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# Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data

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[1] Geologically recent small gullies on Mars display morphologies consistent with erosion by water or by debris flows. Suggested formation models are divided into two main categories: (1) groundwater or (2) melting of near-surface ice/snow sourced from the atmosphere. We have measured location and orientation and recorded the local contexts of gullies to constrain the likely models of gully formation. More than 22,000 Mars Orbiter Camera Narrow Angle (MOC NA) and >120 Mars Express High Resolution Stereo Camera (HRSC) images in the southern hemisphere were searched for gullies. Discrete gullied slope sections with consistent orientation were recorded rather than individual gullies. Slope setting (impact crater, valley wall, etc.), location, and orientation were recorded for each slope section. More than 750 MOC images with gullies (>900 distinct gullied slope sections) and more than 40 HRSC images (>380 distinct gullied slope sections) were identified. From both MOC and HRSC, gullies were found to be most common between  $-30$  and  $-50$  degrees latitude and to have an overall pole facing preference. The preferred gully orientation for HRSC is southeast rather than south in MOC, owing to illumination effects that make gullies difficult to detect on south- to southwest-facing slopes in HRSC. In both MOC and HRSC surveys, higher-latitude gullies show less preference for pole facing than those at mid latitudes. Both data sets produced similar results, demonstrating that our data are reliable. We suggest that the observed latitudinal and orientation distributions of gullies show that insolation and atmospheric conditions play a key role in gully formation.

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## 1. Introduction

[2] Liquid water is unlikely to persist on the surface of Mars under current atmospheric conditions [Ingersoll, 1970; Haberle *et al.*, 2001]. However, geologically recent Martian hillside gullies, discovered in Mars Orbiter Camera (MOC) Narrow Angle (NA) images [Malin and Edgett, 2000], exhibit characteristic morphologies similar to terrestrial features formed by flowing water or water rich slurries, leading Malin and Edgett [2000] to suggest that they, too,

were formed by the action of water. Processes other than water erosion have been proposed to explain the formation of gullies, including the action of CO<sub>2</sub>-based debris flows [Hoffman, 2000; Musselwhite *et al.*, 2001] and granular avalanches or mass wasting of CO<sub>2</sub> frost [Ishii and Sasaki, 2004] or aeolian material [Treiman, 2003]. However, it is the possibility of the existence of recent liquid water on Mars that makes these features so intriguing, not only from the point of view of hydrogeology and planetary geology, but also astrobiology and future exploration of the planet.

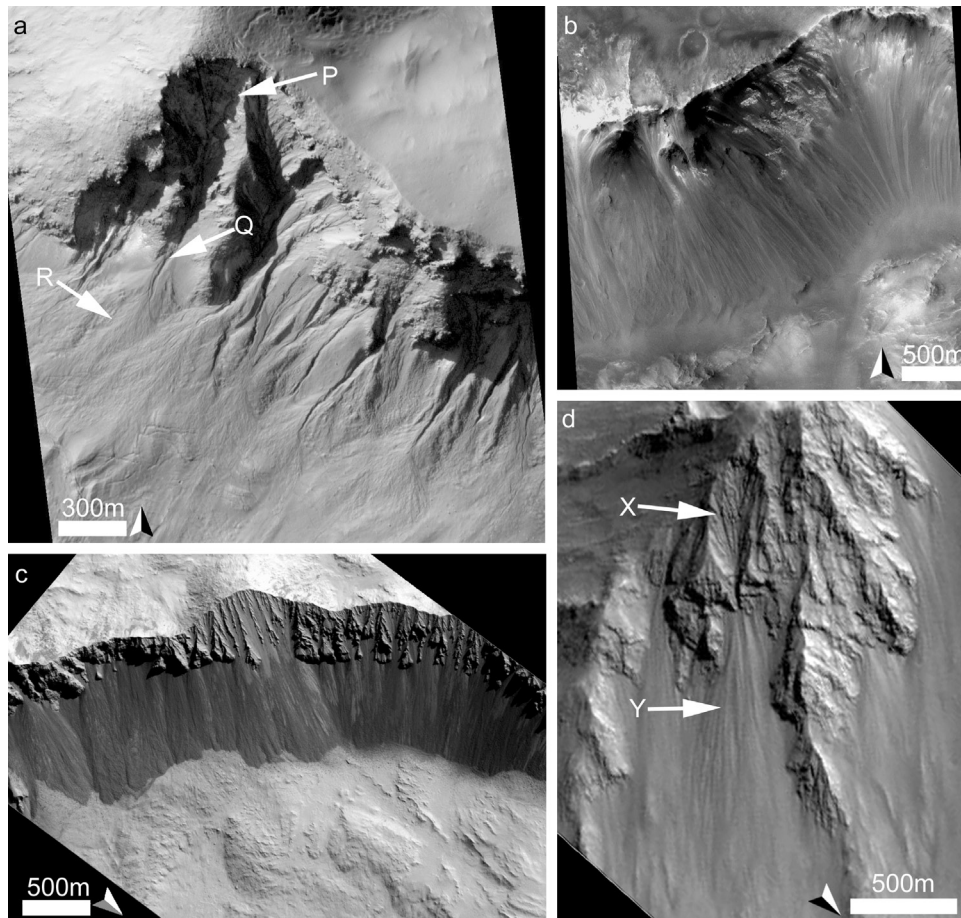
[3] Various mechanisms for the formation of gullies by water have been proposed, although fundamentally they can be divided into either atmospheric or groundwater processes depending on the source of the water. Proposed formation mechanisms are constrained by the available observational data. Morphological observations have led the way, but reliable statistics of location, orientation, and setting can also constrain the formation mechanism; obtaining these is the aim of this paper. Until recently the only available images with sufficient resolution to detect gullies have been

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**Figure 1.** Example of gullies and gully like features in MOC NA images. (a) Typical gullies with alcoves (P), channels (Q), and debris aprons (R); part of image R0200691. (b) Mass wasting on impact crater inner wall with albedo streaks; part of image R0902899. (c) Mass wasting on impact crater inner wall with well-developed debris apron and gully alcove-like incisions in exposed bedrock strata; part of image R0500984. (d) Mass wasting on impact crater inner wall showing gully like alcove (X) and gully like debris aprons (Y). There is no unambiguous channel present between the alcove and the debris apron, so this feature was not classified as a gully; part of image R0202243. Note north arrow in all images.

MOC NA data and most previous studies have used this data set. However, MOC NA images are small (typically a few kilometers in width and up to a few tens of kilometers in length), only cover a few percent of the Martian surface and have been specifically targeted at regions of interest. Thus, frequently, only a small part of a crater or valley wall can be imaged, possibly leading to unreliable orientation and distribution data. To combat this, we have combined a search for gullies using thousands of MOC NA images with another using Mars Express (MEX) High Resolution Stereo Camera (HRSC) data. HRSC data have medium, but sufficient, resolution (down to  $\sim 12.5$  m pixel $^{-1}$ ) but more importantly, have extremely large spatial coverage (up to approximately hundreds of kilometers in width and up to thousands of kilometers in length).

## 2. Background

### 2.1. Gully Morphology

[4] Martian gullies are found incised into hillslopes in terrains such as impact crater walls, valleys, pits, knobs,

buttes, hills, and escarpments. They comprise three identifiable components: alcoves, channels and depositional aprons or fans (Figure 1a). A detailed description of gully morphology is given by *Malin and Edgett* [2000], and here we summarize only the main observations and measurements.

[5] The uppermost components of the gullies, the alcoves, are generally located below or at the brink of the host slope. They presumably represent the source region for the flow and are probably formed by headward erosion. They take the form of “theater-shaped” depressions [*Malin and Edgett*, 2000], typically up to a few hundreds of meters across and up to  $\sim 1000$  m in length [*Mellon and Phillips*, 2001; *Heldmann and Mellon*, 2004] that can be narrow, broad or complex in shape. They are sometimes either completely absent or too small to be seen in MOC NA images. Alcoves frequently narrow downslope [*Treiman*, 2003; *Heldmann and Mellon*, 2004] and sometimes contain boulders up to tens of meters in diameter, or other in-filling material. Alcove “floors” sometimes contain anastomosing tributary channels or lineaments [*Malin and Edgett*, 2000].



The transition from alcove to channel can be abrupt (typical of wide alcoves) or indistinct (typical of longer, narrow alcoves).

[6] The channels, generally up to a few tens of meters in width [Mellon and Phillips, 2001] and up to a few kilometers in length [Heldmann and Mellon, 2004], begin at the base of the alcoves, and are incised into the hillslopes and often into the lower depositional aprons where they terminate. They are apparently V-shaped in cross section and have one dominant channel per alcove, although secondary channels are not uncommon [Malin and Edgett, 2000]. They often become narrower and shallower downslope, are often slightly sinuous, and sometimes display complex morphologies such as levees, tributary and distributary systems and streamlining around obstacles [Malin and Edgett, 2000]. In contrast to alcoves, channels rarely contain boulders.

[7] Depositional aprons are approximately triangular in plan view. The transition between channel and apron is either via a distributary network incised into the apron, an abrupt termination at a depositional flow, or a gradual fading of the channel into the apron deposit. The aprons are generally smooth on the decameter scale, lack boulders and can display digitate or distinct lobate swells and flows that decrease in relief downslope [Malin and Edgett, 2000]. Treiman [2003] suggests that most aprons extend beyond the local hillslopes onto the adjacent flat plain, but Heldmann et al. [2005b] disagree, finding that 80% of all gully systems terminate on the slope.

[8] Martian gullies are remarkable for their youthful ages. In MOC NA images they have been observed to superpose young aeolian duneforms, rarely show signs of impact craters and often have “pristine” well-defined morphology and a distinct albedo from their surroundings, suggesting limited dust cover [Malin and Edgett, 2000, 2001]. Also, Reiss et al. [2004] measured crater retention model ages for dunes overlain by gully deposits. Although their study could only obtain data for a single location, they found that the gullies were active within the last 3 Myr, possibly within the last 300,000 years. There are few observations of eroded or remnant gullies, leading Hartmann et al. [2003] to argue that the lack of gullies at various stages of evolution can only be explained by episodic formation and that the repeat times between episodes must be long enough such that previous generations are removed by erosion before the next are formed. By contrast, rare observations of interleaved apron deposits, overlapping alcoves and gully aprons overlain by aeolian deposits by Malin and Edgett [2001] and Treiman [2003] lead them to suggest that there is a range of gully ages (although this is probably narrow compared with the timescale between episodes of gully formation).

## 2.2. Geographic Location and Orientation of Gullies

[9] Gullies are more common in the southern hemisphere than the north [Malin and Edgett, 2000, 2001; Edgett et al., 2003; Miliken et al., 2003] but in both hemispheres occur most frequently between 30° and 50° latitude [Malin and Edgett, 2000, 2001; Costard et al., 2002; Miliken et al., 2003; Heldmann and Mellon, 2004; Heldmann et al., 2005a]. In the south, there is an additional population of gullies between -70° and -75° [Malin and Edgett, 2000, 2001; Miliken et al., 2003; Heldmann and Mellon, 2004]

that are located in polar pitted terrain [Plaut et al., 1988] that contains steep slopes not seen in the corresponding latitude range in the north. Gullies are found on slopes in terrain of all ages [Treiman, 2003] and frequently occur in “clusters” [Malin and Edgett, 2000, 2001; Edgett et al., 2003] with regional gaps where there are few or no gullies, even though the terrain is apparently similar. The cause of this “clustering” is unknown. All studies report an almost complete absence of gullies near the equator.

[10] The global distribution of gully orientations is complex. Initial studies suggested that pole-facing gullies were most common [Malin and Edgett, 2000; Costard et al., 2002], but as more data have been acquired the picture has become more confused: equator-facing gullies seem to be more common in the high northern latitudes but not in northern midlatitudes [Bridges and Lackner, 2005; Heldmann et al., 2005a]; pole-facing gullies are common in the southern midlatitudes but are less common farther south [Heldmann and Mellon, 2004; Berman et al., 2005]. Recently, some authors have found no preference for orientations of gullies [Edgett et al., 2003; Mohan and Bridges, 2004].

[11] Locally, gullies form where steep slopes are present, with the large majority being sited on the inner walls of impact craters. However, they are occasionally found on central peaks and exterior walls of impact craters [Baker, 2001; Costard et al., 2002; Dickson and Head, 2005]. Some studies suggest that gully alcoves commonly occur in, or immediately beneath, outcropping layers of more resistant rock within the slope [Malin and Edgett, 2000; Mellon and Phillips, 2001; Gilmore and Phillips, 2002; Edgett et al., 2003; Gilmore and Goldenson, 2004], although they are also present on slopes with no exposed strata [Treiman, 2003; Dickson and Head, 2005]. Treiman [2003] notes that rock masses with layers of dissimilar mechanical strengths often erode to form steep cliffs, and suggests that the statistical association of gully alcoves with layers might be due to the steepness of the slopes rather than the layers.

[12] In summary, other than the requirement for steep slopes, local geology does not control gully formation, but there is a strong latitudinal and regional variation in gully frequency and perhaps an asymmetry in orientation that is presumably a clue to their formation mechanism. These observations suffer from limitations of study size and data coverage and it is partly this lack of a definitive data set that motivated this study.

## 2.3. Formation Mechanisms for Gullies

[13] The morphology of gullies suggests that they are formed by the action of a fluid, but the composition and source of this fluid is unknown. Various fluids and sources have been suggested. Gullies have been suggested to form by granular flow of either aeolian debris [Treiman, 2003] or CO<sub>2</sub> frost [Ishii and Sasaki, 2004]. However, these models do not explain the presence of morphological features such as sinuous and leaved channels, and headward erosion of alcoves seen in many gullies.

[14] Carbon dioxide, either as subsurface cryogenic liquid or permafrost, was proposed as the channel-forming agent by Hoffman [2000] and Musselwhite et al. [2001], but numerical modeling [Stewart and Nimmo, 2002] suggests that the exit speed of decompressing CO<sub>2</sub> liquid is too great



to form gullies. The stability of subsurface liquid CO<sub>2</sub> in the regions where gullies are observed has been questioned, and it is unexplained how CO<sub>2</sub> reservoirs could account for the observed geographical distribution of gullies [Heldmann and Mellon, 2004].

[15] From the standpoint of gully morphology, the physical properties of water, salt-rich brine or water-rich debris flows are the most likely channel forming fluids [Malin and Edgett, 2000] and estimates of flow velocity, and viscosity of the channel-forming fluid for gullies on dunes [Mangold et al., 2003a] are more similar to terrestrial-style debris flows than CO<sub>2</sub> supported flows.

[16] Water-based models for gully formation can be classified as “subsurface” or “atmospheric” depending on the source of the water. Subsurface models suggest that gullies form in a similar way to springs on Earth. These models are supported by observations of gully alcoves being often associated with exposed rock layers, suggesting that aquifers control and concentrate the flow of groundwater until they breach the surface, allowing the liquid to debouch onto slopes and form gullies [Malin and Edgett, 2000]. Because slowly seeping water would quickly evaporate in Mars’ atmosphere, these models suggest the aquifer is “plugged” by ice to form a substantial reservoir of liquid water behind it, at depths of a few hundreds of meters. The springs are only active when the plug is sporadically ruptured, and form ephemeral flows that erode gullies. Possible sources for liquid water include melting of the ice table by localized geothermal activity [Hartmann, 2001], or shallow melting beneath ground ice in areas with insulating soils [Mellon and Phillips, 2001]. In addition, if salts are dissolved in the water, the freezing point of the liquid can be substantially lowered [Knauth et al., 2000; Knauth and Burt, 2002] allowing more water and less ice to form near the surface and permitting potentially larger reservoirs.

[17] These models agree with the latitudinal distribution of gullies in that gullies are preferentially found poleward of 30° where ground ice might be stable enough to allow an icy plug to form that could cap the aquifer [Mellon and Phillips, 2001]. However, observations of gullies forming high on impact crater walls, on isolated knobs and hills, and on impact crater central peaks raise the question as to whether enough liquid can be concentrated within these small areas to form gullies.

[18] Alternatively, scenarios of gully formation by atmospheric processes related to insolation or climate changes have been proposed to explain preferential latitudes and orientations of gullies. Costard et al. [2002] propose that gullies are formed by melting of near-surface ice by insolation during periods of high obliquity. This model is based on terrestrial analogues in Greenland, where gullies form by melting of snow and near-surface ground ice, which triggers debris flows that form gullies very similar to those on Mars, with alcoves, leveed channels, debris fans, etc. For Mars, Costard et al. [2002] suggest that ice accumulates within the regolith during periods of obliquity higher than ~35° when a humid atmosphere is thought to occur. Fall and winter accumulations of CO<sub>2</sub> frost protect the ice from melting until late spring when the CO<sub>2</sub> finally sublimates, allowing sudden, strong insolation to melt the ice and form debris flows. At high obliquity, insolation

becomes higher on poleward facing slopes at latitudes higher than 30°, thus explaining the distribution and supposed asymmetry of gully orientation.

[19] This model agrees with many of the observations, but it should be noted that some models of the Martian climate [Mellon and Phillips, 2001] do not predict any melting of near surface ice at midlatitudes, even at high obliquity. Also, Heldmann et al. [2005a] suggest that observations of gully alcove heads occurring underneath layered scarps are inconsistent with the surface melting model. However, observations of terrestrial analogues show that gullies formed by debris flows often start at the steepest point of debris apron materials, just underneath layered scarps [Mangold et al., 2003b].

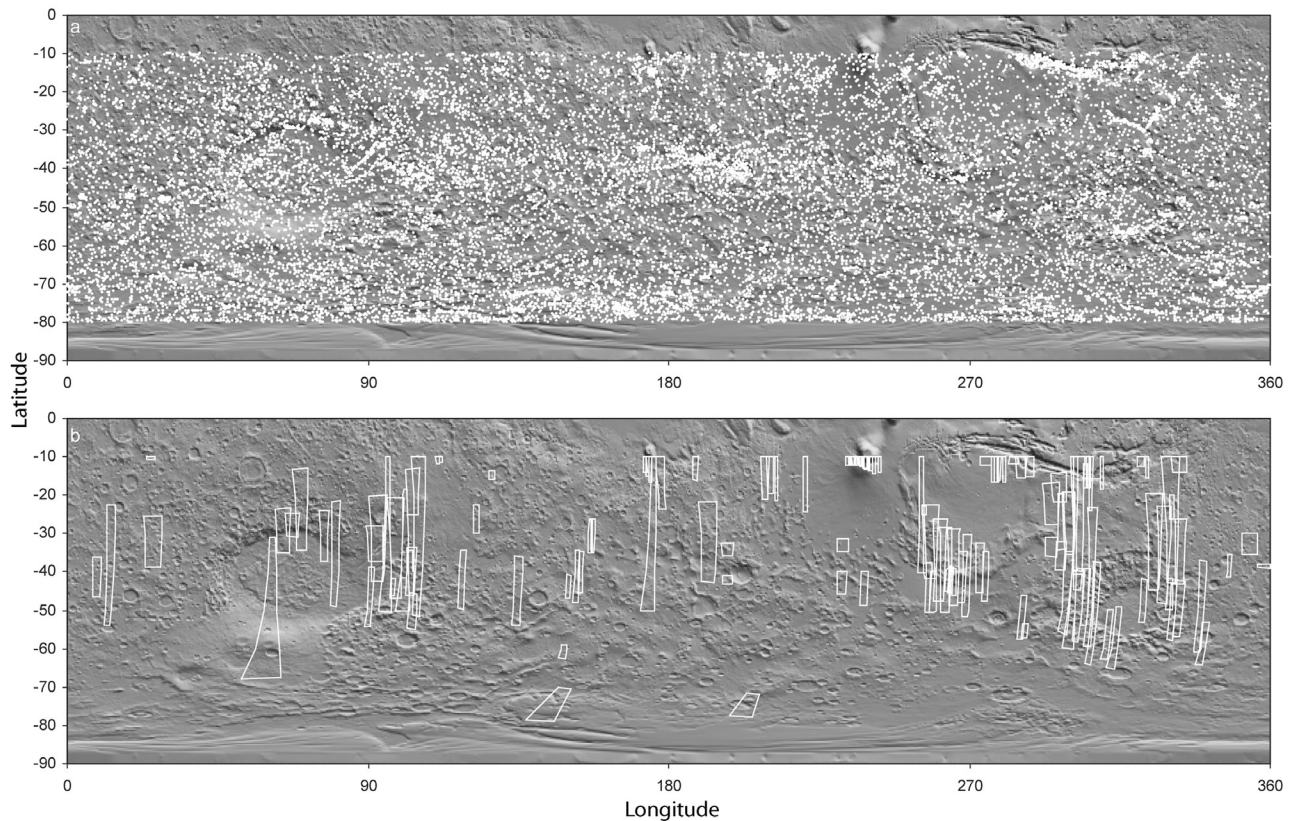
[20] Other atmospheric models suggest that gullies are formed by massive snowmelt [Lee et al., 2002; Christensen, 2003]. Christensen observed that gullies are frequently associated with mantling materials on pole-facing slopes and suggested that these represent water-rich materials, the melt products of which are responsible for forming gullies. Water-rich snow deposits form in midlatitudes during high obliquity periods; melting then occurs at low obliquity. Because melting occurs beneath the snow cover, Christensen [2003] suggests that liquid is sheltered from the low temperature and pressure of the Martian atmosphere. When the mantling material is finally removed, the effects of erosion beneath the snow are revealed as gullies. This model predicts that gullies might take thousands of years to form, in contrast to observations suggesting a quick and episodic formation for gullies [Malin and Edgett, 2000; Costard et al., 2002; Mangold et al., 2003b; Heldmann et al., 2005b].

[21] In summary, while most of the above models explain many of the traits associated with gullies, each has a weakness, either in conflicting morphological observations or in terms of physical modeling. However, it seems likely that the source of water for gully formation (either atmospheric or subsurface) can at least be determined if reliable, widespread data for gully orientation and latitudinal distribution can be obtained.

### 3. Approach

[22] The study area used in this project (−10° to −80°) covers most of the southern hemisphere. The region was chosen to maximize both the area searched and the number of gullies found. The data set used includes all MOC NA images from MOC mission subphase AB1 through R09 (see [http://www.msss.com/moc\\_gallery/](http://www.msss.com/moc_gallery/)) and all HRSC nadir images from orbits 1 through 1500 within or overlapping the study area and having sufficient image quality and resolution to allow gullies to be detected. MOC and HRSC data were chosen because they represent end-members in the resolution/areal coverage spectrum of currently available Mars imaging data sets that have sufficient resolution to identify gullies.

[23] For the MOC survey, the center latitude and longitude of the image and the orientation of any visible gullies were recorded (in one of eight 45° wide zones centered on north, northeast, east, etc., as for Costard et al. [2002, supplementary material] (available at [www.sciencemag.org/cgi/content/ful/1066698/DC1](http://www.sciencemag.org/cgi/content/ful/1066698/DC1)). In the HRSC survey the



**Figure 2.** Map of image coverage in this study. (a) Center points of all MOC NA images searched in this study. (b) HRSC image coverage for images used in this study. Longitude is given positive east.

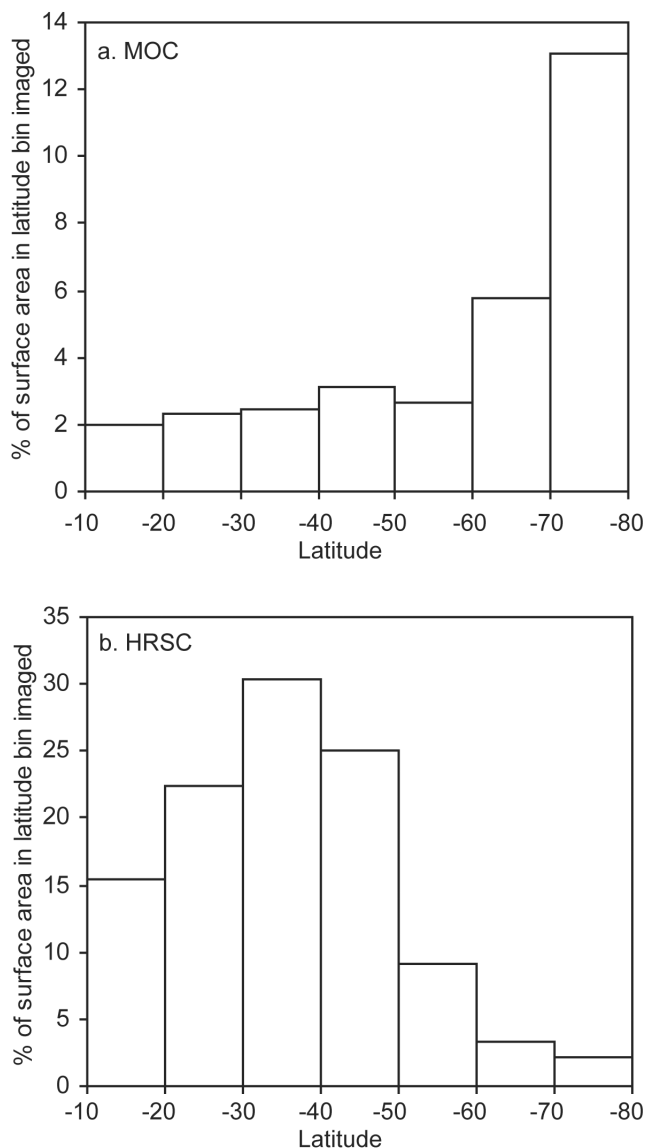
latitude and longitude of the head of the alcove and termination of the debris apron for each gully was recorded to allow location, orientation and length to be determined. For both surveys, the setting of the gullies was classed as either “impact crater rim inner wall”; “knob/hillslope”; “valley, fracture, or channel wall”; “pit wall”; “impact crater rim outer wall”; “impact crater central peak”; “isolated escarpment”; or “unknown” (“unknown” classifications occasionally occur in MOC images for which there is no context image and in which the gully is truncated by an image edge).

[24] The orientations and locations of gullies were recorded using slope sections, rather than by measuring all individual gullies. This was done to simplify the data collection process, to remove bias from areas with many gullies in a confined geographical area (e.g., valley walls), and also because smaller gullies cannot always be identified in HRSC data. We define a gullied slope section as being a continuous slope containing gullies that has a consistent orientation within one of the eight zones described above. Thus an impact crater gullied on all inner slopes would be recorded as having eight individual slope sections. For wider slopes such as valley walls or sections of very large crater walls, long slope sections were sometimes divided into several smaller ones on the basis of a maximum of six to ten gullies per slope section. For the MOC survey, where images contained more than one slope section with gullies, multiple orientation and latitude/longitude records were made for that image. Some MOC images contained up to

ten different gullied slope sections. For the HRSC survey, the geographic locations of the start (top of alcove) and finish (end of debris apron) point were measured for all the gullies in a slope section up to a maximum of about six individuals. If more gullies were present, or if some smaller examples could not be unambiguously identified, detailed measurements were made only for those that were clearest, and best represented the trend of the slope section. For each HRSC slope section, the orientation, latitude and longitude were then averaged from the geographic data and the mean orientation classified into one of the same eight zones as for the MOC survey. Some HRSC images examined contained up to several tens of gullied slope sections.

[25] Approximately 22,500 MOC NA images were searched for gullies (Figure 2a), an area of  $\sim 2$  million square kilometers. Three researchers (M. G., N. M., and M. B.) worked to search the MOC images and their results periodically checked against the others to ensure consistency. More than 760 images were found to contain gullies. Of these,  $\sim 145$  were excluded because they contained only gullies that had already been recorded from another image in the data set. This left  $\sim 615$  MOC NA images. In classifying which features were gullies we followed the description of *Malin and Edgett* [2000], who note that Martian gullies are distinct from granular mass wasting landforms found on the moon and the Earth in that they are formed by “fluid erosion” and are geologically very recent. The classification of a landform as a “gully” was therefore mostly based upon identification of a channel with





**Figure 3.** Percentile surface coverage of images used in (a) the MOC survey and (b) the HRSC survey. Percentages are calculated from the total area of all images within each bin divided by the total area in each latitude bin. Overlapping areas are not taken into account, so these values represent a slight overestimate of coverage.

the association of one or both of an alcove or depositional apron.

[26] In MOC NA images, the identification of gullies is usually unambiguous due to the high spatial resolution of the data (up to  $\sim 1.5$  m pixel<sup>-1</sup>) but some landforms with intermediate morphology between granular mass wasting deposits and recent Martian “gullies” have also been observed (Figures 1b, 1c, and 1d). We have not classified them as gullies. Also, we have not included dune face gullies [Mangold et al., 2003a] in the study as they have a distinct morphology (few alcoves or terminal deposits) and a specific setting (dune faces).

[27] We used the medium resolution nadir images for the HRSC survey of gullies rather than the super resolution data. At the time of writing, approximately 170 such images

were available that intersected the study area. Images that were corrupt, of poor quality, had central resolution poorer than 50 m pixel<sup>-1</sup>, or had only a very small section within the study area were excluded. This left 124 usable images with central resolution ranging between  $\sim 10$  and  $\sim 48$  m pixel<sup>-1</sup>; a total area of  $\sim 11$  million square kilometers. In contrast to the MOC coverage, there are few HRSC data at high latitudes (Figure 3) but at midlatitude the coverage is very high (nearly 30% of the surface area between  $-30^\circ$  and  $-40^\circ$  has been imaged).

[28] Although HRSC image resolution is approximately an order of magnitude lower than MOC, gullies are obvious in many images (e.g., Figure 4). However, positive identification of gullies in HRSC is sometimes difficult. Alcoves are recognizable in HRSC data by their wedge or teardrop shapes but often the channels are too small to resolve. In general, the depositional apron is the most difficult feature to make out in HRSC images. Therefore, unlike the MOC survey, the main indicator for gullies in HRSC data is from the presence of an alcove. Where possible, MOC data were used to confirm observations from HRSC and “calibrate” morphologies that represent gullies. Some gullies have very small or nonexistent alcoves [Malin and Edgett, 2000], and it is likely that this HRSC survey underrepresents this type of gully. Intermediate morphologies seen in MOC images and described above were also seen in HRSC data and again were not classified as gullies. For these reasons we have been very conservative in classifying features as gullies in the HRSC survey and have included only the most reliably identified examples as gullies.

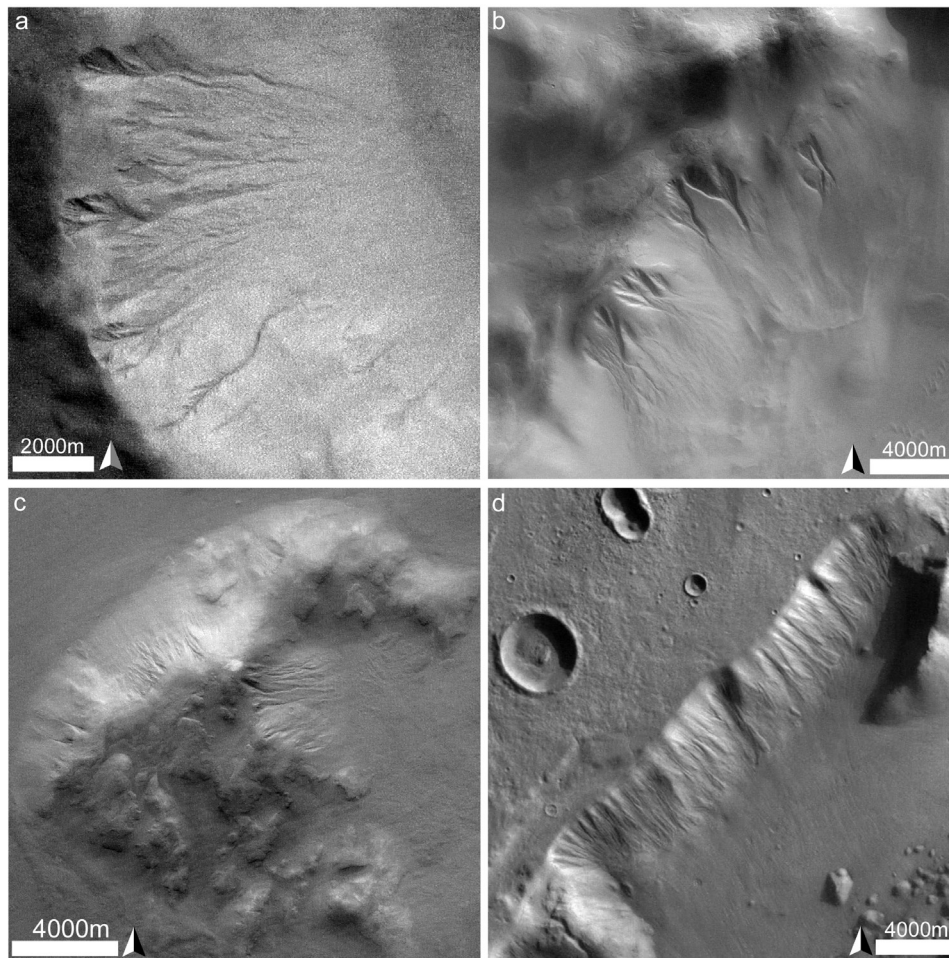
[29] In addition to the poorer resolution, identifying gullies in HRSC images is more difficult than in MOC NA data due to issues of illumination and contrast. First, although the MOC and HRSC nadir images used in this study are both eight bits (256 gray scales), these eight bits comprise a larger range of radiance for HRSC than MOC images. This is due to the large variations in illumination conditions in HRSC images caused by their extremely large latitudinal extents. This often means that a local area has poorer radiometric resolution in an HRSC image than the same area in a MOC image. Second, most of the HRSC images used in this study were taken in the morning when the solar incidence angle is low and shadows are long, compared to early afternoon for MOC (Figure 5). The combination of these two effects means that gullies are particularly difficult to identify in HRSC images on the northeast inner walls of impact craters and other southwest-facing slopes (Figure 6).

[30] In short, gullies are less likely to be identified in the HRSC than the MOC survey and it is likely that some gullies within HRSC images went unrecorded in our survey. However, HRSC images have the advantage of covering much larger areas individually and in total (Figure 3). This means that larger areas have been searched, that the complete gully is almost always visible in the image, and that larger craters and hills can be imaged completely without directional bias or slope sections being omitted.

#### 4. Results

[31] In total, 943 individual gully slopes were found from the MOC survey and 382 from HRSC. Although the MOC





**Figure 4.** Examples of gullies found in HRSC images. (a) Impact crater inner wall gullies; image is a part of HRSC image h0383\_0000 centered on  $-43.78^{\circ}$ ,  $322.63^{\circ}$ . (b) Impact crater inner wall; image is a part of HRSC image h0416\_0000 centered on  $-52.04^{\circ}$ ,  $304.79^{\circ}$ . (c) Knobs/hills gullies; image is a part of HRSC image h0155\_0000 centered on  $-47.25^{\circ}$ ,  $330.1^{\circ}$ . (d) Valley wall gullies; image is part of HRSC image h0528\_0000 centered on  $-33.86^{\circ}$ ,  $92.09^{\circ}$ .

survey covered approximately 5 times less area than the HRSC survey, more than twice as many slopes with gullies were identified; about 10 times fewer gullied slopes were found per square kilometer in HRSC than MOC. This is probably due to MOC images being often targeted at steep slopes (where gullies are likely to form) and also the HRSC survey missing smaller gullies.

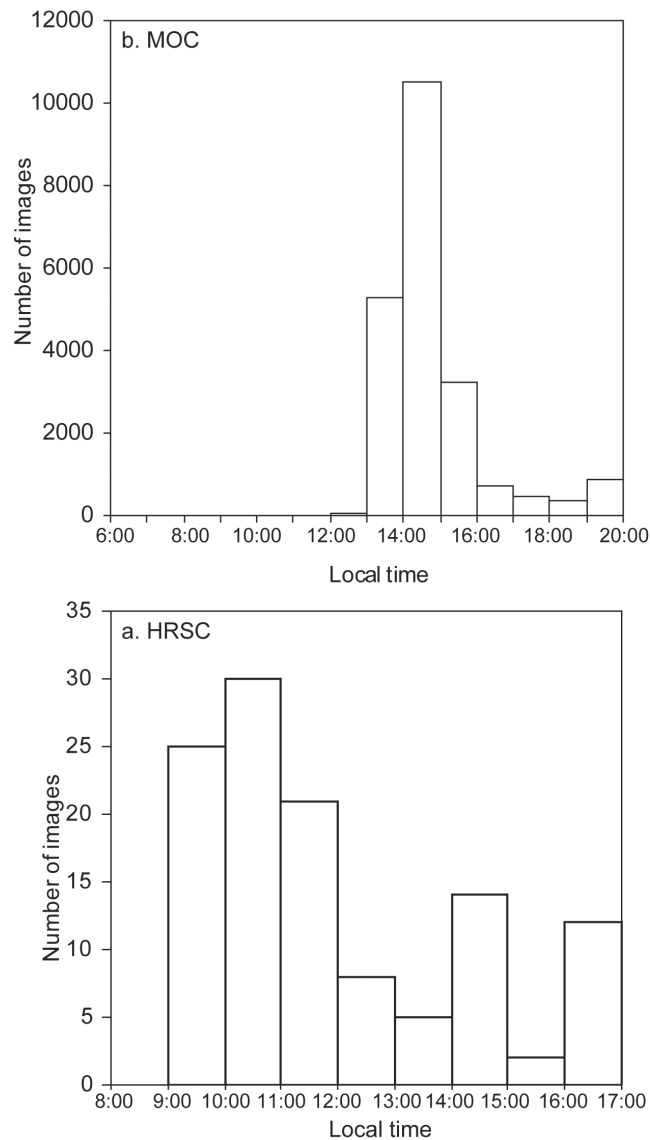
#### 4.1. MOC Survey

[32] The locations of all gullied slopes found in the MOC survey are shown in Figure 7a. Gullies are mainly found in a broad band encircling the planet between about  $-30^{\circ}$  and  $-50^{\circ}$ , but are most common between  $\sim 140$  to  $210^{\circ}$ E in the Terra Sirenum region. The low-lying regions of the Hellas Basin and Argyre Planitia notably lack gullies. Approximately 62% of gullied slopes were classified as “impact crater inner walls,”  $\sim 16\%$  as “pit walls,”  $\sim 10\%$  as “valley walls,” and  $\sim 10\%$  as “knob/hillslopes.” Very few gullies ( $\sim 1\%$ ) were classified in other groups (impact crater outer walls, impact crater central peaks, isolated escarpments, unknown context). These four dominant groups are referred

to from this point onwards simply as “impact crater,” “knobs/hills,” “valley walls” or “pit walls” gullies.

[33] Impact crater gullies are found throughout the study area. Knobs/hills gullies are the next most ubiquitous, but are predominantly found on and around the slopes of Argyre Planitia and in Gorgonum Chaos. There are other isolated examples throughout the study area. Pit wall gullies are common in the south of the area, mainly in Sysiphi Planum and, south of  $-60^{\circ}$ , pits are the most common context for gullies (pitted terrain is very common in the south of the study area). Gullies are also common in a ring of pits associated with a  $\sim 100$ -km-diameter crater in Noachis Terra (centered at  $-47^{\circ}5^{\circ}$ E; denoted “Xn crater” by Fenton [2005]). Valley wall gullies are most common in the large systems of Dao, Harmakhis, Niger, and Nirgal Valles, but are not present in similar contexts farther north such as the Samara, Ma’adim or Al-Qahira Valles. Additional valley wall gullies occur in troughs in Gorgonum Chaos. No gullies were found in the larger chasmata.

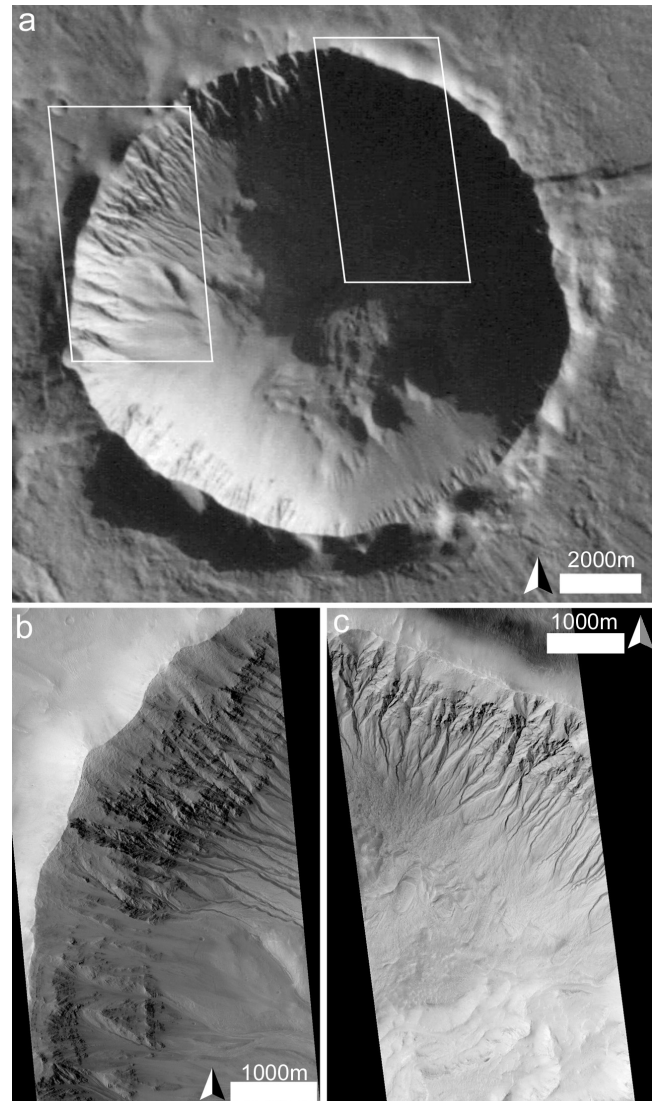
[34] The global orientations and distribution of gullies are summarized in Figure 8, which shows that for the southern hemisphere, there is a strong preference for gullies to face



**Figure 5.** Local times of images used in the (a) MOC survey and (b) HRSC survey.

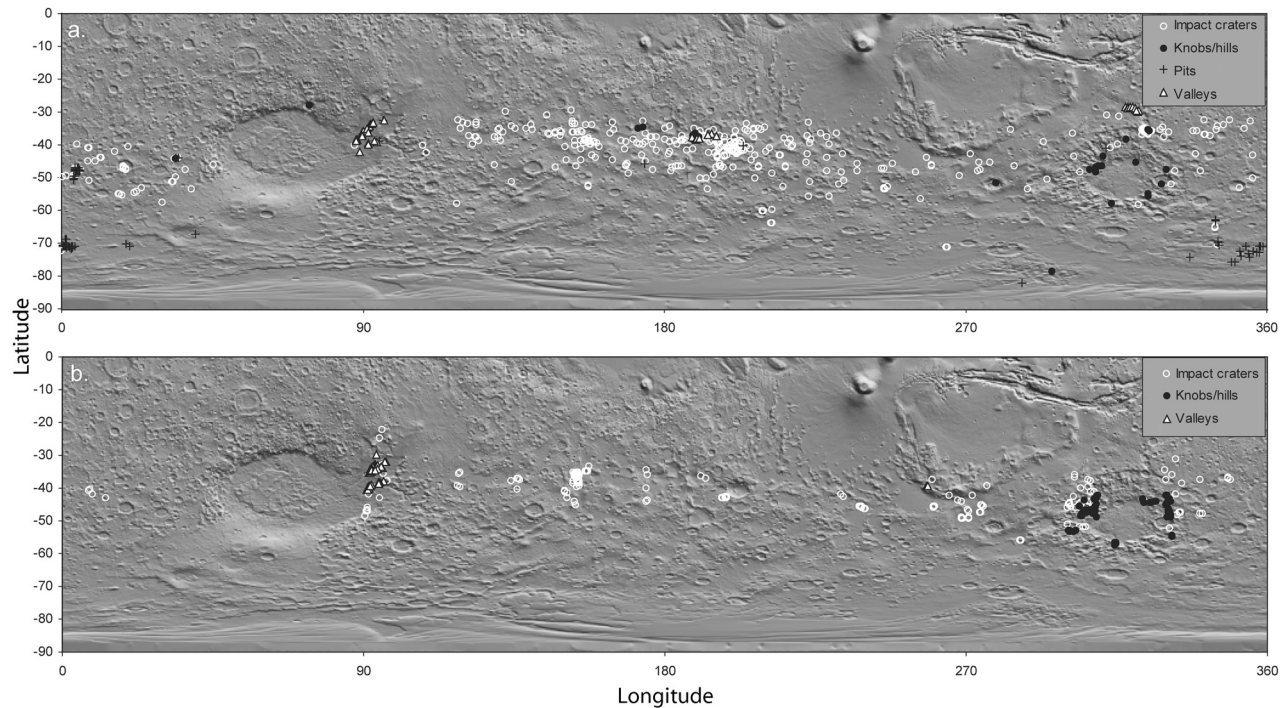
toward the pole: approximately 4 times more gullied slopes were found to face southwest, south or southeast than face northwest, north or northeast. Figure 8b (showing the numbers of gullied slopes observed, normalized by area to remove sampling bias) reveals that gullies are most common between  $-30^\circ$  and  $-40^\circ$ , and decrease in abundance toward the poles. The exception to this is that there are markedly more gullies between  $-70^\circ$  and  $-80^\circ$  than between  $-60^\circ$  and  $-70^\circ$ . Impact crater and knobs/hills gullies follow the trend of the whole population (Figures 8c–8f), except that there is no marked increase in gully abundance between  $-70^\circ$  and  $-80^\circ$ . Valley wall gullies (Figures 8g and 8h) differ in that there is a marked tendency for south- to southeast-facing slopes, and that gullies located between  $-20^\circ$  and  $-30^\circ$  make up a higher proportion of the total, and that there are almost no examples south of  $-40^\circ$ . Pit wall gullies (Figure 8i and 8j) are most common south of  $-70^\circ$  and between  $-40^\circ$  and  $-50^\circ$ , and display less of a tendency for pole-facing slopes than the other groups.

[35] The variation of orientation of gullied slopes with latitude is explored in Figures 9 and 10. Because impact crater gullies are most ubiquitous and because impact craters contain approximately equal areas of slopes facing in each direction (unlike knobs, valleys, pits, etc., which frequently have asymmetric slope distributions), the results are displayed both for all gullies in the survey (Figure 9) and for only impact crater gullies (Figure 10). Figure 9 shows that gullies are almost exclusively pole facing between  $-20^\circ$  and  $-40^\circ$  (although it should be noted that there are only 18 gullied slopes north of  $-30^\circ$  and most of these are valley wall gullies in Nirgal Vallis). Further south there is less preference



**Figure 6.** Example of gully slopes in both MOC and HRSC images. (a) Gullies are visible on southeast- and possibly south- and east-facing slope segments in the HRSC image but are not seen, even with image processing, on the southwest-facing slope section; part of HRSC image H0538\_0000 centered at  $-37.07^\circ$ ,  $191.98^\circ$ . Gullies are clearly visible in both (b) southeast- and (c) southwest-facing slope sections from MOC images. Figure 6b is part of MOC image R0801064, Figure 6c is part of MOC image E1301465.





**Figure 7.** Location of gullies from (a) MOC and (b) HRSC surveys.

in orientation (although in Figure 9e the sample population is low: only 17 slopes). The data in Figure 9f,  $-70^{\circ}$  to  $-80^{\circ}$ , are predominantly for pit gullies and show more random orientations. In Figure 10, only the data for  $-30^{\circ}$  to  $-60^{\circ}$  are shown because outside this region there are few impact crater gullies. Impact crater gullies are strongly pole facing in the midlatitude region between  $-30^{\circ}$  and  $-40^{\circ}$  (Figure 10a) but less so farther south (Figure 10b), and between  $-50^{\circ}$  and  $-60^{\circ}$  (Figure 10c), there is almost no dominant orientation.

#### 4.2. HRSC Survey

[36] The results of the MOC survey are supported by those from HRSC. Figure 7b shows a similar distribution of gullies, particularly in their latitudes. Although longitudinal coverage of HRSC (Figure 2b) is patchy, the preponderance of gullies in Terra Sirenum and the absence of gullies in Argyre Planitia and Hellas Basin are still obvious. No pit wall gullies were found in the HRSC survey, probably owing to the lack of coverage in the areas with pits. From HRSC,  $\sim 60\%$  of gullied slopes were classified as “impact crater,”  $\sim 16\%$  as “valley wall” and  $\sim 23\%$  as “knobs/hills.” More than 1% was classified as other contexts. Valley wall gullies were only identified in Dao, Niger and Harmakhis Valles and a few examples in an unnamed valley near Claritas Fossae. Note that Nirgal Vallis was not included in the image coverage. Knobs/hills gullies were found only in and around the walls of Argyre Planitia.

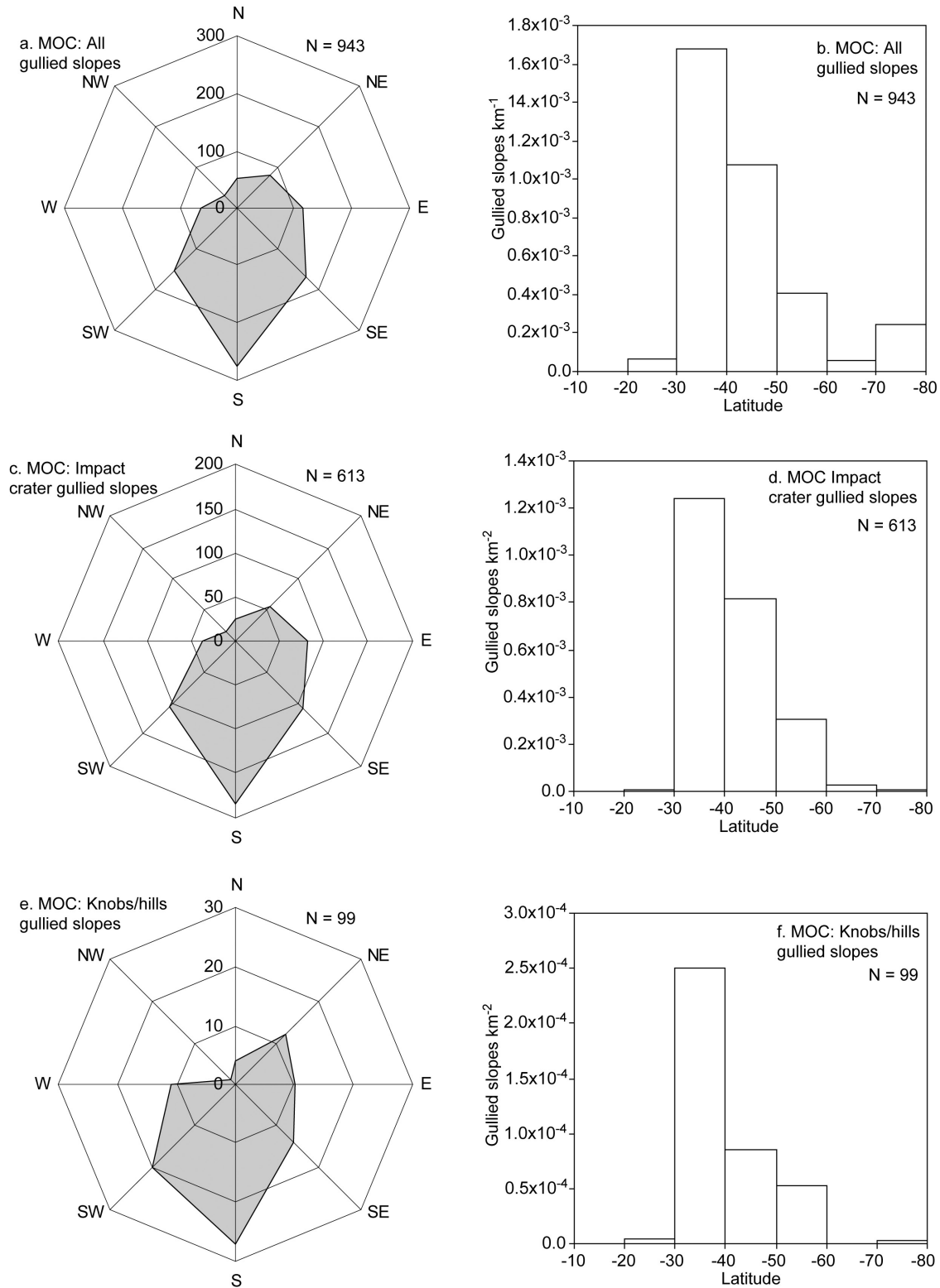
[37] Figure 11 shows the orientation, latitudinal distribution and length distribution of gullies found in HRSC images. Similar to the MOC survey, the HRSC data (Figure 11a) show that many more gullies occur on pole-facing slopes than equator-facing slopes (more than 5 times more gullied slopes face southwest, south or southeast than northwest, north or northeast), but in contrast to the MOC survey, by far the most

common orientation is southeast, rather than south. Again, similar to MOC, gullies are most often found between  $-30^{\circ}$  and  $-50^{\circ}$  although the proportion of gullies found between  $-40^{\circ}$  and  $-50^{\circ}$  is higher for HRSC than for MOC (Figure 11c). Unlike MOC (and almost certainly owing to the lack of pitted terrain in HRSC coverage), there are no gullies found south of  $-60^{\circ}$ .

[38] Impact crater gullies (Figures 12b, 12d, and 12f) have orientation, latitude and length distributions very similar to the entire gully population. Valley wall gullies (Figures 12g, 12i, and 12k) display a much stronger preference for southeast orientations than gullied slopes in other contexts. Similar to the MOC survey they are almost entirely found between  $-30^{\circ}$  and  $-40^{\circ}$ . Knobs/hills gullies (Figures 12h, 12j, and 12l) display the largest variety of orientations and their most common orientation is not southerly, but to the east. Knobs/hills gullies in HRSC data are concentrated between  $-40^{\circ}$  and  $-50^{\circ}$  latitude rather than between  $-30^{\circ}$  and  $-40^{\circ}$  as found for MOC.

[39] The lengths of  $>750$  individual gullies were measured in the HRSC survey. These data are shown in Figures 11e, 11f, 11k and 11l. Geometric mean lengths are shown in Table 1. Figure 11e reveals an approximately inverse relationship of frequency with length, except for gullies shorter than 1 km. The paucity of small gullies is probably due to image resolution rather than an actual characteristic of the population. Impact crater gullies have the shortest mean lengths; next are valley wall gullies, which have similar mean lengths to the population as a whole. Knobs/hills gullies are generally longer than those in other contexts, having a mean 50% longer than gullies in other contexts and a mode in the 2 to 3 km bin rather than the 1 to 2 km bin (Figure 11l). In addition, very few knobs/hills gullies have length  $<1$  km.





**Figure 8.** Results of MOC gully survey. Orientation and latitudinal distribution are shown for (a, b) all gullies, (c, d) only impact crater gullies, (e, f) only knobs/hills gullies, (g, h) only valley wall gullies, and (i, j) only pit wall gullies. Latitudinal results in terms of gullied slopes per km<sup>2</sup> were calculated by dividing the total number of gullied slopes found in each bin by the total area of MOC images searched in that bin. Again, overlapping images were not taken into consideration and so these data slightly underestimate the total amount of gullies slopes per km<sup>2</sup>.

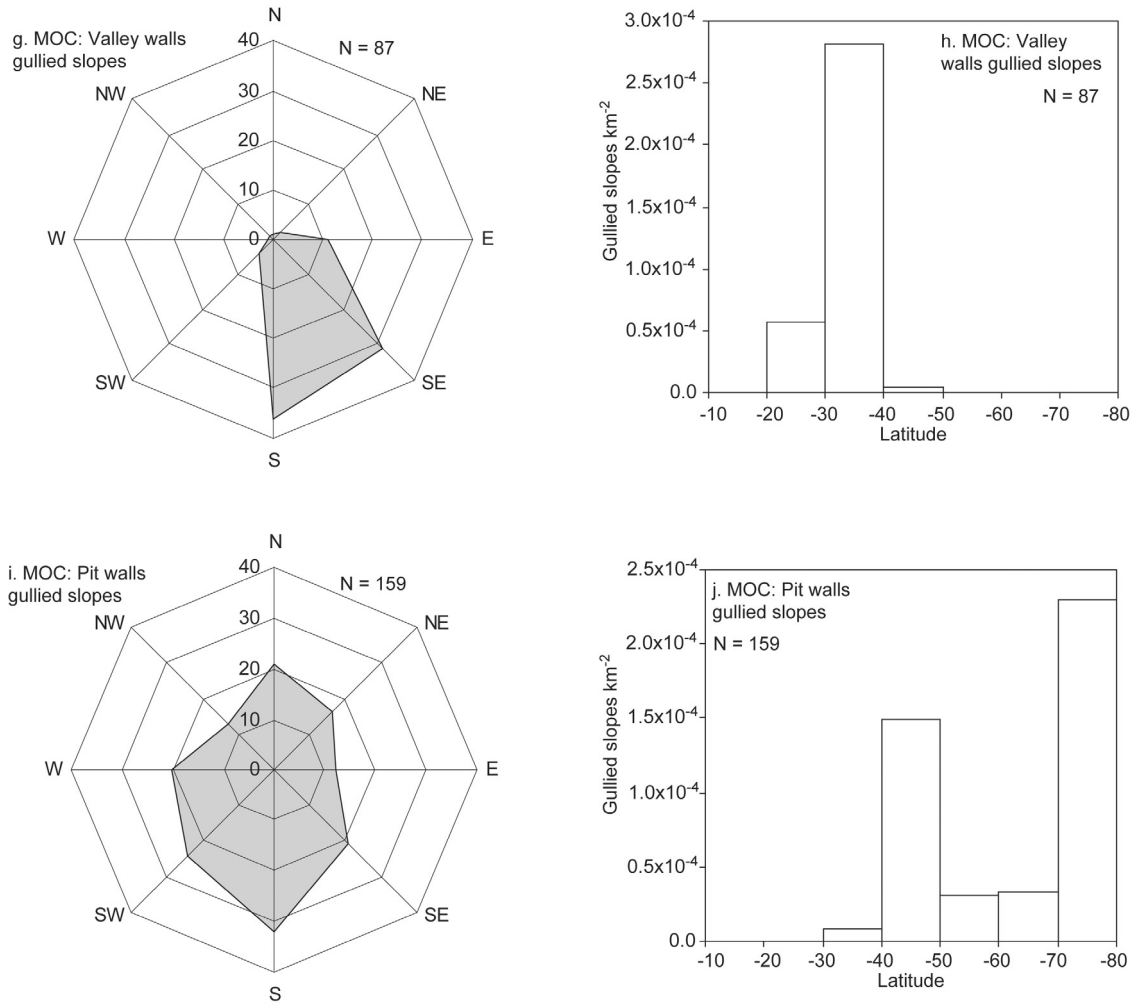


Figure 8. (continued)

[40] The latitudinal variations of gully orientation (Figure 12) are again similar to the MOC survey, although the latitudinal changes are less pronounced and the sample population smaller. There are less than 10 north-facing gullied slopes between  $-30^\circ$  and  $-40^\circ$  (Figure 12a) and almost none in impact craters (Figure 12b). This compares with nearly 150 pole-facing slopes at this latitude for all gullies and nearly 100 pole-facing slopes in impact craters. There is only a slight decline in pole-facing orientations from  $-30^\circ$  to  $-60^\circ$  for impact crater gullies (although Figure 12e is inconclusive as only seven slopes are represented), but when all contexts are considered there is a noticeable shift from strongly pole facing (Figure 12a) to a more diverse orientation distribution (Figure 12e) at higher latitudes.

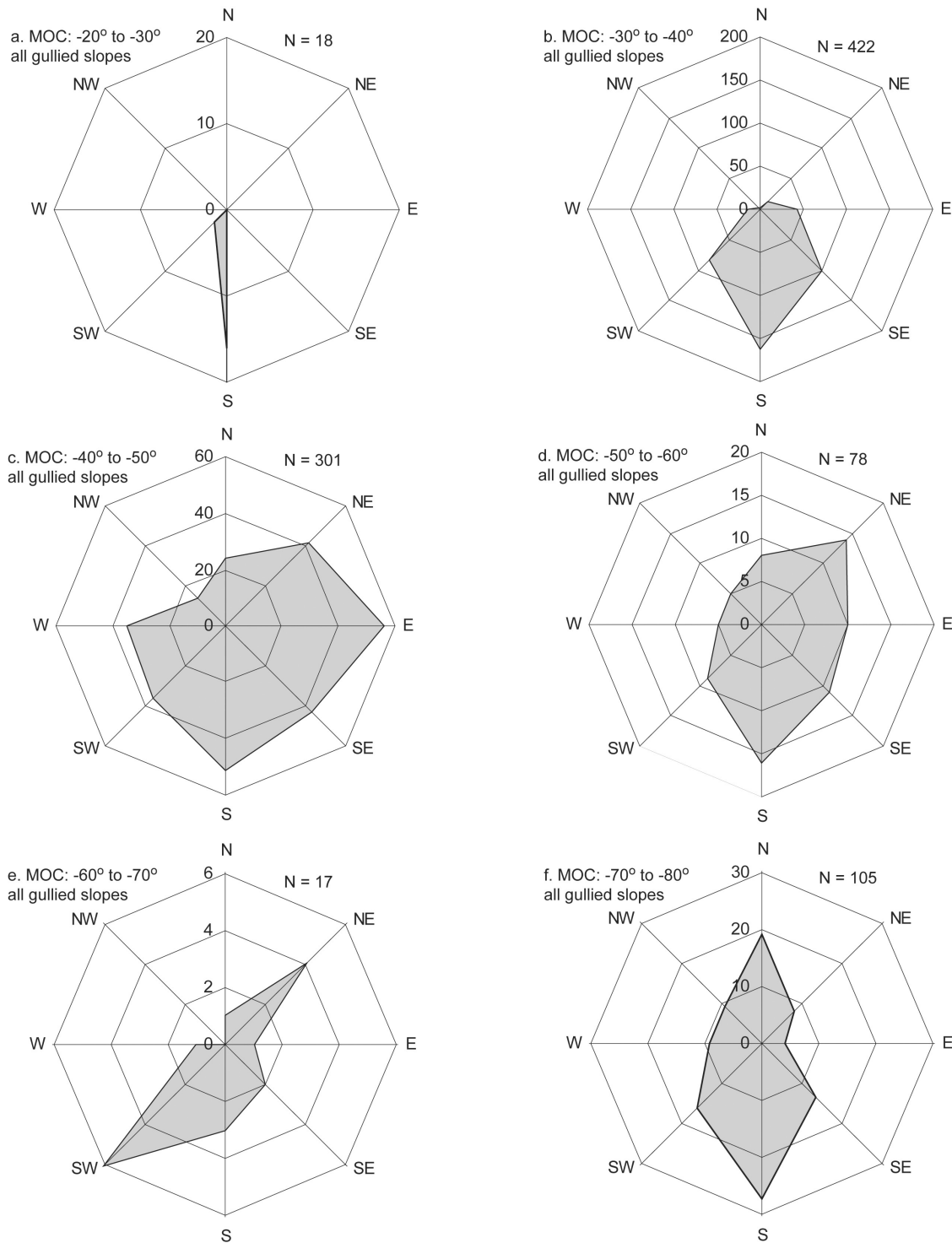
[41] In summary, both the MOC and HRSC data show that gullies have an overall preference for pole-facing slopes in the southern hemisphere. This is most pronounced north of  $-40^\circ$ ; at higher latitudes the orientations become more diverse. HRSC gully orientations are strongly skewed toward the southeast and northwest compared to MOC, probably owing to illumination effects and lower radiometric resolution in HRSC images as shown in Figure 6.

### 4.3. Regional Results

[42] In order to investigate regional variations in orientations, maps of mean orientations of gullied slope were produced from the MOC and HRSC surveys (Figures 13 and 14). One point on these maps represents the mean orientation of gullied sections within a sliding cell of a given diameter. The mean orientation is defined as the azimuth of the mean gully vector:

$$\vec{v} = \frac{1}{n} \sum_{i=1}^n \cos(\theta_i)\vec{x} + \sin(\theta_i)\vec{y}, \quad (1)$$

where  $n$  is the number of gullied sections within a cell,  $\theta_i$  is the azimuth of each gullied slope section within a cell, and  $x$  and  $y$  are the unit vectors in the north-south and east-west directions, respectively. For MOC, azimuths were given by one of the eight possible angles corresponding to the eight sections, as defined above. For HRSC, we used the azimuths obtained from the geographic measurements. We chose a cell diameter of 300 km. The size of the cell has been empirically optimized, and results from a compromise between the highest possible resolution of regional varia-



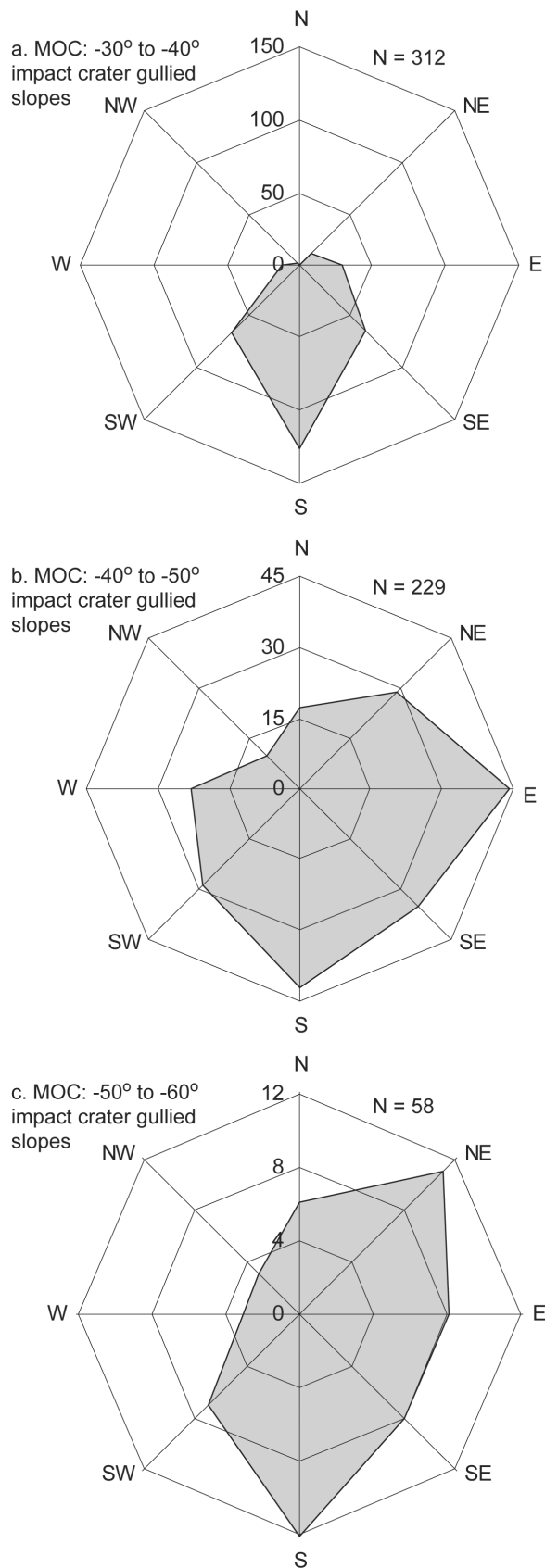
**Figure 9.** Orientation data for all gullied slopes from the MOC survey split by latitude. Note the poor sampling in Figures 9a ( $N = 18$ ) and 9e ( $N = 17$ ).

tions and the largest number of gullies within each cell to allow good statistics when averaging orientation. The interpolation step corresponds to the distance between each successive center of the sliding cell. The interpolation step must be less than the cell diameter and results from a compromise between the amount of smoothing of the map and the computation time. A value of 1 degree in longitude and latitude has been used. The standard deviations of the

azimuths within each cell are also presented as maps (Figures 13b and 14b) to indicate whether the mean orientations result from a clear trend within a given cell (low standard deviation) or from more random orientations (high standard deviation).

[43] Figures 13 and 14 confirm the results from the orientation histograms for the MOC and HRSC surveys in that south-facing gullied slopes dominate between  $-30^\circ$  and





**Figure 10.** Orientation data for only impact crater gullied slopes from the MOC survey. Only data for  $-30^{\circ}$  to  $-60^{\circ}$  are given because of the lack of gullies outside this region.

$-40^{\circ}$  but nearer the poles the orientations are more varied. There is little longitudinal variation of this latitudinal trend. Both MOC and HRSC data show very similar orientation trends and there is good agreement between Figures 13a and 14a. Note that the larger areal coverage of HRSC images results in fewer cells containing only one gullied slope (black pixels in Figures 13b and 14b) and these are therefore statistically more reliable, although illumination direction caveats described above must also be taken in to consideration.

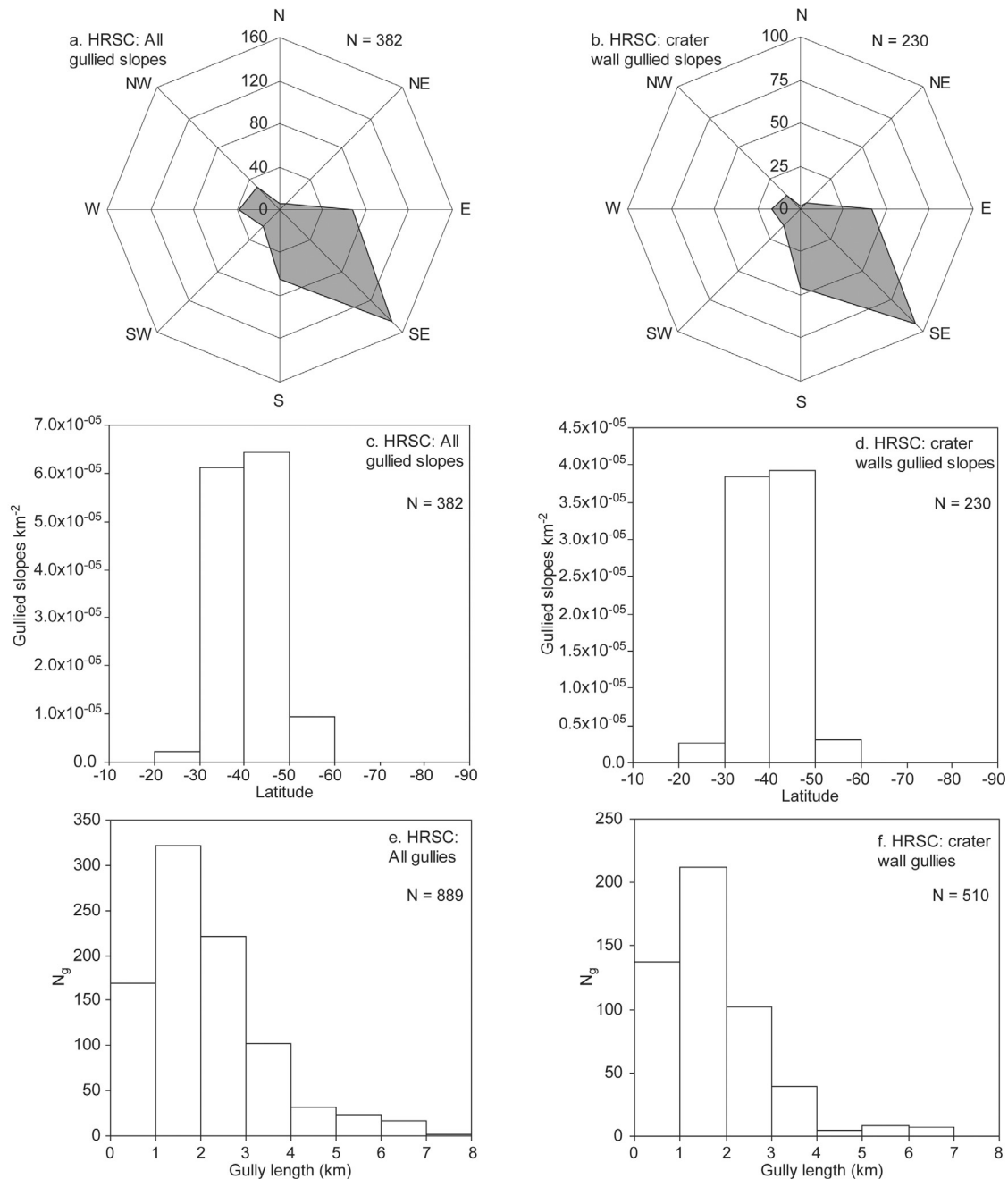
[44] Particularly noticeable in both MOC and HRSC data is a band of south-facing gullied slopes between  $-30^{\circ}$  and  $-45^{\circ}$  latitude that extends from  $\sim 135^{\circ}$  to  $\sim 230^{\circ}$  east longitude. In this region almost all the gullied slopes are south facing and have low standard deviation. There are few distinct cells with only north-facing gullied slopes and also low or medium standard deviation; most are associated with regions of high standard deviation (yellow to red in Figures 13b and 14b) or cells containing only one gullied slope and thus are either cells containing a range of orientations or isolated gullied slopes. One region of consistent north-facing gullies is the south and southeast slopes of Argyre Planitia that contains cells with north-facing mean orientation and low to medium standard deviation. Many of the gullied slopes in this region are classified as knobs/hills.

## 5. Discussion

[45] The HRSC and MOC surveys were very different in total areal coverage, individual image size, and the total number of images available, yet yielded consistent data for location and orientation of gullied slopes. This confirms that our results are reliable and suggests that similar results would be found if other data sets with intermediary resolution and coverage (e.g., Mars Odyssey THEMIS visible images) had been used. More gullies per  $\text{km}^2$  were found in the MOC survey than the HRSC survey, owing to the better spatial resolution and possibly targeting of MOC images at steep slopes. The one major discrepancy between our two data sets is the preponderance of southeast-facing gullied slopes in the HRSC survey compared to south-facing slopes in MOC, but this can readily be explained by differences in illumination angle and direction and radiometric resolution between MOC and HRSC images.

[46] The use of HRSC data allowed us to measure gully lengths without truncation of the gullies by the edge of the image. The mean gully lengths we observed are slightly larger than other studies of gully lengths [e.g., *Heldmann and Mellon, 2004*], and in addition we observed a substantial population of longer gullies up to  $\sim 7$  km in length that were not seen in previous studies that used only MOC data. This reinforces the utility of a multidata set, multiresolution approach in this kind of study.

[47] We observed an overall preference for pole-facing slopes for gullies in the southern hemisphere. In addition, at midlatitudes, almost all gullies are pole facing, but this preference becomes less marked at higher latitudes. South of  $-50^{\circ}$ , gully orientation is split almost equally between north- and south-facing slopes. Our results support previous observations from less extensive surveys of gully orientation [*Malin and Edgett, 2000; Costard et al., 2002; Forget et al., 2003; Heldmann and Mellon, 2004; Berman et al.,*



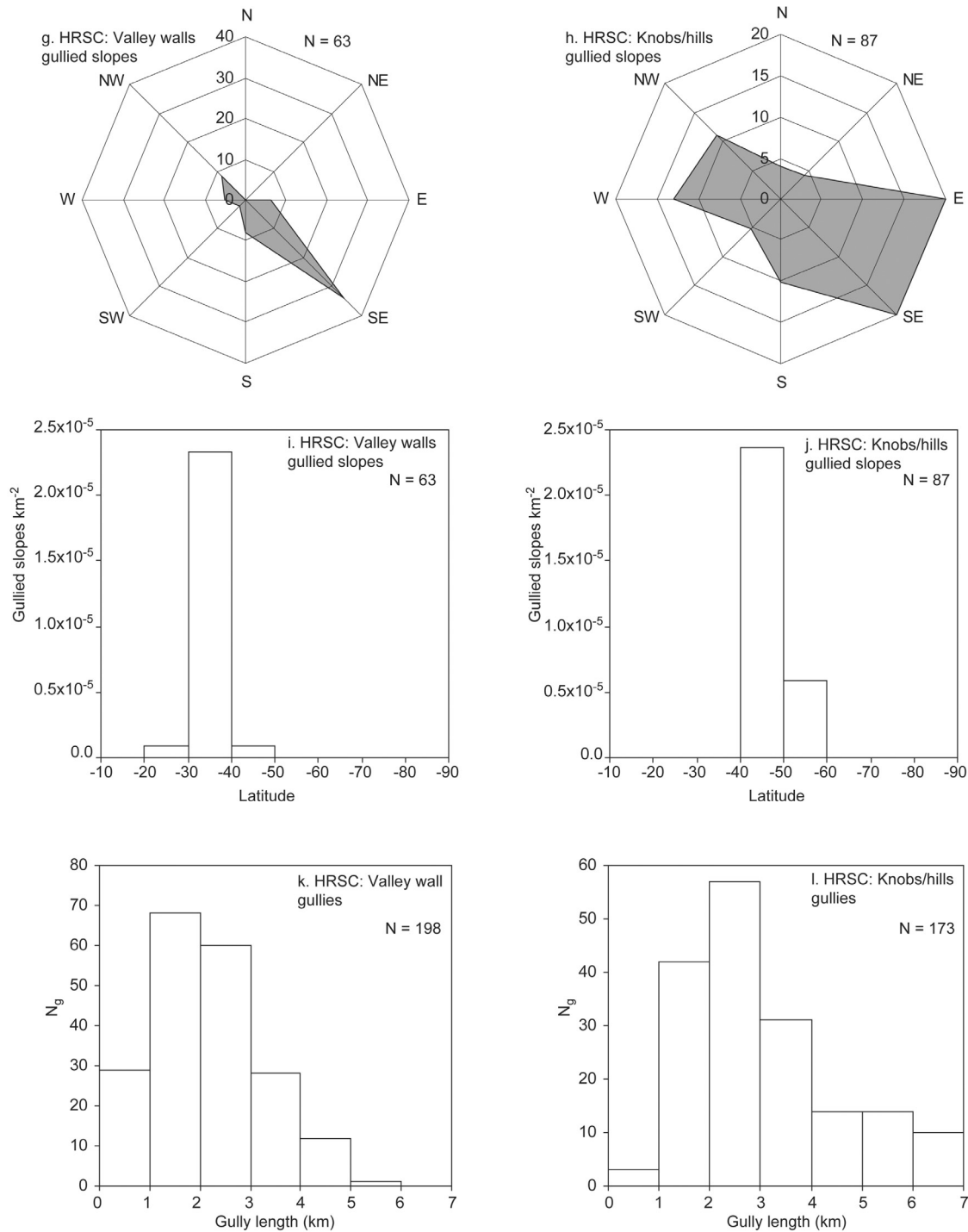
**Figure 11.** Results of HRSC survey. Orientation, latitudinal distribution, and length data are shown for (a, c, e) all gullies, (b, d, f) only impact crater gullies, (g, I, k) only valley wall gullies, and (h, j, l) only knobs/hills gullies. Latitudinal results are calculated as for Figure 8.

2005] but contrast with the work of *Edgett et al.* [2003], who found no orientation preference. The observed strong latitudinal trends and weak region-to-region variations emphasize the role of insolation and atmospheric conditions (temperature, pressure, etc.) in gully formation.

[48] Furthermore, we have found that  $\sim 10\%$  of gullied slopes in the MOC survey and  $>20\%$  in the HRSC survey occur on isolated knobs or hills. Together with previous observations of gullies emanating from isolated sites on crater walls and central peaks, our data strongly suggest that many gullies cannot have formed by groundwater processes; no substantial volumes of water can form in small and

topographically isolated aquifers. Taken together with the orientation data, these observations suggest an atmospheric, rather than subsurface, origin for the gully forming fluid.

[49] Using the data of Figures 7, 8, 10, 13, and 14 we can cross check orientations and gully contexts. Gullied slope orientation trends are broadly similar for impact craters, valleys and knobs/hills contexts. The population of pit wall gullies is distinct in that it contains slopes with a variety of orientations. We suggest two possible reasons to explain this: (1) These terrains are concentrated near the poles; thus similar to gullies in other contexts at these latitudes, they have no preferred orientation; and (2) slope orientations are

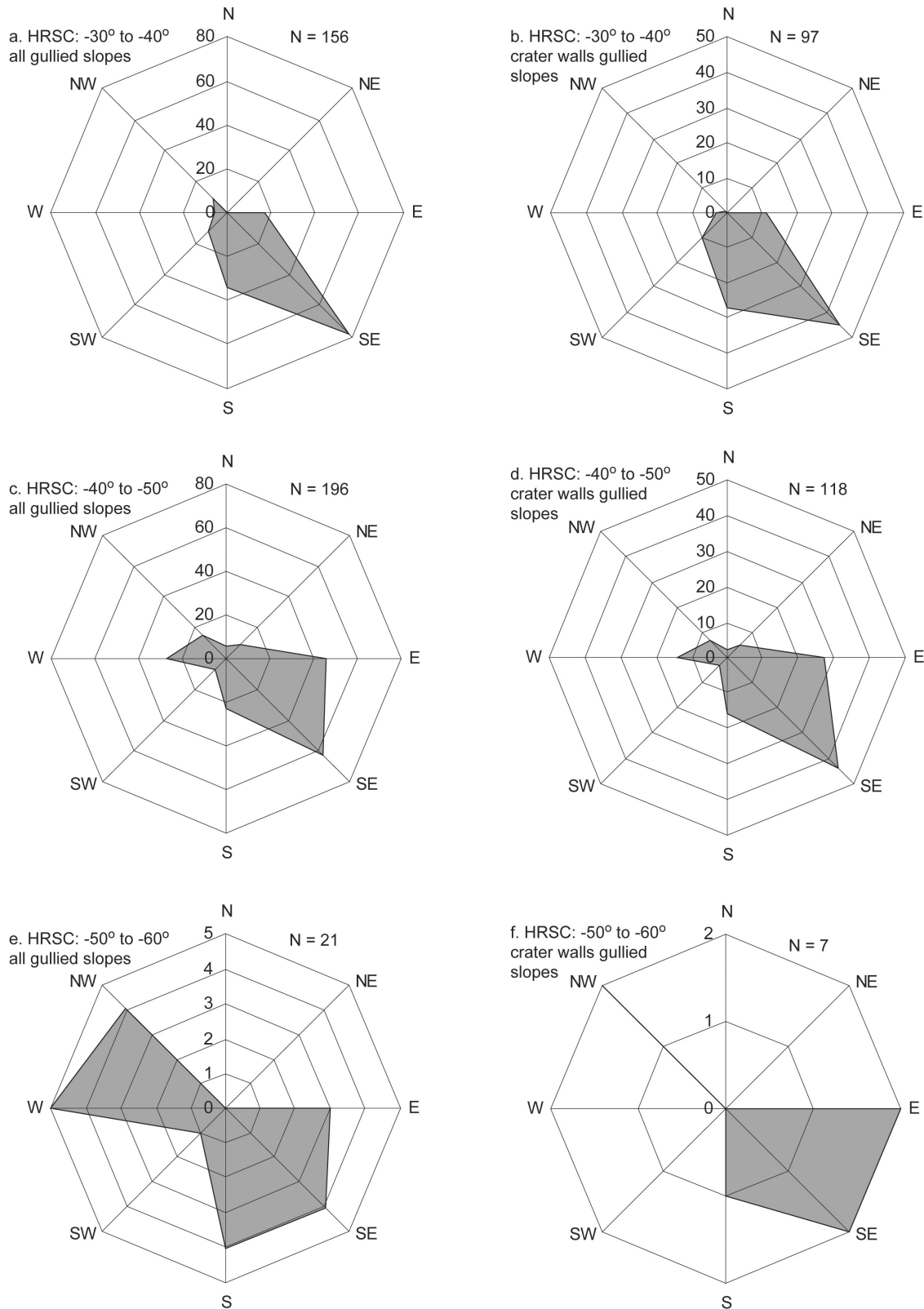


**Figure 11.** (continued)

not equally represented in pitted terrain, in contrast to impact crater walls. Knobs/hills gullies differ slightly from those in craters and on valley walls in that their lengths are greater and that (at least in the HRSC survey) they have a lesser tendency to form on south-facing slopes. Knobs/hills gullies are particularly common around Argyre Planitia, the southeast segment of which is the only area that appears to have consistently north-facing gullies. The orientation data are perhaps explained by nonuniform slope distributions on knobs and hills compared to impact craters, in the same way as pitted terrains described above. We also suggest that the

substantial topography of knobs and hills on the Argyre rim might explain why the gullies are longer here than those in impact craters. Furthermore, the observation that gully lengths are greatest on knobs/hills is inconsistent with an aquifer model for gullies as the longest gullies would be expected to form from the largest aquifers, and isolated knobs/hills are unlikely to hold large aquifers.

[50] Gullies are most common in a broad belt surrounding the planet between  $-30^\circ$  and  $-50^\circ$  but are almost completely absent in the topographically lowest regions in the study area (Argyre Planitia and Hellas Basin). There are few



**Figure 12.** Orientation data for (a, c, e) all gullied slopes and (b, d, f) only impact crater gullied slopes from the HRSC survey. Only data for  $-30^{\circ}$  to  $-60^{\circ}$  are given because of the lack of gullies outside this region.



**Table 1.** HRSC Survey Gully Lengths<sup>a</sup>

Context	N	$\bar{L}$ , km	$\sigma_L$ , km
All gullies	382	1.8	1.9
Impact craters	230	1.5	1.9
Knobs/hills	87	2.7	1.7
Valley walls	63	1.9	1.7

<sup>a</sup>N is number of gullies measured,  $\bar{L}$  is the geometric mean length, and  $\sigma_L$  is the geometric standard deviation on the gully length. Geometric rather than arithmetic means are used because the data have a nonnormal distribution.

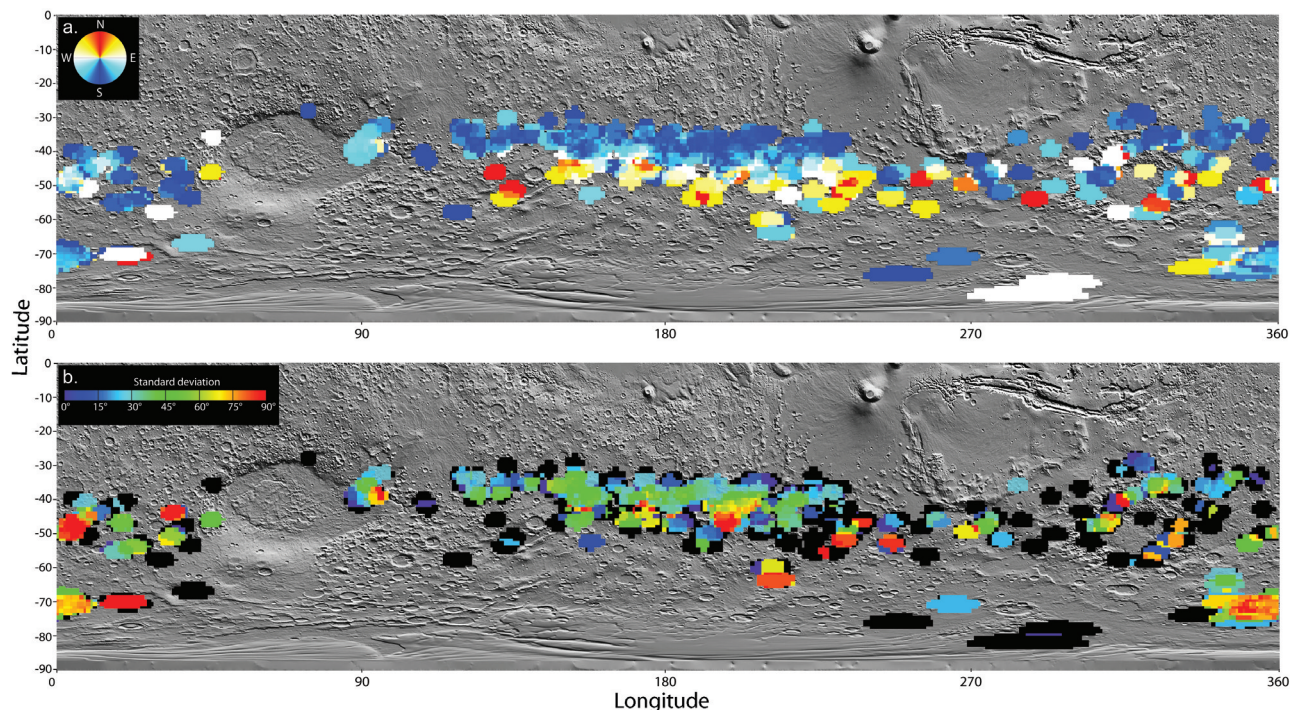
steep slopes in these regions, and this might be the controlling factor. It should also be noted, however, that the floors of these impact basins are among the most likely places for liquid water to be stable under current Martian atmospheric conditions [Haberle et al., 2001], yet no gullies are seen. This might imply that gully location is not affected by the stability of water under present-day conditions. In contrast, Heldmann et al. [2005b] suggest that the short lengths of gullies argue for formation under present-day conditions. However, their survey used only MOC NA images, and this work, utilizing HRSC data, finds evidence for much longer gullies, arguing against formation of gullies by subaerial transport of pure liquid water under present-day atmospheric conditions.

[51] The latitudinal range in which most gullies occur corresponds to a region in which north-facing slopes are systematically steeper than south-facing ones [Kreslavsky and Head, 2003]. Our observation that almost all gullies in this region are pole-facing supports the suggestion of

Kreslavsky and Head [2003] that this slope asymmetry is caused by the erosion of pole-facing slopes by gully formation. A weakness of this model might be that gullies are not observed on all pole-facing slopes. This might be explained, however, by repeated episodes of gully formation throughout Mars' history. Many of the pole-facing slopes might have hosted gullies and become shallow tens of millions of years before the present, and all traces of gullies might now be erased.

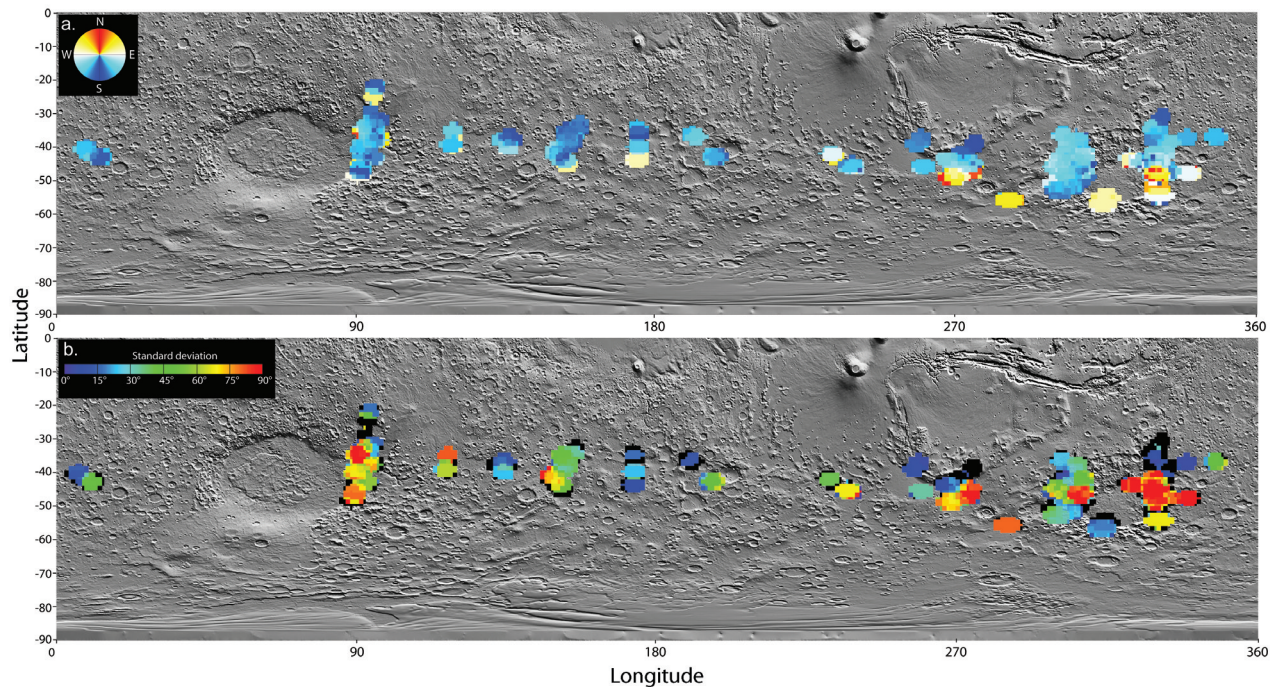
[52] The lack of gullies south of  $-50^\circ$  spatially coincides with a general decrease in roughness of the typical topography at subkilometer scale [Kreslavsky and Head, 2000], possibly caused by repeated removal and deposition of thick water ice-rich mantles [Kreslavsky and Head, 2002]. There is also an absence of steep slopes at high latitudes [Kreslavsky and Head, 2003], and these two effects together suppress gully formation in this region. These observations, together with observations that gullies are predominantly pole facing at midlatitudes, reinforce the point that while steep slopes seem necessary for gully formation, they are not necessarily sufficient, and there is clearly a hierarchy of controlling factors for gully formation.

[53] The latitude range with most gullies is coincident with that of dissected terrain [Mustard et al., 2001] thought to represent degradation of water ice-rich material deposited during Mars' most recent major obliquity excursion. As this region likely contained both material rich in near-surface ice and steep slopes in the geologically recent past (or even in the present), the observations support formation models in which these are prerequisites for gully formation [e.g., Costard et al., 2002; Christensen, 2003].



**Figure 13.** Map of (a) orientation data and (b) standard deviation of orientation for gullies found in the MOC survey. Black areas in Figure 13b represent images with only one gully slope for which standard deviation cannot be calculated. Note that the cells appear larger in the south owing to deformation caused by the cylindrical map projection.





**Figure 14.** Map of (a) orientation data and (b) standard deviation of orientation for gullies found in the HRSC survey. Black areas in Figure 14b represent images with only one gully slope for which standard deviation cannot be calculated. Note that the cells appear larger in the south owing to deformation caused by the cylindrical map projection.

[54] Our observations of a lack of gullies north of  $-30^\circ$ , pole-facing gullies between  $-30^\circ$  and  $-50^\circ$ , and gullies with more diverse orientations south of  $-50^\circ$  are consistent with the model of gully formation by the action of debris flows due to melting of near-surface ground ice at high obliquity [Costard *et al.*, 2002]. This model calculates temperatures from insolation at different obliquity, latitudes and slopes using a Global Climate Model (GCM). The model predicts the occurrence of seasonal thaw at summer solstice for pole-facing slopes in regions of latitude higher than  $30^\circ$  and obliquity higher than  $33^\circ$ . Equator-facing slopes at midlatitudes or equatorial latitudes do not reach  $0^\circ\text{C}$  for any obliquity. In this model, the poleward preference is due to the fact that for several days at the summer solstice during high obliquity periods, the Sun will be high in the sky facing only the polar slopes, thus generating a deepening of the thawed layers in the ground. The distribution of gullies therefore fits the predicted distribution of ground thaw if any ice is present at or near the surface.

[55] Alternatively, these observations are also consistent with a gully formation mechanism governed by the behavior of  $\text{CO}_2$  frost deposition (perhaps  $\text{CO}_2$  supported debris flows or protection from melting of near-surface ground ice by  $\text{CO}_2$  frost followed by sudden heating). For example, the maximum northern extent of the south polar frost cap is  $\sim 55^\circ\text{S}$  and is annually repeatable under present conditions [James *et al.*, 1992, 2001; Benson and James, 2005]. During winter,  $\text{CO}_2$  is deposited on both north- and south-facing slopes in this region. However, recent observations [Schorghofer and Edgett, 2006] and models [Ishii and Sasaki, 2004] show that  $\text{CO}_2$  can also be deposited as far north as  $\sim 30^\circ\text{S}$  on pole-facing slopes under current winter conditions. Thus a consistent  $\text{CO}_2$ -based hypothesis for

gully formation might be that (1) a lack of steep slopes at high latitudes leads to a paucity of gullies at high latitudes; (2) poleward-facing-only deposits of  $\text{CO}_2$  at midlatitudes explain the gully observations between  $-30^\circ$  and  $-50^\circ$ ; and (3) the heterogeneous orientation of the few gullies found at high latitudes are explained by  $\text{CO}_2$  forming on slopes that face in all directions.

## 6. Conclusions

[56] 1. The close agreement in the orientation and latitude data between the MOC and HRSC surveys suggests that our data are reliable. This also suggests that no significant improvements in the data would be obtained through the use of intermediate resolution data. The major discrepancies between the two sets of results are the offset orientations and the reduced number of gullies observed in HRSC compared to MOC, but these are explained by differences in illumination conditions and data resolution.

[57] 2. Measurements from HRSC data reveal that gullies up to a few kilometers in length are common. In addition, larger gullies up to  $\sim 7$  km in length are also observed. The lengths of these gullies argue against their being formed as flows of pure water under present-day conditions.

[58] 3. Observations that 10–20% of gullies occur on isolated knobs and hills are difficult to reconcile with formation from groundwater sources, as any aquifer would be isolated and small. The same conclusion is drawn from observations of gullies starting near the top of impact crater walls.

[59] 4. Gullies in the Martian southern hemisphere are most common in a midlatitude band ( $-30^\circ$  to  $-50^\circ$ ) but are not found in the low lying areas of the Hellas Basin or

Argyre Planitia. They are also fairly common in pitted terrain in the far south. Gullies at midlatitudes have a predominantly pole-facing orientation, but farther south there is little preference for orientation. This latitudinal dependence of orientation and abundance suggests both slope distribution and climate are key controls in gully formation.

[60] 5. The observations reinforce the role of insolation and atmospheric conditions in gully formation. The observations are most consistent with the primary source of the channel forming fluid being atmospheric rather than sub-surface. We suggest that gully formation depends on (1) the presence of steep slopes, (2) the stability of water and/or CO<sub>2</sub> at the surface and near-surface, and (3) changes in insolation and/or atmospheric pressure, humidity and temperature due to variation in obliquity.

[61] **Acknowledgments.** The authors acknowledge the use of Mars Orbiter Camera images processed by Malin Space Science Systems that are available at [http://www.msss.com/moc\\_gallery/](http://www.msss.com/moc_gallery/) and the HRSC Experiment Team of the German Aerospace Center (DLR) Berlin, who provided map = projected HRSC image data. We thank the HRSC Experiment Teams at DLR Berlin and Freie Universitaet Berlin as well as the Mars Express Project Teams at ESTEC and ESOC for their successful planning and acquisition of data as well as for making the processed data available to the HRSC Team. We acknowledge the efforts of the HRSC Co-Investigator Team members and their associates who have contributed to this investigation in the preparatory phase and in scientific discussions within the team. This work was supported by the Programme National de Planétologie and by the European Community's Improving Human Potential Program under contract RTN2-2001-00414, MAGE.

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