The geology of the Navua Valles region of Mars
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ABSTRACT
The Navua Valles are a system of channels and valleys on the inner rim of Hellas Basin. The aim of this mapping study was to determine the geologic history of the Navua Valles region; and the relationships between the basement, flow, and channel units along the northeastern slope of Hellas Basin. We have produced a 1:1 million scale geologic map of the Navua Valles region, utilizing standard USGS geologic mapping procedures, but not within a regular USGS mapping project. We selected the mapping area boundaries specifically to cover the Navua Valles drainage systems. The primary base of this mapping effort was a mosaic of 161 Mars Reconnaissance Orbiter Context Camera images, at approximately 6 m/pixel. This paper is part of a double publication, one paper describing the geology of this area, and this paper presenting the geologic map produced during the investigation.

1. Introduction
We have mapped the Navua Valles region on Mars to understand its unique geologic setting that produced fully and partially integrated drainage systems (Hargitai, Gulick, & Glines, 2017) at the margin of distinct terrains. The mapped area is situated on the northeastern inner rim of Hellas Basin, north of major outflow channels, on hundreds of km long, relatively uninterrupted slopes. Drainage networks in this area have not been previously mapped in detail, although this region is densely dissected by channels, close to the Hadrirac volcanic center that may have influenced the formation of these drainages.

We mapped an area of 267,000 km\(^2\) (445 × 600 km) between 79.58°E, 28.1°S and 87.1°E, 38.2°S, which overlaps with MC-21 and MC-28 map quadrangles. The mapping area completely covers higher-resolution MTM quad-35277 and most of quad-30277. However, this map’s boundaries were chosen to cover the drainage systems of Navua Valles. The mapping was made utilizing the standard USGS planetary mapping procedures (Tanaka, Skinner, & Hare, 2011, updated after this map was completed: Skinner et al., 2018).

In the geologic map (Main Map), we mapped the structural features and the individual material units formed during a specific geologic event in this area on Mars, using photogeologic methods. The full-sized map sheet consists of six distinct map elements: (1) the geologic map at 1:1,000,000 scale with marginalia; (2) map symbols, generated in ArcMap; (3) a table called the Correlation of Map Units (COMU) where the map units are placed chronologically on the Y axis and classified into groups based on formative processes on the X axis; (4) Locator maps that show the location of the mapping area; (5) the Description of Map Units (DOMU), which also serves as an explanation of unit names and colors used in the map. It also lists each unit’s full designation, age, morphologic, and thermal inertia descriptions, and geologic interpretation of the material and its formative processes, and (6) cross-sectional profiles along two lines crossing the mapped region.

2. Methods
We mapped the region using ESRI’s ArcMap software. We used 161 Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) images as a primary base map (~6 m/pixel resolution, 99.17% coverage). These were selected using the USGS Planetary Image Locator Tool (PILOT) (Bailen, Sucharski, Akins, Hare, & Gaddis, 2013). Raw CTX images were processed using the USGS Astrogology Cloud Processing tool ‘Map Projection on the Web’ (POW) (Hare, Akins, Sucharski, Baien, & Anderson, 2013), which updates camera pointing information, applies radiometric correction, removes striping, stretches, and projects the images into equi-rectangular map projection. The Mars Odyssey Thermal Emission Imaging System (THEMIS) night-time IR mosaic (100 m/pixel resolution) was used to infer unit contacts within the visually indistinct plains units based on distinct thermal
inertia properties. Additionally, we used 62 MRO High-Resolution Imaging Science Experiment (HiRISE) images (25–50 cm/pixel resolution) to support the morphological analysis of the surface units. The displayed map base, the background behind the colored geologic units, however, is not the CTX mosaic used for identifying the units, but a controlled, seamless THEMIS daytime IR mosaic, which is more uniform in illumination than the mosaic of various CTX images. Mapping was conducted at a digital scale of 1:150,000 to 1:60,000, depending on the terrain details.

First, we produced contact lines that delineate the boundaries of geologic units. In practice, these boundaries follow changes in albedo or surface pattern, and assume that similar albedo and patterned terrain are composed of a single material unit that was emplaced in a single event, having a uniform erosional-depositional history. Next, all craters visible on CTX images were counted in these units but only those larger than approx. 300 m were used for crater age calculations. Calculations of surface ages were conducted using craters in the entire mapping area, except where secondary clusters or chains dominated the scene. Based on the results, preliminary units were merged or separated and new calculations were made until the unit boundaries were the most consistent with stratigraphy. A satisfying consistency was reached after 37 iterations. Units were colored according to their formative processes and were the most consistent with stratigraphy. A satisfactory result was reached after 37 iterations. Units were colored according to their formative processes and named according to their ages and geomorphic characteristics. Different shades of the same color were used for impact units formed at different times.

Geological symbology was partly taken from Nass, van Gasselt, Jaumann, and Asche (2011). Structural features are landforms that formed within a material unit. They were classified as different types of location: point features (cataract sites, streamlined forms, cauldron-like forms, which are too small to be displayed as a polygon feature at the print scale); linear features (channels, tectonic features, etc.); and surface features. The latter are patterns or clusters of dunes, knobs, or mounds, extending to smaller areas and being different from the underlying material unit. Each structural feature type was mapped in a separate layer (shapefile).

We mapped channels into two separate layers: one with uniform width, and another with line width scaled according to the actual channel width. The latter layer was used in some figures in our hydrological analysis (Hargitai et al., 2017), but not in the geologic map. Relatively wide channel belts are represented by polygons and not polylines on the map.

Colors of the material units dominate the map and they are perhaps the most important map design element. We followed planetary geologic mapping standards that come mainly from practiced traditions. Brownish colors represent the oldest rock strata (Noachian age), which are typically densely cratered terrain. The brightest of these colors is yellow, which is used for all individual impact crater’s units, and include the crater depression, rim, and ejecta. This way Noachian-aged craters and younger craters are visually linked. ‘Plains units’ are pink to violet, in order to express their geologic interpretation as volcanic plains; as volcanic units are traditionally represented by reddish colors. Since volcanic plains are dominantly emplaced during the Hesperian, pinkish colors are also representative of Hesperian-aged strata. Layered and fill units are displayed using green to blue colors, representing some type of sedimentary process. Finally, channel-associated sediments are shown in light blue (cyan) and paleochannels are represented by cyan solid lines. This decision is subjective, since ‘fluvial sediment’ and ‘paleoriver’ are interpretations and showing them in blue colors may visually overemphasize these interpretations. Valleys and channels could have been shown with brown or black colors, which would be less subjective, or dashed lines, which is closer to the ‘ephemeral stream’ symbol according to terrestrial standards, since these forms have probably been dry for billions of years but they did transport liquid material when they formed. However, this map should communicate the geologic history of this terrain. Therefore, the blue (cyan) colors and solid lines for the putative fluvial valley and channel features are the most obvious visual symbols to communicate the results of our geologic analysis. We also note that channels or valleys are not regular features in geologic maps. They may be shown by a variety of symbol types or not shown at all. Valleys and channels are sufficiently wide to be visible at print scale and their interior is in places covered by material that is different from the overbank deposits. Most of the channels and valleys are erosional, and hence, structural features (instead of material features). In our case, however, the main aim of this study was to investigate the origin of drainage networks in the Navua Valles region by geologic mapping. Therefore, channels have a special importance and they play a central role in the geologic history of this region. We have hydrologically analyzed the Navua Valles paleodrainages previously (see Hargitai et al., 2017). Drainage networks, along with potential paleolakes, are the most important sites where habitats might still exist in this region. Putative paleolakes, however, are not shown on the map because they are not expressed in a single and obvious geologic unit type or landform. These ephemeral hydrologic features can form several indicator morphologies, such as shorelines, desiccation polygons (El-Maarry et al., 2014), subaqueous deltaic deposits (Ansan et al., 2011) and pairs of inlet and outlet channels (Hargitai, Gulick, & Glines, 2018).

The cross-sectional profiles were generated along two intersecting lines that extend across the entire mapped region. These profiles are intended to show the 3D placement of the geologic units, with their
width and subsurface extent. Since there are no drilling or seismic data for Mars, these representations of the structure of the Martian subsurface were constructed by interpolating surface stratigraphy. Although the resulting configurations are logical and their exposed surface profile exactly follows surface topography and the identified material units, the subsurface representation is probably the most subjective part of the map sheet. As Malin and Edgett (2001, their Fig. 31) showed, the subsurface stratigraphy is probably much more complex than what is visible and can be inferred on the surface. Similar to the terrestrial geologic record, many layers of buried and overlapping features may be present without surface expression, in addition to completely eroded past landforms, especially in the Noachian megabreccia. One such example is the Hellas Basin at the lower Noachian boundary, which is filled by thick layers of material and its rim is significantly eroded – this is where our mapped region is located.

Names of planetary surface features are kept at minimum as per IAU’s policy. In the geologic map, we only show approved place names, with the exception of five major drainage networks that we previously designated informally as Navua A, B, C, E, and Channel D (Hargitai et al., 2017). The latter does not belong to Navua Valles valleys as it originates directly at Hadriracus Mons.

For calculating the ages of the units, we used crater counting. For the resulting crater retention model ages, we implemented the Ivanov (2001) production function, the Hartmann and Neukum (2001) chronologic function, and the ‘Neukum system’ of Martian period boundaries, which are built into CraterStats II as default (Michael, 2013). We determined these ages in an iterative process, and then merged those units that had similar crater size frequency curves, and also exhibited similar visual patterns. Crater size frequency diagrams are not shown on the map sheet, but they are included as supplementary material. This information is built into the map unit colors and the COMU. We have also determined the ages of channel sections. We show these model ages in Figure 1 and in Supplementary Table 2.

3. Geologic results

Major results on the geology of the region are presented in the accompanying paper (Hargitai et al., submitted to Icarus). Here we only list the most important results. We determined that the terrain on the interior slopes of the eastern Hellas Basin were formed by episodic volcanic and fluvial activity. Several of the Navua Valles drainage systems are discontinuous, and Navua A is probably precipitation-fed (Hargitai et al., 2017). In another study, we mapped all potential paleolakes in this region (Hargitai et al., 2018), that were previously unidentified, including lakes fed by direct precipitation, ground water and channel-transported water, likely in the form of ephemeral rivers. We identified geomorphic evidence for the reactivation of both channels (Hargitai et al., 2017) and paleolake basins (Hargitai et al., 2018). Our results suggest that floods and sustained flows periodically formed primary or interior channels and lakes from the Noachian until the Amazonian in this region.

4. Conclusions and significance

While this work contributes to the geologic understanding of Mars, and particularly, to the volcanic and fluvial evolution on the planet, it is also one of the few geologic mapping projects that were conducted outside the USGS Planetary Geology Program. The USGS is still the single publisher for peer-reviewed, professionally edited planetary geologic maps that are published in a coordinated manner since 1961 (Shoemaker & Hackman, 1961). USGS also leads in forming a standard protocol for planetary geologic mapping with the aim to guide USGS and non-USGS, including international, mapping efforts (Skinner et al., 2018). European planetary researchers do not have any single publishing house that would edit and publish European-produced planetary maps, since many mapping projects run at national or institutional levels. This has led to map publications distributed in a variety of journals, online platforms, creating difficulties in finding the published maps and a variety of standards, formats, and qualities of works. Standalone mapping efforts have become more common in recent years and the number of published major (large-size) planetary geologic maps in journals are now (as of 2017) comparable to those released by USGS (Pitura, 2017). International cooperation within single space missions, such as Dawn and Cassini, resulted in mapping tasks distributed over groups in different nations, according to the origin of suppliers of cameras or other instruments aboard the spacecraft. The need to quickly publish geologic maps during the active missions also generated geologic maps outside the slow peer-review process (Williams, Yingst, & Garry, 2014; Williams, Buczkowski, Mest, & Scully, 2017). European plans for landing or flying their missions also resulted in the publications of various geologic and geomorphic maps (Guzzetta, Galluzzi, Ferranti, & Palumbo, 2017). Chinese scientists, using their own lunar data, have begun producing a new lunar geologic map series (e.g. Liu et al., 2017). Maintaining an international planetary map database (Hargitai & Pitura 2018) is therefore a critical part of the global planetary mapping infrastructure.

Software

Mapping was conducted in ArcMap 10. Crater counting to determine ages and verify preliminary contact lines were done within CraterStats II and CraterTools. Final editing and marginalia were produced in Adobe
Illustrator. Photoshop was used to edit the legend (Map Symbols).

Data

The map (Main Map) published as part of this paper is a static pdf map created to contain all content and design elements in a layout that esthetically best displays these elements. The mapped linear and surface units, contact lines, and geologic units are included as vector data in the pdf file. The THEMIS map base image mosaic is embedded in a separate raster layer. The map segment can be further used for analysis using the GIS-ready format that contains the layers...
(shapefiles) of structural features and material units (see supplementary data). This can be imported directly into any GIS project. This map uses the IAU Mars2000 reference surface. The crater counting data behind the chronology are supported in a supplementary file.

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References
Ansar, V., Loizeau, D., Mangold, N., Le Mouèlic, S., Carter, J., Poulet, F., … Neukum, G. (2011). Stratigraphy, mineralogy, and origin of layered deposits inside Terby crater, Mars. Icarus, 211(1), 273–304. doi:10.1016/j.icarus.2010.09.011
Bailen, M. S., Sucharski, R. M., Akins, S. W., Hare, T., & Gaddis, L. (2013). Using the PDS Planetary Image Locator Tool (PILOT) to identify and download spacecraft data for research. 44th Lunar and Planetary Science Conference, Abstract #2246.
El-Maariry, M. R., Watters, W., McKeown, N. K., Carter, J., Noe Dobrea, E., Bishop, J. L., … Thomas, N. (2014). Potential desiccation cracks on Mars: A synthesis from modeling, analogue-field studies, and global observations. Icarus, 241, 248–268. doi:10.1016/j.icarus.2014.06.033
Guzzetta, L., Galluzzi, V., Ferranti, L., & Palumbo, P. (2017). Geology of the Shakespeare quadrangle (H03), Mercury. Journal of Maps, 13, 227–238.
Hare, T. M., Akins, S. W., Sucharski, R. M., Baien, M. S., & Anderson, J. A. (2013). Map projection web service for PDS images. 44th Lunar and Planetary Science Conference, Abstract #2068.
Hargitai, H. I., Gulick, V. C., & Glines, N. H. (2017). Discontinuous drainage systems formed by precipitation and ground-water outflow in the Navua Valles and southwest Hadriacus Mons regions, Mars. Icarus, 294, 172–200. doi:10.1016/j.icarus.2017.03.005
Hargitai, H. I., Gulick, V. C., & Glines, N. H. (2018). Paleolakes of northeast Hellas: Precipitation, ground-water-fed, and fluvial lakes in the Navua–Hadriacus– Ausonia region. Astrobiology, 18(12), (In print).
Hargitai, H., & Pitura, M. (2018). International catalog of planetary maps 1600–2017. 49th lunar and planetary science conference, LPI Contrib. No. 2083. Retrieved from https://www.hou.usra.edu/meetings/lpsc2018/pdf/2608.pdf
Hartmann, W. K., & Neukum, G. (2001). Cratering chronology and the evolution of Mars. Space Science Reviews, 96, 165–194.
Ivanov, B. A. (2001). Mars/Moon cratering rate ratio estimates. Chronology and Evolution of Mars, 12, 87–104.
Liu, J., Ji, J., Zhang, L., Head, J. W., Guo, D., Wang, J., … Ouyang, Z. (2017). New geologic map of the LQ-19 (Mare Nubium) quadrangle on the Moon. Lunar and Planetary Science XLVIII, Abstract #1447.
Malin, M. C., & Edgett, K. S. (2001). Mars global surveyor Mars orbiter camera: Interplanetary cruise through primary mission. Journal of Geophysical Research: Planets, 106(E10), 23429–23570.
Michael, G. G. (2013). Planetary surface dating from crater size–frequency distribution measurements: Multiple resurfacing episodes and differential isochron fitting. Icarus, 226(1), 885–890.
Nass, A., van Gasselt, S., Jaumann, R., & Asche, H. (2011). Implementation of cartographic symbols for planetary mapping in geographic information systems. Planetary and Space Science, 59, 1255–1264.
Pitura, M. (2017). 2017 in review 2: New planetary geologic maps. International Cartographic Association Commission on Planetary Cartography. Retrieved from https://planetcarto.wordpress.com/2017/12/23/2017-in-review-2-new-planetary-geologic-maps/
Robbins, S. J., & Hynek, B. M. (2012). A new global database of Mars impact craters ≥1 km: 1. Database creation, properties, and parameters. Journal of Geophysical Research, 117, E00504. doi:10.1029/2011JE003966
Shoemaker, E., & Hackman, R. J. (1961). Lunar photogeologic chart LPC 58. Copernicus, Prototype Chart, USGS. Retrieved from https://www.lpi.usra.edu/resources/mapcatalog/LunarPhotogeologicChart/
Skinner Jr, J. A., Huff, A. E., Fortezzo, C. M., Gaither, T. A., Hare, T. M., & Hunter, M. A. (2018). Planetary geologic mapping protocol – 2018. The Planetary Geologic Map Coordination Group, Astrogeology Science Center, USGS. Retrieved from https://planetarymapping.wr.usgs.gov/Page/view/Guidelines
Tanaka, K., Skinner, J., & Hare, T. (2011). Planetary geologic mapping handbook – 2011. USGS.
Williams, D. A., Buczkowski, D. L., Mest, S. C., & Scully, J. E. C. (2017). Introduction: The geologic mapping of Ceres. Icarus. doi:10.1016/j.icarus.2017.05.004
Williams, D. A., Yingst, R. A., & Garrity, W. B. (2014). Geologic mapping of Vesta. Icarus, 244. doi:10.1016/j.icarus.2014.03.001