A Preliminary Regional Geomorphologic Map in Utopia Planitia of the Tianwen-1 Zhurong Landing Region

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Abstract  A geomorphologic map is an important step to understanding the geologic context and history of a site; here, we present an initial geomorphologic map for an area spanning 22°–26°N, 108°–112°E in the Utopia Planitia (UP) region on Mars. This site is of special interest because it contains the May 2021 landing site of the Zhurong rover from Tianwen-1. Utopia Planitia exhibits many lobate features that have been proposed to be lava or mud flows. Lander and rover data should help solve the scientific question concerning the origin of UP flows. We use our map to generate an initial stratigraphic framework of geomorphological features in order to help place future Zhurong data into the regional geologic context. Our mapping effort has detailed the distribution of three geomorphologic units and 11 types of surface features.

Plain Language Summary  Mapping the locations of terrain features and their patterns of interactions helps to understand the geology of a locality. Our initial geomorphologic map is presented here, covering the area of 22°–26°N, 108°–112°E on Mars, and contains the May 2021 landing site of the Zhurong rover from the Chinese Tianwen-1 mission to Mars. The map area, Utopia Planitia, exhibits features that may have been made by flowing lava or mud. Our map has three kinds of terrain and 11 kinds of surface features, which we use to interpret the regional geology surrounding Zhurong. We expect future Zhurong data will be able to test our hypotheses.

1. Introduction

Utopia Planitia (UP) is a 3,300-km-diameter circular basin in the northern plains of Mars (see Figure 1 for the approximate basin outline and other regional features). Southern UP is of special scientific interest because it contains the landing site of the Tianwen-1 lander and Zhurong rover (25.067°N, 109.926°E), sent to Mars by the China National Space Administration and successfully landed on May 15 (May 14 in the United States) 2021 (Wan et al., 2020; Yongliao et al., 2021). Given the expected in situ exploration at this site, understanding the local and regional geologic context is important. Some of that detailed context has been provided by Skinner and Tanaka (2007) and will be provided in the future by an ongoing geomorphologic mapping campaign by Buban and Okubo (2021), but here we provide a targeted study of the landing site and surrounding local region.

UP is bounded by the Elysium volcanics to the southeast, the ancient highlands of Terra Sabaea and Terra Cimmeria to the south and southwest, respectively, and the circum-polar plains of the Vastitas Borealis to the north. UP is interpreted to be an ancient impact basin that has been infilled by an unknown mix of sediments, volatiles, or lavas transported by water, wind, and other processes (Searls et al., 2006; Tanaka et al., 2005, 2011). Some largely debated features present in this region are ~100–1,000-m-diameter cratered cone-like features. Previous studies have suggested that UP cones, and cones in nearby basins such as Acidalia Planitia, have resulted from sedimentary volcanism (the extrusion of unconsolidated wet sediment and fluids to the surface from a pressurized subsurface reservoir) (Brož & Hauber, 2013; de Pablo & Komatsu, 2009; Ivanov & Hiesinger, 2020; Ivanov et al., 2014, 2015; Oehler & Allen, 2010; Okubo, 2016; Okubo et al., 2016; Pozzobon et al., 2019; Skinner & Tanaka, 2007; Tanaka et al., 2005, 2011). The prospect of sedimentary volcanism and upwelling subsurface fluids is interesting because it could bring material up from deep habitable environments in the Martian subsurface to the surface where it could be sampled (Ivanov et al., 2014; Mazzini & Etiope, 2017). The UP mud eruption hypothesis is of particular interest because, based on the size of the UP basin and evidence of recent resurfacing, it would represent a remarkably...
voluminous amount of sedimentary volcanism that may require the existence of a much-debated former ocean (Ivanov & Hiesinger, 2020; Ivanov et al., 2015). In this paper, the term mud is used as a strictly textural description (Folk, 1954), encompassing a range of sediment grain sizes from fine clay-sized particles to coarser mobile sediments, and is independent of mineral composition. This broad definition is used because particle sizes are unknown.

The extent of mud volcanism in the northern lowlands is debated, however, and alternate interpretations have been proposed (Brož & Hauber, 2013; Lanz et al., 2010). Other studies have interpreted the cratered cones as volcanic in origin (Dapremont & Wray, 2021; Lanz et al., 2010). Given the regional proximity of UP to the volcanic rocks surrounding Elysium Mons (EM), lava flows from EM likely entered at least the easternmost parts of UP (Hamilton et al., 2018). Observations of cratered cones in the Hephaestus Fossae, Hrad Vallis, and southern UP have also been suggested as evidence of large-scale lava flows (Dapremont & Wray, 2021; Hamilton et al., 2018; Lanz et al., 2010). The question of a sedimentary or volcanic origin for UP cones is currently unanswered. UP surface samples analyzed by Zhurong along with accompanying ground-based images should help resolve this (Yongliao et al., 2021).

Figure 1. An overview of our study area (red unshaded rectangle, shown in detail in Figure 2) in regional context using the global Mars Orbital Laser Altimeter data set (MOLA Team, 2014; Smith et al., 2001). This digital terrain model shows the topography change along the Martian dichotomy boundary, to which the Utopia Planitia basin (dashed white line) is proximate. Other marked features include neighboring spacecraft (marked in white text), Elysium Mons (marked in white text as EM), a study area currently being mapped by Buban and Okubo (2021) (unshaded black rectangle), and an area studied by Skinner and Tanaka (2007) (patterned black rectangle). The spacecraft are marked as follows: V = Viking 2, Z = Zhurong, P = Perseverance, B = Beagle 2, I = Insight, and C = Curiosity.
2. Mapping Methods

Our mapping focuses on a 4 × 4 degree area in UP (222 km by 237 km), ranging from 22°–26°N and from 108°–112°E, containing the landing site of the Tianwen-1 lander and accompanying rover (see Figure 1). The map area is encompassed entirely by the Early Amazonian Vastitas Borealis Interior unit of Tanaka et al. (2005). Our 1:120,000 scale map was produced using a digitization scale of 1:30,000 (Figure 2). Contacts were traced in ArcMap 10.8 using a portion of the NASA Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) global image mosaic (Dickson et al., 2018) as the basemap. We also used a single CTX image to fill a gap in the global mosaic (CTX ID D20_035219_2029_XN_22N249W). The pixel scale for CTX imaging is ∼6 m and the mosaicked image is produced at the same scale.

Although contacts and other features were mapped systematically on the CTX mosaic, a limited number of digital terrain models (DTMs) produced from the MRO High Resolution Imagining Science Experiment (HiRISE) stereo images were also used. The images have a pixel scale of ∼25 cm, providing DTMs with a vertical resolution of better than ∼0.5 m at a 1-m posting. These topographic models were used to check
mapped CTX contacts where possible. Based off the DTM and associated 25 cm/pixel orthomosaics, we confirmed that contacts are not missed systematically (such as missing all east-facing slopes due to lighting) when mapping at CTX resolution. We note some marginal processing artifacts in the CTX mosaics (seams and mosaic blending effects). These artifacts likely create small uncertainties in contact locations throughout the mapping area, but appear negligible when considering the entire mapping area. We note that image quality may cause local systematic errors, such as missing map contacts in small areas because of base images captured when the Martian atmosphere was hazy. These errors will persist until higher resolution and higher signal-to-noise images have been acquired for the particular areas with limited coverage or low-quality images.

Additionally, we used the ~100 m/pixel global daytime image mosaic from the Mars Odyssey Thermal Emission Imaging System (THEMIS) (version 12) (Edwards et al., 2011). THEMIS data were used to identify and map crater ejecta deposits. However, we found boundaries between our geomorphic units identified in CTX imagery did not readily correspond to boundaries in the THEMIS data. Finally, we used the global Mars Orbiter Laser Altimeter (MOLA) data set (MOLA Team, 2014; Smith et al., 2001) to look for any spatial trends of mapped features and units that were associated with topography.

We also investigate the thickness of the surficial deposits through an analysis of Concentric Grabens, which are large half graben structures (tens of km in diameter) that make weakly linked ring-shaped structures and often occur in a concentric set of two rings formed from grabens (see Figure 3). Concentric Grabens have been proposed to be infilled ancient impact craters with the inward collapse of the fill resulting in extensions and concentric graben formation into double ring features (Buczkowski & Cooke, 2004). By measuring the diameters of these structures and the distances between rings, and assuming the rings of graben sit symmetrically astride a buried crater rim, one can estimate the thicknesses of the infill in the impact craters and the subsequent degree of collapse. We utilize the numerical model developed by Buczkowski and Cooke (2004) to study six such structures. These were chosen because they are the only features within the mapping area that display a preserved double ring structure for measuring inter-ring distance. Measurements were done in ArcMap 10.8. We measure the average diameter of each feature, choosing four sites around the feature border, each site spaced 90° apart. We record the spacing between concentric rings using the same method, calculating the average inter-ring distance.

3. Geomorphic Unit and Feature Descriptions

We have identified three geomorphic units: Bumpy Terrain, Crater Ejecta, and Plains. A characteristic image of each unit morphology and a description is detailed in Figure 3. Our descriptions are broadly based on Buban and Okubo (2021) and have been modified as necessary to accurately describe the morphologies within our mapping area. Bumpy Terrain is covered in irregularly spaced rounded mounds ~100 m in diameter. Boundaries between Bumpy Terrain and adjoining units are unclear. The unit was mapped around the spatial extent where the mounds occurred in dense clusters. Crater Ejecta is a generally high albedo, lobate, sometimes fluidized, topographically high unit that surrounds an impact crater feature. This unit superposes many mapped geomorphic units and features, but the age of this unit is likely highly variable. The Plains unit appears smooth at the ~100-m-scale, but has an “orange peel” texture at the ~10-m-scale. The boundaries of this unit with adjoining units are lobate with convex slopes.

Along with the geomorphic units, we have identified 11 types of geomorphic features. These are the aforementioned Concentric Grabens, as well as Crenulated Ridges, Fractures, Impact Craters, Lobate Margins, Mesas, Pitted Cones, Pitted Mounds, Ridges, Rimless Pits, and Troughs. A characteristic image and description of each geomorphic feature is shown in Figure 3. Some descriptions are loosely based on Buban and Okubo (2021) and have been modified to represent our mapping area specifically. Crenulated Ridges are asymmetric ridge features that exhibit more irregular curving than either Lobate Margins or Ridges (see Figure S3). Crenulated Ridges occur in local sets, or groups, in a spatial clustering that neither Lobate Margins nor Ridges have. Fractures are linear crosscutting features that degrade the features they cross. Impact Craters are approximately circular depressions with raised, sloped rims, and are generally associated with ejecta material. Lobate Margins are lobate features with convex slopes, often locally curving (see Figure S2a). Mesas are flat-topped, topographically high landforms with sloped sides that occur in irregular-shaped
platforms (see Figure S5). Pitted Cones are conical features hundreds of meters in diameter, which often display a central crater and steep slopes. These features are observed to occur singly and also in groups. Pitted Mounds are flat, elliptical, platform-shaped mounds with bowl-shaped central craters hundreds of meters in diameter. Ridges are linear, concave features with symmetric slopes. Rimless Pits are elliptical depressions hundreds of meters in diameter that may exhibit a central topographically raised feature that sometimes resembles the cratered depressions found in Pitted Cones (see Figure S4). Troughs are wide, curving linear depressions that can link together into an apparent system.

4. Results and Discussion

Based on the distribution of units and features in our preliminary geomorphologic map (Figure 2), we have drawn some initial interpretations about the geologic history of this region of UP. Lobate Margins are commonly found in Plains, exhibiting lobate convex slopes (see Figure S2a). These features could be evidence of past lava or mud flow boundaries. Microscopic imaging and compositional data from the Zhurong rover may be the next step in understanding the lobate features in UP and the predominant process that formed them. Such imaging, similar to other rovers, can record grain size distributions and mineral compositions, both of which are currently unknown in this region, which can help differentiate mud flows from lava...
flows. Lobate slopes appear along some boundaries with populations of pitted cones where some of the cones appear truncated and irregular in shape. We have interpreted the boundary cones as a topographic halting of flowing fronts as the fronts encounter cones and the surrounding topography. The convex slopes and apparent truncations suggest that Plains has embayed populations of pitted cones in this area (see Figure S2b). Evidence of embaying flows implies the majority of Pitted Cones are older than Plains. Further study of the cone spatial trends may prove important for stratigraphic relations, particularly for intersections of Pitted Cones and Lobate Margins.

Tectonic features in this region are sparse, consistent with a low differential stress environment within UP. We find two fractures, which give a primary strike direction of ∼135°/315°; however, more mapping of fracture-like features will need to substantiate this trend. Both fractures crosscut a pitted cone, indicating that at least some Fractures are younger than some Pitted Cones in this region.

An additional feature potentially caused by tectonics that we mapped is a Trough. From the initial study of our map, we observe that Troughs appear to be more common in the northern portion of the mapping area. We observed 11 troughs in 30 km² in the northwest corner of the map area, nine troughs in the northeast corner, and zero troughs in the southwest and southeast corners. If Troughs are tectonic in origin, it may be that the northern map area experienced localized deformation due to an undetermined source of stress. Also, resurfacing was possibly more widespread in the southern part of the map area, effectively erasing more southern troughs while allowing northern troughs to remain. Also, given the few fractures we observed, it is possible Troughs are not influenced by tectonics and form through a different process. For robust trends, Troughs require additional mapping, especially in the northern direction.

We observe a set of Crenulated Ridges, which correlates to a positive topographic ridge in MOLA data (MOLA Team, 2014; Smith et al., 2001) (see Figure S6). This ridge set is the NE/SW trending group near 24°N, 108–109°W in Figure 2. Based on their approximately parallel spacing and alignment with the MOLA ridge, we interpret that such ridge sets may form when a viscous flowing source encounters a topographic obstacle and is eventually halted by topography. As the flowing material encountered the slope, it would begin to slow and could amass into an initial ridge. This would be particularly effective if the flowing material could solidify (like lava) or freeze (like mud). Subsequent material behind it would then slow and accumulate, creating another ridge, leading to the sets of ridges we observe. Because ridge sets display similar orientations locally, we infer that ridges populating a set may have a common source, though we cannot correlate between different sets. We observe several crenulated ridges near 24°N, 108°W that are asymmetric and have scarps facing SE (see Figure S3); therefore, if a flow generated these ridges, the most likely source direction would be to the NW or SE of this set.

Rimless Pits are depression-like features, which are sometimes observed to have central features that resemble the central craters of Pitted Cones (see Figure S4). We propose that such pits formed when some pitted cones were embayed by cover material, which is why the central features appear similar; then the corresponding pit formed by inflation of the cover material after deposition.

We interpret Mesas as relatively older features in our mapping area. We cannot conclude any lithostratigraphic or chronostratigraphic relations between units and features based on our geomorphologic mapping. Mesas resemble high-standing landforms that commonly occur along the highland-lowland boundary located ∼350 km to the south. These features could be outliers of highland terrain because the highland-lowland boundary is a broad transitional region. This interpretation is supported by the higher Mesa population density toward the southern portion of our mapping area, nearer to the highland-lowland boundary. They could also be slightly older basin-filling materials of UP, which have undergone significant modification and have been subsequently surrounded by the material that filled UP. Some mesas have “collar-like” morphologies interpreted as the regional paleotopographic surface prior to deflation as subsurface sedimentary material was expelled (Salvatore & Christensen, 2014) (see Figure S5). A similar morphology in our map area can be seen in CTX F05_037619_2045_XN_24N251W and just west of our map area in HiRISE ESP_046850_2035. We note that deflation of lava can also leave highstand deposits.

Of special interest is the locality surrounding the Tianwen-1 and Zhurong rover landing sites. We examine our mapping in this local area to produce an initial categorization of the nearby units and features. The rover landing site and locality is outlined with a black rectangle in Figure 2 and shown in more detail in
Figure 4. The site and its surroundings appear to be composed entirely of Plains. A 997-m-diameter Pitted Cone sits ∼3.8 km to the northwest, with several others grouped together toward the northeast. Lobate Margins occur across the site, exhibit a range of orientations. Troughs are also present. The troughs have two dominant trends: one running north-south and one running northeast-southwest. The two trends appear to be composed of single troughs that linked together. Two Ridges are observed, one to the north of the landing site and one to the south. Finally, ∼12 Crenulated Ridges occur near the northeast corner of the locality, showing a general east-west orientation.

Our mapping was motivated by the possibility of in situ data returned from the Zhurong rover to help determine the origin mechanism for Pitted Cones. Our observations of lobate structures in the region support the idea of mud or igneous volcanism resurfacing this region and creating the observed cones. A larger surrounding region of UP has been studied in a previous work by Skinner and Tanaka (2007) (see Figure 1). They observe similar pitted cone features, lobate margins, and mounds that they propose may be linked with sedimentary volcanism. They observe that the pitted cones appear to be constructional in nature, and they note that there appear to be compressional structures nearby. This supports the sedimentary volcanism origin theory because compression can force subsurface fluids to the surface, and also because compressional environments are atypical of igneous volcanism. The cones that they discuss and that we have mapped are larger than cones observed in other plain regions of Mars, and do not tend to form observed rows or patterns like the cone features suggested to be pseudocraters. Skinner and Tanaka (2007) support a sedimentary origin hypothesis for their cones because of the pitted morphologies, association with lobate margins, and occurrence in a region where compressional structures have been found. In HiRISE photos covering portions of the Zhurong landing area, we see smooth surfaces and do not observe the kind of surface roughness typical of lava flows. This initial observation is not evidence against volcanic activity having resurfaced parts of UP. Zhurong and its returned data will be important tools to answer the question concerning volcanic or sedimentary flows in this region of UP.

Using the methods developed by Buczkowski and Cooke (2004), we estimate the thicknesses of the infill in Concentric Grabens. This is to estimate the amount of resurfacing material, which may have been emplaced in the region. We find a bifurcated population of the six features, with four corresponding to an average cover thickness of approximately 1.2 km and two corresponding to an average cover thickness of approximately 0.6 km. We do not find a clear spatial trend of cover thickness over the region; however, we do note that the two graben features with less infill are both associated with populations of pitted cones. The other four grabens are primarily superposed by Plains. This supports the interpretation that Plains has embayed Pitted Cones, causing an additional layer of infilling material in parts of our mapping region.

Shallow subsurface ice has been observed in UP, particularly in the northern portions. Throughout our mapping, we find a lack of geomorphological evidence of this ice. This is likely due to the fact that our mapping area lies south of the 39° latitudinal limit of where it has been observed (Dundas et al., 2021).

5. Conclusions

Here, we present an initial geomorphologic map of a region in UP. Given our mapping-based interpretations, we propose the following geologic history for this region. Mesas formed as highland material along the periphery of the Utopia impact basin. Lava or sediments then infilled the UP basin. Pitted Cones developed on top of the basin-filling material. The Plains unit was then emplaced and resurfaced much of the area. Bumpy Terrain then formed on top of Plains, followed by the emplacement of Impact Craters and their ejecta. A future way to test and validate the proposed stratigraphy may be to use crater counting studies.

The origin of Pitted Cones and other geomorphologic units and features in this area remains an open question. Given that the Tianwen-1 lander touched down in Plains, observations by the Zhurong rover may provide the in situ observations needed to better understand the origin of this unit, which we suggest is, at least locally in our map area, the youngest deposit and is potentially responsible for widespread resurfacing of the region. Additionally, in situ rover exploration of nearby pitted cones may yield the mineralogic and lithologic data needed to distinguish between an igneous or sedimentary volcanic origin for these enigmatic features.
Figure 4. (a) Shown in map context as the black rectangle in Figure 2, this is the locality surrounding the Zhurong landing site, here approximately denoted by a “Z.” (b) A portion of the global CTX mosaic (Dickson et al., 2018) used for mapping the local Zhurong landing area extent shown in (a).
In summary, we anticipate that this map will provide context for geologic interpretations of Zhurong observations and higher spectral or spatial-resolution orbital images. This map area, a 4 × 4 degree area (222 km by 237 km) of the Martian surface, provides a useful representative tool to extrapolate local rover observations to the southern UP region. With it, we are better able to categorize and describe the enigmatic features and geology found in UP and are closer to identifying the processes that formed the observed landforms and terrains.

Data Availability Statement

The data set for this research is available in Mills et al. (2021), [CC By-NC-SA], https://doi.org/10.25422/azu.data.14707311.v1, URL: https://doi.org/10.25422/azu.data.14707311. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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