New Slope-Normalised Global Gully Density and Orientation Maps for Mars

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Abstract

We re-analyse the global distribution of gullies in order to provide a set of observational constraints that models of gully formation must explain. We validate our results derived from the global data with four detailed case-studies. We show that the availability of steep slopes is an essential factor to consider when assessing the spatial distribution and abundance of gullies. When availability of steep slopes is taken into account it reveals, with a few exceptions, that gullies are found almost uniformly across the whole 30-90° latitude band. Our analysis also reveals that massive ice deposits are anti-correlated with gullies, and that the undulations in the equatorward limits of the gully distribution could be explained by longitudinal variations in maximum surface temperatures (controlled by variation in surface properties including thermal inertia, and albedo). We find a sharp transition in both hemispheres between pole-facing gullies, which extend from 30° to 40° to a more mixed, but dominantly equator-facing orientation of gullies poleward of 40°. We have no definitive explanation for this transition, but based on previous studies we suggest it could be linked to the availability of near-surface ice deposits.

Kilometre-scale gullies are found ubiquitously on steep slopes at the mid-latitudes of Mars (e.g., Balme *et al.*, 2006; Dickson *et al.*, 2007; Heldmann *et al.*, 2005; Kneissl *et al.*, 2010). They formed within the last few millions of years (Johnsson *et al.*, 2014; Reiss *et al.*, 2004; Schon *et al.*, 2009a) and resemble water-carved gullies on Earth (Malin and Edgett, 2000). Martian gullies are defined as features comprised of an alcove, channel and debris apron (Malin and Edgett, 2000) and are found on crater walls, knobs, valley walls and sand dunes (e.g., Balme *et al.*, 2006). The distribution of gullies has a clear latitude dependence: they are very rare and maybe even absent altogether, in the equatorial latitudes between 30°N and 30°S and they are extremely common at latitudes around 35°N and S, with the number of gullies observed dropping off towards the poles (e.g., Dickson *et al.*, 2007). It is known that the frequency of steep slopes generally decreases towards the poles (Kreslavsky *et al.*, 2008; Kreslavsky and Head, 2000), which is thought to be partly due to the presence of a draping deposit that mutes the topographic relief at scales of tens to hundreds of metres. The general decrease of gully density from the mid-latitudes to the poles is thought to be partly explained by the decrease in the number of steep slopes (Dickson *et al.*, 2007). However, this has not been quantitatively assessed. In addition, the orientation of gullies is dependent on latitude: at the mid-latitudes gullies tend to face the pole and at high latitudes they have less preference, but some studies have found an equator-facing preference (Bridges and Lackner, 2006; Heldmann *et al.*, 2007).

Together, the latitudinal trends in gully orientation and density suggest an insolation, or climatic, factor is acting in their formation (Costard *et al.*, 2002). However, in order to be able to test different models of gully formation, reliable and precise data are needed on the slope-angle, slope-orientation and latitudinal distribution of gullies.

Here we undertake a re-analysis of the global gully dataset recently published by Harrison *et al.* (2015) in order to quantify the effect of slope, orientation and latitude on gully density. We complement this with similar analyses performed on a more detailed dataset in four regions of interest. The second analysis is performed in order to verify the results derived from the global data.

Approach

Global data reanalysis

The global gully dataset compiled by Harrison *et al.* (2015) comprises a series of points placed on features which host gullies. Each point is attributed with a dominant orientation. We perform the following three analyses: gully density, gully density normalized by steep slopes, and a N-S orientation analysis. In all cases we use the standard MOLA 128ppd gridded product, which has a simple cylindrical projection on a spherical Mars datum (radius 3396 km). In order to calculate gully density, we use a 250 km x 250 km moving window and sum the number of gully points in this window for each pixel. We then take account of the distortion of area caused by the map projection, by dividing this by the true area of the moving window, to produce a number of gully points per km^2 (Fig. 1a). Note that, because of the nature of the original mapping, this method of quantifying gully density does not take into account the density/extent of the gully-features themselves, but rather the features that host them. In some cases this may lead to a single gully being given the same "weight" as an extensive suite of gullies. To generate the slope-normalized gully density, instead of dividing by the true area of the moving window, we divide by the area covered by "steep" pixels in the moving window (Fig. 1b). We define "steep" as being pixels with greater than 20° slope. In order to correct for the influence of the projection in the slope calculation, the fractional slope (S_m) is first calculated in a conformal Mercator projection. These data are then re-projected into the initial simple cylindrical projection and then corrected as follows: $180/\pi \operatorname{atan}(S_m / \cos(L))$, where L is the latitude. The number of pixels with slopes greater than or equal to 20° is then counted per 250 km x 250 km moving window; this count is weighted to take account of the projection, therefore compensating for over-counting towards the pole. Each count is then multiplied by the true area of a pixel for that latitude.

Finally, we calculate the ratio between the frequency of pole-facing gullies and the summed frequency of pole- and equator-facing gullies for a 250 km x 250 km moving window in order to better visualize the global trends in gully orientation (Fig. 1c).

Regional site analyses

Gully slopes are mapped as polygons using ArcGIS and the Java Mission-planning and Analysis for Remote Sensing (JMARS) software package (Christensen *et al.*, 2009) (Fig. 2). The base layer is generated principally by using the Mars Reconnaissance Context camera (CTX) images at 6 m/pix. Where there is no CTX coverage, poor CTX image quality or deep shadows on slopes, we use the Mars Express High Resolution Stereo Camera (HRSC) at 12.5 m/pix and Mars Odyssey's Thermal Emission Imaging Spectrometer visual images (THEMIS-VIS) at 18 m/pix. The detail of the mapped polygon outlines is simplified to the 100 m-scale, because the aim was to sample the underlying Mars Orbiter Laser Altimeter (MOLA) elevation data, which have a grid-spacing of ~463 m.

The MOLA data are projected into a Lambert Conformal Conic projection with standard parallels of 34°S/N and 56°S/N and a centre latitude of 45°S/N preserving the pixel size of 463 m. For Terra Cimmeria a central meridian of 154°E is used, 43°W for the two Argyre sites and 15°W for Acidalia Planitia. We split the Argyre region into two sites along the 42.4°E longitude line, to allow us to compare sites with similar spatial extents. We derive slope and aspect from the reprojected MOLA data and then use the polygons to define pixels that contain or do not contain gullies. We considered using the raw MOLA point data to derive slope and aspect. However, erroneous tracks have not been adjusted/removed from this dataset (see discussions in: Neumann *et al.*, 2001; Smith *et al.*, 2001; Som, 2008) and such erroneous tracks cause topographic steps, which are exaggerated in derivative data-products. These discontinuities would be more detrimental to our results than the inclusion of interpolated pixels present in the gridded data. In our Lambert Conformal Conic projection the maximum linear distortion is found at 45° latitude, where it is < 2%, resulting in up to ±0.5° error in slope at slope of 45° and ±0.2° at 10°. This linear distortion results in the real areal extent of a pixel varying by up to 2% of the nominal 214 369 m^2 value and hence the calculated pixel densities having an uncertainty of the same magnitude.

Results

Gully density

The global gully density map in Fig. 1a reinforces the observations reported in other works, most recently Harrison *et al.* (2015). In brief, gullies begin to be visible poleward of ~30-35° in both hemispheres, with the highest densities being found in the southern hemisphere at ~35°S in Promethei Terra, Terra Sirenum and Terra Cimmeria, at ~45° around the rim of the Argyre Basin and high-latitude outliers at ~70-80°S in the south polar pits (Sisyphi Cavi and Cavi Angusti). For latitudes above 30˚, gully density has an inverse relationship with latitude, *i.e.* gully density tends to decline towards the poles. Densities range up to 19 gully sites per 100 km^2 with a mean of 0.64.

The global trends noted above are supported by our regional studies. The percentage of pixels occupied by gullies in each of the study sites divided up by latitude is shown in Fig. 3a and has a maximum value of 1.4%. Gullied slopes are concentrated in a band between 30° and 55° in the Terra Cimmeria (in the southern hemisphere) and Acidalia Planitia (in the northern hemisphere) sites. In the west Argyre site they are found between 35 and 60°S; by contrast, they are found across a wider latitudinal band from 30°S to 60°S in the east Argyre site. The peak in density in Terra Cimmeria (incidentally coinciding with the Newton Basin) lies in the 35-40°S bin and is consistent with the peak in density in the published data from the southern hemisphere study of Heldmann and Mellon (2004). They found that gully density peaked between 33-36°S, where density was measured as the fraction of MOC (Mars Orbiter Camera) narrow-angle (>1.4 m/pix) images containing clear evidence of gullies. However, at the two Argyre sites the peak in gully density lies within the 45-50°S interval, with a particularly large peak in the west Argyre site located in the western Nereidum Montes, the area studied by Raack *et al.* (2012). Here, the highest regional density of gullied slopes is found. Gullies are of universally low density across the Acidalia Planitia site.

Gully density on steep slopes

We know that gullies only occur on slopes, because they are formed by gravitational transport, hence a better comparison of gully density is necessary to consider gully density on only sloping terrain – this is shown for our global data in Fig. 1b and for our regional data in Fig. 3b.

Compared to the simple density map in Fig. 1a, the slope-normalized-density-map does not show such clear latitudinally distinct regions of gully concentration. Zones with high density are more evenly scattered across the whole distribution. Gullies tend to be denser towards the higher latitudinal limits of their distribution, rather than the mid-latitudes as suggested by the non-normalized data. Densities on steep slopes range up to 1 million gully sites per 100 km^2, which is a result of gully sites present in zones with very small areas of steep slopes. The mean density is 940 gully sites per 100 km^2 of steeply sloping terrain.

For our regional sites, when the frequency of gullies per latitude is considered in terms of the percentage of pixels with slope-values ≥20° occupied by gullies, instead of simple frequency, the sites now have more similar densities to one another, as suggested by the global data. The percent of pixels occupied by gullies now extends up to ~30%. Most notably the

Acidalia Planitia site now has similar densities to the other three sites and it is now this site which possesses the overall highest density. The gully density is almost uniformly high between 40°S and 55°S in Terra Cimmeria, with both the Argyre sites having similar densities to Terra Cimmeria in the interval 45-50°S. The West Argyre site no longer has an unusually high density compared to the other sites, but does retain a significant peak associated with the western Nereidum Montes. In the 35-45°S interval in both Argyre sites there is a lower density of slopes with gullies compared to both Terra Cimmeria and the global trends. West Argyre, Terra Cimmeria and Acidalia Planitia have peaks in density in the 45-50° latitude interval. The previously published global trends in gully density no longer match very well with any of our regional datasets (Fig. 3b).

Gully orientation

Our global analysis of the ratio of poleward-to-equatorward-facing gully sites agrees in general with previous work (Balme *et al.*, 2006; Dickson *et al.*, 2007; Heldmann and Mellon, 2004; Kneissl *et al.*, 2010), but reveals a sharp transition between pole-facing only gully sites to dominantly equator-facing sites at ~40°. At latitudes equatorward of 40° almost all gully sites have a poleward facing preference, with some exceptions on the northern rim of Hellas and in the northern hemisphere. In contrast, at latitudes poleward of 40° the orientation preference tends to be equatorward, but is more mixed, with notable patches having dominant pole-facing preference. Fig. 3c has been filtered to remove zones with low gully density.

Fig. 4 shows gully orientation in our four detailed study regions, for slopes ≥10° and although these data provide more detail, the overall patterns agree with the global data in Fig. 3c. East Argyre, Terra Cimmeria and Acidalia Planitia follow the global orientation trends; where from 30° to 40° gully sites are oriented towards the pole, 40-45° is a transition zone and at >45° the orientation is predominantly equatorward. West Argyre, also follows this general pattern, but has an additional population of pole-facing gullies at latitudes >40°S, which was previously identified by Raack *et al.* (2012).

The sparse nature of northern gullies provides an explanation for the conflicting orientation results of previous studies. Bridges and Lackner (2006) found gullies in 72 MOC images (>1.4 m/pix) and 24 THEMIS-VIS images (18 m/pix) and Heldmann *et al.* (2007) found gullies in 137 MOC images and both studies reported an equator-facing orientation preference at all latitudes. However, Kneissl *et al.* (2010) found a transition from pole-facing at 30°-40°N to equator-facing at 30°-40°N with contradictory results >50°N using MOC and HRSC images (12.5 m/pix). *et al.et al.*From our new analysis it is clear that orientation trends are only clearly visible where there are dense populations of gullies, a criterion which was not used in the previous studies, hence these new density maps are particularly useful where gullies are sparse in the northern mid-latitudes.

Discussion

Reconsidering factors influencing the global gully density

Our analyses show that in general the latitudinal distribution of gullies, poleward of 40°, is well-explained by the availability of steep slopes – a relation cited by previous work (*e.g.*, Dickson *et al.*, 2007), but not quantified. Further, our analyses reveal that there are places in this latitudinal zone with steep slopes yet no gullies, or a low density of gullies. In the northern hemisphere, these zones coincide with the scarps of the polar cap, individual impact craters, and Phlegra Montes. In the southern hemisphere these zones coincide with scarps of the polar cap, a few individual impact craters, Promethei and Thyles Rupes, and a zone to the east of Hellas in Promethei Terra. The polar cap scarps are comprised almost pure ice sculpted by wind (Howard, 2000) and hence are not expected to host gullies. The scarps associated with Promethei and Thyles Rupes could be very short hillslopes which therefore might host gullies not detectable at the CTX resolution of the Harrison *et al.* (2015) survey. In Fig. 5a we plot the distribution of Lobate Debris Aprons (LDA) collated by van Gasselt (2007) and of Glacier Like Forms (GLF) from Souness *et al.* (2012) along with our global gully density and slope-distribution data, and it can be seen that in the vast majority of areas with LDA and GLF have either low gully density or have no mapped gullies. Therefore, the presence of LDA/GLF could explain the relative paucity of gullies in Nereidum Montes, Promethei Terra, Phlegra Montes, Erebus Montes and in Deutero-Protonilus Mensae noted above.

LDA are features where the presence of thick (tens to hundreds of meters) ice has been confirmed in certain examples through analysis of radar data (Holt *et al.*, 2008; Plaut *et al.*, 2009). The present day morphology of LDA and GLF is indicative of relict debris-covered ice (*e.g.*, Arfstrom and Hartmann, 2005; Head *et al.*, 2010; Hubbard *et al.*, 2011; Squyres and Carr, 1986) and these comprise the most substantial ice deposits outside the polar areas (Levy *et al.*, 2014). The presence of substantial ice in the subsurface will increase the thermal inertia of the surface, which could inhibit gully-formation mechanisms related to ice-thaw, or CO_2 sublimation. Alternately the morphology of the terrain associated with the presence of LDA and GLF could be inhibiting gully-formation. Another possibility is that such features could cover-up gullies (de Haas *et al.*, 2017). Gullies are known to occur in close association with arcuate ridges (interpreted to be end-moraines; Arfstrom and Hartmann, 2005; Berman *et al.*, 2005; Head *et al.*, 2008) and other signs of degraded “glaciers” (Dickson *et al.*, 2015). Hence, the interrelation between these two features appears to be complex. In any case, this is a new factor that should be taken into account when assessing mechanisms of gully-formation.

Although we do not show the distribution of Concentric Crater Fill (CCF), which are infilled craters also believed to contain extant ice under a lag cover (e.g., Levy *et al.*, 2010; Squyres and Carr, 1986), their distribution covers almost uniformly the whole 30-50° N and S latitude bands (Dickson *et al.*, 2012; Levy *et al.*, 2010). Therefore, conversely to LDA/GLF their distribution does not seem to affect the distribution of gullies. CCF does not generally extend up onto the walls of the host craters, thus we might not expect an influence on gully-distribution. Because CCF infills the crater it reduces the total length of the crater-wall (but likely not its slope), so we might expect a reduction of the length of the gullies in such craters. Some of the individual craters without gullies at latitudes >60° in both hemispheres are those filled with mounds of polar-cap-like deposits (Conway *et al.*, 2012; Westbrook, 2009). For other individual craters we found no obvious reason that could explain the lack of gullies.

The undulations in the lower latitude boundary of the gully distribution at around 30-35°N/S is not caused by a lack of steep slopes (Fig. 5a), or by the presence of massive ice deposits. As suggested in previous work this boundary could be imposed by the ability to emplace, or to melt surface ice deposits under previous high obliquity climate excursions (Costard *et al.*, 2002; Madeleine *et al.*, 2014). Fig. 5b shows that for any given latitude gullies tend to be present where the annual day mean surface temperature is the highest for that latitude, under current orbital and climate conditions, suggesting ability to melt/sublimate might be the dominant factor, rather than ability to deposit ice. We emphasize that the correlation is not perfect, there are gullies found in "cold spots" on the Tharsis bulge and in Promethei Terra. Additionally we have used surface temperature data derived from a GCM where present data orbital and atmospheric parameters were used. This simulation included the assimilation of Mars Climate Sounder temperature profiles and dust optical depths. The assimilation procedure allows us to obtain the best possible representation of the present-day climate. Full details of the GCM and assimilation procedure can be found in Lewis *et al.* (2007) and Steele *et al.* (2014).. However, we feel that it is reasonable to expect that the longitudinal variations in maximum daily average surface temperature should not vary significantly with changes in orbital parameters, providing the surface properties are similar. This is because for a given latitude, the longitudinal temperature variation is mostly driven by changes in the albedo and thermal inertia of the regolith (e.g., Mellon and Jakosky, 1993). Areas with the highest mean daily surface temperatures tend to have low albedo and high thermal inertia (and vice versa for the areas with the lowest mean daily surface temperatures). Detailed climate model runs are beyond the scope of this work, but should be performed in the future to verify this apparent correlation.

Orientation

The latitudinal distribution of gullies overlaps with that of the "Latitude Dependent Mantle" (LDM): a surface-draping deposit thought to comprise an airfall deposit of ice and dust (Kreslavsky and Head, 2002; Mustard *et al.*, 2001). At the mid-latitudes where gullies are most common, the LDM exhibits signs of degradation (pitting, erosional scarps) and becomes more intact with increasing latitude (Milliken *et al.*, 2003; Mustard *et al.*, 2001). The same climatic arguments have been raised to explain the increasing degradation of the LDM towards the equator (e.g., Mustard *et al.*, 2001), as to explain the latitude dependent distribution of gullies. This had led some researchers to link gullies with degradation of the LDM (Bridges and Lackner, 2006; Dickson *et al.*, 2015; Levy *et al.*, 2011; Raack *et al.*, 2012; Schon and Head, 2012). Although no systematic mapping has been performed to ascertain the orientation of the slopes hosting LDM, in the 30-40° latitude range where pole-facing gullies are observed, Vincendon *et al.* (2010) noted that the geographical distribution of seasonal CO_2 frost indicated subsurface water-ice must be present on pole-facing slopes in this latitude range. Dickson *et al.* (2015) suggest that the LDM provides an erodible substrate, allowing gully channels to be expressed, therefore the fact that the LDM is generally found on pole-facing slopes in the 30-40° latitude range, could explain the predominantly pole-facing gully orientations.

However, it is worth noting here that the degraded terrain-muting unit mapped by Mustard *et al.* (2001) and referred to in many other papers (Kostama *et al.*, 2006; Kreslavsky and Head, 2002, 2000; Milliken *et al.*, 2003; Schon *et al.*, 2009b), may not be the same unit as the deposit which hosts the gullies, originally called "pasted-on terrain" by Christensen (2003), but often named LDM in subsequent publications (Conway and Balme, 2014; Dickson *et al.*, 2015; Dickson and Head, 2009; Levy *et al.*, 2011, 2009). Conway and Balme (2014) noted the polygonally patterned and often ribbed unit into which gullies incise is substantially thicker (up to 30 m) than the LDM measured on the plains (around several metres; Kreslavsky and Head, 2002; Mustard *et al.*, 2001; Schon *et al.*, 2009b). Soare *et al.* (2017) have also noted that the polygonally-patterned unit into which gullies incise is located stratigraphically below the LDM found on the inter-crater plains and exhibits a different suite of degradation features from the LDM. This "pasted-on" unit could be related to the mid-latitude crater asymmetry noted by Conway and Mangold (2013), or incipient formation of glacier-like-forms (e.g., Head *et al.*, 2008). In addition, many gully systems do not originate in areas covered in "LDM" (Aston *et al.*, 2011) and there are also examples of gullies present where no evidence for "LDM" is found at all (Johnsson *et al.* 2014, de Haas *et al.*, 2015a, 2015b).

Conclusions

We conclude that the availability of steep slopes must be taken into account to perform a fair assessment of global gully density.

From these analyses we conclude that any model of gully formation would have to explain the following:

- The onset of gully forming processes at ~30°N/S and the undulations in that boundary.
- The generally uniform gully forming potential in the whole 30-55° latitude band.
- Local paucity of gullies (e.g. Promethei Terra), which appear to coincide with massive ice deposits.

- The sharp transition from almost uniquely pole-facing to dominantly equator-facing, being consistently located at ~ 40°N/S.

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Figure Captions

Figure 1: Maps derived from re-analysis of the Harrison *et al.* (2015) gully database and the global MOLA topography data. A) Point-density of gullies in number sites per 100 km^2. B) Point-density of gullies in number sites per 100 km^2 of steeply sloping terrain, where "steep" is defined as ≥ 20°. This representation gives an unbiased view of the distribution of gullies and should be used in preference to A). C) The ratio between the frequency of pole-facing gullies and the summed frequency of pole- and equator-facing gullies, where 1= 100% pole-facing and 0 = 100% equator-facing. Pink outlines are the four sites studied in greater detail, EA = East Argyre, WA = West Argyre, TC = Terra Cimmeria and AP = Acidalia Planitia.

Figure 2: Digitisation of gullies as polygons. CTX image P14_006572_1367_XN_43S051W, with colour-coded MOLA topography in the background and digitised gullies as pink outlines. The black and white box in the top-left shows the size of a MOLA pixel for illustration.

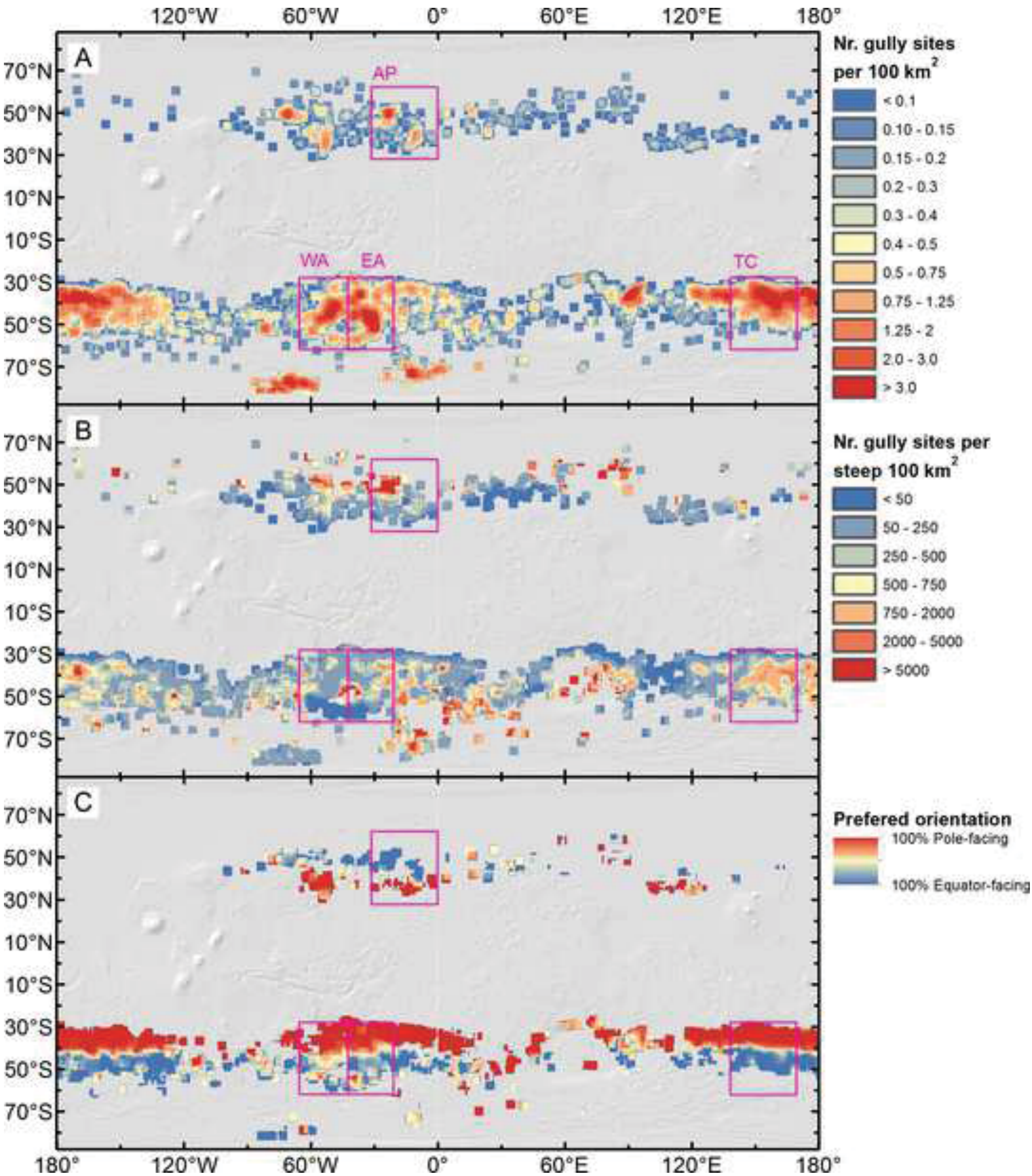
Figure 3: Top: Percent of pixels with gullies per latitude bin per region. Bottom: Percent of gully occupation on pixels with slopes > 20°, per latitude bin, per region. Map projected data were used to calculate the number of pixels, hence the real areal extent could be ±2% the value represented by these bars (and therefore is too small to be visually represented). The grey line is the normalized southern-hemisphere frequency of gullies taken from Dickson and Head (2009), based on data by Heldmann and Mellon (2004), who calculated the percentage of Mars Orbiter Camera images with gullies per 3° latitude bin.

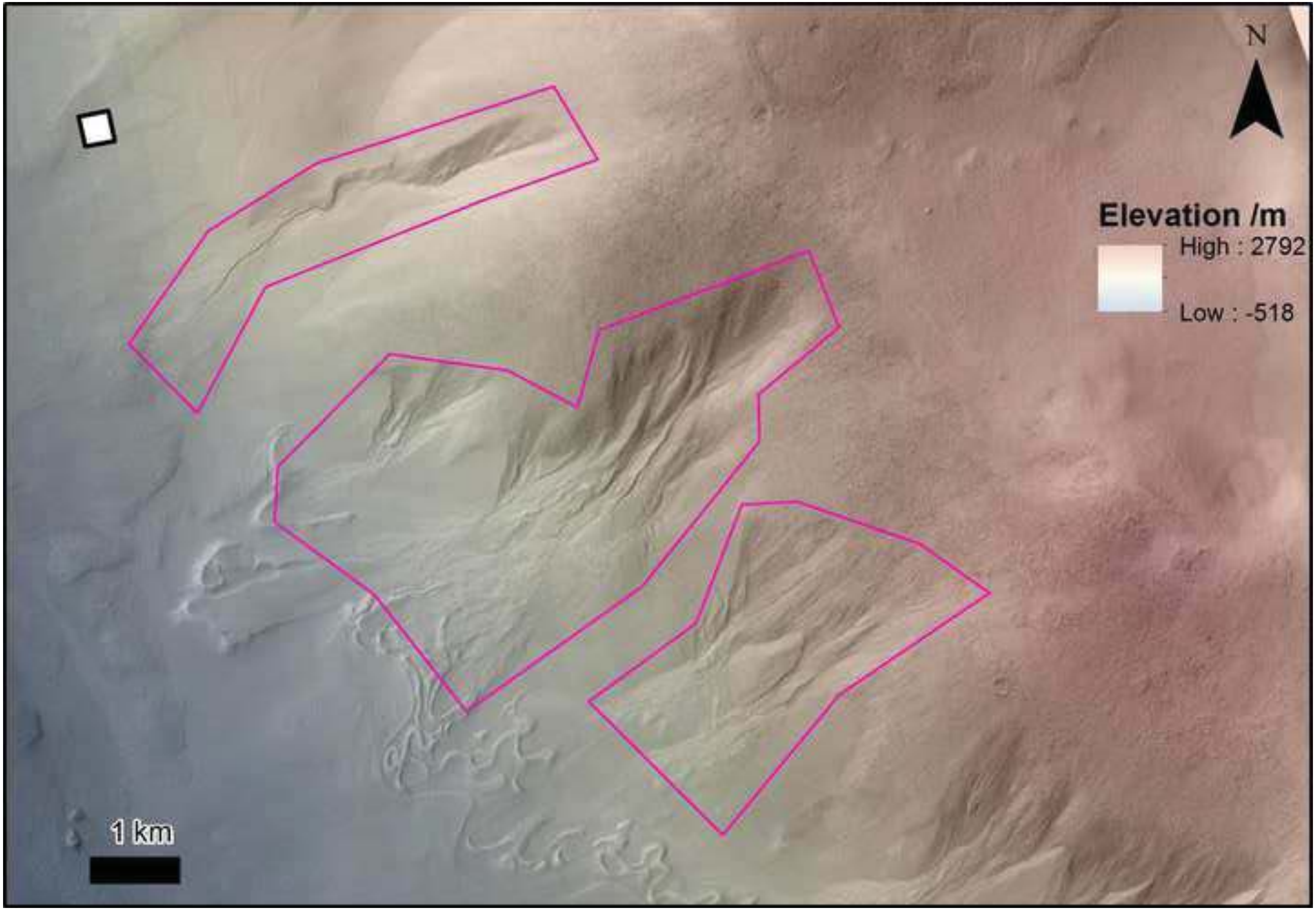
Figure 4: Orientation (aspect) of MOLA pixels containing gullies, per latitude, for the four detailed study sites. Red numbers indicate the value of the outer-ring on the polar-axis, which is the relative frequency of gullies on slopes > 10° for any given orientation in that latitude bin (we used a 10° threshold in this case, otherwise the number of samples per orientation was too small). Therefore gully density ranges between 2.5 and 25%. Note: the northern hemisphere site Acidalia Planum has been mirrored across the x-axis, so that pole-facing slopes are oriented down-page, for ease of comparison with the southern hemisphere sites.

Figure 5: Exploration of variables that may explain the global gully distribution. A) Slopes, LDA, GLF and gullies. Masked out in white are areas with few steep slopes (i.e. < 15,000,000 "steep" slopes per km^2). B) A map of the year-maximum day-average surface temperature, derived using a similar methodology to Kreslavsky *et al.* (2008), where the temperatures have been re-scaled, so that 1 = maximum temperature for each latitude and 0 = minimum temperature for each latitude.

Figure 1 (jpg, tiff at link)

Click here to download Figure Conway_GSL_Fig1_GullyReanalysis.jpg




N
Elevation /m
High : 2792
Low : -518
1 km

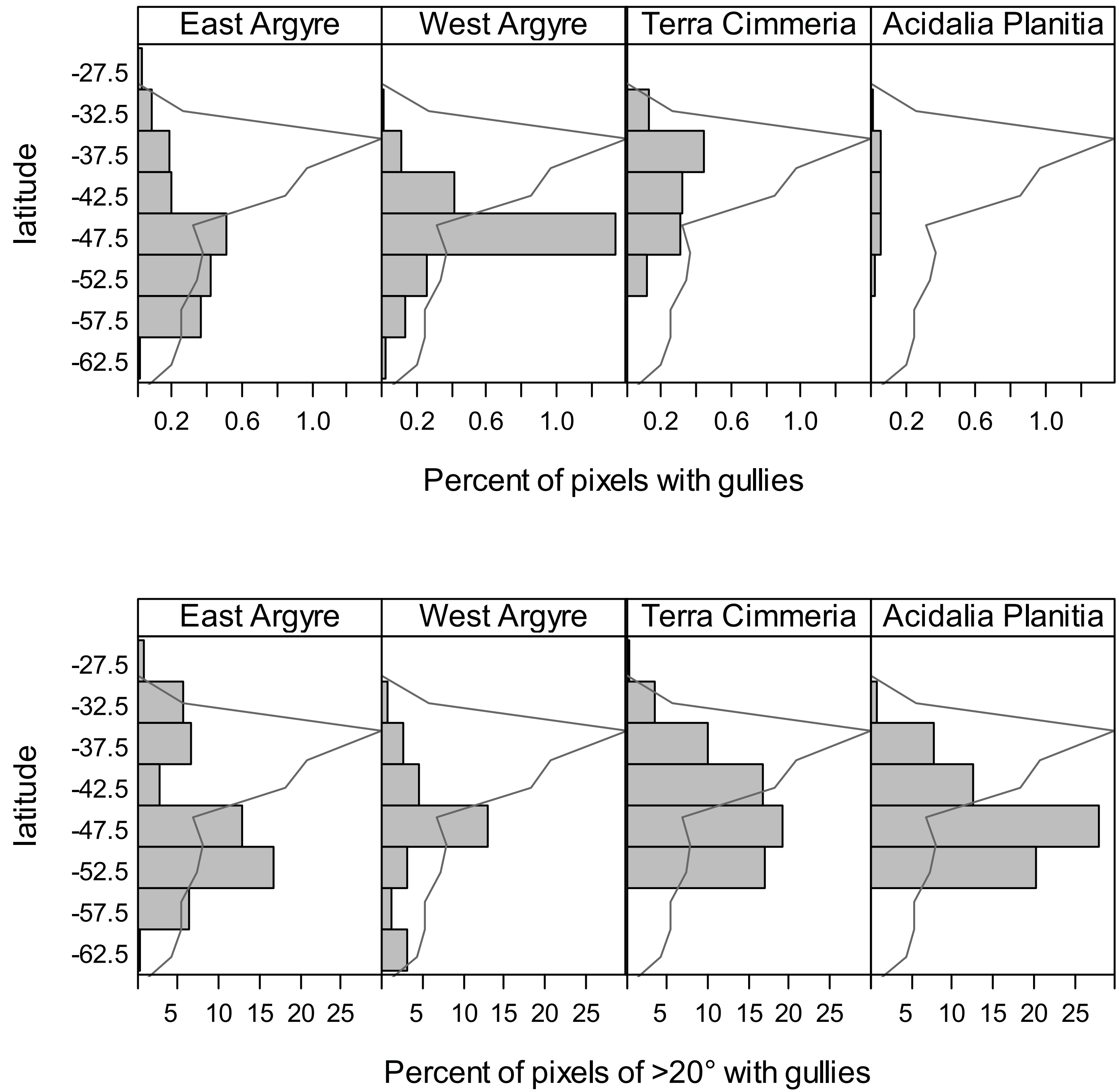

East Argyre
West Argyre
Terra Cimmeria
Acidalia Planitia
latitude
-27.5
-32.5
-37.5
-42.5
-47.5
-52.5
-57.5
-62.5
0.2 0.6 1.0
Percent of pixels with gullies
5 10 15 20 25
Percent of pixels of >20° with gullies

Figure 4

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Conway_GSL_Fig4_localOrientation.eps

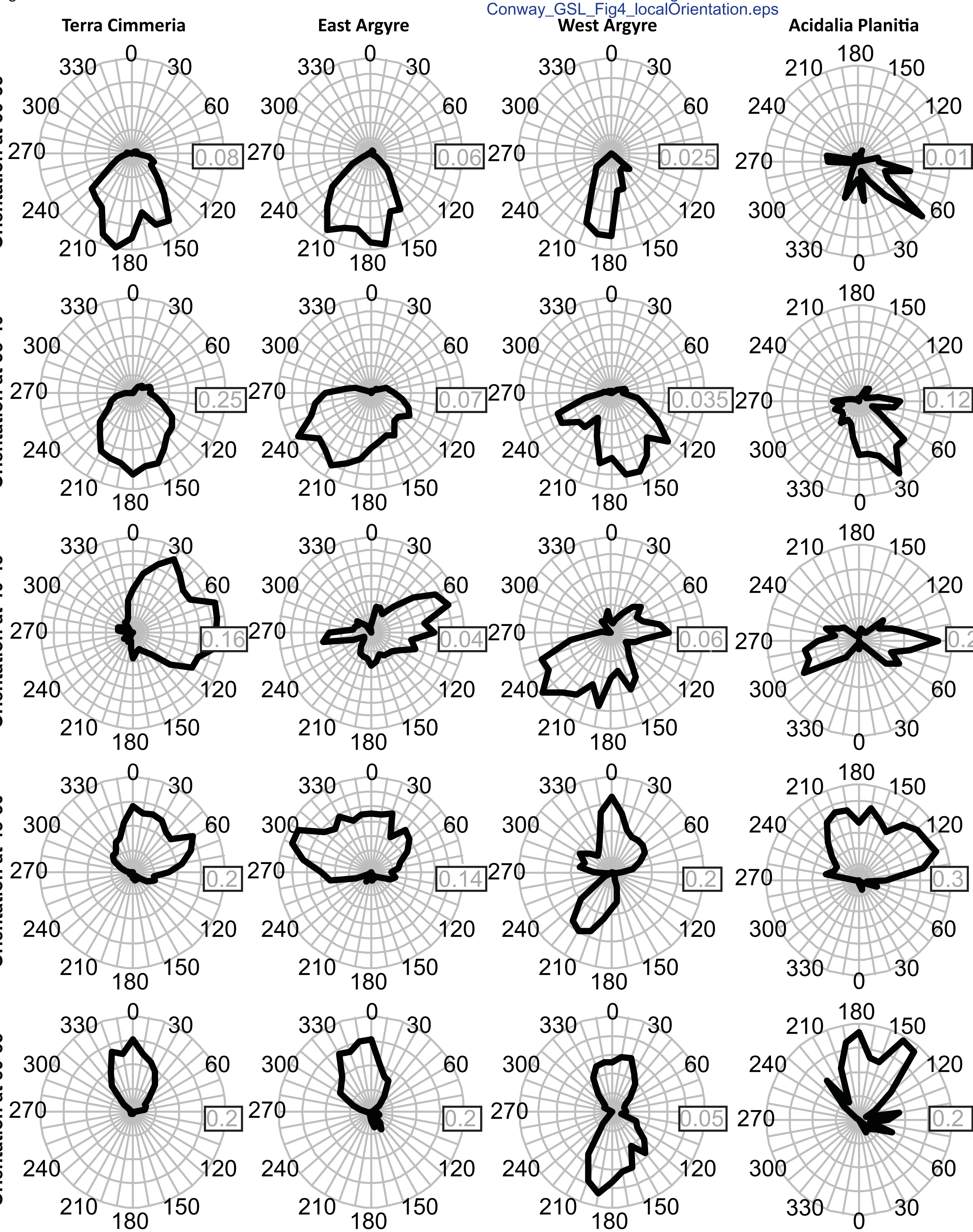

Figure 5 (jpg, tiff at link)