granular flows when the supply is cut is an empirical parameter of the friction law [7, 8].

Difference between levees formed by dry and wet flows: A dry granular flow compared to a wet debris flow can show very similar characteristics, but details of the shape of levees show differences. We describe hereafter three main parameters:

(1) Occurrence of sinuosities: Granular flows can present changes of direction when the slope changes downward and, in some conditions of grains angular texture and diversity, they can show changes of directions [9]. However, they never show cyclic sinuous changes of direction resembling to meanders.

Bingham fluids are viscous materials that can exhibit properties of fluid flows with inertia leading to produce sinuosities, resembling those of channels meandering, when the slope decreases and the fluid slows down. Parameters controlling the sinuosities are likely different from meanders in channels and are not well understood despite they are frequently observed on Earth [10]. Therefore, the presence of cyclic sinuosities is an argument in favor of wet debris flows.

(2) Shape at the end of flows: The end of granular flows is always constituted by a terminal tongue which corresponds to the progressive decrease of levees size and a simultaneous increase of the channel before it stops to flow [6,7,8]. Terrestrial debris flows controlled by liquid water mixed with rocks present end of flows frequently with terminal levees [10]. This possibility is not unique because terminal tongues with no levees can also exist, as well as debris deposits with a various of shapes. Therefore, the presence of terminal levees rather than a tongue favors wet debris flows, whereas the presence of a tongue is not discriminating.

(3) Slope at the end of the flows: Granular flows have their final tongue controlled by the critical angle of repose. This angle is generally >20° for usual spherical grains, sand size grains [e.g. 6]. Inertial effects could significantly decrease the slope of the deposit. Actually, deposit's slope < 20° are possible in certain conditions: when a large amount of material is transported with large elevation difference, or when the flow is permanently fed by material, as for pyroclastic flows [6, 9]. However, in most case, the shape of the flow is different at low slope because accumulation dominates [9]. The final slope of Bingham flows is controlled by the critical shear stress that can be very low if the material is enough fluid [10]. End of flows over slopes at 1° to 10° are frequent [5, 10]. At such low slope, wet flows can show the

same shape at low slope (leveed channels) as on steep slope, at the difference of the dry material. Therefore, the end of flows on slopes <10° favors wet flows when they still shows a leveed channel, whereas dry flows would better stop over relatively steep slopes (>20°) or show different shape on lower slopes. This argument nevertheless requires a close look to the overall shape of the flow and can not be used blind as a “yes or no” test. These parameters are under tests using numerical models [11].

Martian examples: HiRISE images of gullies show a larger variety of landforms than visible with MOC images. Levees are frequent, despite not everywhere. Here we report preliminary results.

Images of Russell dunes gullies show 1 km long sometimes sinuous leveed flows (Fig. 1). These gullies were previously interpreted as wet debris flows from their shape and sinuosity [4]. Given the difference in properties of dry and wet flows, the three parameters are positively in favor to wet debris flows. For example, the end of flows are often terminal levees different from tongues observed in dry cases, sinuosities exist for several channels, and the slope on which flow this material is of about 10° over 100s of meters. Notice that these channels have ends often showing small pits suggesting that some specific processes also concur at these locations such as sublimation or infiltration of volatiles.

One image of a typical crater wallslopes show lot of gullies with some of them showing sinuous channels (Fig. 2). Despite we can not tell if this flow was unique, they might be different episodes to explain the observed landforms, the presence of cyclic and well expressed sinuosities favor a wet debris flow.

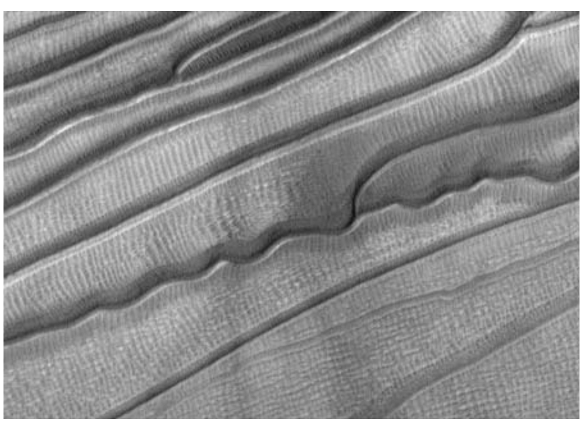

Fig. 1: Close-up on HiRISE4038_1255 with straight and sinuous gullies over Russell crater dune megadune.

Fig. 2: Close-up of HiRISE 3464_1380 showing sinuous channel. Levees are less visible than on figure 1 possibly due to multiple episodes of flows.

Conclusion: The morphometry of levees can be used as a discriminator between granular and wet flows for those of the Martian gullies having levees around channels. The shape of several levees channeled flows match better wet flows than dry flows for the examples studied. These examples are preliminary and require more statistical study.

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DISTRIBUTION OF GULLIES IN THE MARS-LIKE ANTARCTIC DRY VALLEYS: RELATIONSHIP TO MICROCLIMATE ZONATION. D. R. Marchant[1] and J.W. Head, III[2]. [1]Dept. of Earth Sci., Boston Univ., Boston, MA 02215 (marchant@bu.edu); [2]Dept. Geol. Sci., Brown Univ., Providence, RI 02912 USA (James_Head@Brown.edu)

Introduction: The Antarctic Dry Valleys (ADV) are generally classified as a hyper-arid, cold-polar desert. The region has long been considered an important terrestrial analog for Mars because of its generally cold and dry climate and because it contains a suite of landforms that closely resemble those occurring on the martian surface. Subtle variations in climate parameters in the ADV result in considerable differences in the distribution and morphology of viscous-flow features, including solifluction lobes, gelifluction lobes, and debris-covered glaciers [1]; contraction-crack polygons, including ice-wedge, sand-wedge, and sublimation polygons [2,3], and gullies [4-6]. Here we outline field evidence documenting the spatial variation in gully morphology that arise from measured variations in microclimates and resultant geomorphic processes.

Microclimate Variation: On the basis of measured climate variation in the ADV, we distinguish a coastal thaw zone (CTZ), an inland mixed zone (IMZ), and a stable upland zone (SUZ) (Fig. 1, inset; Table 1). Slight changes in atmospheric temperature and soil-moisture, particularly across microclimate boundaries, are sufficient to produce major changes in equilibrium geomorphic processes and surface topography.

Katabatic winds, active-layer cryoturbation, and cold-based glaciation are the three fundamental processes that influence the morphology of the ADV. Of these, the style and degree of active-layer cryoturbation is the most important factor in determining gully morphology. Traditionally, an active layer is defined as the surface horizon in permafrost regions that experiences seasonal temperature fluctuations above and below 0°C (273 K). Its thickness depends primarily on atmospheric temperature, and secondarily on substrate heat conduction. The great variation in microclimate in the ADV requires a precise understanding of active-layer variability process. We distinguish a "wet" active layer from a "dry" active layer on the basis of subsurface moisture content. A wet active layer contains visible ice and/or liquid water, whereas a dry active layer contains minimal soil moisture, generally <5% gravimetric water content (GWC). In the coastal thaw zone, a wet-active layer up to ~25 cm in thickness is common. In the inland mixed zone, dry active layers are the norm, and in some places in the stable upland zone there are no active layers at all (or if present, dry active layers are only a few cm thick) [7].

Valley asymmetry, slopes, and gullies: *Coastal thaw zone (CTZ)***:** Slopes in the CTZ display a classic asymmetry (Fig. 2). North-facing slopes that receive relatively high levels of incident solar radiation [e.g., 8]) are shallower (averaging ~20°) than south-facing slopes (~25°). Consistent with this marked valley-side asymmetry is a well-expressed drainage-basin asymmetry (drainage basin asymmetry is defined here as the ratio of the valley-half width [measured south of the valley "thalweg", i.e., south of the main valley axis] to the total valley width). An AF of ~65 for the CTZ indicates preferred degradation along north-facing walls. The size and spacing of gullies on valley walls in the CTZ also displays local variation with aspect. In lower Ferrar Valley, for example, gullies on the north-facing slopes appear deeper and spaced further apart than those on south-facing slopes (Fig. 3).

Melting occurs preferentially on north-facing slopes, with meltwater commonly percolating centimeters to tens of centimeters into soils. In places, this meltwater elevates soil-pore pressures sufficiently to induce downslope movement via solifluction, e.g., the slow flow of saturated materials, and or cuts narrow channels 3-5 m deep in unconsolidated till. A saturated hyporheic zone, 1-2 m wide [9], commonly fringes these channels during summer months and helps sustain a unique biota of several varieties of cold-adapted nematodes [10]. Evaporation of meltwater produces visible salts that coat rock surfaces and intervening soil. Variations in the size of these salt crystals, arising from expansion and contraction upon hydration-dehydration, permits rock breakdown, as salts pry away loosely bound crystals [11].

Inland mixed zone (IMZ): The IMZ shows less valley-side asymmetry and less drainage basin asymmetry than the CTZ (Fig. 2). In addition, gullies in the IMZ are relatively shallow, appear closely spaced, and show sharp, knife-like interfluves. Although the average air temperature in the IMZ is less than that of the CTZ, minor snowmelt fringes most snowbanks: snow melts alongside rocks that are heated by solar radiation to temperatures >0°C. In addition, snow may be blown from local snowbanks onto the surface of solar-heated rocks; in this way the distribution of meltwater is increased well beyond the immediate margins of snowbanks, although it is localized in the downwind direction. The total meltwater contributed by these processes is minor (and does not commonly support solifluction), but appears sufficient to maintain a shallow, discontinuous ice-cemented layer within the upper few centimeters of debris, and may also contribute to shallow subsurface meltwater flow in saline soils [e.g., 12]. Perennial snowbanks and seasonal windblown snow trapped in lows (alcoves, channels, polygon troughs) may form significant sources for meltwater that lead to gully formation in the IMZ [4-6].

Stable upland zone (SUZ). Given that the current climate conditions in the SUZ (Table 1) prohibit significant meltwater, there is little evidence for ongoing, macroscale geomorphic change. Gullies, where present in this zone, are interpreted to be relict and inactive because overlying colluvium is commonly interbedded with near-surface ashfall dated to ≥11 Ma [13].

Synthesis: The observed variation in valley-side asymmetry, drainage-basin asymmetry, and gully development in the ADV is plausibly related to spatial variations in the melting of snow and ice. The mature gully system of the CTZ most likely reflects 1) the preponderance of rock breakdown associated with snowmelt, freeze-thaw, and salt-weathering, and 2) the downslope transport of these weathering products by water, solifluction, and wind. Given the direct correlations among the magnitude of observed surface melting and the size and spacing of gullies in the IMZ and CTZ, we suggest that gully maturation may be analogous to the development of rills to master rills observed in cohesive sands in humid temperate regions [14]. If so, mature gullies form at the expense of immature gullies by progressive capture, a process that requires significant meltwater and some component of lateral flow. As gullies grow, they are capable of trapping increasing amounts of wind-blown snow, which on melting enables cross-grading (i.e., lateral flow on walls of newly formed gullies); the latter promotes the wide spacing of gullies. If the above sequence is correct, then the relatively high density and narrow morphology of gullies in the IMZ could reflect stagnation within the maturation sequence due to insufficient meltwater.

Among additional parameters that could be responsible for the observed variation in gully morphology is the duration of gully incision. We contend that time is not the most critical factor in differentiating gully morphology because many slopes in the IMZ (as well as in the SUZ) have been dated on the basis of 40Ar/39Ar analyses of overlying ashfall to ≥7 Ma [13]. Given the time available for slope evolution in the IMZ, we postulate that gullies would have achieved mature forms if sufficient meltwater had been available (i.e, comparable to that now found in the modern CTZ). The extremely low levels of meltwater produced in the SUZ lead to a preponderance of inherited slopes that likely formed under wetter, and most likely warmer, climate conditions before the onset of cold-polar desert conditions [15].

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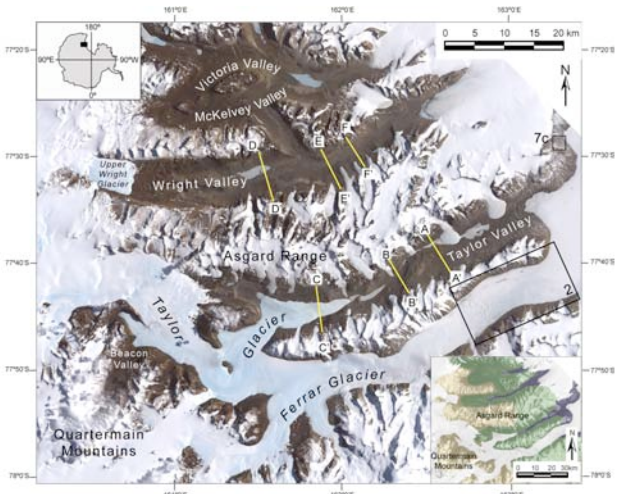

Figure 1. Antarctic Dry Valleys: Location map showing major geographic features. Location of cross-valley profiles (Fig. 4) plotted as yellow lines; location of other figures in text shown as labeled boxes and dots. Upper left inset: Black dot shows location of Dry Valleys within Antarctica. Lower right inset: Map showing general range for coastal thaw zone (CTZ; blue), inland mixed zone (IMZ; green), and stable upland zone (SUZ; yellow).

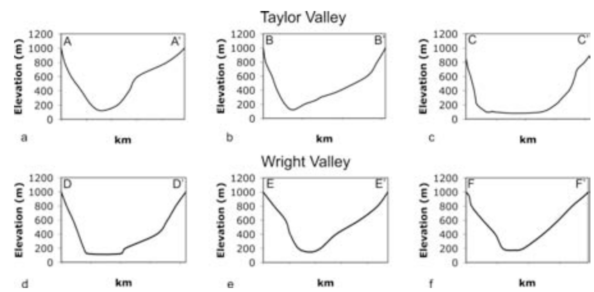

Figure 2. Cross-valley topographic profiles for the CTZ and IMZ; Locations shown in Fig. 1. North (equator-facing) slopes possess gentle slope angles.

Figure 3. Landsat satellite image of lower Ferrar Valley illustrating gully asymmetry on north-facing (bottom of image) and south-facing (top of image) slopes. See Fig. 1 for location and scale.

TABLE 1

Parameter	SUZ	IMZ	CTZ
Mean summer air temp C (@ 2 cm)	-10	-7	-5
Mean summer soil temp C (@10 cm)	-6	-4	1
Mean summer RH (2 cm)	41	67	64

Data from McMurdo LTER weather stations: http://huey.colorado.edu/LTER/meteordata.html

GULLY FORMATION AND EVOLUTION IN THE ANTARCTIC DRY VALLEYS: IMPLICATIONS FOR MARS.
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Introduction: The utilization of terrestrial analogs to understand martian environments provides the only means of exploring the three dimensional structure of gully systems and such environments are an essential natural laboratory for testing gully formation processes. A range of gully sites throughout the arctic have been investigated [e.g. 1-3] since their identification on Mars in 2000 [4]. This work has produced a diverse collection of gully formation models. For example the nature of perennial saline springs forming channels on Axel Heiberg Island in the Canadian High Arctic has been used to support the argument that martian gullies formed from subsurface groundwater springs [2]. In contrast, field work in Greenland has demonstrated the potential for near surface ice melt to generate gully channels [1]. In this analysis we report on results obtained from field studies within the Antarctic Dry Valleys (ADV), a hyper-arid polar desert that has long been held as the most Mars-like of terrestrial analogs [5, 6].

Previous field research has demonstrated that the ADV can be subdivided into three microenvironments, each of which has distinctive geomorphic characteristics [7]. The majority of the ADV surface is unconsolidated sediment (e.g., colluvium, till) modified by contraction-crack polygons. Ice-cemented permafrost occurs in most places throughout the ADV and is most commonly encountered at depths of 0-50 cm; above the ice table, a wet active layer is seen in the warmer coastal microenvironment zone, a dry "active" layer occurs in the intermediate zone, and in the stable upland zone, soil temperatures generally fail to rise above 0°C. Fluvial features including streams and gullies occur in the warmer and intermediate zones, commonly on north-facing slopes, and contain the major geomorphic components (alcove, channel, fan) seen on Mars (Fig. 1) [8]. Streams and channels vary in width from 1-30 m and can be up to 30 km in length [9]. Lack of rainfall and associated distributed runoff means that gullies and streams have little interaction with the broader landscape [7].

In order to best constrain the Martian conditions we concentrated our efforts within the most elevated (and hence driest) portion of the intermediate microclimate zone situated within the South Fork region of upper Wright Valley. This region marks the most inland extent of fluvial features within the dry valleys and is most analogous to Mars during Amazonian periods of high obliquity [8].

Water Sources: No deep subsurface groundwater springs (below the permafrost) have been reported within the ADV as a potential source for fluvial activity. The majority of fluvial research has concentrated on the stream systems which have been observed to form largely by meltwater runoff from cold based glaciers during the austral summer [9]. Our work concentrated on previously undocumented gully systems which are not found in proximity to glaciers. Instead we found that top-down melting of snow and localized ice deposits due to enhanced summer solar insolation was the dominant source of water to the gully systems [10-16]. Here we report on the sources of snow/ice deposits that were observed to contribute meltwater to the gully systems.

Alcoves. The northern edge of the Asgard Mountains in Upper Wright Valley contains a number of alcoves and alcove-like terraces and depressions along the margins of the valley. These are largely cut into dolerite sills. Additionally the upper portions of the flanks of the Asgard range slope in excess of 30° and exhibit slope cross sections that are similar to the impact craters into which the majority of martian gullies are carved. Many of the alcoves contain visible snow and ice and some are the source areas for gully systems. We report here on two of these gully systems, the longest of which begins in an alcove containing a patch of snow and underlying ice ~500 m wide. The gully system begins at the edge of the snowpack about 1000 m above the valley floor, and extends downslope for over 2 km to the floor. Observations of aerial photos for multiple years show that at least the central portions of this snow/ice is perennial. During storm events low lying clouds were observed to hug the alcoves and preferentially deposit snow within them, building up snow deposits over multiple years. By early December 2006, marginal parts of the snow bank had started to melt, and the channel was occupied by water actively flowing from the ice toward the scarp and cascading over the cliff; the stream was ice-covered in the mornings and became progressively less ice-covered during the day. Although the water in the upper part of the channel was cloudy, the sediment load was minimal and largely confined to bed load movement of sand-sized particles. Subsequent to the flow of water over the scarp, the water was lost within the coarse bouldery deposits (D: ~ 50 cm) on the steepest and most inaccessible parts of the cliff.

Perennial Snowbanks. In the more distal parts of the gully and within the lower reaches of a smaller gully system to the west, the slope shallows and the steep colluvium gives way to a series of fans, which form from sediment and reworked colluvium transported in the channel. In the mid to lower reaches of this gully systems, water derived from melting of patches of wind-blown snow [12] form intermittent surface flows. Despite the low amount of annual precipitation, strong winds are capable of transporting snow and depositing and concentrating it within topographic hollows such as gully channels. In late November the lower channels were completely filled by snow banks in some portions. During November to January the snow banks shrank and eventually disappeared completely due to a combination of sublimation and melting. This was clearly modulated by insolation and air temperature, restricting peak meltwater generation to cloud free conditions, when the sun was at its highest point in the sky. In-channel surface flow was only achieved after a sufficient volume of meltwater had soaked into the active layer to permit runoff through the generation of a hyporheic zone which advanced both laterally and downstream ahead of the surface flow.

Surface runoff eroded inner channels (10s of cm – 1 m wide) within the sediments lining the floors of the main gully channel systems. Throughout the period of activity, small-scale fluvial features developed including terraces several cms deep that were cut into channel floor and islands which formed around boulders and other elevated debris. Such features are consistent with HiRISE images of martian gullies which reveal fluvial morphology associated with inner channels eroded into the floors of main gully channels [17]. Large slumps consisting of small boulders (> 1 m long) within a sand grained sized matrix were actively observed to form along the edge of the channel due to the propagation of wide cracks within the slope colluvium, causing the blocks to fall into the channel.

Continual end-to-end surface water flow in the channel and gully system was not observed in December 2006-early January 2007. However, activity along the length of the gully is restricted by the significant temperature variations associated with the 1 km difference in elevation between the alcove and the fan (fig. 2). This concentrates activity within the lower portions of the gully. In addition to differences in slope the temperature differences have most likely led to different erosion processes and rates operating at different points along the gully, demonstrating how even relatively simple gully systems can have complex formational histories.

Implications for Mars: Our field research has demonstrated how the melting of snow and ice deposits in a hyperarid polar desert environment is responsible for gully activity and thus supports martian gully formation hypotheses based on snow melt models [18]. This suggests that melt water from concentrations of wind blown snow could contribute to gully formation on diurnal, seasonal and orbital parameter variation timescales [19] under slightly different environmental conditions [8]. Based on this model, gullies on Mars could form due to top-down melting and experience varying degrees of modification after the initial gully system has been developed.

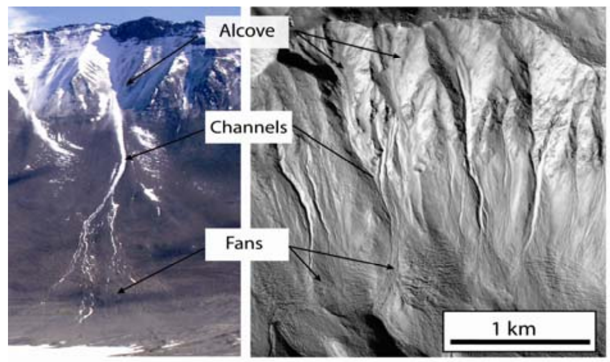

***Fig. 1** Snow filled gully system in the ADV (left) compared with martian Gullies.*

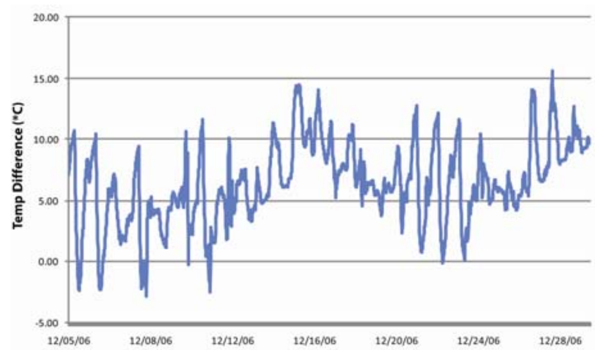

***Fig. 2.** Top 1 cm of soil temperature difference between the alcove and the top of the fan of the ADV gully studied.*

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TEMPERATURE ANALYSIS OF GULLIED AND NON-GULLIED SLOPES ON MARS: EVIDENCE FOR A THERMAL CONTROL ON GULLY FORMATION. A. M. Ollila[1], M. S. Gilmore[2], and H. E. Newsom[1], [1]Univ. of New Mexico, Institute of Meteoritics, Dept. of Earth & Planetary Sciences, Albuquerque, NM 87131, (aollila@unm.edu), [2]Department of Earth & Environmental Sciences, Wesleyan University.

Introduction: Martian gullies are found in the mid and high latitudes (~30-70°) in both the northern and southern hemispheres [1,2]. These features, defined by an alcove, channel, and apron, were first identified in Mars Orbiter Camera (MOC) imagery and interpreted to be fluvial [1]. Gullies are thought be formed recently (within 1 Ma) and are possibly forming today [1,3]. The mechanism and agent of formation is yet unknown. Proposed theories include melting of surface frost (water [4] or CO_2 [5]), the release of liquid water [1,2,6,9] or CO_2 [7] from a subsurface aquifer or dry granular flows [8]. A significant difference in temperature between gullied and non-gullied slopes implies a volatile is involved in gully formation. The CO_2 frost point is around 150 K and the water frost point is typically 196 K. The melting point is 273 K. Near surface frost may register with the Thermal Emission Imaging System (THEMIS) if it is not buried too deeply. If a volatile is implicated, temperature data can distinguish between water and CO_2.

Methods: This study focuses on Acidalia Planitia (30° - 55°N, 8° - 75°W) and Utopia Planitia (30° - 57°N, 90° - 165°E) in the northern hemisphere and Dao Vallis (32° - 40°S, 86° - 93°E), Hale Crater (34° - 37°S, 34° - 78°W), and Nirgal Vallis (27° - 30°S, 37° - 42°W) in the southern hemisphere. MOC images and overlapping THEMIS images were collected using JMARS. MOC images were processed in ISIS and imported into ArcMap. Surface brightness temperatures were calculated from THEMIS Band 9 using Arizona State University's THMPROC program. THEMIS and MOC images will not align in ArcMap without manual georeferencing. Once aligned, slopes were outlined in ArcMap and the temperatures extracted. Night and day temperatures were collected to constrain diurnal temperature variations. Data from gullied and adjacent non-gullied slopes were gathered to determine if there is a difference between them.

Results: Fifty-one gullied slopes and 56 non-gullied slopes have been measured to date in the northern hemisphere; 45 gullied slopes and 22 non-gullied slopes have been measured in the southern hemisphere. Daytime temperatures for gullied slopes reach an average temperature of 240 K, with a maximum of 252 K during the summer in the northern hemisphere (Table 1). In the southern hemisphere, daytime temperatures average 220 K and reach a maximum of 231 K during the fall. Nighttime temperatures for gullied slopes average values span 178-205 K over the year in the northern hemisphere while average temperatures in the southern hemisphere span 161-209 K. The number of measurements is not distributed equally across the year (Figs. 1 and 2), therefore statistical analyses are conducted by season. The Mann-Whitney non-parametric t-test is used to determine if there is a significant difference in nighttime temperatures between non-gullied and gullied slopes during the winter and spring in the southern hemisphere. At night during the winter there is no significant difference between the temperatures on gullied versus non-gullied slopes. However, at night during the spring there is a significant difference (5% level, p-value=0.0170) between these slopes. In the northern hemisphere, there is a significant difference between gullied and non-gullied population temperatures during the summer (5% level, p-value=0.0036) but not during the fall.

Discussion: Surface temperatures on gullied slopes over all available times and seasons are not high enough to melt water ice today.

In two instances (both occurring on non-gullied slopes during a fall night) temperatures in the northern hemisphere extend below 150 K, the frost point of CO_2, meaning that frost could condense at these locations. Nighttime temperatures regularly drop below the frost point of water in both hemispheres, indicating atmospheric water will be deposited onto the surface as frost. This amount is likely insufficient to form a gully [10].

Since there is a significant difference in temperature regimes on gullied compared to non-gullied slopes during at least one season in both hemispheres, we can be fairly confident in stating that temperature is a critical factor in gully formation. The temperature difference implies that the erosive agent must be affected by temperature, which in turn implies that it is volatile (not granular material). Because the range of temperatures is well above the frost point of CO_2, and the pressure requirements for liquid CO_2 are high, it is probable the volatile in question is water.

Conclusions: Daytime and nighttime temperatures on gullied slopes in the northern and southern hemispheres through most of the Mars year are above the frost point of CO_2, consistent with water ice as the gully source. Temperatures do not currently exceed the melting point of pure water, requiring insulation of ground ice to facilitate present-day melting. Significant differences in temperatures between gullied and non-gullied slopes imply a volatile is involved in gully formation and temperature ranges indicate the most likely volatile is water.

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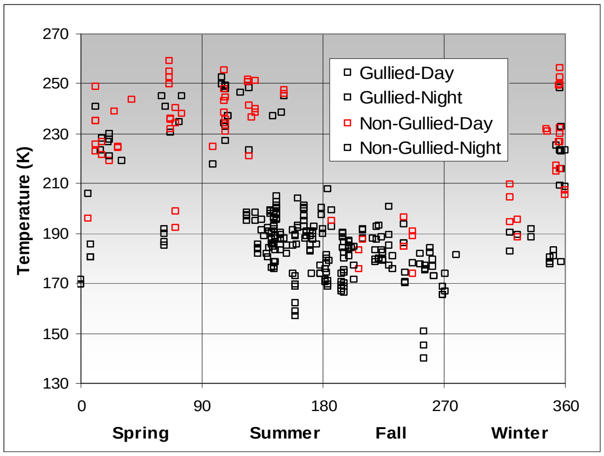

Fig. 1: Night and day seasonal temperatures for gullied and non-gullied slopes by Ls in the northern hemisphere.

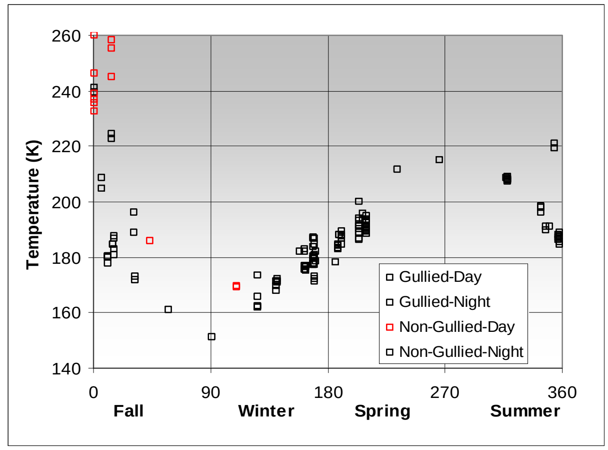

Fig. 2: Night and day seasonal temperatures for gullied and non-gullied slopes by Ls in the southern hemisphere.

Average Seasonal Temperatures (K); Northern [Southern]				
	Gullied		**Non-Gullied**	
	Day	**Night**	**Day**	**Night**
Spring	231 [NA]	179 [188]	231 [NA]	196 [193]
Range	206-245 (39)	170-192 (22)	192-259 (67)	170-228 (58)
	[NA]	[178-200 (22)]	[NA]	[187-211 (24)]
Summer	240 [220]	191 [195]	241 [NA]	186 [201]
Range	218-252 (34)	162-205 (43)	221-255 (34)	157-200 (43)
	[219-221 (3)]	[184-209 (25)]	[NA]	[190-215 (25)]
Fall	188 [218]	178 [179]	186 [245]	176 [180]
Range	178-201 (23)	165-192 (27)	174-196 (22)	140-208 (68)
	[189-241 (52)]	[161-185 (24)]	[186-266 (80)]	[172-188 (16)]
Winter	212 [NA]	179 [176]	222 [169]	181 [173]
Range	179-248 (69)	167-188 (21)	189-256 (67)	174-192 (18)
	[NA]	[162-187 (25)]	[169-170 (1)]	[151-183 (32)]

Table 1: Average seasonal temperatures and temperature ranges for gullied and non-gullied slopes during the day and night. Northern hemisphere data is presented first and southern hemisphere data follow in brackets. NA indicates no data has been collected yet.

REGIONAL DIFFERENCES IN GULLY OCCURRENCE ON MARS: A COMPARISION BETWEEN THE HALE AND BOND CRATERS.
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Introduction: Gullies on Mars are interpreted to indicate liquid water in the recent past. The strong latitude-dependence of gullies [e.g. 1] suggests a climatic influence on their formation. However, in some regions multiple gullies occur in one crater while none form in another crater nearby. This is the case for the Hale (gullies) and Bond (no gullies) craters, respectively. These regional differences have been interpreted as an argument against a climatic influence on gully formation [2]. The formation of gullies on Earth depends on several parameters including; rainfall and/or melting of snow, the presence of steep slopes and sufficient amounts of fines/debris [e.g. 3]. We compared the Hale and Bond craters and considered the thermosphysical properties, slopes, and morphologies to investigate why the occurrence of gullies in neighboring craters is so different.

Data: We investigated the Hale/Bond region (north of the Argyre Basin, 325°E and 35°S, Figure 1) with Mars Orbiter Camera – Narrow Angle (MOC-NA), Thermal Emission Imaging System – Infrared (Themis-IR) nighttime, and High Resolution Stereo Camera (HRSC) topographic data.

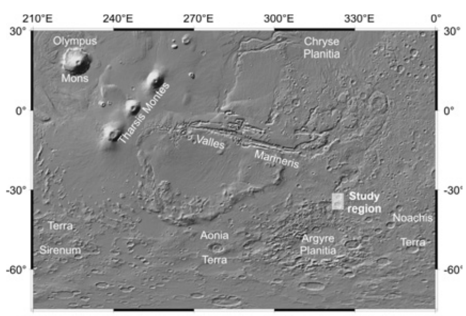

Figure 1. Location of the study region on Mars (MOLA shaded relief).

Results: A survey of MOC-NA images (releases AB-S16) (Figure 2) for the presence of gullies revealed that they occur - with one exception – exclusively on slopes of the Hale crater. The exception in Bond crater are small gullies that occur on slopes of a small crater which is superposed on the central Bond crater floor.

Thermal Properties. Differences in the thermophysical surface properties were derived from nighttime THEMIS-IR images. South-facing gullied slopes in the Hale crater show low nighttime temperatures (indicating unconsolidated material), while higher temperature slopes (indicating consolidated material) occur in the Bond Crater.

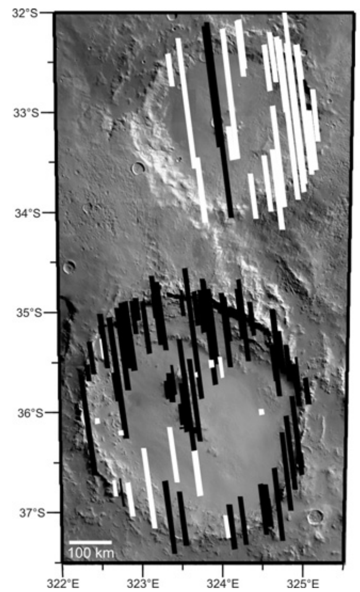

Figure 2. Survey of MOC-NA images. Black areas are MOC footprints representing images with gullies and white areas are footprints representing images with no gullies (Background: Mosaic of HRSC images 511 and 533).

Slopes. The Bond crater is highly degraded with crater wall slopes varying between 10° and 20°.This is in contrast to the more pristine Hale crater with slopes in the range of 20° to 30°. Slope angles were derived from HRSC stereo data (100 m/pxl). Figure 4 shows a typical traverse across the Bond and Hale craters with measured slope values.

Morphology. The different thermophysical surface properties of unconsolidated (gullies) and consolidated (no gullies) material is confirmed in the morphology as analyzed in MOC–images. Bond crater slopes show degraded mantle deposits which are interpreted to be cemented material (Figure 5, A and B). South-facing slopes of the Hale crater show gullied slopes incised into talus material. Themis-IR temperatures of gullied north-facing slopes in the Hale crater indicate consolidated material, however gullies are found on slopes ≥ 20°. One explanation for the occurrence of gullied slopes in consolidated material might be that these gullies are old and the surface material is cemented. Figure 6 shows an example of this region. The debris aprons of these gullies are cratered in contrast to the pristine morphology of gullies on the south-facing slopes. Furthermore, the debris aprons have been eroded leaving behind steep scarps indicating that the debris aprons consist of cemented material.

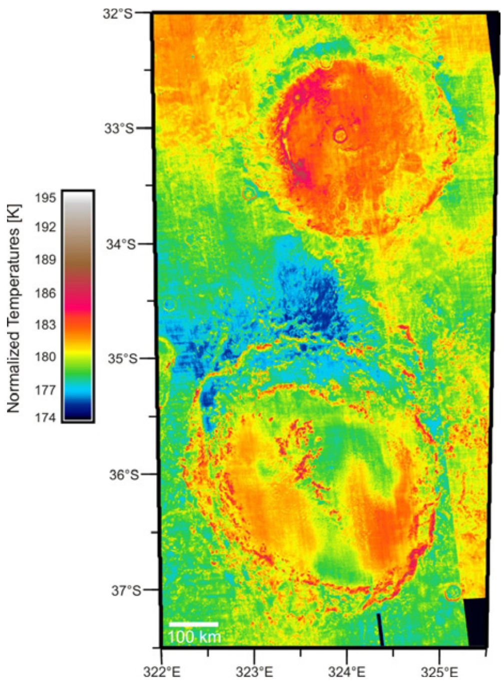

Figure 3. THEMIS-IR Band 9 nighttime image mosaic with normalized temperatures. Blue colours indicate fine grained material and red colors indicate consolidated material.

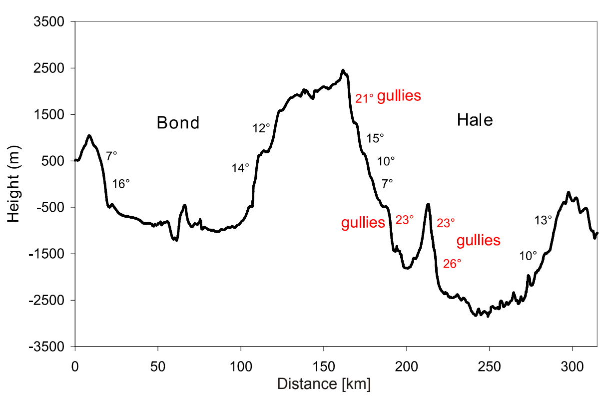

Figure 4. Topographic profile across the Bond and Hale craters (North-south direction) derived from a DTM of orbit 2526_1 (100 m/pxl). Gullies are generally found on slopes > 20° (red color).

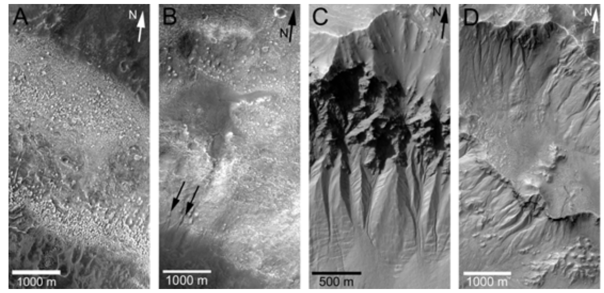

Figure 5. Examples of the northern slope morphology for the Bond (A, B) and Hale (C, D) craters. Gentler slopes of the Bond crater show a degraded mantle morphology with sublimation pits. Arrows in B indicate the possible remnants of the former intact mantle (smooth unit at the base of the slope). Steeper slopes of the Hale crater show gullies incised into talus material. A: E1103249; B: R1301793; C: E0502006; D: E1400853.

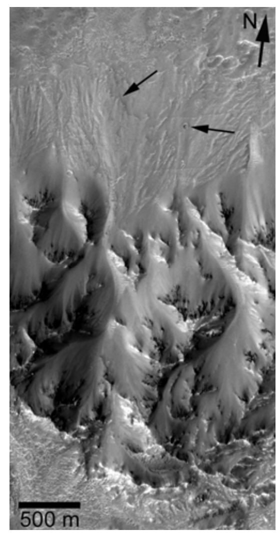

Figure 6. Example of a gullied north facing slope in the Hale crater. Arrows show an eroded debris apron at the distal end leaving behind a steep scarp and a crater superposed on gully deposits (R1103008).

Conclusions: We conclude that the occurrence of gullies in the Hale/Bond region more likely depends on the distribution of unconsolidated material and/or steep slopes. The regional and local gully distribution is likely to vary because of differences in topography and surface material composition and is not an argument against a climatic influence on gully formation.

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ASSOCIATION BETWEEN LATITUDE-DEPENDENT MANTLING DEPOSITS AND RECENT GULLY ACTIVITY: EVIDENCE OF TOP DOWN MELTING. S. C. Schon[1] and J. W. Head[1], [1]Dept. of Geological Sciences, Brown University, Box 1846, Providence, RI 02912; Samuel_Schon@brown.edu.

Introduction: Gullies on Mars are young, insolation-dependent features. As first described by Malin and Edgett [1] in 2000, they consist of an alcove, channel, and fan. Since their initial identification, numerous hypotheses for their formation have been proposed, such as groundwater discharge [e.g., 1], debris flow [e.g., 2], granular flow [e.g., 3], and surface melting [e.g., 4]. These hypotheses can be classified into two categories: dry formation mechanisms and fluid mechanisms. Dry formation mechanisms, such as granular flow, do not require conditions amenable to fluid flow and are essentially climatically independent processes. Alternatively, fluid mechanisms, such as groundwater discharge, require a fluid source and metastable conditions to support flow. Fluid mechanisms principally consist of: groundwater discharge, release of subsurface brines, water-lubricated debris flows, and top-down melting of surface snow/ice. Detailed analysis of HiRISE data allow for discrimination between the two categories of hypotheses based upon observed association with latitude-dependent mantling deposits and channel morphologies that are not evident in the MOC data first used to identify gullies.

Mantle Observations: Recent high-resolution imaging [5] has confirmed earlier observations of latitude-dependent morphologies associated with ice-rich mantling deposits. Morphological observations of young surface textures ranging from smooth and continuous (higher latitudes) to highly degraded, sublimation-pitted (lower latitudes) is consistent with the recent emplacement of ice-cemented loess undergoing dissection/degradation [6,7,8,9]. We document layered mantle outcrops that provide genetic evidence of syn-depositional layering interpreted to be the result of cyclical deposition of an ice-rich eolian dust material. Individual units are hypothesized to represent geologically recent obliquity excursions.

Latitude Dependence. Observations of layering within mantling units are concentrated between 35-40°, a region which corresponds to the transition between predominately smooth and undissected mantle texture and degraded mantle texture. This latitudinal range is also commensurate with a band of strong slope asymmetry attributed to obliquity-controlled insolation geometry that favored down slope movement on pole-facing slopes [10] as well as the occurrence of young gullies [11].

Orientation Control. Smooth mantle textures are observed preferentially on equator-facing slopes, while degraded mantle textures exhibit a preference for pole-facing slopes. Asymmetrically mantled craters illustrate this phenomenon and are common in the latitudinal band between smooth and degraded textures where layering is most commonly observed: smooth mantle morphology dominates the equator-facing interior wall, while the pole-facing interior wall is degraded. Commonly crater walls are too steep and altered (e.g., gullies, slumps, viscous flow features) to be conducive to mantle layering outcrop exposure, but pole-facing slopes from raised crater rims are frequently observed locations for outcrops of layered mantle units. This insolation control of preserved mantle texture is highlighted by observations where a pole-facing, steep slope is dominated by degraded texture, but benches of much gentler slope have smooth mantle texture; see Figure 1. This exposed layered latitude-dependent mantle is in very close proximity to the gully alcoves; see Figure 1.

Gully Channel Observations: HiRISE data contain unprecedented detail on gully channel morphology near the mantle. Many gully channels show evidence of recent flow consistent with a braided fluvial system (Figure 1, B & C). Gully channel features such as terraces, cross-cutting channels and cross-channel bars, longitudinal bars, and bifurcating channels incising previously deposited fans are common, especially on steep, poleward facing slopes in the transition zone between mantle textures described earlier, in accordance with the distribution of gullies documented by [11]. Gully alcoves are not always associated with the same stratigraphic level.

Correlation and Conclusions: Braided fluvial system morphology within gully channels near mantle layer exposures suggests geologically recent aqueous flow. The significant latitudinal correlation between degradation of youthful mantle morphology and gully abundance suggests that top-down melting sourced from a recent episode of obliquity-driven mantle deposition may be responsible, a correlation consistent with climate trends [12].

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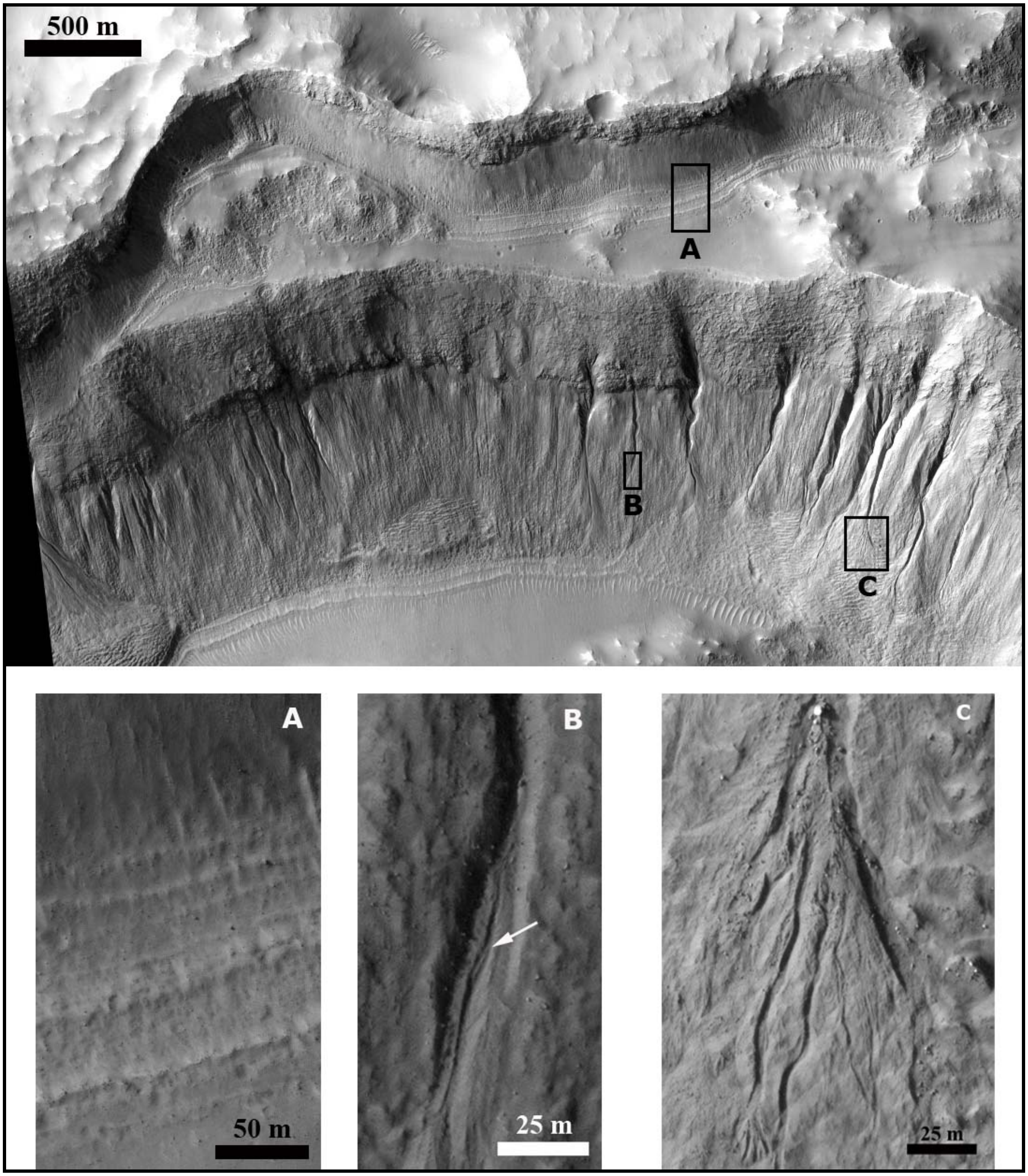

Figure 1: This portion of HiRISE observation PSP_002317_1445 (34.9°S, 195.1°E) illustrates the close relationship between layered latitude-dependent mantling deposits (**A**), and recent gully activity as indicated by longitudinal bars (**B**, highlighted with arrow) and bifurcating incision of fan deposits (**C**). North is up in all frames. Mantle preservation is controlled by insolation geometry as evidenced by the preservation of smooth mantle texture on the topographic benches in this scene and dissection on poleward facing slopes.

CLIMATE CHANGE AND GULLY FORMATION IN THE CANADIAN ARCTIC: AN EARTH-BASED PERSPECTIVE ON THE ORIGIN AND EVOLUTION OF MARTIAN NEAR-RIM, IMPACT-CRATER GULLIES. Soare, R.J.[1], Osinski, G.R.[2], Roehm, C.L.[3] [1]Dept. of Geography, Planning & Environment, Concordia University, 1455 De Maisonneuve W., Montreal, Qc., Canada H3G 1M8 (rsoare@colba.net); [2]Dept. of Earth Sciences, University of Western Ontario, London, Ont., Canada N6A 5B7; [3]Climate Impact Research Center & Dept. of Ecology and Environmental Science, Umeå University, SE -981 07, Abisko, Sweden.

Introduction: The origin of Martian gullies remains a controversial topic within the planetary science community. Several different hypotheses have been proposed. In this work, we report on ongoing investigations involving a comparative study of gullies in the northern plains of Mars and possible analogues in Arctic Canada. In earlier work [1], we hypothesised that the formation of some near-rim impact-crater gullies (Fig. 1) in Utopia and western Elysium Planitia was related to obliquity-driven rises in late Amazonian mean temperatures and to the localised thawing of near-surface ice-rich regolith This periglacial hypothesis was consistent with the occurrence of landforms such as scalloped depressions (alases or drained thermokarst lakes), pingo-like mounds and small-sized polygonal patterned ground in the surrounding landscape and throughout the northern plains identified above [2–5].

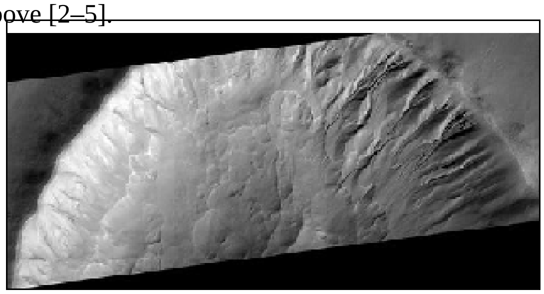

Fig. 1. Impact crater in Utopia Planitia. Notice gullies high on the crater wall near the crater rim. (MOC S04-00681, 50.5°N, 276.0°W). Image is ~3.1 km across.

Here, we briefly discuss the origin and development of low-arctic lake-side gullies that border Eskimo Lakes (68°52' N, 133°19 W) in the Tuktoyaktuk Coastlands of Canada (Fig. 2). We hypothesise that the gullies are the product of near-surface thaw conditions (active-layer deepening of ice-rich ground) mobilised by recent regional rises in mean temperature.

Fig. 2. Air photo of bluff-side gullies at Eskimo Lakes. Image is ~750 m across.

The development of these gullies has exposed massive-ice beds (Fig. 3) (emplaced by periglacial or glacial processes) in the near-surface permafrost that could be mid-Wisconsonian in age. The chronological gap between emplacement and exposure comprises thousands of years and numerous periods of climate change. As such, studying the Eskimo Lakes' gullies may further our understanding of obliquity-driven processes associated with the emplacement and thaw of near-surface ice-rich ground in Utopia and western Elysium Planitia, as well as with the formation of near-rim impact crater gullies in the region.

Fig. 3. Massive-ice exposure at gully head.

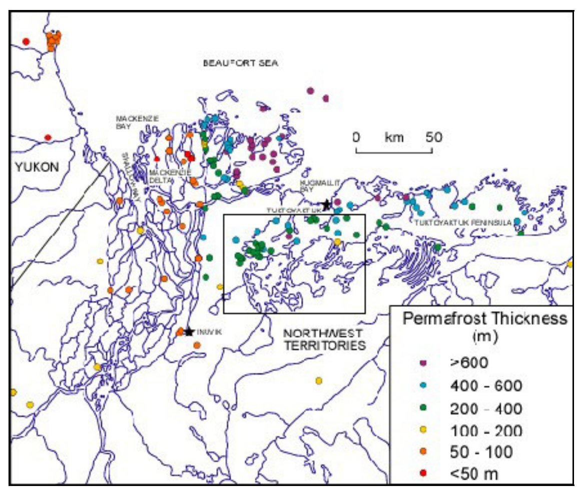

Fig. 4. Thickness of permafrost in the Eskimo Lakes region (highlighted in box). Image: NRCan.

Massive ice in the Eskimo Lakes' region: The Tuktoyaktuk coastlands comprise a region of continuous permafrost. Permafrost depth ranges from 400–600 m (Fig. 4). Around the margins of Eskimo Lakes, the depth of permafrost attenuates to ~200 m [6]. Extensive sheets of massive ice are widespread in the region (often ≥ 13 m thick [7]). The sheets are most common between depths of 6 and 25 m [8], although around the margin of Eskimo Lakes, massive beds of ice are found at depths as shallow as 3–4 m.

There is no consensus as to origin of the massive-ice beds. Some researchers point to post-glacial ice segregation and permafrost aggradation; they argue these processes were induced by the retreat of early- to mid-Wisconsonian glaciers and the subsequent freezing of basal meltwater in the glacial till [9–11]. Others suggest that the beds are buried basal ice [12,13].

Fig. 5. Air photo of Eskimo Lake gully; grey-coloured sediment highlights areas of massive ice thaw/exposure and of gully discharge.

Discussion: Although these lake-side gullies are numerous and commonplace around the margins of Eskimo Lakes, they have neither been reported nor discussed in the periglacial literature. The gullies occur in a region dotted with thermokarst lakes and alases, pingos and small-sized polygonal patterned ground. It is clear that the Eskimo Lakes gullies are derived from the thawing and melting of near-surface ground ice. Gully formation is ongoing (Figs. 3 and 5) and could be linked to regional rises in mean temperatures (Fig. 6). These rises in temperature deepen the active layer, mobilising and introducing melt-water (i.e. periglacial or glacial in origin) that was previously unavailable for hydrological activity in the near-surface sediments. Figure 5 shows a three-tiered hydrological gradient running from a sparse, small-hummock covered plain above the gully alcoves through to alder and willow-dominated slopes surrounding the gullies. Preliminary work suggests that the changes in vegetation density and type are the product of slight increases in the depth of the active layer and in the volume of water in the hillslope system. Further hydrological and bio-geographical mapping will be carried out in order to evaluate the validity of this finding. Stable isotope studies are also underway in order to help constrain the relative environments and age associated with the emplacement of the massive-ice beds.

In the case of the Eskimo Lakes' gullies and the near-rim impact crater gullies of Utopia and western Elysium Planitia, relatively recent changes of regional temperatures could be the agent responsible for gully formation. Equally interesting, gully formation in both environments could be occuring in areas where ice-rich permafrost, emplaced much earlier in the respective geological histories of the low arctic and of the two Martian northern plains, has thawed. Studying these arctic gullies and their climate-driven origin could help constrain our understanding of the boundary conditions and processes associated with the formation of the Martian near-rim craters in Utopia and western Elysium Planitia.

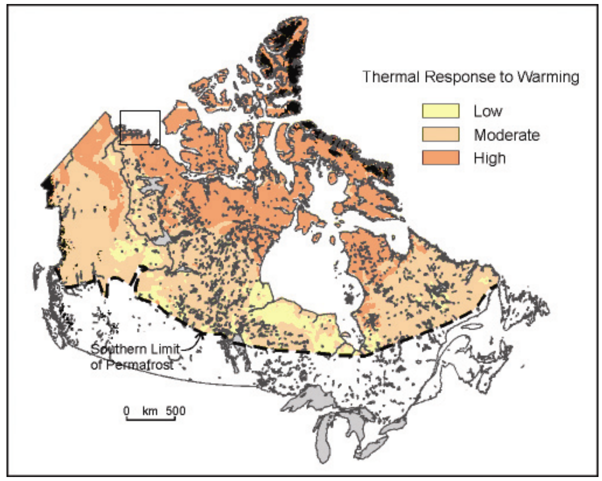

Fig. 6. Sensitivity of permafrost to warming and temperatures rises. The Tuktoyaktuk Coastlands are in a region of high sensitivity (highlighted in box). Image: NRCan.

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WIND AND THE ORIGIN OF MARTIAN GULLIES: A LOCAL AND REGIONAL TEST IN CIMMERIA.
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Martian gullies are composite landforms, representing massive transport of debris down a slope [1]. Most explanations of gullies involve liquid water (groundwater, ground ice, snowmelt), and two have invoked wind and eolian deposition. Gullies might form by solar melting of dust-ice mantles, which were wind-deposited onto wind-facing slopes [2]. Or gullies might form as dry flows of sand and dust, wind-deposited in the lee of obstacles like crater wall [3]. I test these hypotheses using a crater and surroundings in Cimmeria, where wind direction has been relatively constant (to SE). In this area, most gullies face S and SE, to the lee of the prevailing winds, as predicted in [3].

Methods: Inspired by the impact crater and its gullies in MOC press release MOC2-1302 (Fig. 1), I examined MOC and Themis [4] images of the area surrounding it in Cimmeria (MC-29). I noted the locations and facing directions of gullies, and of wind direction indicators (especially wind streaks).

Crater 1302: The inspiration for this work, called impact crater 1302 (Fig. 1), is a relatively fresh simple bowl, ~4 km diam., in Cimmeria (35.4°S 152.5°E). Crater 1302 is excavated in rolling Noachian plains material [5], and sits on a broad low rise with indistinct fluvial (?) channels to the south. Much of the crater's geology reflects deposition and erosion from winds blowing NNE to SSW. {1} The crater floor is marked by elongated hills (yardangs) aligned NNE-SSW along broad streaks of lighter and darker tone materials. {2} Dune forms decorate the boundary between 1302's floor and walls. At the north edge of the floor are long linear dunes oriented E-W (~parallel to the nearby crater rim); at the south edge of the floor are many short linear dunes oriented N-S (perpendicular to the nearby crater edge). {3} Linear dunes on the plains surrounding 1302 appear asymmetrical, with steeper (slip) faces to the SSE. Linear dunes near 1302 have more divergent orientations, with slip faces to the S and E.

Crater 1302 has gullies on its S- and W-facing interior walls (Fig. 1, MOC E0101585). On the former wall, overlapping debris deposits imply at least three episodes of gully formation from the same alcoves. The deposits are cut by minor circumferential faults, and pitted as by wind etching. Walls between alcoves show at least one episode of sediment deposition followed by etching.

Thus, recent geological processes at crater 1302 are dominated by eolian effects ascribable to winds blowing towards the S and SE. Gullies on the interior walls of crater 1302 also face to the S and E, which is as predicted if they form from sediment deposited (behind obstacles) from winds blowing to the S and E [3].

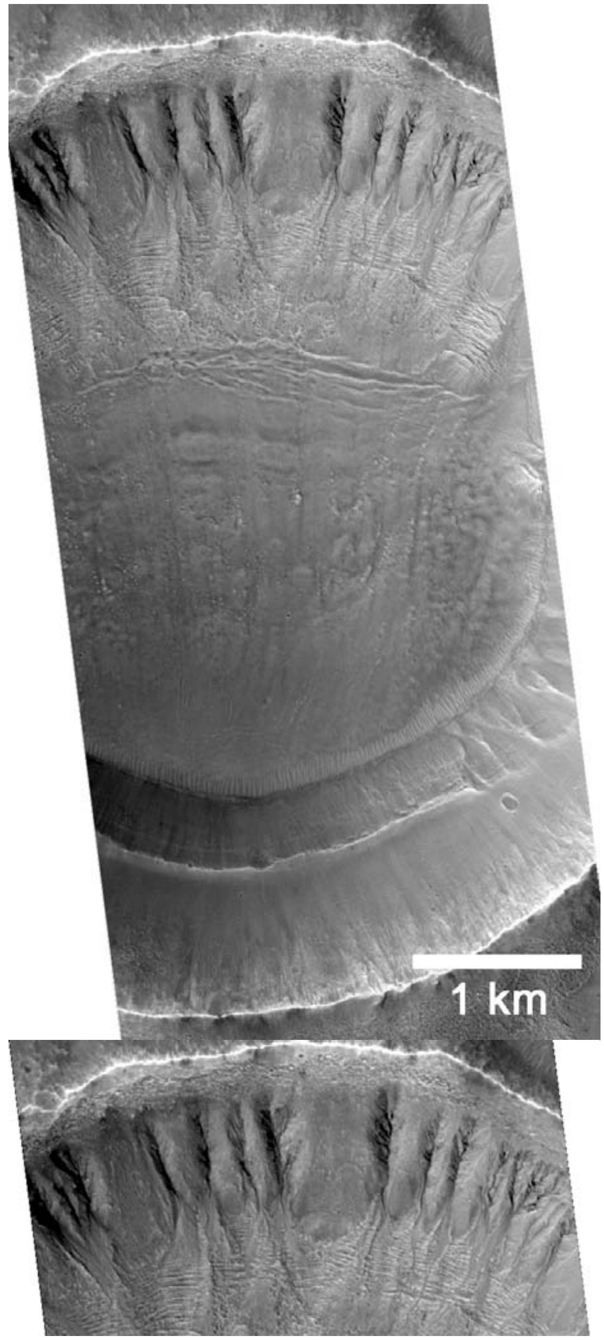

Figure 1. Crater 1302 (MOC S1000476). Above: abundant gullies on S-facing interior wall. Transverse dunes below gullies on floor; central floor with N-S wind streaks and yardangs, and longitudinal dunes at S edge of floor. Below: detail of gullied wall.

Regional Setting: Crater 1302 might be atypical, so I investigated wind direction markers and gully orientations in Cimmeria surrounding 1302. Wind orientations from wind streaks are shown in Figure 2a; the area of crater 1302 is in a broad area of consistent southeasterly winds [6], with a few windstreaks indicating other directions. GCM results for this area are consistent with the streaks, and imply that wind directions vary little with season or storm condition [7].

Most gullies in this part of Cimmeria face to the south or southeast ([8], Fig. 2b). Despite this variability in gully facings, it is clear that the majority of gullies face in the same direction as the present-day winds blow (Fig. 2a).

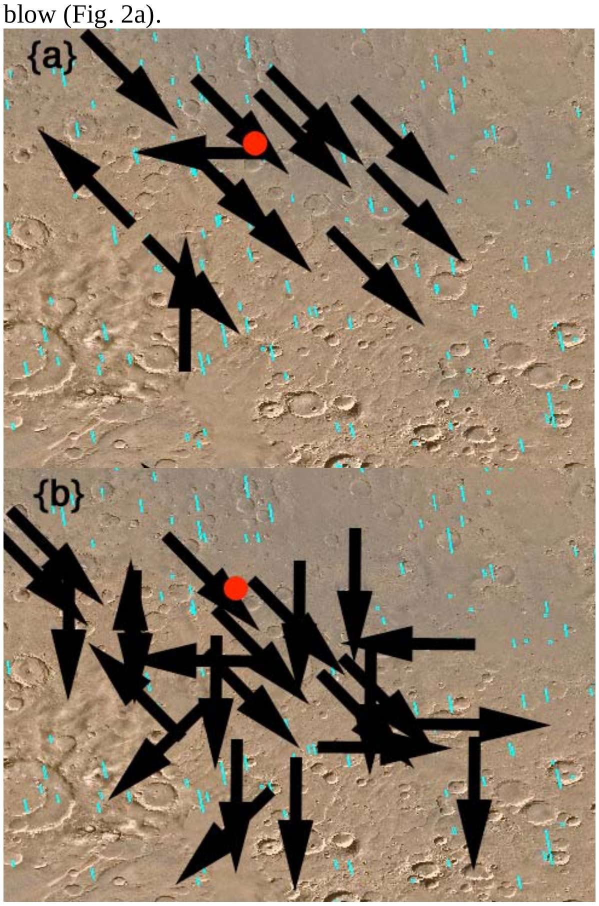

Figure 2. Orientations of selected features in part of Cimmeria (MC-29), 140-170°E, 30-52°S, north to top. Base is MOC mosaic. Red dot is crater 1302 (Fig. 1). Blue bars are MOC image locations (R10-R15). {a}. Windstreaks, arrowhead to inferred wind direction. {b}. Gullies, arrohead in facing direction (i.e., downhill).

Interpretations: Evidence uncovered here is most consistent with gullies in this part of Cimmeria forming from wind-deposited dust and sand.

The gullies in crater 1302 and environs are not easily explained in the model of [2], which starts with dust-ice mixes plastered onto wind-facing slopes. Were that so, prevailing winds from the NW would place the dust-ice mixtures onto the NW-facing walls of craters, where very few gullies are observed (Fig. 2b). Nor is dust-ice deposition onto lee slopes (facing S & SE) likely, because the ice would have to travel from the northern hemisphere, across the equator.

Hypotheses of gully formation invoking groundwater [9] remain problematic [10]. Rock in the walls of impact craters (Fig. 1) is too broken to support aquifers and aquitards, so groundwater cannot easily be present near alcove sites to initiate gullies. Hypotheses relying on ground ice seem unlikely here because, in the vicinity of crater 1302, little near-surface H is detected [11], and ground ice is calculated to be unstable [12].

Finally, evidence developed here is consistent with the model of [3], in which gullies develop from wind-deposited dust and sand. Wind directions in crater 1302 and surrounding Cimmeria are dominantly to the S and SE, as shown by several types of markers and by GCM simulations. The recent geology of crater 1302 is dominated by eolian effects, indicating that wind is an active geologic agent. Most gullies in crater 1302 and its surroundings are on S- to SE-facing walls, which would be in the lee of the prevailing winds, as predicted by [3].

Extensions: Several other ideas on the eolian origin of gullies have come from this study. {1} Gullies need not originate at their alcoves, but can enlarge uphill to form alcoves [13]. {2} Gullies can only form in areas of alternating deposition and erosion of dust/sand. {3} Gully formation is episodic; no large gullies have formed in the years of high-resolution Mars observations [14], so may require wind events more severe than witnessed so far. These ideas can be discussed as time permits.

Acknowledgments: I used Mars Orbiter Camera images processed by Malin Space Science Systems (http://www.msss.com/moc_gallery/). Supported by USRA/LPI through its CAN with NASA.

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DRAG FORCES FROM CONCENTRATED SALT SOLUTIONS IN MARTIAN GULLIES

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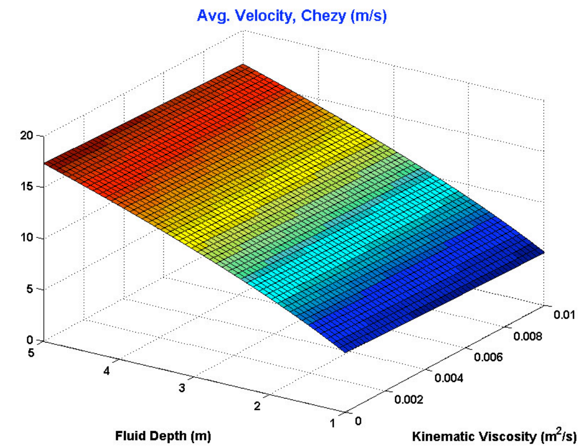
Introduction: Almost all flow models for Martian gullies to date have assumed liquids that exhibit viscosities on the order of 1 cP such as pure water [1, 2] and liquid carbon dioxide [3, 4]. However, we have recently characterized the density and viscosity of concentrated aqueous solutions of salts known to be present on Mars [5,6]. This work was carried out on various solutions of Fe^{2+}, Fe^{3+}, Mg^{2+}, and Ca^{2+} with Cl^- and SO_4^{2-} up to 65% by weight (for $Fe_2(SO_4)_3$) under Martian temperatures, from 273 to 220K. The resulting liquids exhibit densities and viscosities far in excess of those previously used in gully simulations, either modeling or experimental. This paper reports on the results of gully flow modeling using these types of liquids, with the expectation that this will lead to the same solutions being studied in our experimental gully simulator to identify geomorphological characteristics that might be observed on Mars [7, 8]. Specifically, in this study we estimate the flow velocity and the drag forces on boulders for these highly viscous and dense fluids in a representative Martian gully. Recent observations of boulders in gullies and gully-like features suggest that they might be a probe of the forces and processes involved in gully formation [9].

Modeling: The gully modeled was V-shaped with a 60° bottom angle, a 15° slope, and an average roughness of 0.1 m. The independent variables were kinematic viscosity (10^{-6} to 10^{-2} m^2/s, corresponding at water densities to 1 to 10,000 cP) and depth of liquid in the gully (1 to 5 m). Gravity was 3.73 m/s^2 and the flow was uniform and steady.

Most equations relating open channel flowrate to gully morphology are semi-empirical in nature, assume turbulent flow and water-like viscosity, and usually assume gentle slopes (<2°) and high width to depth ratios. In order to circumvent these limitations, our model was a more general Bernoulli energy balance relating potential energy supplied by the 15° slope to energy dissipated by friction against the wetted perimeter. To validate this approach, we compared our results to those of a standard open-channel logarithmic velocity model utilizing the Chezy coefficient, as shown in Figure 1. The two models agree very well in the turbulent region, with the Bernoulli modeling also showing a region of laminar flow at high viscosity and low liquid loading in the gully.



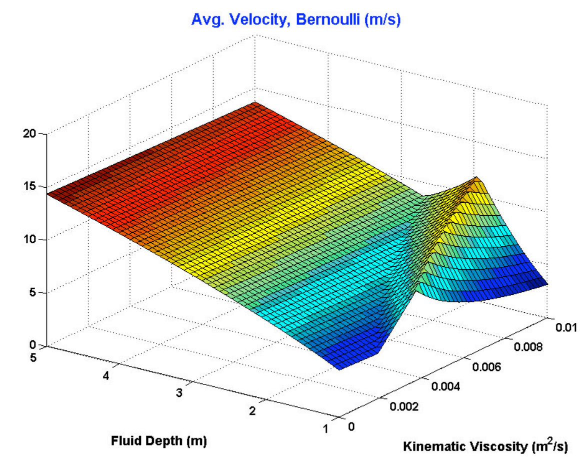


Figure 1. Comparison of estimated average velocities in Martian gullies from a standard terrestrial gully model and our adapted Bernoulli approach.

Liquid water would lie in a line along the left-front edge of the data. In regions of turbulence, the flowrate is a very weak function of viscosity. While this may seem counter-intuitive, it is well known in highly-turbulent flow through rough pipes. At very high Reynolds number (Re), in excess of about 10^5, and in any type of conduit (gully or pipe) with a relative roughness exceeding about 0.01, the flow is "fully turbulent". This means that increasing the flowrate does not appreciably change the average velocity profile, which is quite flat at high degrees of turbulence. Increasing the flow only amplifies the random eddy motion without changing its scale. It is the average velocity profile, not the random fluctuations, that dominates the frictional losses against the walls and sides.

The Bernoulli treatment predicts a laminar region at the right-hand corner of the data, as Re drops below 2300. The sudden increase of average velocity is due to the flow profile changing to the organized laminar configuration, eliminating losses due to turbulent eddies resulting in a drop in the friction factor. Pure water would not be expected to show laminar behavior in any gully size greater than a fraction of a cm.

Drag Forces on Boulders: One way to experimentally test for the possibility that viscous solutions are responsible for gully formation would be to compare the sizes of spherical boulders that could be moved by these predicted flows to the size of boulders seen to be moved by actual flows on Mars. To get an idea of the factors involved, a force balance was set up between the weight of a boulder immersed in the dense liquid, F_B, and the lateral drag force, F_D, exerted on the same boulder by the flows from Figure 1. The two forces are:

$$F_B = \left(\frac{\pi}{6}d^3\right)\left(\rho_b - \rho_f\right)g$$

$$F_D = \frac{1}{2}\rho_f C_D\left(\frac{\pi}{4}d^2\right)V^2$$

The density of the boulder (ρ_b), and the solution (ρ_f) was taken to be 3000 and 1200 kg/m^3, respectively, and the drag coefficient (C_D) was a function of the boulder's Reynols number, Re. Setting the two forces equal and numerically solving for d (since C_D is a tabulated function of d) gives the diameter of the largest boulder for which the fluid flow past it exerts a force equal to its weight.

While this may seem a fairly arbitrary measure, it is in line with the type of analysis required to determine if large-scale bodies can be moved by such a flow. The force ratio used here is unity, and a different ratio (amounting to a different coefficient of rolling resistance) would be used in practice. We will obtain these from literature or measure them in our gully apparatus. Figure 2 shows the critical boulder diameter for the flows in Figure 1.

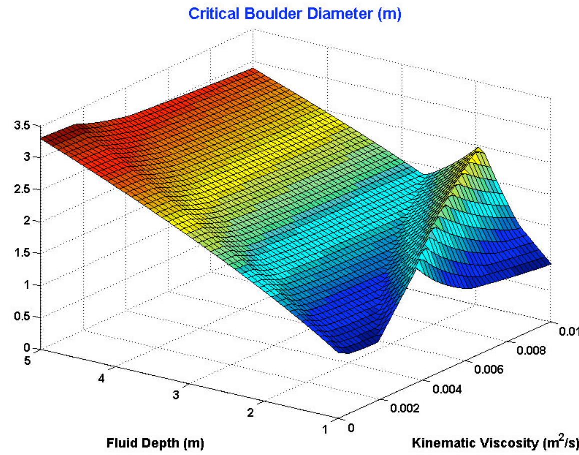


Figure 2. Boulder diameter for which the lateral fluid flow forces equal the weight of the boulder immersed in the fluid.

These results indicate that the expected flow forces are substantial in comparison with the vertical resting force of basaltic boulders immersed in the liquid. This is true for pure water and, interestingly, for more viscous solutions at low liquid loadings due to the increased velocity in the laminar flow region. From these results, boulders with diameters approximately half the liquid depth would experience this much force.

Conclusions: Based on in-situ analyses of unconsolidated surface deposits on Mars, a considerable amount of very soluble salts are present that, when mixed with water, would create viscous and dense solutions under Martian temperature conditions. These liquids could be responsible for the creation of at least some morphological features on Mars such as gullies. Preliminary modeling has revealed the possibility of laminar as well as turbulent flows that may be capable of transporting rocky material large enough to be imaged by HIRISE. The goal of our program is to consolidate laboratory studies of low temperature fluids, numerical modeling, flume-based experimentation and spacecraft images of gullies to determine the physical properties responsible for fluvial features on Mars.

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Modeling Martian Snowpacks and Implications for Gully Formation. K. E. Williams[1], O. B. Toon[2], J. Heldmann[3] [1]Department of Atmospheric and Oceanic Sciences. & Laboratory for Atmospheric and Space Physics (LASP UCB 392, University of Colorado – Boulder, CO 80309-0392 kaj.williams@colorado.edu), [2] Department of Atmospheric and Oceanic Sciences& Laboratory for Atmospheric and Space Physics (LASP UCB 392, University of Colorado , Boulder, CO 80309-0392 btoon@lasp.colorado.edu), [3] NASA Ames Research Center, Space Science Division, Moffett Field, CA 94035

Synopsis: An improved numerical snowpack mass and energy model is developed and used to model the thermodynamic stability of a hypothetical mid-latitude snowpack on Mars. Our findings suggest that both vigorous melting and sublimation occurs producing significant amounts of meltwater runoff, regardless of slope geometry. We use our model results to speculate on the feasibility of the melting snowpack model of gully formation [1].

Introduction and Background: The presence of geologically recent gully-like features on Mars [2] has spurred numerous hypotheses relating to gully formation. Musselwhite et al. [3] propose that a liquid subsurface CO_2 reservoir may be responsible for carving the gullies. Heldmann [4] and others have argued that subsurface aquifers with impermeable boundaries may be weakened by freeze-thaw cycles or suddenly exposed by slope failures, causing a cascade of water that could have incised some gullies. Christensen [1] has suggested an alternative model for gully formation. Christensen hypothesizes the following:

1. Water is transported from the Martian poles to mid-latitudes during periods of high obliquity.
2. Melting occurs at mid-latitude during low obliquity, producing liquid water that is stable beneath snow.
3. Gullies are eroded by this meltwater.
4. Gullies incised into the substrate are observed where snow has been removed.
5. Patches of snow remain today where they are protected from sublimation by a layer of desiccated dust/sediment.
6. Melting could be occurring at present in favorable locations in these snowpacks.

Christensen [1] provides several photographs of a curious mantling on crater walls in the Dao Valles region located ~33 deg. South by 93 deg. East. He suggests that the mantling is a remnant snowpack and that several gullies can be seen protruding from this mantling, suggesting that they therefore could be the result of the snowpack snowmelt.

The object of our research is to model a hypothetical snowpack at the location suggested by Christensen to determine whether melting could be achieved under both current *and* past Martian climate conditions. In this presentation, however, we mostly present findings for the *current* climate. Note that this model says nothing about *if* or *how* such a snowpack might be deposited on such a slope. Two snowpacks are modeled, both containing dusty snow. The first snowpack is modeled without an initial dust lag (but dust enrichment is permitted in the surface layers), and the second with an initial 1-cm thick dust lag.

The snowpack we model is for a simple geometric configuration consisting of a planar slope and a semi-infinite plane at the foot of the slope. Our model is a 1-D mass and energy model, utilizing a finite-volume solver for the energy transport between the model layers. The model layers are permitted to have varying amounts of water ice, CO_2 ice, liquid water and dust. The atmospheric fluxes at the surface include latent and sensible heat, as well as atmospheric heating and reflected and emitted energy from the planar surface at the foot of the slope.

A two-stream radiative transfer model is utilized for the solar wavelengths within the snow. Snowmelt percolation is evolved according to a threshold model, where the excess liquid mass fraction in the layer is permitted to move down a layer until refreezing or runoff occurs.

The modeled snow is allowed to have varying amounts of dust within the snowpack, as well as an initial dust lag if desired. If no initial dust lag is specified, then the sublimation of ice from the surface creates a natural dusty sublimation till. The radiative transfer model used is that of McKay et al. [6] and is able to respond to the non-homogenous dust distribution and evolution.

Results: Previous results of a simpler model have been presented at DPS 2006 and LPSC 2006. The model has since then been updated and improved, and some errors have been identified and corrected.

The new model was run with various amounts of dust, slope aspect and angle, eccentricity, ice emissivity and many other parameters. For the "base" case, the latitude was fixed at 33.0 deg South. The snowpack density was fixed at 550 kg/m^3, ambient atmospheric pressure at 8.75 mb and 15 prum of atmospheric water (constant) was included. For the base cases, 100 ppmw of red dust were homogenously mixed into the snow. The results show that in most cases the snowpack lifetime and melting state are most sensitive to slope orientation and inclination.

The first scenario we present is for an uncovered snowpack under current Mars conditions. A 1 m thick snow column on the slope was modeled. Simulation was started at Ls=90, and the model was stopped when the snowpack disappeared. The snow column disappeared in less than one season, and during that time 95 liters/m^2 of meltwater runoff were produced and 437 kg of snow was sublimed. In all sensitivity tests (cases) we found that the modeled snowpack both sublimes vigorously and melts during the summer season. In addition, in all cases modeled we found that a significant amount of runoff was achieved: varying between 38-146 liters of water per 1 m^2 snow column. Approximately 74,500 BP the eccentricity was higher (~0.12), but the obliquity has *not* been higher than the present value (~25.19°) for that same time period [5]. Model runs with this higher eccentricity increased the amount of meltwater runoff significantly. This is expected since higher eccentricity results in more vigorous heating.

The second scenario we present is for a snowpack covered by a permeable 1 cm dusty lag. In this case there was no melting, and hence no runoff. Nevertheless the ice sublimed in a single season. The presence of the dust lag, while darkening the snow surface, had a more dramatic impact on the ice thermodynamic stability by reducing the solar penetration in the snowpack. Our model suggests that solar penetration is vital to the melting / runoff process. Merely heating the surface by lowering the albedo is much less important to the melting process than the at-depth heating provided by solar shortwave penetration.

Discussion and Conclusion: Our model runs show that an uncovered 1 m snowpack at mid-latitudes on a poleward facing slope in Dao Valles would have both sublimed and melted very quickly, producing considerable amounts of runoff. A covered snowpack did not melt, but nevertheless did sublime very quickly. In both cases, 1 m of firn disappeared in a single season. Therefore we conclude that under either scenario an exposed 1 m snowpack would never survive for 74,500 years.

If the initial snowpack was much thicker and dustier, it is conceivable that it might have survived much longer if it developed the protective sublimation till before a season had elapsed. Mellon et al. [7, 8] has shown that on a similar slope the snowpack could stay stable if buried by at least 1 m of dust. Such a burial would have to occur very quickly (within a few years of snow deposition) in order for the snowpack to be preserved. However, if lag deposition were to occur quickly (for example, via a slope failure) this would be expected to be a highly localized phenomenon, and probably not extensive enough to blanket large tracts of snowdrifts.

In sum, a 1 m snowdrift on a poleward slope at mid-latitudes would have both sublimed and melted very quickly unless it was immediately buried by at least 1 m of dust. Nevertheless it is an interesting result that both melting and runoff occurred in large quantities. Our findings suggest that melting of fully exposed surface ice may be occurring under the present-day Mars climate.

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NOTES