AN INVESTIGATION OF THE HYPOTHESES FOR FORMATION OF THE PLATY-RIDGED-POLYGONIZED TERRAIN IN ELYSIUM PLANITIA, MARS

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ABSTRACT:

The origin of the platy-ridged-polygonized (PRP) terrains on Martian surface has long been debated. The terrain has generally been classified as water, pack ice, or basalt lava related flow. The crater counting results of the PRP terrains suggest they are geologically very young; therefore, they are significant in understanding the recent evolution of Mars. This work evaluated the current hypotheses through detailed analysis of the distribution and microtopographies with the High Resolution Imaging Science Experiment (HiRISE) images for the PRP terrains in Elysium Planitia, Mars. Quantitative measurements and statistics of the typical features of the PRP terrains were also made. In addition, we also found an analog site in Tarim Basin in Xinjiang, China. Our results suggest that mud flow is responsible for the formation of the PRP terrains on the Mars surface, although the hypothesis of low-viscosity basalt lava floods cannot be completely excluded. This finding implies that a regional environment suitable for liquid water may have existed in recent geologic time, which has great importance for future Mars scientific exploration.

1. INTRODUCTION

The discovery of geologically young (late Amazonian age) Platy-Ridged-Polygonized (PRP) terrain in Elysium Planitia, Mars can be traced back to earlier geologic mapping from the Viking images (Mouginis-Mark et al., 1984; Tanaka, 1986). However, the detailed morphology and structure of the PRP terrain could be studied only recently with high resolution images. Typically, the PRP terrain comprises rubbly plates, sinuous or linear ridges, and polygonally patterned smooth ground (Figure 1). The plates (PL) are usually of low albedo, commonly contain meter-sized clasts (Balme et al., 2011), and typically have irregular polygonal shapes. The polygonal (PO) terrains are usually of high albedo and are relatively smooth (Figure 1). The ridges can develop in the smooth polygonal ground as shown in Figure 1 or can appear as the boundaries of the platy regions.

A number of models have been proposed to explain the origin of the PRP terrains, and these can be generally classified into two categories based on the agents of water or lava. In early geologic mapping, the PRP terrain in Elysium Planitia, Mars was considered a water-formed landform based on the morphologies (Mouginis-Mark et al., 1984; Tanaka, 1986). The hypothesis was strengthened in subsequent regional studies by the discovery of small channels, and the water was supposed to have arisen from the interaction between volcanic flows and ice on Mars (Scott and Chapman, 1991; Edgett and Rice, 1995). Rice et al. (2002) also favoured an ice-rich fluvial flow emplacement process for the formation of PRP terrain, and they

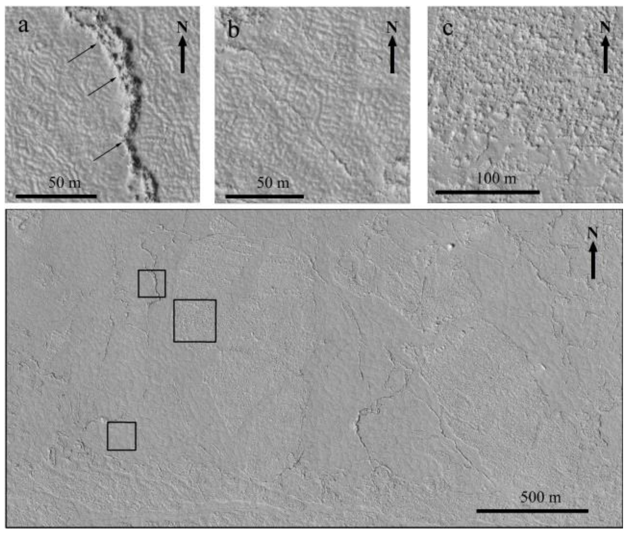

Figure 1. Platy-ridged-polygonised terrain (Part of HiRISE image PSP_003571_1880_RED.jp2). The ridges are highlighted by arrows and in inset (a) in detail, the smoother material are the polygonised terrain (labelled by PO and shown in inset (b) in detail), and the rougher material is the platy terrain (labelled by PL and highlighted in inset (c)).

interpreted the ridges to be ice pressure ridges while the plates were slabs of sediment rich ice rafted along in the debris flow. Based on morphology, size, and an analogy with terrestrial ground ice forms, Burr et al. (2005) proposed the ground ice hypothesis for the polygonal terrain and other related landforms.

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In addition, Page (2007) and Page et al. (2009) proposed that the polygonally patterned ground and the platy surfaces are essentially periglacial landforms. Murray et al. (2005) also favoured the formation of the PRP terrain being related with water; however, they presented a slightly different model proposing that the PRP terrain was consistent with a frozen body of water with surface pack ice. It is important to note that the PRP terrain also appears in other regions of Mars, for example, Williams and Malin (2004) found such landforms in the immediate proximity of the southern Kasei Valles inner channels, and they speculated that this texture may be related to waning floodwaters moving through the inner channels and leaving a mudflow deposit.

Conversely, the PRP terrain has been proposed as a lava flow in many studies. Schaber (1980) interpreted the curvilinear ridges as the compressional foldover of moving lava sheets from the Viking Orbiter images and Earth-based radar observations of Mars. Plescia (1990) interpreted the terrain as having been formed by the massive eruption of low-viscosity flood lavas as demonstrated by the lack of well-defined proximal flow margins. Based on a comparison with the morphology of large terrestrial lava flows and thermal modelling, Keszthelyi et al. (2000) concluded that basalt flows produced the PRP terrain. In addition, Keszthelyi et al. (2004) observed that Icelandic lava flows have a similar surface morphology to the PRP terrain. Jaeger et al. (2007, 2010) also supported the idea that the PRP terrain was formed by a thin layer of solidified lava. Currently, the origin of the PRP terrain remains debated (see reviews by Page, 2010), and the debate is open-ended because it is closely related to the Mars climate in recent geologic time.

These above workers have made interesting arguments on the origin of the PRP terrain; however, any viable model of the formation of the PRP terrain and the type of erosive fluid must be consistent with the observational constraints, especially with the high resolution data recently acquired. In this research, we primarily use the highest resolution images from High Resolution Imaging Science Experiment (HiRISE) onboard Mars Reconnaissance Orbiter (MRO) to explore the detailed geomorphic characteristics and regional properties of the PRP terrain. We also focused on quantitative spatial measurements of the morphological characteristics in the topographic data from the stereo HiRISE images, which are the first quantitative measurements of the microtopography of the PRP terrains and precisely describe the details of the PRP terrain. We compare the proposed models with numerous observations of the dimensional properties of the PRP terrain features in order to better constrain these models and to support future modelling efforts. We were also very lucky to find a terrestrial analogue of the PRP terrain in Xinjiang, China, where the environment is extremely arid and cold. The observations show that a similar geologic process has occurred there, which has important implications for our understanding of the formation of the PRP terrain on the Mars surface. In subsequent sections we will describe the data sets located in Elysium Planitia, (Figure 2A) (the region boundary is taken according to the International Astronomical Union (IAU) Working Group for Planetary System Nomenclature, http://planetarynames.wr.usgs.gov/Feature/1784), as well as measurements and estimates of the attributes of the PRP terrain. These observed properties and their trends are analysed for implications relevant to the PRP terrain formation and then place additional constraints on these mechanisms.

2. DATA SETS AND METHODOLOGY

2.1 Data sets

In this research, HiRISE images are the main data source to identify the PRP terrain. HiRISE is a Charge-Coupled Device (CCD) camera onboard the Mars Reconnaissance Orbiter (MRO) spacecraft, which was launched in August 2005. The HiRISE camera has a high signal to noise ratio (SNR), a large image size, and high resolution. The focal plane contains a total of 14 CCD arrays; of which 10 operate in red wavelengths, providing continuous coverage of a swath 20,048 pixels wide used for this research. The HiRISE data products were processed through radiometric correction, geometric transformation, format conversion, and lossless compression to the JPEG2000 format.

In this research, we collected 866 HiRISE images from the study area of Elysium Planitia from the mission phases of transition, primary science, and extended science prior to April 3, 2015. The footprints of these data are shown in Figure 2B. The data products used here had been resampled to 0.25 m/pixel or 0.5 m/pixel, and could be directly integrated into the ArcGIS software platform because they were geometrically projected. Among these images, we also found a pair of stereo images where the PRP terrain exists, which was used to generate a high resolution DEM data for 3D analysis.

We also used context camera (CTX) images from MRO (Edwards et al., 2011). CTX has a spatial resolution of about 6 m from MRO's nearly circular, nearly polar mapping orbit, and it can provide a 30-km-wide swath from 290 km altitude. We used Chinese high resolution GF-2 images to study the terrestrial analogy terrain found in Xinjiang, China. GF-2 has a resolution of 0.81 m and 3.24 m for panchromatic and multispectral images respectively in nadir-imaging mode with a swath about 45 km wide (Pan, 2015).

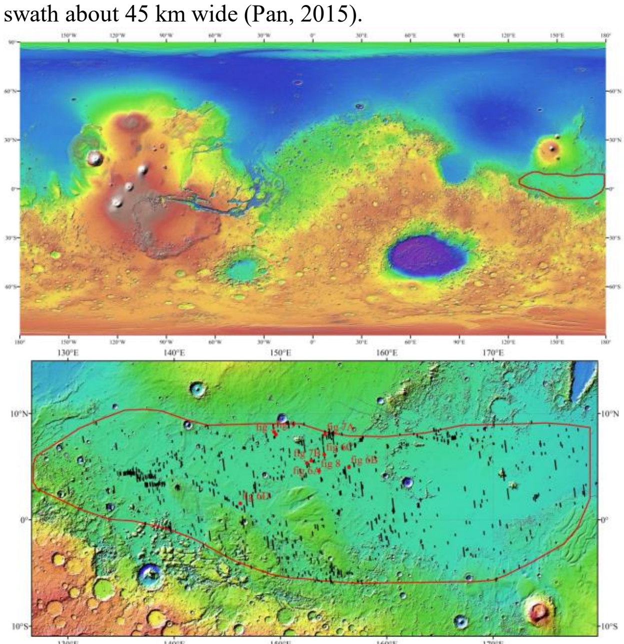

Figure 2. Locations of the study area and the footprints of the datasets used in the research. (A) Top panel, the location of the study area is represented by the red polygon. (B) Bottom panel, the footprints of the HiRISE images (black) used in the research. The locations of the subsequent images used in the paper are also labelled. Mars Orbiter Laser Altimeter (MOLA) data is the background image.

Setting	A4 size paper	
	mm	inches
Top	25	1.0
Bottom	25	1.0
Left	20	0.8
Right	20	0.8
Column Width	82	3.2
Column Spacing	6	0.25

Table 1. Margin settings for A4 size paper

2.2 Estimation of the height of ridges on PRP terrain

In this research, we have generated a Digital Terrain Model (DEM) from a pair of HiRISE images to measure the features of the PRP terrain wherein. The selected stereo images are downloaded from the planetary data system website (http://pds-geosciences.wustl.edu/), and then the interior and external orientation elements are retrieved and added to the image cube. The photogrammetry method of bundle adjustment is finally used to generate a DEM with a resolution of 1.5m. In our study, the above processing work is done using the Stereo Pipeline software (https://ti.arc.nasa.gov/tech/asr/intelligent-robotics/ngt/stereo/).

To measure the height of the ridges of the PRP terrain, we first identify these ridges and sketched their outlines in the HiRISE images. In sketching the ridges, the ridges are initially marked with a polyline, and then a buffer with a radius of 10 m is expanded around each ridge (Figure 3). From the DEM profiles within the buffer zone, it can be seen that a crest usually appears in a typical profile of the ridge (Figure 3). It indicates that the buffer zone with a radius of 10m can represent the ridges reasonably well. For simplicity, the height of the ridges in PRP terrain is considered as the elevation difference between the highest and lowest elevation value in the buffer zone. All of the above work was carried out with the ArcGIS software.

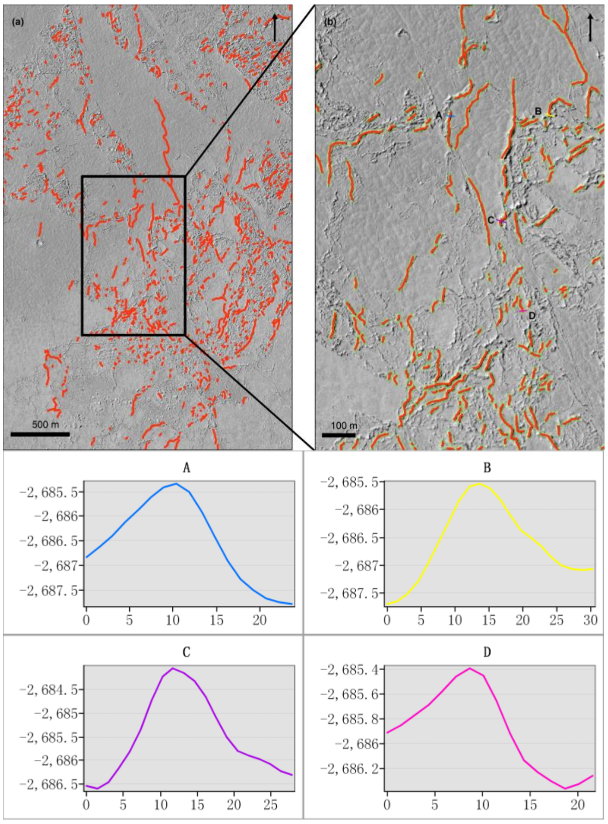

Figure 3. Extracted ridges and the buffered zones in HiRISE image (ESP_018036_1880_RED.jp2). The ridges are first extracted along the crest (top left), and then a buffer with a radius of 10 m is expanded around each ridge (top right). Below shows typical cross profiles of the ridges in the PRP terrain corresponding to the positions in top pannels. And the elevation data is derived from the pair of stereo images of ESP_018036_1880 and ESP_043710_1880.jp2.

3. OBSERVATIONS

3.1 Observations from the HiRISE images

The footprints of the HiRISE images where the PRP terrains exist are shown in Figure 4. Among the 866 HiRISE images inside Elysium Planitia, 328 show features of PRP terrain. In general, the PRP terrains are located in the regional depressions surrounded by the heavily impact-cratered terrains.

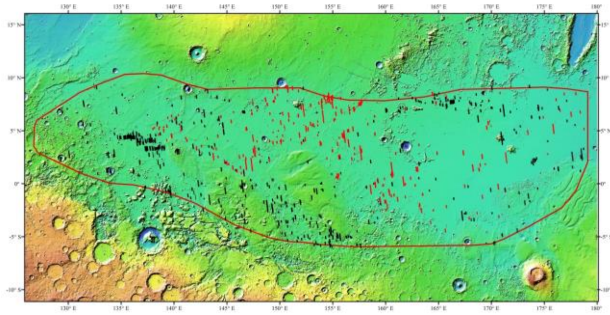

Figure 4. Distribution of PRP terrain in Elysium Planitia. The footprints of the HiRISE images wherein the PRP terrain exists are shown in red while others are shown in black.

Figure 5 displays some typical detailed morphologies of the PRP terrain in this area. Figure 5A shows that many circular or irregular ridges (indicated by arrows) can develop within the plates; however, the smoothly textured polygons are poorly developed or absent. Figure 5B shows that the plates appear ripple-like (labelled R) where clasts were involved, while the polygons (labelled PO) are embedded in circular or polygonal features. Figure 5C shows that the polygons occur as networked structure with strips of different sizes (labelled PO). Figure 5D shows the PRP terrain lap against topographic obstacles (exemplified by the arrows), indicating that the agent for the formation of the PRP terrain may have some fluidity. In this situation, ridges or polygonised terrain might not be well developed, but the rubbly surface indicates that the flows have similar textures to the typical PRP terrain, and are actually a variation of the plates.

Figure 6 shows the situations where the agent for the formation of the PRP terrain encountered high terrain. In Figure 6A, the formation of the PRP terrains was impeded by the crater rim, and a thick frontier was formed outside the rim as the arrows indicate. Figure 6B shows a situation in which the crater was heavily eroded and the agent was pushed over the rim depositing material in the interior of the crater, with plates, polygons, and ridges inside the crater.

In this area, we also noticed a phenomenon that some kind of trails was formed behind obstacles. Figure 7A shows the obstacles and long trails behind them, and length-width ratios are almost 10:1. Figure 7B is the DTM derived with the elevation data with the resolution of 20 m from CTX images, which shows that north is a little higher than other regions while the terrain is generally very flat with the slope being about 0.38°

in this area. It can be derived that the agent for the PRP terrain moves from north to south, and the previous terrain is smooth as seen from the trails behind the obstacles. Although it is difficult to obtain a travelling speed, it appears that the agent should move very slowly.

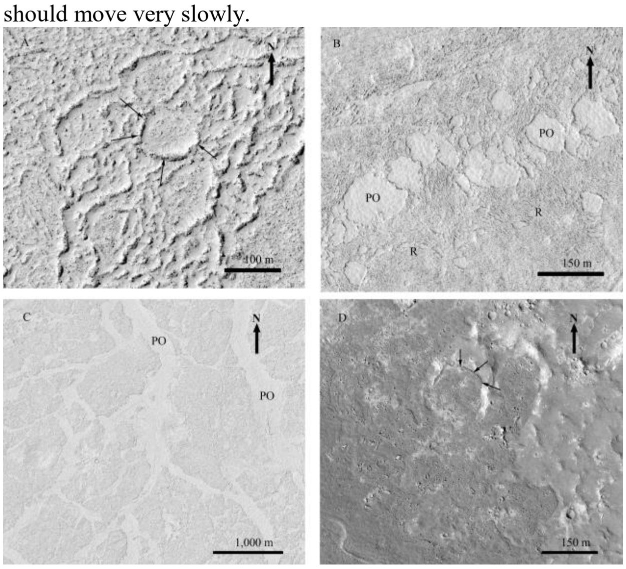

Figure 5. Different detailed morphologies of the PRP terrains in the study area. (A) Circular or irregular ridges developed in the plates (subset of HiRISE image TRA_000854_1855_RED.jp2); (B) Ripple-like plates with embedded smooth polygons (subset of HiRISE image ESP_011759_1850_RED.jp2); (C) Polygons occurring in long strips (subset of HiRISE image ESP_026475_1865_RED.jp2); and (D) Flows with rubbly surfaces filling shallow depressions (subset of HiRISE image ESP_012577_1815_RED.jp2).

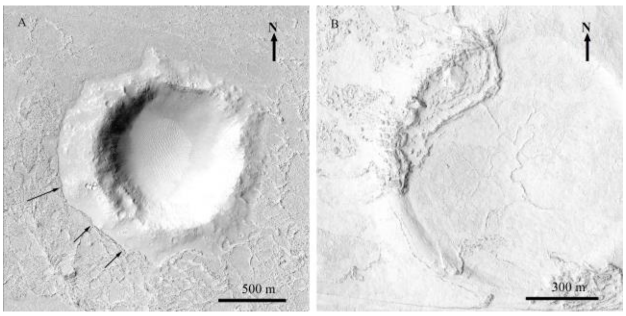

Figure 6. Observations of PRP terrains in Elysium Planitia. (A) The PRP terrain lapped against one crater rim with a thick frontier as shown by the arrows; subset of HiRISE image ESP_018049_1885_RED.jp2. (B) The flow crossed over the crater rim seen in its interior; subset of HiRISE image PSP_006472_1855_RED.jp2.

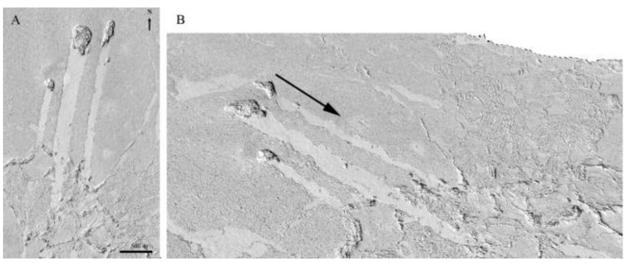

Figure7. The narrow traces behind the obstacles. (A) The length-width ratios of the traces are almost 10:1 measured in the sub set of HiRISE image ESP_033622_1845_RED.jp2. (B) The DTM derived from stereo images of D16_033622_1845_XN_04N206W.IMG and F20_043433_1848_XN_04N206W.IMG with the vertical exaggeration factor of 8 shows that the materials move from north to south.

Figure 8 shows a trace that is cut through the previous ridges, indicating that the trace was formed after the polygons. According to the topography data, some material must have moved from the north-east to south-west. There is no obvious deposition different from the background in the terminal, indicating that the amount of the agent for the trace is very small and mostly from the background.

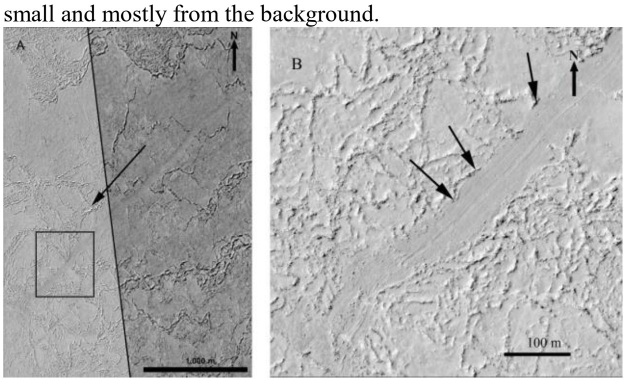

Figure 8. The pre-existing ridges exemplified by the arrows were destroyed by the track of the late flow. The image (A) is a mosaic of subset of HiRISE image ESP_018036_1880_RED.jp2 (left to the line) and CTX of B10_013368_1876_XN_07N210W.jp2 (right to the line). The arrow in (A) indicates the direction of motion of the trace, while the arrows in (B) indicate the previous polygons which were destroyed by the track.

3.2 Heights of the ridges in PRP terrain

In this research we extracted 1326 ridges and measured their heights. Figure 9 is the histogram of the heights of the ridges, which shows that the majority of the height of the ridges ranges from 1.0 m to 1.8 m with the mean value of 1.7 m.

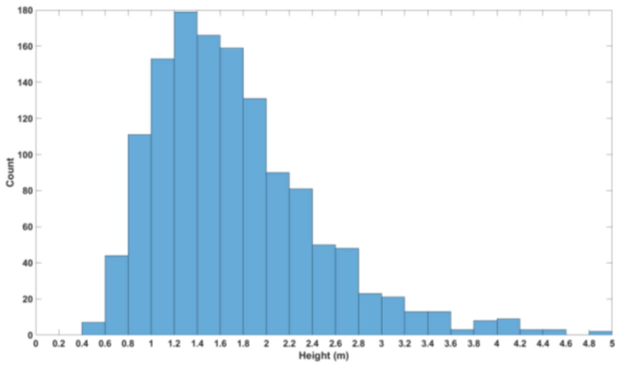

Figure 9. Histogram of measured ridge heights.

3.3 Possible analog site: Tarim Bain, Xinjiang, China

We found landforms similar to Figure 8 in Tarim Basin in Xinjiang, China, where the environment is currently extremely arid and cold. Figure 10A is a sub image of this analogy area from China's GF2 satellite, which has a resolution of 1m. In this area, there were lakes tens of years ago and currently there is water or ice in the shallow sub-surface. There also exist polygons and water is necessary for their formation. It is worth noting that there are several traces flowing through the area (Figure 10B is a picture from field investigation, with the camera pointing to west from the site marked on Figure 10A), which were formed when a small amount of liquid water existed over a short time. This demonstrates that a muddy flow has the potential to form a PRP-like terrain, given that Mars has also experienced temporary warm conditions within the recent past.

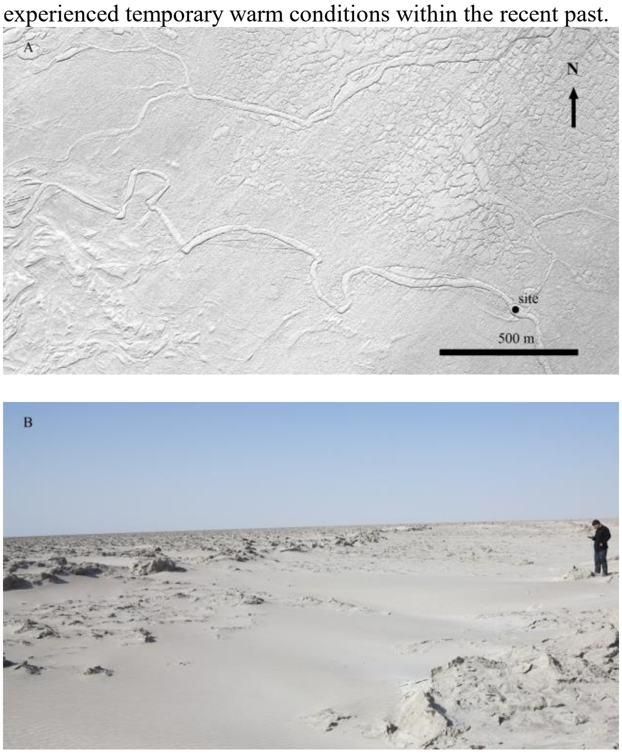

Figure 10 Similar landforms in Xinjiang, China. (A) The GF-2 image (ID: 1878208) shows the polygons and traces which are very similar to those on Mars. (B) The picture taken from the site marked in (A) with the camera pointing to the northwest.

4. DISCUSSION

4.1 The PRP terrain and fluid

According to the examination of the PRP terrain in this area, most of the terrain is distributed in the lowland (Figure 4), which shows that the agent for the formation of the PRP terrain has some fluidity. This examination is consistent with the hypothesis of both muddy flow and basalt lava, in which the agent for the formation of the PRP terrain is considered as some kind of fluid. In fact, even in the hypothesis of pack ice proposed by Murray et al. (2005), the fluidity of the agent was not completely rejected because they considered that the PRP terrain was formed as a moving and fracturing of ponded floodwater that *later* froze. However, we want to point out that the fluidity of the agent should be mostly responsible for the formation of the PRP terrain. This explanation can be demonstrated in the observations of Figure 5D, Figure 6, Figure 7, and Figure 8, where the agent shows obvious fluidity in the formation of the PRP terrain.

4.2 Characteristics of the flow

In this research we have measured the heights of the typical ridges in the PRP terrain for the first time, and our results indicate that most of the ridges are less than 2.0 m. The low topographic relief probably reflects the low viscosity when the fluid is flowing, which is more difficult to explain for a lava flow. For example, in the field investigation in the Laki flow field in Iceland by Keszthelyi et al. (2004; where they proposed that the PRP terrain is from a lava flow), the topographic ridges were found to be generally 5~15 m high. Therefore, the muddy flow is more likely the agent for the formation of the PRP ridges considering it has a lower viscosity than a lava flow.

The detailed observation of the microtopography also supports that the agent for the formation of the PRP terrain is a muddy flow. Since there is no obvious source, the agents for forming the trace must be same as for the PRP terrain (Figure 8). Thus we may conclude that under Martian conditions in recent geologic history, the surficial material can be melted and flow. If this is the case, it is likely that the water at shallow depth, rather than lava, is the agent producing the flow.

The observation of a similar phenomenon on Earth (Figure 10) further strengthens the impression that a muddy flow is responsible the formation of the PRP terrain in Mars surface. Considering the weather conditions are very similar between Tarim basin and Mars surface (e.g., both are very arid and cold), the Martian surface has the potential to experience a similar process to that occurring in Tarim basin.

4.3 Proposed scenario for the formation of PRP terrain

Based on the observations and analyses, we propose that the PRP terrains were formed through the following stages.

(1) The water ice was stored in the shallow surface in Elysium Planitia. Currently the mechanism for the origin of the ground ice at its various locations is not well understood (Sizemore et al., 2015). It may be from frost (Bapst et al., 2015) or ice in the Martian atmosphere (Mateshvili et al., 2009). While a detailed discussion on the subject is out of the scope of this study, water ice has been verified to exist in the shallow Martian sub-surface in many locations (Arvidson et al., 2009; Dundas and Byrne, 2010; Martín-Torres et al., 2015; Stuurman et al., 2016).

(2) Melting of the water ice occurred when the conditions were suitable, and the shallow surface layer became muddy and mobile, because of the existence of ice below the liquid-sediment contact. The mobility of the mud flow heavily depended on the water content and topography, and a significant flow speed could make it transverse across a crater rim (Figure 6B). However, in most cases, the mud flow probably only moved slowly over a short distance and was stopped against higher terrain (Figs. 5D, 6A). Such a situation may have occurred several times, with later activity covering or partially destroying the previous polygons as shown in Figure 8.

The necessary climate change could be caused by a variation of the obliquity of Mars (Laskar et al., 2004), which was indeed the case a few hundred thousand years ago (Touma and Wisdom, 1993). In addition, Conway et al. (2011) conducted laboratory experiments in which a stream of water flowed over test beds at low temperature and low pressure, which proved that both basal freezing and low pressure can increase the flow propagation speed.

(3) The water in the muddy flow was refrozen and evaporated and finally the textures and morphologies of the PRP terrain were formed. In this period, the polygonized terrain may be formed where the water content is high enough. Wilson and Mouginis-Mark (2014) obtained similar conclusions through a detailed dynamic analysis for the flow deposit in Cerberus Fossae, which also shows similar textures of the PRP terrains.

5. CONCLUSION

In this research, we have conducted a comprehensive investigation into the PRP terrains in Elysium Planitia, Mars. Our investigation supports that the PRP terrains are from some kind of muddy fluid. The fluidity exhibited during the formation process is reflected by the fact that the PRP terrains lap against obstacles and form an elevated frontier. Further analysis of the characteristic of the fluid shows that muddy flow instead of lava flow should be responsible for the formation of the PRP terrain. If this is the case, our study indicates Mars indeed experienced relatively warm period in some local areas within recent geologic history, which is important to understand the evolution of Mars.

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