Multiple layers of lava flows and channels characterize the region adjacent to the eastern slope of Olympus Mons, the largest volcano on Mars. We have mapped this volcanic region to survey and classify individual channel systems and determine their formative processes. As a final output of this mapping effort, we have produced a 1:1.9 million scale channel map that is first published in this paper in both GIS and static formats.

1. Introduction

Northwest Tharsis became the focus of study following a global survey of raised-relief, typically tear-dropped or diamondshaped landform (‘islands’) on Mars (Hargitai et al., 2016). This group includes forms that are enclosed by or contained within channels, and their shapes include round, streamlined, polygonal, scalloped and irregular outlines with a variety of origins. Their formation commonly involves a high discharge (> $10^5$ m$^3$/s) of liquid (usually water) that converges on an obstacle (e.g., a hill or impact crater rim) and erodes and streamlines the landform. A number of the raised-relief forms are located within outflow channels on Mars. Interestingly, teardrop-shaped raised-relief forms are almost absent in valley networks. Our global survey revealed an unusual concentration of these forms in a predominantly volcanic region covered with lava flows East of Olympus Mons. Approximately one-third of all ‘islands’ on Mars that we have previously mapped globally (Hargitai & Gulick, 2018) were situated in the Northwestern part of the Tharsis Rise. Streamlined islands on Mars are common and are attributed to formation by catastrophic floods (Baker, 1982; Baker et al., 2015).

In the mapped region, previous mappers identified a fluvial system within the tectonic Olympica Fossae (Mouginis-Mark, 1990) and Sulcii Gordi (Basilevsky et al., 2006; Mouginis-Mark & Christensen, 2005;
Sutton et al., 2016). However, a less prominent channel was found to be leveed channelized lava (Glaze et al., 2009). This signaled a complex, fluviovolcanic history of the channels, closely associated with graben and fissures, or a differing interpretation of channel morphologies. The streamlined islands, smooth-floored sinuous single channels, layered deposits and even pitted channels could be interpreted as the results of fluvial or volcanic flows, or both.

2. Methods

We mapped channels, rilles, pits, raised-relief channel forms, fractures, lava flow fronts and low volcanic centers in an area of approximately 2,800,000 km² (Figure 1). We used 167 Mars Reconnaissance Orbiter CTX (Context Camera) images projected at 5.4–5.6 m/pixel resolution (the image IDs are listed in Supplement 2). Some CTX images were geometrically shifted with offset correction to the THEMIS dataset. The scale of the final static pdf map is 1:1,900,000. The paper size of the map layout is ISO A0 (841 mm × 1189 mm).

Channels were mapped at a digital mapping scale of 1:60,000, which corresponds to approximately 1:250,000 printed scale. Lava flow fronts and linear graben were mapped at 1:250,000 digital mapping scale. We have delineated all raised-relief channel forms and channels in this region using ArcMap, and we have identified several channels, raised-relief ‘islands’ and volcanic constructs that have not been previously mapped. In total, we have delineated ∼1300 raised-relief channel-associated features. We have mapped low-relief volcanic centers, 29 of which were previously identified (Hargitai, 2016; Hauber et al., 2009; Hodges and Moore 1984, p. 69).

We have also mapped related landforms beyond the CTX mapping area boundaries, but only at 1:250,000 scale and focusing on raised-relief forms and adjacent channels; and we also mapped lobate margins of lava flows at THEMIS resolution in the rectangular map view region. We used 100 m/pixel THEMIS daytime images as fillers. We determined the mapping area using an iterative survey for raised-relief channel forms and channels. We identified only a low number of previously unmapped channels beyond the mapping area; therefore, the mapping area represents a region that was geologically more active in producing channels.

3. General geography of the mapped region

Northwest Tharsis is the region east of Olympus Mons, mostly covered with lava flows. Its topography slopes down towards the northwest. This slope ascends towards the three members of Tharsis Montes: the dividing line is between Ascreaus Mons (the northernmost Tharsis volcano) and Pavonis Mons (the middle one). At the lower end of the slope, north of Olympus Mons, there is a rough area between Lycus Sulci and Olympus Mons where lava did not cut through towards Amazonis Planitia. The topographic

Figure 1. Location map of the mapped region. Red regions show channels. Channels outside the mapped area show results of preliminary, unpublished mapping. Background: THEMIS daytime IR mosaic (Edwards et al., 2011) with MOLA-HRSC DTM hillshading (Fergason et al., 2017) and elevation colors (Fergason et al., 2018).
trough between Olympus Mons (to the West) and Ceraunius Fossae (to the East) is almost exactly linear for more than 1700 km. This is the sink for lava flows that were collected and moved towards the northwest. The lava flows originate from the area between Ascreaus and Pavonis Montes. Moving upslope, eventually, the lava flows became obscure at the region near the margin of Pavonis Sulci, the fan-shaped northern deposit from Pavonis Mons and at Poynting crater, a 70-km diameter, lobate ejecta crater suggesting that the lava flows predate the impact and the fan-shaped deposit. It is ambiguous if these flows originate from Pavonis or Ascreaus Mons, or locally sourced. Lava flows on the other, southern side of Poynting crater turn towards the north and terminate at Ascreaus Chasmata.

4. Cartographic description

The Channel map of the NW Tharsis region is a multithematic complex map that focuses on surface features associated with channel activities. Its aim is to show the extent and locations of channel forms and geomorphic features associated with channel formation. It is not a paleohydrologic map, because many of the channels are clearly volcanic in origin and there is no geomorphic evidence for fluvial processes operating within those channels; however, many of the channels have morphologies similar to fluvial systems. These might have been produced by postvolcanic hydrothermal groundwater outflows (Gulick & Baker, 1989) or low-viscosity lava materials (e.g. Dundas & Keszthelyi, 2014). This ambiguity of the potential formation processes explains why the title of the map is purely descriptive, although the mapping is part of the geological investigation of the region.

This map uses the IAU Mars2000 coordinate system (East positive 0-360°) with a spherical reference surface used for the Mercator projection. Longitude values had to be manually modified from the ArcGIS Pro output because ArcGIS Pro cannot display the planetary 360° coordinate systems.

We used the THEMIS 100 m/pixel mosaic as background mixed with 200 m/pixel MOLA-HRSC hillshading; and colored MOLA-HRSC DEM tints to show elevation that is essential to give context to channel formation. We applied a custom gray–white–orange–brown color ramp to reflect the unearthly, vegetation- and water-free environment of Mars.

The manually produced CTX mapping raster mosaic is not displayed on the map in any form. The THEMIS and HRSC/MOLA base image mosaics are embedded in a single raster layer in the pdf version. The pdf layout file was exported at 300 dpi vector and 100 dpi raster resolution from ArcGIS Pro into InDesign, and re-exported, keeping the original settings. The final ‘print’ resolution of the merged raster base layer in the pdf layout is about 300 m/pixel.

To achieve an aesthetically acceptable layout, we made the raster layers semi-transparent (colored elevation: 40%, shaded relief: 50%, THEMIS: 60%). The scene in the shaded relief layer is illuminated from the northwest; and in the THEMIS mosaic, it is illuminated from the west.

We distinguished wide-floored ‘flood’ channels and channel belts from ‘rilles with pits’ and ‘rilles’ and used the closest analog standard symbols and colored them magenta to reflect a volcanic interpretation. Rilles are sinuous, shallow, narrow (approx. up to 100 m wide) channels. Fractures are straight or arcuate, deep or shallow, wide to narrow (approx. up to 1 km wide) and may be faults or fissures. Fissures are single features characterized by lava flows (flow patterns) emanating on both sides of the linear depression that may continue in narrower rilles or fractures. The fissures become narrower towards their termini. Fissures were identifiable at the top of low shields and at the sources of most of the Gordii channel systems. Fractures often exhibit stepover (overlap and separation) pattern, and they commonly cross each other or change direction at acute angles. Fractures frequently transition into rilles (straight channels into sinuous channels) and those in some places become pitted. Channels or channel belts include raised-relief diamond-shaped forms (colored yellow), channels, cross-bar channels and may also include fractures or fissures as the deepest part of the feature. Around fissures, the terrain is often eroded into a low level. Rilles or channel pathways are shown within channel belts. We mapped each individual island (within a low-relief channel) with polygons to enable area calculations. Channels were mapped with polygon symbols and not polylines appropriate at the map scale. We also mapped major fractures (graben, fissures) because they are closely associated with the channels. Fields of bedforms termed Transverse Aeolian Ridges (TARs) (e.g. Berman et al., 2018) are shown with a dotted surficial unit symbol. TARs appear to be degraded. We used a unique asterisk symbol for cataracts where the liquid material created a parallel series of raised-relief channel forms along a topographic step. Deep and shallow channels were not distinguished. We mapped some of the major features beyond the mapping area for orientation.

5. Geomorphologic results

We identified three distinct channel morphologies in the region (Hargitai & Gulick, 2018): Type (1) perched channels interpreted as channelized lava flows, Type (2) fissure-fed multilevel systems interpreted as surface channels of fluvial, volcanic or fluvo-volcanic
origin and Type (3) trough-rille-pit systems interpreted as surface manifestations of subsurface conduits. Both tectonic graben and islands are closely associated with all channel types. Narrow troughs and rilles with and without pits are shown with two different polylines, while all wide channels are shown with polygon symbols. Lobate lava flow fronts (both smooth and rough surfaced) and fissures are also shown on the map which makes type 1 and type 2 channels distinguishable.

In addition to morphologic classification, we identified several groups of channels that we grouped into channel systems. The channel systems are spatially proximal and originate from the same group of sources, although they may be morphologically distinct. We previously (Hargitai & Gulick, 2018) labeled each system using a local placename from the IAU nomenclature and a number. All these names were informal. We also used the name Eunostos that at the time of mapping was listed as a classical albedo name in the region; however, in 2021, it was discovered that the IAU Planetary Gazetteer had a typo that caused it to be misplaced by a hemisphere. To avoid further confusion, we removed all informal labels from this map and only use them in this paper.

The groups in the Olympica systems originate from graben. Olympia 5 of Hargitai and Gulick (2018) centered originating at 27.5°N 244.3°E is the only channel that terminates with a lava delta, just proximal to Eunostos 2 of Hargitai and Gulick (2018) centered at 24.7°N 235.6°E, a unique anabranching network of raised channels reminiscent of inflated lava flows. The Cyane systems of Hargitai and Gulick (2018) are located within a broad SE-NW trending valley. The Gordii systems of Hargitai and Gulick (2018) are the most proximal to Olympus Mons, they are short, they originate from fissures and include narrow, pitted channels. The clustered distribution patterns of the channels suggest that their formation was controlled by local processes (Gulick, 2001). The Eunostos 1b system of Hargitai and Gulick (2018) originates from a graben at 20.5°N 241.9°E that we interpret as water outflow from a subsurface layer. This system was also interpreted as fluvial by Vijayan and Sinha (2017).

The model ages of the channel floors calculated from crater counting were 94 and 140 Ma, as reported in detail in Hargitai and Gulick (2018). This is the time period when the channels presently on the top of the lava layers formed (Hargitai & Gulick, 2018). We interpret these periods as times of magmatic pulses that heated hydrothermal systems. These periods could have lasted several tens of millions of years (Gulick, 1998). These youngest lava layers likely buried traces of the records of older processes. However, channel forms on the surface are rare around the Tharsis shield volcanoes outside the mapped region. Some of the fissures had built low shields without channels or islands. The 700-km-long valley segment between the Pavonis 2b channel system centered 15.2°N 241.8°E and Pavonis/Ascraeus Montes, has only two minor channels, only a few fractures and are characterized by overlapping raised, lobate margin lava flows, similar to those in the mapped region.

6. Conclusions and significance

We mapped the channels east of Olympus Mons and distinguished channel forms based on common sources, similar morphologies, feature assemblages and location. We identified tectonic, volcanic and likely fluvial processes operating in the same region, approximately 94–140 million years ago. This volcanic region was, therefore, active in the Late Amazonian. The cartographic work included channel mapping where geologic material units were not mapped. The most problematic task was to distinguish between ‘rilles’ formed by surface lava flows, ‘flood channels’ where lava or water could be equally transported, tectonic fractures, and fissures, which all smoothly transition into each other without elevation change and many of them also transition into series of pits. The channel–island systems resemble the setting at outflow channels on Mars, including Athabasca Valles and Mangala Valles which are also interpreted as systems with fluvial and volcanic episodes (Keske et al., 2015). As a result of this investigation, we found morphologic evidence for Late Amazonian channelized volcanic lava flows that suggests that the Tharsis region still has available subsurface heat and may be reactivated in the future; therefore, it is one of the cartographic, scientific and actual ‘hot spots’ of Mars.

Software

Mapping was started in ArcMap 10 and completed in ArcGIS Pro. Final editing and marginalia were produced in Adobe Illustrator and Adobe InDesign.

Data

The map published as part of this paper is a static pdf map created to contain all content and design elements in a layout that aesthetically best displays these elements. A GIS version is published in the supplement. The GIS version contains only vector shape files and excludes the raster layers, such as the THEMIS daytime mosaic v.12 (Edwards et al., 2011), the MOLA-HRSC DEM (Fergason et al., 2018), the MOLA-HRSC shaded relief (Fergason et al., 2017). The MRO CTX images in the mapping area were
identified with the USGS Planetary Image Locator Tool. The map was created in 2016 and corrected through 2020-2022.

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Data availability statement
The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. Manually produced high-order cartographic data produced in this research is included in the supplementary files that include shapes and attributes. The original image files are openly available through USGS at https://pilot.wr.usgs.gov/ and are in the public domain. The age data that support the findings of this study are available from Elsevier (Hargitai & Gulick, 2018). Restrictions apply to the availability of these data, which were used under license for this study, published at https://doi.org/10.1016/B978-0-12-813018-6.00004-2, Copyright © 2018 Elsevier Inc.

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