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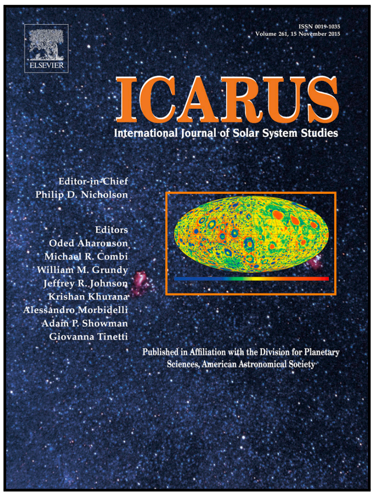

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Highlights

- A large survey of HiRISE images was conducted for three study areas in Acidalia, Arcadia and Utopia Planitiae on the northern plains of Mars.
- Features including clastic patterned ground, lobate hill slope features and scalloped depressions were catalogued.
- The proximity of these features to medium sized impact craters was assessed to determine whether they occurred in a preferential microclimate associated with such craters.
- It was found that lobate hill slope features and clastic patterns occurred further south than expected, beyond the southern extent of many previous studies.
- Clastic stripes and lobate hill slope features are often found on crater walls, but clastic networks are frequently found on the inter crater plains. This suggests that they do not require a crater associated microclimate in order to form.

The Distribution of Putative Periglacial landforms on the Martian Northern Plains

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Abstract

In this investigation, HiRISE images were surveyed across three regions of the Northern Plains of Mars; Acidalia, Arcadia and Utopia Planitiae. A sample of HiRISE images within each of these areas was examined. The aim of the investigation was to determine the distribution of three varieties of landform; clastic patterned ground, lobate hill-slope features and scalloped depressions. These features are of importance, as they are morphologically similar to terrestrial periglacial features.

Examples of these landforms were found across the study areas. Scalloped depressions are common at mid latitudes in each of the three regions. Sorted patterned ground was not as widespread. Some examples of sorted patterned ground were found in all three study areas, but the main concentration occurs in the north-western region of Acidalia Planitia. Lobate hill-slope features were the least common of the three landform types. Despite occurring infrequently, several possible examples of lobate features were found to occur in proximity to other putative periglacial features.

It was found that lobate hill-slope features and clastic patterns occurred further south than expected, beyond the southern extent of many previous studies. These features, and by extension the processes that form them, could thus occur more widely than previously thought.

It also appears that although putative periglacial features are often found in crater interiors they are not limited to these environments. Extensive areas of patterned ground were found on the inter-crater plains. Lobate features and sorted stripes were often found on crater walls, which would support the hypothesis that they are analogous to hill-slope features on Earth. Scalloped depressions were most often found in crater interiors, or on crater ejecta, although examples on the inter-crater plains were not uncommon.

Keywords

Mars; Mars Surface; Terrestrial planets; Geological Processes; Periglacial Processes.

1. Introduction

Periglacial landforms are relatively common in terrestrial cold climate environments (French, 2007). They form in regions where permafrost thaws on a seasonal timescale, producing a variety of distinctive landforms. It has been suggested that similar landforms may occur on the northern plains of Mars, with a variety of types being documented (Gallagher and Balme, 2011; Kerrigan, 2013; Lefort et al., 2009; Mellon et al., 2008; Soare et al., 2005, 2016, 2017; Ulrich et al., 2012; Van Gasselt et al., 2011).

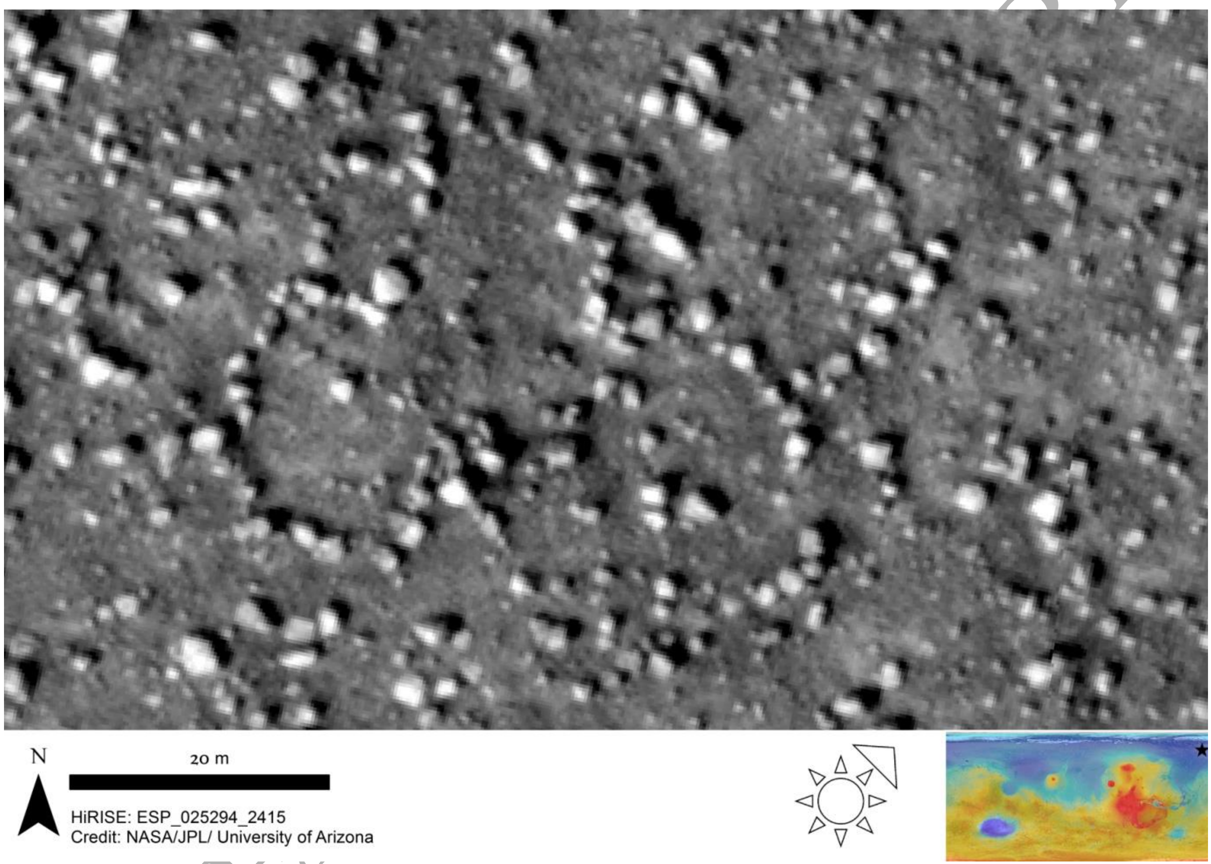


Figure 1: Clastic Polygons Type Example. A relatively flat area is covered by a network of clasts which range in size from sub metre material to blocks up to four metres across. Some regions of this pattern are continuous, while the clasts in others are more spread out. Overall this region has a high grade of sorting, as more areas have continuous or well expressed patterns, rather than discontinuous lines of clasts. **The context map shows Mars Orbiter Laser Altimeter (MOLA) topographic data, where red and blue indicate areas of high and low topography, respectively..**

On Earth, sorted patterned ground occurs when the repeated freezing and thawing of the permafrost active layer creates stripes and polygons of alternating coarse and fine grained material (Kessler and Werner, 2003; Washburn, 1956). These patterns of stones and gravel are very distinctive, and can often be observed in high-resolution aerial images. They are also characteristic of a periglacial environment, as no other process produces these patterns on Earth.

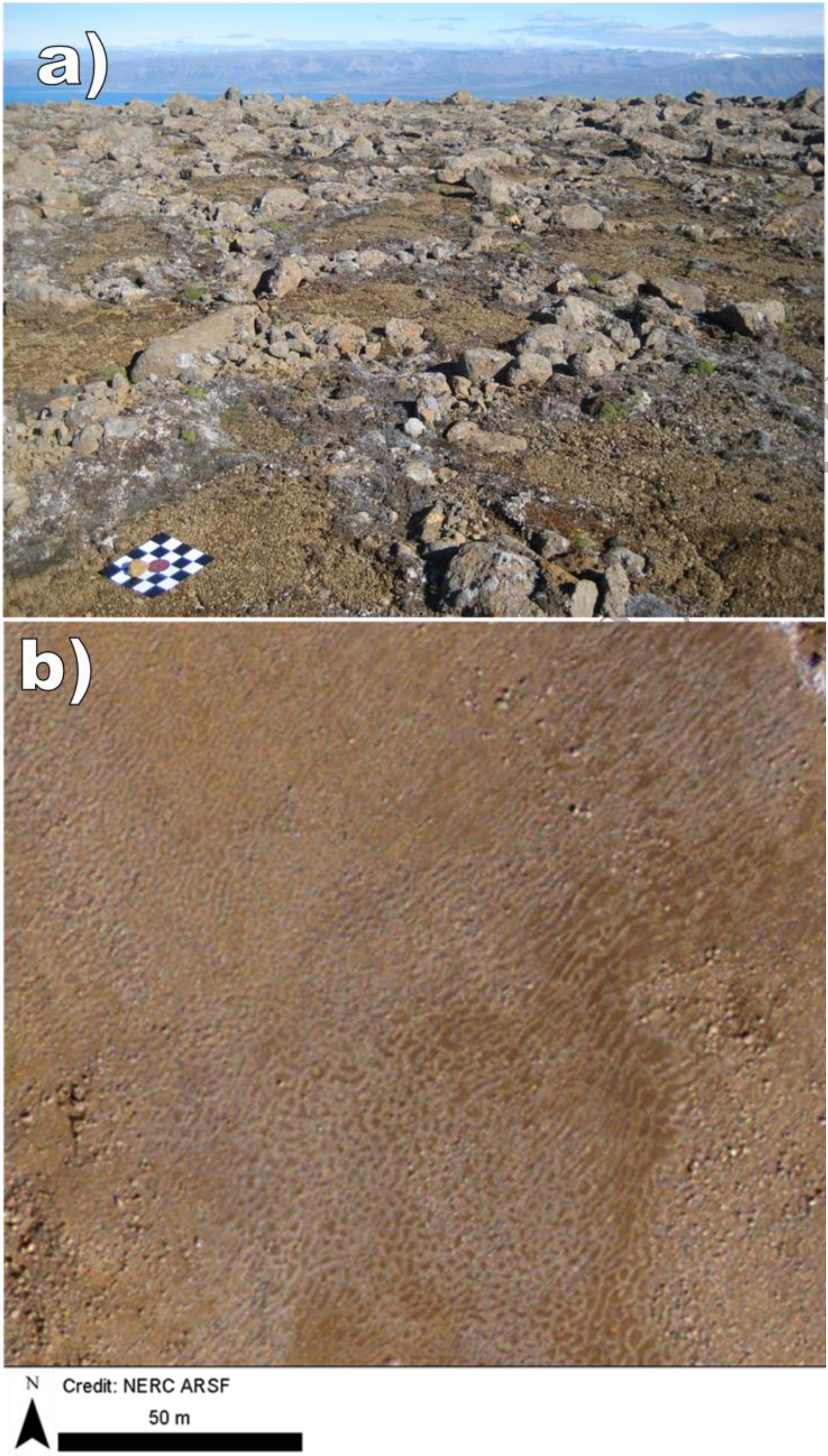


Figure 2: Sorted clastic polygons on Tindastóll, northern Iceland. a) in-situ observation. The scale bar is 25cm square, with 5cm segments. The polygons are 2-3m in diameter, making

them substantially smaller than martian analogues. The coarse domains are primarily comprise sub metre scale clasts, grading to small cobbles. b) Air photograph showing network of bright polygons grading into stripes. There are a few discernible clasts, but most are below the horizontal resolution of the air photo (15cm per pixel). The majority of clastic material at this site would be below the resolution of a HiRISE image. Patterns would only be distinguishable as variations in albedo between the generally dark fine domains, and the brighter coarse material.

Since sorted patterned ground is one of the most characteristic landforms in a terrestrial periglacial assemblage, the identification of these features on Mars could indicate environments where thawing has occurred in the geologically recent past. Several regional studies have described organisation in the arrangement of 0.5-2 m scale boulders (Balme et al., 2009; Gallagher et al., 2011; Johnsson et al., 2012; Soare et al., 2016).

Gallagher et al. (2011) observed examples of clastic stripes and lobate structures across the martian high latitudes (between 59-78 ^{o}N). These were reported to often occur in proximity to gullies, supporting the hypothesis that the landscape was influenced by ground ice thaw (Gallagher et al., 2011). Other research by the same group detected similar features elsewhere in the Vastitas Borealis region, and in Elysium Planitia (e.g. Balme et al., 2009; Balme and Gallagher 2009; Gallagher and Balme 2011). These landforms frequently occur at larger scales than their terrestrial analogues but are otherwise similar in appearance. Many occur within assemblages reminiscent of periglacial landscapes on Earth.

Other studies have suggested that clastic patterns could emerge without the need for thaw (Levy et al., 2010, 2008; Mellon et al., 2008; Orloff et al., 2011, 2013; Orloff, 2012). They have proposed a variety of dry sorting hypotheses to explain these features. These studies have provided useful examples of boulder organisation across the northern plains.

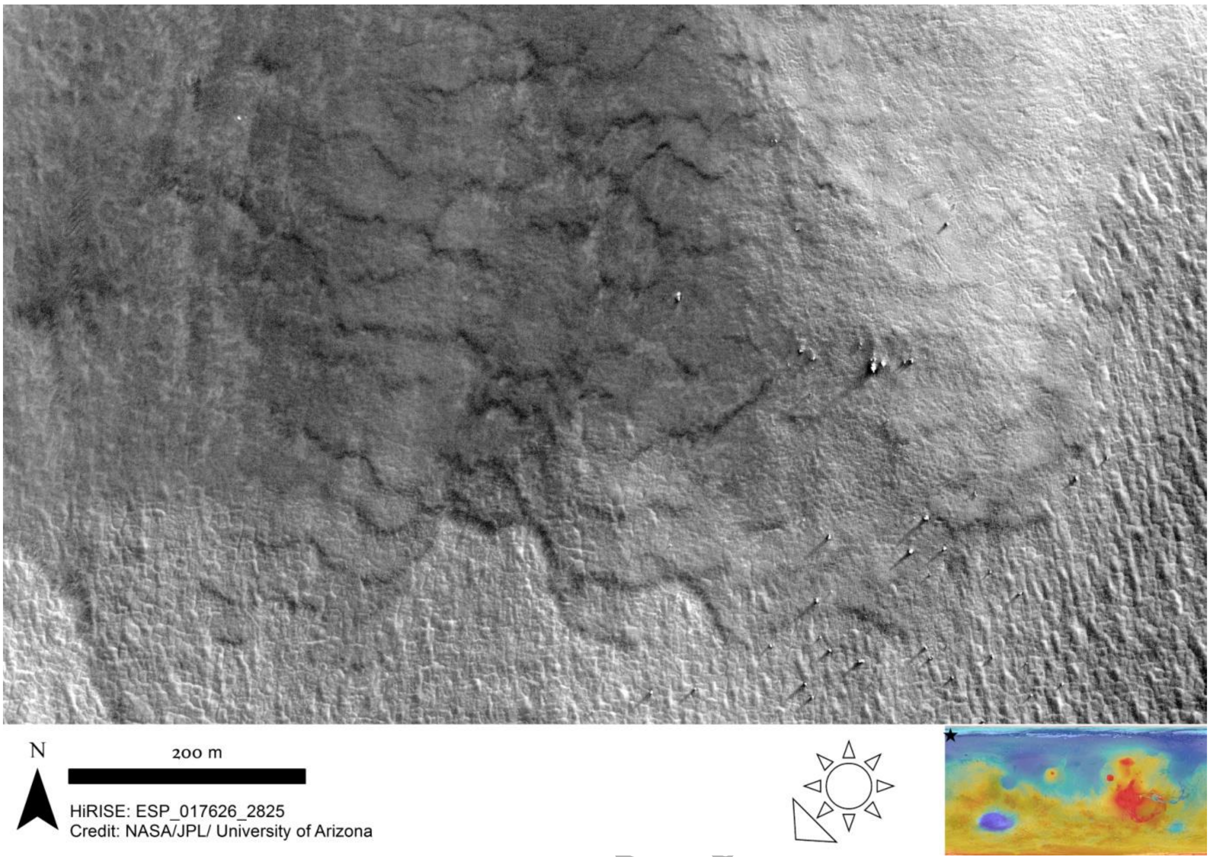


Figure 3: Lobate Hill-slope Features Type example. Down slope is towards the bottom of the Figure. A series of arcuate lobes are angled perpendicular to the hill-slope. These form a series of risers. The edges of many of the banks of lobes are irregular. They have a similar morphology to terrestrial solifluction features. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

Lobate hill-slope features on Earth frequently occur through solifluction, which encompasses a variety of thaw related mass wasting processes which deform hill-slopes in cold climate environments (French, 2007; Matsuoka, 2001). Solifluction results in banks of lobate structures forming on hillsides, perpendicular to the direction of slope. The leading edge of these lobes can contain clastic material which has been displaced by the solifluction process. On Earth the presence of segregated ice lenses is generally involved in solifluction processes (Matsuoka, 2001; Higashi and Corte, 1971). Such ice lenses would also be required for the formation of sorted patterned ground. It is possible that such lenses may occur on Mars. They have been suggested to explain the presence of excess ice at the Mars Phoenix landing site (Mellon et al., 2009; Sizemore et al., 2015). This suggests that ice lens formation could occur under Martian conditions, and thus allow for contingent periglacial processes to occur.

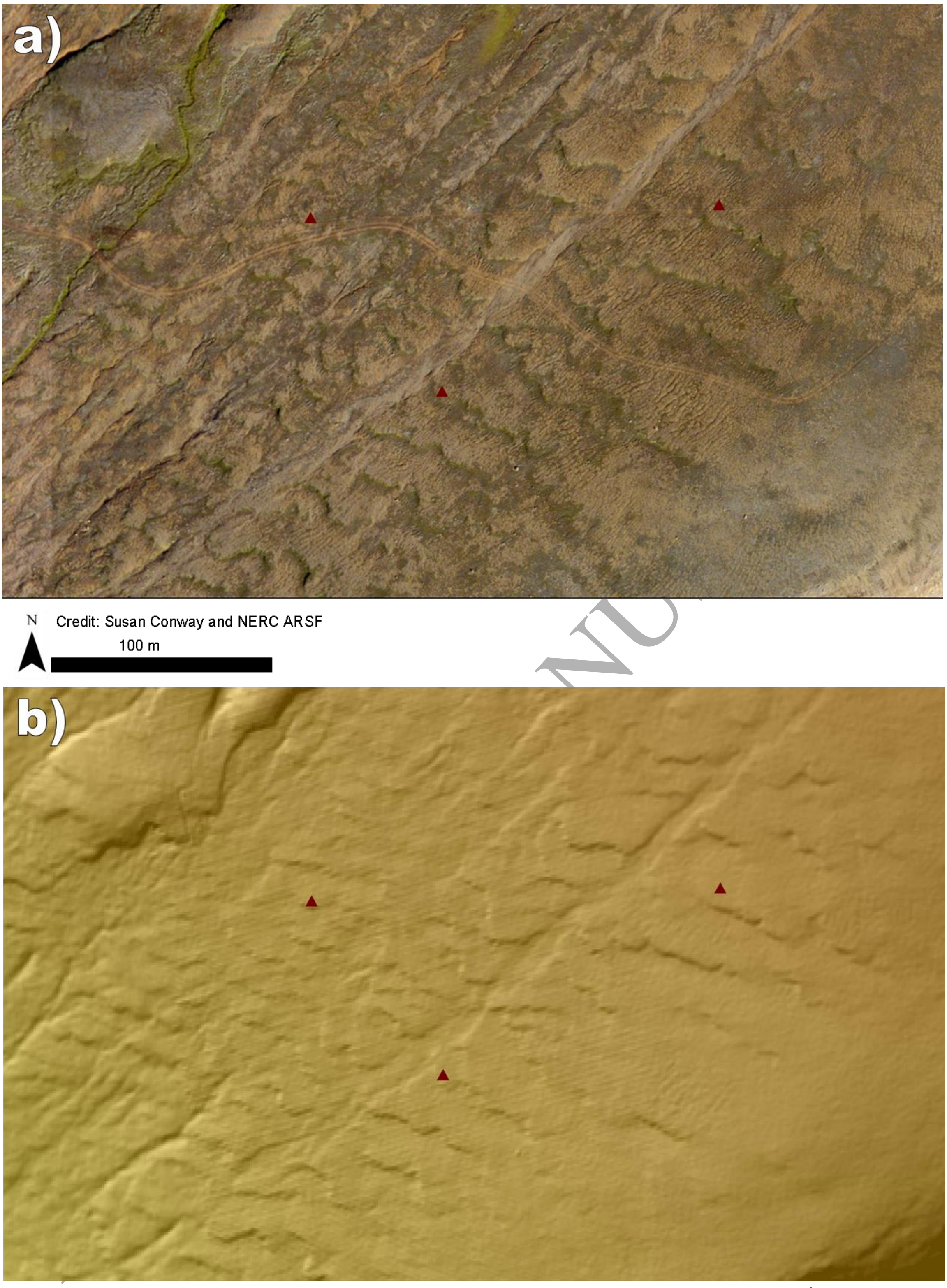


Figure 4: Solifluction lobes on the hillside of Tindastóll, northern Iceland. a) Air photo, b) Lidar hillshade. Red triangles mark the crests of three lobes, to aid comparison of the two images.

On Earth solifluction typically occurs on relatively shallow slopes between 5-20^o. On steeper slopes mass movement would occur much more rapidly, in the form of a landslide or active layer detachment (Beirman and Montgomery, 2014; Benedict, 1976). A similar trend would be expected on Mars, where lobate features have generally been reported on hillslopes, and crater walls (Balme et al., 2013; Gallagher et al., 2011; Johnsson et al., 2012; Johnsson, 2013).

The morphology of terrestrial solifluction features is influenced by the volume of water facilitating their formation. Lobes which form through gelifluction require more water than those that result from frost creep (Benedict, 1970). Lobes which form through frost heaving generally have low risers, with a height less than 20 cm. Gelifluction lobes are typically higher than 20 cm tall, and are also generally wider and longer (Matsuoka et al., 2005). They can also have a higher surface gradient (Matsuoka et al., 2005). These features occur on a relatively small scale, and the surface expressions of solifluction can be subtle.

Distinguishing between these two types of landform will thus be challenging due to their small size relative to the resolution of HiRISE images, and general lack of high resolution topographic data in the areas surveyed. Given the climatic conditions expected on present day Mars, a frost heaving formation mechanism would be expected to be more likely. A comprehensive survey of lobate features on Mars, of both clastic and non-clastic varieties, has been conducted by Johnsson et al. (Johnsson et al., 2012; Johnsson et al., 2018). They catalogued these features in both the northern (Johnsson et al., 2012) and southern (Johnsson, 2013) hemispheres. Johnsson et al. compared the features observed in crater interiors on Mars with terrestrial analogues in Svalbard and suggested that the martian features had likely formed through thaw related processes in the geologically recent past. Their northern hemisphere study found lobate features between 60 and 80^{o}N. These studies provided useful type examples to inform the present investigation.

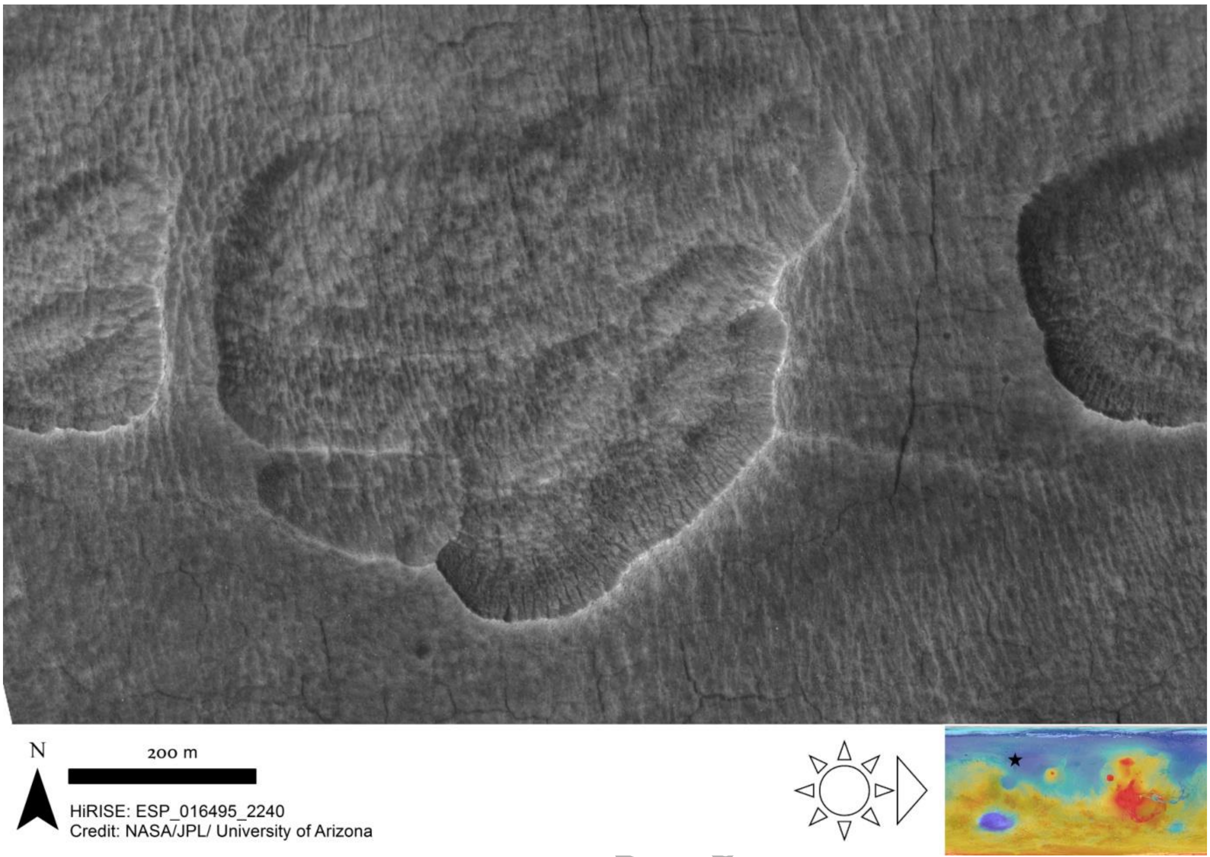


Figure 5: Scalloped Depression Type Example. A fractured plain is incised by shallow depressions. These have a scalloped edge, and the floor is marked by small ridges, where several sections of degradation have met. The features are also slightly asymmetric, with a better defined pole facing slope. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

Scalloped depressions have been proposed to result from thermokarst-like processes, although sublimation driven mechanisms may be more likely (Dundas et al., 2015; Lefort et al., 2010; Zanetti et al., 2010). A variety of studies informed the analysis of these features (Haltigin et al., 2014; Morgenstern et al., 2007; Séjourné et al., 2011; Soare et al., 2017, 2012, 2008; Ulrich et al., 2010). These studies mainly established the extent of scalloped terrains around Utopia Planitia and compared and contrasted them with terrestrial thermokarst landscapes. Similar features have also been reported in the Argyre basin of Mars's southern hemisphere (Soare et al., 2017). However, most past studies on scalloped depressions have been focused on the Utopia Planitia region where these features are very numerous. The examples presented by these studies formed the first suite of type examples which were used to assess the likelihood that other features conformed to these landform types.

Since periglacial landforms require ice to form, this study also relied upon past studies that have established the distribution of ground ice across the Northern Plains. This includes the geomorphological studies of Costard (1989) and later mapping of near surface ground ice and water equivalent hydrogen using the Mars Odyssey Neutron and Gamma Ray

Spectrometers (Boynton et al., 2010; Feldman et al., 2004, 2002).The modelled distribution of ground ice was subsequently tested by Byrne et al. (2009), using observations of fresh impact craters. As a result of these studies the threshold at which ground ice is expected to occur at shallow depths is well constrained, and likely occurs around 60^o north.

1.1. Aims

The main aim of this investigation is to constrain the distribution of possible periglacial features on the Northern Plains of Mars, and so provide a new suite of examples for study. It is the intention of this study to examine the broad regional distribution of these features, and to assess the role of topography in controlling the locations in which they are found. By expanding upon the geographic extent of previous studies (e.g. Gallagher et al., 2011; Gallagher and Balme, 2011) we hope to provide a comprehensive catalogue of putative periglacial sites for the regions surveyed. Studies of Acidalia and Arcadia Planitia were undertaken in order to provide a comparison to Utopia Planitia which has been a focus of the previous Mars periglacial literature.

In and of itself, this study does not hope to resolve the question of environmental control, or prove or disprove the wet or dry hypotheses for the formation of possible periglacial features. Rather, by expanding the catalogue of periglacial features we hope to provide a larger suite of sites, which future studies of these landforms can examine. Comparing the distribution of these features to regional climate models would be a good next step towards determining the environmental parameters responsible for the distributions reported herein, but was felt to be beyond the scope of this project.

The following hypothesis will also be examined:

- Putative periglacial landforms occur preferentially in crater interiors, or in the near crater environment (as observed in Gallagher et al., 2011 and Gallagher and Balme, 2011).

Since previous studies have observed putative periglacial features in proximity to craters it has been suggested that an impact crater might provide a favourable microclimate for the formation of periglacial features. The crater control hypothesis is examined by comparing the distribution of features within crater interiors, on ejecta blankets, and on the inter-crater plains.

Methods

Three surveys were conducted, covering areas of Acidalia, Arcadia and Utopia Planitiae. It was decided that the available images should be selectively, rather than randomly, sampled so as to focus on images which included a range of environments. Gallagher et al. (2011) had observed putative periglacial features within impact craters and suggested that crater walls could provide a favourable microclimate for a suite of periglacial processes. To test this hypothesis HiRISE images which overlapped 2-10 km impact craters were selected. Craters are a frequent HiRISE target, so there is a large sample of these sites available.

These images provide a variety of terrains, including the crater interior, the ejecta, and the low-relief plains that surround them. Most include a section of the crater wall and sometimes a central peak. These are the environments where hill-slope features such as gullies, sorted stripes and solifluction lobes were predicted to occur. Mapping their distribution across an image thus illustrates whether these are in fact preferential environments.

Most images include areas which are beyond the crater's ejecta. These are expected to be representative of the inter-crater plains. Images with both inter and intra-crater regions are very useful for this analysis, since they are sites where both terrain types are present in reasonably close proximity. Thus the same regional environmental parameters would be expected to influence the development of landforms in all parts of the image. Thus any differences in landform distribution between the intra and inter-crater zones would be expected to be due to local environmental and topographic factors rather than regional ones. To provide a control, the Acidalia survey was expanded to include images which did not intersect impact craters at all. At these sites the cratering process would not be expected to control the landscape. This expanded survey was used to ensure that the inter-crater regions of the surveyed images were representative of the plains as a whole.

1.2. Study Areas

The Northern Plains of Mars cover much of the northern hemisphere. Their southern extent is bordered by the planetary dichotomy boundary which constrains a roughly triangular region consisting of three large basins; Acidalia, Utopia and Arcadia Planitiae. To the north these plains merge into the Vastitas Borealis, which extends to the edge of the polar ice cap. HiRISE coverage in these regions is generally very good. At the time of this survey a total of 10,531 HiRISE images covered 2.9%, by area, of the Northern Plains, north of 30^{o}N. There is a good spread of images over most of the different geological units and terrain types.

Three study areas were defined, each spanning a 50^{o} latitude swath of the mid to high latitudes between 30^{o} and 80^{o}N. 30^{o}N was selected as the southern boundary as this is the southern limit at which stable ground ice is expected to be present (Boynton et al., 2010; Feldman et al., 2004). In many areas, this included the edge of the southern highlands. The northern edge of the study areas extended to the polar cap in some places.

The Utopia and Arcadia study areas consist of 60^{o} wide regions covering the centre of the respective basins. The Arcadia study area extends from 160-220^{o}E, while the Utopia study area covers the region from 80-140^{o}E. The Acidalia survey area consisted of a 50^{o} wide block on the eastern rim of the basin between 20^{o}W and 30^{o}E.

The survey areas were not defined to have an equal area at all latitudes. There are typically more images in the southern regions, but they are more spread out. These variations must be considered when patterns are observed in the resulting data. However, there is a sufficient spread of images and sufficient representation of all latitudes and terrain types within the survey to produce a representative catalogue of the Northern Plains.

A Geographic Information System (GIS) with Mars Crater Consortium (e.g. Barlow et al., 1990) data was used to locate craters with diameters of one kilometre or more. All the HiRISE images that intersected these craters were identified. The qualifying HiRISE images were downloaded and put into a series of GIS. These datasets were periodically expanded to include newly released images which met the selection criteria. In total 468 HiRISE images were surveyed as shown in Figure 6. They cover an area of 69845.2 km^2 or 21.9% of the total area imaged by HiRISE in these regions.

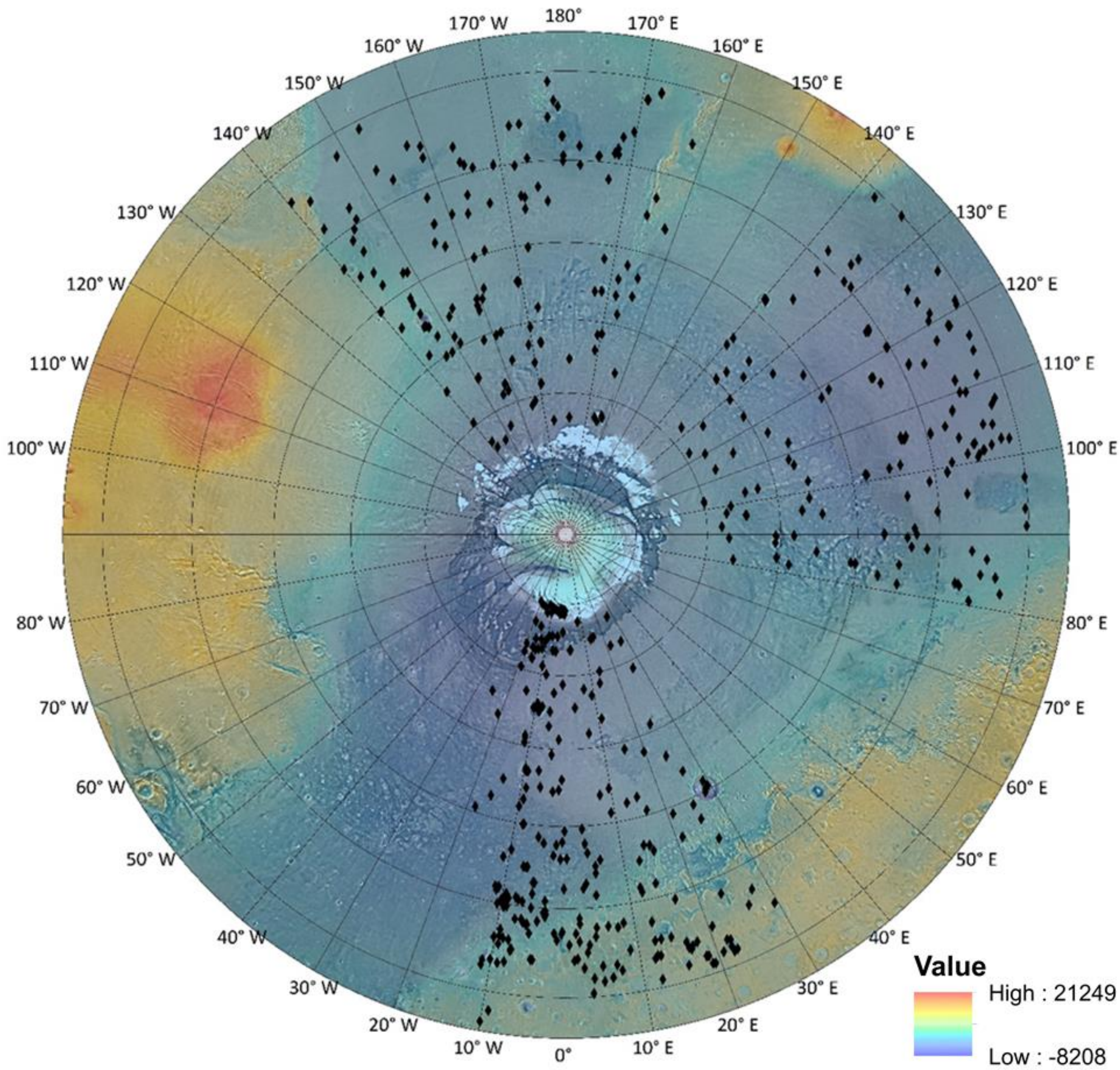


Figure 6: The locations of the images used within this survey. Black diamonds indicate HiRISE images. Clockwise from the top the three clusters of images are the Arcadia,

Utopia, and Acidalia study areas. The background shows the topographic map from the Mars Orbital Laser Altimeter (MOLA), for context.

Details of the study areas are as follows: Arcadia Planitia (160-220^{o}E, 30-80^{o}N), 175 HiRISE images were surveyed, covering an area of 18,110 km^2.

Utopia Planitia (80-140^{o}E, 30-70^{o}N), 126 HiRISE images were surveyed, covering 20,186 km^2. This survey only extends to 70^{o}N since no HiRISE images north of this latitude met the selection criteria for the survey. Utopia Planitia has been a focus of martian periglacial research, as it is believed to have a high concentration of putative periglacial landforms. One aim of this survey is to compare the distribution of features in this region with those in Acidalia and Arcadia. This will help to determine whether Utopia is a unique case or whether it is representative of the rest of the region, but has simply received more attention than other areas.

Acidalia Planitia (20^{o}W-30^{o}E, 30-80^{o}N), 167 HiRISE images were surveyed, covering 31,549 km^2. These consisted of all of the images overlapping medium to large diameter impact craters in the 30^o east of the prime meridian and all HiRISE images in the western 20^o of the study area (as of summer 2013).

Area Surveyed km^2	Acidalia	Utopia	Arcadia	Northern Plains >30 ^{o}N
Total	31548.68	20186.1	18110.4	69845.2
30-40^{o}N	12186.2	8219.16	5188.19	25593.55
40-50^{o}N	6557.02	4940.64	3647.79	15145.45
50-60^{o}N	3159.49	3071.29	4100.88	10331.66
60-70^{o}N	2779.59	3955	2808.86	9543.45
70-80^{o}N	6866.38		2364.71	9231.09
% of HiRISE Coverage	**Acidalia**	**Utopia**	**Arcadia**	**Northern Plains >30 ^{o}N**
Total	26.75	22.44	16.36	21.92
30-40^{o}N	31.54	25.45	16.07	24.80
40-50^{o}N	18.19	16.35	14.60	16.60
50-60^{o}N	31.02	19.00	19.36	21.74
60-70^{o}N	48.04	35.07	27.92	35.18
70-80^{o}N	25.18	0.00	10.65	18.66

Table 1: Area covered by the HiRISE Survey broken down by study area and latitude band.

1.3. Survey Procedure

All surveys were conducted manually. Each HiRISE image was systematically examined on-screen in the GIS, typically at a map scale of 1:10,000. 'Native' HiRISE resolution is approximately 1:1000, with 25-50 cm per pixel. This allowed large features to be easily examined. Areas containing possible smaller scale features such as sorted polygons or solifluction lobes were then examined at or near the full resolution, so that more detailed analysis could be conducted.

Whenever landforms with morphological similarity to periglacial features were found, their positions were marked using GIS shape files, and classification parameters were entered into the database. The variety of features likely to be found had been assessed during a small pilot study and a classification scheme for each landform type developed. A semi-quantitative five-point grading scheme was used to record the degree to which a feature resembled the type examples. This indicates how representative it is for its class, and thus how likely it is to be an example of this landform type. Examples of features for each grade are presented in Figures 8, 12 and 18 for clastic, lobate and scalloped features respectively. Grade one features are the least representative, and in most cases are ambiguous. Grade five examples are the most representative of their class, and considered most likely to be examples of the relevant terrain type. A detailed discussion of the grading scheme for sorted patterned ground can be found in Barrett et al. (2017) and additional type examples are presented in Barrett (2014).

In addition to morphological criteria, the situation of a candidate landform is also assessed. Some terrestrial periglacial landforms, in particular sorted stripes and solifluction features, are generally topographically controlled. If the same relationships hold true for martian features then they should be assigned a higher grade. If incorrect topographic controls are observed then it is much less likely that the features in question are periglacial in nature. Specifically, clastic stripes and lobate features are expected to be found preferentially on crater walls, whereas polygonal networks and scalloped depressions are expected to be more common on flatter ground.

2. Results

In the following sections the distribution of each of the landforms catalogued in these surveys are described and examples presented. Table 2 summarises the distribution of all the features discussed above, as well as gullies and fracture polygons, which are frequently found in association with these features.

	HiRISE Images Surveyed	Area Surveyed /km^{-2}		
Acidalia Planitia	167	31548.68		
Landform	**Number of Occurrences**	**% Images**	**Min Latitude /^{o}N**	**Max Latitude /^{o}N**
Sorted Polygons	38	22.75	37	74
Sorted Stripes	9	5.39	46	73
Rubble Piles	21	12.57	43	77
Lobate Structures	7	4.19	32	74
Scalloped Depressions	28	16.77	30	57
	HiRISE Images Surveyed	**Area Surveyed /km^{-2}**		
Utopia Planitia	126	18110.4		
Landform	**Number of Occurrences**	**% Images**	**Min Latitude /^{o}N**	**Max Latitude /^{o}N**
Sorted Polygons	17	13.49	40	68
Sorted Stripes	3	2.38	46	64
Rubble Piles	1	0.79	69	69
Lobate Structures	4	3.17	53	67
Scalloped Depressions	36	28.57	40	67
	HiRISE Images Surveyed	**Area Surveyed /km^{-2}**		
Arcadia Planitia	175	20186.1		
Landform	**Number of Occurrences**	**% Images**	**Min Latitude /^{o}N**	**Max Latitude /^{o}N**
Sorted Polygons	17	9.71	36	73
Sorted Stripes	6	3.43	34	64
Rubble Piles	5	2.86	36	73
Lobate Structures	5	2.86	38	68
Scalloped Depressions	27	15.43	40	64

Table 2: Summary of landform distributions across the three study areas, normalised by number of images surveyed.

2.1. Clastic Patterned Ground

Sites with possible sorted patterns have been found across all three study areas. These features can be grouped into several different feature types such as stripes, polygons and rubble piles.

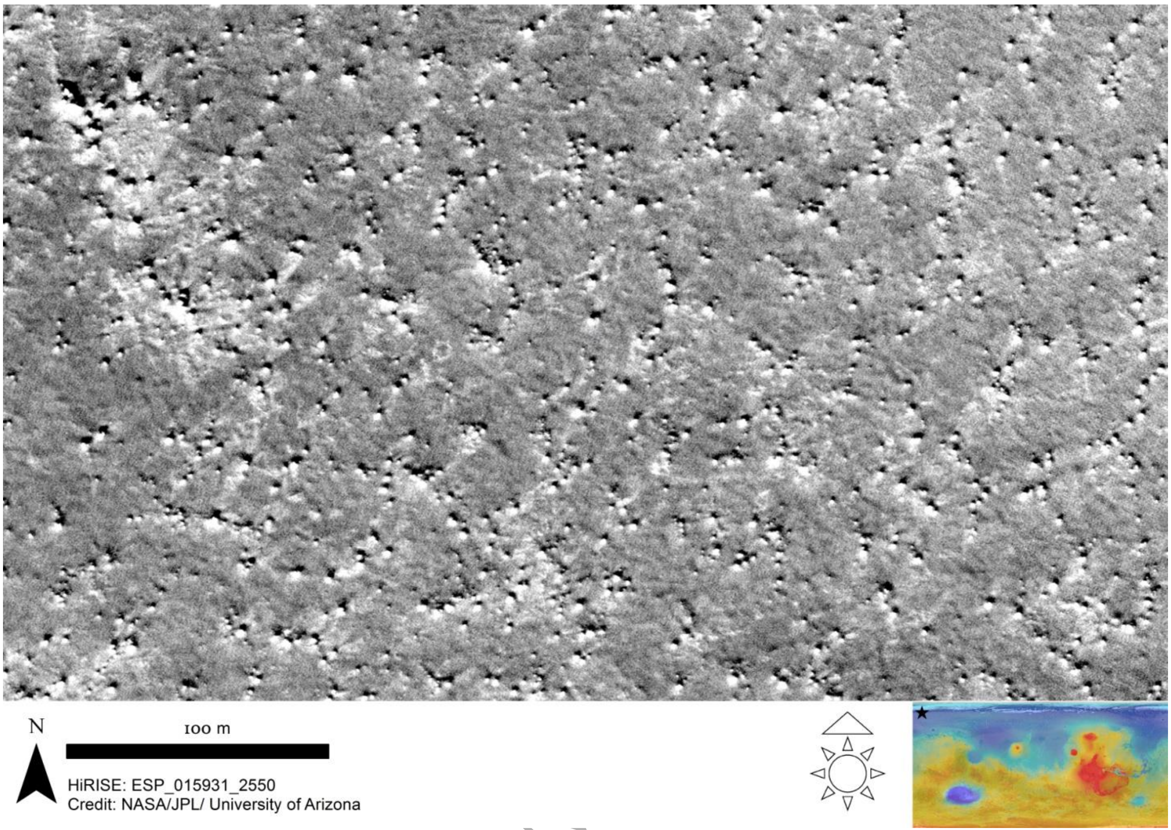


Figure 7: Grade 3-4 polygonal patterned ground in northern Acidalia Planitia. A discontinuous network of polygons can be seen, defined by the arrangement of 1-5 m blocks. Some of these polygons are more circular than others, but there is no clear trend in the direction of the most elongated features. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

The most common variety of clastic patterned ground consists of apparently sorted polygons, where clasts are arranged into a network of boulders surrounding patches of non-boulder-strewn ground. These networks are frequently discontinuous, consisting of lines or arcs of clasts which appear to be aligned into a polygonal structure.

Clastic stripes consist of parallel lines of clasts, which extend for a substantial distance in one direction. There were far fewer examples of stripes within the areas surveyed than polygons. If they are analogous to terrestrial sorted stripes, then these features would be expected to occur on shallow hill-slopes. Therefore, it is possible that the generally flat morphology of the northern plains accounts for their low frequency of occurrence.

Rubble piles consist of small piles of clasts interspersed with large areas of relatively boulder free ground. Rubble piles are reasonably common at high northern latitudes but occur far less frequently further south.

These three morphologies are similar in structure to the sorted polygons, stripes and islands most common on Earth. Consequently these features are considered to be possible examples of sorting and are referred to as such hereafter. However there are several key points in which they differ from terrestrial analogues. The first is scale; terrestrial sorted polygons occur on a range of scales, but are rarely larger than ten metres in diameter (Hallet, 2013; Washburn, 1956). A few unusual examples from the Canadian arctic are as large as medium-sized martian features (Ballantyne, 2013; Gallagher et al., 2011). However these are far from typical. Not only are circles larger in size, but so are the clasts which comprises them. Even the largest of terrestrial sorted circles rarely include boulders four to five metres across.

The dramatically larger size of the martian clasts could potentially be the result of the lower gravity. The acceleration due to gravity at the martian pole is 3.758 ms^{-2} (Kieffer et al., 1992), approximately one third that of Earth. This means that larger clasts will not weigh as much as their terrestrial equivalents. However, the upwards force of frost heaving is derived from the growth of ice lenses (Matsuoka et al., 2003) and so would not be expected to be altered by the lower gravity. Consequently, the force of frost heaving would be expected to be proportionally stronger on Mars, potentially moving material three times mor massive than in terrestrial patterned ground. However, some features are substantially larger than this, casting doubt as to whether a freeze thaw mechanism would be capable of arranging them. The sorting process also relies on the regular repeated freezing and thawing of interstitial water, and cannot be explained by unusual or sporadic thawing events of the sort which could trigger a debris flow or solifluction feature. Without in-situ observations, and long term monitoring of martian clastic patterns, it will be difficult to assess whether frost heaving is occurring at these sites.

Furthermore the martian examples often appear discontinuous, which is not a common feature of terrestrial patterned ground. Large gaps can be seen between the large clasts in most of the examples presented herein. This could be a limitation of the data. Since only the largest clasts are above the resolution of a HiRISE image (usually 25-50 cm per pixel) evidence of sorting is often ambiguous. Many features exhibit lines of aligned boulders, sometimes converging or intersecting, but with too few clasts to form a coherent polygon. Even if the upper limit of sorting is increased, smaller material would still be expected to undergo organisation, forming coherent coarse domains between the larger blocks.

It is possible that smaller clasts are below the resolution of the HiRISE images used in this survey, and are in fact present. However a variation in albedo would still be expected were this the case. Another possibility is that these features are the result of deflation processes, where large, buried clasts are exposed by aeolian erosion. Smaller material could still be buried, while the upper parts of the largest blocks are now exposed. Without in-situ observation it is impossible to tell whether smaller material is present, either on the ground or at depth.

It is also possible that deflation is exposing the largest elements of some other buried pattern, and that the blocks seen in these images are not, in fact, loose clasts. The patterns at many of these sites have been shown to be significantly different from a random distribution (Barrett et al., 2017), but this does not mean that they have been produced by a process analogous to terrestrial freeze-thaw sorting.

Sorting sites were indentified in locations where a large number of clasts appeared to diverge from a random distribution. A set of morphological grades were established as shown in Figure 8. These grades describe the extent of organisation present at the site. Possible sorted sites were compared to type examples and ranked out of five based on the extent to which they expressed the key attributes of terrestrial sorted terrains. This classification scheme was applied across each study area. Several sites in the Acidalia study area were used to verify this approach by means of a nearest neighbour analysis. The results of this analysis informed the classification of all of the sites, across the three study areas. For a detailed methodology see Barrett (2014) and Barrett et al. (2017). Examples with nearly continuous lines of clasts, often forming polygonal shapes were ranked more highly. Areas with discontinuous lines and arcs of clasts received lower rankings. Any feature with a grade of 3 or above is considered likely to be an example of a clastic network.

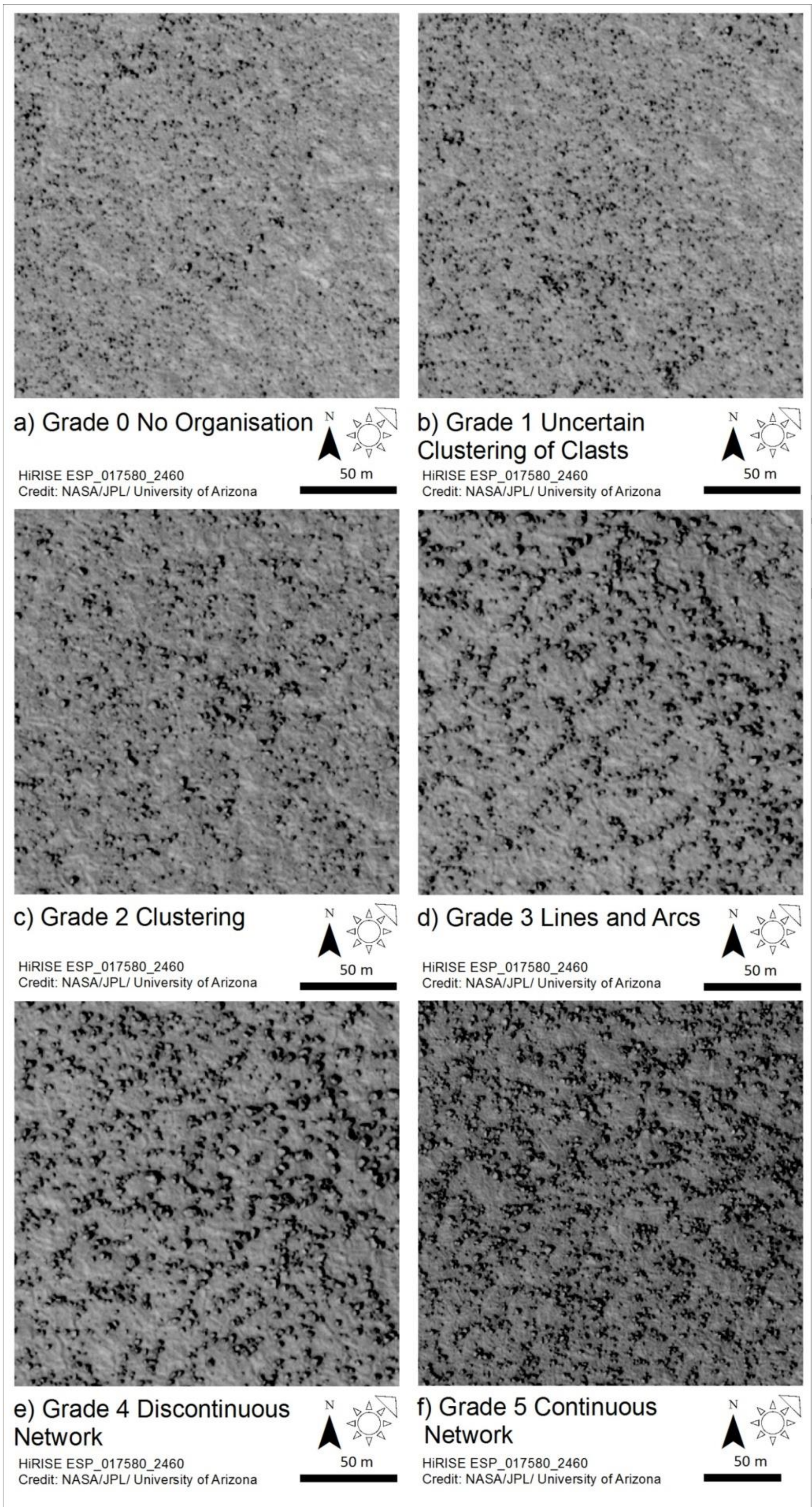


Figure 8: Illustration of sorting grade classification. a) Randomly arranged boulders with no discernible organisation, b) uncertain clustering of clasts, c) definite clustering, d) lines

and arcs, e) discontinuous network, f) clear network. Reproduced from Barrett et al. 2017 (fig 4)

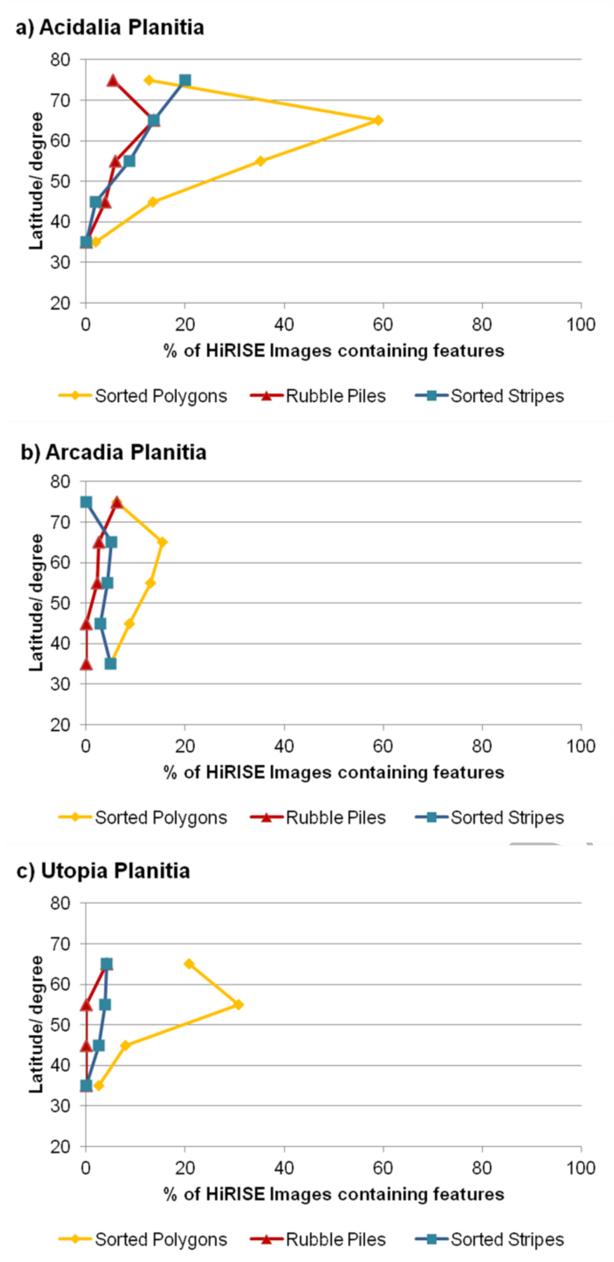


Figure 9: Latitudinal distribution of clastic patterns on the northern martian plains. a) Acidalia Planitia, b) Arcadia Planitia, c) Utopia Planitia. These data indicate the proportion of surveyed HiRISE images in which features occur.

Figure 9 summarises the latitudinal distribution of clastic patterns on the Northern Plains. Occurrences of sorted polygons peak between 60 and 70^{o}N in all study areas except Utopia where it occurs in the 50-60^{o}N range. Rubble piles are generally more common in the northern latitudes, although the latitude of peak occurrence varies. There are too few examples of sorted stripes to draw definite conclusions, but they also appear to be slightly more common at higher latitudes. Figure 8 plots the locations of all features found within the HiRISE survey. Sorted features were found more frequently in Acidalia than in either Arcadia or Utopia. Utopia Planitia has the fewest examples, few features are found at lower latitudes in this area.

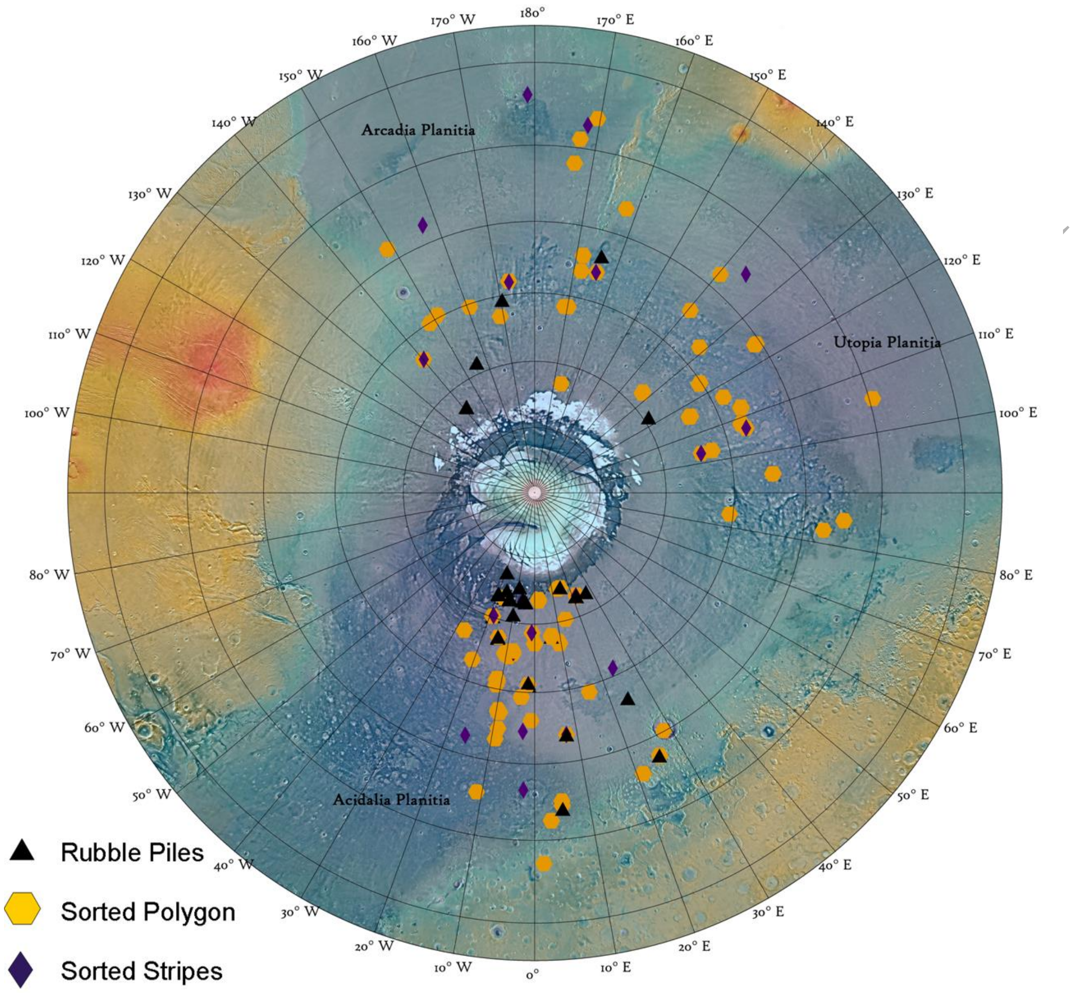


Figure 10: Distribution of different types of clastic patterned ground across the northern plains. Polygons are most common, with many rubble piles at high northern latitudes and several examples of possible sorted stripes scattered across the areas surveyed. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

The region around Lomonosov crater in northern Acidalia Planitia has the highest concentration of possible sorting sites. 51 sites across 17 HiRISE images exhibit sorting of grade three or above, and most of the best examples are found here. Elsewhere in Acidalia Planitia, 21 possible sorted patterns were found, mostly to the north of 40°N. The highly-graded sites occur north of 50°N and are much more common in the western part of the study area. Rubble piles are predominantly found at high latitudes although one uncertain feature may occur at 43°N. Possible stripes are found between 35°N and 70°N.

In Arcadia Planitia possible sorted polygons are found between 36°N and 73°N, with the majority of features, including the higher graded ones, occurring north of 55°N. Six possible sorted stripes were observed, with large scale stripes located between 64°N and 37°N, and smaller stripes at 34°N. Rubble piles are found between 54°N and 73°N. This fits with the distribution seen in Acidalia Planitia where rubble piles and higher graded sites occur further north with a few low-grade polygons further south.

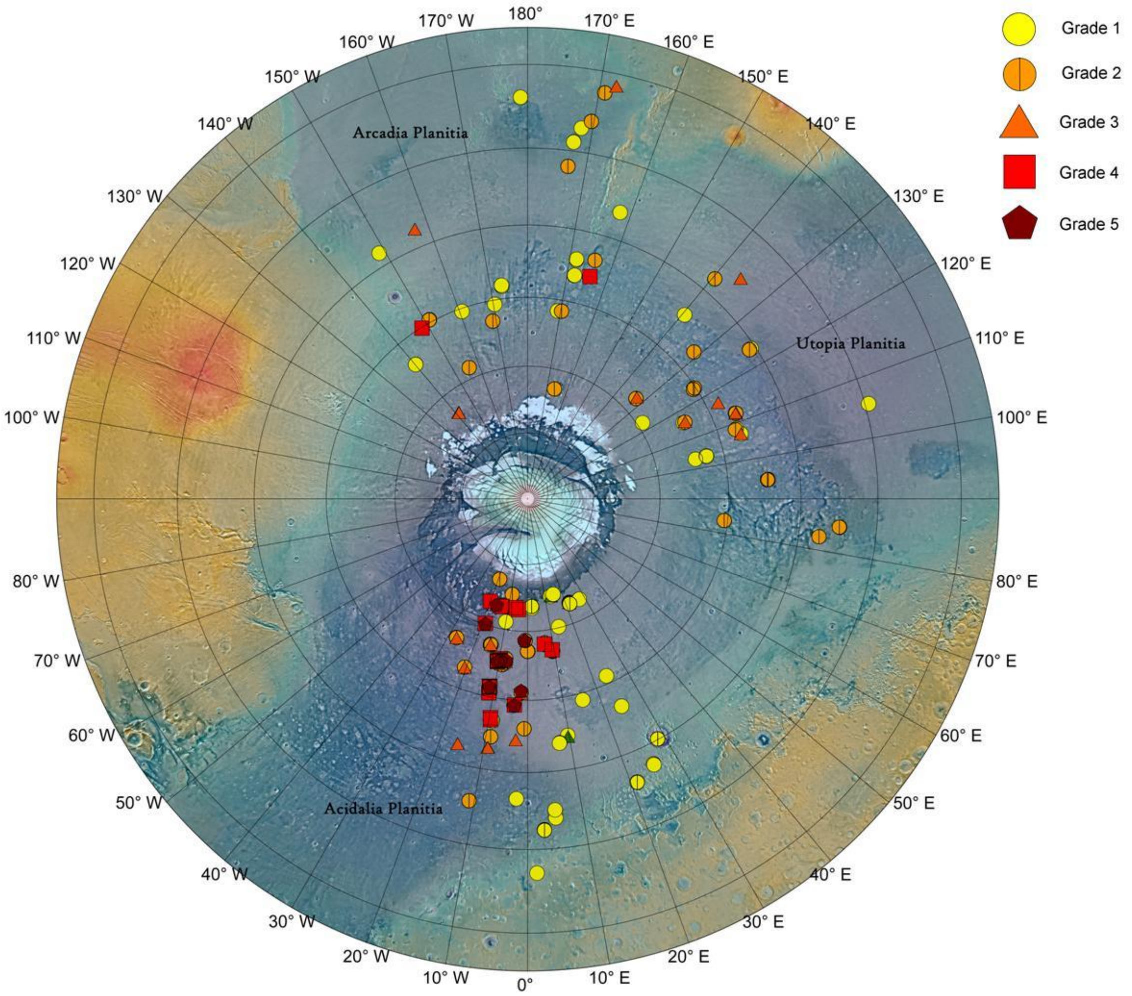


Figure 11: Possible sorted features classified by similarity to the type examples. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

This trend is supported by the results from the Utopia Planitia study area where areas of possible sorting occur between 40°N and 68°N, but most, including the higher graded sites, occur between 50°N and 65°N. Sorted polygons are always found most frequently, with fewer occurrences of stripes and rubble piles. Three possible examples of sorted stripes were found at 46, 57 and 64°N. However, rubble piles were absent from this study area except for one very uncertain example.

Sorted patterns are not common across most of the areas surveyed, but they are present over a wider area than previously thought. Most prior surveys were restricted to high northern latitudes. Balme et al. (2009) found sorted patterns at equatorial latitudes, but this was an unusual case since it occurred in proximity to the Athabasca Vallis where water has been in abundance in the geologically recent past (Murray et al., 2005). Most southerly regions are expected to have much less ground ice, precluding the easy formation of periglacial features.

These data indicate that possible sorted features occur as far south as 35°N, albeit with a lower confidence than many of those sites found further to the north. This is on the edge of the region where ground ice is expected to be stable. There is no clear reason why the most numerous examples of this terrain should be found in the western part of the Acidalia study area.

2.2. Lobate hill-slope features

Several sites exhibiting structures of a lobate morphology have been found in this survey, but most are highly uncertain. These features are extremely uncommon and have only been found in a few isolated locations. Very few examples of lobate terrains were found within this study area, and even fewer were classified with high grades. Figure 12 shows examples of each grade of lobate feature. Only those of grade three and above are considered likely to be evidence of solifluction processes. Those with lower grades have some morphological similarities to lobate hill-slope features, but are too ambiguous for a definite classification. They are not distinct enough from other terrains to be reliably identified.

In Figure 12, Inset a) shows possible lobate structures at the end of gully fan deposits in HiRISE image ESP_017534_2390. This site, in the Arcadia study area, is included as it is in proximity to both gullies and scalloped depressions. However the lobate features are highly ambiguous and it is possible that the way in which the gully fan overlays the underlying fracture polygons is producing the appearance of a lobate morphology, where none in fact exists.

Inset b) shows faint lobate bands in HiRISE image ESP_017026_2535 in the Acidalia mapping area. These features have been classified as grade two, since they have a more convincing lobate morphology. However the image is not clear enough for any clasts to be resolved, and it is hard to see whether these features form banks down the hillside.

The features in inset c) have a similar morphology to those in b) but are much more distinct. These features are thus classified as grade three. These features are found in HiRISE PSP_010077_2520 and appear as dark lobate bands on a hillside, overlain by a fracture pattern.

Inset d) shows lobate features adjacent to small clastic stripes in ESP_016810_2260. These have a very distinct lobate morphology. The shadow of the riser can be seen, indicating that these features form a series of lobate banks. However, they are not entirely perpendicular to the slope and so are classified as grade four, rather than grade five. This site is discussed in more detail in Figure 15.

Finally inset e) shows very distinct clastic lobes in ESP_016573_2475. This is the best example of lobate features found during this survey. See Figure 16 for a more detailed view of this site.

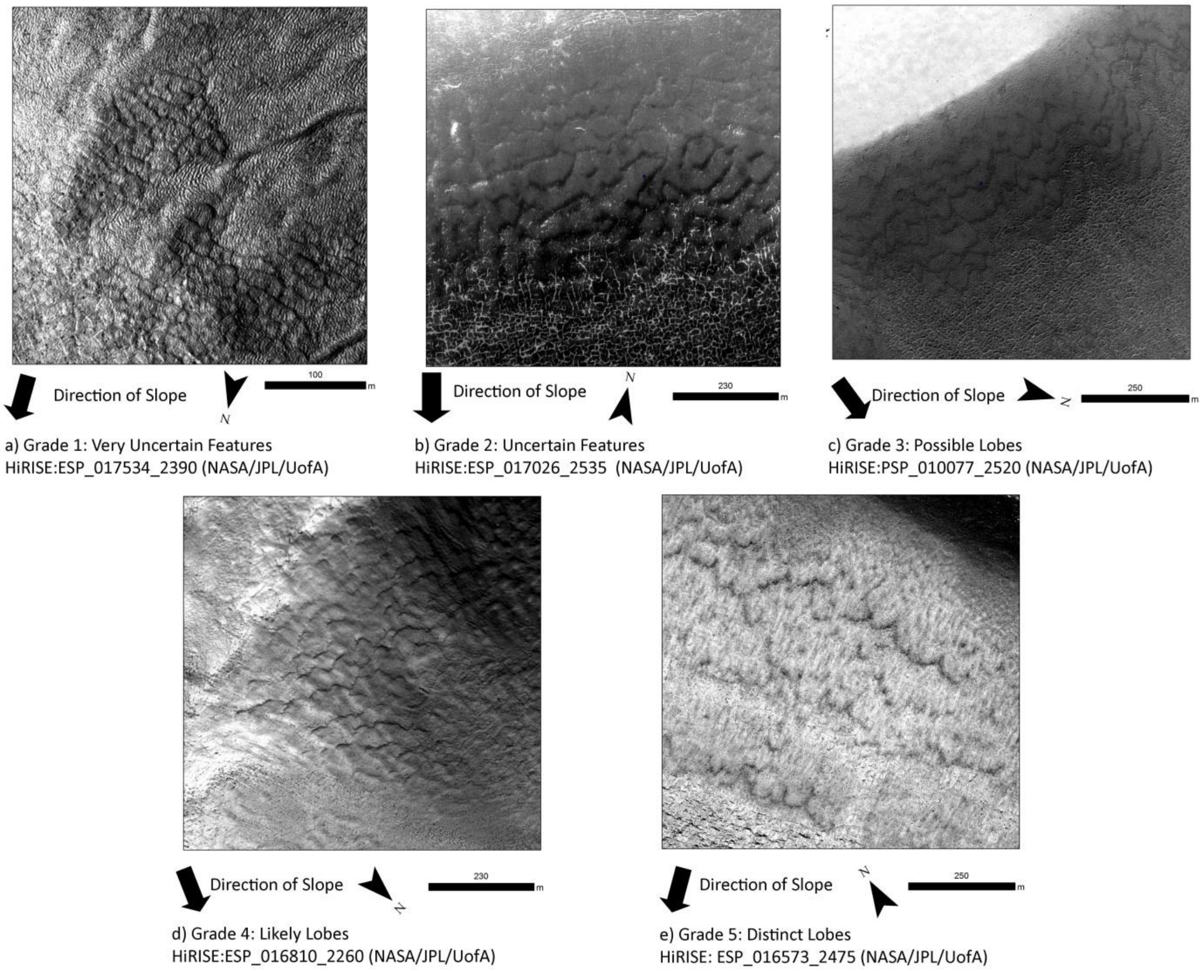


Figure 12: Examples of lobate terrain, showing the classification of grades one to five. a) highly uncertain features, which might have a lobate morphology, b) faint bands on hillside cautiously identified as lobes, c) more distinct bands with a similar morphology to those seen in b), d) distinct lobate structures where the shadow of a riser can be seen, these features are located near to thin clastic stripes, e) very distinct clastic lobes on crater wall.

Figure 13 summarises the distribution of these features by latitude, showing the location of HiRISE images where lobate structures are found. There seems to be a peak in occurrence in the 60-70^{o}N latitude band. This matches the peak occurrence of possible sorted features as shown in Figure 14. However due to the scarcity of these features, and particularly of good examples, this result should be treated with extreme caution.

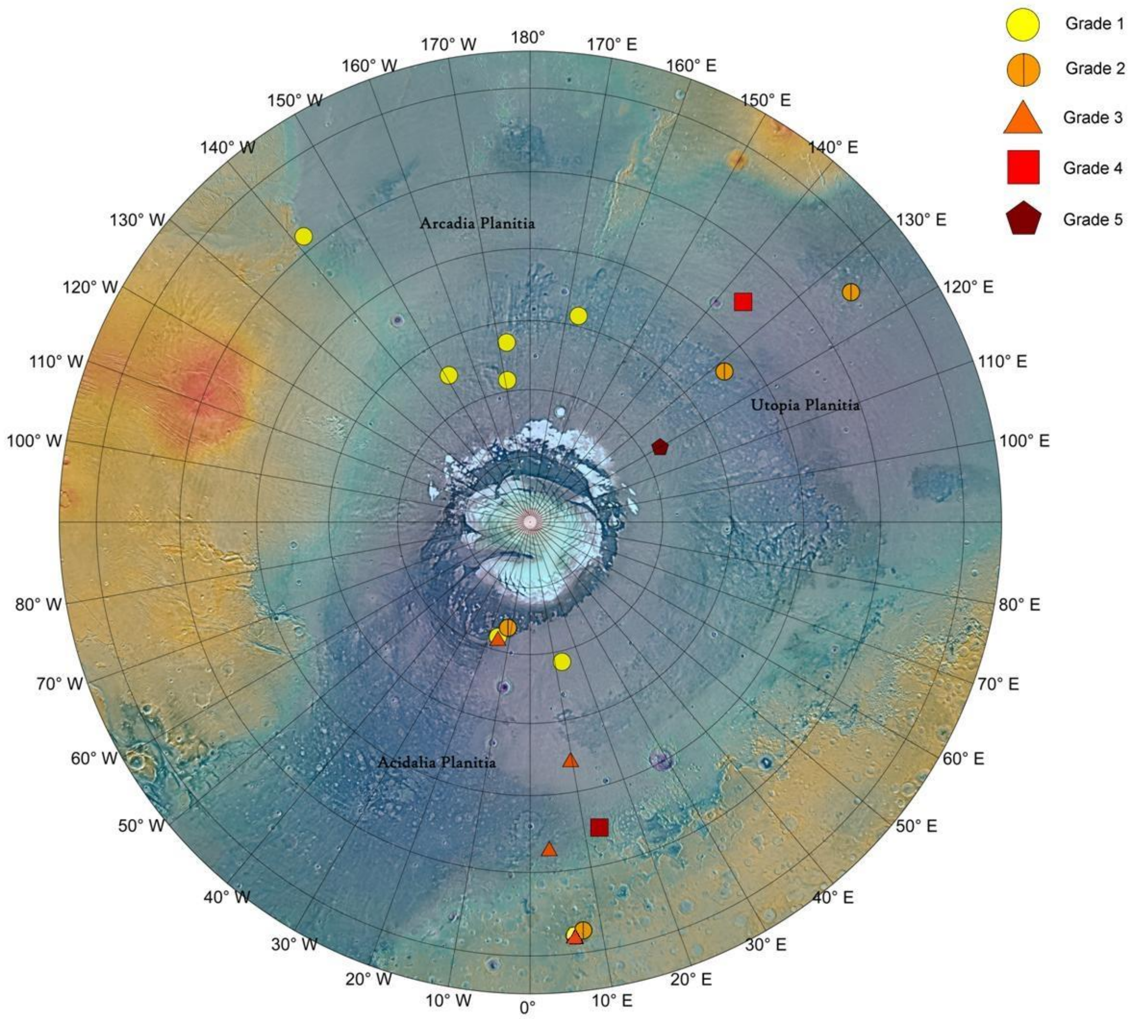


Figure 13: Distribution of possible lobate structures in HiRISE surveys. Grades between 1 and 5 indicate the degree of morphological similarity to solifluction features. The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.

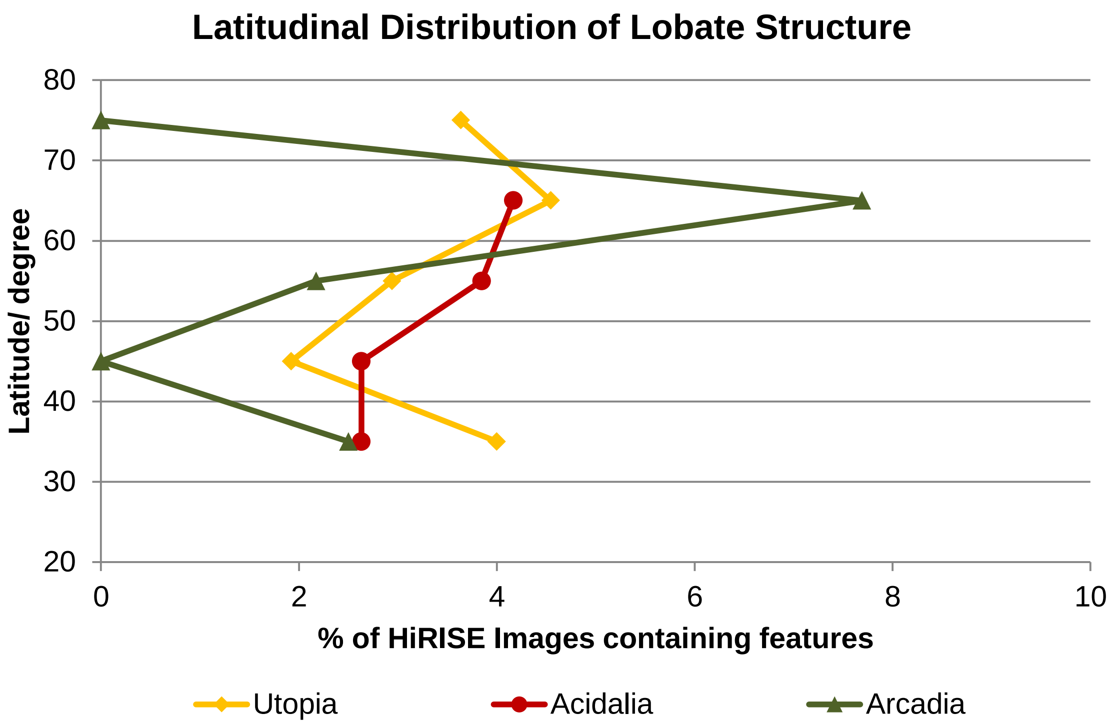


Figure 14: Latitudinal distribution of lobate structures on the Martian Northern Plains; proportion of surveyed images in which features were present.

Acidalia Planitia has the most structures with a lobate morphology, with nine sites across five HiRISE images. However, many of these sites were ranked with a very low grade. Surprisingly most of these features are clustered at low latitudes, below 50°N. The few sites found further to the north had a lower grade. The southernmost possible examples come from a rocky crater around 32°N. However, these features occur on a shallower slope than would be expected for terrestrial lobate structures and are not ranked especially highly. They are thus not considered a strong candidate to be lobate hill-slope features. Much higher ranked examples were also found at unusually low latitudes.

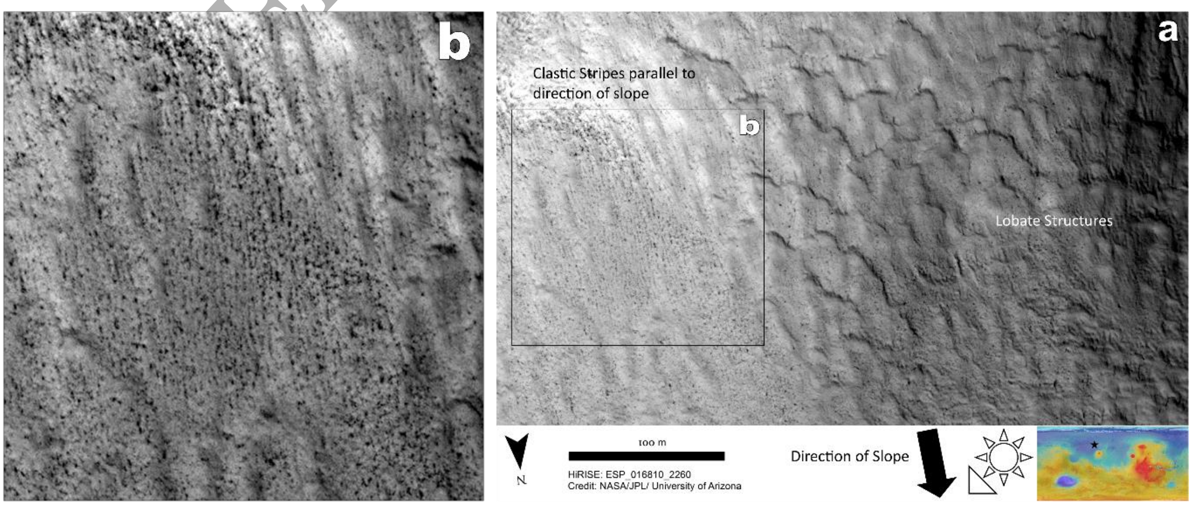


Figure 15: possible solifluction lobes in proximity to thin clastic stripes on the wall of a

small impact crater in Utopia Planitia. a) Overview of site, showing lobate structures at an angle to the direction of slope. b) Very thin lines of sub-metre to metre scale material can be seen to the left hand side of the image. These form discontinuous lines parallel to the direction of slope. The Figure is orientated so that down slope is towards the bottom of the image. This is for ease of comparison with the previous examples of lobate features, which occur on south facing slopes. The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.

The example shown in Figure 15 occurs at 45°N, far further south than the latitude range over which these landforms were expected to occur. The location of these features is surprising. Previous studies had suggested that lobate structures would likely be limited to higher latitudes (e.g. Gallagher and Balme, 2011; Gallagher et al., 2011). If these features are evidence of solifluction it would suggest that such processes are viable further south than previously thought.

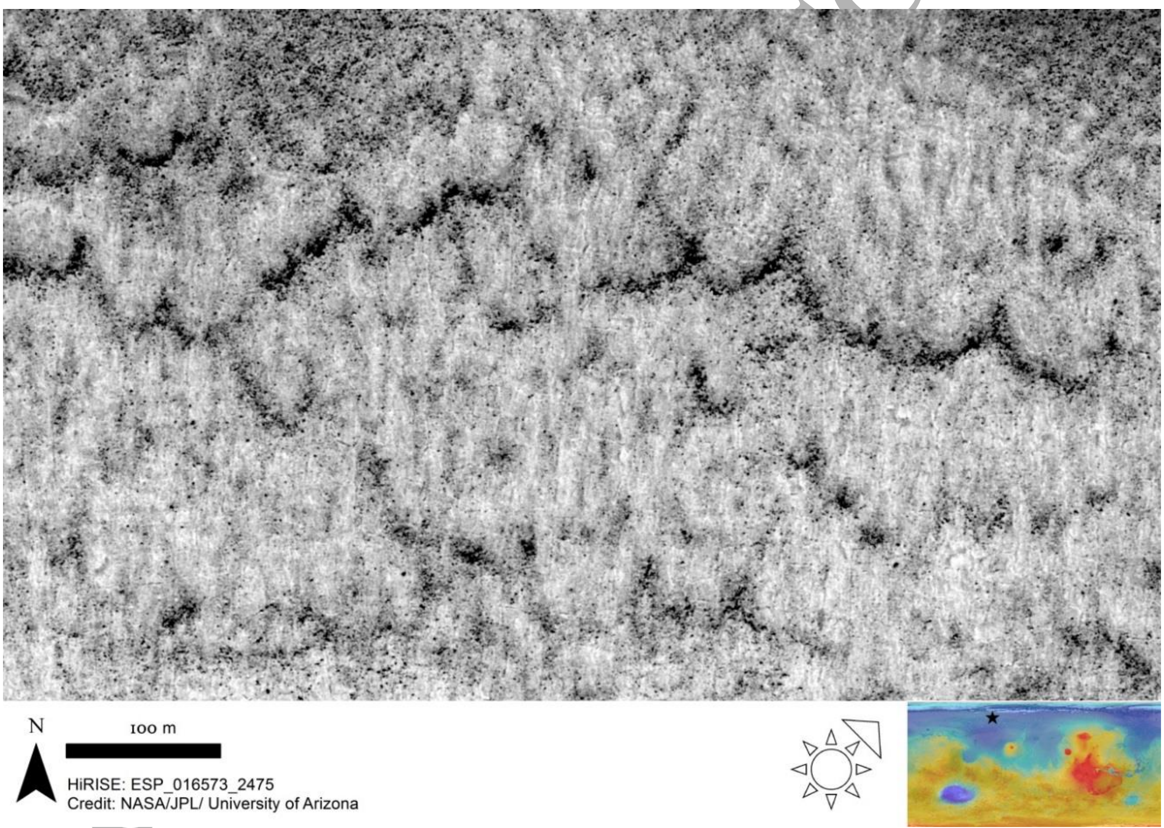


Figure 16: Clastic lobes on the wall of a small impact crater in Utopia Planitia. Down slope is towards the bottom left. A series of arcuate bands can be seen, the edges of which are defined by small clusters of mostly sub metre scale clasts. These are largely perpendicular to the direction of slope. **The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

Utopia Planitia has four sites with possible lobate features. There is no clear trend in latitudinal distribution as possible sites are found between 35 and 67°N. Figure 16 shows clastic lobes at 67°N which appear similar to those described at 68°N in Heimdal Crater by

Gallagher et al. (2011). These clastic lobes are also similar to the "zebra stripes" reported in the hyper-arid environment of Earth's Atacama desert (Owen et al., 2013). While the dry, salty conditions in this desert might make it a good analogue for martian processes, the terrestrial zebra stripes are believed to develop through sheetwash, which would not be expected under martian climatic conditions.

Other clastic features are found at 54^{o}N in Acidalia. The other sites in the Utopia study areas are not stone banked, although one, shown in Figure 15, is in proximity to features which could be very thin sorted stripes. In Arcadia Planitia there are five sites with possible lobes between 59^{o}N and 68^{o}N and one site at 38^{o}N. Only non-clastic features are observed in this area, and few of the examples have a strong resemblance to the type examples.

In summary, lobes are found in a few isolated locations across the study areas, but are not found frequently enough to infer any clear patterns from their distribution. Non-clastic lobes are found across a range of latitudes, and some of the better examples are found at lower latitudes than expected. This suggests that these features may not be limited to the high latitudes as previously thought. Clastic lobes are only found at high latitudes, although very few examples of this type have been found, so no real trend can be drawn.

2.3. Scalloped Depressions

Scalloped depressions were found to be present in all study areas. They were most numerous in Utopia Planitia where 132 sites were found across 36 HiRISE images, ranging in latitude between 40^{o}N and 67^{o}N. Such features occur in 24 images in the Acidalia study area ranging in latitude between 30^{o}N and 57^{o}N. Scalloped depressions in this region extend further to the south than in the Utopia study area, but are not found as far north. In the Arcadia Planitia study area scalloped depressions are primarily found between 37 and 64^{o}N. There are a total of 37 features, across 27 HiRISE images.

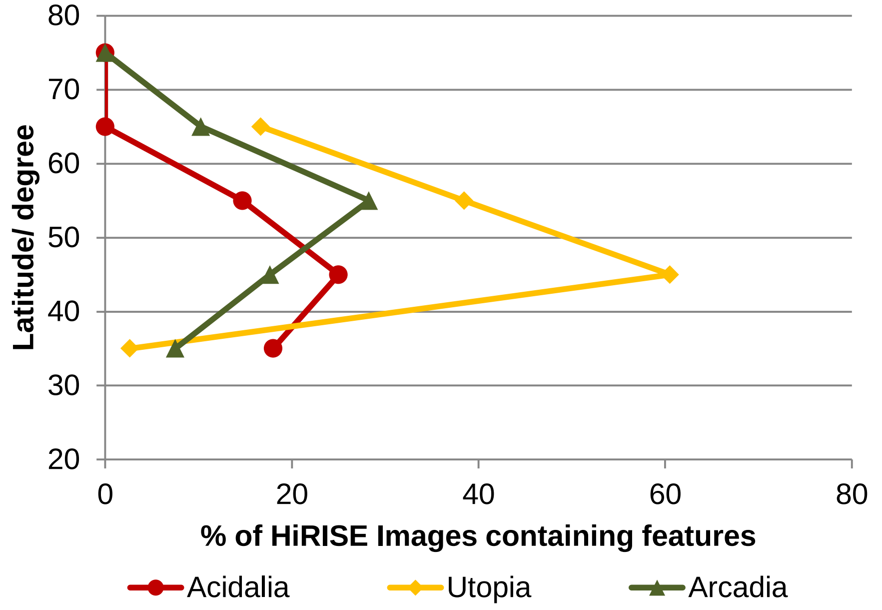


Figure 17: Distribution of Scalloped Depressions on the Northern Martian Plains. Proportion of surveyed images in which features occur.

Figure 17 shows that the peak occurrence of scalloped depressions occurs in the 40-50^{o}N band for both Acidalia and Utopia Planitiae, but is slightly further north in Arcadia Planitia. Occurrences drop off steeply at higher latitudes in all three study areas. More features are found in the 30-40^{o}N band in Acidalia and Arcadia, whereas in Utopia Planitia scalloped depressions at low latitudes are scarcer. Figure 18 shows the geographical distribution of these features. Grades are not shown for this landform, since each occurrence generally consists of a field of scalloped depressions of various grades and types.

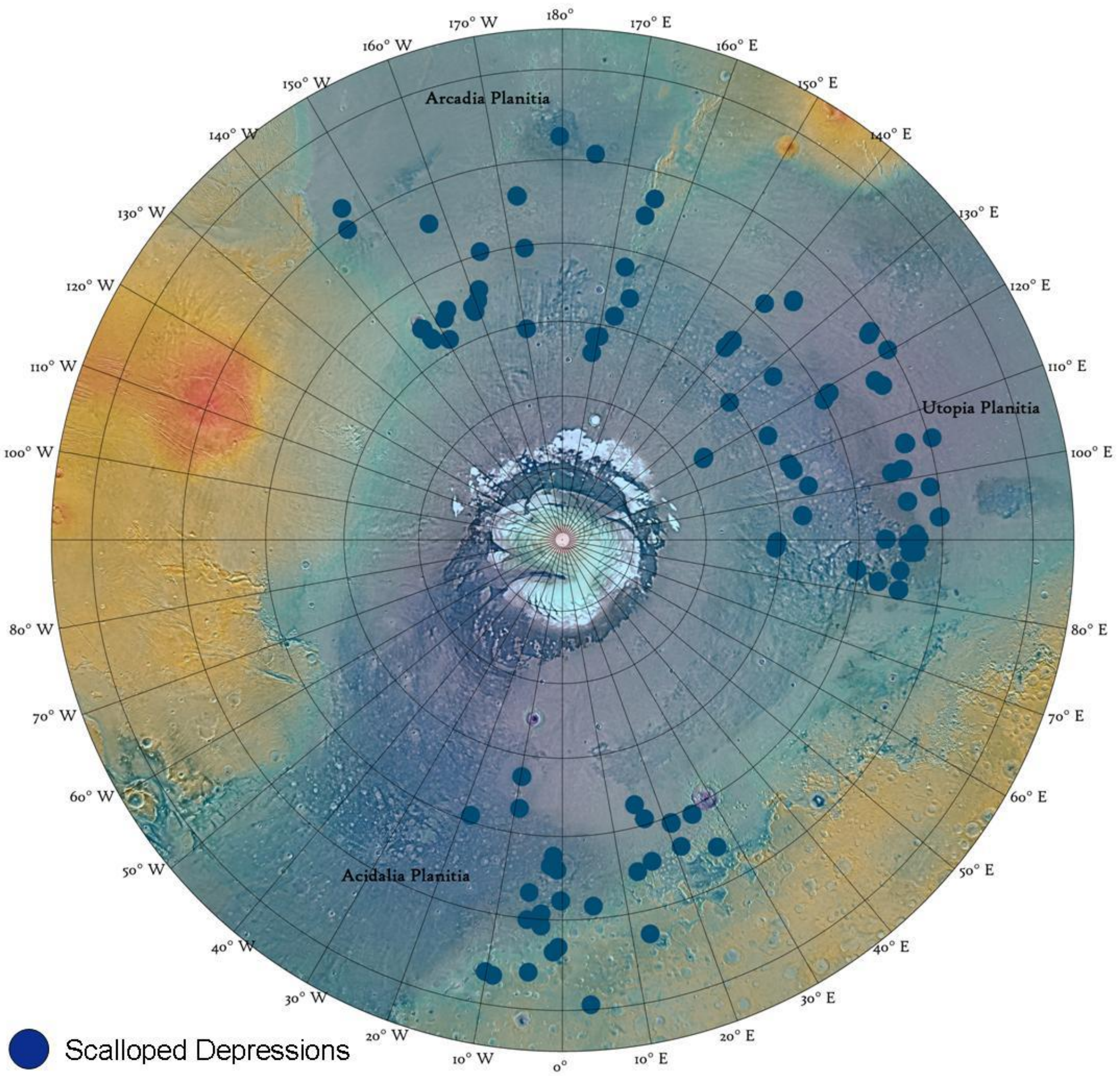
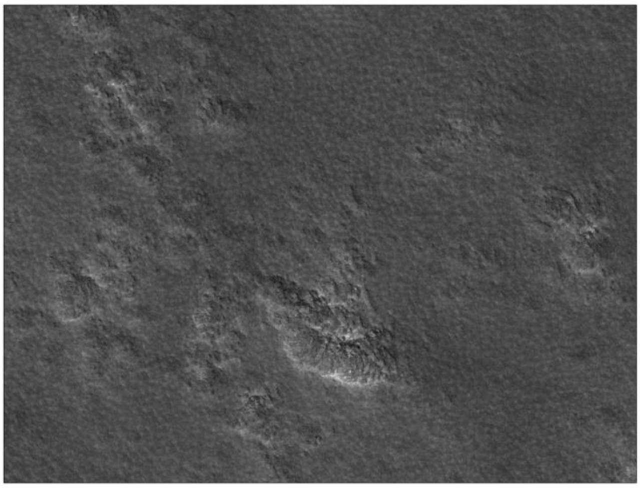


***Figure 18: Distribution of scalloped depressions on the northern plains of Mars from the HiRISE Surveys.* The context map shows MOLA topographic data, where red and blue indicate areas of high and low topography, respectively.**

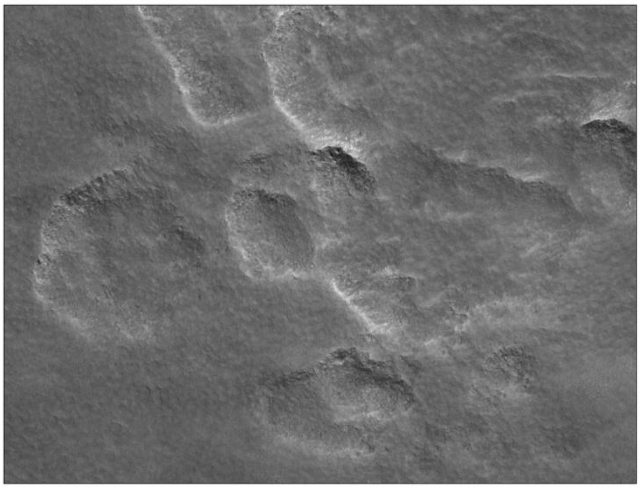
It initially appears that these features are much less widespread in Acidalia Planitia, where they seem to be confined to the regions south of 55°N. However an examination of CTX images confirmed that this was due to a bias in the available HiRISE images. Scalloped depressions in Acidalia Planitia do cover the same latitude range as those in the other study areas, but are not as well represented in HiRISE.

Compared to the sorted and lobate landforms, scalloped depressions are much easier to identify since their appearance is less subjective. The majority of occurrences have either been positively identified as conforming to a scalloped morphology, or disregarded entirely. Consequently, the system of grades applied to the other two landform types is less useful here.

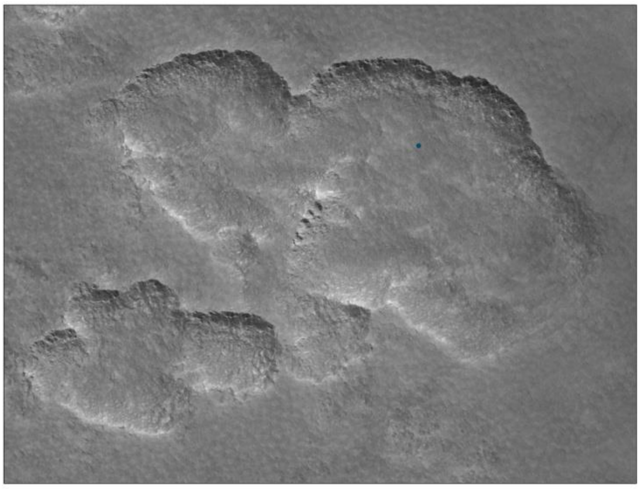
While substantial morphological variations are seen between different types of scalloped depression, these are largely a product of the size, and maturity of the features. As shown in Figure 19 the medium sized depressions tend to be the most characteristic features. They are typically distinct depressions, which exhibit a clear scalloped edge. These features were typically classified as grade 5. The lowest graded areas consist of small patches of pitted or degraded ground, which frequently include numerous small depressions, some of which appear to be in the process of merging to form larger structures. While these depressions may overlap, they generally do not yet have a well developed scalloped morphology. The largest scalloped features occur where large amounts of degradation have occurred and numerous basins have combined to form extensive areas of degraded ground. In these areas the scalloped morphology is also harder to discern, as the actual limits of the structures can be ambiguous. Consequently they are generally classified with grades 3-4.



a) Grade 1-2 features: Pitted ground and the early stages of scallop development



b) Grades 3-4: Shallow depressions and areas of heavily degraded ground.



c) Grade 5: Distinct depressions with clear scalloped morphology.

N 0.5 Km

ESP_025352_2355
NASA/JPL/University of Arizona

Figure 19: Examples of scalloped depression grades. a) Small scale features of grades one and two; b) features of grades three and four, including both small, less developed structures, and larger, more mature features; c) distinct, medium sized scalloped depressions of grade five.

The result is that both small and large features can potentially be classified at the same grade, while the medium sized features are graded most highly. There is generally substantial overlap between the categories, since an area of scalloped ground will typically include representatives of multiple grades.

A more useful classification scheme can be expanded from that of Séjourné et al. (2011). They define a classification system based on the evolution of scalloped depressions from small sub-circular structures to increasingly complex basins, where multiple features merge, suggesting multiple phases of development. Mature structures merge and overlap, developing increasingly scalloped edges as they expand. In many places scalloped depressions appear to occur in proximity to patches of heavily pitted or degraded ground. This may represent an early stage of development. As pits are formed, sublimation or melting of the exposed ice is facilitated. This allows an increasing amount of degradation to occur. Pits widen and coalesce forming scalloped depressions. A similar evolution from isolated pits to more complex connected systems is seen in thermokarst environments on Earth (Wallace, 1948). This is a useful analogue, even if the martian features form through sublimation, rather than thaw.

The Séjourné et al. classification scheme includes more detail at the early stages of development, with the first four categories being equivalent to the “young” landscapes defined by Wallace, while the fifth and final category, “merging features”, corresponds to Wallace’s “mature” landscapes. Wallace additionally describes “late mature” and “old age” thermokarst features where the landscape is dominated by a large scale assemblage of linked basins. This type of landscape is found in some parts of the survey area, necessitating a sixth type to be added to Séjourné’s classification system to describe these “late mature” features.

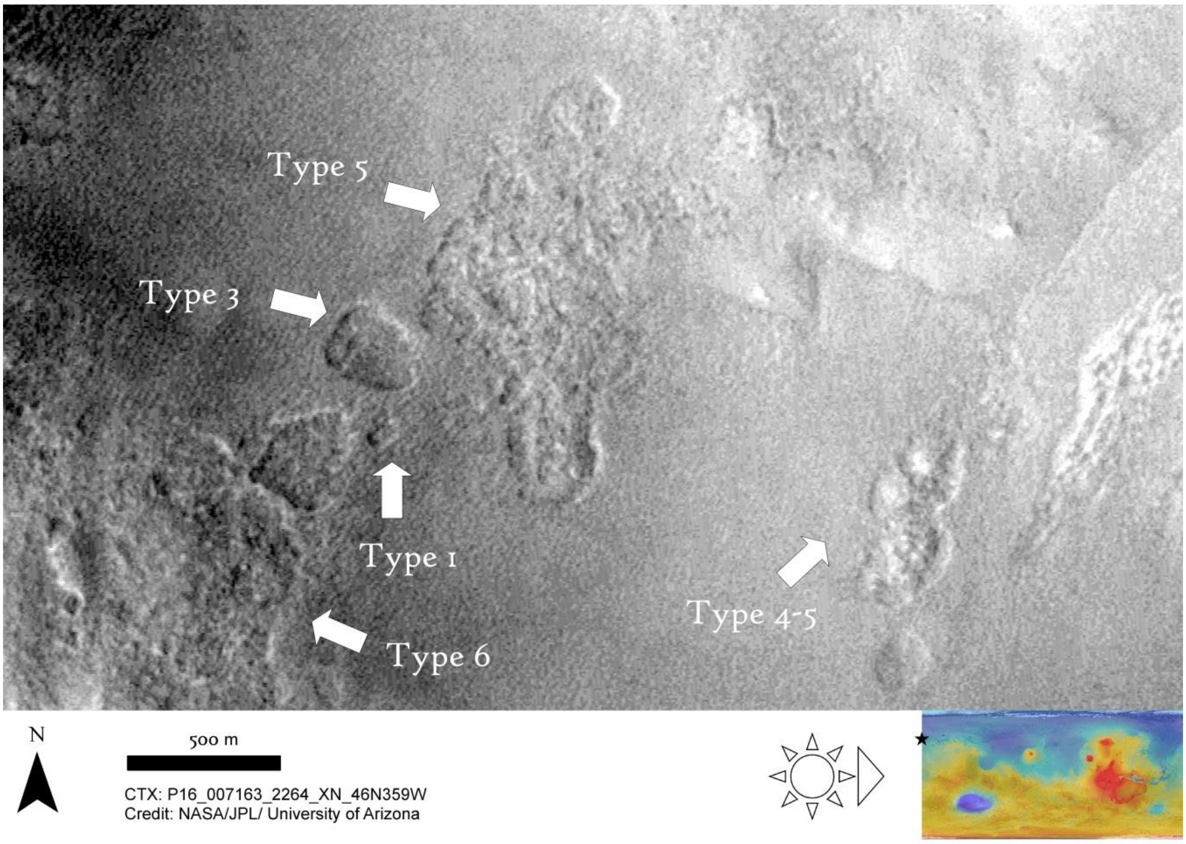


Figure 20: A variety of Scalloped depression types, as defined by Séjourné et al. (2011) including a sixth category, based on the "late mature" stage of terrestrial thermokarst development described by **Wallace, (1948). The context map shows MOLA topographic data, where red indicates high terrains, and blue low terrains.**

Since most scallop fields contain examples of a variety of both grades and types, presenting a regional distribution across each study area is not possible for these landforms. A more useful approach is to examine smaller scallop fields in more detail. Such an analysis is beyond the scope of this investigation, a preliminary study of this sort is presented as part of Barrett (2014).

3. Discussion

Table 4 shows the range of latitudes over which various features are found and compares this to the ranges published in previous studies. In general, the latitudinal distributions of landforms found in this survey support those reported in the literature.

Feature	This Survey	Published Studies	
Sorted Patterned Ground	36-77°N	59-78°N	(Gallagher et al., 2011)
		60-70°N	(Orloff et al., 2011)
Lobate Structures	45-74°N	60-80°N	(Johnsson et al., 2012)
		59-75°N	(Gallagher et al., 2011)
Gullies	30-67°N	30-70°N	(Levy et al., 2009b)
		30-80°N	(Kneissl et al., 2010)
Scalloped depressions	30-67°N	~45°N	(Morgenstern et al., 2007)
		40-55°N	(Soare et al., 2012)
		40-55 °N	(Kerrigan, 2013)
		38-54 °N	(Harrison et al., 2017)
Fracture Polygons	30-77°N	50-75°N	(Mangold, 2005)
		35-75°N	(Levy et al., 2009a)
		40-55°N	(Soare et al., 2012)
Hypothesised ice-rich terrains		47-65°N	(Costard, 1989)
		>60°N	(Feldman et al., 2002)

Shallow subsurface ice (<10 cm deep).	>45-55 ^{o}N depending on region.	(Byrne et al., 2009)

Table 4: Comparison of the latitudinal distributions of various putative periglacial landforms to those found by previous studies.

Sites containing clastic patterned ground and lobate hill-slope features occurred most frequently at high northern latitudes. This fits with the observations of previous studies such as Gallagher et al. (2011) and Gallagher and Balme (2010) who reported clastic lobes between 59^{o}N and 71^{o}N and Johnsson et al. (2012) who observed them between 60^{o}N and 80^{o}N. However, examples of clastic polygons and lobate features were also found as far south as 36^{o}N, beyond the southern limits of these studies. While they are more common at high latitudes they are not exclusive to them.

This could imply that the more southerly features developed during past periods when more ground ice was present at mid latitudes. The observation of well-defined sorted circles at equatorial latitudes by Balme et al. (2009) would appear to support this hypothesis. These features, which occur at 5^{o}N, show a clear circular pattern and exhibit denser and more continuous coarse domains than most of the structures observed during the current investigation. However, it is important to note that these features have clearly formed as an out of equilibrium event as a result of the presence of ice from catastrophic flood events and thawing during unusually favourable conditions.

The clastic lobes in Figure 16 occur at 67^{o}N. This is a very similar latitude to that at which similar features described by Gallagher et al. (2011) were observed. Johnsson et al. (2012) also reports clastic lobate structures at, and north of, this latitude. These features occur in the latitude range where most clastic polygons are found. All of the anomalously southerly lobate structures either lack a stone banked morphology, or stones are below the resolution of the image.

The site illustrated in Figure 15 is located at 45^{o}N. The lobe morphology strongly resembles examples from Johnsson et al., (2012). The proximity to stripes is similar to sites which Gallagher et al. (2011) describe further north. This indicates that similar associations of putative periglacial landforms occur at dramatically different latitudes. This suggests that conditions for the development of such an assemblage can occur over a wider latitudinal range than previously thought.

Most scalloped depressions in these study areas are found to occur within the range 30-55^{o}N. This is comparable to those mapped in Utopia Planitia by the studies of Soare et al., (2007b, 2012) and Séjourné et al. (2011) which were focused around 45^{o}N. Morgenstern et al. (2007) observed greater amounts of degradation and scalloped depression formation at lower latitudes and this is supported by the findings of this study.

3.1. Topographic relationships

In many cases the morphology of a landform, and the physical environment in which it is situated, could indicate how likely it is to have formed through periglacial processes. Martian periglacial features are expected to have a similar morphology to their terrestrial counterparts, and to form the same, consistent assemblages.

Topography plays a key role in the formation of many periglacial features, in particular sorted patterned ground and solifluction landforms. Solifluction is a hill-slope process, which occurs over a relatively small range of gradients (generally 5-20^{o} (Beirman and Montgomery, 2014; Benedict, 1976)). The morphology of sorted patterned ground also changes depending on the gradient on which it forms. Circles and polygons occur on flat ground, while stripes form on slopes (Kessler et al., 2001; Kessler and Werner, 2003; Washburn, 1956). A site containing periglacial sorting would be expected to occur on flat ground if polygonal features are observed, or on shallow slopes in the case of sorted stripes. In areas where a transition from stripes to polygons occurs, a change in gradient should be responsible.

Consequently, constraining the relationships between putative periglacial features and topography is a key tool in determining whether they are in fact periglacial. This is challenging due to the small size of many periglacial features. The topographic variations which are expected to control their morphology are often too small to be resolved when comparing their distribution to data from the Mars Orbital Laser Altimeter (MOLA). A better method is to generate Digital Elevation Models (DEMs) using stereo data from overlapping HiRISE images. However, at the time of this survey stereo images were not available for the majority of sites with highly graded putative periglacial features. As more HiRISE stereo pairs become available it will be possible to assess whether instances of putative lobes and clastic stripes occur on slopes which would be expected to generate such features on Earth.

It was decided to assess the role of topography qualitatively by examining the morphology of features which occur on or near crater walls. The survey results were classified based on their relationship to underlying crater topography, to determine which features occurred within craters, which were on the crater ejecta and which were on the inter-crater plains. The near crater environment was chosen for this analysis, since the approximate slope of different sections of a crater is apparent from the geomorphology. The interior of most simple craters is relatively flat, while the slope of the crater wall is fairly well constrained. Crater ejecta generally consists of rough topography, while the inter-crater plains are usually flatter.

A GIS was used to compare feature locations to the mapped extents of craters (Robbins and Hynek, 2012). Features within the interior of the crater are defined as those on the crater floor or walls. Near crater features are those within five kilometres of the crater rim. These features are almost always on the crater ejecta. Inter-crater features are defined as those further than five kilometres from the edge of the crater. In most cases this is beyond the extent of the crater’s ejecta, however there are larger impact craters within the survey area such as Lomonosov and Lyot Craters. In these cases features could be classified as inter-crater despite still being on the ejecta so care had to be taken in interpreting these results. Table 5 summarises the distribution of all graded features between the three classes.

			Interior			
Feature Grade:	**5**	**4**	**3**	**2**	**1**	**Total**
Sorted Stripes	1	0	5	1	5	12
Sorted Polygons	3	12	16	21	22	74
Rubble Piles	0	0	2	1	9	12
Scalloped Depression	3	13	45	48	20	129
Lobate Structures	1	1	4	4	5	15
			Near crater			
Feature Grade:	**5**	**4**	**3**	**2**	**1**	**Total**
Sorted Stripes	1	0	1	0	4	6
Sorted Polygons	0	0	4	18	21	43
Rubble Piles	1	0	2	3	2	8
Scalloped Depression	0	7	15	14	5	41
Lobate Structures	0	0	2	2	3	7
			Inter-crater plains			
Feature Grade:	**5**	**4**	**3**	**2**	**1**	**Total**
Sorted Stripes	0	0	1	0	0	1
Sorted Polygons	4	14	20	15	7	60
Rubble Piles	1	6	4	8	0	19
Scalloped Depression	1	1	4	11	1	18
Lobate Structures	0	0	0	0	0	0

Table 5: Location of graded features relative to impact craters.

It was found that most putative periglacial features occur either in crater interiors (242 putative features) or in the near crater environment (105 features). 98 features were found on the inter-crater plains. These do not seem to have any relationship to a crater. However, there was substantial variation between the different feature types. Scalloped depressions were primarily found within crater interiors, with a smaller population occurring in the near crater region. Very few were found on the inter-crater plains.

Lobate structures and clastic stripes were almost always found in or around craters. Most were found on the inner crater walls. A few were found on the ejecta blankets, which characterise the near crater environment. No lobate features and only one set of grade three clastic stripes were found in the inter-crater area. This distribution could be explained by a tendency for these features to form on slopes. On Earth both sorted stripes and solifluction features are the results of hill-slope processes, so would be expected to occur on crater walls, or other sources of topography. On the inter-crater terrain, there are fewer sources of high relief, so fewer locations where hill-slope features can form.

Mellon et al. (2008) have reported the presence of stripe like features on flat ground, in an analysis of images from the Mars Orbiter Camera (MOC). However those features lacked the clastic morphology of the stripes examined in this study. It is possible that such a morphology is present, but is below the resolution of the MOC images. There is thus a precedent for martian stripe morphologies on flat surfaces.

However, the results of the present study do seem to support the hypothesis that clastic stripes occur preferentially on hillslopes. Several examples of clastic stripes were observed on the perimeters of the crater interior, and were seen to grade into isolated rubble piles towards the middle of the crater (for example in PSP_007597_2530 and ESP_017685_2490). At both of these sites the morphology is most stripe-like on the crater walls, becoming more discontinuous and breaking into rubble piles as they approach flatter ground.

The other clastic features did not exhibit the same pattern. A roughly equal proportion of sorted polygons were found in crater interiors as on the inter-crater plains. Slightly fewer occurred in the near-crater region. A similar pattern was seen for rubble piles, which were less numerous overall. Sorted networks on Earth are found on flat ground, so the observation that they occur equally within crater interiors and on the surrounding plains supports this hypothesis. Clastic polygons are more frequently found on the flatter floors of craters than on the steeper crater walls, although there are some exceptions.

These findings support the hypothesis that the distribution of these features is topographically controlled. Furthermore, the nature of that control appears to fit with that predicted by terrestrial analogues.

3.2. Expanded survey

The additional HiRISE images surveyed in western Acidalia Planitia do not intersect craters. If putative periglacial landforms occur most frequently in crater environments, then this area would not be expected to yield a substantially larger number of feature detections. It thus provides a test for the crater control hypothesis, which was formulated as a result of the observations of Gallagher et al., (2011).

The results of the survey show that the presence of impact structures does not appear to control the distribution of clastic patterns in this region. Sorted polygons are found much more frequently in western Acidalia Planitia than in other regions. This is largely due to the presence of an area of concentrated patterned ground in the region around Lomonsov crater. However, a large number of these sites occur beyond the Lomonosov ejecta blanket, and do not appear to be associated with an impact structure of any sort. Many of these features occur in images which do not contain medium sized impact craters and so would not have been sampled in other study areas. Whether the increased number of detections is due to the larger number of images surveyed, or the prevalence of clastic networks in this region is harder to determine. Similar concentrations of sorted features were not found in the other two study areas.

It is interesting to note that features such as lobate structures and sorted stripes, which are predicted to be topographically controlled, have similar numbers in the Acidalia region as elsewhere. This suggests that a similar number were sampled in the areas where craters were targeted as in the region where all images were surveyed. This could potentially support the hypothesis that these features form preferentially in or near craters, although, the same trend is seen with number of scalloped depressions in these regions.

3.3. Microclimates and brine facilitated thaw

Some of these landforms, in particular scalloped depressions, can be explained by sublimation processes (e.g. Dundas et al., 2015). Dry mechanisms for the formation of clastic patterned ground rely on the gravitational slumping of clasts into fracture polygons (Levy et al., 2010; Mellon et al., 2008), or the interaction with fracture polygons and CO_2 frost (Orloff et al., 2011, 2013; Orloff, 2012). However neither of these mechanisms can adequately explain many of the features observed in this study, where boulder patterns do not appear to be fracture controlled (Barrett et al., 2017).

Lobate hill slope features are difficult to explain without the action of thaw. Dry granular avalanches have been observed on the moon (Kokelaar et al., 2017). These have lobate ends, and frequently contain clastic material. However they are morphologically distinct from the examples of lobate features observed in the present study. The martian lobate features do not occur at the ends of long debris flows, and have a stepped morphology, with a series of banks of lobes progressing down a hill side. This is not characteristic of the examples presented by Kokelaar et al., (2017), and is instead a much closer match for terrestrial lobate hill slope features.

On Earth, solifluction features are a very common expression of mass wasting processes in ice rich environments. The relative lack of such features on Mars is thus surprising, unless the conditions required for them to form only occur in very unusual microclimates which have not been sampled frequently in this survey. However the lack of detections may partly be due to their very small size relative to the larger scale features such as gullies and scalloped depressions. The surface expression of lobate forms is often ambiguous, and they can be difficult to identify in low resolution images. Relatively small size of these features also means that they would be expected to degrade faster than larger scale landforms.

Gallagher and Balme (2011) proposed that crater interiors might be atypically wet environments, as they would be a source of high insolation slopes where the thawing of cryobrines could take place. This hypothesised thawing mechanism suggests that the depression of the freezing point of water by near-surface brines could facilitate periglacial processes (Möhlmann and Thomsen, 2011). Cryobrines could allow for regular freezing and thawing within the range of temperatures common at the martian surface (e.g. Davila et al., 2010; Möhlmann and Thomsen, 2011) providing a source of liquid water at the regular intervals required for seasonal periglacial cycles. Brines such as magnesium perchlorate, are believed to be present on the Northern Plains of Mars, having been observed at the Phoenix landing site (e.g. Cull et al., 2010; Hecht et al., 2009). This region is close to examples of clastic stripes and lobes observed by (Gallagher et al., 2011).

Möhlmann (2011) has suggested that cryobrines should be stable between 60-80^{o}N during the late northern spring. They state that occurrences of cryobrines will be less common at mid to low latitudes. The majority of examples of clastic patterns are found at latitudes where cryobrines would be expected to form. Almost all the grade four and five features occur above or around 60^{o}N. However, many lower graded examples occur much further south. Many of these features also lie beyond the region in which ground ice is currently stable and where the presence of excess ice is estimated from Water Equivalent Hydrogen (WEH) data (Boynton et al., 2010; Feldman et al., 2004, 2002).

This could rule out a cryobrine facilitated explanation for these low latitude features. However, another possibility is that low latitude features formed during a period when conditions at those latitudes were more favorable for periglacial processes, either facilitated by cryobrines, or due to thawing of purer water. In this case the low graded nature of these structures could be the result of substantially more degradation disrupting older, relict features.

This explanation may account for the presence of lobate features at low latitudes. Only two examples of lobate structures with a grade of 3 or above are found to the north of 60^{o}N, so it seems likely that these features can develop at a wider range of latitudes than that over which ‘freeze-thaw’ of cryobrines is currently expected. If these are relict landforms this could account for their relative scarcity.

Alternatively, the fact that fewer examples of lobes are found might indicate that they are occurring in unusual microclimates where thawing of cryobrines is possible. Möhlmann (2011), does not rule out their presence at lower latitudes completely. Möhlmann and Thomsen (2011) suggest that cryobrines are most likely on sun facing slopes, such as those found on the walls of impact craters. A wet microclimate within crater interiors would thus be favourable for periglacial processes.

However, the fact that many features are as widespread on the inter-crater plains as in the craters themselves suggests that they can be sustained in a variety of locations without the large scale topographic control, and stratigraphic inversion, provided by a crater. They are not restricted to a specific, topographically induced microclimate, although this does not make locations with such microclimates any less suitable for them.

This is significant as it means that putative periglacial features are potentially more widespread than previously suggested. Future investigations should not focus on crater interiors at the expense of surveying the inter-crater plains. Further research is needed to constrain which more subtle factors, whether chemical, climatic or topographic, control the occurrence of wet environments. Determining whether hydrated salts exist in the near subsurface of putative periglacial sites could be a key tool in testing this formation hypothesis. The presence of both ground ice and cryobrines would indicate the strong possibility that thawing could occur. If cryobrines are not present, then thaw could still occur if local environmental conditions are favourable.

4.5. Further Work

These results summarise the regional and latitudinal distribution of features which have frequently been proposed to be analogues for terrestrial periglacial landforms. The purpose of this work was to expand the catalogue of putative periglacial sites, and draw attention to locations where multiple features are present within the same HiRISE image. These results open the door to more in depth climatic and geomorphological analysis.

Firstly, it appears that many of these features do not occur preferentially within crater interiors, but are found with similar frequency on the inter-crater plains. Consequently it would be valuable to expand upon this survey to examine all HiRISE images within the target areas. When an expanded survey was conducted in the Acidalia region it provided a substantial number of sites which occur far from medium sized impact craters.

Secondly, it would be valuable to compare the distribution of features presented herein to regional climatic and environmental parameters. Preliminary research into this area is presented in (Barrett, 2014) where distributions are compared to water equivalent hydrogen maps for the northern plains (Feldman et al., 2004). It would also be interesting to compare these findings to the results of regional scale climate models (e.g. Steele et al. 2017a; Steele et al. 2017b), in order to determine whether there is any correlation between sites with putative periglacial landforms and areas where liquid water would be expected to be stable in the geologically recent past. Further work in this area could use data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) to determine the likelihood that water, or hydrated salts are present at specific sites where highly graded landforms are present (e.g. Ojha et al. 2015).

Finally, in depth geomorphologic mapping can be conducted at sites with numerous highly graded features. This would allow the exact relationships between the different features to be assessed, and more precisely constrain topographic control. HiRISE stereo pairs could be acquired for sites of specific interest, so that high resolution digital elevation models of these locations can be produced.

5. Conclusions

Analogues for a wide variety of terrestrial periglacial features are found across the Northern Plains. Some, such as scalloped depressions and gullies are common, while others such as sorted patterned ground are relatively rare. Lobate hill-slope features were found to be particularly uncommon, yet examples of these landforms were still observed in multiple HiRISE images.

Many of these features have been found at lower latitudes than previously known, although the better examples often form preferentially at high latitudes. Some of these landforms are frequently found within craters or in the near-crater environment, as would be expected if they formed because of specific microclimates and in response to the seasonal thaw of cryobrines. However, this was not universally the case.

Clastic polygons were frequently found on the inter-crater plains as well as in crater interiors, so a crater induced microclimate does not seem to be required for pattern development. Other landforms, such as lobate structures and clastic stripes, do appear to occur more often on crater walls, which fits with their hypothesised formation mechanism as hill-slope features. Scalloped depressions occur frequently in and around craters, and are less common on the inter-crater plains. This might suggest that they form preferentially in the near crater environment.

The thawing of cryobrines remains the preferred option to facilitate the formation of sorted patterned ground. In the case of possible sorting, the transition from higher graded to lower graded sites does seem to occur at the latitudinal threshold for cryobrine stability. This would seem to support cryobrine facilitated thaw as a possibility for a formation mechanism, and rule out the southerly landforms as recent periglacial structures. However the size of sorted features casts doubt upon a periglacial origin, as it has yet to be demonstrated that material of this size can be moved by frost heaving under martian conditions.

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