GEOMETRIC AND THERMAL CONTEXT OF GULLIED SLOPES IN THE NORTHERN HEMISPHERE OF MARS: PREDICTION AND MEASUREMENT. Martha S. Gilmore¹, Ann M. Ollila², Nina L. Lanza¹,², and Ashwin R. Vasavada³ ¹Department of Earth and Environmental Sciences, Wesleyan University, 265 Church St. Middletown CT 06459 mgilmore@wesleyan.edu, ²Dept. of Earth and Planetary Sciences, Univ. of New Mexico, Albuquerque, ³Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Introduction: Martian gullies are geologically recent phenomena interpreted to be fluvial features formed by the action of liquid water [1,2]. Gullies are limited to latitudes greater than ±30-40° on both hemispheres [1,2], coincident with the predicted stability range [3,4] and measurements [5] of near-surface ground ice and its geomorphic indicators [6,7]. Reported azimuthal trends of gullies [1,8,9] are inconsistent, most likely due to differences in individual gully surveys, however most models for gully formation predict that gullies should display a preferred range of azimuths that facilitate the emplacement and/or melting of near-surface or surface ice [1,9-14].

To better understand the potential effect of insolation on gully formation, we measure the geometry of gullies in the northern hemisphere and calculate the resulting insolation received on these slopes at three obliquities. We also measure daytime and nighttime temperatures of these slopes using the Thermal Emission Imaging System (THEMIS) data. These parameters are also calculated and measured on slopes that lack gullies, to determine whether gullies form in a restricted thermal environment.

Methods: Slope geometry and insolation. As in the southern hemisphere, gullies in the northern hemisphere are regionally clustered, where most occur within Acidalia and Utopia Planitiae. Slope, elevation, depth from surface and azimuth were measured for 154 gullies and 234 nongullied slopes in these two regions. A digital elevation model (DEM) was created using Mars Orbiter Laser Altimeter (MOLA) data using the method of [15]. Mars Orbiter Camera (MOC) images were overlaid onto the DEM in ArcGIS and geometric parameters measured. The measured slope and orientation data were used to calculate the maximum and average daily irradiance received by each slope on the equinoxes and solstices for obliquities = 5°, 25° and 60°; all calculations assume perihelion occurs at its present value of Ls=250 [16].

Slope temperatures. 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, physical units (i.e., rock layers, sandy slopes, or mantled units) were outlined in ArcMap and the temperatures extracted. Night and day temperatures were collected to constrain diurnal temperature variations. Temperatures were measured for 51 gullied slopes and 56 slopes without gullies in at least one season. The majority of these slopes were included in the geometry and insolation calculations, but the populations are not identical due to the availability of THEMIS data.

Results: Slope geometry. Gullies are measured to emanate an average of 202 m below the local surface and have average slopes of 17° (less than the angle of repose); these values are similar to their southern counterparts, and other measurements of northern hemisphere gullies [9,11,21]. Gully azimuths [17] are found to occur at all orientations, but vary as a function of latitude where gullies at latitudes <~40° are dominantly pole-facing and gullies at latitudes ~40°-53° are dominantly equator-facing (Figure 1). The nongullied population shows no orientation preference with latitude.

Figure 1. Orientation of slopes.

Slope irradiance. Results for the maximum (noon-time) irradiance received on gullied and nongullied slopes at present-day obliquity are shown in Figure 2. For the nongullied population, the slopes see the least sunlight in the winter and the irradiance received decreases with higher latitudes and on poleward-facing
slopes in each season. This contrasts with the gullied population. The maximum irradiance received on gullied slopes is less than that of nongullied slopes for latitudes \(<-40^\circ\) and greater than that of nongullied slopes at latitudes \(>-40^\circ\). This is most pronounced in the winter, where the gullied population \(>-40^\circ\) latitude receives an average maximum irradiance of 270\(+70\) W/m\(^2\) compared to 16\(+12\) W/m\(^2\) for the nongullied population. Equator-facing gullies also receive more irradiance in winter than their nongullied counterparts.

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The average daily irradiance at the solstices and equinoxes at present-day obliquity (not shown) for gullied slopes shows a more limited range with latitude and azimuth than the nongullied population. For gullied slopes, irradiance is \(\sim\)constant with latitude in the spring, winter and fall and increases with latitude during the summer.

Slope temperatures. Average daytime temperatures for gullied slopes are 240\(+3\) K \((1\sigma)\), with a maximum of 252 K during the summer, and 212\(+2\) K during the winter (Figure 3). Average nighttime temperatures for gullied slopes values span 162-205 K over the year.

Linear regressions are plotted.

These trends are exacerbated at an obliquity of 5\(^\circ\) (not shown), where wintertime irradiance can exceed summertime in some cases. At obliquity = 60\(^\circ\), all slopes are permanently shadowed in winter, but gullies lie within a more restricted range of irradiance than nongullied slopes as they do for all obliquities.

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Due to the uneven distribution of available THEMIS data seasonally and the variable effects of albedo on daytime temperatures, we focus our statistical analysis on nighttime summer and fall temperatures (Figure 4). Gullied slopes \((T_{ave} = 191\) K\) are found to be significantly \((p<0.05)\) warmer than nongullied slopes \((T_{ave}=186\) K\) in the summer. No significant differences are found in the fall.

Comparison of the populations as a function of latitude and orientation show significant differences in the summer data (Figure 4). Gullied slopes are found to be significantly warmer \((T_{ave} = 191\pm9\) K\) than nongullied slopes \((T_{ave} = 186\pm10\) K\) at latitudes \(<-43^\circ\) and at poleward orientations \(|180^\circ-\text{orientation}|-110\)^\circ\. Effect of a rock layer. Several authors have noted that many gullies emanate from a particular rock layer along a slope, suggesting a genetic relationship \([1,8-11]\). For gullied slopes with rock layers, summer nighttime temperatures are significantly warmer \((T_{ave} = 198\pm8\) K\) than the remainder of the slope \((T_{ave} = 191\pm9\) K\).

Discussion: In the northern hemisphere, gullies show a more limited range in both maximum and average insolation and temperature than slopes that lack gullies. Gullied slopes are also warmer than nongullied slopes in the summer. These results strongly support a thermal control on gully formation. We posit that gullies form on the slopes that have an orientation, elevation and slope at particular latitude that results in a restricted range of local surface temperatures.

Hypothesis: A Three Bears scenario? Both the insolation modeling and the temperature data show a correlation with latitude and orientation. Slopes that lack gullies show no such correlations. Our data show that gullies at low latitudes occur on slopes with lower irradiance and temperature, suggesting that water ice cannot persist on warmer slopes where it would rapidly sublimate. At higher latitudes, ice can persist on all
slopes, however, our data show that gullies will occur on slopes that currently receive relatively high irradiance throughout the year or have high nighttime summer temperatures. This is consistent with the idea that melting can only occur on the warmest slopes at the higher latitudes in our survey (Figure 5). Furthermore, gullies are seen to emanate from rock layers, which are themselves the warmest locations on a slope. Slopes with high nighttime temperatures are predicted to have the warmest daily average temperatures [19]. Thus rock layers may facilitate daytime melting by reducing the energy needed to melt ice formed during the night. Near surface ground ice condensed within or adjoining such rock layers may consequently be the first and easiest to melt during the summer, which may explain the apparent link between gully heads and rock layers.

**Extant gully formation?** Measured daytime temperatures do not exceed the melting point of pure water. Thus direct melting of ice at the surface is not predicted at these sites at today’s obliquity. Greater summertime irradiance values are predicted for gullied slopes at higher obliquity (not shown) which may result in warmer temperatures, particularly at higher latitudes during times when perihelion is closer to summer solstice (Ls=90°).

Contemporary summer daytime temperatures could be above the melting point of brines [20]. A brine reaching the surface by some mechanism would be expected to flow at these temperatures.

**Melting constraints.** Gullied slopes are calculated to receive relatively high winter irradiance. This suggests that the source ice for the gullies cannot get too cold in the winter because: 1) the temperature of subsurface ice needs to be closer to the melting point so that the energy of the summer thermal wave is great enough to overcome the specific heat capacity of the ice, 2) these slopes have the most warm days over the year, maximizing melt volume, and/or 3) subsurface vapor diffusion is integral to the supply of the gully source, and diffusion is inhibited by cold temperatures. That the gullies have a dependence on winter irradiance suggests that the seasonal thermal wave, which affects the upper ~10 m of the subsurface is a driver for gully formation. A seasonal thermal wave facilitates the melting of surface and subsurface ice in several theories of gully formation [10-14].

Figure. 3 Annual temperatures of gullied and nongullied slopes determined from THEMIS surface brightness temperatures (Band 9).
Conclusion: Gullies are sensitive to seasonal solar insolation and temperatures. We propose that gullies form on slopes with geometries (elevation, slope, azimuth) that result in a specific temperature pressure environment (not too hot and not too cold) conducive to both the preservation and melting of ice in the uppermost subsurface.


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Figure 4. Measured temperatures of gullied and nongullied slopes.

Figure 5. A Three Bears Scenario. Northern hemisphere gullies form on slopes where temperatures are warm enough to allow melting and cool enough to prevent sublimation of ice.