Geomorphology of the southwest Sinus Sabaeus region: evidence for an ancient hydrological cycle on Mars

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ABSTRACT
We have produced a 1:650,000 scale geomorphological map of the southwest Sinus Sabaeus, a region of Mars approximately centered at 25.0°S and 6.5°E and located in the topographic transition between Arabia Terra and Noachis Terra, in the Martian highlands. This heavily cratered region, subjected to extensive surface erosion, shows a complex valley network system known as Marikh Vallis. In this work, we study the history and role of water in and around Marikh Vallis, focusing on the modification and evolution of this area during the earliest Martian times, the Noachian period. The map described in this paper was produced through the analysis of a combination of available imagery data, topography, and thermal inertia, which together allow defining different geomorphological units in this area. This new map provides a basis for identifying the ancient presence of water in the region, both in the liquid state and in the ice phase.

1. Introduction

Mars shows an extensive geologic record of the presence of liquid water over most of its surface (Baker, 2001; Carr, 2012; Carr & Head, 2010; Davis et al., 2019; Fairén et al., 2003). The best geomorphological examples can be found in the ancient southern cratered highlands, in the form of dry valley networks and lake basins (Cassanelli & Head, 2019; Cawley & Irwin, 2018). Due to extensive surface erosion spanning billions of years, these records are frequently modified and even obliterated, leaving only traces remaining of previous processes (Hynek & Phillips, 2001). Sinus Sabaeus (0° - 45°E; 0° - 30°S) is one of the regions in the highlands that still shows noticeable signs of the presence of water in the past. Previous works highlighted the abundant fluvial and glacial paleo-morphologies in the Sinus Sabaeus region, for example, Craddock et al. (1997), Forsberg-Taylor et al. (2004), Shean (2010), or Craddock et al. (2018). Our study area is in the southwest of the Sinus Sabaeus region (Figure 1), at the south of Arabia Terra and at the northwest of Hellas Planitia, located between Newcomb and Bakhuyzen craters, with Greeley crater to the south. This area in Sinus Sabaeus can be considered a representative section of the densely cratered highlands (Craddock et al., 1997; Craddock et al., 2018; Forsberg-Taylor et al., 2004).

Previous studies provide global and regional maps of Sinus Sabaeus (Figure 2). Two geologic maps with a scale of 1:5,000,000 had covered the area before: Moore (1980) and Ruj et al. (2017), the latter having a more morphostructural focus. Our study area has been included in two global geologic maps of Mars: Greeley and Guest (1987), with a scale of 1:15,000,000, and Tanaka et al. (2014), with a scale of 1:20,000,000. In this study, we provide a detailed 1:650,000 scale geomorphological map, which allows characterization of the southwest of the Sinus Sabaeus region, with the aim of better understanding the role of water in the modification of its surface. For this purpose, we mapped a rectangular-shaped area to the southwest of the Sinus Sabaeus quadrangle (3° E, 21° S and 10° E, 29.5° S; Figure 1A), with an extension of approximately 206,600 km² (417 × 495 km), to constrain the ancient presence of water on the region, which also bears significant astrobiological interest because the sedimentary infillings record its aqueous history.

Our study area (Figure 1B) shows regional resurfacing (Hynek & Phillips, 2001), resulting in degraded valley networks and modified craters. A longitudinal valley, a plateau and large impact craters stand out in the topography of our area. The longitudinal valley located at the west part of the
area, flows from south to north. There is a plateau in the central portion of our study area, which is the highest part in the area, reaching a maximum elevation of about 2,600 m above the Martian datum (a.m.d.), and is framed by a stepped slope that is regularly carved by gullies. The points of lower elevation in the area are located inside impact craters, being the lowest point -996 m a.m.d. Most impact craters appear highly modified and infilled by sedimentary deposits. Two large, irregular and eroded impact craters are noteworthy: Margulis crater (name approved by the IAU on April 21, 2021), about 198.8 km in diameter, to the northeast, and Roemer crater (name approved by the IAU on April 21, 2021), about 121.7 km in diameter, located to the southeast.

2. Methods: data collection and mapping procedure

2.1. Data

The base map of this study was the high-resolution imagery provided by the Context Camera (CTX, on board the Mars Reconnaissance Orbiter; 6 m/pixel; Malin et al., 2007). We used the beta 01 version of the CTX mosaic, available through the Bruce Murray Laboratory for Planetary Visualization (http://...
As the study area coverage was not complete in the mosaic by the time of completing this work, we also used the individual images available through the Mars Orbital Data Explorer website (https://ode.rsl.wustl.edu/mars/indexproductsearch.aspx). Elevation data we used was the Digital Terrain Models (DTM) derived from the Mission Experiment Gridded Data Records (MEGDRs) of the Mars Orbiter Laser Altimeter (MOLA, on board Mars Global Surveyor; 463 m/pixel; Smith et al., 2001), . The mosaic dataset is accessible at the USGS (United States Geological Survey) PIGWAD (Planetary Interactive GIS on the Web Analyzable database) webpage. We complemented the topography with the MOLA and HRSC (High-Resolution Stereo Camera, on board Mars Express) mosaic that yields better resolution (200 m/pixel; Fergason et al., 2018), where the HRSC topography is available. This blended mosaic dataset is accessible from the USGS Astropedia (https://astrogeology.usgs.gov/search/map/Mars/Topography/HRSC_MOLA_Blend/Mars_HRSC_MOLA_BlendDEM_Global_200mp).

Additionally, we included the qualitative thermal inertia mosaics generated from the Thermal Emission Imaging System (THEMIS, on board Mars Odyssey) nighttime infrared images (100 m/pixel, Christensen et al., 2004; Fergason et al., 2006), accessible at the USGS (United States Geological Survey) site (https://astrogeology.usgs.gov/maps/mars-thermis-derived-global-thermal-inertia-mosaic), to infer better the morphological limits within visually distinct landform units based in their thermal properties.

Figure 2. Previous studies of the area examined here. A) The Geologic map of the Sinus Sabaeus Quadrangle of Mars (Moore, 1980), that defines 8 units in our area of interest: ‘material of youngest craters’ (c5), ‘material of young craters’ (c4), ‘material of intermediate age craters’ (c3), ‘material of old craters’ (c2), ‘material of oldest craters’ (c1), ‘cratered plains material’ (pc), ‘plains material’ (p), ‘hilly, channeled and cratered material’ (hcc); and 3 structures: ‘crater rim crests’, ‘buried crater rim crests’, and ‘small channels’. B) The Generic identification and classification of morphostructures in the Noachis-Sabaea region, southern highlands of Mars (Ruj et al., 2017), which includes 3 different units: ‘early Noachian highlands’ (eNh), ‘middle Noachian highlands’ (mNh) and ‘early Hesperian highland unit’ (eHh); and some structures: 4 types of impact craters according to their degradation state, going from ‘type 3’ (the youngest) to ‘ghost crater’ (the oldest), ‘normal faults’, ‘wrinkle ridges’ and ‘lobate scarps’. C) The Geologic map of the eastern equatorial region of Mars (Greeley & Guest, 1987), with 3 structures: ‘crater rim and ejecta material’ (c), ‘smooth floor material’ (s) and ‘wrinkle ridges’ (Hr); and 4 units: ‘mottled smooth plains’ (Hplm), ‘ridged’ (Nprl), ‘etched’ (Nple), and ‘dissected’ (Npld). D) The Geologic Map of Mars (Tanaka et al., 2014), which only differentiates between 3 units in our study area: ‘early Noachian highlands’ (eNh), ‘middle Noachian highlands’ (mNh) and ‘late Noachian highlands’ (Inh).
2.2.1. Pre-mapping activities

- **Defining spatial reference and extent**

Our 1:650,000 geomorphological map may be considered small-scale, which is useful for wide regions and allow us to represent the geomorphological history of major depositional and erosional structures and units (Dramis et al., 2011). For a 1:650,000 scale map, we use a minimum mapping area of 4 km² and we mapped at 1:75,000 scale to collect a consistent detail in delimitation, adequate to the ultimate 1:650,000 scale of the layout. We used the Mars 2000 spheroid geographic coordinate system and the equidistant cylindrical projection system with a central meridian at 0°.

- **Obtaining remote sensing data**

The orbital data we needed to generate our map consisted of high resolution images to avoid limited identification of landforms (Dramis et al., 2011; Versstappen, 2011). Using multiple datasets allows a better interpretation of the different morphologies (Alemanno et al., 2018). We searched for the most recent datasets that covered our area and downloaded them in a GIS-compatible format.

- **Creating a GIS project**

We created a GIS project including all the data described above for implementing two approaches to geomorphological mapping: automated techniques and manual mapping (Sejmonsbergen et al., 2011; Smith, 2011) (Figure 3). We used automatic techniques to produce derived datasets, as the slope map or the drainage networks from MOLa topographic data. We used manual mapping to define map structures and units and having more control over them.

- **Hydrological flow modeling**

The automatic ArcHydro-derived drainage network is based on the D8 flow model, which determines the flow direction. We use the Strahler (1952) method for ordering streams resulting from the drainage network extraction. It assigns an order to each segment, starting with order 1 at headwater segments. Each time two channels of the same order converge, the channel after the intersection increases its order by 1. If the confluence occurs between two different order channels, the higher order prevails after the confluence. We used the automatic ‘ArcHydro’ tools as guidance and support for the manual mapping. It is a quick way to obtain a model drainage network based on the contemporary topography and as an input for the manual identification outline. The automatic drainage network limitations were taken into account. It assumes a fluvial origin for the channels and that the topography was modified by processes postdating the flow, e.g. impact craters.

2.2.2. Mapping efforts

- **Defining the units and features to be mapped**

Our map follows the cartographic criteria of planetary geology, based on texture and relief, distinguishing geomorphological structures and units (Wilhelms, 1990). Geomorphological boundaries were determined following differential morphological, topographical, and textural patterns after using high-
resolution images, topography, and thermal inertia datasets.

The use of thermal inertia data contributes to identifying surface materials because high values indicate that the surface contains exposed bedrocks, large particle sizes, and/or cemented fines forming duricrust (e.g. Jakosky & Christensen, 1986). This is the case of the exposed bedrocks in crater floors or eroded surfaces, like valleys, which present indurated materials on their floors and usually exhibit a gradational increase of thermal inertia in the downstream direction (Mellon et al., 2000). However, not all the eroded features exhibit high thermal inertia values, as mantled material could mask them (Mellon et al., 2000).

We followed the design principles outlined by Otto et al. (2011) to map major units (appendix 1) and features (appendix 2) based on map legibility, including: visual contrast between symbols, figure ground perception for distinguishing between an object and its surrounding, chose of different tones or values, and hierarchical organization to differentiate between levels in line symbols (e.g. in valley networks). The legend is organized into 12 different units (appendix 1) and 14 structures (appendix 2). Symbols of the legend have been represented following the FGDC (2006) criteria for planetary geology features, which can be represented as points, lines, or polygons. Point symbols are used for landforms too small to be represented at scale but important for their implications on the area (Gustavsson et al., 2006; Otto et al., 2011). In our map, inverted impact craters smaller than 4 km² are drawn as point symbols. Line symbols are commonly used to represent linear features (Otto et al., 2011), e.g. wrinkle ridges or valleys in our map. Polygons are used for wide areas (Otto et al., 2011), for example, all units represented in our map. How we delimited the geomorphological boundaries adds a component of certainty to the information because they are delimited by continuous outlines when they form certain boundaries or by discontinuous outlines when they form uncertain boundaries (Gustavsson et al., 2006).

3. Conclusions

We have presented here a new 1:650,000 scale geomorphological map of the southwest Sinus Sabaeus region of Mars, in the transition between Arabia Terra and Noachis Terra, aimed to build a better understanding of this regional environment during the earliest Martian times. Our analysis has revealed several important events contributing to the geological understanding of this understudied region of Mars. Our map provides an unprecedented description of the area, including mapping 12 different units (appendix 1) and 14 features (appendix 2) to constrain better the hydrological context. Our work corroborates the existence of past aqueous activity in the region, suggesting complex and long-lasting water-related modification processes on the Sinus Sabaeus area during the Noachian and into the Hesperian.

Software

We used ArcGIS 10.3 Desktop Software (ESRI) to draw and compile the 1:650,000 scale, geomorphological map. Using as a base the CTX mosaic (Bruce Murray Laboratory for Planetary Visualization) and the Context Camera images (Mars Orbital Data Explorer website), we integrated the topography derived by MOLA and MOLA-HRSC (United States Geological Survey) and THEMIS Thermal Inertia (United States Geological Survey) imagery, to facilitate the mapping process. The layout was produced using ArcGIS 10.3 as well. The ArcHydro Tools have been used to generate the automatic drainage network.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author [C. Robas], upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the author(s).
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