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# The Periglacial Landscape Of Utopia Planitia; Geologic Evidence For Recent Climate Change On Mars.

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Graduate Program in Geography
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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The School of Graduate and Postdoctoral Studies
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## Abstract

The northern plains of Utopia Planitia, Mars, hosts an abundance of potential periglacial landforms including scalloped depressions, gullies, and polygon networks. This research was undertaken to investigate the distribution and stratigraphy of scalloped depressions in Utopia Planitia and to reconstruct the past environment in which this periglacial landscape formed. To that end a revised geologic map of the region has been produced. We define, for the first time, a new Periglacial Unit, the youngest geologic unit in Utopia Planitia. We have also developed a model for the formation and evolution of the periglacial landscape examined by assessing the use of scalloped depressions as indicators of climate change, and combining our geologic evidence with recent climate model predictions. It is concluded that in the recent past Utopia Planitia has experienced an intensified regional climate and a dynamic, evolving landscape that has recorded the changing climate on Mars.

## Keywords

Mars, Utopia Planitia,

Periglacial, scalloped depressions,

Climate change

# Co-Authorship

Contributions to this thesis were made by Dr. Gordan Osinski, Dr. Marco Van de Wiel, and Dr. Radu Capitan. Dr. Osinski and Dr. Van de Wiel provided commentary and feedback on all thesis chapters. Dr. Capitan provided assistance with the production of the figures. Mary Kerrigan is lead author on all chapters and is primarily responsible for all research, writing, and data processing.

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# 1 Chapter 1: Introduction

## 1.1 Periglacial Landscape of Mars

Mars is a frozen world. With a global mean annual temperature of -69 °C (Mellon et al., 2004) the surface of Mars is in a continually frozen state. Compared to the energetic nature of Earth's environment, the ostensibly unchanging appearance of Mars makes the planet seem stagnant, even "dead". But it has not always been so; the Martian landscape presents us with evidence to a more dynamic past, traces of a history punctuated with episodes of volcanic activity (Carr, 1973), impact bombardment (Strom et al., 1992; Carr and Head, 2010), global dust storms (Zurek, 1982; Strausberg et al., 2005), flowing rivers (Baker and Milton, 1974; Irwin et al., 2008), huge oceans (Clifford and Parker, 2001), tropical glaciers (Head et al., 2005; Fastook et al., 2008), and vast ice sheets (Baker et al., 1991). Martian scientists strive to understand these landscapes and ascertain what they can reveal to us about the past environments of Mars and how they have changed over time.

This thesis focuses on the periglacial landscape, a type of landscape that has only been possible to explore fully in the last decade through the incredible high-resolution image data provided by the Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Global Surveyor missions. Many features of the periglacial landscape are so small as to have not been identified until these missions made imagery at <10 m/pixel available. Features such as patterned ground (Mangold, 2005; Balme et al., 2009), networks of polygons (Levy et al., 2009), and scalloped depressions (Séjourné et al., 2011) have now been documented in both hemispheres, stretching from the polar regions (Mellon et al., 2008; Gallagher et al., 2011) to the low, equatorial latitudes (Balme and Gallagher, 2009).

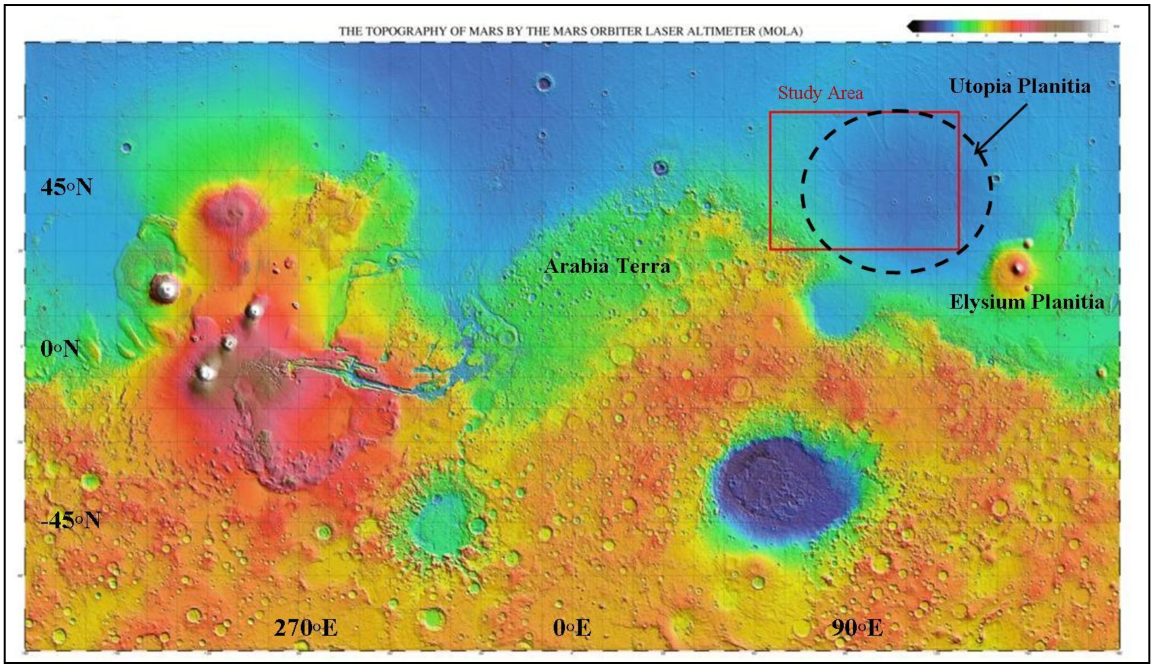


**Figure 1.1** Global topographic map of Mars. The total study area is indicated by the red box. Mars Mercator map projection. Image credit MOLA Science Team (http://marsoweb.nas.nasa.gov/globalData/).

### 1.2 Utopia Planitia

Utopia Planitia, in the northern plains of Mars, is a large, shallow depression approximately 3,300 km in diameter. Centred at 49.7° N and 118.0° E, it lies northwest of the volcanic province of Elysium Planitia and northeast of Arabia Terra (Fig. 1.1). The general geologic history of the region will be discussed in Chapter 2. This region was chosen for examination due to the presence of a large number and variety of periglacial features.

Many studies on the periglacial landscape of Mars are either very broad as to encompass global distribution of periglacial features (e.g., Head et al., 2003), or very narrow focussing on process oriented study of individual features and speculating how they might have formed (e.g., Séjourné et al., 2011). This thesis conducts a study at a regional scale, concentrating on Utopia Planitia. We consider this intermediate scale to be an important link between the features of the landscape and placing the landscape as a whole into a broader geographic context. By investigating how the landscape relates to its surrounding terrain we aim to better understand both the spatial and temporal evolution of the landscape.

### 1.3 Analogue Studies

The periglacial features of Mars all have their corresponding landform on Earth with analogue studies carried out in the Canadian Arctic (Soare et al., 2011), Scandinavia (Hauber et al., 2011), Siberia (Ulrich et al., 2010), and Antarctica (Levy et al., 2009). These analogue landscapes and landforms will be discussed further in Chapter 4 of this thesis.

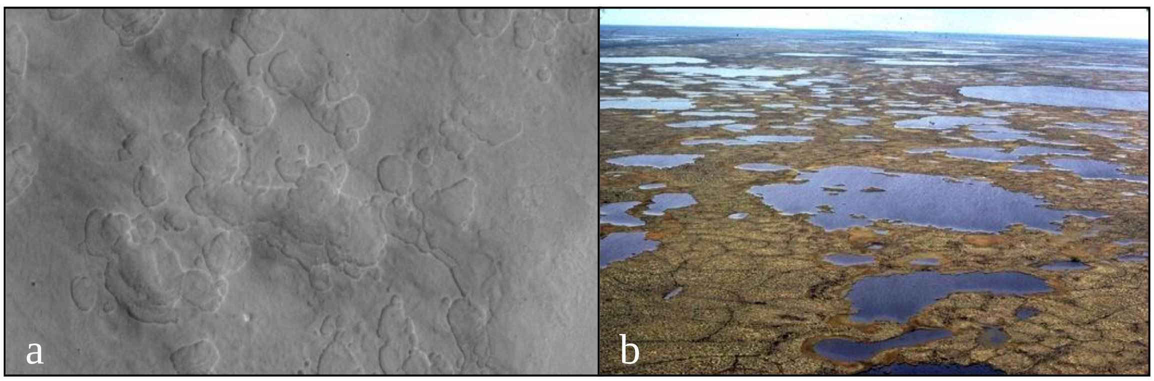


**Figure 1.2** Martian Landforms and their Earth Analogues. a) Scalloped depressions in Utopia Planitia. CTX Image 10 km wide, north at top. B17_016390_2231. b) Thermokarst in Northern Canada. Image ~1 km wide from Geological Survey of Canada.

As with all planetary analogue studies the comparisons are rarely ideal but mostly sufficient. Mars is similar to Earth but never the same. Our knowledge of the physical processes that result in these analogue landforms and landscapes is based on the observation of these processes in action under Earth conditions. Earth could be considered to be a single planetary data point raising a problem whereby landforms on other planets that look the same may have developed through different processes and under different initial conditions.

This problem of equifinality, or the convergence of form where similar landforms are the result of dissimilar processes, is one that pervades all planetary analogue studies but so long as the problem is recognised, tests for validity are applied, and alternative hypotheses are sought, analogue studies are very useful (Balme et al., 2011). Until the Martian landscape can be extensively observed and analysed in situ, Earth analogues, lab experimentation, and computational simulation are not ideal but sufficient.

This thesis will incorporate hypotheses of formation based on analogue studies when discussing how the periglacial landscape of Utopia Planitia evolved. These hypotheses are developed by combining this information with new climate models, which suggest possible climate scenarios in the recent past. This thesis will contribute to Mars periglacial research by bringing together these multiple strands of high-resolution mapping, analogue formation theories, and climate modeling, resulting in a more comprehensive picture of the periglacial landscape of Utopia Planitia in the recent past.

Chapter 2 of this thesis aims to answer the following questions:

1. What is the geographic extent of the periglacial activity in Utopia Planitia?

2. Are the periglacial landforms surface modifications of older units or are they present in a discrete geologic unit?

3. Where does the periglacial activity occur in the stratigraphy of Utopia Planitia?

Chapter 3 gives a summary of the climatic history of Mars and in Chapter 4 we aim to answer the follow questions:

4. What unique characteristics of Utopia Planitia could lead to the formation of the Periglacial Unit? (e.g. latitudinal location, geology, topography, or climate?)

5. What does the record of environmental and climatic change in Utopia Planitia tell us about global climate change on Mars?

Chapter 5 summarises the major finding of this research and outlines areas for future work.

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# 2 Chapter 2

## The Distribution and Stratigraphy of Periglacial Landforms in Utopia Planitia, Mars

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## 2.1 Introduction

Images taken during the Mariner missions in the 1960s and 70s showed the first evidence of a possible periglacial landscape on Mars. Scalloped depressions, pits, and hummocky terrain were identified and thought to be visually similar to thermokarst landforms on Earth (Belcher et al., 1971). Thermokarst areas on Earth are associated with permafrost, ground ice, and the pooling of water at the surface (French, 2007). The prospect of identifying features on Mars that may indicate the presence of present-day subsurface ice and the possibility of surface water in the past have generated interest in their study. Most of periglacial features on Mars are found along the mid to high latitudes in both hemispheres with only rare occurrences below 20°. While they are spread throughout the planet along these latitudinal bands, there are notable areas where periglacial features are concentrated. In the southern hemisphere, the region around the southern rim of Hellas Basin and the north of Malea Planum has a heavy concentration of scalloped depressions (Zanetti et al., 2009). In the northern hemisphere, Utopia Planitia contains the largest and most varied collection of periglacial landforms on the planet. Periglacial landforms, including polygons, scalloped depressions and pingo-like features have been documented in Utopia Planitia by numerous workers (e.g., Costard and Kargel, 1995; Soare et al., 2008; Lefort et al., 2009) and are believed to have formed in the last 10 to 20 million years.

As higher resolution imagery has become available these landforms have been studied in greater detail with the assemblages being recognized as analogous to permafrost and periglacial landscapes on Earth. However, despite studies by numerous workers over the past few years there are still fundamental questions that remain to be answered, including timing and the importance of sublimation versus thaw. It is also important to note that it is more common in the literature for studies to focus on very small spatial scales, sometimes limited to just a few individual landforms, rather than the landscape as a whole. This paper takes a broader approach, identifying and mapping the distribution of periglacial landforms across a wide landscape with the aim of placing the landscape in a regional and stratigraphic context. Understanding the spatial and temporal relationships between the periglacial activity and the activity (e.g., volcanic, depositional) represented by surrounding geologic units will in turn allow us to further postulate the environmental conditions in which this landscape developed. This paper focuses on the periglacial landscape of Utopia Planitia as it is spatially very large, contains a variety of periglacial (and glacial) landforms, is lightly cratered which suggests a youthful age and also means that the landforms are well preserved and visually very clear, and the area has a high level (~90%) of image data coverage.

### 2.2 Study Area

Utopia Planitia is a large basin in the Northern Plains of Mars centred at 49.7° N and 118.0° E with a diameter of approximately 3,300 km. A roughly circular basin, likely formed as a result of a major impact early in Mars' history, forms the basement of Utopia Planitia (McGill, 1989). The first evidence for this basin was indirect as it is entirely buried beneath Utopia Planitia, but the presence and distribution of knobs, mesas, partially buried craters and ring fractures are thought to represent the buried and modified fragments of a basin ring (McGill, 1989). As well as this geological evidence there is also a positive gravity anomaly centred on Utopia Planitia, which also supports the idea of a massive buried depression (McGill, 1989).

During the Hesperian and into the Amazonian periods, Utopia has undergone modification from tectonic and volcanic activity and sedimentary deposition. Early Hesperian ridged plains represent a unit of volcanic flows hundreds of metres thick (Thomson et al., 2001). These volcanic plains were then deformed by tectonic processes resulting in distinctive wrinkle-ridge features. During the late Hesperian the Utopia Basin was a major depocentre for the water and sediments carried by outflow channels and these deposits are known as the extensive Vastitas Borealis formation (Thomson et al., 2001).

Extensive flows in the east of the region towards the Elysium Province are indicative of the volcanic activity of the Early Amazonian (Platz and Michael, 2011). During the Late Amazonian period, approximately the last 500 million years, the basin has been a major depocentre resulting in its gentle slope from rim to centre. This infilling material is an ice and dust mixture thought to be the result of periodic atmospheric deposition driven by changes in Mars' obliquity (Head et al., 2003). The glacial and periglacial activity in the region during the Amazonian represents a complex sequence of geologic and geomorphologic landscape change driven mainly by climatic forcing. This paper will re-examine the ground-based evidence of glacial and periglacial landforms and produce the first detailed stratigraphy for the Late Amazonian in Utopia Planitia. The area studied in detail in this paper is shown in Figure 2.1. It stretches across western Utopia Planitia from approximately 35° to 55° N and 70° to 120° E. The area surrounding this approximately 10° to 20° in all directions was also examined to place our findings in the broader geologic context of the whole region. The whole region surveyed spans almost 6,500,000 km$^2$

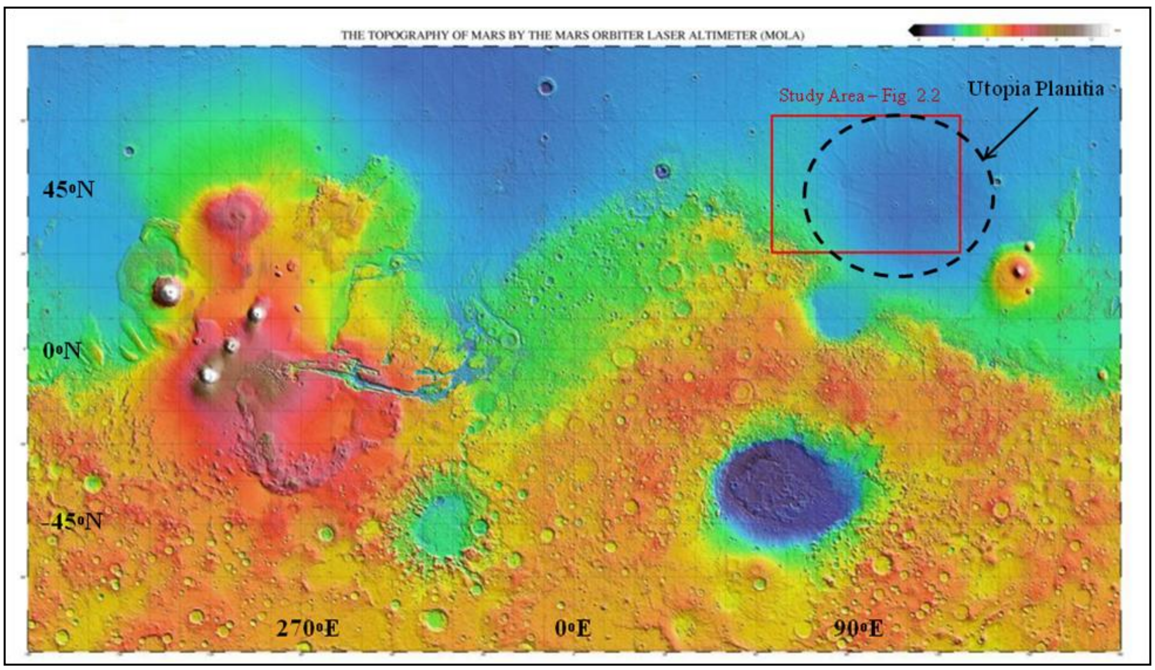


**Figure 2.1** Global topographic map of Mars. The total study area is indicated by the red box. Mars Mercator map projection. Image credit MOLA Science Team (http://marsoweb.nas.nasa.gov/globalData/).

### 2.3 Methodology

Mapping of planetary surfaces is achieved almost exclusively through remote sensing techniques with sporadic, localised information gathered from robotic landers and rovers. Datasets available to the planetary mapper include topographic, spectral, and visual information that can aid in the interpretation of the current state of the area of interest as well as piece together the evolution of the landscape through its geologic past. The construction of a geologic map in this manner involves careful observation and interpretation of the area of interest.

The first step in constructing a geologic map is the identification and delineation of distinct units within the study area. As this map is building upon the work done by Tanaka and others, we also followed the approach demonstrated in Tanaka et al. (2005) with some modifications when deciding how best to distinguish and present a new unit. Since our knowledge of the lithological characteristics of the area of interest is somewhat limited, it is difficult to define units on this basis, especially at the scale desired in this study. Initial observations of the area, however, revealed that the features present may provide clues as to the nature of the material in which they have formed.

In using surface features for defining units it is important to distinguish between primary and secondary features and to determine whether they are diagnostic of a geologic unit. In this case primary features refer to those features formed at the time of the unit's deposition or emplacement. Secondary features refer to those features that have formed after the deposition or emplacement of the unit. Hansen (2000) states that "secondary features absolutely cannot constitute a part of a material unit(s) descriptor or characteristic", on the basis that the formation of the secondary features represents a temporal event distinct from the deposition or emplacement of the unit itself. We would argue, however, that once it is made clear precisely what is being mapped either primary or secondary or both types of features can be used in delineating units for the purpose of constructing a map. In this study, the purpose of the geologic map produced is not only to help construct the geologic history and stratigraphy of the area of interest, but also to build up an understanding of the changing climatic conditions of the area in the time since the deposition or emplacement of the units. In that respect, a unit's evolution since its deposition or emplacement and the secondary features that have formed in it are vital markers to the evolution of the landscape as a whole.

As with any geologic map the contacts between units are presented depending on the degree of certainty of their presence and location. Throughout the region there are challenges in identifying contacts accurately and precisely due mainly to data quality and coverage. There are also challenges resulting from the geology of the region itself. The proximity of visually very similar units means that the contacts between them can be quite subtle. The types of deposition in the region have also resulted in units not having sharply defined edges but rather they dissipate out over a large area. In order to produce a map that is as clear and objective as possible we have classified the unit contacts presented in the map depending on the level of confidence in the accuracy and precision of the placement of the line. Where the difference between units is very clear from the imagery the contact can be placed with confidence and is said to be “certain”. Where the contact is not as clear due to lower quality image data or where the difference between units is more subtle, the drawn contact is said to be “approximate”. This may also be the case where the actual contact between two units is gradual rather than a sharp contact. And, finally, where it is difficult to see the contact between two units (mostly due to lower quality or lack of image data) the contact is placed following on from the nearest certain or approximate contact and it is said to be “inferred”.

With approximately 600 images analysed, this study represents the most detailed investigation of this area of western Utopia Planitia to date. The base map image used is a digital elevation model (DEM) derived from data collected by the Mars Orbiter Laser Altimeter (MOLA) instrument onboard the Mars Global Surveyor (MGS). Overlying the MOLA DEM is a mosaic of visual and daytime infrared images from the Thermal Emission Imaging System (THEMIS) instrument onboard the Mars Odyssey spacecraft. This mosaic has a high level of coverage for the area of interest with some gaps above approximately 50° N between 90° and 100° E. The MGS also carried the Mars Orbiter Camera (MOC), which returned narrow and wide angle images. The narrow angle images were very useful in identifying small landforms while the wide angle images helped put these in a broader, regional context.

| **Instrument** | **Resolution** | **Percent coverage of total study area** |
|---|---|---|
| Mars Orbiter Laser Altimeter (MOLA) | 140m/pixel | 100% |
| Thermal Emission Imaging System (THEMIS) | Infrared – 100m/pixel<br>Visual – 19m/pixel | ~80% |
| Mars Orbiter Camera (MOC) | Narrow angle – 1.5-12m/pixel<br>Wide angle – 240m/pixel | Narrow – ~5%<br>Wide – 100% |
| Context Camera (CTX) | 6m/pixel | ~75% |
| High Resolution Imaging Science Experiment (HiRISE) | 0.3m/pixel | ~2% |

**Table 2.1** Summary of data sources used in this study.

The Mars Reconnaissance Orbiter carries the Context Camera (CTX) and the High Resolution Imaging Science Experiment (HiRISE). CTX images are at a resolution of 6m/pixel and are 30 km wide (Table 2.1). With this level of detail and coverage, CTX images proved to be the most valuable visual dataset in mapping the area of interest. The high resolution allowed small-scale landforms to be indentified while the coverage ensured that they could be viewed in a broader regional context. Often it was in CTX images that a contact between two units was first identified. Where there were gaps in the CTX coverage a contact may become apparent in the THEMIS images after seeing it in adjacent CTX images. HiRISE images were not extensively used for mapping this area. HiRISE captures the highest resolution images of the Martian surface at 0.3m/pixel. This shows small-scale landforms in unprecedented detail, but is not as useful as CTX images in terms of broader regional context.

All images used were retrieved from the Arizona State University Mars image galleries and through JMARS software available online. Images were imported and georeferenced in ArcMap 10 so they could be examined in geographical context rather than through the catalogued sequence of the galleries. A shapefile containing points for occurrences of various landforms was created over the images. In the case of scalloped depressions where they are sparse a point represents an individual depression and where they occur in high density (towards the centre of the study area) a point represents an image which is covered in scalloped depressions. The points in Figure 2.2 therefore displays the spatial distribution of the scalloped depressions not their density.

### 2.4 Results

Early observations of the periglacial landscape in Utopia Planitia indicated that there was an abundance of scalloped depressions (e.g., Lefort et al., 2009; Soare et al., 2008). Through the examination of the available image datasets occurrences of scalloped depressions were plotted and are presented in Figure 2.2. This work, therefore, confirms earlier suggestions that scalloped depressions are abundant in this region, albeit with much better image coverage and resulting spatial resolution. While scalloped depressions are the focus of this study other periglacial landforms observed in the area are also noted on the map. As can be seen in Figure 2.2, when the occurrences of these landforms are

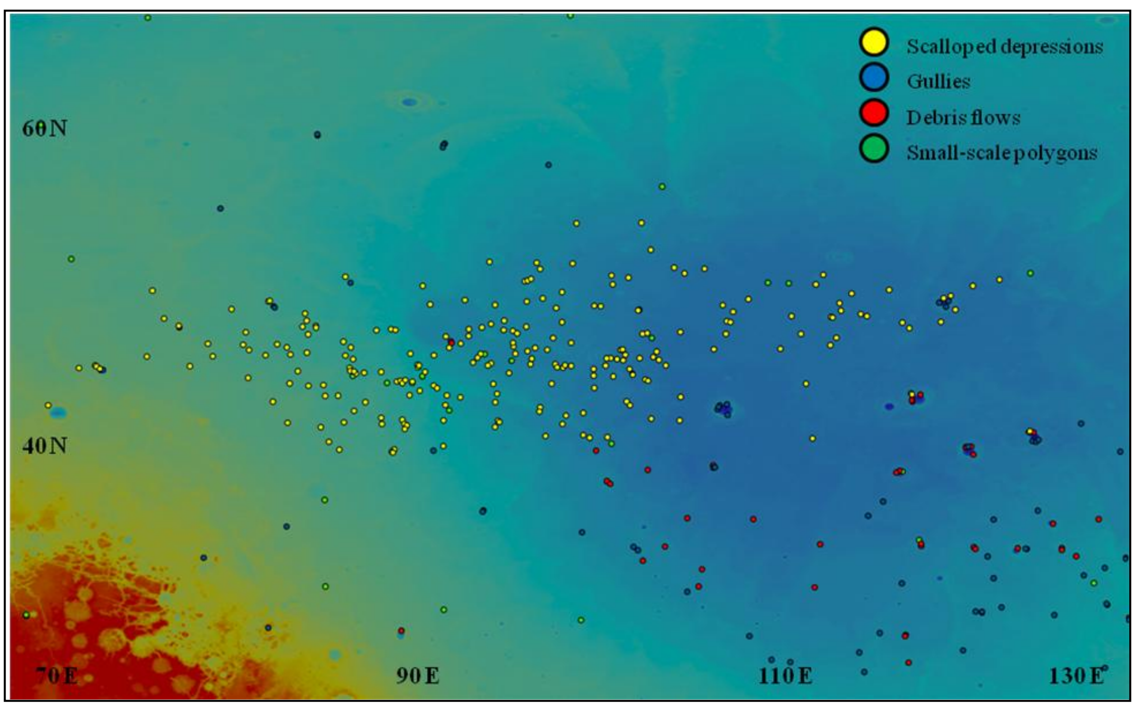


**Figure 2.2** The Distribution of Periglacial Landforms in Utopia Planitia (on MOLA DEM map, Simple Cylindrical projection, GCS_Mars_2000_Sphere). Area shown is the study areas indicated in Figure 2.1.

mapped some trends in their distribution emerge. There is a distinct band of scalloped depressions that stretches across the extent of the study area. Small-scale polygons (~<25 m) occur within this band and also to the south west of the area where scalloped depressions are absent. Also of interest is the spatial separation of scalloped depressions and gullies. Gullies are common both to the north and south of the scalloped depressions band, but only occur in three craters within it. The stratigraphic relationships of these landforms will be discussed later in this paper.

Within the band or terrain of scalloped depressions the morphology and density of these landforms varies. Based on their observed morphology, scalloped depressions are subdivided here into four classes as follows:

- Coalesced scalloped depressions (Fig. 2.3a): these are scalloped depressions that grow very close together in a way that makes them appear as though joined together. They occur in areas of heavy degradation, mostly in the north and east of the area.

- Isolated simple scalloped depressions (Fig. 2.3b): these are scalloped depressions that are simple circular to oval shapes with no apparent internal complexity and are not joined to any other scalloped depression. They occur more frequently in the centre and to the west side of the area. They can occur in association with small scale polygons but more often do not.

- Isolated complex scalloped depressions (Fig. 2.3c): these are “classic” scalloped depressions with circular to oval shapes and internal complexity in the form of steps or terraces. They are not joined to any other scalloped depression and usually are associated with small-scale polygons. They usually occur in the centre and to the west of the area.

- Crater scalloped depressions (Fig. 2.3d): these are any of the above categories of scalloped depression that occur within a crater. These scalloped depressions occur all over the area as craters and mostly evenly distributed.

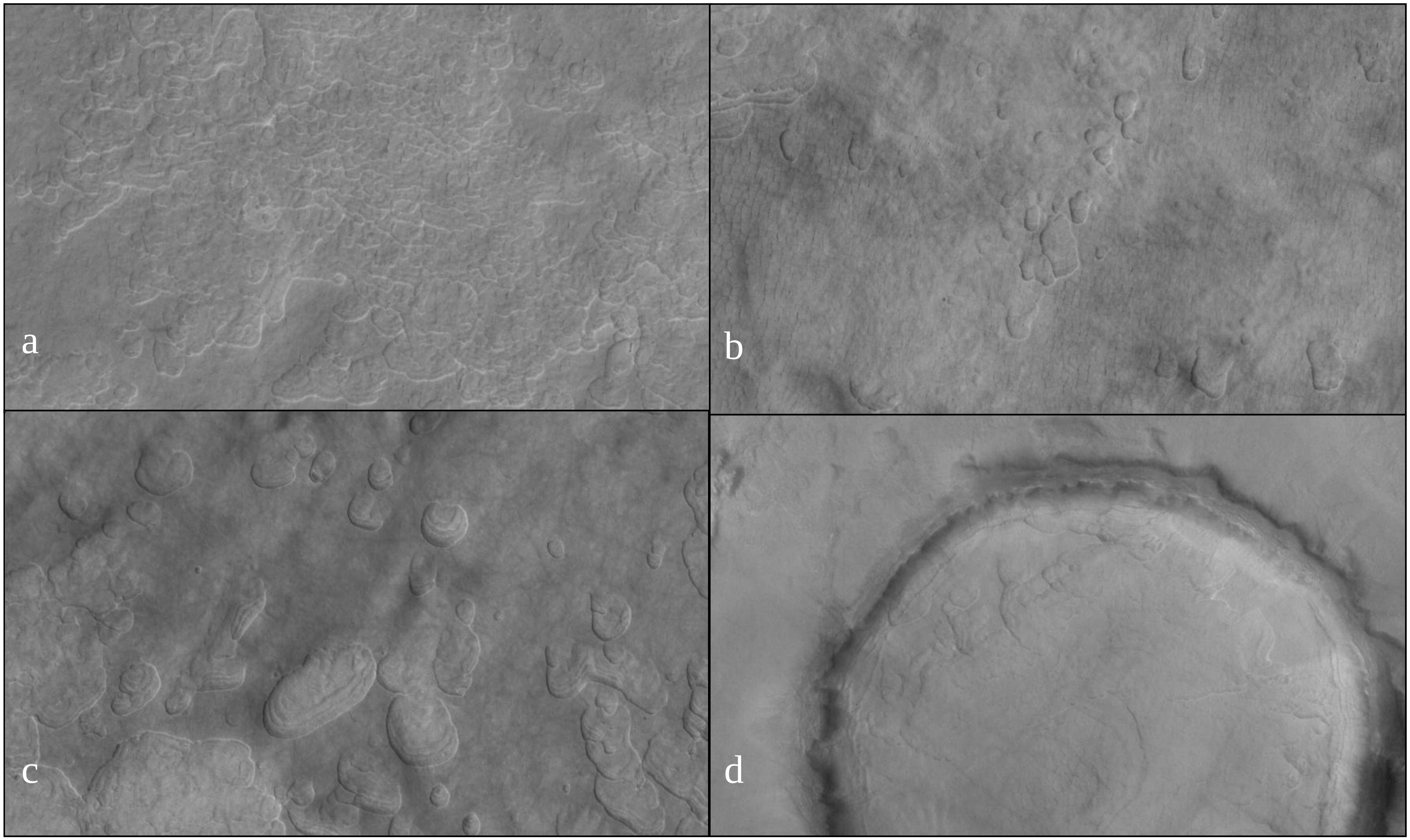


**Figure 2.3** Types of scalloped depressions. a) Coalesced depressions G20_025989_2265. b) Isolated simple depressions B01_010034_2248. c) Isolated complex depressions P02_001938_2263. d) Crater depressions B17_016324_2313. CTX Images are 10 km wide, North at top.

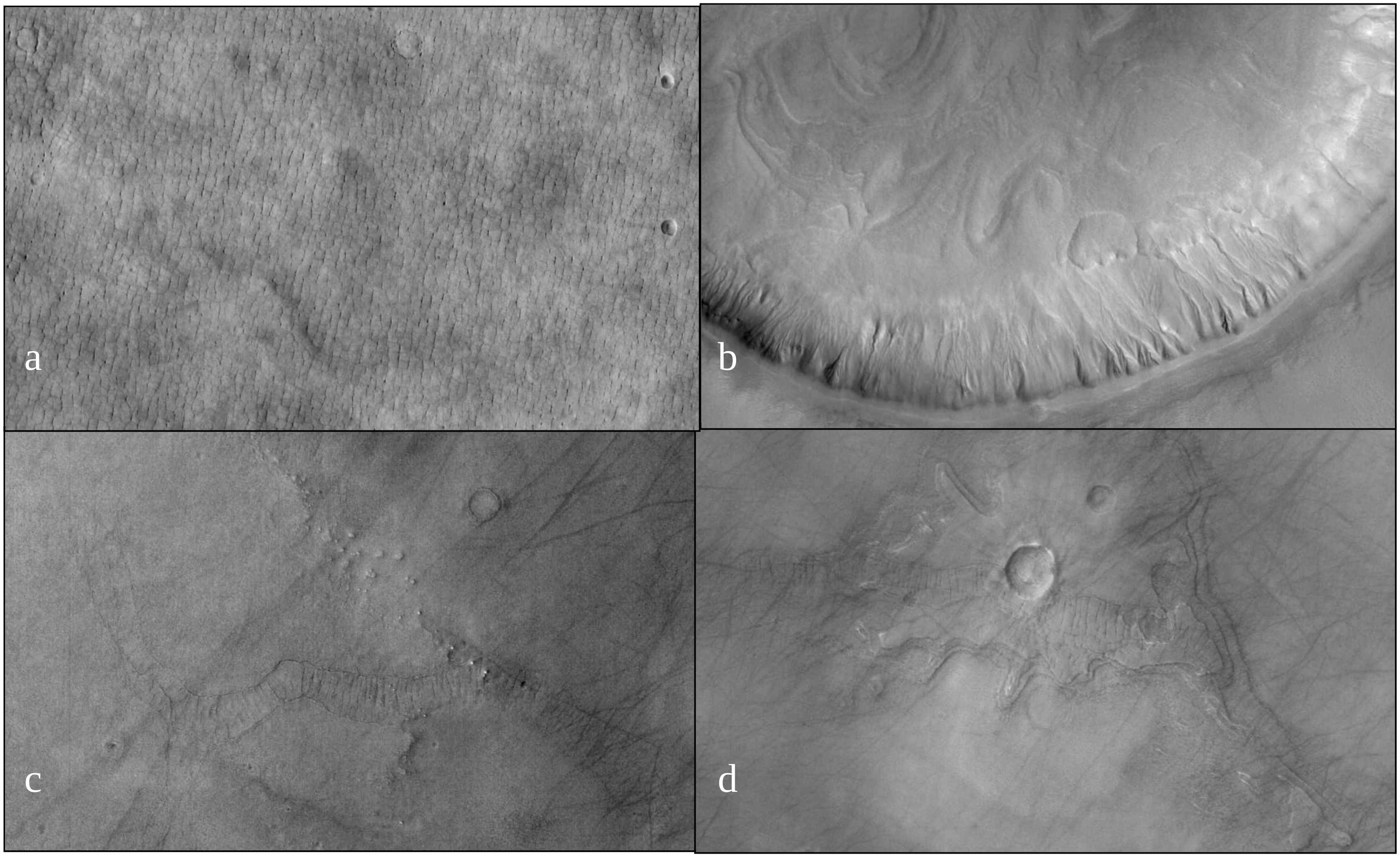


**Figure 2.4** Other Periglacial Features in Utopia Planitia. a) Small scale polygons B02_010456_2248. b) Gullies on crater wall B22_018038_2353. c) Branched polygon channel P17_007858_2329. d) Polygon channel over pedestal crater B19_017141_2333. CTX Images are 10 km wide, North at top.

Though we here present distinct categories for scalloped depressions of different morphologies, in reality these features are physically expressed over a continuous range. As a consequence some overlap and ambiguity may occur in the classification of the depressions.

Other landforms are also observed in the area including small-scale polygons (Figure 2.4a) and gullies (Figure 2.4b). After the scalloped depressions, the most abundant of these landforms are the polygons and often the two occur together. Polygons are also observed to occur in channels, which continue for several kilometres and are sometimes branched (Figures 2.4c and d).

In order to define the area of scalloped depressions the furthest extent of their occurrence was examined in all directions. A boundary for this area was drawn following the methodology for contact types as outlined above. This boundary can be seen in Figure 2.5 and is further described below.

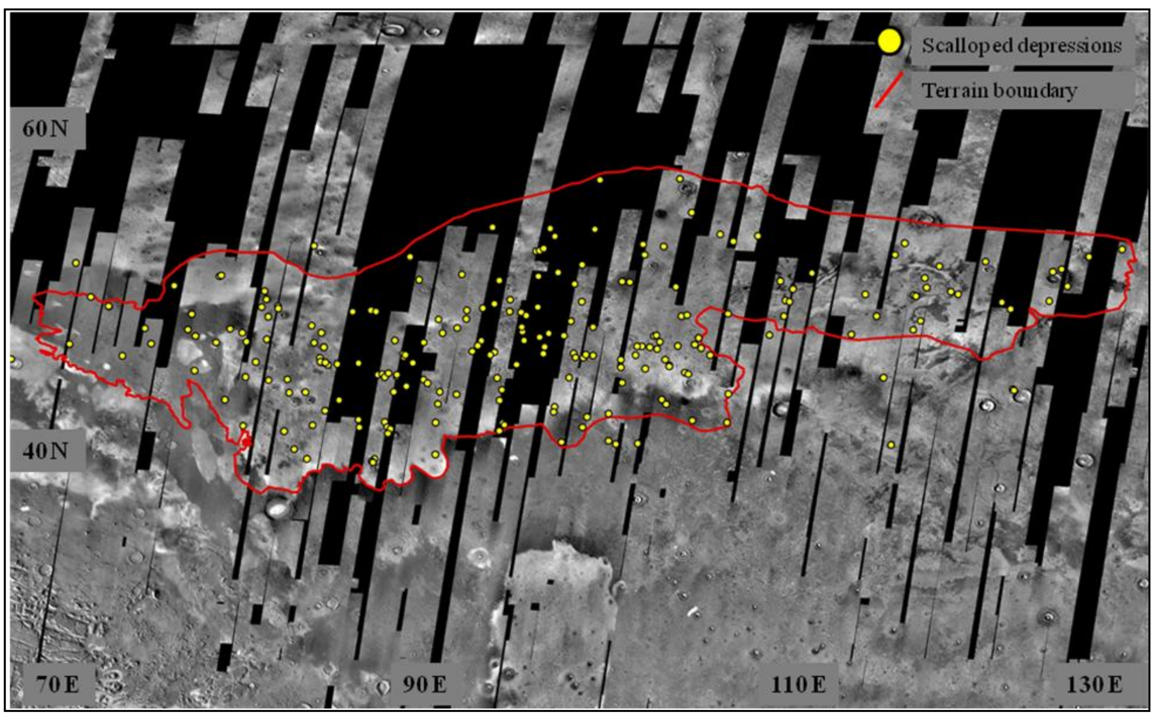


**Figure 2.5** Scalloped Depressions Terrain. The extent of the scalloped depressions terrain in the study area displayed over daytime IR-THEMIS image mosaic (Simple Cylindrical projection, GCS_Mars_2000_Sphere).

Towards the north of the area from approximately 50° N, there is a very gradual change in terrain where the scalloped depressions become smaller, fainter, and less frequent. Overall the terrain appears to get smoother to the north and craters appear more heavily blanketed. As there is no sharply defined edge to the scalloped depressions terrain along this extent the contact is approximate. Also the lack of image data in this area necessitates the contact to be inferred in places. It follows on from the more certain contacts at the northeast and northwest of the area and is guided by the northern most occurrences of scalloped depressions.

In the east of the area from 102° E, the terrain in which the scalloped depressions occur becomes intermittent with terrain that is generally smoother and has a higher albedo. The high level of contrast between these two terrains allows the contact here to be drawn as certain where CTX imagery is available and is approximate along THEMIS images. Although the resolution of the THEMIS images does not allow the landforms to be clearly identified the albedo difference is still evident. This higher albedo terrain has been interpreted by Tanaka et al. (2005) as volcanic material of the Elysium Rise and Tinjar Valles units. This contact is seen in Figure 2.6a. The scalloped depressions terrain extends south to approximately 40° S. Further south the terrain has a higher albedo and overall it appears smoother than the scalloped depressions terrain but also has knobbly patches and craters that are not as heavily blanketed as those that are further north. This contact can be seen in Figure 2.6b. In the south west of the area the scalloped depressions occur less frequently until the terrain is heavily dominated by polygons (Figure 2.6c). This polygon terrain then continues south to approximately 36°S and then appears in a few isolated patches as far south as 25° S.

The west of the scalloped depressions terrain (70–80° E, 40–50° N) has almost 100% coverage with CTX imagery. This has allowed the contact to be drawn as certain where there is a clear edge to the scalloped depressions terrain and where it transitions gradually and becomes patchy the contact is approximate. This contact can be seen in Figure 2.6d. The terrain to the west of the scalloped depressions is very smooth and has been interpreted by Osinski et al. (2012) to be a glacial unit. In the northwest the

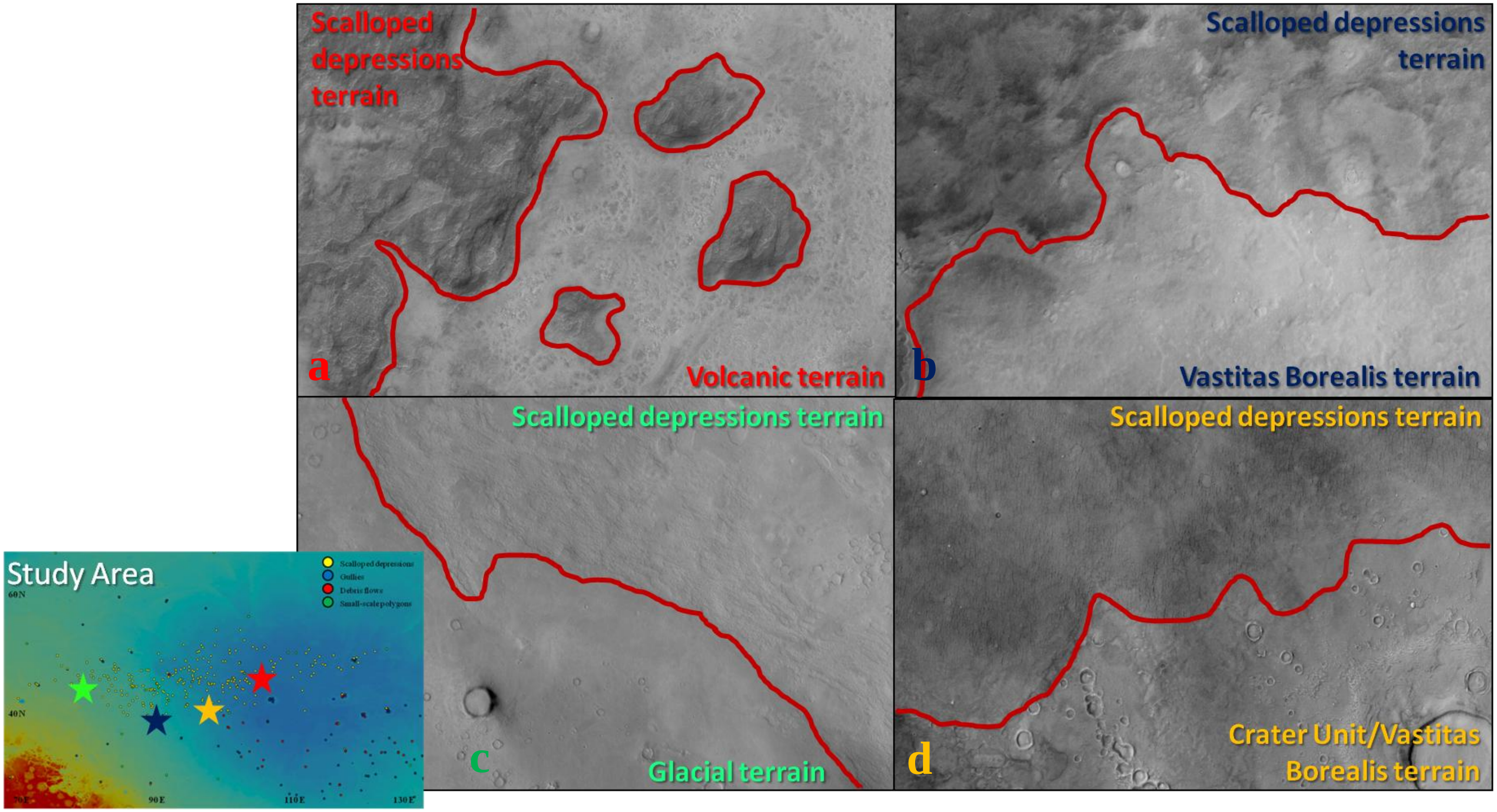


**Figure 2.6** Contacts between scalloped depression terrain and surrounding terrains. Inset shows locations in the Study Area. a) The scalloped depressions terrain on the left with a lower albedo than the brighter volcanic terrain on the right. B17_016442_2252. b) The scalloped depressions terrain at the top of the image. P18_008188_2228. c) The southern edge of the polygon dominated terrain in the south west of the area. P20_008676_2186. d) The scalloped depressions terrain on the top right of the image. B18_016575_2255. CTX Images are 10 km wide, North at top.

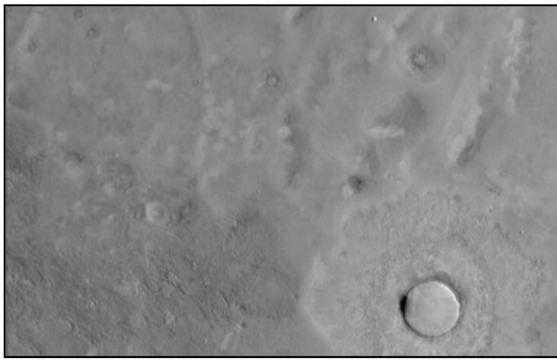

**Figure 2.8** Concentric curved ridges. P20_008716_2296. CTX Image is 10 km wide, North at top.

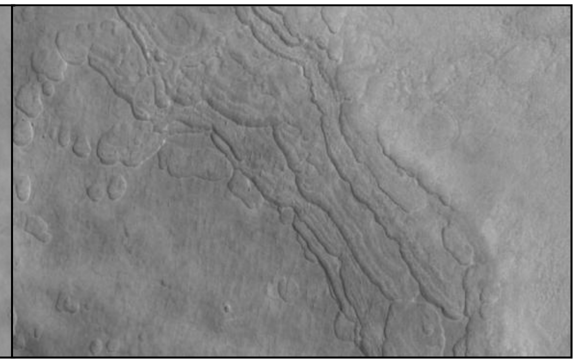

**Figure 2.7** Internal layering with the scalloped depressions terrain . P03_002070_2250. CTX Image is 5 km wide, North at top.

scalloped depressions terrain becomes patchy where it is next to terrain with concentric curved ridges as seen in Figure 2.7.

### 2.5 Interpretations and Discussion

Numerous workers have suggested that the periglacial landforms seen in western Utopia Planitia are the surface modifications of older, previously identified geologic units. Lefort et al. (2009) suggests that these landforms are bound within a latitudinal band between 40 and 55°N because obliquity driven insolation changes controls their formation. However, if the distribution of these landforms as in Figure 2.5 is investigated it is evident that they do not continue along this latitudinal band arbitrarily but are also bound longitudinally between 70–120°E. This longitudinal boundary cannot be explained by insolation control alone and suggests a difference between the terrains in which these landforms are found and from which they are absent.

After identifying the extent of the scalloped depressions terrain and the nature of its contact with surrounding terrains, we have concluded that it represents a discrete geologic unit. This newly identified unit will hereafter be referred to as the Periglacial Unit (ABp) and is presented in Figure 2.9. The unit covers an area of approximately 1,150,000 km$^2$. It overlies the Elysium Rise volcanic unit on its eastern extent and an unnamed glacial unit to the west. To the north and south the unit dissipates gradually and as such the boundaries here are difficult to accurately determine.

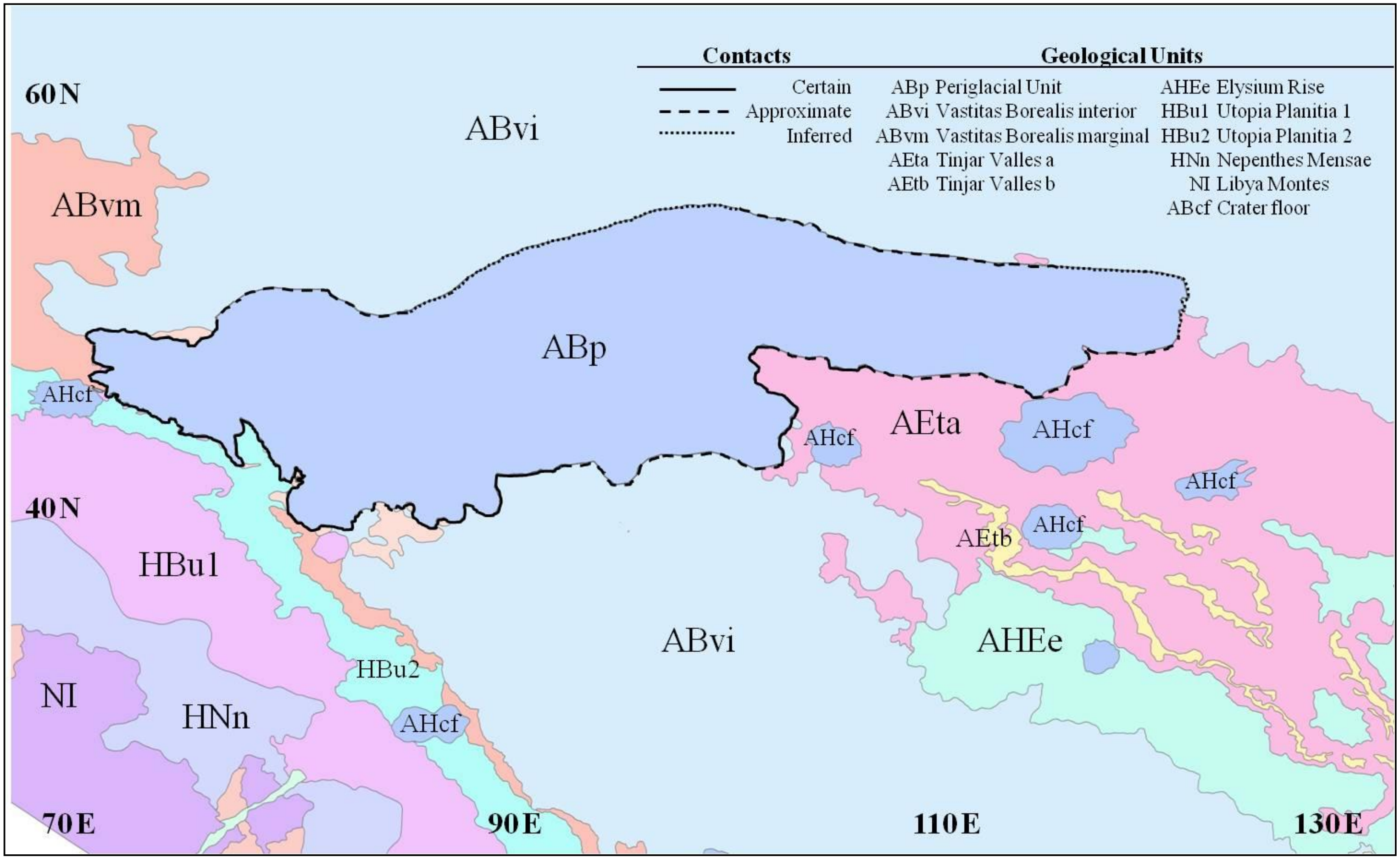


**Figure 2.9** A revised geological map of Utopia Planitia showing the extent of the newly identified Periglacial Unit (ABp). Other units are based on the map produced by Tanaka et al. (2005) and detailed descriptions can be found therein.

The eastern extent of the Periglacial Unit overlies the Tinjar Valles deposits of Elysium Rise (Fig. 2.6a). These units, Tinjar Valles a and b (AEta and AEtb) are described by Tanaka et al. (2005) as lobate deposits of Early Amazonian age that overlie the Vastitas Borealis units (ABvi, ABvm). This stratigraphic relation is important to note as with the evidence we present here for the Periglacial Unit overlying the Tinjar Valles deposits this undoubtedly points to the Periglacial Unit being a geologic unit distinct from and not simply surface modifications of the Vastitas Borealis units.

In the west, the Periglacial Unit is in contact with a terrain that has been recently described by Osinski et al. (2012) as a glacial unit. As can be seen in Figure 2.6c the Periglacial Unit overlies this, as yet unmapped, glacial unit perhaps indicating a climatic shift in this region from a period of ice accumulation to a period of ice loss. The youthful age (~<100 Myr) estimated for the glacial activity also implies a recent timeline for the periglacial activity represented by the Periglacial Unit.

The exact nature of the substrate of the Periglacial Unit is difficult to accurately determine without ground based measurements. It is of varying thickness, possibly up to many hundreds of metres (Madeleine et al., 2009). A recent suggestion by Soare et al. (2012) is that this substrate is similar to loess, a type of well-sorted silt, which is transported by wind (French, 2007). This compliments the idea first suggested by Head et al. (2003) that the atmospheric deposition of dust and ice lead to the accumulation of this substrate. This type of deposition would occur periodically, driven by changes in Mars' obliquity over millions of years. These cyclical changes in obliquity and climate would also vary over time meaning that depositional events would also vary in the amount of dust and ice mobilised, the ratio of dust to ice, and the location of where these deposits settled. Head et al. (2011) identifies areas in Utopia Planitia where layering within this substrate is clear (e.g., Figure 2.8). This would suggest that Utopia Planitia may be host to many overlapping layers of ice rich substrate representing multiple episodes of deposition. The percentage of ice present is an important controlling factor on the development of periglacial landforms in a substrate. If ice content varies among layers it is possible that individual layers may be identified by their unique landform or assemblage of landforms. In this study we have focused on the distribution of scalloped depressions in Utopia Planitia, however, there are many more types of periglacial landforms whose distribution also warrant investigation to build a complete picture of the depositional and periglacial history of the region.

### 2.6 Conclusion

The Periglacial Unit (ABp) of Utopia Planitia is a distinct geologic unit identified by its assemblage of scalloped depressions. In defining its extent, contacts, and stratigraphical relationships with surrounding units we have concluded that it is the youngest geologic unit in Utopia Planitia and that the scalloped depressions are representative of the most recent phase of periglacial activity in the region. We suggest that the distribution of other periglacial landforms in the region, such as gullies, be investigated in further detail to build a more complete geologic map of the region.

Concluding that all instances of periglacial geomorphology are representative of a single occurrence of periglacial activity is to underestimate the vastness of Utopia Planitia both spatially and temporally. It is worth remembering that this area is approximately 6 times the size of the Canadian High Arctic where a complex geologic and climatic history is recorded in the stratigraphical relationships between numerous distinct units.

By using observations of the landforms present on the surface of Utopia Planitia and investigating how they relate to each other, a clearer understanding of the area as a whole and the history of its landscape can be attained. While geological mapping of Utopia Planitia will always be somewhat limited when confined to imagery and satellite data, the high resolution imagery and the increasing coverage of the region now available is allowing a start to be made on constructing a more detailed stratigraphical history of Utopia Planitia.

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# 3 Chapter 3: Past Environments on Mars

## 3.1 The Climate History of Mars

The Noachian Period (~>3.6 Ga) has long been considered the “warm and wet” era in Mars climate history (e.g., Pollack et al., 1987) with valley networks often cited as geological evidence of vast, flowing rivers on the planet’s surface (Gulick, 2001). Interest in the early climate of Mars is closely associated with the search for evidence of past life as the warm, wet environment envisioned seems conducive to the presence of habitable niches (McKay, 1997). The accuracy of this tropical scenario is currently being challenged however, with new evidence that may make a “cold and dry” early history more plausible (Head, 2012).

The Hesperian Period (~3-3.6 Ga) is marked by huge channels representing catastrophic outflow events, which some workers suggest resulted in a large ocean in the northern lowlands (e.g., Head et al., 1999). Significant volcanic events injected large volumes of volatiles into the atmosphere (Jakosky and Phillips, 2001) and while there is evidence of surface liquid water forming in localized areas, the northern ocean hypothesis remains in doubt (Head, 2012).

The climate of the Amazonian Period (present-~3 Ga) consists of cycles of ice migration from the poles to the low latitudes driven by changes in Mars’ orbit (Head, 2012). The remnants of the latest of these migrations may be found in the periglacial landscapes in the middle latitudes, such as that mapped in Utopia Planitia (Chapter 2). For the recent or Late Amazonian Period (present-~20 Ma) there exists reliable models of orbital dynamics (e.g., Laskar et al., 2004) offering predictions that, when combined with geological evidence, are useful to developing palaeoenvironment and climate scenarios for the recent past. These orbital and climate models will be discussed further in Chapter 4.

### 3.2 Geology and Climate

To reconstruct past environments on Earth palaeoclimatologists have a wealth of data to investigate from a variety of sources. Biological, geological, geochemical, and historical records from around the globe can all be combined to form a detailed representation of how the climate differed then to its current state. On Mars, widespread orbital data coverage and sparse ground data from landers and rovers form the basis of our understanding of Mars' current climate but to decipher how the climate may have behaved in the past, the geology and landforms visible on the surface of the planet guide the hypotheses put forward.

Periglacial landscapes are valuable climate indicators due to their sensitivity to even very small changes in the thermal, hydrologic, and edaphic conditions in their surrounding environment (Karte, 1983). The spatial and temporal positioning of the scalloped depressions in Utopia Planitia (as discussed in Chapter 2), as well as opposing theories on their formation regarding the presence, or lack thereof, of surface liquid water (e.g., Soare et al., 2008; Sejourne et al., 2011) warrant an assessment into the suitability of scalloped depressions as climate indicators for recent climate change on Mars. This is explored in the following chapter.

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# 4 Chapter 4

## Scalloped Depressions as Indicators of Recent Climate Change in Utopia Planitia, Mars

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### 4.1 Introduction

The intricate valley networks, deltaic systems and fluvial channels that span vast areas of Mars are geomorphologic fossils, remnants of a time marked by a wetter and potentially warmer and dynamic environment, a time in the ancient past when Mars was not the cold desert we see today (Baker, 2001). As with the study of Earth’s changing climate, work has begun to reconstruct the past environments of Mars and to understand how its climate has shifted so dramatically. Recently, evidence has been mounting for a period of dynamic climate change on Mars during the last 100 million years. Layered deposits in the polar regions (Milkovich and Head, 2005), equatorial mountain glaciers (Head et al., 2006), and young glacial and periglacial landforms in the mid-latitudes (Soare et al., 2008), all provide some indication about the movement of volatiles between the subsurface and atmosphere (Jakosky and Phillips, 2001). Along with these geologic observations, computer simulations modeling the current and past trends in orbital and atmospheric fluctuations all point to a changing climate in Mars’ recent past (e.g., Forget et al., 2006; Madeleine et al., 2009).

Often the study of Mars’ climate in the recent past has been guided more by what is predicted by the climate models rather than the geologic evidence. The reason for this is twofold. Firstly, the orbital and atmospheric models are beginning to be robust enough to confidently predict climatic cycles (Laskar, 2012). Secondly, the major problem with geologic evidence is establishing its chronology. This currently relies on crater counting techniques, which are sometimes problematic and not always suitable – especially in spatially small geologic units. Ideally, both geologic evidence and climate models would be used in combination to form a full picture of the history of climate change. The aim of this study is to reconstruct the palaeoenvironment in which the scalloped depressions of Utopia Planitia formed. To do this we present a model of this environment based on geologic evidence we have found in the study area, combined with recent predictions from climate models.

### 4.2 Study Area and Methodology

Utopia Planitia is a large topographic depression in the Northern hemisphere of Mars centred at 49.7°N and 118°E and measures approximately 3,300 km in diameter. The area of interest for this study is in the west of the region and is shown in Figure 4.1. Utopia Planitia was formed by a large impact early in Mars' history (McGill, 1989) and since then has experienced a long sequence of deposition (Thomson and Head, 2001). The geology of the study area is shown in Figure 4.2. The volcanic units of Elysium Rise (AHEe) and Tinjar Valles (AEta, AEtb) in the east, the glacial-like units in the west, and the Vastitas Borealis units (ABvi) in the north and south of the area are discussed in Chapter 2. The nature and extent of the Periglacial Unit (ABp) is also discussed in Chapter 2. This paper will further discuss its formation and its role in climate studies. This unit was identified by the abundance of periglacial landforms, particularly scalloped depressions, in the area. There are scalloped depressions and other periglacial landforms present in other regions of the northern hemisphere (e.g., Costard and Baker, 2001; Warner et al., 2010) and some occurrences in the southern hemisphere (Zanetti et al., 2010), but none in the quantity that is seen in Utopia Planitia. This would suggest that Utopia Planitia has some unique feature(s) that encourages the development and preservation of these landforms.

The significance of periglacial landforms lies in their diagnostic value as environmental indicators, both on regional and localized scales (Karte, 1983). The occurrence and morphology of periglacial landforms are determined by a complex combination of geologic and climatic conditions. As such, the study of an ancient periglacial landscape is useful in reconstructing the past environmental conditions at the time of formation. Also, its preservation and/or level of degradation can tell us something about the environmental change in the intervening time. It must be noted, however, that in doing this assumptions are made on the process-form relationship between the environmental conditions and the landforms – assumptions that are perhaps a 'best guess' scenario, but whose validity can be strengthened on the basis of additional evidence, such as climate models and Earth analogue studies.

Often the study of periglacial landscapes tends towards the descriptive rather than analytical (Karte, 1983), meaning the diagnostic association between climate and specific landform has not been extensively studied other than the general association between a periglacial landscape and a cold climate. Field experiments on periglacial sites are limited to small, localized scales (French, 2007). On these small scales, the influence of non-climatic factors is often much stronger than the influence of the larger scale, regional climatic conditions.

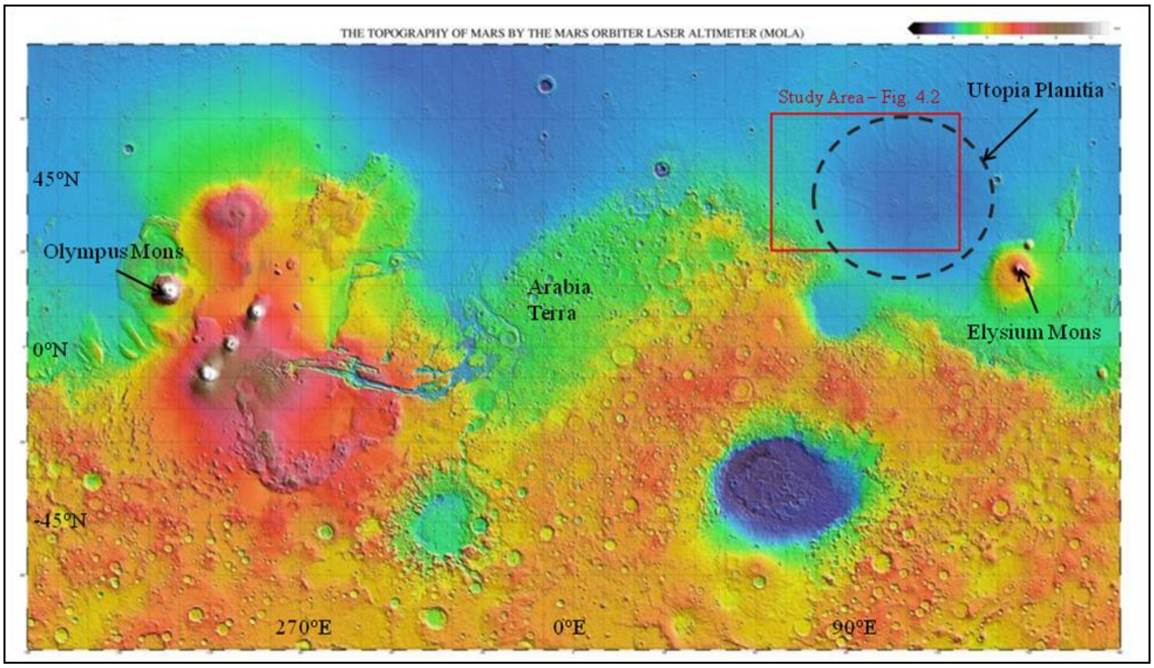


**Figure 4.1** Global topographic map of Mars. The total study area is indicated by the red box. Mars Mercator map projection. Image credit MOLA Science Team (http://marsoweb.nas.nasa.gov/globalData/).

At its simplest level the presence of periglacial landforms indicates the presence of frozen ground, which in turn points to a cold climate. Usually this also indicates the presence of water in its solid state, although periglacial landforms can also form in a dry environment (French, 2007). The difficulty lies in understanding what environmental conditions are manifested in specific landforms. Table 4.1 provides a brief summary of some common periglacial landforms and the climatic and substrate conditions they indicate. The chain leading from environmental conditions to physical and chemical processes to morphology of the landform has variations too numerous for easy understanding, and elements whose effects may be too subtle can have their importance overlooked. The presence of specific periglacial landforms is likely an indicator of the smaller scale, localized conditions for example, the physical and chemical nature of the material they form in, topography, and hydrological variations (Karte, 1983). The size of periglacial landforms can also be related to their stage of growth or their response time to environmental changes. Small landforms, therefore, may be valuable in that they may represent a simpler system of cause and effect, where their formation and growth may be linked more directly to specific changes in environmental conditions. The narrower the range of environmental conditions needed to form a specific landform, the higher the diagnostic value of that landform. The goal is defining the range for a specific landform in the first instance, which is difficult given the complex nature of the environment-process-form relationship, but made easier when aimed at simpler forms, which are dependent on fewer processes and conditions.

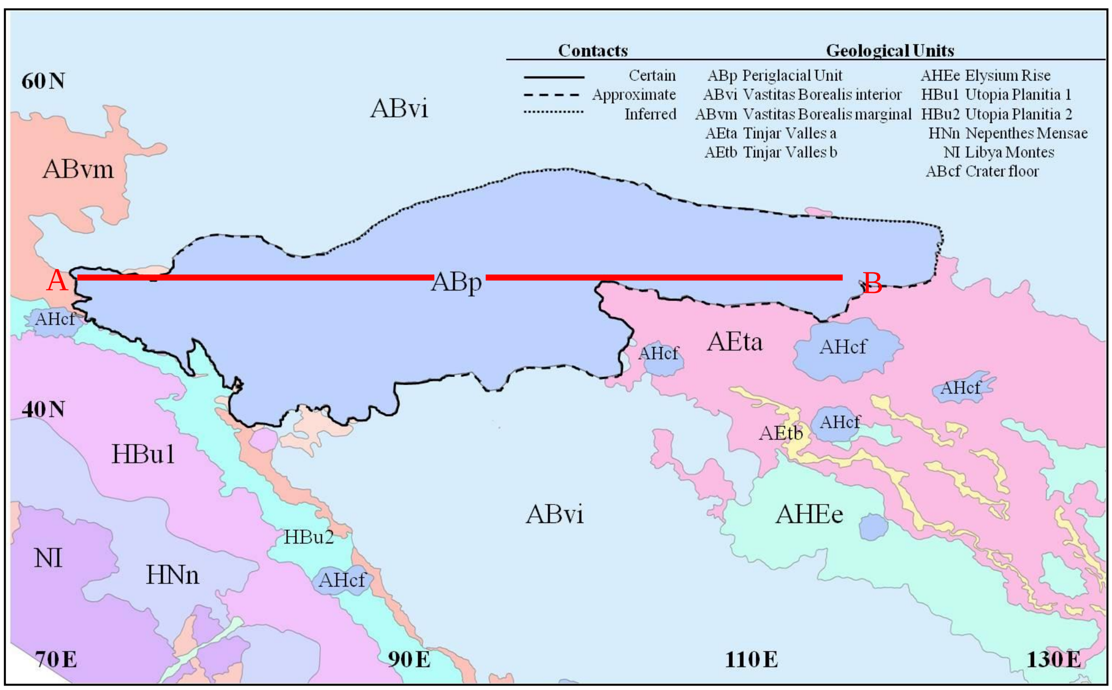


Figure 4.2 Revised geological map of study area in Utopia Planitia, showing the extent of the Periglacial Unit (ABp). Other units are based on the map produced by Tanaka et al. (2005) and detailed descriptions can be found therein. Red line A to B indicates location of schematic diagram as seen in Fig. 4.5. Based on Figure 2.9 in this thesis.

This study, therefore, focuses on scalloped depressions, periglacial landforms that range in size from tens of metres to kilometres wide and tens of metres deep. They typically exhibit an asymmetrical profile with the north-facing slope slightly steeper than the slope facing south. Most theories on their formation agree that they are the result of the removal of ice from the shallow subsurface and the consequent collapse of the overlying sediment (e.g., Morgenstern et al., 2007; Soare et al., 2008; Ulrich et al., 2010; Sejourne et al., 2011).

### 4.3 Scalloped depressions

The scalloped depressions of Utopia Planitia are often likened to thermokarst activity on Earth (e.g., Costard and Kargel, 1995; Soare et al., 2008). Although Earth thermokarst is considered a good analogue for scalloped depressions, there are some discrepancies between how these features form. Thermokarst develops as a result of the thaw of permafrost that leads to the instability, collapse, subsidence, and erosion of the ground surface. The thaw is initiated by a disturbance in the thermal equilibrium of the permafrost, which on Earth can have natural (geomorphic, vegetational, climatic) and man-made origins (French, 2007).

Considering permafrost degradation on Earth as an analogue for the periglacial activity on Mars, the thermal equilibrium of the Martian permafrost can be disturbed by either geomorphic or climatic factors (although another possible external heat source that may potentially initiate localized thaw is volcanic activity which will be discussed in Section 4.4). Most thermokarst activity on Earth is located along the margin between continuous and discontinuous permafrost in Siberia, the Canadian Arctic, Alaska, Scandinavia, and sporadic areas in the Alps, Andes, and the Tibetan plateau (French, 2007). The topography, geology, and vegetation of these areas vary greatly, but the thermokarst features present show remarkable similarities in form (French, 2007). Recent studies of thermokarst areas suggest that the activity is affected more by climate than any other factor (e.g., Nelson et al., 2002) meaning that these areas will be sensitive to change in the climate.

| Minimum duration of formation | | | | | Climate conditions | | Substrate conditions | Frozen ground conditions | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 year | Several years | Decades | Centuries | Millenia | Indication of mean annual air temperature (MAAT) | Periglacial landforms | Edaphic control and indication | Continuous permafrost (MAAT: -5/-8 C | Discontinuous permafrost (MAAT: -3/-4 C) | Sporadic permafrost (MAAT: -1/-2 C) | Seasonally frozen ground (MAAT 0/-1 C) |
| | | x | x | x | <-12 to <-20 C | Sand-wedge polygons | Coarse grained material, low ice content | x | | | |
| | | x | x | x | <-4 to <-8 C | Ice-wedge polygons | Fine-grained, moisture-rich substrate, high ice content. Poorly drained gravel, high ice content, permafrost table near surface | x | x | | |
| | | x | x | x | <-5 to <-1 C | Pingos | Silty or saturated fine grained sediments, locally high ice content, near surface aquifers in permafrost | x | x | x | |
| | | | x | x | <+2 to 0 C | Rock glaciers | Bedrock which distinegrates into coarse angular debris | x | x | x | |
| | x | x | x | | <0 to <-4 C | Seasonal frost crack polygons | Well drained, well sorted fines or gravel, predominantly silty, highly frost susceptible material | x | x | x | x |
| x | x | x | x | x | <-1 C | Thermokarst | Poorly drained, frost-susceptible silty, loamy and peaty soils with formerly and adjacent high ice content, permafrost table near surface | x | x | x | x |
| | x | x | | | <-2 C | Non-sorted circles | Heterogeneous frost susceptible, silty, sandy fine material with moisture controlled density differences, seasonally supersaturated | x | x | x | x |
| | x | x | | | <-4 C to <+3 C | Sorted circles and stripes | Originally poorly sorted, frost-susceptible material with at least 10% silt and clay, moderately moist | x | x | x | x |
| | x | x | x | x | <0 C to <-3 C | Palsas | Peat cover overlying frost-susceptible silty material, high ice content | | x | x | x |

**Table 4.1** Summary of some periglacial landforms and the environmental conditions they indicate. Modified from Karte, (1983).

The current warming trend in Earth's climate should, therefore, be reflected in these climate sensitive areas. This has been seen to be true with rapid degradation of permafrost and development of thermokarst in many areas (e.g., Hinzman et al., 2005; Osterkamp, 2005).

Current climatic and atmospheric conditions on Mars, however, do not allow for thaw and liquid water to be present on the surface. If Mars' climate has been stable since the formation of the scalloped depressions, this excludes the possibility that scalloped depressions are formed by the thaw of ground ice and the pooling of water on the surface. Recently, some workers (e.g., Lefort el al., 2009; Sejourne et al., 2011) have described formation processes for scalloped depressions that do not involve a liquid stage in the removal of the ice. They suggest varying ways in which sublimation of the ice directly to the atmosphere will cause scalloped depressions to form.

There is one location on Earth where sublimation, rather than thaw, of ice occurs. The McMurdo Dry Valleys in Antarctica are used as an analogue for cold, hyper-arid environment of Mars. With the average mean annual air temperature of -25°C, little precipitation, and exposure to harsh katabatic winds, this area is the largest mostly ice-free region of Antarctica (Marchant and Head, 2007). Covering over 4000 $km^2$ from the Ross Sea to the East Antarctic Ice Sheet the Dry Valleys are a series of east-west trending trunk valleys separated by mountain ranges approximately 1500-2000 m in elevation. The main bedrock surfaces are covered in a thin (3 m) layer of unconsolidated glacial and non-glacial deposits, which have persisted for at least the last 14 million years (Marchant and Head, 2007). Polygon networks are present in the Dry Valleys and the similar cold, dry, and sublimation-driven environment to Mars makes their formation analogous to polygon networks on Mars (Levy et al., 2011). Features similar to thermokarst or the Martian scalloped depressions, however, are notable by their absence in the Dry Valleys. This may suggest a problem with the Dry Valleys being a suitable analogue for these particular landforms either with respect to the soil and/or climate conditions. However, it may also suggest a problem with sublimation being the controlling factor in formation.

The sublimation theory stems from a need to understand how the scalloped depressions formed in conditions that are the same as present day Mars. However, the general consensus is that the scalloped depressions have formed in the last 20 million years (e.g., Soare et al., 2008), and it is not unreasonable to suggest that the climatic and atmospheric conditions may have changed during that time. Indeed recent climate modelling studies (as discussed in Section 4.4) suggest that significant changes in climate would be expected in the recent past. Soare et al. (2008) describe aspects of the morphology of scalloped depressions, particularly the internal steps seen in many depressions, as evidence of periods of standing water. If water is integral to the formation of scalloped depressions, this suggests that the climatic and atmospheric conditions at the time of formation were significantly different to present day conditions. The thermokarst analogy could, therefore, not only be used to help explain how scalloped depressions formed on Mars but could also give an indication as to how the climate has changed during and since their formation.

### 4.4 Volcanic Activity

To the east of Utopia Planitia lies the Elysium volcanic province. The main volcanic vent, Elysium Mons, is located at 25°N and 147°E but the volcanic plains extend well into Utopia Planitia as far as 45°N and 125°E (units AHEe, AEta and AEtb in Figure 4.2). These volcanic plains show an extensive history of lava flows, mega-lahars, and other volcanic flows formed by the interaction of magmatism and subsurface volatiles (Tanaka et al., 2005). Whereas most of the volcanic activity in this region happened early in Mars' history (prior to 3 billion years ago) (Werner, 2009), there are some suggestions that more recent activity is possible from the Elysium Mons vent within the last 100 million years or even continuing to the present day (Platz and Michael, 2011).

The possibility that the periglacial activity and degradation of the permafrost in Utopia Planitia was initiated or promoted by a volcanic heat source in a neighbouring region must, therefore, be considered. Geologic evidence for volcano-ice interactions has been found along the furthest extent of Elysium Rise into Utopia Planitia (Pedersen and Head, 2012), where mega-lahars are spatially associated with channels and dendritic ridges. This would suggest that the heat from volcanic and associated tectonic activity could disrupt the subsurface thermal regime and possibly melt ground ice and initiate a groundwater system. However, these volcano-ice interactions are only evident in a localized area immediately adjacent to the edge of the Elysium flows, and so volcanic activity is not thought to be a likely trigger for the widespread periglacial activity across Utopia Planitia being discussed here.

### 4.5 Climate Models

The most likely controlling factor of Mars' global climate is its orbital cycles. Mars experiences variations in its orbital motion that can be quantified into cycles similar to the Milankovitch cycles of Earth. On Mars, procession has a short 51 kyr oscillation, obliquity has a longer span of 120 kyr, and eccentricity has two periods of 95 and 99 kyr. Mars' variations are more extreme than Earth's, however, and are more difficult to model and predict. This is due to the interaction of the planet's orbit with the orbits of asteroids whose chaotic nature introduces an irreducible uncertainty into orbital models. The most commonly used orbital model solution is La2004, as derived by Laskar et al. (2004). This model predicts the behaviour of Mars' orbital motion for the last 40 million years. Recent improvements to the model in Laskar (2012) have extended that prediction for the last 50 million years. Attempting to extend it back further would be futile, given the chaotic nature of the system (Laskar et al., 2012).

Mars' obliquity varies within a very large range, from approximately 5 to 60 degrees, again making it difficult to model the long-term behaviour of the cycle. La2004 does, however, consistently predict the obliquity to be up to 40 degrees 5 million years ago and since then has oscillated between high and low, but the overall trend has been a decrease to approximately 25 degrees at the present day (Figure 4.3). Prior to 5 million years ago the obliquity had remained high until at least 25 million years ago. Further back than 20 million years ago the obliquity cycle is modelled to behave in a variety of ways (Laskar et al., 2004). One possible way to constrain these solutions is from the geological evidence. This, however, requires a reliable method of dating the geologic features and units, which so far remains problematic.

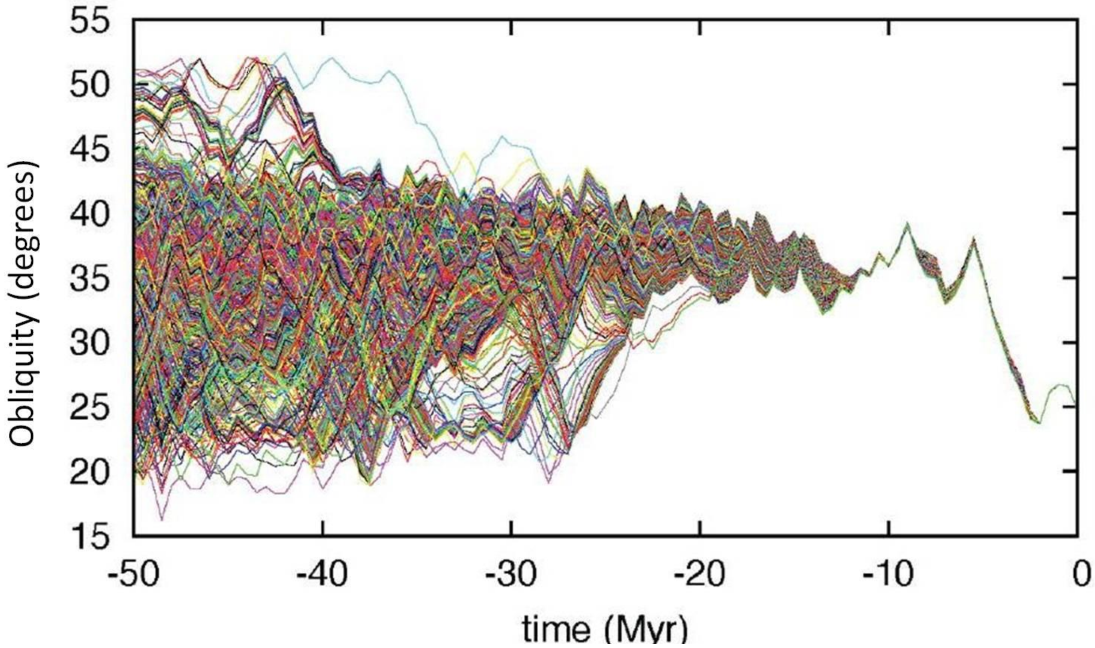


**Figure 4.3** All 1001 averaged solutions using the La2004 model showing predicted obliquity over the last 50 million years. The model is consistent over the last 10 million years and is considered valid for the last 20 million years. From Laskar et al., (2012).

As well as having a direct effect on the insolation conditions on the surface, orbital variations also force changes in the atmospheric mass, wind patterns, and global cloudiness. All these factors play a role in the changing climate on Mars and influence where and to what degree the changes are felt on the ground. The detailed complexity of the long-term variations and seasonal cycles of dust, water, and $CO_2$ are beyond the scope of this paper, but they will be discussed briefly to indicate how these cycles may have combined to influence the regional climate in Utopia Planitia.

During periods of high obliquity the North and South poles of Mars are exposed to more direct sunlight and higher temperatures, allowing more ice to sublimate. This mobilisation of volatiles from the poles increases humidity and affects atmospheric density and circulation. These conditions would be conducive to the precipitation and accumulation of ice in the middle latitudes and on the western flanks of Olympus Mons (Fig. 4.1). Accumulation rates have been calculated to be up to 60 mm per year, allowing glaciers or ice sheets up to 3 km thick to grow (Forget et al., 2006). The case made by these model predictions is strengthened by geological evidence for glacial activity in these middle and low latitude areas (Head et al., 2006).

Clouds have both a cooling effect by reflecting sunlight, and a warming effect by absorbing infrared radiation and emitting some back into the surface. The net cooling or warming of clouds depends on the balance between these two effects and this in turn depends on the cloud optical depths, altitudes, and particle sizes. As obliquity increases, Hadley and monsoon circulation strengthens and this is likely to result in more frequent dust storms. An increased amount of dust in the atmosphere has a significant influence on the opacity and, therefore, warming of the upper atmosphere (above 10 km) by up to 40 K and approximately 10 K cooling in the lower atmosphere (Haberle et al., 2012). With these same obliquity conditions, another model (Madeleine et al., 2009) states the wind patterns would encourage the development of opaque cloud coverage over a southwest-northeast oriented zone from western Arabia Terra along a jet stream which abruptly decelerates over Utopia Planitia (Fig. 4.4). This deceleration would lead to precipitation and deposition of ice and dust into this region, and with mean annual precipitation up to 10 mm and a surface temperature of -75 C, these conditions could lead to regional ice sheet formation.

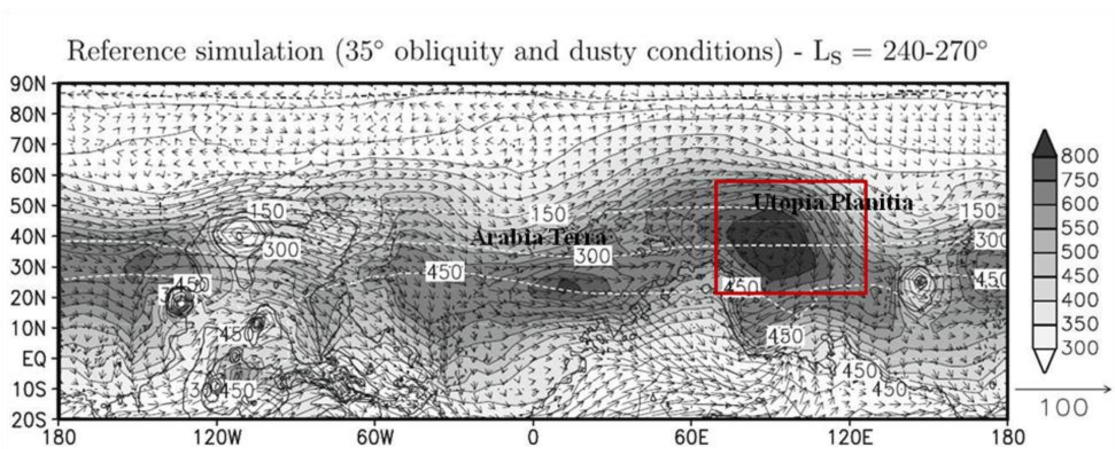


**Figure 4.4** Predicted wind and cloud cover map modified from Madeleine et al. (2009). Average cloud ice content (shaded regions, pr. µm) and horizontal wind field at the 5.6-km level (m $s^{-1}$). White lines indicate water vapor column (pr. µm). Study area indicated by red box.

### 4.6 Results and Discussion

Combining the predictions from recent climate models, (e.g., Laskar et al., 2004; Madeleine et al., 2009; Haberle et al., 2012) with geological evidence gathered in this study, we present here a model for the recent periglacial activity in Utopia Planitia.

The sequence of deposition and modification in Utopia Planitia has been driven by climatic changes in wind patterns, precipitation, and temperature. Atmospheric and climate models as described earlier indicate that during times of high obliquity Utopia Planitia becomes a centre for deposition of dust and ice. High obliquity, however, does not refer to one stable set of conditions. Between 20 and 5 million years ago obliquity cycled between 30° and 40°. Given the control obliquity has on the movement of volatiles into the atmosphere, different degrees of obliquity would lead to varying amounts of ice transported and different ratios of ice to dust deposited during a given cycle. These subtle variations may be reflected by the types of periglacial landforms present, since their presence and form are so delicately regulated by the nature of the substrate as well as the local climate. This study focussed on one depositional unit, the Periglacial Unit (ABp) characterised by the presence of scalloped depressions, although the surrounding terrain contains other periglacial landforms whose distribution may reveal additional discrete depositional units. The sequence of events leading to the formation of the Periglacial Unit and its appearance today is outline in Figure 4.5.

Recent work by Osinski et al. (2012) identified an area to the west of the Periglacial Unit that shows evidence of recent glaciation. The large volume of ice required to form glaciers and ice sheets would likely be deposited during periods of very high obliquity when the most ice would be transported from the poles. As predicted by Madeleine et al. (2009), jet streams from Arabia Terra, which lies to the west of Utopia Planitia, would decelerate over the topographic low of Utopia and deposit ice and dust into this region (Figure 4.5a). As obliquity gradually decreases, so does the amount of ice in the atmosphere and the amount of deposition in Utopia Planitia. Thinner layers of dust with less ice content are laid down, burying the remains of former ice sheets beneath them (Figure 4.5b). When obliquity drops below approximately 30°, deposition slows enough to allow the formation of periglacial landforms (Figure 4.5c) as the ground ice begins to be lost to the atmosphere and is eventually deposited back at the poles. In present day conditions, the ice is lost through sublimation directly to the atmosphere. During the past 5 million years, as obliquity has lowered, the atmospheric conditions may have been suitable for thaw to occur and possibly for liquid water to pool on the surface. As predicted by Madeleine et al. (2009), during periods when obliquity is approximately 35°, Utopia Planitia is a region of above average cloud coverage. This would also mean above average temperatures, as suggested by Haberle et al. (2012).

Measurements from the Viking 2 Lander in eastern Utopia Planitia indicated atmospheric pressure of between 7.3 and 10.8 mb and temperatures between -120 and -14° C (Hess et al., 1977). With increased pressure and temperatures as suggested by models such as those described by Madeleine et al. (2009) and Haberle et al. (2012), it is reasonable to suggest the possibility of some localised thaw and the temporary surface pooling of water during the formation of scalloped depressions. Obliquity continues to fall and water is again removed from the atmosphere to be deposited at the poles. At the present day low obliquity of 25° deposition has ceased at the middle latitudes, and sublimation of ground ice slows as it is insulated by the overlying surface dust lag (Figure 4.5d). Periglacial activity may be initiated at very recent crater sites, where an impact may disrupt the ground thermal regime; but on a regional scale activity has ceased or at least slowed to a rate, which cannot be identified by current orbital analysis.

### 4.7 Conclusions

The study of permafrost and periglacial landscapes on Earth is closely linked to the study of recent climate change trends and concerns. The reason for this is that these environments are particularly reactive to a changing climate. Permafrost is melting, active layers are thickening and landform assemblages are constantly changing at alarming rates. Environments sensitive to the climate show the effects of any changes in the climate more readily than less extreme, more stable environments. Knowing this to be true of periglacial environments on Earth, we may assume that the periglacial environments on Mars are also the first to react to and, more importantly, record a changing climate. In this way it could be that the periglacial environments on Mars, particularly that which is present in Utopia Planitia, acts as a climate canary – informing us as to when the climate changed and the nature of the adjustment. This region is an area of predicted dust and ice accumulation leading to an enormous volume of ground ice, possibly much more than other areas located along the same latitude, and models also predict Utopia Planitia as a region that could experience cloud coverage and net warming well above the global average.

These regional conditions are such that they could even allow for the presence of water on the surface in the geologic past, if only for brief intervals. The hypothesis of thaw and the temporary pooling of water as a mechanism for the formation of scalloped depressions need not be dismissed based on the present day environment in Utopia Planitia. Orbital dynamics change the global climate in a predictable, if complicated, manner.

The topography, altitude, and latitudinal location all combine to cause Utopia Planitia to experience a regional climate that, while is still likely to be representative of the climate on a global scale, is intensified so that any changes on the global scale are magnified and, owing to the ground conditions, recorded by the changing periglacial and glacial landscape present. By investigating the history of periglacial activity in Utopia Planitia we are therefore not limited to simply that region but gain a broader understanding of the global trends in climate in Mars' recent past.

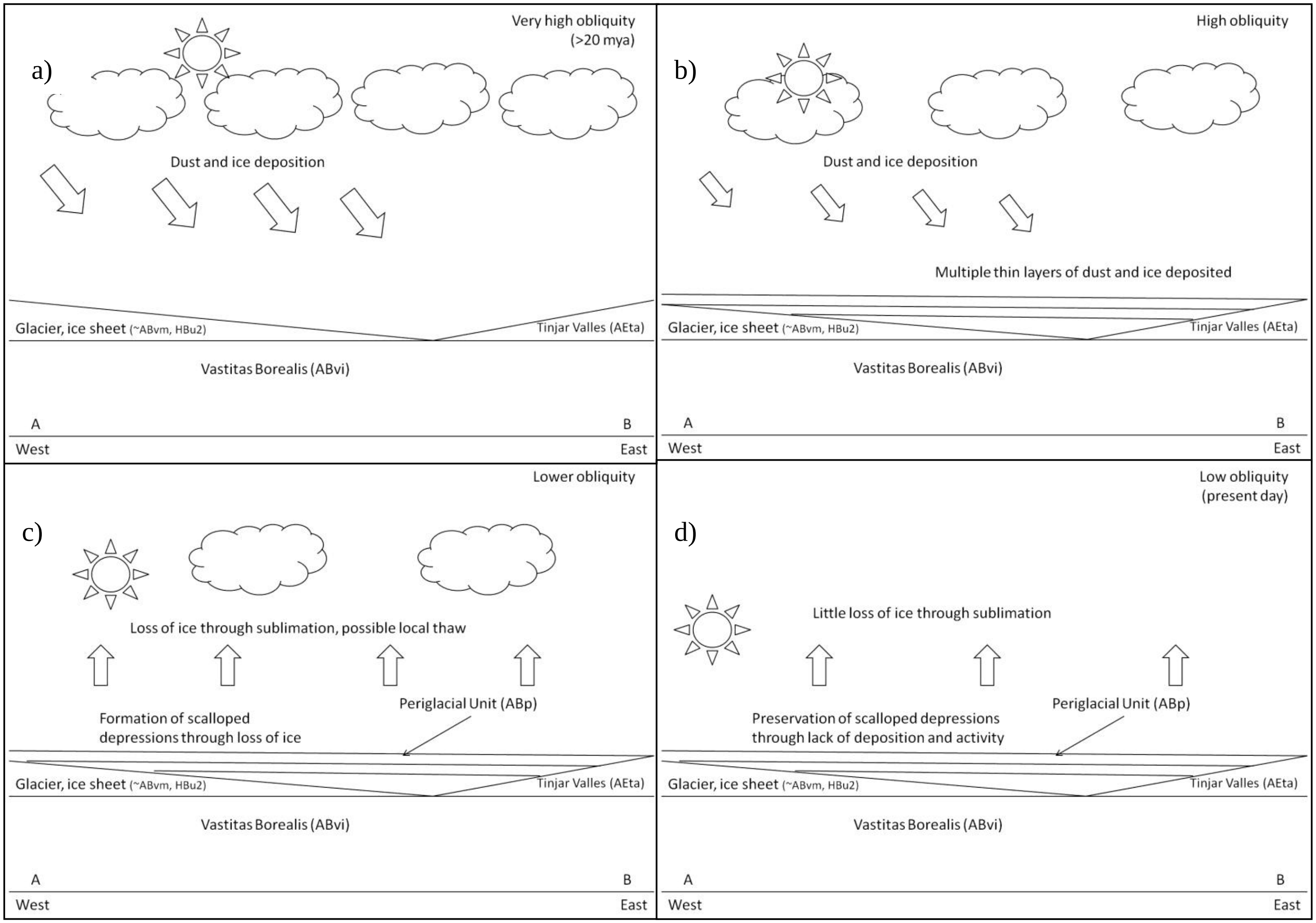


**Figure 4.5** The deposition and formation of the Periglacial Unit (ABp) in Utopia Planitia (not to scale). a) very high obliquity, deposition of dust and ice, accumulation of glacier/ice sheet in west, dissipates towards east b) high obliquity, deposition of dust and ice in thin layers c) lower obliquity, loss of ground ice, formation of scalloped depressions d) present day low obliquity, stable conditions.

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# 5 Chapter 5: Research Conclusions and Future Work

This research was undertaken to investigate the distribution and stratigraphy of scalloped depressions in Utopia Planitia and to reconstruct the past environment in which this periglacial landscape formed. Building upon recent studies on the periglacial landscape of Utopia Planitia (e.g., Lefort et al., 2009; Sejourne et al., 2011; Soare et al., 2008), a revised geologic map of Utopia Planitia has been produced (Chapter 2). We have also developed a model for the formation and evolution of the periglacial landscape examined by assessing the use of scalloped depressions as indicators of climate change, and combining our geologic evidence with recent climate model predictions (e.g., Forget et al., 2006; Laskar, 2012; Madeleine et al., 2009) (Chapter 4).

## 5.1 Major Findings

The first major finding of this research was to define a new geologic unit in Utopia Planitia. The Periglacial Unit (ABp) is a distinct geologic unit identified by its assemblage of scalloped depressions. In defining its extent, contacts, and stratigraphical relationships with surrounding units we concluded that it is the youngest geologic unit in Utopia Planitia and that the scalloped depressions are representative of the most recent phase of periglacial activity in the region.

Secondly, this research developed a model for the formation and evolution of the periglacial landscape in Utopia Planitia which suggests that regional conditions are such that they could allow for the presence of water on the surface in the geologic past, if only for brief intervals. The thawing of ground ice and the temporary pooling of water is a viable mechanism for the formation of scalloped depressions and need not be dismissed based on the current climate and atmospheric conditions on Mars. It is concluded that in the past Utopia Planitia has experienced an intensified regional climate and dynamic, evolving landscape that has recorded the changing climate on Mars.

In summary, the questions proposed at the beginning of this research have been answered as follows:

1. What is the geographic extent of the periglacial activity in Utopia Planitia?

Utopia Planitia has a substantial and varied region of periglacial activity unlike anywhere else on Mars.

2. Are the periglacial landforms surface modifications of older units or are they present in a discrete geologic unit?

A new geologic Periglacial Unit (ABp) is identified and defined.

3. Where does the periglacial activity occur in the stratigraphy of Utopia Planitia?

The Periglacial Unit (ABp) is identified as the youngest unit in the region.

4. What unique characteristics of Utopia Planitia could lead to the formation of the Periglacial Unit?

Obliquity driven changes in wind patterns, climate, and deposition, and the loss of subsurface ice lead to the formation of the scalloped depressions of the Periglacial Unit.

5. What does the record of environmental and climatic change in Utopia Planitia tell us about global climate change on Mars?

Utopia Planitia has experienced an intensified regional microclimate whose record will assist in understanding the history of global climate change on Mars.

### 5.2 Further Mapping in Utopia Planitia

As this research has shown, there is a cornucopia of periglacial landforms present in Utopia Planitia. We have focussed on the distribution and formation of scalloped depressions and it is imperative that similar investigations of other landforms (e.g., gullies, debris flows, polygon networks, and concentric crater fill) are carried out in the future if a comprehensive understanding of this landscape is to be achieved.

The 2013-2022 Planetary Decadal Survey is a NASA commissioned report (Committee on the Planetary Science Decadal Survey, 2012) summarizing the current state of knowledge in planetary science and outlining a strategy for continued advancement in this field through the next decade. It identifies the three major scientific goals of Mars exploration as:

- to determine if life ever arose on Mars,
- to understand the processes and history of climate on Mars, and
- to determine the evolution of the interior and surface of Mars.

In the short time since the Decadal Survey was published, our understanding of the amount, distribution, and possible nature of subsurface ice has increased significantly; so much so that the recent Concepts and Approaches for Mars Exploration workshop listed the "identification and exploration of modern aqueous/icy environments" as one of the main science topics to motivate future mission concepts (Mackwell, 2012).

The research presented here, focused on a modern aqueous/icy environment, directly addresses two of the scientific goals identified by the Decadal Survey and has implications for the third. By determining the evolution of the periglacial landscape in Utopia Planitia we have begun to piece together the history of the regional climate and how it may reflect global trends in climate in Mars' recent past. Unraveling the history and nature of the movement of water in this unique environment will also enhance calls our understanding of the geologically recent and current habitability of Mars and its subsurface niches.

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# Appendix

The following table lists the images in which scalloped depressions were recorded. This data is visualised in the form of a landform distribution map in Figure 2.2.

| Sensor | Image | Longitude | Latitude | Coalesced SD | Isolated Simple SD | Isolated Complex SD | Crater SD |
|---|---|---|---|---|---|---|---|
| CTX | B21_017656_2235_XI_43N281W | 78.350000 | 44.630000 | | | x | |
| CTX | P16_007437_2220_XI_42N280W | 79.790000 | 43.250000 | | | x | |
| THEMIS | thm_dir_N30_060 | 80.760000 | 44.320000 | x | x | x | x |
| CTX | P02_001701_2219_XI_41N279W | 80.650000 | 42.020000 | | | x | |
| CTX | P17_007516_2245_XN_44N278W | 81.850000 | 44.170000 | x | | x | x |
| CTX | B18_016746_2252_XN_45N277W | 82.730000 | 44.210000 | x | x | x | x |
| CTX | B18_016746_2252_XN_45N277W | 82.820000 | 43.590000 | x | x | x | x |
| CTX | P18_008162_2207_XN_40N277W | 82.580000 | 41.770000 | | | x | |
| CTX | P18_008162_2207_XN_40N277W | 83.050000 | 40.910000 | x | x | x | |
| CTX | B20_017313_2253_XI_45N276W | 83.580000 | 43.610000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 83.920000 | 42.040000 | | | x | x |
| CTX | P15_006804_2207_XN_40N276W | 83.650000 | 40.460000 | x | | | |
| CTX | P03_002202_2249_XN_44N275W | 84.420000 | 45.000000 | x | x | x | x |
| CTX | P03_002202_2249_XN_44N275W | 84.630000 | 44.890000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 84.510000 | 42.720000 | | | x | |
| CTX | P17_007740_2250_XN_45N275W | 85.090000 | 44.930000 | x | x | x | x |
| CTX | B19_017102_2224_XN_42N274W | 85.170000 | 43.230000 | x | x | x | x |
| CTX | G02_018882_2262_XN_46N273W | 86.090000 | 44.980000 | x | x | x | x |
| CTX | P16_007384_2216_XN_41N273W | 86.080000 | 42.310000 | x | | x | |
| CTX | P16_007384_2216_XN_41N273W | 86.130000 | 41.940000 | x | x | x | x |
| CTX | B01_009889_2210_XI_41N272W | 86.840000 | 40.470000 | | | x | |

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|---|---|---|---|---|---|---|---|
| CTX | P16_007384_2216_XN_41N273W | 86.710000 | 40.350000 | x | x | x | x |
| CTX | P16_007384_2216_XN_41N273W | 86.770000 | 40.290000 | | | x | |
| CTX | B02_010456_2248_XI_44N273W | 87.000000 | 44.420000 | x | x | x | x |
| CTX | B02_010456_2248_XI_44N273W | 87.200000 | 44.460000 | x | x | x | x |
| CTX | P16_007173_2244_XN_44N272W | 87.320000 | 44.330000 | x | | | x |
| CTX | B01_010034_2248_XI_44N272W | 87.490000 | 44.500000 | x | | x | x |
| CTX | P16_007173_2244_XN_44N272W | 87.890000 | 44.350000 | x | | | x |
| CTX | P19_008465_2235_XN_43N272W | 87.900000 | 44.420000 | x | x | x | x |
| CTX | B18_016759_2236_XN_43N272W | 87.740000 | 43.630000 | | | | x |
| CTX | P01_001384_2239_XN_43N271W | 88.340000 | 43.890000 | x | x | x | x |
| CTX | B01_009889_2210_XI_41N272W | 87.320000 | 42.200000 | | x | | |
| CTX | B01_009889_2210_XI_41N272W | 87.440000 | 41.960000 | | x | x | x |
| CTX | B01_009889_2210_XI_41N272W | 87.580000 | 41.870000 | x | | x | |
| CTX | B01_009889_2210_XI_41N272W | 87.460000 | 41.650000 | x | x | x | x |
| CTX | P18_008109_2220_XI_42N270W | 89.140000 | 44.190000 | | x | | |
| CTX | P18_008109_2220_XI_42N270W | 89.340000 | 44.040000 | | | x | |
| CTX | B01_010179_2220_XI_42N269W | 89.910000 | 43.620000 | x | | | x |
| CTX | P18_008109_2220_XI_42N270W | 89.830000 | 43.050000 | x | | x | x |
| CTX | P18_008109_2220_XI_42N270W | 89.720000 | 42.170000 | | x | x | x |
| CTX | B01_010179_2220_XI_42N269W | 89.700000 | 40.670000 | x | | x | |
| CTX | B02_010245_2304_XN_50N275W | 84.000000 | 50.510000 | | | | x |
| CTX | P17_007753_2292_XN_49N271W | 88.510000 | 49.990000 | | | | x |
| CTX | B16_016021_2258_XI_45N283W | 76.010000 | 46.610000 | | | x | x |
| CTX | B17_016377_2258_XI_45N282W | 76.300000 | 45.890000 | x | x | x | x |
| CTX | B20_017511_2304_XI_50N283W | 77.390000 | 48.630000 | x | | | x |
| THEMIS | thm_dir_N30_060 | 79.530000 | 49.070000 | | | | x |
| THEMIS | thm_dir_N30_060 | 79.610000 | 49.110000 | | | | x |
| CTX | B19_016944_2254_XI_45N282W | 78.220000 | 47.280000 | x | x | x | |

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|---|---|---|---|---|---|---|---|
| CTX | B19_016944_2254_XI_45N282W | 78.050000 | 46.560000 | x | x | x | x |
| CTX | B19_016944_2254_XI_45N282W | 78.400000 | 46.250000 | | | x | |
| THEMIS | thm_dir_N30_060 | 79.370000 | 45.950000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 81.260000 | 0.000000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 81.540000 | 0.000000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 81.750000 | 0.000000 | x | | x | |
| THEMIS | thm_dir_N30_060 | 81.840000 | 0.000000 | x | | x | |
| THEMIS | thm_dir_N30_060 | 82.260000 | 0.000000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 82.290000 | 0.000000 | x | | x | x |
| THEMIS | thm_dir_N30_060 | 80.770000 | 0.000000 | x | x | x | |
| THEMIS | thm_dir_N30_060 | 80.640000 | 0.000000 | x | x | x | |
| THEMIS | thm_dir_N30_060 | 80.980000 | 0.000000 | x | | x | x |
| THEMIS | thm_dir_N30_060 | 81.780000 | 0.000000 | x | x | | x |
| CTX | P17_007516_2245_XN_44N278W | 81.220000 | 44.000000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 83.840000 | 0.000000 | x | | x | x |
| THEMIS | thm_dir_N30_060 | 84.000000 | 0.000000 | x | x | x | x |
| CTX | B17_016469_2259_XN_45N275W | 84.440000 | 45.820000 | x | | | x |
| CTX | B18_016535_2259_XN_45N275W | 84.200000 | 45.140000 | x | | | x |
| CTX | B18_016535_2259_XN_45N275W | 84.280000 | 45.060000 | x | | | x |
| CTX | B17_016469_2259_XN_45N275W | 84.540000 | 45.010000 | x | | | x |
| CTX | G02_018882_2262_XN_46N273W | 85.880000 | 47.400000 | x | | x | x |
| CTX | G02_018882_2262_XN_46N273W | 86.640000 | 47.480000 | x | | x | x |
| CTX | G02_018882_2262_XN_46N273W | 86.900000 | 47.390000 | x | | x | x |
| THEMIS | thm_dir_N30_060 | 85.350000 | 46.400000 | | | | |
| CTX | G04_019594_2267_XN_46N272W | 87.800000 | 46.030000 | x | x | x | x |
| CTX | G04_019594_2267_XN_46N272W | 88.200000 | 45.430000 | x | x | x | x |
| THEMIS | thm_dir_N30_060 | 88.200000 | 45.330000 | | | | x |
| THEMIS | thm_dir_N30_060 | 88.290000 | 45.350000 | | | | x |

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|---|---|---|---|---|---|---|---|
| CTX | P03_002070_2250_XI_45N271W | 88.640000 | 45.070000 | x | | | x |
| CTX | B20_017471_2268_XN_46N270W | 89.110000 | 45.990000 | x | x | x | x |
| CTX | B20_017405_2270_XN_47N269W | 89.850000 | 47.110000 | | | | x |
| CTX | P17_007753_2292_XN_49N271W | 88.970000 | 48.900000 | | | | x |
| CTX | G18_025132_2260_XN_46N267W | 93.530000 | 44.910000 | x | x | x | x |
| CTX | P18_008188_2228_XN_42N268W | 92.620000 | 44.280000 | | | x | |
| CTX | P22_009691_2233_XI_43N267W | 92.840000 | 43.710000 | x | | x | x |
| CTX | B01_010179_2220_XI_42N269W | 90.700000 | 43.500000 | | x | x | |
| CTX | P18_008188_2228_XN_42N268W | 92.730000 | 43.220000 | | | x | |
| CTX | P22_009691_2233_XI_43N267W | 92.880000 | 42.150000 | x | | x | x |
| CTX | P22_009691_2233_XI_43N267W | 92.970000 | 42.060000 | | x | | |
| CTX | P18_008188_2228_XN_42N268W | 92.720000 | 41.790000 | | | x | |
| CTX | B18_016495_2244_XI_44N263W | 96.010000 | 44.300000 | x | x | x | x |
| CTX | B02_010337_2246_XN_44N261W | 98.450000 | 44.770000 | x | x | x | x |
| CTX | P14_006632_2241_XI_44N261W | 98.500000 | 44.050000 | | x | | x |
| CTX | B01_009994_2253_XN_45N260W | 99.600000 | 44.720000 | x | | x | |
| CTX | G20_026055_2240_XN_44N264W | 95.330000 | 42.920000 | x | x | x | x |
| CTX | P16_007476_2243_XN_44N265W | 95.290000 | 42.670000 | | x | x | |
| CTX | G03_019330_2217_XN_41N264W | 95.650000 | 41.240000 | | | | x |
| CTX | B16_016073_2240_XI_44N263W | 96.640000 | 41.940000 | | x | | |
| CTX | B18_016495_2244_XI_44N263W | 96.850000 | 42.440000 | x | x | x | x |
| CTX | P16_007199_2216_XN_41N262W | 97.860000 | 42.600000 | | | x | |
| CTX | P16_007199_2216_XN_41N262W | 97.860000 | 41.310000 | x | x | x | x |
| CTX | P16_007199_2216_XN_41N262W | 98.220000 | 41.160000 | x | x | x | |
| CTX | P03_002175_2211_XI_41N260W | 99.250000 | 41.190000 | | | x | x |
| CTX | B02_010350_2253_XI_45N259W | 100.720000 | 44.870000 | | x | | |
| CTX | B02_010350_2253_XI_45N259W | 100.730000 | 44.810000 | x | x | x | |
| CTX | B19_016864_2245_XN_44N258W | 101.460000 | 44.530000 | | | x | |

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|---|---|---|---|---|---|---|---|
| CTX | B17_016442_2252_XI_45N257W | 101.620000 | 44.460000 | x | | | x |
| CTX | B19_017075_2238_XN_43N259W | 100.370000 | 43.270000 | x | | x | x |
| CTX | B19_017075_2238_XN_43N259W | 100.580000 | 43.030000 | x | | x | x |
| CTX | B17_016442_2252_XI_45N257W | 101.810000 | 42.260000 | | | x | x |
| CTX | B21_017932_2240_XI_44N256W | 103.460000 | 42.170000 | | | x | |
| CTX | B21_017721_2245_XN_44N256W | 103.510000 | 43.530000 | | | x | |
| CTX | B18_016772_2318_XN_51N267W | 92.400000 | 51.390000 | | | | x |
| CTX | G01_018763_2302_XI_50N265W | 94.450000 | 50.250000 | x | | | x |
| CTX | G01_018763_2302_XI_50N265W | 94.610000 | 50.290000 | x | | | x |
| CTX | G01_018552_2302_XN_50N264W | 94.810000 | 50.390000 | x | | x | |
| CTX | B19_017141_2333_XN_53N262W | 97.460000 | 53.620000 | | | | x |
| CTX | G23_027044_2320_XN_52N266W | 97.230000 | 51.290000 | x | x | x | x |
| CTX | G23_027123_2323_XI_52N263W | 95.130000 | 51.330000 | | | x | x |
| CTX | P17_007700_2313_XN_51N264W | 95.340000 | 50.960000 | | | | x |
| CTX | G22_026846_2329_XN_52N261W | 99.490000 | 50.580000 | | x | x | x |
| CTX | B18_016508_2297_XN_49N259W | 99.570000 | 50.080000 | | | | x |
| CTX | P17_007858_2329_XN_52N258W | 101.230000 | 53.660000 | x | x | x | |
| CTX | P17_007858_2329_XN_52N258W | 101.780000 | 52.090000 | | | x | |
| CTX | B18_016508_2297_XN_49N259W | 100.470000 | 50.470000 | | | | x |
| THEMIS | thm_dir_N30_090 | 103.130000 | 51.050000 | x | x | x | x |
| THEMIS | thm_dir_N30_090 | 103.750000 | 50.720000 | | | x | x |
| CTX | G20_026081_2307_XN_50N254W | 104.910000 | 50.980000 | | | | x |
| CTX | P16_007252_2277_XN_47N269W | 90.960000 | 49.160000 | x | x | x | x |
| CTX | G20_025910_2296_XN_49N266W | 92.720000 | 48.880000 | x | x | x | x |
| CTX | G21_026266_2278_XI_47N265W | 94.560000 | 49.070000 | x | x | x | |
| CTX | B01_010113_2254_XI_45N269W | 90.730000 | 46.630000 | x | x | x | x |
| CTX | B20_017405_2270_XN_47N269W | 90.040000 | 46.400000 | x | | | x |
| CTX | P16_007252_2277_XN_47N269W | 91.190000 | 47.470000 | x | x | x | x |

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|---|---|---|---|---|---|---|---|
| CTX | P16_007252_2277_XN_47N269W | 91.170000 | 47.060000 | x | x | x | x |
| CTX | P02_001938_2263_XI_46N267W | 91.880000 | 46.030000 | x | | | x |
| CTX | P02_001938_2263_XI_46N267W | 91.700000 | 45.810000 | x | | x | |
| CTX | P02_001938_2263_XI_46N267W | 91.440000 | 45.520000 | x | | x | |
| CTX | G19_025554_2288_XN_48N268W | 91.950000 | 47.570000 | x | x | x | x |
| CTX | G19_025554_2288_XN_48N268W | 92.490000 | 47.770000 | x | x | x | x |
| CTX | G19_025554_2288_XN_48N268W | 93.240000 | 47.960000 | x | x | x | x |
| CTX | G18_025277_2277_XN_47N266W | 93.210000 | 47.410000 | x | | x | |
| CTX | G21_026622_2280_XI_48N266W | 93.750000 | 47.370000 | | x | x | |
| CTX | G19_025620_2273_XN_47N266W | 94.000000 | 47.220000 | x | | x | x |
| CTX | G21_026266_2278_XI_47N265W | 94.530000 | 47.620000 | | x | x | x |
| CTX | P16_007476_2243_XN_44N265W | 94.790000 | 45.430000 | x | x | x | |
| CTX | P16_007476_2243_XN_44N265W | 94.850000 | 45.750000 | | | x | |
| CTX | P16_007476_2243_XN_44N265W | 94.610000 | 46.190000 | | x | x | x |
| CTX | P02_001872_2259_XI_45N266W | 93.890000 | 46.050000 | x | x | x | |
| CTX | G20_026121_2280_XI_48N266W | 93.800000 | 46.470000 | x | x | x | |
| CTX | G20_026121_2280_XI_48N266W | 93.770000 | 46.670000 | x | x | x | |
| CTX | P04_002439_2263_XI_46N267W | 92.490000 | 45.480000 | x | | | x |
| CTX | P02_001938_2263_XI_46N267W | 92.300000 | 45.370000 | x | | | x |
| CTX | B18_016495_2244_XI_44N263W | 96.230000 | 45.440000 | x | | x | x |
| CTX | B18_016495_2244_XI_44N263W | 96.320000 | 45.240000 | x | | x | x |
| CTX | B18_016495_2244_XI_44N263W | 96.680000 | 45.220000 | x | | x | x |
| CTX | B18_016495_2244_XI_44N263W | 96.790000 | 45.380000 | x | | x | x |
| CTX | G19_025567_2262_XN_46N262W | 97.140000 | 45.340000 | x | x | x | |
| CTX | G19_025633_2243_XI_44N264W | 95.050000 | 46.380000 | x | x | x | x |
| CTX | B18_016495_2244_XI_44N263W | 95.760000 | 46.270000 | x | | x | x |
| CTX | G20_026200_2282_XI_48N264W | 96.100000 | 46.950000 | x | | x | |
| CTX | G19_025567_2262_XN_46N262W | 96.610000 | 47.880000 | x | | x | x |

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|---|---|---|---|---|---|---|---|
| CTX | G20_025989_2265_XN_46N263W | 96.270000 | 48.700000 | x | x | x | x |
| CTX | G01_018552_2302_XN_50N264W | 95.490000 | 49.260000 | x | | x | |
| CTX | G22_026978_2305_XI_50N263W | 96.620000 | 49.620000 | x | | x | |
| CTX | P17_007634_2280_XN_48N261W | 98.500000 | 48.820000 | | | x | |
| CTX | P17_007634_2280_XN_48N261W | 98.870000 | 48.790000 | | x | x | x |
| CTX | G19_025567_2262_XN_46N262W | 97.140000 | 46.670000 | x | | x | x |
| CTX | B01_009994_2253_XN_45N260W | 99.810000 | 45.730000 | | | | x |
| CTX | P17_007634_2280_XN_48N261W | 99.440000 | 45.780000 | | x | x | |
| CTX | P17_007634_2280_XN_48N261W | 99.210000 | 45.770000 | x | x | x | |
| CTX | P17_007634_2280_XN_48N261W | 99.150000 | 45.350000 | | | x | x |
| THEMIS | thm_dir_N30_090 | 98.450000 | 45.140000 | x | x | x | x |
| CTX | P18_008214_2288_XN_48N259W | 101.100000 | 48.600000 | | | x | |
| CTX | P18_008214_2288_XN_48N259W | 101.080000 | 48.560000 | x | x | x | x |
| CTX | P18_008214_2288_XN_48N259W | 101.040000 | 48.570000 | | x | | |
| THEMIS | thm_dir_N30_090 | 101.300000 | 47.190000 | | x | x | x |
| CTX | P02_001964_2272_XI_47N258W | 101.570000 | 47.240000 | | x | | |
| THEMIS | thm_dir_N30_090 | 103.490000 | 47.300000 | x | x | x | x |
| CTX | B17_016442_2252_XI_45N257W | 102.650000 | 45.360000 | | | x | |
| CTX | B17_016442_2252_XI_45N257W | 102.240000 | 45.690000 | x | x | x | |
| CTX | B17_016442_2252_XI_45N257W | 101.930000 | 45.840000 | | x | | |
| CTX | B17_016442_2252_XI_45N257W | 102.120000 | 46.170000 | x | x | x | x |
| CTX | B20_017431_2235_XN_43N258W | 101.130000 | 45.790000 | x | | x | x |
| CTX | B02_010350_2253_XI_45N259W | 100.540000 | 45.140000 | | x | x | |
| CTX | B01_009994_2253_XN_45N260W | 100.160000 | 45.650000 | x | | x | |
| CTX | G22_026635_2283_XN_48N260W | 100.290000 | 45.970000 | x | | x | x |
| CTX | G22_026635_2283_XN_48N260W | 100.020000 | 46.250000 | | x | x | |
| CTX | G22_026635_2283_XN_48N260W | 100.130000 | 46.280000 | | | x | x |
| CTX | G23_027083_2222_XN_42N248W | 110.820000 | 44.300000 | | | x | |

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|---|---|---|---|---|---|---|---|
| CTX | B19_017167_2220_XN_42N249W | 111.190000 | 41.110000 | x | x | x | |
| CTX | G02_018960_2236_XI_43N243W | 116.920000 | 43.740000 | x | | x | x |
| CTX | G02_018960_2236_XI_43N243W | 116.980000 | 43.680000 | x | x | x | x |
| CTX | P16_007238_2331_XN_53N249W | 111.820000 | 50.630000 | | x | | |
| CTX | B02_010521_2300_XN_50N248W | 111.380000 | 50.080000 | x | | | |
| CTX | G23_027281_2266_XN_46N254W | 105.450000 | 46.300000 | | x | x | |
| CTX | B01_009941_2287_XN_48N254W | 105.970000 | 48.850000 | x | | x | |
| CTX | B05_011431_2290_XN_49N253W | 106.560000 | 48.470000 | | x | | |
| CTX | B17_016310_2266_XN_46N253W | 106.210000 | 47.940000 | x | | | x |
| CTX | B17_016310_2266_XN_46N253W | 106.400000 | 47.880000 | x | | x | |
| CTX | B17_016310_2266_XN_46N253W | 106.140000 | 47.200000 | | | x | |
| CTX | G21_026516_2246_XN_44N250W | 109.320000 | 46.330000 | x | x | x | x |
| CTX | G23_027294_2279_XN_47N250W | 109.970000 | 48.230000 | x | x | x | |
| CTX | B01_009875_2289_XN_48N252W | 107.450000 | 49.220000 | | x | | |
| THEMIS | thm_dir_N30_090 | 110.510000 | 47.190000 | | x | x | x |
| CTX | B16_015901_2285_XN_48N248W | 112.260000 | 48.180000 | | x | | |
| CTX | B16_015901_2285_XN_48N248W | 112.360000 | 48.140000 | x | x | x | x |
| CTX | B01_009888_2287_XN_48N247W | 112.580000 | 46.960000 | | | x | |
| CTX | B01_009888_2287_XN_48N247W | 112.230000 | 46.540000 | x | x | x | x |
| CTX | B01_009888_2287_XN_48N247W | 112.770000 | 48.990000 | x | | x | |
| CTX | B02_010244_2288_XN_48N246W | 112.850000 | 48.550000 | x | | x | |
| CTX | B02_010244_2288_XN_48N246W | 113.460000 | 49.540000 | | x | | |
| CTX | B17_016191_2286_XN_48N245W | 114.000000 | 48.340000 | x | x | x | x |
| CTX | B17_016191_2286_XN_48N245W | 114.350000 | 48.230000 | | | x | |
| CTX | B17_016336_2279_XI_47N244W | 115.640000 | 49.760000 | x | x | x | x |
| CTX | B17_016125_2284_XN_48N243W | 116.410000 | 47.850000 | | | x | |
| CTX | B17_016125_2284_XN_48N243W | 116.820000 | 47.530000 | x | x | x | x |
| CTX | B18_016837_2289_XI_48N241W | 118.810000 | 49.280000 | x | | x | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| CTX | B21_017760_2286_XN_48N241W | 119.230000 | 49.400000 | x | | x | |
| CTX | B21_017760_2286_XN_48N241W | 119.500000 | 48.610000 | | x | x | |
| CTX | B18_016837_2289_XI_48N241W | 118.650000 | 47.900000 | x | | x | |
| CTX | P20_008716_2296_XN_49N287W | 72.770000 | 49.710000 | x | | | |
| CTX | P18_008215_2296_XN_49N286W | 73.460000 | 48.090000 | x | | | x |
| CTX | P16_007213_2300_XN_50N285W | 74.320000 | 47.650000 | x | | x | x |
| CTX | B18_016654_2253_XI_45N285W | 74.310000 | 47.660000 | | x | | |
| CTX | B17_016153_2260_XN_46N287W | 72.460000 | 45.870000 | x | x | x | x |
| CTX | B18_016654_2253_XI_45N285W | 74.960000 | 45.320000 | | | x | x |
| CTX | B18_016496_2263_XN_46N291W | 68.500000 | 45.210000 | | x | x | x |
| CTX | B21_017775_2262_XN_46N290W | 69.450000 | 45.370000 | | | x | x |
| CTX | B21_017775_2262_XN_46N290W | 69.520000 | 45.300000 | x | x | x | |
| CTX | B21_017775_2262_XN_46N290W | 69.720000 | 45.160000 | | | x | |
| THEMIS | thm_dir_N30_060 | 61.390000 | 48.540000 | x | x | x | x |
| CTX | P17_007477_2247_XN_44N293W | 66.710000 | 43.040000 | x | | | x |
| CTX | G20_025935_2296_XN_49N230W | 133.140000 | 55.060000 | | x | | |
| CTX | G21_026476_2313_XI_51N238W | 122.070000 | 50.350000 | x | | | x |
| CTX | B20_017483_2288_XN_48N238W | 120.520000 | 49.990000 | | | | x |
| CTX | P03_002372_2215_XN_41N236W | 123.770000 | 41.480000 | | | x | |
| CTX | P03_002372_2215_XN_41N236W | 123.840000 | 41.540000 | x | x | x | |

Curriculum Vitae

| | |
|---|---|
| **Name:** | Mary C. Kerrigan |
| **Post-secondary Education and Degrees:** | Dublin University, Trinity College<br>Dublin, Ireland<br>2004-2008 B.Sc. |
| | The University of Western Ontario<br>London, Ontario, Canada<br>2010-2012 M.Sc. |
| **Honours and Awards:** | Enterprise Ireland Scholarship<br>2008 |
| | European Space Agency – International Space University Scholarship<br>2009 |
| **Related Work Experience** | Teaching Assistant<br>The University of Western Ontario<br>2010-2012 |

**Selected Conference Presentations:**

Kerrigan M. C., Osinski G. R., Capitan R. D., Barry N., Blain S., and Van De Wiel M. J. (2012) The Distribution and Stratigraphy of Periglacial Landforms in Western Utopia Planitia, Mars. *Mars Recent Climate Change Workshop*. NASA Ames, CA

Kerrigan M. C., Shankar B., Marion C., Francis R., Pickersgill A. E., Capitan R. D., Osinski G. R., and the ILSR Team (2012) Real-time Mission Control Tracking of Astronaut Positions during Analogue Missions. *43rd Lunar and Planetary Science Conference*. Houston, TX

Kerrigan M. C., McDonnell G., Meade F., Troll V. R., and Chew D. (2008) Multiple versus Composite: Revisiting Judd's Dykes on the Isle of Arran, Scotland. *Volcanic and Magmatic Studies Group Conference.* Dublin, Ireland

**Non-refereed publications:**

ACCESS Mars – Mission architecture for an initial settlement on Mars assessing the feasibility of cave habitation as an alternative to proposed surface-based solutions – International Space University SSP (2009) at NASA Ames