Program
Planetary Geologic Mappers Annual Meeting

June 12–14, 2019 • Flagstaff, Arizona

Institutional Support

Lunar and Planetary Institute
Universities Space Research Association
U.S. Geological Survey, Astrogeology Science Center

Conveners

David Williams
Arizona State University
James Skinner
U.S. Geological Survey

Science Organizing Committee

David Williams
Arizona State University
James Skinner
U.S. Geological Survey
Abstracts for this meeting are available via the meeting website at

[www.hou.usra.edu/meetings/pgm2019/](http://www.hou.usra.edu/meetings/pgm2019/)

Abstracts can be cited as


Abstract #XXX.

LPI Contribution No. 2154, Lunar and Planetary Institute, Houston.
Guide to Sessions

Wednesday, June 12, 2019
8:30 a.m.  Introduction and Mercury, Venus, and Lunar Maps
1:30 p.m.  Mars Volcanism and Cratered Terrains
3:45 p.m.  Mars Fluvial, Tectonics, and Landing Sites
5:30 p.m.  Poster Session I: All Bodies

Thursday, June 13, 2019
8:30 a.m.  Small Bodies, Outer Planet Satellites, and Other Maps
1:30 p.m.  Teaching Planetary Mapping
2:30 p.m.  Poster Session II: All Bodies
3:30 p.m.  Plenary: Community Discussion

Friday, June 14, 2019
8:30 a.m.  GIS Session: ArcGIS Roundtable
1:30 p.m.  Discussion: Performing Geologic Map Reviews
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<td>8:30 a.m.</td>
<td>Williams D. A. *</td>
<td>Introduction and Welcome</td>
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<td>8:35 a.m.</td>
<td>Williams D. A. *</td>
<td>Logistics</td>
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<td>8:40 a.m.</td>
<td>Skinner J. A. *</td>
<td>Remarks from the Planetary Geologic Mapping Coordinator</td>
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<td>9:10 a.m.</td>
<td>Hunter M. *</td>
<td>GIS Update and Future Efforts</td>
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<td>9:40 a.m.</td>
<td>Gaither T. A. *  Skinner J. A. Jr.</td>
<td>Planetary Nomenclature: Information and Guidelines for Geologic Mappers [#7031] Planetary nomenclature is an essential part of USGS-published planetary geologic maps. This presentation will provide information and guidelines for mappers on how to request official names and accurately display nomenclature on their geologic maps.</td>
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<td>10:00 a.m.</td>
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<td>BREAK</td>
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<td>10:30 a.m.</td>
<td>Whitten J. L. *  Fassett C. I. Ostrach L. R.</td>
<td>Can the Intercrater Plains Unit on Mercury be Meaningfully Subdivided?: Characterization of the Derain (H-10) Quadrangle Intercrater Plains [#7016] Subdivision of the intercrater plains unit on Mercury is explored through mapping the H-10 quadrangle. The intercrater plains has gradational contacts with other plains units and these differences could be mapped as separate units or many facies.</td>
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<td>11:10 a.m.</td>
<td>Garry W. B. *  Yingst R. A.  Mest S. C. Ostrach L. R.</td>
<td>Updating the Geologic Maps of the Apollo 15-16-17 Landing Sites — Year 1 [#7029] We will present the results of our PDART project to create six new geologic maps at 1:200k and 1:24k of the Apollo 15, 16, and 17 landing sites.</td>
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<td>11:30 a.m.</td>
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**Wednesday, June 12, 2019**  
**MARS VOLCANISM AND CRATERED TERRAINS**  
**1:30 p.m.  Building 6 Library**  
**Chair: David Williams**

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| 1:30 p.m. | Mouginis-Mark P. J. * | **1:200,000-Scale Geologic Map of Olympus Mons Caldera, Mars [#7005]**  
Lava flows going uphill identified on southern rim of Olympus Mons caldera! Geologic mapping at 1:200K suggests post-caldera collapse inflation of the volcano rim and deformation of the floor, illustrating a fascinating chronology for the summit. |
| 1:50 p.m. | Garry W. B. * Williams D. A. | **1:1M Geologic Map of Pavonis Mons, Mars [#7021]**  
We will present results for our 1:1,000,000 map of Pavonis Mons volcano on Mars based on observations of CTX images. |
| 2:10 p.m. | Crown D. A. * Berman D. C. Scheidt S. P. Hauber E. | **1:1M-Scale Geologic Mapping Investigations of Alba Mons, Mars [#7023]**  
1:1M-scale geologic maps of Alba Mons’ western flank and summit region characterize geologic processes and derive age constraints for the northernmost volcano in the Tharsis region. |
| 2:30 p.m. | Bernhardt H. * Williams D. A. | **Integrated Local and Regional Photogeologic Mapping of Neukum Crater and Eastern Noachis Terra, Mars [#7013]**  
We mapped Neukum crater (CTX) as well as surrounding eastern Noachis Terra (THEMIS-IR). Integration of mapping products at different scales and wavelengths allowed continental-scale extrapolation of detailed observations. |
| 2:50 p.m. | Robbins S. J. * Hoover R. H. Kirchoff M. R. | **Fully Controlled 6 Meters/Pixel Mosaic of Mars’ South Pole and Equator from Mars Reconnaissance Orbiter Context Camera, II [#7022]**  
Wicked awesome stuff / On Mars: Controlled CTX / Data for science! |
| 3:10 p.m. | Bernhardt H. * Williams D. A. | **Photogeologic Mapping of Malea Planum: A New View of the Oldest of Mars’ Large Volcanic Provinces [#7014]**  
We produced the first comprehensive, detailed map of Malea Planum and identified 25 geomorphologic units. Six major depositional units (~3.8–3.5 Ga) likely contributed ~500,000 km³ of material to the infill of the adjacent Hellas basin. |
<p>| 3:30 p.m. | | <strong>Break</strong> |</p>
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<td>3:45 p.m.</td>
<td>Burr D. M. * Jacobsen R. E.  Lefort A. Borden R. M.  Peel S. E.</td>
<td><strong>Understanding the History of a Diverse Inverted Fluvial Landscape: 1:500k Geologic Mapping of the Aeolis Dorsa Region, Mars [#7008]</strong> The motivation for mapping the Aeolis Dorsa region, north of the Highland-Lowland Boundary, was to investigate the history of extensive inverted fluvial deposits. Later investigations led mapping of tectonic and possibly lacustrine features as well.</td>
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<td>4:05 p.m.</td>
<td>Weitz C. M. * Berman D. Rodriguez A. P.  Bishop J. L.</td>
<td><strong>Geologic Mapping and Studies of Diverse Deposits at Noctis Labyrinthus, Mars [#7011]</strong> We have completed mapping of the western portion of Noctis Labyrinthus (−6 to −14°N, −99.5 to −95.0°W), which includes some of the most diverse mineralogies identified on Mars.</td>
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<td>4:25 p.m.</td>
<td>Edgar L. A. * Skinner J. A. Jr. Fortezzo C. M.  Bennett K. A.</td>
<td><strong>Geologic Mapping and Stratigraphic Analyses in South-Western Melas Chasma, Mars: Year 1 Progress [#7018]</strong> Update on Year 1 progress as part of a three-year study to produce a 1:150,000-scale geologic map of southwestern Melas Chasma. This study will also produce nine detailed geologic reference sections, currently in progress.</td>
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<td>4:45 p.m.</td>
<td>Sun V. Z. * Stack K. M.</td>
<td><strong>Geologic Mapping of the Jezero and Northeast Syrtis Regions of Mars [#7002]</strong> We will present an geologic map of the Jezero and Northeast Syrtis regions, which may facilitate the connection of common geologic units at both sites, which have previously been hypothesized to represent different types of habitable environments.</td>
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<td>5:05 p.m.</td>
<td>Williams D. A. *</td>
<td>COMMUNITY DISCUSSION</td>
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| Aubele J. C. | *Shimti Tessera (V-11) and Vellamo Planitia (V-12 Quadrangles, Venus* [#7033]  
Revised geologic maps of V11 and V12 have now been submitted to the Planetary Mapping Program. The new maps provide new evidence for the difference between shield fields and shield plains units on Venus. |
| Keszthelyi L. P. Laura J. Huff A. E. Jaeger W. L. | *Geologic Mapping of Athabasca Valles, Mars: Now and Again* [#7006]  
We are responding to reviewer comments on the 1:1M geologic map of the Athabasca Valles region. We also discuss plans for testing the value of controlled CTX image mosaics for mapping at ~1:50K. |
Geologic mapping is being undertaken to investigate the geologic history of an area within the southern Utopia basin. This presentation will discuss the investigation’s background, motivation and current results. |
| Wolak J. M. Robbins N. N. Bohanon A. M. Blaylock H. E. | *High-Resolution Geologic Mapping of Terraced Fans in Xanthe Terra, Mars* [#7009]  
This presentation summarizes high-resolution mapping results from two terraced fan locations in Xanthe Terra: the Camichel Crater fan (2.69N, 308.33E) and Dukhan Crater fan (7.59N, 321.02E). |
| Koeppel A. H.D. Edgar L. | *Recognizing Stratigraphic Diversity Through 1:10,000 Scale Geologic Mapping of Northwest Aeolis Mons, Mars* [#7015]  
In this study, we bridge the gap between MSL planning-related targeted observations and previously-derived geologic maps for Aeolis Mons by producing a detailed 1:2,000 scale geologic map of a ~70 km$^2$ area on the mound’s northwest flank. |
| Gullikson A. L. Okubo C. H. | *Large-Scale Geologic Mapping of Southeast Nia Mensa in Eastern Candor Chasma, Mars* [#7024]  
This abstract summarizes the current efforts in mapping the southeastern portion of Nia Mensa using a HiRISE stereo pair for high-resolution structural and geologic mapping. |
This poster presents the final global geologic map of Ceres from the Dawn Science Team, made using Low Altitude Mapping Orbit images at 35 m/px resolution. |
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<td>8:30 a.m.</td>
<td>Yingst R. A. * Berman D. C. Garry W. B. Mest S. C. Williams D. A. Gregg T. K. P.</td>
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<td><strong>Geologic Mapping Methods for Small, Rocky Bodies: The Vesta Example [#7030]</strong></td>
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<td>Vesta is used to test methods of mapping small, rocky bodies by incorporating multiple types of datasets.</td>
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<td>Compiling a global Dataset out of 15 individual maps, a GIS template is needed to generate a geometrically and visually homogeneous map project representing a thematically consistent global map. A review of such a template will present here.</td>
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<td><strong>Geologic Map of the Interior of Occator Crater, Ceres, and Its Bright Faculae, Based on 2D and 3D Perspective Views of Highest Resolution (Meter-Scale) Dawn Data [#7012]</strong></td>
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<td>We present a 1:200,000 geologic map of Occator crater on Ceres, which is based on the highest resolution (~3 m) data returned from the Dawn mission. Our geologic map addresses key questions about the emplacement mechanism of Occator’s bright faculae.</td>
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<td><strong>Geologic Feature Mapping on Asteroid (101955) Bennu to Inform Sample Site Selection on the OSIRIS-REx Mission [#7025]</strong></td>
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<td>Coordinated mapping efforts of various geologic features on the surface of asteroid Bennu are ongoing. Geologic mapping is a key component in identifying a sample site which meets various spacecraft and mission requirements.</td>
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<td>9:50 a.m.</td>
<td>Leonard E. J. * Patthoff D. A. Senske D. A.</td>
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<td><strong>Geologic Mapping of Europa at Global and Regional Scales [#7032]</strong></td>
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<td>Updates on the global geologic map of Europa and the revisions that have been made post-USGS reviews. We will also present plans for regional mapping on Europa.</td>
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<td>10:10 a.m.</td>
<td>BREAK</td>
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<td><strong>Ridges of Enceladus’ Leading and Trailing Hemispheres [#7026]</strong></td>
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<td>We present maps of Enceladus’ ridges on the leading and trailing hemispheres.</td>
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<td>10:45 a.m.</td>
<td>Martin E. S. * Patthoff D. A. Bland M. T. Watters T. R. Collins G. C. Becker T.</td>
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<td><strong>Mapping Neptune’s Moon Triton [#7020]</strong></td>
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<td>We present updates to the new Triton USGS SIM.</td>
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<td>11:05 a.m.</td>
<td>White O. L. * Singer K. N. Williams D. A. Moore J. M. Lopes R. M. C.</td>
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<td><strong>A Forthcoming Global Geologic Map of Pluto [#7001]</strong></td>
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<td>We present a summary of what mapping has been performed for Pluto by the authors to date, as well as our mapping rationale for our forthcoming global USGS Science Investigations Map of Pluto.</td>
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<td>11:25 a.m.</td>
<td>Wright S. P. * Goliber S. A.</td>
<td><em>Geologic Mapping of Both Alteration Mineralogies and Shock Stages of Ejecta Lobes at Lonar Crater, India Using GPS/GIS, Sample Analyses, and High Resolution Imagery</em> [7017]</td>
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<td>As the Lonar crater ejecta blanket contains many varieties of altered basalt and degrees of shock metamorphism, we aim to construct a high resolution geologic map of ejecta lobes for ground-truthing future analog work with rovers and astronauts.</td>
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<td>DISCUSSION</td>
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TEACHING PLANETARY MAPPING
1:30 p.m.  Building 6 Library
Chair:  David Williams

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<td>1:30 p.m.</td>
<td>Coles K. S. *  Fang S. P.  Lewis V. A.  McAdoo C. S.  Pagan C. J.</td>
<td><em>Learning Planetary Geologic Mapping as an Undergraduate Non-Major</em> [#7028] Undergraduates from science and other majors make maps in a planetary geology course. The results suggest what goals are and are not realistic in such a brief experience.</td>
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<tr>
<td>1:50 p.m.</td>
<td>Robbins N. N.  Bohanon A. M.  Wolak J. M. *</td>
<td><em>Planetary Geologic Mapping Using ArcGIS Pro: A Tutorial Series for Students</em> [#7010] This presentation showcases a series of four new planetary geologic mapping tutorials for ArcGIS Pro users. The tutorials are designed for undergraduate/graduate students or planetary mappers who wish to complete a primer as they upgrade from ArcMap.</td>
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<tr>
<td>2:10 p.m.</td>
<td>Williams D. A. *</td>
<td><em>Plans for a Planetary Geologic Mapping Summer Workshop</em></td>
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Thursday, June 13, 2019
POSTER SESSION II:  ALL BODIES
2:30 p.m.  Building 6 Library

*See Poster Session I on Wednesday afternoon for a complete listing of posters*

Thursday, June 13, 2019
PLENARY:  COMMUNITY DISCUSSION
3:30 p.m.  Building 6 Library
Chair:  David Williams

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<td>3:30 p.m.</td>
<td><em>Including Creation of List of High Priority Geologic Maps for NASA and Election of New Planetary Mapping Community Representative for MAPSIT</em></td>
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GIS SESSION:  ARCGIS ROUNDTABLE
8:30 a.m.  Building 6 Library
Chairs:  David Williams and Marc Hunter

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<td>8:30 a.m.</td>
<td><em>Using ArcGIS for Planetary Mapping, Including Migration to ArcPro</em></td>
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Friday, June 14, 2019
DISCUSSION:  PERFORMING GEOLOGIC MAP REVIEWS
1:30 p.m.  Building 6 Library
Chairs:  David Williams and James Skinner

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  H. Bernhardt and D. A. Williams .............................................. 7013

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SHIMTI TESSERA (V-11) AND VELLAMO PLANITIA (V-12) QUADRANGLES, VENUS

J. C. Aubele, New Mexico Museum of Natural History & Science Albuquerque, NM; jayne.aubele@state.nm.us

Introduction. Adjoining quadrangles Shimti Tessera (V-11) and Vellamo Planitia (V-12) were partially mapped in the mid-90s, early 2000s. Initial results included description and interpretation of what was then a proposed new unit named shield plains (Akkrva shield plains) consisting of widespread small shield volcanoes and associated lava flows [1]. Following the initial study, many other mapped Venus quads also identified shield plains or shield terrain units [2]. Revised geologic maps of V-11 and V-12 have now been completed using GIS map standards and submitted to the planetary mapping program. The new maps provide better stratigraphic control on the shield plains in the type location.

Shimti Tessera (V-11) and Vellamo Planitia (V-12) are located in the northern hemisphere of Venus, from 25° to 50°N and from 90° to 150°E. During analysis of the Venera 15/16 data [3] some regions on Venus were recognized as extensive areas of small hills and given the feature name “colles.” One of these regions is an unusual terrain, Akkrva Colles, [4] that extends across the V-12 and V-11 quadrangle boundary. The hills were interpreted to be volcanoes based on Venera 15/16 data [5]. During analysis of the Magellan data [6] these regions were confirmed as extensive areas of abundant, small, predominantly shield-type volcanoes.

Map Units and stratigraphic relationships for these quadrangles are defined based on full resolution Magellan synthetic aperture radar (SAR) data and incorporate Magellan altimetry, emissivity, Fresnel reflectivity, and roughness data. Material units are mapped independently of tectonic structures, but in some cases, structure is a consistent characteristic of a unit and is used to define it. Material units are interpreted to represent one (or a range of related) material(s) deposited by one (or a range of related) process(es) over a specific geologic time interval. Mapping has defined four general categories of material units in these quadrangles and general stratigraphic relationships. The oldest units are characterized by bright radar backscatter, elevated terrain, and structural elements. Tessera (t) is stratigraphically the oldest unit in both quadrangles and characterized by closely spaced ridges and grooves oriented in at least two directions. Densely lineated plains material (pdl) and Ridged and grooved plains material (prg) overlay tessera and are characterized by closely spaced narrow parallel to anastomosing lineaments (pdl) and sets of relatively broad, sinuous, parallel ridges, arches, and lineations (prg). Plains Units are the most widespread units in both quadrangles. Shield plains material (psh) covers the eastern portion of V-11 and the western portion of V-12 and consistently overlays the units described above (where stratigraphic relationships can be observed) and is consistently overlain by Regional plains material (pr) in both quadrangles. (Fig.1). Local Plains Units associated with individual volcanic centers are the youngest plains units in both quadrangles. In V-11 these include the Lobate plains material of Maa-Ema Corona (plme) and Hei Chu Patera (plhc) as well as a shield field (psf) and associated flow field (pdsf) (Fig.2), and in V12 Lobate plains material of Ved-Ava Corona (plva).

Shield Fields and Shield Plains. Two end-member interpretations of areas of small shields have been debated over the years: (a) they represent a local or regional time-stratigraphic unit [7]; or (b) they represent a global time-stratigraphic unit [8]. Attempts to test the two hypotheses have focused on inconsistencies in stratigraphic relationships between surrounding plains and the clusters of small volcanoes, or shield fields, a term that follows terrestrial usage of the term volcanic field [9]. V11 and V12 quadrangles include examples of the difference between shield fields and shield plains and illustrate the two distinct processes in their formation. Shield fields are comparable to terrestrial volcanic fields; melt areas of limited extent and low magma rates delivered to the surface occurring locally throughout Venus geologic history. Shield plains, however, are more analogous to the Snake River Plains shield volcanoes [10] or terrestrial seamounts [11]; that is, volcanism associated with widespread melt sources available during a restricted period of geologic time. Shield plains differ from shield fields in larger number and greater areal extent and in their restriction to a limited stratigraphic interval. Stratigraphic relationships in V-11 and V-12 indicate a major accumulation of small shield activity occurred during a specific period in Venus geologic time prior to formation of the vast regional plains [12]. The question remains whether the shield plains surface is produced in a punctuated, catastrophic or continuous formation [13,14].

Acknowledgements: The initial mapping was funded by the Venus Data Analysis Program, NASA. I thank Sarah Noble, Jim Skinner, and the U.S.G.S. Planetary Mapping Group.
**Introduction:** Integrating local-scale with regional to continental-scale photogeologic maps allows extrapolating the geomorphologic inventory of large areas at a detail beyond regional-scale datasets. As part of an upcoming, comprehensive investigation of the region as well as a tribute to the late Gerhard Neukum, we present a case study based on Neukum crater, which we employ as representative local morphologic ensemble for surrounding eastern Noachis Terra. Neukum is a 102 km large crater in eastern Noachis Terra, a ~1.8 x 10^6 km^2 large part of the cratered highlands west of the Hellas basin in the southern hemisphere of Mars. Eastern Noachis Terra is the type area of the middle Noachian stratigraphic system [1-3], hosts several exposures of “felsic/anorthosite-like/plagioclase-rich” signatures associated with infrared-dark areas [4,5], and preserved the effects of the Hellas impact event (ejecta, secondaries, impact/related tectonics) because of a general lack of volcanic and fluvial overprint [e.g., 6-8]. Thus, it is a key region to better understand the martian impact chronology, the geologic and climatic effects of large impact events on the planet’s history [e.g., 9], as well as early crustal evolution. However, despite some local, isolated investigations, no comprehensive analysis of the region has been conducted yet.

**Data:** We used mid-infrared data from version 12 of the Thermal Emission Imaging System (THEMIS) Daytime global mosaic (100 m/px) [10] as well as High Resolution Stereo Camera images (HRSC; 12.5-50 m/px) [11,12] as basemap for our regional mapping (1:1,000,000). To assess thermophysical properties of the surface, we also used the global thermal inertia mosaic based on THEMIS-IR [13]. Our local map (Fig. 1) is based on images by the Context Camera (CTX; ~6 m/px) [14-16]. Stereographic digital terrain models (DTMs; 50 m/px) based on HRSC images [17] covering Neukum crater were used to improve topographic information, which enabled better resolved stratigraphic observations. For the remainder of eastern Noachis Terra, the global DTM by the Mars Orbiter Laser Altimeter (MOLA) with a horizontal resolution of 463 m/px served as topographic basemap [18,19]. Further datasets (HiRISE, CRISM, and OMEGA) will be used for detailed unit interpretations in our final publication.

**Technique:** We used standard symbology defined by the US Geological Survey and employed the general techniques for planetary mapping as outlined by [20-22]. While contact classification is ongoing for the regional map, we defined standard contact types (certain, approximate, inferred, covered) for the local map. In addition to relative dating via stratigraphic analyses, we have derived absolute model ages by measuring crater-size frequency distributions (CSFD) on suitable local map units using techniques described in [23,24], with the aid of CraterTools in ArcMap [25] and CraterStats for plotting and fitting the distributions [26]. For the regional map, CSFD measurements are ongoing and several different production and chronology functions [27-30] will be used to derive model ages in order to ensure comparability with previous investigations.

**Preliminary results and discussion:** Integrated local and regional observations showed that Neukum crater’s geomorphology is representative for eastern Noachis Terra (overall crater degradation stage, relatively smooth infill dissected by 10s of km-scale pits, infrared-dark zones on crater floor, furrowed inner crater wall, dark dune field). The IR-dark zones, previously associated with “felsic” or plagioclase-rich signatures in several craters of northeastern Noachis Terra [4,5], do not correlate well with CTX-based photogeologic units. Instead, HiRISE and CRISM observations show Neukum’s larger pit, which dissects an IR-dark zone, to expose bright, layered, smectite-bearing material. We interpret the bright, smectite-bearing material as hydrothermal alteration product of the “felsic”/plagioclase-rich outcrops. As the often terraced walls and floors of all the crater floor pits of eastern Noachis Terra expose up to ~250 m of this bright, layered material, we submit that hydrothermal alteration followed or accompanied the emplacement of plagioclase-rich volcanic material (possibly via fractional crystallization of basalt [4,5]) and persisted over extended time spans in a large area. Lastly, despite having similar combined volumes (~1,600 km^3), the bright, smectite-exposing pits of eastern Noachis Terra are unlikely to be significant sources of the dune fields of the region (as suggested by [31]), which completely lack such characteristics, but are very dark and show mafic signatures.
Figure 1: Our local-scale map of Neukum crater along with a description of map units and stratigraphic observations (orthographic projection centered at crater center; location indicated by black box on global overview). While local mapping is based on CTX data, the product is shown with a THEMIS-IR day background for better visibility. This local-scale map complements our ongoing regional-scale mapping of surrounding eastern Noachis Terra (not shown in this abstract; outlines indicated by white box on global overview).

References:
PHOTOGEOLOGIC MAPPING OF MALEA PLANUM: A NEW VIEW OF THE OLDEST OF MARS’ LARGE VOLCANIC PROVINCES  H. Bernhardt and D. A. Williams. School of Earth and Space Exploration, Arizona State University, Tempe, USA (h.bernhardt@asu.edu).

Motivation: Late Noachian to early Hesperian-aged Malea Planum has been suggested as the site of large-scale volcano-ice interactions and as a major source for deposits now filling the adjacent Hellas basin to the north [1-4]. Activity on Malea Planum might also have affected the south polar Dorsa Argentea Formation immediately to the south, which has repeatedly been interpreted as a product of widespread wet-based glaciation affected by volcanic heat [e.g., 5,6]. Furthermore, it has been stated that such large-scale volatile mobilization and potential gas release should have affected the early martian climate and regional habitability [e.g., 7,8]. However, despite the potential of new datasets and its significance for volcanic and glacio-fluvial processes on Noachian and early Hesperian Mars, Malea Planum had not undergone a dedicated, detailed mapping effort. Here we present our photogeologic map and preliminary quantitative geologic analyses of that region (Fig. 1).

Data: For a description of our basemap and topographic datasets (THEMIS-IR and MOLA), please see our companion PGM Meeting abstract #7013. In addition, we used mid- to high-resolution visible image data from the High Resolution Imaging Science Experiment (HiRISE; 25-50 cm/px) and the Context Camera (CTX; ~6 m/px) [9-11]; the latter also in the form of the consolidated global mosaic by [12]. We also employed nadir as well as color images by the High Resolution Stereo Camera (HRSC; 12.5-50 m/px) on Mars Express (MEx) [13,14], although most HRSC data are compromised by atmospheric opacity at this latitude.

Technique: The mapping is conducted in ArcMap at 1:1,000,000 for a 1:2,000,000 end product. The mapping area was defined as a quadrangle comprising the entirety of the wrinkle ridged plains constituting Malea Planum (Fig. 1, purple unit). Otherwise the mapping process as well as absolute unit dating via crater size-frequency measurements are conducted in the same manner as already described in our companion PGM Meeting abstract (#7013). While not part of the mapping process, further analyses of the following hyperspectral and RADAR datasets, conducted by us or previous investigations, further complements unit interpretation and correlation: The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [19,20], the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) [21,22], the Shallow Radar instrument (SHARAD) [23,24], and the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) [2,25].

Select results and preliminary conclusions: Using all state-of-the-art datasets, we identified 25 geomorphologic units assigned to six groups. We compiled a stratigraphy based on superposition relations, with preliminary apparent model ages (AMAs) of the dominant wrinkle-ridged plains, as well as plains- and paterae-AMAs derived by [1,2], as provisional anchor points pending further crater size-frequency measurements on more of our units.

Disregarding crater ejecta and Amazonian veneers, we identified at least six distinct, major depositional units (Nml, HNpr, Hst, Hs, Hpc, and AHpc2) in our mapping area spanning a time period from ~3.8 Ga to at least 3.5 Ga. While the wrinkle-ridged plains (HNpr) still cover the majority of the region, we suggest that only small percentages of the other five deposits remain. Based on our ongoing mapping and morphometric analyses, volumes on the order of 400,000 to 500,000 km$^3$ of these units might have been removed from Malea Planum. Therefore, while Hesperia Planum likely contributed the majority of the once ~10$^6$ km$^3$ of Hellas infill [4], Malea Planum should also have decisively contributed to the basin’s infilling. While large-scale volatile mobilization of up to ~10$^5$ km$^3$ via volcanic heating has previously been suggested [3] for Malea Planum, our preliminary assessment of the region’s geomorphologic record implies not one catastrophic event, but several distinct episodes of erosion that occurred over several 100s of Ma. Furthermore, some (glacio)-fluvial landforms traverse the entirety of Malea Planum from south to north, therefore implying a ~1,600 km long drainage system that also fed the Hellas basin with sediments and volatiles from today’s South Pole region.

Lastly, we found that HNpr around Malea, Peneus, and Amphitrites Paterae hosts concentric normal faults, i.e., patera-forming collapse likely occurred after the plains were emplaced. Conversely, the lack of normal faults surrounding Pityusa Patera might indicate that it predates, and thus possibly contributed to, HNpr’s emplacement.
Figure 1: Downscaled version of our photogeologic map of the Malea Planum volcanic province (original map product is 1:2,000,000). Orthographic projection centered at 45°E, 67°S; background is version 12 of the global THEMIS-IR day mosaic.

GEOLGY OF THE LACHESIS TESSERA QUADRANGLE (V-18), VENUS. D. L. Buczkowski¹, E. M. McGowan², L. R. Ostrach¹, and G. E. McGill¹ ¹Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, debra.buczkowski@jhuapl.edu; ²University of Massachusetts, Amherst, MA; ³USGS Astrogeology, Flagstaff, AZ.

Introduction: The Lachesis Tessera quadrangle (V-18) lies between 25° and 50°N, 300° and 330°E. We present a first draft of a geologic map of the quadrangle and the associated tectonic analysis started by George McGill before his death.

Methods: Mapping was based on a 250 m/pxl Magellan cycle 1 synthetic aperture radar (SAR) mosaic prepared by the U.S. Geological Survey (USGS) planetary team. Most of the mapping was carried out using 75m/pxl FMAPS provided by the USGS in digital format. During the mission, data for the Lachesis Tessera quadrangle were collected in left-looking mode at incidence angles ranging between 43.73°-32.85°. The final base map is a 1:5M-scale controlled mosaic of SAR data. Topographic information was derived from digital elevation models and from gridded elevation data; the altimetry data were combined with the SAR data by the USGS to create synthetic stereoscopic images.

Geology: The Lachesis Tessera quadrangle includes parts of Sedna and Guinevere Planitiae; regional plains [1] cover approximately 80% of the quadrangle. In addition, the quadrangle includes two deformation belts and embayed fragments of one or two possible additional belts, 3 large central volcanoes, abundant small shield volcanoes and associated flow materials, 13 impact craters, 3 named coronae, and a number of corona-like features [2].

Plains: The most areally extensive materials are regional plains. These are mapped as two units, based on radar backscatter. The brighter unit appears to be younger than the darker unit, based on the common presence within the lighter unit of circular or nearly circular inliers of material with radar backscatter characteristic of the darker unit. The circular inliers are most likely low shield volcanoes, which are commonly present on the darker unit, that were only partially covered by the brighter unit. Clear cut examples of wrinkle ridges and fractures superposed on the darker unit but truncated by the brighter unit have not been found to date. These relationships indicate that the brighter unit is superposed on the darker unit, but that the difference in age between them is very small. Because they are so widespread, the regional plains are a convenient relative age time “marker”. The number of impact craters superposed on these plains is too small to measure age differences [3], and thus we cannot estimate how much time elapsed between the emplacement of the darker and brighter regional plains units. More local plains units are defined by significantly lower radar backscatter or by a texture that is mottled at scores to hundreds of kilometers scale. A plains-like unit with a homogeneous, bright diffuse backscatter is present as scattered exposures in the eastern part of the quadrangle. These exposures have been mapped as “bright material”, but it is not clear at present if this is a valid unit or if it is part of the brighter regional plains unit.

Tessera: Tessera is primarily found along the western border of the quadrangle, where Lachesis Tessera refers to southern exposures, and Zirka Tessera refers to northern. A second tessera unit appears to be deformed by the requisite 2 sets of closely spaced structures, but is so extensively flooded by regional plains materials that the structural fabric is partially obscured.

Deformation belts: Ridge and fracture belts are both present, but not as extensive as is the case in other quadrangles [e.g. 4, 5]. As is commonly the case, it is difficult to determine if the materials of these belts are older or younger than regional plains. A recent study using radar properties [6] demonstrated that at least most ridge belts appear to be older than regional plains. The materials of fracture belts probably are also older than regional plains, but the fractures themselves can be both older and younger than regional plains [e.g., 4].

Coronae: Three named coronae are present, but only Zemira Corona has significant associated flows. An interesting nearly linear structure extends from the fracture belt Breksta Linea in the western part of the quadrangle east-southeastward through Zemira Corona to Pasu-Ava Corona. The tectonic significance of this composite structure is unclear at present. A feature named Jaszai Patera is very likely another corona.

Volcanoes and shield flows: Volcanic materials and landforms are abundant in the Lachesis Tessera quadrangle. Small domes and shields are abundant and widespread. In places, small shields are not only exceptionally abundant, but are associated with mappable materials, and thus define a “shield flows” unit. Isolated flows are common, and where areally large enough they have been mapped as undifferentiated flows. Other volcanic features include two relatively large shield volcanoes, both with complete calderas and with flows extensive enough to map. A number of pancake domes occur in the Lachesis Tessera quadrangle.

Impact craters: The 13 impact craters in the Lachesis Tessera quadrangle range in diameter from 2.4-40 km. Four of these are doublet craters, while five have associated radar-dark halos or parabolas. Only 2 of the 13 are significantly degraded. All 13 craters are superposed on either regional plains or on flows that are, in turn, superposed on regional plains.
**Tectonic Analysis:** Important individual structural features identified within the Lachesis Tessera quadrangle include radar-bright lineaments, graben, and wrinkle ridges, all of which are abundant and pervasive. These belts vary widely in trend with respect to each other, and some also exhibit significant variations in trend within individual belts. In addition, there are broader ridges scattered around the quadrangle that may be isolated inliers within younger regional plains or else local folds involving regional plains—these alternatives commonly are not easy to separate [6].

Wrinkle ridges are locally abundant, and range in length from a few to scores of kilometers, but are generally less than one kilometer in width. The general interpretation is that these ridges formed approximately normal to compressive stresses in the shallow crust [e.g. 7; 8; 9]. The greatest abundance occurs in the northern and eastern parts of the quadrangle, particularly the portion that lies within Sedna Planitia, where the wrinkle ridges define a wavy east-west trend. This is similar to the wrinkle ridge trends in many quadrangles in the northern hemisphere [e.g. 7; 8; 9]. To the south and west, within Guinevere Planitia, wrinkle ridges are much less abundant. This distribution of wrinkle ridge abundances coincides approximately with local topography, expressed as RMS slopes.

The Lachesis Tessera quadrangle includes abundant, radar-bright, straight to arcuate linear features. Most of these are too narrow to define their geometries, but locally are wide enough to be resolved as graben. Thus most are inferred to be small faults or fractures of extensional origin. Individual linear and arcuate features range in length from the limit of detection (1-2 km) to hundreds of kilometers. In places, there are 2 trends of straight linear features at high angle to each other, defining a “grid” pattern. Where wrinkle ridges cross plains with gridded lineaments it is clear that the wrinkle ridges are younger than the grid pattern.

Shishimora Dorsa is a ridge belt centered at 39°N, 302°E that trends northeast and is some-what elevated relative to adjacent regional plains. Although dominated by ridges, the belt also includes radar-bright lineaments, possibly fractures, that have two distinct azimuths which define a pattern of parallelograms. The age of Shishimora Dorsa relative to adjacent plains materials is ambiguous.

Breksta Linea, centered at 34°N, 306°E, is a belt of closely spaced fractures and graben, most of which trend with about the same azimuth as the belt itself. The fractures appear to be younger than and also elevated relative to the adjacent regional plains.

Arguably the most interesting structural feature within the Lachesis Tessera quadrangle is a linear grouping of prominent structural belt, coronae, and coronae-like structures oriented NW to SE in the southern half of the quadrangle. This belt links Breksta Linea, Zemire and Pasu-Ava coronae, several small deformed coronae-like features, pancake domes and a putative corona. The highest elevation of the linear group is in the west, adjacent to a fracture belt in the Beta Regio quadrangle [10].

**Discussion:** The fragmented record of tessera and some deformation belts suggests that flooding by regional plains materials has had a significant effect on the distribution of materials older than the regional plains. This, in turn, indicates that regional plains must be relatively thin in the Lachesis Tessera quadrangle, or else the tessera and deformation belts exhibit less relief than generally is the case.

**References:**
UNDERSTANDING THE HISTORY OF A DIVERSE INVERTED FLUVIAL LANDSCAPE: 1:500K GEOLOGIC MAPPING OF THE AEOLIS DORSA REGION, MARS. D. M. Burr¹, R. E. Jacobsen¹, A. Lefort¹, R. M. Borden¹, S. E. Peel¹. ¹University of Tennessee, Knoxville, TN, 37996 USA (dburr1@utk.edu).

Introduction: This abstract summarizes our fifth and final year of work on a 1:500k USGS geologic map of the Aeolis Dorsa (AD) region, Mars [1-3]. The work plan presented in the Planetary Geologic Mappers Meeting of 2018 [4] for our first no-cost extension was accomplished, and the map has passed compliance review as described in section 6.5.2 of the Planetary Geologic Mapping Protocol – 2018 (PGMP) [5; see link]. This abstract summarizes the map and scientific findings, most of which preceded the past year’s technical completion of the map and so were presented in 2018 [4].

The AD region is located north of the Highland-Lowland Boundary (HLB), ~800 km east of Gale Crater, and south of the Cerberus lavas [Fig. 1A]. The primary motivation and focus of the proposed work was to investigate thousands of sinuous ridges, interpreted to be inverted fluvial features [6,7 and refs. therein]. The great diversity of AD landforms led to additional investigations of lacustrine, tectonic/collapse processes [8], and aeolian features associated with the Medusae Fossae Formation (MFF) [e.g., 4,9].

Scientific results: As noted in the 2018 summary of the scientific results associated with the mapping effort [4], analysis of local-scale stratigraphy and estimates of paleodischarges and paleohydrology of the AD deposits elucidate the history of ancient fluvial activity in the region. The global Martian hydrologic timeline, as represented by the inferred transition from older widespread valley networks to younger alluvial fans within craters, is represented in the stratigraphy of Aeolis Dorsa. In particular, this global evolution is shown in the AD region in the transition from wide meandering fluvial deposits and channel fills to alluvial fans [10-11 and refs. therein]. Close examinations of AD features and comparisons with terrestrial analogs suggest features in southern AD formed in the presence of weathered sediments [11]. The apparent absence of such features in the northern areas suggests enhanced weathering in the south, possibly caused by orographic precipitation near the HLB [6,11]. Additional research associated with this map entailed comparisons of meandering deposit morphomteries with those of terrestrial analogs, leading to improved accuracy and precision of empirical relationships for estimating paleodischarges on Mars [12]. Results from morphometric analyses and comparisons with terrestrial analogs suggest confounding factors in interpreting eroded fluvial landscapes [13]. Mapping in nighttime infrared data of a moderately bright unit located between the two plana suggests fluvial deposition by centripetal [14] and potentially southward flow.

Several large (>10km-diameter) craters in the trough between Aeolis and Zephyria plana preserve post-impact sedimentary deposits with branching ridges and layered outcrops [15]. Mapping and analysis suggest that these deposits are most consistent with deltaic and sedimentary deposition in lacustrine environments [15]. Local geologic mapping of these interplana crater deposits, along with analysis of their regional topographic setting, is focused on evaluating the possibility that these larger, lower-elevation craters hosted paleolakes and, if so, their potential water source(s).

The AD region exhibits numerous tectonic features [e.g., 8,10]. Aeolis Chaos, sitting ~1 km below the surrounding terrain and ~2 km below the southern highlands, separates AD from the highlands [Fig. 1B] and is interpreted to have formed by extension along the HLB [16]. Wrinkle ridges [10] have orientations that range between NW and NE, with this variability in orientation suggesting variability in the compressive stress field over the time of their formation [17]. Normal fault scarps are inferred locally on the interior (western side) of southern Zephyria Plana [18].

Mapping results: GIS files and the geologic map show six map unit groups with a total of 19 map units [Fig. 1]. Linear feature types were used to denote large crater, tectonic [e.g., 17], and fluvial features [11]; location feature types indicate small cones and craters.

These mapping results show Noachian to early Hesperian-age highlands moderately deformed by impact cratering, and, to their north, transitional units deformed by extensional tectonics [e.g., 16]. These units are inter-leave with aeolian and volcanlastic plana units (i.e., MFF). Fluvial deposition occurred with waning geomorphic effective during the Hesperian and Amazonian periods [4,14,18]. These fluvial deposits, and the potential lacustrine interplana deposits, were repeatedly buried by widespread aeolian and/or volcanlastic deposition (MFF), later exhumed by aeolian processes that formed yardangs and aeolian bedforms [e.g., 3,4,18].

Map package submission: A new basemap of blended CTX images was incorporated into the project [19], which required warping of GeoContacts and features to align with the new basemap. The map package, including the Description of Map Units and Correlation of Map Units [Fig. 1, right], is under technical review [18]. We look forward to responding to the reviews during the final few months of our No Cost Extension.

Acknowledgements: We appreciate the assistance of the Astrogeology Planetary Geologic Map Coordination Group throughout this process.

Figure 1: (A, below) Context image of MOLA topography. Black box north of southern highlands shows map area. (B, below) Aeolis Dorsa 1:500k map with geologic units (70% transparency) overlain on blended CTX mosaic [20]. Linear features, including scarp and crater crests and depression margins (in black with standard symbology), representative inverted fluvial and alluvial ridges (cretan blue with white diamonds; N=497 shown on map), and mapped wrinkle ridges (Mars red with black diamonds; N=35), are shown. For readability, location features, including pitted cones (N=93) and small craters (1-4 km dia.; N=19,677), are not shown in this figure, but are displayed on the accompanying poster, along with channels (N=35) and grooves (N=12). (right) Correlation of Map Units.
LEARNING PLANETARY GEOLOGIC MAPPING AS AN UNDERGRADUATE NON-MAJOR. K. S. Coles1, S. P. Fang2, V. A. Lewis3, C. S. McAdoo3, and C. J. Pagan3, 1Geoscience Dept., 2Management Dept., 3Biology Dept., all at Indiana Univ. of Pennsylvania (Indiana, PA, 15701 USA, kcoles@iup.edu).

Introduction: Planetary geologic mapping requires a host of skills, including searching out imagery and other data, preparation of a base image map at appropriate scale, and interpretation of geologic features and relationships. The resulting points, lines, and polygons form the basis for a geologic map in GIS or other format.

Because geologic mapping has always been a key method for teaching students to recognize and interpret rock relationships and history, it is part of the undergraduate planetary science course, GEOS 341, at Indiana University of Pennsylvania (IUP). Students come from various science majors, mathematics, and other fields such as business. Students studying to become secondary science teachers also take the course.

Project Format: Students are assigned an area on one of the terrestrial bodies. Over the course of several weekly lab periods they learn the basics of the mapping software, searching for images, and adding point, line, and polygon features to their map layers. They do a simple crater count on at least one map unit and interpret it in terms of a numerical timescale, if available (as for Moon [1] and Mars [2, 3]). Throughout this project, other activities give experience with mapping units by hand, crater counting, and manipulating digital images.

Software. Experience has shown that full-featured GIS software (such as ArcGIS) has a learning curve that is too steep for a multi-week lab project. The use of JMARS [4, 5] has proven practical, as it combines availability for multiple platforms, is easy to install on student-owned laptop computers, and has free documentation available. Once the basic map is complete and approved by the instructor, it is exported for final editing in a graphics program. The completed map may be presented either in digital or hard copy form.

Student and Instructor Experience: Once the technical challenges were addressed, this project proved to be a great addition to an undergraduate planetary science course. Students engage in geologic thinking on a more sophisticated and analytical level than they did with lectures and traditional labs alone.

One Biology Education major commented, "I found myself looking for similar geologic settings on Earth to what I was seeing on Mars. As a biologist, I would think about what exactly is going on in these locations on Earth that allows for life to thrive (or keeps it from thriving). I often wondered, if the conditions were just right, could life be found in an area of Mars like the one I was mapping?"

Among the improvements evident from this experience were that only 3 lab periods, not 4, need be devoted to working on the project; most work after this could be done outside of class. Additional experience looking at and analyzing images of geologic relationships and examples of geologic maps would strengthen student work. The added incentive of a public display of finished work, for example to a class of geology majors, is also a potential motivator that could be added to this project in the future.


Figure 1. Example of a student map, part of Ceraunius Fossae and the adjacent region. This example highlights the importance of interpreting onlap of lava flows, timing of fracturing and faulting, and extent of a particular unit.
**1:1M-SCALE GEOLOGIC MAPPING INVESTIGATIONS OF ALBA MONS, MARS.** David A. Crown¹, Daniel C. Berman¹, Stephen P. Scheidt¹, and Ernst Hauber², ¹Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson, Arizona 85719 (crown@psi.edu); ²Institute of Planetary Research, German Aerospace Center, Berlin, Germany.

**Introduction:** Two 1:1M-scale geologic maps of Alba Mons are being produced in order to document the volcanic evolution and geologic history of the northernmost volcano in the Tharsis region. We are using mapping of the summit region (32.5-47.5°N, 245-255°E) and western flank (37.5-47.5°N, 230-245°E) to characterize geologic processes and derive age constraints from cross-cutting relationships and crater size-frequency distributions. Mapping uses GIS software and analysis tools with THEMIS, CTX, and HiRISE images and MOLA and HRSC topography.

**Geologic Mapping Results:** Research to-date has produced detailed digitized map layers that show the distribution of and interactions between geologic features [20-27] (Figure 1). Systematic mapping of volcanic, tectonic, erosional, and impact features throughout the western flank map area has been completed. Preliminary mapping of volcanic, fluvial, and impact features has been completed for the summit and mapping of tectonic features is in progress. MOLA datasets (DEMs, slope maps, and derived curvature statistics) have been integrated into mapping to enhance topographic aspects of geologic features whose primary characteristics may be obscured by surface degradation or discontinuously defined.


![Figure 1. Maps of geologic features on the western flank (above) and in the summit region (next page) of Alba Mons shown over THEMIS IR daytime mosaic (100 m/pixel) merged with MOLA color topography (463 m/pixel) in Simple Cylindrical projection. Elevation range is -1969 - 6796 m. Blue = fluvial valleys, purple = lava flow margins, red = lava tubes (denoted by circular to elongate depressions), and black = various structural features. Impact crater materials outlined by dashed lines.](2019 Planetary Geologic Mappers 2019 (LPI Contrib. No. 2154) 7023.pdf)
Figure 1 continued: Alba Mons summit region
Introduction: The Valles Marineris canyon system contains some of the thickest, most laterally continuous, and diverse exposures of sedimentary rocks on Mars [1-7]. Understanding the dominant processes that led not only to the accumulation of these rocks but also the tectonic environment that provided the accommodation space for their deposition is critical to understanding currently unresolved geologic problems on Mars, including pre-, syn-, and post-tectonic processes of sedimentation as well as the geologic effects of long-term climate oscillations. Though the Valles Marineris system has been studied with a variety of datasets over the past several decades, the diversity in type and spatial resolution of modern datasets afford a renewed look into these deposits and how they fit together in space and time.

Sub-basins within the broader Valles Marineris system provide unique insight into the diverse tectonic, depositional and erosional processes that have occurred throughout the canyon, e.g. [5-9]. The informally named Melas basin, located in southern Melas Chasma in central Valles Marineris, is one such location. Melas basin is a ~34 km long enclosed basin that contains geologic units, dispersed landforms, and hydrated minerals that are indicative of punctuated episodes of aqueous activity spanning from the Hesperian to Early Amazonian [10-12]. However, despite being the focus of multiple historical and modern geologic investigations, this region has not yet been placed into a broader geologic, structural, and stratigraphic context.

The overall objective of this work is to characterize basin-forming processes and material provenance within the Melas basin, and to place the Melas basin into a broader geologic, structural, and stratigraphic context. This study will test the hypothesis that geologic processes were spatially and temporally variable across the basin, which implies that sub-basin architecture in the Valles system is more complex than previously recognized.

Geologic Setting and Background: Melas basin is a topographic basin that contains geologic units, landforms, and hydrated minerals that document an extensive history of tectonic, mass-wasting, and aqueous processes. Rocks that outcrop within Melas basin are predominantly stratified and are interpreted to have been emplaced during or after the Early Hesperian [4, 13, 14]. Dense valley networks are identified in the higher-standing margins of Melas basin and are interpreted to have been fed by precipitation [10, 15]. The valleys drain into a closed basin, which follows an elevation contour at -1800 m [10], as well as -2085 m and -2250 m [12] suggesting that there may have been up to three episodes in which a standing body of water occupied Melas basin during the Late Hesperian. The center of the basin exposes light-toned, laterally extensive layers, some of which show clinoform geometries that have been interpreted as either a channel-levee complex or a delta complex [16]. On the western side of the basin, flat multi-lobe fans have been interpreted as a deep subaqueous depositional fan system on the basis of channel properties and comparison with terrestrial fans [17]. Additional stratigraphic and morphometric analyses of fans have revealed a variety of depositional settings, including deep subaqueous, shallow subaqueous and subaerial environments, indicating fluctuations in lake level over centuries to several millennia [12].

Datasets and Methods: This investigation focuses on the production of a 1:150,000-scale regional geologic map of the Melas basin and surrounding terrain, along with the production of 9 detailed geologic reference sections mapped at 1:15,000-scale. The regional mapping scale was chosen to complement the existing detailed mapping of a portion of the Melas basin [18-19] and because it affords important contextual examination of geologic relationships. Regional mapping is based on a CTX mosaic that has been geo-referenced to the controlled THEMIS daytime IR mosaics [20]. The study region covers an area between lat -75.5 and -77.5 E. and long -8.9 and -10.4 N (Fig. 1). To produce a 1:150,000-scale regional geologic map, we are using a digital mapping scale of 1:30,000 and a vertex spacing of 30 m.

The 9 detailed map areas are based on HiRISE images (Fig. 2). To produce publishable maps at a scale of 1:15,000, we are using a digital mapping scale of 1:3,000 with vertex spacing of 3 m. These 9 locations were selected to capture the diversity of geologic features across the Melas basin, and to test hypotheses raised in a pilot study [21]. The 9 areas cover features including other small sub-basins, wall rock type sections, the relationship between plateau and wall rock units, basin floor and fan deposits, valley networks, convoluted bedding, and a range of sedimentary features within the Melas basin. After detailed geologic mapping, we will construct measured stratigraphic sections using HiRISE Digital Terrain Models to extract approximate bedding orientations. These stratigraphic sections will be used to evaluate changes in sediment supply and accommodation space, to further refine our understanding of the depositional history within the Melas basin.
LPI 2019

Summary of initial results: Preliminary mapping carried out here and in an initial pilot study have revealed diverse geologic units exposed on the plateau, wall rock, and basin floor. Regional geologic units can be divided into four distinct groups: wall rocks, plateau rocks, basin floor deposits, and surficial deposits. The weakly stratified nature of the wall rock outcrops could be interpreted as either sedimentary and/or igneous in origin. Wall rocks exposed on the northwest side of Melas basin have a more massive and heavily cratered expression that may suggest an origin as crystalline basement rocks. Basin floor deposits record a complex aqueous history. Consistent with previous work, we interpret the basin floor deposits to record fluvial, deltaic and lacustrine environments. Surficial units are interpreted as the product of eolian and mass-wasting processes. The absence of impact craters in most surficial units suggests that these are the product of relatively young and potentially still active processes. Further detailed mapping will refine these interpretations.

Ongoing Work: The next steps include:

- Continue 1:150,000-scale geologic mapping.
- Continue 1:15,000-scale geologic mapping.
- Construct stratigraphic sections and evaluate bed thickness distributions.
- Compile geologic history that places localized observations into a broader, standardized context for cross-comparison to other similar regions within the Valles Marineris basin system.

References:

PLANEY NOMENCLATURE: INFORMATION AND GUIDELINES FOR GEOLOGIC MAPPERS. Tenielle Gaither and James Skinner, Jr. USGS Astrogeology Science Center, Flagstaff, Arizona (tgaither@usgs.gov);

Introduction: The task of naming planetary surface features, rings, and natural satellites is managed by the International Astronomical Union’s (IAU) Working Group for Planetary System Nomenclature (WGPSN). The volunteer members of the WGPSN and its task groups have worked since the early 1970s to provide a clear, unambiguous system of planetary nomenclature that represents cultures and countries from all regions of Earth. WGPSN members include Rita Schulz (chair) and 8 other members representing countries around the globe. Since the 1980’s, the USGS Astrogeology Science Center has managed (for the IAU and with the financial support of NASA) the ever-growing database of planetary names, the online Gazetteer of Planetary Nomenclature. This abstract provides a summary of the program status as well as guidelines for geologic mappers.

Status: There are currently 15,548 non-terrestrial surface feature names in use for all planets, satellites, and small bodies. The average number of name approvals per year is 131. Requests for one or two feature names at a time are the most common, but years in which there are active missions to new bodies, or new higher resolution image data become available, can bring name requests containing dozens of features.

Purpose and Rules: Planetary nomenclature is a tool that helps to uniquely identify features on the surfaces of planets and satellites, so that they can be reliably located, described, and accurately discussed and compared within the scientific community. The names are particularly helpful in publication, including peer-reviewed geologic maps. Approved names are listed in the Transactions of the IAU [1] and on the Gazetteer of Planetary Nomenclature website [2]. Any names currently in use that are not listed in References 1 and 2 are not official.

Planetary names must adhere to rules and conventions established by the IAU WGPSN (see http://planetarynames.wr.usgs.gov/Page/Rules for the complete list):

- Planetary names should be simple, clear and unambiguous.
- Features should be named only when they are scientifically significant and when the naming is useful to the scientific and cartographic communities at large.
- Name duplication on two or more bodies is discouraged.
- Solar system nomenclature should be international in its choice of names.
- Names having political, military, or religious significance are not allowed.

Guidelines for Geologic Mappers: Standardized planetary nomenclature is particularly useful in planetary geologic maps. These names provide reliable points of reference for mappers to describe features, units, and histories. As such, planetary mappers are some of the heaviest users of planetary names. To facilitate the correct use of these names, mappers should continuously review the official nomenclature in their map area early in the mapping process, as all names in the map area must be shown on the published map (provided the map scale allows). To facilitate correct application of the nomenclature in GIS mapping, point shapefiles are available for download on each planetary body’s homepage. Polygon shapefiles will be available for select bodies (Mercury, Mars, Moon, Ceres, Io, Pluto) by June 2019. Online PDF maps of all current nomenclature for each body are available in the Gazetteer as well. Authors of geologic maps submitted for technical review are encouraged to use these resources for identifying and placing nomenclature. However, mappers should be aware that names should be scaled and extended across the associated feature, preferably as feature annotation in GIS (i.e., labeled point files are inadequate for technical review). USGS will assist with final placement but good faith efforts should be made to assist with placement of names.

Geologic mappers should also assess any implications of the nomenclature for the mapping. For example, if there is an approved crater name but no crater unit has been mapped, the mapper should consider whether a crater unit should be mapped. Likewise, feature types should be checked with the geologic units (e.g., if there is a dorsum name on a feature mapped as a fossa, the terminology should be corrected). Using the online nomenclature maps as a guide, the mapper should ensure that names...
are placed correctly, so that the positioning of each name shows the location and extent of the feature. The correct fonts must be used for each feature name (see Table 1).

<table>
<thead>
<tr>
<th>Nomenclature Fonts for USGS Geologic Maps</th>
<th>Times New Roman Italic</th>
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<tbody>
<tr>
<td>Albedo features</td>
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<tr>
<td>Arcus, arcēs</td>
<td>Corona, coronae</td>
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<td>Crater, craters</td>
<td>Dorsum, dorsa</td>
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<tr>
<td>Eruptive centers</td>
<td>Facula, faculæ</td>
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<td>Planitia, planitae</td>
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<td>Corona, coronae</td>
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<td>Labes, labēs</td>
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<td>Labyrinthus, labyrinthi</td>
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Table 1. Fonts used for different feature types in USGS-published geologic maps. Font sizes should be scaled to the size of the feature.

Only official names may appear on USGS-published maps. An official name should be requested for any unnamed morphological or topographic feature that will be a primary focus of the mapping and/or map text. New name requests should come as early as possible in the mapping phase, so that name proposals do not delay map production.

**Submitting a Name Request:** The Gazetteer includes an online Name Request Form (http://planetarynames.wr.usgs.gov/FeatureName Request) that can be used by members of the professional science community. A specific name may be suggested for a feature, but the name is subject to IAU review and there is no guarantee it will be approved. A published reference is required for each name (reliable web sites and scanned online books are permitted). Suggested names must also fit the approved theme for each feature type on each body (see http://planetarynames.wr.usgs.gov/Page/Categories). Requests to name a crater specifically to honor an individual rather than for scientific needs are not accepted.

Before submitting a name request, the online database and maps showing named features (http://planetarynames.wr.usgs.gov/Page/Images) should be consulted to confirm that the feature is not already named. If a specific name is included in the request, the database should also be checked to ensure the name has not already been approved for a different feature.

**Name Approval Process:** Name requests are first reviewed by one of six task groups (Mercury, Venus, Moon, Mars, Outer Solar System, and Small Bodies). After a task group has reviewed a proposal, it is submitted to the WGPSN. Allow four to six weeks for the review and approval process, but more time may be necessary if the proposal is complicated, multiple feature names are being requested, or if questions are raised during the review process. Name requests should be submitted well in advance of publication deadlines. Upon WGPSN approval, names are considered formally approved and it is then appropriate to use them in publications. Approved names are immediately entered into the database and shown on the website.

**Summary:** The USGS Planetary Nomenclature project supports ongoing planetary research and geologic mapping, and the participation of knowledgeable scientists and experts in this process is vital to its success. Questions about the nomenclature database and the naming process can be sent to Tenielle Gaither, USGS Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, or by email to tgaither@usgs.gov.

**Acknowledgments:** Funding for T. Gaither has been provided by NASA-USGS PSDI IAA.

Introduction: Pavonis Mons (1.48°N, -112.96°E) is the central edifice of the three Tharsis Montes volcanoes on Mars and is considered the most underdeveloped of the three [1]. Our 1:1,000,000-scale geologic map of Pavonis Mons investigates the spatial distribution of geomorphic units, interpreted as volcanic and glacial in origin [2]. This new geologic map, based on high-resolution CTX imagery from Mars Orbiter and informed by additional data sets from Mars Reconnaissance Orbiter and Mars Express, highlights the sequence of events and contrasting eruption styles and morphologies [3].

Our science objectives for this map are 1) determine the areal extent and distribution of different lava flow morphologies across Pavonis Mons to provide insight into the identified late Amazonian change in effusive style; 2) determine the areal extent and distribution of any glacial and aeolian deposits on the flanks and nearby plains and investigate their relationship to the lava flows; and 3) characterize the nature of presumed collapse and erosional features, such as rift zone graben and the channel networks, to determine their relationships to mapped volcanic features.

Figure 1. Extent of map boundary for the Pavonis Mons 1:1M geologic map (7.75°N to 3.1°S and 106.5°W to 123.0°W) MOLA hillshade.

Methods and Data: We have made updates to our project software, basemap, and map extent to take advantage of recently released data sets and conform the map to ongoing map projects for Arsia and Ascreaus Mons.

Software Update. Our mapping is now being completed in ESRI’s ArcMap 10.6.1, upgraded from 10.3.

Updates to Basemap. Our linework is now drawn on a CTX basemap, changed from THEMIS Daytime IR. We georeferenced 60 tiles of the uncontrolled global CTX mosaic (7 m/px) available from the Bruce Murray Lab at Cal Tech [4] to the controlled THEMIS Daytime IR mosaic (100 m/px).

Map Boundary. The extent of the mapping region (Fig. 1) was expanded to overlap with map boundaries for Arsia and Ascreaus Mons [5], plus cover the western extent of plains lava flows from Pavonis Mons that reach Ulysses Tholus and additional vents in the eastern small-vent field.

Geologic Mapping: The Pavonis Mons map has gone through multiple iterations in the last few months (Figs. 2, 3) to conform to revisions for Arsia and Ascreaus Mons and to correspond to the CTX basemap.

Map units. Our map units and features are geomorphic units, versus the traditional geologic units based on ages (Fig. 3). Map unit names correspond to specific regions (caldera, shield, apron, fan-shaped deposit, and plains). We are currently revising our description of map units to apply suggested revisions for the 1:1M maps of Arsia and Ascreaus Mons.

Point Features. Five unique features are mapped—cone (pitted), cone (rootless), fan apex, pit, and vent (volcanic), with the latter used for vents on low-shields. While a single ‘vent’ symbol could have been used, we wanted to differentiate between the geologic context and morphology of each.

Linear Features. Over 25 linear features are mapped, most traditional geologic structural features with solid and dashed versions to indicate certain and approximate for several of them. Our main change is to the symbology and naming for volcanic ridge crest types. We use a combination of red diamonds and line colors to distinguish between lava tubes, rootless cones, and raised, sinuous ridges. In addition, linear vents/fissures, ridge lines for features in the fan-shaped deposits, and wrinkle ridges in the caldera have unique symbols.

Geologic Contacts. Our two main contact types are certain and approximate (Fig. 2). Buried/concealed lines are used where the large tabular flow units are partially buried or the upper extent of a feature is concealed. The bold boundary line maps the boundary between flows that originate from the different volcanoes (Figs. 1-3). We draw our lines at 1:50,000 and use a stream tolerance of 250 map units.

Observations from Mapping: Some of our geologic observations based on mapping include: geologically recent eruptions from graben on the flank of the main shield feed extensive lava flows and tube systems...
in the lava plains. Extensive flow fields in the lava plains are traced back to single source areas. These flow fields were initially mapped as several individual map features, but CTX images revealed they were connected to a common eruptive event. We are still working on how to combine or subdivide the changes and transitions in flow morphologies associated extensive volcanic features to indicate they are different, but related. The boundary between flows from each volcano is elusive due to the overlapping nature of flow margins, though details of flow directions observed in CTX and contour lines have helped to constrain the contacts.

**Future Work:** We are finalizing the linework and supportive files (map text, COMU, DOMU) for submission to the USGS this year.

UPDATING THE GEOLOGIC MAPS OF THE APOLLO 15-16-17 LANDING SITES – YEAR 1.  W. B. Garry1, R. A. Yingst2, S. C. Mest2, L. R. Ostrach1 1NASA Goddard Space Flight Center, Greenbelt, MD 20771, brent.garry@nasa.gov, 2Planetary Science Institute, Tucson, AZ, 3USGS Astrogeology Center, Flagstaff, AZ.

Introduction: Our team is funded by NASA PDART to produce updated geologic maps of the Apollo 15-16-17 landing sites at a regional (1:200k) and landing site (1:24k) map scales. As part of the project, we will map craters to determine crater-age models for newly defined map units and renovate the original, pre-mission geologic maps of each landing site to LRO base maps in ArcGIS (Table 1). These pre-mission geologic maps of the Apollo landing sites preserve a unique moment in the history of human space exploration – the initial interpretations of the lunar surface prior to exploration by the Apollo astronauts. Our new maps will incorporate findings and interpretations from nearly 50 years of studies of the original Apollo data, surface observations, sample analyses, and recent remote sensing data.

Table 1. Summary of project goals

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
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<tbody>
<tr>
<td>Task 1</td>
<td>Digitize pre-mission geologic maps</td>
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<tr>
<td>Task 2</td>
<td>Create 6 new USGS SIM maps at 1:200k &amp; 1:24k</td>
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<tr>
<td>Task 3</td>
<td>Determine crater-derived ages for new units</td>
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Project Milestones – Year 1:

Task 1. Renovation of Pre-Mission Geologic Maps: We have renovated the regional geologic maps for each mission to LROC WAC 100 m/px mosaic: Apollo 15 (1:250k) [1], Apollo 16 (1:250k), and Apollo 17 [2], and Apollo 17 (1:250k) [3]. We created an ArcMap 10.6.1 projects for each map that consisted of a personal geodatabase with layers for nomenclature, map units, geologic contacts, linear/structural features, location features, and surficial deposits. LROC WAC, Clementine, and SLDEM data in Mercator projection were downloaded from the USGS Map-A-Planet website. High-resolution scans of the pre-mission geologic maps (300 dpi, *.jpg2000) available from LPI were cropped in Adobe Photoshop, saved as a *.tif, and imported into the ArcMap projects. Approximately 150-200 control points were used to georeferenced each original map to the WAC base maps. Linework was digitized at 1:10,000 with vector spacing at 50 m, following recommendations in USGS’s Standard Operating Procedures for GIS Digitization and Renovation to a New Base Map. Polygons were created from the geologic contacts layer and colorized to resemble the original map color schemes.

Task 2. Updating the Geologic Map of Apollo 15 Landing Site:

GIS Projects. The USGS has created individual ArcGIS projects for each regional and landing site map. The basemaps for the 1:24k maps include NAC mosaics (1.4 m/px), NAC DTM, and hillshade rasters. For the 1:200k maps, base maps include WAC 100 m/px, WAC color, SLDEM topography. Mapping layers for both the
1:24k and 1:200k projects include geologic contacts, linear features, location features, and surface features.

Apollo Stations and Traverse Routes. Collaborator Noah Petro provided shapefiles for the Apollo missions which included point locations of each landing site and science station, and line work for the traverse path of each EVA. These layers were added to the 1:24k maps.

Mapping. We have begun to rough in the line work for linear features for the Apollo 15 1:24k map (Fig. 3) to gauge the types of features that will be mapped and appropriate symbology.

Post-Mission Studies. The Apollo 15 Preliminary Science Report [4] included a sketch map of the local geology (Fig. 4), but no in depth geologic maps to use as primary reference for our project. However, there was significant discussion about the outcrops in Hadley Rille [4] and we will adopt a style used by [5] to map Rima Marius and apply it to our map of Hadley Rille. Additional studies are being reviewed for information about possible map units.

Figure 3. (Top) Original pre-mission geologic map of Apollo 15 landing site [x]. (Bottom) We have started to rough in the linear features for the new Apollo 15 1:24k landing site with traverse paths and stations.

Figure 4. (Left) The Apollo 15 preliminary science report only included a general sketch map of the landing site [4]. (Right) Mapping style for used for Rima Marius [5] that will be applied to Hadley Rille.

Task 3. Determine crater derived ages for new units: We will begin mapping the craters for each map project starting in year 2.

Note: New geologic maps of the Apollo 11, 12, and 17 landing sites have been produced by another research group unrelated to our project [6, 7].

LARGE-SCALE GEOLOGIC MAPPING OF SOUTHEAST NIA MENSA IN EASTERN CANDOR CHASMA, MARS. A. L. Gullikson¹, and C. H. Okubo¹, ¹USGS Astrogeology Science Center, 2255 N. Gemini Dr, Flagstaff, AZ, 86001, agullikson@usgs.gov.

Introduction: This abstract summarizes the current efforts in mapping the southeastern portion of Nia Mensa using a High-Resolution Imaging Science Experiment (HiRISE) [1] stereo pair for high-resolution structural and geologic mapping.

The goal of this work is to better understand the evolution of eastern Candor Chasma and the sedimentary deposits within. Our mapping effort is focused on the southeastern edge of Nia Mensa (fig. 1), where both landslide deposits from the southern wall of Candor Chasma and stratified sedimentary deposits have been observed. We plan to identify and characterize all stratigraphic units, and work to determine the origin of the sedimentary units within our mapping area.

Layered deposits within Valles Marineris remain enigmatic in their origin. Currently, there are two main hypotheses that address the formation of these deposits in relation to Valles Marineris. 1) Layered deposits predate the formation of the chasmata. Hesperian-aged plains materials and Noachian-aged bedrock of layered deposits were cut into by the forming chasmata, subsequently exposing the preexisting layered materials [e.g., 2-4]. 2) Layered deposits formed concurrently and possibly after the formation of the chasma. The layered deposits then are estimated to be Hesperian to Amazonian in age, emplaced over Noachian-aged bedrock [e.g., 5-8]. By using HiRISE imagery for our mapping purposes, we can identify subtle features and unit relationships that were not possible using lower resolution data. As we map this area, we will work to identify onlapping relationships, distinctions between layered deposits and landslide debris, and estimate relative ages in order to further develop these hypotheses.

Methods: The primary datasets used for our mapping purposes are two HiRISE stereo pairs (23 cm/pix) (ESP_039749_1720 and ESP_039604_1720). A 1-m post spacing Digital Terrain Model (DTM) was extracted from these and subsequently used to orthorectify the associated HiRISE images [10]. The map area is defined by the bounds of the stereo pair. For geologic context and regional stratigraphic relationships outside of the map area, Context Camera [11] observations and Mars Orbiter Laser Altimeter mosaic [12] were used.

We are mapping allostratigraphic units (defined by unconformities at their upper and lower contacts). Allostratigraphy is used because at HiRISE scale, bounding unconformities can be directly observed, are the most prominent stratigraphic divisions, and are mappable in a systematic way.

Current results: Our mapping area represents a unique confluence of debris flows, interior layered deposits, and aeolian bedforms.

Aeolian bedforms are located throughout the map area in local depressions. Where these bedforms thicken and mask the underlying bedrock we have mapped them as their own unit. Along the western edge of the map are interior layered deposits. These deposits are medium-toned, and form a smooth, undulating erosional surface. Near the southern edge of this unit appears more eroded and rugged, no longer displaying the relatively uniform layers. Numerous medium-light toned yardangs extend through the central-eastern portion of the map. These yardangs are comprised of thinly bedded layers and erode to form terraced slopes (fig. 2). The western-facing slopes tend to be steep (~30°) and have been smoothed by wind erosion. The terraced slopes on the eastern-facing sides are much broader, and therefore has better exposures of the layered stratigraphy. On the northeastern slopes of several yardangs are remnants of younger material draping over the layered yardangs (fig. 3). The younger unit extends over the top of the layered yardangs and drape down the slopes as thin ridges.

The highest point on the map are the layered deposits along the western edge (i.e., 2045 m). The yardangs to the east sit in a localized high (~1640 m in elevation), and as the yardangs taper off both to the north and south, the floor lowers in elevation (i.e., 1020 and 1000 m, respectively).

We are now working to finish mapping unconformities and will begin to delineate geologic units and identify relative timing between sedimentary layered deposits and erosional processes (i.e., debris flows).

Figure 1. HiRISE colorized DTM of map area outlined in blue. Red indicates high elevation and blue/purple is low elevation. HiRISE footprint is overlain onto a CTX mosaic. Image in upper right corner is a MOLA colorized layer overlain onto THEMIS Daytime IR, and shows location of map (blue rectangle) in reference to east Candor Chasma.

Figure 2. Example of a yardang in the mapping area. White arrows point to slope terraces and orange arrows point to finely bedded layers.

Figure 3. Remnants of younger material draping over finely bedded yardangs. Blue arrows point to beds that comprise the yardangs. Yellow arrows point the narrow ridges that drape down the northeastern slope of the yardangs.
GEOLOGIC FEATURE MAPPING ON ASTEROID (101955) BENNU TO INFORM SAMPLE SITE SELECTION ON THE OSIRIS-REx MISSION. E. R. Jawin, K. J. Walsh, T. J. McCoy, H. C. Connolly, Jr., O. S. Barnouin, E. B. Bierhaus, K. N. Burke, C. A. Bennett, D. N. DellaGiustina, B. E. Clark, M. C. Nolan, H. L. Enos, D. S. Lauretta, and the OSIRIS-REx Team. 1Smithsonian National Museum of Natural History, Washington, DC (jawine@si.edu), 2Southwest Research Institute, Boulder, CO, 3Rowan University, Glassboro, NJ, 4Applied Physics Laboratory, Laurel, MD, 5Lockheed Martin Space, Littleton, CO, 6Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, 7Ithaca College, Ithaca, NY.

Introduction: The OSIRIS-REx asteroid sample-return mission is currently investigating the primitive B-type asteroid (101955) Bennu [1]. Preliminary analyses of Bennu show it to be a rubble pile asteroid rich in hydrated materials and boulders [2-5]. Geologic analyses of Bennu showed that it has experienced a diverse history which has created various geologic features including impact craters, linear features, and boulders [5, 6]. At the time of the meeting the mission will be in its Orbital B phase [1]. Current observations will feed forward to inform sample site selection occurring in July 2019, with sample collection in July 2020. It is a priority to collect a sample of surface regolith that can address fundamental scientific questions about the origin and evolution of Bennu.

Sample Site Selection: The ongoing remote sensing analyses and geologic mapping all feed forward to support the sample-return objective of the mission. Coordinated observations will contribute to four thematic maps that each address a different aspect of sampling logistics: Deliverability, Safety, Sampleability, and Science Value [1]. Deliverability addresses whether the spacecraft can maneuver to a given sample location; Safety ensures the spacecraft and sampling head will not become damaged during contact with the surface that would prevent successful sample return; Sampleability addresses whether a sample site will permit at least 60 g of regolith to be collected; and Science Value ensures the sample site contains materials that provide maximum likelihood of returning pristine carbonaceous regolith [1].

Geologic Feature Mapping: Global mapping of geologic features is critical for both Sampleability and Science Value. The Sampleability map identifies optimal sampling locations by quantifying the expected mass of regolith that would be collected there [1]. Critical to this assessment is the identification of deposits of regolith on the surface, as well as the distribution of resolvable particles at all sizes (cobbles to boulders). Regolith deposits are generally free of large particles too large to be ingested by the sample head, and are important for initial sample site assessment. Maps of boulder locations are useful for first look assessments of potential sample sites, while calculations of the size-frequency distribution of particles will help generate average grain size maps at sample site-scale resolution.

Inputs to the Science Value map include global maps of four types: (Chemical Composition, Mineralogy, Geological Features, and Temperature) to identify a sample region that contains fresh surface material that has not experienced extensive space weathering and/or impact events [7]. Geologic feature maps are used as a proxy to indicate potential freshness of a region, and are ranked in order of priority: proximity to an active particle ejection site is of highest priority, as that region may contain very recently exposed material; the next-highest priority is space weathering; then particle size-frequency distribution (mapped as rocks); brittle deformation (mapped as linear features); and finally crater materials [7]. The four Science Value inputs will then be integrated to create a “treasure map” – an aid in sample site assessment.

Teams of researchers are currently tasked with identifying and mapping the distribution of geologic features on Bennu. Mapped features include boulders, craters, linear features, regolith, and particle ejection sites (these locations are determined by following particle motion vectors back to the surface, and up to now the surface locations are not unusual in any way). Current geologic feature maps show a diverse suite of geologic features that are globally distributed (Figure 1) [6], indicating a prolonged geologic history with low resurfacing rates. The high concentration of crater candidates on the equator suggest that the equatorial ridge may be one of the oldest regions on the surface [6], while several longitudinal ridges and grooves suggest that Bennu contains a degree of internal strength and cohesion [5]. The source and nature of particle ejection events are being actively investigated [8]. We are currently assessing specific areas on the surface of Bennu to determine locations of abundant regolith ingestible by the sampling mechanism (≤2 cm) and for Science Value. Primary and secondary sites will be selected by the Science and System Engineering teams in mid-July 2019. Hence, this is a very active time for creating 2D and 3D maps of a multitude of asteroid properties.

Acknowledgments: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program.

Figure 1. Mapped distribution of geologic features on Bennu. Cyan: linear features, red: crater candidates, yellow: particle ejection sites.
GEOLeIC MAPPING OF ATHABASCA VALLES, MARS: NOW AND AGAIN. L. P. Kesztelyi, J. Laura A. E. Huff, and W. L. Jaeger, USGS Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ. 86001 (laz@usgs.gov).

Introduction: The geologic mapping of the Athabasca Valles region of Mars (MTM quads 05202, 05207, 10202, 10207) was submitted for review in mid-2018 and, as of this writing, we are addressing recently received comments from the reviewers. While originally proposed in 2006 as four separate USGS SIM products at 1:500,000 scale, it was decided that it is more helpful to publish this as a single map at 1:1,000,000 scale.

We are also proposing to use this area in FY20 to test the hypothesis that controlled CTX mosaics would significantly aid high-resolution geologic mapping at certain scales. Okubo [1,2] finds that controlled CTX was not essential for mapping at 1:150,000 scale but mapping done at 1:18,000 scale on overlapping HiRISE images did not extend past the coverage of those images. It is plausible that detailed mapping at ~1:50,000 scale over areas larger than HiRISE images, but smaller than an entire MTM quadrangle, would significantly benefit from a base of controlled CTX images.

Mapping Methodology: The scientific focus of this mapping effort is on the extremely recent (i.e., Late Amazonian) volcanism in and around Athabasca Valles. Mapping on the controlled THEMIS daytime IR base-map was augmented with MOLA, CTX, and HiRISE data. Many of the key lava flow contacts are not readily apparent in the THEMIS data and are ambiguous even at CTX resolution. Therefore, we used HiRISE data to determine the nature of flow contacts and CTX data to map them.

Given the extremely young and pristine lavas that dominate this map region, an attempt was made to strictly map lithochronostratigraphic units – i.e., units delineated on the basis of (1) lithology, (2) age, and (3) stratigraphic position (Table 1). While this is the norm in terrestrial geologic mapping, it is often not practical in planetary geologic mapping. Even in this area the lithologic and age constraints become progressively poorer with age. This mapping methodology does violate some cherished traditions in planetary geologic mapping. Perhaps most jarring is that impact craters are considered to be a form of modification of map units as opposed to being a distinct map unit. The extreme level of detail in the presented stratigraphic relationships between the young volcanic units was also disconcerting to the reviewers.

We considered displaying facies variations within lava units but found this impractical at the 1:1,000,000 scale. Instead, we chose to set the coloring of map units transparent enough to allow surface textures visible in the THEMIS basemap to show through. Arrows indicating the flow directions help the reader discern the kinematic interpretation of rafted crustal plates and other features that are prominent in the THEMIS data. The downside of this decision is that it highlights the fact that the contact relationships that are visible only in HiRISE/CTX data do not follow the features visible in the THEMIS basemap.

Geologic Summary: Noachian Period. Remains of the highly cratered ancient surface of Mars are present in the map area in the form of patches of cratered terrain and isolated massifs at the southern end of the Tartarus Montes (eNtm). This rugged terrain was extensively degraded into colluvium that is interpreted to be part of the widely mapped Nepenthes Planum Formation (lNnp) [2-5].

Hesperian–Amazonian Transition. The region seems to have been quiet through much of the Hesperian but geologic activity picked up in the Late Hesperian and Early Amazonian. Lavas from the Elysium Rise (AHer) covered the northern part of the map area and a prominent set of NW–SE trending wrinkle ridges formed. At about the same time, the Medusae Fossae Formation (AHmf) began to be laid down in the southern part of the map area. There is strong evidence that this formation has temporally distinct members in the map area but we have not been able to confidently map their extents. However, as described below, the youngest portion of the AHmf must be broken out in our stratigraphy. Our observations support previous interpretations that the AHmf is reworked and subsequently cemented pyroclastic material [6-8].

Late Amazonian. Atypically for Mars, the most vigorous geologic activity has taken place in the last epoch. The lavas of the Cerberus Tholi (IAct) form a textbook example of plains volcanism [9] with intercalated low shields and flood lavas. We are able to discern thirteen separate eruptive episodes that are classified as members of this formation. The volcanism in the region was capped with the cataclysmic emplacement of the Athabasca Valles Basalt (lAav) as a turbulent flood. Curiously, there is a significant deposit of AHmf atop this most recent lava which may be reworking of older AHmf [8] or deposits of pyroclastics from the fountains that fed the lAav.
Future Work: The unanswered geologic questions in this region range from the Noachian to latest Amazonian. We are specifically interested in investigating (1) the possible role of aqueous fluids in the degradation of the Noachian terrains (conversion of eNtm into lNnp); (2) detailing the time evolution of eruption style and vigor of the recent volcanic activity in this region; and (3) the relationship between the Medusae Fossae Formation and the Athabasca Valles flood lava.

We expect that these questions can be addressed with high-resolution geologic mapping. We observed interesting features and relationships in the CTX and HiRISE images that could not be represented at the 1:1,000,000 map scale. The misalignment of the CTX data was sufficient to frustrate mapping at the more appropriate 1:50,000 scale. Controlled CTX data should enable such mapping of key regions within this map area.

We are currently working to control >500 CTX images from this area. For FY19, the goal is the develop methods and procedures that could be used to create a global controlled CTX data product. However, creation of such a product would take years of effort at considerable cost to NASA. An uncontrolled global CTX mosaic is already available [8] and we need to establish if the cost of controlling CTX adds sufficient value to justify the cost. Our proposal for FY20 is to conduct 1:50,000-scale mapping of selected areas using the uncontrolled and controlled CTX data to ascertain if there is a substantial difference in the geologic interpretations.

The Athabasca Valles region seems especially well-suited for this investigation. We hope to present those results at next year’s mappers’ conference.


<table>
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<tr>
<th>Unit name</th>
<th>Unit symbol</th>
<th>Lithology</th>
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<th>N(5)</th>
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<td>Volcaniclastics</td>
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<td>Basalt</td>
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<td>0</td>
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Table 1. Characteristics of geologic units in the map region: areas, crater densities, and superposition relations. *Based on crater-density boundaries as determined by Werner and Tanaka [11]. A, Amazonian; H, Hesperian; N, Noachian; e, Early; m, Middle; l, Late. **<** indicates “younger than”, ***~*** indicates “overlaps in time with”, and ***>*** indicates “older than”. Only adjacent units listed.
Tectonics of Earth: octahedron frame and antipodean continents and oceans
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Approximation of the Earth’ globe by various polyhedrons is practiced rather long ago [1]. Because behind these constructions occur various regularities, periodicities, symmetries in disposition of terrestrial objects, all proposed figures are not fantasies but more or less objective reflect structural peculiarities of the planet. Now one may definitely state that at the base of these spatial regularities and symmetries lie wave processes. Their essence is in regular recurrence of phenomena. Stational inertia-gravity waves warping terrestrial spheres (this concerns all celestial bodies) and propagating in them along 4 ortho- and diagonal directions, appear in them due to applied orbital energy because celestial bodies move in non-round keplerian orbits implying periodically changing acceleration and curvature. Interference of the various directions waves leads to formation in planetary spheres regularly changing uplifting (+), subsiding (-) and neutral (0) tectonic blocks of various sizes. The sizes depend on the wave lengths. So far as any body is warped by waves of various lengths, starting from the fundamental one long as the great planetary circle, its overtones and individual waves (their lengths depend on orbital frequencies), then various geometric figures inscribed in a globe can exist.

Always present fundamental waves (long 2πR, where R is a body radius) are responsible for the tectonic dichotomy of celestial bodies (Theorem 1[2]), their first overtone (πR) gives tectonic sectoring – tectonic octahedron (Fig. 1, 2)[Theorem 2, [2]). The individual characteristic waves, lengths of which are inversely proportional to orbital frequencies, produce tectonic granulation making various polyhedrons (Theorem 3 [2]). The characteristic terrestrial wave connected with the frequency 1/1 year has length πR/2 giving in the great circle alternating 4 tectonic bulges (+) and 4 holes (-) with length of πR/4 (cross-like configuration). With this peculiar wave warping is connected the figure cube manifestation of which in geospheres were noted by several authors [1 and others]. Vertexes, edges and faces of cube coincide with real very characteristic elements of the geospheres tectonics [1] but has no direct relation to their main structural blocks – continents and oceans. The wave tectonics for the first time shows and explains that the main tectonic blocks of Earth – continents and oceans are the elements of the octahedron frame of Earth. Become clear the typical sizes of these blocks (sizes of the octahedron faces) and remarkable regulation in their position on Earth. The chaos in their disposition is seeming.

An octahedron made by interference of waves 2 of 4 directions is observed in all celestial bodies [3]. Six antipodean vertexes of the Earth’s octahedron (1. New Guinea – 2. Equatorial Atlantic; 3. Easter Isl. – 4. The Pamirs-Hindukush; 5. Bering Strait – 6. Bouvet Isl.) are placed in zones of the equator, tropics and the polar rings, thus indicating a cosmic orientation of the octahedron. Thus, the principal structure of Earth is caused by its cosmic movement (“orbits make structures”) [4]. Orbits make structures, that is a combination of +, - and 0. This combination determines position in cosmos of the rotation axis, as this imaginary line has a zero angular momentum and it is formed by the whole sum of variously uplifted tectonic blocks of a rotating body. The rotation axis can by jump change its position in a body when blocks rapidly change their tectonic sign (an essence of the standing wave). It is known that the Earth’s axis was changing its position a body when blocks rapidly change their tectonic sign (an essence of the standing wave). And it is formed by the whole sum of various geometric figures inscribed in a globe.

The Earth’s structural octahedron also has other regularities related to its wave nature. To each of the six vertexes gather four faces-sectors by certain algorithm (Fig. 3). Always there is an opposition of two variously uplifted sectors separated by two variously subsided ones. By the tectonic “bisectors” the sectors are divided in two hypsometrically and tectonically different subsectors. To the relatively uplifted subsector is opposed relatively subsided subsector in the opposite sector and vice versa. This also confirms the wave nature of the global structurization.

In the New Guinea structure (Fig. 3, 1) oppose Indonesian (++) and Melanesian (+) sectors separated by Pacific (- -) and Indoceanic (-) ones. In the Atlantic structure (Fig.3, 2) oppose African (++) and South-American (+) uplifted sectors separated by North-American (- -) and South-Atlantic (-) ones. In the Easter sector (Fig. 3, 3) oppose NE (++) and SW (+) sectors separated by NW (- -) and SE (-) ones. In the Pamirs-Hindukush sector (Fig.3, 4) oppose African-Mediterranean (++) and Asian (+) sectors separated by Eurasian (-) and Indoceanic (-) ones. In the Bering structure (Fig. 3, 5) oppose Asian (++) and North-American (+) sectors separated by Pacific (- -) and Arctic (North ocean) (-) ones. In the Bouvet sector (Fig. 3, 6) oppose African (++) and Antarctic (+) sectors separated by Indoceanic (- -) and South-Atlantic (-) ones.

On every of 8 faces of the octahedron there are 3 sectors as a face has 3 vertexes. Naturally, that every face summarizes whether (+, +) or (-, -) but amplitude of uplift or subsidence is different: every face has an individual sum of + or -. The African face (6+) is antipodean to Pacific (6-); the Asian (5+) to South-Atlantic (3-); the North-
American (4+) to Indoceanic (5+); the Antarctic (3+) to North-Atlantic (4-). The sharpest contrast is between antipodean African (6+) and Pacific (6-) faces, the smallest between Antarctic (3+) and North-Atlantic (4-). Thus, the structural octahedron has different signs (uplift or subsidence) of antipodean vertices and faces that reflect its wave nature. This might be called “quantum tectonics”. Long ago noted intriguing opposition of Arctic and Antarctic is, thus, result of the wave structurization. The Arctic-Antarctic symptom is shown in all cosmic bodies and especially in small bodies with rather characteristic opposition of sharp and blunt ends [5].

Thus, the main tectonic blocks of Earth – continents and oceans are made by waves 1 and 2. There is significant regularity, antipodality in their disposition due to their relation with faces of the structural octahedron. Small continent Australia and subcontinent Hindustan not like other continents belongs to the strongly subsided Indoceanic face. This is reflected in their on the whole low hypsometry, proximity of the relatively dense (ferruginous) mantle and, as a result, specific metallogeny.

The wave structurization of celestial bodies acquiring properties of polyhedrons compel us to remember the I. Kepler’s explanation of twinkling stars by their polyhedron shape. This idea of the great scientist was not taken seriously and is not estimated up to now. In essence, Kepler was right.

References:

Fig. 1. Earth’s octahedron; Fig. 2. Octahedron sectors (thick lines) and their inverse reflection in the core-mantle boundary [6]; Fig. 3. Sectors and subsectors around the octahedron vertexes.
RECOGNIZING STRATIGRAPHIC DIVERSITY THROUGH 1:10,000 SCALE GEOLOGIC MAPPING OF NORTHWEST AEOLIS MONS, MARS

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Introduction: As the Mars Science Laboratory (MSL) Curiosity rover ascends the northwest flanks of Aeolis Mons (informally known as Mt. Sharp) in Mars’ Gale crater, it has the opportunity to conduct in situ investigations of the diverse array of sedimentary units noted previously from orbital imagery. Measurements taken on the ground allow researchers to better constrain the validity and significance of orbital observations. Yet, in order to fully gauge how in situ observations may be used to ground truth orbital observations, it is imperative to generate geologic observations at multiple scales.

In this study, we bridge the gap between MSL planning-related targeted observations (1:500 scale) [1] and previously-derived geologic maps for Aeolis Mons (i.e. [1–7]) by producing a detailed 1:10,000 scale geologic map of a ~70 km² area of the mound’s northwest flank. This map area is comformable with previous 1:10,000 scale mapping efforts to the north [8].

As noted in previous studies [1-12], the region contains prominent alluvial deposits and distinct channel incisions, as well distinct finely bedded outcrops, which mark it as a prominent example for studying past conditions and depositional settings on Mars’ surface.

Figure 1. Gale crater is ~154 km in diameter. This study’s map area is outlined in red and centered at 137.3179° E, -4.8770° N. The Black ellipse represents the MSL landing ellipse (adapted from NASA/JPL).

Methods:

This work advances our knowledge of Aeolis Mons stratigraphy by mapping a continuous section from the lower moat to the upper high-albedo unit at an intermediate scale. Digital mapping was carried out at 1:2,000-scale to produce a publishable map at 1:10,000-scale. This ~70 km² section, located approximately 5 km south and east of the planned MSL ascent route, offers well-exposed outcrops of the diversity of geologic units and alteration surfaces thereby providing important context for the strata that may eventually be investigated by MSL.

Mapping was conducted using 25 cm/pixel Mars Reconnaissance Orbiter High-Resolution Imaging Science Experiment (HiRISE) [13] imagery. A 1 m/pixel Digital Terrain Model produced from HiRISE stereo pairs was used as well to help identify the lateral extent of units, as well as calculate the strike and dip of bedding planes. Strike and dip measurements were acquired using the LayerTools ArcMap extension[14].

Thermal Emission Imaging System (THEMIS - ~100 m/pixel, 6.78-14.88 μm, ~1 μm/band) [15] spectral observations provided further characteristics for differentiating between units. Thermal inertia (TI) derived from THEMIS nighttime infrared observations yielded thermophysical information that was used to determine transitions in unit properties. Daytime THEMIS data (decorrelation stretch) provided a multi-band map that was used to identify changes in mineralogy. Key criteria for identifying geologic unit boundaries included major transitions in surface albedo, texture, thermal inertia, mineralogy, bedding structure and elevation.

Figure 2. HiRISE imagery with example LayerTools strike and dip calculation. White crosses indicate locations of measured points along individual beds. Most bedding is gently dipping to the north.
Summary:

Based on relationships elucidated by this 1:10,000-scale map and prior works, we summarize and confirm geologic observations and interpretations for this representative vertical section of the mound.

Figure 3. Top: THEMIS daytime IR on CTX background showing mafic minerals in yellow-green, sulfate-bearing material in pink and spectrally sloped material in blue. Bottom: qualitative TI.

This map exposes lateral variation in post-lithification process for some units, demonstrates evidence for multiple erosion-deposition episodes, and exposes some of the major variations between units adjacent units, signifying distinct environmental changes and depositional mechanism changes over time.

There is evidence for:

- Lacustrine and/or aeolian deposition was interspersed with ash fall events (marker beds) in the mound’s construction.
- Episodic fluvial and/or aeolian regimes that led to vigorous erosion, evidenced by gullies, channels and yardangs.
- An up mound water source, such as melting ice, localized rain or groundwater that likely produced diagenetic alterations and induration.
- A highly cohesive (high TI) mantle that originally overlay some of the mound, but has since eroded to the mound’s base, as evidenced by dip measurements and unit contacts.
- Bright aeolian deposits higher in the mound that unconformably overlie previously eroded and cratered sediment.

Through detailed geologic mapping this work identifies a number of new units in the lower mound that may indicate more variability in the depositional and erosional history than previously identified. This work provides observations that may be used to further support ongoing science at the central mound within Gale crater.

References:

GEOLeGIC MAPPING OF EUROPA AT GLOBAL AND REGIONAL SCALES. E. J. Leonard1,2, D. A. Patthoff3, and D. A. Senske1 1Jet Propulsion Laboratory, California Institute of Technology (Erin.J.Leonard@jpl.nasa.gov; David.a.senske@jpl.nasa.gov), 2University of California, Los Angeles, (erinleonard@ucla.edu) 3Planetary Science Institute (apatthoff@psi.edu)

Introduction: Evaluating the potential habitability of Europa requires an understanding of the geology that drives the interaction between the surface and the deeper interior of the body. To this end, we have constructed a global geologic map at the scale of 1:15M (Fig. 1) [1]. To provide greater insight into the broad global stratigraphic relations, we are currently mosaicking and mapping, with a consistent set of units, ~10% of the surface imaged at the 100-220 m scale placed in the global-scale context (Fig. 1 and 2). In this paper, we discuss the general results of our global mapping and preliminary results from regional scale mapping of the Canamara Chaos region.

Europa Global Geologic Map: Our geologic mapping [1] has established four primary global material unit types, crater material, chaos, bands, and regional plains (Fig. 1). These units are divided into geologic subunits: (1) continuous crater ejecta (ce) and discontinuous crater ejecta (dce), crater ray material (cr), and central peak structure (cp)—materials associated with impact craters including the primary impact crater (c) and its local deposits and farther ranging ejecta material; (2) various morphological types of chaos materials identified as high albedo chaos (chh), mottled chaos (chl) and knobby chaos (chk). Small (10 to 75 km in diameter) disrupted terrains, microchaos (mch), possess textures that vary, relative brightnesses that range from high to low, and are ubiquitous and significant enough to be identified on the map as a point; (3) Bands (b) are linear to curvilinear belts that are greater than 15 km in width and can have a distinct, abrupt relative brightness change from the surrounding region; and (4) regional plains (pr)—high-albedo, compared to the surrounding terrain and smooth at global resolution. We also identify structures which are too small be mapped aerially but are significant enough to be mapped with linear features (Fig.1).

Based on the relationships among the various map units, we have established a general stratigraphic chronology for Europa. The first and oldest period is dominated by the formation of regional plains, ridgets, and undifferentiated linea, an epoch characterized by ridge building processes. The second, or middle, period is dominated by band and undifferentiated linea formation. The band unit generally appear younger and cross-cut the regional plains unit. Cycloids also appear to have formed during this period. The third, and most recent period, is dominated by chaos terrain formation including the emplacement of microchaos. At the global-scale, chaos terrain does not appear to have any cross-cutting units besides craters and their ejecta, troughs in the northern leading hemisphere, and potentially depression margins. Likewise, microchaos is observed breaking up previously formed bands, ridges, cycloids and other features, indicating that it is generally younger.

Geologic Map of the Conamara Chaos Region: Extending our mapping to the regional scale in Conamara Chaos (Fig. 2), initial results [2] provide greater insight into the regional plains unit by establishing relations between assemblages of key tectonic terrains. The regional units consist of: Wide bands (bw) made up of parallel ridges spaced between 550 m and 1.25 km apart. The overall width of the band assemblages ranges from 4 to 10 km; Bands (b) that are made up of several sets of parallel ridges spaced between 525 m and 950 m apart with individual bands ranging in width between 2 and 4 km (narrower than wide bands); Double ridges (rd) that are composed of two distinct parallel ridges separated by a central trough; and fractures (f) that are single troughs that lack discernable raised rims. Fractures are typically linear, through going, and cross cut most other units. Other geologic units include: Chaos (c) which are complex regions 10s to over 100 km across composed of disrupted pre-existing crustal blocks and a smoother “matrix” material between the outcrops and microchaos (mch). In comparison with the global units, the regional plains and band units can be subdivided into a wider array of outcrop units allowing for a more detailed set of stratigraphic relationships to be identified.

Future Work: The global map will have been revised and resubmitted to the USGS by May 2019. Our regional-scale mapping will include the generation of new mosaics of the regions labelled A to G in Fig. 1, defining a consistent set of regional-scale units for use in all areas [e.g. 4] and incorporation of each region into the global context. The results will provide greater insight into how the icy crust of Europa formed and evolved.

Figure 1. Global geologic map of Europa and unit descriptions [1]. Regional plains and chaos make up 53% and 40% of the surface respectively. The areas being mapped at the regional scale are labelled A to G. The Conamara region (“C”) is shown in detail in Figure 2.

Figure 2. (a) Global base image showing the Conamara Chaos region. The black polygon outlines the location of regional-scale images. (b) Global-scale geologic map of the Conamara Chaos region showing that it contains ridge plains, distal crater ejecta, microchaos and numerous lineaments. (c) Regional-scale mosaic of the Conamara Chaos region and corresponding geologic map (d). Many of the ridge and band units are distinct stratigraphic markers allowing greater detail of the history of this region to be determined. In comparison with regional-scale mapping of the leading and trailing hemispheres [3] similar assemblages of units are identified in both areas.

Introduction: Neptune’s moon Triton (Fig. 1) was imaged with high resolution in 1989 during the Voyager 2 encounter. Triton was revealed to be a geologically active moon [1], and its very young surface has been linked to its dynamical history as a captured Kuiper Belt Object (KBO) [e.g., 2] as well as a potential ocean world.

Triton is a unique world that bridges a gap between KBOs and icy satellites as well as member of an ice giant system rather than the more well characterized gas giant systems. As a likely KBO captured into Neptune’s orbit [e.g., 2] Triton contributes to the diverse population of icy satellites, but its origin is unique relative to those of the icy satellites and likely contributes to its young surface and exotic terrains (Fig. 1) [3]. The capture of Triton by Neptune likely resulted in a massive heating event that resulted in resurfacing [4, 5], possibly by cryovolcanism [6, 7]. Crater counts for both Triton [8] and portions of Pluto [9] suggest that both surfaces are exceptionally young, which may indicate that neither Triton nor Pluto retain their original surfaces.

Mapping of Pluto and Charon is in progress [10, 11, 12], but as no comparable geologic map of Triton exists, a direct comparison between these two KBOs cannot be performed at a fundamental level. Furthermore, as Triton serves as a bridge between KBOs and icy satellites, characterization of its terrains is important for advancing comparative planetological studies. To-date, no peer-reviewed, broad-scale, detailed geologic map of Triton exists to characterize, classify, and identify geologic surface units and features on Triton.

We are in the process of creating a digital Triton data archive that will recover and restore original data products and provide context for future investigations by creating a geologic map across Triton’s Neptune-facing hemisphere. This effort entails using the 43 images of Triton that are better than 2 km/pixel and creating a new mosaic of the southern portion of the moon. This new mosaic will use the most up to date image pointing data to improve the locations of each of the images. See Bland et al, (this meeting for additional details on the new mosaic.

Previous geologic mapping efforts on Triton (Fig. 2) did not include a Scientific Investigations Map (SIM) by the U. S. Geological Survey (USGS), nor is it available in a digital format for distribution and use by the community. Detailed descriptions of geologic units are further illustrated with Voyager images of terrains and structures; however, poor printing quality makes it impossible to verify these geologic units. It is necessary for an accessible, digitized, USGS SIM be created to firmly establish the geology of Triton’s surface.

Mapping Triton’s Geology: Understanding Triton’s geologic history is essential to unraveling its origin and evolution. Geologic mapping of Triton will allow for identification of geologic units and structures that are recently formed, and those that are ancient, revealing more about Triton’s evolution. Our mapping of Triton is supported by existing maps of Triton [e.g., 13].

Figure 1: Orthographic projection of Triton’s Neptune-facing hemisphere. Image No PIA00317

Figure 2: Geologic map of Triton from [13].
We will present preliminary mapping results of the Neptune-facing side of Triton at a scale of 1:5,000,000. The printed map product will be produced at 1:5M, however the digital product that will be published by the USGS will be 1:2.5M, higher than any Triton map product to date.

Mapping will occur on the USGS Voyager 2 orthographic color mosaic with a resolution of 600 m/pixel (Fig. 3); however, for the purposes of mapping the color will be removed to create a gray-scale mosaic. This mosaic covers approximately 1/3 of Triton’s surface from 45° to -60°N latitude and -75° to 90°E longitude. This map will provide a framework for future Triton research, future KBO research, and preparation for future missions.

![Figure 3: Triton controlled photomosaic from Voyager 2 with exaggerated color.](image)

1:200,000-SCALE GEOLOGIC MAP OF OLYMPUS MONS CALDERA, MARS. Pete Mouginis-Mark, Hawaii Institute Geophysics and Planetology, Univ. Hawaii, Honolulu, HI 96822 (pmm@higp.hawaii.edu)

Introduction: The martian volcano Olympus Mons (18.65°N, 226.20°E) is the highest and most prominent shield volcano in the Solar System. It is ~600 km in diameter and rises ~22 km above the northwestern edge of the Tharsis rise [1, 2]. The summit displays a nested series of pits (“paterae”), which collectively comprise the summit caldera [3]. Via formal geologic mapping at a scale of 1:200K (Fig. 1), details of the summit geology and topography of the caldera provide key insights into the relative timing of collapse episodes, as well as the post-emplacement deformation of the summit.

Geologic Mapping: HiRISE [4] and CTX [5] images were used for mapping and elevation data were obtained from MOLA [1] and the HRSC [6]. For this area, the HRSC data have a resolution of 100 m/pixel, and a vertical accuracy of 10 m. A subset of topographic data were derived from CTX images covering parts of the caldera floor at a spatial resolution of 24 m/pixel and vertical accuracy of ~3-5 m [3]. As is conventional for terrestrial shield volcanoes, the individual paterae have been given formal names by the International Astronomical Union (Fig. 2). They are named after the Greek Olympian gods who were believed to habit Mount Olympus, the highest mountain in Greece and purported to be the seat of the gods by Homer, the legendary Greek author of the Iliad and the Odyssey. This map includes Pangboche crater (10.4 km in dia.), which offers the opportunity to study the effects of cratering with minimal influence from the thin Martian atmosphere and the lack of volatiles in the target [7].

Physical Volcanology: Within the 80 x 65 km diameter structure, the chronology of the six nested paterae (Fig. 3) indicates that the preserved summit has undergone multiple collapse episodes, flooding by lava, and subsequent deformation [3]. Numerous tectonic features on the caldera floor have been interpreted to have formed by compression (wrinkle ridges) and extension (graben), believed to have been associated with subsidence associated with magma chamber deformation [8].
Mapping at 1:200K allows the distribution of 351 lava flows to be identified at the summit. Correlating these flows with the current topography from MOLA, numerous flows south of the caldera rim appear to have moved uphill [9]. This disparity is most clearly seen to the south of the caldera rim, where the elevation increases by >200 m along the apparent path of the flow (Fig. 4). Additional present day topographic anomalies have been identified, including the tilting towards the south of the floors of Apollo and Hermes Paterae within the caldera, and an elevation difference of >400 m between the northern and southern portions of the floor of Zeus Patera. It is inferred that inflation of the southern flank after the eruption of the youngest lava flows is the most plausible explanation [9]. This implies that intrusive activity at Olympus Mons continued towards the present beyond the age of the youngest paterae, which may be <200 Myr [6, 10].

Conclusions: It is proposed [9] that intrusion of lateral dikes to radial distances >2,000 km is linked to the formation of the individual paterae at Olympus Mons. Two specific dikes to the SE of the volcano are inferred to have volumes of ~4,400 km³ and ~6,100 km³, greater than the volumes of individual calderas and implying triggering of both caldera collapse and lateral dike injection by the arrival of large inputs of magma from the mantle. A comparable disparity between lava flow direction and current topography, together with a tilted part of the caldera floor, has been identified at Ascreaus Mons [9], opening the opportunity for new research via additional mapping of this Tharsis volcano at higher resolution than is currently underway [11].


Introduction: One aim of the NASA Dawn mission was to generate global geologic maps of the asteroid Vesta and the dwarf planet Ceres. The geological mapping campaign of Vesta was completed and results have been published in e.g. [1]. Recently also geologic mapping of Ceres has been completed. The tiling used in this mapping project is based on recommendations by [2], and is divided into two parts (for Ceres described in [3,4]): four overview quadrangles (Survey Orbit, 415 m/pixel) and 15 more detailed quadrangles (High Altitude Mapping HAMO, 140 m/pixel). The atlases are available to the public through the Dawn webpage (dawngis.dlr.de/atlases) and the NASA Planetary Data System (PDS) (pdsdeobastro.umd.edu).

The first global geologic map at a scale of 1:2.5 M is based on survey and HAMO images. This served as basis for generating a more detailed view of the geologic history and also for defining the chronostратigraphy and time scale of Ceres [5]. A more detailed view could be expected within the 15 quadrangles (HAMO tiles) which was completed by the Low Altitude Mapping (LAMO) data (35 m/pixel). For the interpretative mapping one responsible mapper was assigned for each quadrangle. Once individual tile mapping has been finished, datasets are expected to be “combiable” within ESRI’s ArcGIS platform.

To handle this task, a map template is needed to generate a geometrically and visually homogeneous map project representing a thematically consistent global map. Therefore, the mapping process was supported by a mapping template which was developed within the ArcGIS environment. Once set up using a set of specifications, templates can be distributed and facilitate the mapping process through pre-defined symbols, object attributes, geometric properties and map sheet elements. Templates like this are very established in multi-user projects, and were also used by and within the Geologic Mapping Program conducted and guided by the USGS Astroglobe Science Center.

The template presented here contains different layers (termed feature classes) for different object/geometry types including predefined attribute values as well as cartographic symbol specifications. The cartographic symbols follow guides set up in [6] as far as possible, and colors for geological units were defined according to individual needs and requests within the mapping team. The color choice was based on established color values used in geologic maps, e.g., defined and used within standardized planetary maps generated by USGS. Previous statuses of the mapping compilation process are described in [7, 8].

Background for the mapping: The global geological map was created by merging the 15 individual quadrangle maps, which were mapped at a scale of 1:100K-125K, and published at a scale of 1:1M in the special volume on "The geological mapping of Ceres" [9]. The quadrangle map boundaries based on the HAMO atlas published by [4]. The basemap mosaic of Ceres was created using camera data from LAMO (Low Altitude Mapping Orbiter) orbit phase (over 31,300 clear filter images with a resolution of about 35 m/pixel during the eleven cycles). This global mosaic is also the basis for a high-resolution Ceres atlas that consists of 62 tiles mapped at a scale of 1:250K. The LAMO atlas was published by [10] and is available through the Dawn GIS web page and the NASA PDS (linked above).

Final map package: The entire mapping project will be available to the community via the PDS annex. All mapping data is saved in an ArcGIS File Geodatabase, FGDB: this FGDB contains two feature data sets: the map sheet layer with boundary data and graticule, and mapping layers divided into contacts, units, linear, point, and surface features. The needed metainformation is also defined within the ArcGIS environment. Furthermore, additional data are included:

- layer files contain the cartographic visualization stored for every individual thematic layer (*.lyr). Especially helpful for comparable cartographic visualization if *.shp are being used instead of feature classes.
- shapes are extracted from the filegeodatabase using in other GIS environments (*.shp).
- projection files described the four primary projections are stored for visualizing the global data set in different views.
- project files are created as *.mxd which this shows the whole mapping project within a proprietary map document using ArcGIS. *.mpk and *.lpk, which stored the map project within a compressed proprietary map document using ArcGIS.
- image files as *.png which show 1. the cartographic legend of the global map, and 2. the global geologic dataset conducted by the merged quadrangle maps is visualized as separate map sheet (in plate carrée and stereographic projection, as*.pdf).

It should be noted that the merged project still contains some excess objects in overlap areas along the boundary between the quadrangles. This is primarily due to different scientific interpretations of mappers. In
order to homogenize this, follow-up discussions among mappers are required. A detailed description of all those interpretations is published in the papers listed in [9]. Due to this, the map dataset could currently not have a clean topology.

Critical Review: The current template has served as a necessary basis for mappers to generate their individual – but still comparable – maps, and thus gives the possibility to merge the 15 quads in the future to one global map. The final status and general information of the mapping project are summarized in [11]. Because the creation of the mapping template was an iterative process, there are still some topics (focus on GIS and cartographic visualization) to discuss on the way to a homogeneous and comparable map layout. These are:

1) Boundary regions: Within the review process the mappers again should engage in a discussion with all quad neighbors to allow for a clean and consistent description of Ceres.

2) Map scale and minimum object dimension: Mapping scale and minimum dimension of planetary objects have to be fixed during the mapping process and double-checked during the review process. Otherwise the impression may arise that some regions show more features than others, where the differences are only a result of the different mapping techniques and lack of mapping constraints.

3) Boundaries of the quad maps as supplemental material: The map boundaries defined by the HAMO atlas schema should be consistent for the supplemental material map sheets, independently of whether or not important objects are fully included. Otherwise it would reject the character of the schema which is established for giving a first fully covered and consistent description of the geologic/geomorphologic of Ceres – visually similar to the HAMO atlas [3].

4) Additional units and colors: The color scheme was generated by defining one color for each of the units expected by the mappers. These colors should be distinguishable on the map sheet but should still allow a visual affiliation or distinction of the units. Thus, it has to decide very carefully if additional colors for individual and regional phenomena should be used. The global color scheme will be updated if all geologic units are clearly and consistently interpreted.

5) Additional information on the map sheet: to support the general understanding of the map content it will be useful to provide additional information (like DTM sources, quad schema, or CoMU) on the map sheet. If so, this information should be included uniformly and consistently for all map sheets.

6) Global relevant feature catalogue: to describe the different units and features generically and visually it would be useful to conceive an updated version of the already existing feature catalog and the generated map legend (applicable to all map quads). This will provide a first global overview of the objects and units identified on Ceres and could be used for a final discussion on individual interpretations and serves as base for a more detailed investigation in the future.

7) Transferable template: Beside the proprietary usage within ArcGIS the GIS-based template was also used in the open source software QGIS [12]. The template for the final graphical work was transferred into an open format .svg, so it could be used in a wide range of graphic software tools, e.g., in Inkscape, and web-based environments. In the future the FGDB schema will also be made transferable to open-source database systems (e.g., PostgresQL).

Conclusion: The final map product presented here represents the first global map showing the geology of Ceres on LAMO resolution data at a mapping scale of 1:100-125K within an GIS-based map package, and is published digitally at a scale of 1:2.5M in A0 (as combination of 15 1:1M quadrangle maps [in 9]). Thus, the global map serves as an accessible basis for upcoming investigations, and is available via the PDS annex with all relevant information. The template developed specifically for Ceres mapping serves as a basis to enable consistent and homogeneous compilation of a global map from 15 individual quadrangle maps.

However, while a map template provides the technical framework and allows for consistency, human interaction, iteration and a certain degree of flexibility, a homogenization of the global interpretation is still indispensable in order to arrive at common approach and understanding of mapping boundaries. Thus, only through a final scientific review of the global map dataset and subsequent adjustment of remaining cartographic issues would allow the creation of the homogenized and unified global map product.

**Introduction:** Geologic mapping is being undertaken to investigate the geologic history of an area within the southern Utopia basin. This work will produce a 1:150,000 scale map published as a USGS Scientific Investigations Map. This presentation will discuss the investigation’s background, motivation and current results.

**Background:** Numerous studies have presented interpretations of widespread subsurface sediment mobilization and mud volcanism on Mars based on studies of landforms in areas such as the northern lowlands [e.g., 1, 2], impact craters [e.g., 3], and Valles Marineris [4]. These findings paint a fascinating picture of a Late Hesperian to Early Amazonian Mars characterized by widespread “sedimentary volcanism” (i.e., subsurface sediment mobilization and mud volcanism), with concomitant circulation of water and other fluids between the subsurface, surface and atmosphere, and associated habitable environments—a “muddy Mars”.

Interpretations of sedimentary volcanism on Mars is contentious however, and alternate interpretations of these landforms as products of igneous volcanism [e.g., 5, 6] and periglacial processes [7] have also been proposed.

In 2016, Okubo et al. [8] analyzed MRO HiRISE images of a small area containing pitted cones and rifts in southwestern Utopia Planitia (Figure 1). They showed that stratigraphic, cross-cutting and superposition relationships indicated that the pitted cones and rifts formed contemporaneously through sedimentary volcanism, rather than by the alternative mechanisms of igneous volcanism or periglacial processes.

**Motivation:** Motivated by the results of Okubo et al. [8], the overarching goal of the present work is to investigate and document the stratigraphic, cross-cutting and superposition relationships of landforms in a wide area around the Okubo et al. [8] study area in southwestern Utopia Planitia (Figure 1). The present work aims to gather novel mapping-based observations to provide either refutation of or support for the hypothesis that sedimentary volcanism was widespread in the region and therefore many of the associated landforms are potential water-related, geologic and astrobiologic resources.

The significance of sedimentary volcanism on Mars is best conveyed by considering studies of their terrestrial counterparts. In terrestrial sedimentary basins, the mobilization of subsurface sediments is recognized as a common and significant process that acts to enhance, impede or otherwise alter local patterns of fluid migration and storage within the subsurface. These mobilized sediments often have a higher porosity and permeability than the host rock and therefore increases the volume of subsurface fluid reservoirs, improves hydraulic communication between these reservoirs, and facilitates the release of subsurface fluids into the aboveground environment [10], including gases of biogenic origin [e.g., 11]. Such sediments are mobilized as slurries within the subsurface. The solid phase predominantly comprises sand, silt and clay-sized sediment, with minor amounts of pebble and cobble-sized clasts. The fluid phase typically consists of water, hydrocarbons, carbon dioxide and hydrogen sulfide. A variety of processes have been identified as triggers for the mobilization of subsurface sediments including, seismicity, tectonic compression,
gravity-driven compaction, hydrocarbon generation, dehydration of clay minerals, hydrothermal activity and sediment diapirism.

In the subsurface, these mobilized sediments form deposits often referred to as injectites [e.g., 11]. The slurry can also rise to and discharge on the surface and sometimes recede back to depth, forming a variety of positive and negative relief landforms such as mud volcanoes and mud calderas [e.g., 11].

The patterns of fluid flow established by injectite and mud volcano systems can be areally extensive and persist for millions of years [e.g., 11] and therefore can have a substantive impact on hydrologic, geologic and biologic processes on the surface and in the subsurface environments. Due to their sustained flux of fluids, subaerial mud volcanoes on Earth are oases for bacterial and archaeal communities [e.g., 12, 13]. Therefore, mud volcano systems are important sites for investigating the geologic processes that could have supported past habitable environments on Mars and for seeking evidence of past life in the form of fossils and other preserved biomarkers.

Methods: Mapping will begin by tracing contacts between landforms in the map area. Anticipated landform types that will be mapped are pitted cones, low-relief shields, wide rifts, rift-filling lobate deposits, low-standing mesas, fracture-bounded mesas, impact craters, and impact ejecta. Geologic units will be defined by the contacts between landforms. Areas that are not attributable as a specific landform, i.e., terrain surrounding the landforms, will be classified as a regional plains unit.

MOLA and THEMIS base maps available through the PDS will aid in the preliminary recognition of landforms, and the precise boundaries of those landforms will be identified and mapped using CTX. Rather than creating a single CTX mosaic, individual CTX images will be controlled with SPICE, map projected, and displayed in a virtual mosaic within the GIS project. Previous experience has shown that this technique produces a mapping base that is adequately georeferenced for the proposed map scale, while eliminating the cost of producing a controlled image mosaic.

Where available, non-stereo and stereo HiRISE observations and stereo CTX observations will be used to supplement interpretations of cross-cutting and superposition relationships and landform boundaries made using the (non-stereo) CTX mapping base.

Interpretations of the nature and origin of each map unit will be developed based on previous investigations of the regional geologic setting of the map area (as reported by others in smaller scale maps, topical papers, etc.) and observations made in the present study of landform morphology, cross-cutting and superposition relationships, all the while revising previous interpretations where my new observations warrant. Through the course of this analysis, similar map units will be merged to make the map easier to read and help convey the salient spatial and temporal relationships between units.

Discussion: A fundamental aspect of this work is to assess the hypothesis that sedimentary volcanism was responsible for creating many of the landforms of southwestern Utopia Planitia. A primary test of this hypothesis builds upon the work of Okubo et al. [8] and entails evaluating for the presence of discontinuities (such as a lobate margin) between the rift-filling material and surrounding lowland plains. Such discontinuities could represent a stratigraphic boundary, admitting the possibility that the rift-filling material has a different origin than surrounding plains (e.g., the rift-filling material could be lava flows). Conversely, if discontinuities are not observed between rift-filling material and surrounding plains, this would support the interpretation that the rift-filling material consists of the same material as the surrounding plains, i.e., the sediments of the Vastitas Borealis Formation (VBF). A sedimentary origin for the rift-filling material can then be linked to the origin of adjacent landforms in the following way. If the rift-filling material comprises the sediments of the VBF, and cross-cutting and superposition relationships indicate that the pitted cones formed contemporaneous with emplacement of the rift-filling material, then the simplest and most logical conclusion is that the pitted cones also comprise the sediments of the VBF. Thus, the pitted cones would be mud volcanoes driven by subsurface sediment mobilization within the VBF. In this way, analyses of discontinuities, cross-cutting and superposition relationships will be used to evaluate the possibility that those landforms are the result of sedimentary volcanism.

Introduction: We are completing a geologic map of the northern polar region of Mercury (H-1 Borealis Quadrangle) using MESSENGER orbital observations at 1:5M map scale. Our mapping leverages current and ongoing USGS-supported geologic mapping efforts of the 1:15M-scale Mercury global geologic map [1–4] and the 1:5M-scale H-10 Derain Quadrangle [5] to establish basic standards and practices for quadrangle mapping of Mercury using MESSENGER data.

Mapping Progress: For 2019 (Project Year 3), we are focusing on finalizing the map components and preparing for map submission. This task encompasses finalizing the Description of Map Units (DOMU) and Correlation of Map Units (COMU), along with the text for the map pamphlet, and finalizing the GIS package for map submission. The current map and draft unit definitions for plains materials are shown on the following page [Fig. 1]. We are behind schedule for map completion, in part due to the partial government shutdown from December 2018/January 2019, and expect to submit the map at the conclusion of this project year.

Although we planned to determine relative ages for units and features in Year 2, we were unable to complete that task last year. In particular, we have made preliminary progress in completing the impact crater classification and degradation state assessment and expect to make substantial progress by the Annual Planetary Mappers Meeting in June. Impact structures ≥20 km in diameter and their related materials will be classified according to degradational state using the methodology applied in the global geologic mapping effort [e.g., 4,6]. Current definitions and interpretations for four types of crater materials are shown in Fig. 2; we have worked closely in conjunction with Kinczyk and Whitten to develop and refine these definitions during mapping.

Consistently mapping the intercrater plains, the most areally extensive geologic unit on Mercury [e.g., 7], remains a challenge in H-1 as it does for other USGS-supported mapping investigations [4, 5]. The intercrater plains is comprised of gently rolling plains materials in between large craters and basins, with a high spatial density of small, superposed craters ~5–15 km in diameter that is indicative of a complex resurfacing history [5, 7]. In H-1 we mapped two intercrater plains units primarily distinguished by textural differences. However, we may revise our unit definitions and mapping dependent on current mapping efforts for the global map and the H-10 quadrangle, both of which are employing multiple techniques in an attempt to consistently and confidently subdivide the intercrater plains.

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![Crater Materials](https://example.com/crater_mats.png)
We are working to complete impact crater degradation assessments, which will be included in the next iteration. We are working to subdivide the intercrater plains in a consistent way; see Whitten et al. [5] for additional discussion.

Introduction: Numerous ridges cover the leading and trailing hemispheres of Saturn’s icy moon Enceladus (Fig. 1). Both regions contain only a few craters larger than about 1 km, suggesting a strikingly young surface. The ridges suggest a recent history of shortening in the area given the size and extent of the ridges on both hemispheres. However, the ridges on each hemisphere appear different. The trailing hemisphere contains a suite of large, linear ridges (termed dorsa) centered roughly on the equator (Fig. 2). Conversely, the leading hemisphere is dominated by more numerous, rounded ridges (Fig. 3). Here we will show our most recent detailed maps of the ridges and other structures within the leading and trailing hemispheres of Enceladus. This effort is part of the global geologic map of the icy world.

Trailing Hemisphere: The trailing hemisphere consists of semi-concentric tectonic terrains centered roughly along 0°, 285°W. The primary tectonic structures are two main sets of ridges: a set of smaller ridges (10-25 km long, ~50 m high, 1-2 km wide), and the larger dorsa (~50 km long, ~800 m high, 2.5 km wide) which can bifurcate in a branching manner with branches that can intersect other dorsa near-orthogonally (Fig. 2). A set of north-south fractures cuts across the dorsa, and in some instances they appear to laterally displace the ridges.

In cross section, the dorsa display broad, rounded tops and asymmetrical flanking slopes of ~15–30°. Ebony Dorsum appears to have a dual-component slope on its southwest-facing flank, with the upper slope being steeper (20–35°) than the lower slope (12–18°).

Leading Hemisphere: On the leading hemisphere terrain (LHT) are two different ridge types: a smaller set (1–20 km long, 10 m high, 1-5 km wide), and a larger but less numerous set (~600 m high, 15–35 km long, 5-10 km wide) that have a lens-like shape in map view (Fig. 3). The larger ridges we interpret to be large-scale thrust faults. Few fractures appear to transect this region; however, surrounding the terrain are a series of fractures that cut through some of the leading hemisphere ridges and have a north-south trend.

Previous efforts [1] further divided the leading hemisphere into 3 sub-terrains: northern and southern regions surrounded by a curvilinear terrain. Each region contains different types of ridges. In the northern portion of the leading hemisphere are two ridge types, one smaller in amplitude and wavelength, and a second larger amplitude set (Fig. 2). Here we show that the smaller ridges have a spacing of 1–2 km, are ~10 m high, and 1–20 km long. The larger ridges are ~600 m high, 15–35 km long, show a lens-like shape in map view, and in cross-section are broad with flank slopes of 6–30°. The southern region of the leading hemisphere is dominated by ridges that are similar in size and shape to the smaller ridges to the north; however, this region lacks a larger ridge set.

Discussion: Crosscutting relationships and the deformation of the striated plains on the southern flanks of Cufa Dorsa on the trailing hemisphere indicate that the dorsa are the youngest features in the region. Older structures of the striated plains are apparent on some ridge flanks suggesting uplift. On other ridge flanks the striated plains are not visible but instead truncate the older terrain and may represent fault scarps. These relationships are inconsistent with a cryovolcanic origin [2] of the dorsa. Instead, we favor a tectonic uplift model, likely thrust faulting, to create these prominent ridges.

The branching nature of the dorsa could be explained by multi-directional contractional strain, where the maximum compressional strain was oriented in a NE-SW direction and minimum compression was oriented NW-SE. The western termini of the Cufa Dorsa are against a prominent, long, gently arcuate tectonic trough, which may have served as a transcurrent fault that permitted north-south directed contraction. We support the suggestion that the dorasa are thrust faults, and they could accommodate ~10% shortening.

The leading is likely older than the active South Polar Terrain [1, 3]; however, the region has still been heavily modified by recent tectonic activity [Spencer et al., 2009]. The raised topography, sinuosity, and lack of lobate features strongly suggest the LHT ridges likely formed as a result of a compressional stress event, possibly as much at 10% or more.

Figure 1. Geologic map of the leading and trailing hemisphere major ridges.

Figure 2. Saturn shine image of the trailing hemisphere. Red arrows show large dorsa and black arrows show younger fractures.

Figure 3. Leading hemisphere ridges. Red arrows point to the largest ridges in the region.
Introduction: With geographic information system (GIS) technology evolving toward the adaptation of ArcGIS Pro in place of ArcMap, there is a need to shift geologic mapping efforts into the new ArcGIS Pro interface. A natural transition will occur as students receive training and current mappers begin new projects, and adopting ArcGIS Pro will alleviate the worry of creating map products in a software platform that will not continue to be supported by ESRI.

With respect to functionality, ArcGIS Pro provides more powerful processing capabilities for large datasets like those used in planetary mapping and integrates standard planetary geographic coordinate systems. However, many processing tasks and tools have been shifted in the new software, creating a need for updated mapping tutorials to highlight the changes and help new and existing mappers navigate ArcGIS Pro.

Mapping Tutorials: At the broadest scale, the workflow for any geologic mapping effort consists of five fundamental steps: (1) selecting an appropriate base layer upon which mapping will be conducted; (2) identifying units and drawing geologic contacts; (3) delineating geologic or tectonic features; (4) applying appropriate symbology; and (5) finalizing the map product for presentation and/or publication. Traditional geoscience curriculum includes geologic mapping in field courses as well as upper division classes. It also links mapping efforts to interpretations of depositional environment, stratigraphic context, structural regime, and geologic history.

The tutorials presented here are designed to complement geoscience coursework and offer users—both students and members of the planetary mapping community—an opportunity to conduct mapping in the ArcGIS Pro interface. The level of detail provided in the tutorials assumes that the user has no experience using ArcMap or ArcGIS Pro, an assumption intended to make them suitable for undergraduate students with little to no previous mapping experience. The tutorials would be ideal for students enrolled in a planetary geoscience class or an introductory GIS course.

The target body and datasets for tutorials are designed to showcase high-resolution planetary imagery by utilizing data returned from the Context Camera (CTX) and the High Resolution Science Experiment (HiRISE) onboard the Mars Reconnaissance Orbiter (MRO). Although users can choose to map on any HiRISE base image, four suggested images are provided that illustrate the utility of geologic mapping for interpretation of depositional processes on Mars.

The tutorials, originally designed for student users, are relevant introductions to ArcGIS Pro for planetary mappers who have conducted mapping on other target bodies and/or wish to quickly complete a primer as they upgrade from ArcMap.

Tutorial 1 – Planetary Mapping Project Creation in ArcGIS Pro: This workflow guides the user through creating a new project in ArcGIS Pro and configuring settings for the geographic coordinate system and a custom projected coordinate system. Mappers also prepare and import high-resolution imagery for mapping and link the project to online map products available from the USGS, for example, WMS server products.

Tutorial 2 – Importing Symbology and Creating Linear and Point Features in ArcGIS Pro: Once the project is set up, users are guided through the steps necessary to import USGS standardized planetary symbology. The processes for creating and editing point and linear features in ArcGIS Pro are documented, with special attention to the processes for identifying and editing geologic contacts.

Tutorial 3 – Creating Geologic Map Units Using Polygons and Topology Tools: When geologic contacts are satisfactorily created, users are provided tutorial steps to download and import the USGS Planetary Geologic Mapping Python toolbox. The workflow includes running the Topology Check and Build Polygons tools to turn linear contacts into geologic units and add symbology as needed for interpretation.

Tutorial 4 – Adding Map Elements and Exporting Maps for Publication: The final tutorial in the series helps users prepare their maps for publication by creating a layout in ArcGIS Pro and adding essential map elements such as scale bars and north arrows.

Next Steps: Recent survey results published by the USGS identified the need for tutorials and training opportunities and suggested sustained, innovative approaches from all stakeholders to ensure that the methodologies of planetary geologic mapping are communicated to new and current mappers [1]. These tutorials, available from the author and archived at www.tntechsedgeology.org/tutorials, are a response to the recommendations provided by the USGS. Feedback from all users is encouraged and welcome.

FULLY CONTROLLED 6 METERS/PIXEL MOSAIC OF MARS' SOUTH POLE AND EQUATOR FROM MARS RECONNAISSANCE ORBITER CONTEXT CAMERA, II. S.J. Robbins1, R.H. Hoover1,2, M.R. Kirchoff3. 1stuart@boulder.swri.edu, 2Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, 3University of Colorado Boulder, Boulder, CO.

Introduction: The Context Camera (CTX) aboard NASA's Mars Reconnaissance Orbiter (MRO) spacecraft [1] has been returning high-resolution and -quality data of Mars’ surface for over a decade. As of PDS release 47 (December 2018, including data through May 2018), the instrument has returned over 100,000 images that cover 97.8% of the planet’s surface. However, the images often have ~100s meter offsets from each other and a controlled ground source, resulting in seam mismatches and poor matches to other high-resolution datasets. We have developed an efficient, accurate workflow within ISIS3 software and driven by Python scripts to automate much of the control net process for purposes of creating a fully controlled CTX dataset while maintaining our work environment within the community standard that is ISIS3 (USGS’s Integrated Software for Imagers and Spectrometers v3). Here, we demonstrate the viability of our process by creating a mosaic of the south polar quadrangle (“MC-30”) and an equatorial region (±7.5° N, 0–360° longitude) that total 17.8% of Mars’ surface area.

Workflow, Automated: To begin with manageable regions (generally limited to a few hundred images to facilitate the manual components – see “Workflow, Manual” section), we divide the planet into the historic “Mars Chart” regions, 30 approximately equal-area quadrangles used in the mapping community. We further divide these into 16 equal latitude/longitude regions (thus, each region is roughly 1/480th of the planet). The result is a median of ~200 images per region, though areas of high interest have significantly more images (e.g., poles, Valles Marineris, landing sites). Images in these regions are extracted and processed through a standard CTX data reduction workflow in ISIS3 software, including an empirical horizontal flatfield process to remove edge darkening. Images are then manually screened to ensure surface features are visible with reasonable signal-to-noise, and they are removed if not.

We then use a process of standard tools within ISIS3 to create a relative control network, including FOOTPRINTINIT, FINDIMAGEOVERLAPS*, AUTOSEED*, CNETREF, POINTREG, and JIGSAW. (Relative control is when the same feature in multiple images projects to the same location on a planet, though that location may not be the “correct” location.) Our workflow includes multiple templates to register control points and additional checks for validity of the control points beyond those built into the ISIS3 tools. For example, after a control network is created and validated, high residual points are automatically extracted, attempted to be registered again with different templates, and removed if residuals are not sufficiently reduced.

In most of the 480 regions of Mars, this entire process can fully control all quality images in the region on a high-end modern personal computer in less than one day, and it requires no manual effort. In fact, most of the equator has been running on a 2008 MacPro, and taken 25–30 hours (middle range). However, a modification to this workflow is required for polar regions: Instead of registering all images together initially, sub-sets of images are controlled separately. The sub-sets are grouped by Ls (season) such that the same seasonal processes should be recorded in the images. The Ls boundaries of the image lists overlap each other such that, after each set is completely controlled, they can be merged into a final control solution without islands. The image overlaps ensure there will be one, fully connected network rather than several separate networks. These separate image lists do significantly increase the CPU time required to process the region, and the highly variable south polar features and lighting at CTX scales mean that our extra validation and adding of points steps have more work. This, combined with needing to test more possible points before finding good matches, results in the polar regions requiring on the order of ~10x more time than any other region of Mars (roughly two weeks each).

*In cases of significant numbers of overlapping images, FINDIMAGEOVERLAPS can catastrophically crash, and before crashing, use an extreme amount of computer resources (e.g., 500 GB of RAM). We have created an alternative version in Python of FINDIMAGEOVERLAPS and AUTOSEED that we use near the poles in order to mitigate this issue.

Workflow, Manual: After each region is relatively controlled through these fully automated steps, several control points throughout the region are constrained through registration to a known ground source. For non-polar regions, we use the fully controlled THEMIS Daytime IR mosaic available from USGS, but which does not yet exist for polar areas. For polar regions, we use the MOLA gridded data product which has high enough coverage poleward of ±65° that larger features in CTX data can be reasonably interpolated and recognized. This process is currently manual due to the significant scale differences and resulting false matches between CTX and either THEMIS or MOLA.

Finally, when separate, adjacent regions are fully controlled, the networks are merged together. CTX is a linescan camera and MRO has a tilted orbit such that all images on the edges of regions are also in adjacent regions. So, the networks for adjacent regions merge...
For mosaicking, we use several built-in tools in ISIS3 for image-image equalization and tone-matching. Image order is initially an automated process based on a custom code that assigns scores to images based on Ls, pixel scale, emission angle, and incidence angle compared to a reference ideal. Once completed, we also manually inspect every mosaic to determine if there are seam mismatches (and need to manually add or remove control points) and to adjust image order (to emphasize the highest quality images).

Figure 1 illustrates in a few frames the effect of our process and comparison with THEMIS.

**Standards:** We emphasize that our work uses the community-standard ISIS3 software, meaning that all tracking of uncertainties and other types of output produced by this software are maintained. Our Python wrapper uses standard libraries and, via its nature, Python is a free compiler that can be run on almost any computer. Additionally, we use native Python tools to divide the work into multiple files such that we can take advantage of modern high-core-count computers. Only a few ISIS3 tasks truly need to be done in serial, on one processor (e.g., JIGSAW, and AUTOMOS).

**South Polar Mosaic:** MC-30 (Mare Australe) is about 4.7% of Mars’ surface and, as of PDS release 47, has 8467 images that met our specifications to mosaic (see the manual screening discussion in the “Workflow” section). These cover 95.6% of the surface area of the region, though it is significantly more complete south of about -70°N. Significant seasonal effects made the automated networking difficult in some locations so that some manual effort was required for a few of the images. These manual effort locations coincided with areas of poorer signal-to-noise images and images that had significant variations in appearance. We expect to have a completed mosaic near the time of this meeting that we can present, and it will be submitted to *Earth & Space Science*; when accepted by that journal, the mosaic and SPICE data will be released to PDS.

**Equatorial Mosaic:** We have constructed a fully controlled equatorial mosaic of Mars, spanning ±7.5° latitude. This constitutes 13.1% of Mars’ surface and, as of PDS release 47, has 13,603 images that met our specifications to mosaic. These cover 97.9% of the surface area of the region. Our processing code worked well enough such that no manual effort was required until the full control step, tying the images to THEMIS Daytime IR. We consider this a first step, proof-of-concept for a fully controlled global product and, therefore, we have no plans to broadly publicly release it. However, interested parties can contact us to request a copy.

**Future Mars Work:** Our goal is to create a fully controlled CTX dataset, from which to create a fully controlled 6 m/pix mosaic of the surface, using our established and proven workflow. We would publicly release the mosaics, SPICE solutions, and other data such as the control network. We are currently pursuing funding towards this goal.

**Future Non-Mars Work:** While our workflow was developed specifically for CTX data, it should be generalizable to other imagers that were sent to other bodies. We have done preliminary adaptations of our code for MESSENGER MDIS, Cassini ISS, and New Horizons LORRI, but further work is contingent upon additional funding.


**Funding:** This work was funded internally by Southwest Research Institute.

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**Figure 1:** Mosaic with ⊣ no corrections; ⊢ with tone-matching; ⊢ with tone-matching, flat-fielding, and our automated image ordering. Some seams are still visible, but the mosaic is much more even, and the northeast portion of the volcano is now apparent. ⊜ Uncontrolled mosaic with default SPICE has ~260m offset between these images, while ⊝ is fully controlled and shows no offset, and ⊕ shows the THEMIS Daytime IR mosaic for resolution comparison.
GEOLOGIC MAP OF THE INTERIOR OF OCCATOR CRATER, CERES, AND ITS BRIGHT FACULAE, BASED ON 2D AND 3D PERSPECTIVE VIEWS OF HIGHEST RESOLUTION (METER-Scale) DAWN DATA. J. E. C. Scully1, D. L. Buczkowski2, D. A. Williams3, J. H. Pasckert4, K. D. Duarte5, V. N. Romero6, J. C. Castillo-Rogez7, C. A. Raymond8, C. T. Russell9, 1Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, 2Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, 3School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, 4Institute für Planetologie, University of Münster, Münster, Germany, 5Georgia Institute of Technology, Atlanta, GA, USA, 6University of California, Los Angeles, CA, USA.

Introduction: Dawn explored dwarf planet Ceres from 2015-2018 [1], using its Framing Camera (FC) [2] and additional instruments [3-5]. Occator is a 92 km diameter complex crater, and is one of the most well-known features on the surface because of its enigmatic interior bright deposits [6-8]: (i) Cerealia Facula is in the central pit, which also contains a central dome (Cerealia Tholus), (ii) Pasola Facula is on a ledge above the central pit, and (iii) Vinalia Faculae are in the eastern crater floor. The faculae are ≤6 times brighter than Ceres’ average visual normal albedo [9] and are mostly composed of sodium carbonate and ammonium chloride, which are the solid residues of brines that were exposed on the surface [10-11].

Motivation: Using data from Dawn’s prime and first extended missions (≥385 km in altitude, ≥35 m/pixel FC images), a variety of studies, including geologic mapping, sought to uncover the sources behind Occator’s faculae [12-14]. However, key questions remained about faculae emplacement. During Dawn’s second extended mission (XM2), low elliptical orbits provided FC images of Occator with a ground sampling distance of ~3.3 m/pixel from ~35 km altitude. Here we address these key questions by analyzing the geology of Occator via the creation of a new, XM2-based geologic map, which provides a methodically-derived and self-consistent interpretation of the data that cannot be achieved by visual inspection alone.

Methods:

Data. Our basemap is the ~3 m/pixel XM2 clear filter FC mosaic produced by DLR [15]. It is orthorectified onto the Low Altitude Mapping Orbit digital terrain model (LAMO DTM) [16], which we also used to create 3D perspective views. For small areas not covered by the basemap, we used a XM2 clear filter FC mosaic (~10 m/pixel) produced by D.P. O’Brien (PSI) and the DLR LAMO clear filter FC mosaic (~35 m/pixel) [16].

Mapping procedure. We mapped the crater interior at 1:50,000 and the areas of particular interest (i.e. faculae) at 1:10,000. We used a combination of 2D mapping in ESRI ArcMap and 3D mapping in ESRI ArcScene, which facilitated greater insights into the placement of contacts, stratigraphic relations etc. than 2D mapping alone. We first mapped on the ArcScene 3D perspective view, before transferring the mapping into the ArcMap 2D view for refinement. Our mapping approach was informed by USGS practices.

Results:

Geologic units: crater floor. The XM2 data reveals that the crater floor and terraces are mantled to varying extents by a veneer of lobate material, which is a slurry that flowed around the crater interior prior to its solidification. The massif material is adjacent to the central pit and was not coated by lobate material because it is high-standing. It may be the remnants of an early, transient, liquid-water-dominated central peak [17].

Geologic units: lobate material. The lobate material forms a large, thick sheet in the southern and eastern crater interior, as well as isolated pond-like deposits. We divide the lobate material into three sub-units based on surface texture: smooth, interspersed and hummocky. The smooth and hummocky lobate materials were mapped previously [14,18], while the interspersed lobate material is a new sub-unit: it is smooth lobate material interspersed with knobs (mapped as domes or mounds) and striations. The lobate material was emplaced as a slurry of impact-melted water, salts in solution and blocks of unmelted silicates/salts flowed around the crater interior shortly after crater formation [12]. Striations form when the lobate material flowed shortly before solidifying. The domes and mounds are protruding pinnacles, blocks of unmelted silicates and/or formed by frost-heave-like processes derived from the lobate materials’ solidification/expansion [19].

Geologic units: bright material. We divide the bright material into two sub-units based on texture: continuous and discontinuous. The continuous bright material often forms roughly circular deposits, surrounded by the discontinuous bright material, which in turn is often surrounded by the faint mottled bright material (a surface feature made of dispersed bright material points). Our observations are consistent with the faculae being residual deposits of brines that lost their liquid water when exposed on the surface [e.g. 6,10,12].

The lack of flow fronts in the bright material is caused by multiple overlapping flows, the buildup of ballistic deposits and/or the presence of fine-scale, unresolved flow fronts. Based on the lack of compressional features, a lack of evidence that Pasola Facula and Cerealia Facula were originally connected, and a regular correlation between Cerealia Facula and topography, we interpret that the majority of Cerealia Facula was emplaced prior to the formation of the central pit. The faculae originated from numerous sources of brine.
in a hydrothermal system, based on analogs with the Earth and Mars, the association of the faculae with the crater center and fractures, and impact modeling [20].

**Geologic units: dark material.** Patches of dark material occur within the bright material, and the dark and bright materials superpose each other. We interpret the dark material as (i) ejecta that was excavated from underneath the bright material, (ii) deposits that mass wasted on top of the bright material and (iii) as areas that were not coated by the faculae-forming brines. Pit chains coated in dark material occur throughout the crater, and are often associated with the faculae. Pit chains cross-cut Vinalia Faculae, but may still be the conduits that allowed the faculae-forming brines to reach the surface, because of the relative ease of fracture formation and reactivation on Ceres [21].

**Geologic units: talus/spurs.** The talus material and spur material are located on steeply sloping regions, e.g. the rim of the crater. We interpret the talus material as dry mass wasting material and the spurs, which occur upslope of the talus, as the source outcrops of the talus.

**Thickness estimates.** We estimate localized thicknesses throughout the faculae by using (i) superposing impact craters (and an excavation depth of >0.08 [22]), (ii) the depth of fractures that only expose bright material and (iii) the thicknesses of outcrops of bright material. The Vinalia Faculae are consistently ~2-3 m thick, while Cerealia Facula ranges from <3 m, ~5.5 m or ~31 m thick to ≥50-100 m thick on Cereali Tholus.

**Conclusions:** We interpret that the faculae are hydrothermal deposits emplaced under the control of a complex hydrologic plumbing system formed by fracture networks and hydrologic gradients. The presence of regions of dark material not covered in bright material, and the variation in faculae thicknesses, indicate that the availability of the faculae-forming brines varied from location to location on relatively short spatial scales. Model ages derived from crater size frequency distributions and thermal evolution modeling show that the source of the faculae-forming activity is long-lived (i.e. at least millions of years after crater formation [23-25]), indicating that Ceres is a world on which impact-induced activity can be protracted, and/or on which geologically recent endogenic activity occurred.

GEOLOGIC MAPPING OF THE JEZERO AND NORTHEAST SYRTIS REGIONS OF MARS. V. Z. Sun and K. M. Stack, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Vivian.Sun@jpl.caltech.edu).

Introduction: The landing site for the Mars 2020 rover was recently selected to be Jezero crater, a 50 km diameter impact crater preserving an ancient lake environment and deltaic deposits\(^1-^3\). The ancient Noachian terrains outside Jezero hosted two other landing site candidates: Northeast (NE) Syrtis\(^4-^6\) and Midway, a site with NE Syrtis-like terrains that Mars 2020 may have the opportunity to explore during its extended mission.

The geologic units and history preserved at both Jezero and Midway/NE Syrtis may be correlated, and some units may be correlative, given the close proximity of these two areas. Geologic units with similar morphologic characteristics and mineralogy have been identified at both sites (Fig. 1)\(^1-^6\). Despite the similarities between these Jezero and NE Syrtis units, the two sites have been hypothesized to represent different, and generally unrelated, ancient habitable settings, with Jezero representing surface habitability\(^1-^3\) and NE Syrtis representing subsurface habitability\(^4-^7\).

We will present an initial geologic map of the Jezero and NE Syrtis/Midway regions (Fig. 2). Regional maps over this area have previously been produced for NE Syrtis\(^6\) and Jezero crater\(^2\), but these previous maps cover different spatial extents at variable mapped scales. A geologic map at a consistent map scale that encompasses NE Syrtis and Jezero crater will enable scientists to make connections between two sites with distinct habitable settings, but with similar geologic units and correlated mineralogy. Identifying the distribution and continuity of common geologic units throughout this region will enable our understanding of:

1) The complete geologic history in this region, including source to sink processes and the emplacement of the oldest to youngest geologic units.
2) The relationship between habitable environments in different settings (surface vs. subsurface).
3) The diversity and distribution of habitable environments that may be explored and potentially sampled by Mars 2020.

Methods: We are constructing a geologic map encompassing NE Syrtis, the western portion of Jezero crater, and the area between them. The map is being constructed at 1:20,000 Digital Mapping Scale and printed at 1:75,000 Publication Map Scale. We aim to publish this map prior to the Mars 2020 landing in February 2021, so as to provide a valuable and timely resource for the Mars community. Mapping is being performed in ArcGIS on a CTX basemap, supplemented by HiRISE data to ensure accurate identification and characterization of geologic units. Future work will involve determination of crater count-derived ages to obtain absolute ages of geologic units when possible.

Results: Three main geologic sequences are present throughout the map area: 1) Basement rocks, that are associated with pyroxene and clay spectral signatures in CRISM, of likely Noachian age and that may
exhibit layering, 2) Light-toned fractured units that are associated with olivine and variable carbonate spectral signatures, and 3) A cratered mafic unit that superposes the light-toned fractured units and that occurs within Jezero, on Jezero’s rim, and in NE Syrtis (Fig. 1). Textural variations are observed in all of these three main materials and we will map sub-units as appropriate at our mapping scale.

**Expected Significance:**
This geologic map of the greater Jezero region will enhance future scientific investigations of this important region of Mars. This map will provide broad geologic context for orbiter or future Mars 2020 rover observations of rocks studied and samples collected in this region. The geologic units identified in this regional map could serve as proxies for associated mineralogic composition in areas where there is no orbital spectroscopic data, as distinct geologic units in this region are strongly correlated with particular mineral compositions, but this region has incomplete coverage of orbital mineralogic data, particularly in the area between the Jezero and NE Syrtis ellipses. Lastly, the production of a geologic map following the standardized USGS framework will allow for units in this region to be assigned chronostratigraphic ages through crater-count age dating and comparison with the regional stratigraphy in previous USGS maps.

**References:**

**Figure 2.** A) Extent of the map area, on a CTX basemap. B) The map area with previous maps overlaid.
GEOLOGIC MAPPING AND STUDIES OF DIVERSE DEPOSITS AT NOCTIS LABYRINTHUS, MARS.

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Introduction: Noctis Labyrinthus consists of a network of intersecting linear troughs and pits along the eastern Tharsis rise that connect eastward to the continuous chasmata of Valles Marineris. The pits and troughs may have formed due to withdrawal of magmatic reservoirs at depth [1], or by collapse over conduits developed as a consequence of groundwater flow along pre-existing fault systems [2]. The age of the Noctis Labyrinthus depressions is thought to be Late Hesperian to Early Amazonian based upon disruption of the lava plains along the plateaus [3-5]. Consequently, sediments deposited within the depressions represent this age or younger materials.

Mapping Investigation: For this study, we are mapping the western portion of Noctis Labyrinthus (-6 to -14°N, -99.5 to -95.0°W; Fig. 1), which includes some of the most diverse mineralogies identified on Mars using CRISM data [6-9]. We are using THEMIS daytime IR as a basemap, with a 1:500,000 publication scale. Thus far across the Noctis Labyrinthus region, the following minerals have been identified in association with light-toned deposits (LTDs): several kinds of sulfates (monohydrated kieserite, szomolnokite) and polyhydrated sulfates, jarosite, and Ca-sulfates (gypsum, basanite), clays (Fe/Mg-phyllosilicates and Al-phyllosilicates), clays (Fe/Mg-phyllosilicates and Al-phyllosilicates), a doublet absorption between 2.2-2.3 μm, and hydrated silica/opal. The role of water, both in the formation of the Noctis depressions and the hydrated deposits found within them, is a focus of this investigation. The diverse range of sulfates and phyllosilicates identified within the depressions of Noctis Labyrinthus either resulted from localized aequorous activity [8,9] and/or may have been part of a broader synoptically driven period of late activity during the Late Hesperian to Amazonian [e.g., 10-12].

Mapping Progress: We have completed mapping of all geologic units and linear features (Fig. 1). Numerous structural features, including grabens and scarps, are found throughout the mapping region. Mapping of normal faults and grabens indicates multiple episodes of collapse.

Loose eolian debris and dust covers much of the plateau, trough floors, and wallrock, obscuring geologic contacts between different units at these locations. The dust mantle thins to the east and south, where individual lava flows are evident along the plateau. Two volcanic shields have been mapped in the southwestern plateau and both are embayed by younger lava flows. Beneath the plateau plains unit is the gullied and layered wallrock unit, which is similar in morphology to the layered gullied upper wallrock observed throughout Valles Marineris. Light-toned deposits occur in only one location along the plateau and they are only visible as small patches because a dark mantle and eolian ripples cover much of the plateau, including the light-toned deposits, in this region. CRISM spectra show the presence of opal in association with these plateau deposits.

Floor units within the troughs and pits include light-toned deposits, many of which also exhibit spectral hydration features, and mass wasting deposits, including landslides. Lava flows with Amazonian ages [13] have been mapped on two trough floors. Floor morphology can either be smooth or rough, with the smooth morphology typically the result of eolian fill. No fluvial channels have yet been identified either along the plateau or within the depressions, but a possible volcanic channel sourced by a collapsed rounded depression within one of the troughs indicates younger volcanism occurring after formation of the trough. Dark dunes have been mapped in two troughs.

Relative dating of surfaces employed crater statistics and stratigraphic relationships, where crater statistics were compiled in ArcGIS using a subset of CTX images and CraterTools, a plug-in software for ArcGIS [14]. The resolution of CTX images enabled confident definition of craters >20 m in diameter (D) and counts excluded obvious secondary clusters. Interpreted absolute ages for each count were derived from segments of the plots for each unit that best match the expected production population using “root-2” binned differential histograms and Craterstats2 software [15]. Absolute derived ages are based on the production function of [16] and chronology function from [17, 18]. The geologic epoch associated with each count and range of epochs covered by the error bars are based on the chronology function from [18]. Randomness analyses [19] were also included to ensure lack of clustering.


Figure 1. THEMIS daytime IR basemap with geologic units and linework overlain for our geologic mapping region in Noctis Labyrinthus.

Figure 2. (a) Crater size frequency for the Noctis plateau that shows a model age of Late Hesperian. (b) Crater size frequency for the floors of the pits and troughs that shows a model age of Amazonian.
A FORTHCOMING GLOBAL GEOLOGIC MAP OF PLUTO. O. L. White$^{1,2}$, K. N. Singer$^3$, D. A. Williams$^4$, J. M. Moore$^5$, R. M. C. Lopes$^6$, $^1$SETI Institute, Mountain View, CA, 94043 (owhitet@seti.org), $^2$NASA Ames Research Center, Moffett Field, CA, 94035, $^3$Southwest Research Institute, Boulder, CO, 80302, $^4$Arizona State University, Tempe, AZ, 85281, $^5$NASA Jet Propulsion Laboratory, Caltech, Pasadena, CA, 91109.

Introduction: Following its flyby of the Pluto system in 2015, NASA’s New Horizons spacecraft returned high quality images that reveal an unexpectedly diverse range of terrains on Pluto, implying a complex geological history [1,2]. Pluto’s geological provinces are often highly distinct, and can exhibit disparate crater spatial densities [2-4]. Surface renewal is ongoing, as demonstrated most compellingly by the N$_2$ ice plains of Sputnik Planitia [5,6]. Pluto’s geology displays evidence for having been affected by both endogenic and exogenic energy sources (including internal heating and insolation/climatic effects). Its complex nature is likely caused by combinations of these influences governing the distribution and behavior of different surface compositional suites to strongly varying degrees across even small lateral distances. Recent studies [7-12] have used climate modeling and theoretical considerations to formulate hypotheses regarding how volatile species are transported across Pluto on geological timescales in order to explain the appearance and distribution of certain features. Over the coming three years, we will be using established geologic mapping techniques to produce a global USGS Scientific Investigations Map (SIM) at 1:7M scale for the portion of Pluto that was imaged by New Horizons. Such a map will represent a critical tool for resolving differing hypotheses of Pluto’s evolution. This abstract presents a summary of what mapping has been performed by the authors to date, as well as our mapping rationale for the global map.

Regional Geologic Mapping of Pluto to Date: Published mapping by PI White includes a very rough physiographic map that delineates different terrain types across Pluto’s encounter hemisphere without regard to stratigraphy [2], as well as localized mapping for the “bladed” [13] and “washboard and fluted” [14] terrains. Co-I Singer has mapped the tentative cryovolcanic feature Wright Mons [15]. The most comprehensive mapping study to date, led by PI White, is the geological map of Sputnik Planitia and part of eastern Tombaugh Regio, produced at a 1:2M scale [16]. This study developed hypotheses concerning how climate-controlled volatile transfer, in combination with convection of the N$_2$ ice, have defined the observed variation in morphology and surface albedo across the plains. While the mapping has offered insight into how Sputnik Planitia is evolving, the scientific conclusions drawn from it nevertheless remain isolated to that feature. Crucially, the global and unequal cycling of volatiles on Pluto is evident from climate modeling and a cursory examination of its surface means that the provenance of no single geological province can be considered in isolation, and a complete and fully integrated understanding of how Pluto’s surface has evolved requires the production of a global geological map that identifies distinct geological units and assigns geological processes for their evolution, and also relative ages based on crater age dating and superposition relations.

Mapping Rationale: Our geologic mapping will follow the standard principles of the mapping of extra-terrestrial bodies as outlined in the 2018 Planetary Geologic Mapping Protocols [17]. New Horizons imaged more than 75% of Pluto’s surface, with the encounter hemisphere representing the ~50% of the surface that was imaged at pixel scales between 890 and 76 m/pixel during the hours before closest approach. The remaining >25% of the imaged surface is the anti-encounter hemisphere, imaged at pixel scales between 2.2 and 40.6 km/pixel. Our base map (projected at 300 m/pixel, Fig. 1a) excludes the highest resolution 117 m/pixel and 76 m/pixel strips that cross the encounter hemisphere, meaning that the total pixel scale range for the base map is 40.6 km/pixel to 234 m/pixel (Fig. 1b). Supplementing our monochrome base map is a global color mosaic (reaching 680 m/pixel) and a digital elevation model (DEM) of the encounter hemisphere (Fig. 1c), which can resolve topographic features as small as ~1.5 km across, and which has vertical precision ranging between 100 m and 800 m[18].

We will perform geological mapping of the encounter hemisphere at an equatorial scale of 1:7M, with a minimum feature diameter to be mapped of 7 km. The great contrast in pixel scale between the encounter and anti-encounter hemispheres, however, means that we will map the two hemispheres at different scales. This situation has been encountered in previous mapping projects for outer Solar System bodies. For instance, the global geologic map of Ganymede [19] utilized imaging that was better than 1 km/pixel for less than one-eighth of Ganymede’s surface, meaning that the final map was considerably more detailed in some areas than others. For our map, we have defined a specific dichotomy between the low and high resolution mapping areas, with 1 km/pixel set as the bounding pixel scale. At the pixel scale of the anti-
encounter hemisphere, only surface features on a scale of several to tens of kilometers can typically be discerned, and topographic relief and detailed textures of mapped units that are apparent within the encounter hemisphere will be invisible. The anti-encounter hemisphere mapping will therefore only occur upon completion of that for the encounter hemisphere, and will consist of a handful of undivided units that are defined based primarily on their albedo.

A consequence of the flyby nature of the New Horizons mission is that, for the encounter hemisphere, each point on the surface was only imaged at a single solar incidence and emission angle. The sub-solar point is at 130.5°E, 51.5°N, with the solar incidence angle increasing to 90° at the edge of the encounter hemisphere, while the anti-encounter hemisphere imaging was mostly obtained at incidence angles >75°. The variation in emission angle follows a similar pattern. We will therefore have to account for such variance in order to ensure consistency in unit definition across the map. Much of the base map is illuminated and viewed at an oblique angle such that the relief of the terrain is emphasized. But for the high-Sun and near-nadir viewing angles in the central portion of the encounter hemisphere, we can ameliorate the situation by using the global DEM to assess surface relief, rather than relying on shading in the base map images to convey such relief.

The combination of superposition relations and crater age dating will aid understanding of ongoing activity on Pluto and the relative timing of different events as determined by our unit interpretation. Crater density across Pluto’s surface is highly variable, and in the case of a craterless landscape such as Sputnik Planitia, stratigraphic correlation of units within it is restricted entirely to superposition and crosscutting relations [14]. For elsewhere across Pluto, previous crater analyses [2-4] have focused on measuring crater statistics for the entire encounter hemisphere or for broad physiographic provinces. We will build on previous work by integrating the locations of craters that have already been identified [3,4] into the proposed map, including craters with diameters ≥7 km. These crater densities will be utilized to infer relative terrain ages for the specific units mapped in this proposal, allowing us to define a geologic timescale for Pluto.

CAN THE INTERCRATER PLAINS UNIT ON MERCURY BE MEANINGFULLY SUBDIVIDED?: CHARACTERIZATION OF THE DERAIN (H-10) QUADRANGLE INTERCRATER PLAINS. J. L. Whit-ten1, C. I. Fassett2, and L. R. Ostrach3, 1Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA 70118, (jwhitten1@tulane.edu), 2NASA Marshall Space Flight Center, Huntsville, AL 35805, 3U.S. Geolog-ical Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

Introduction: The intercrater plains are the most complex and extensive geologic unit on Mercury [1, 2]. Generally, the intercrater plains are identified as gently rolling plains with a high density of superposed craters <15 km in diameter [1]. Analyses of the current crater population indicate that the intercrater plains experienced a complex record of ancient resurfacing [3, 4] (i.e., craters 20–100 km in diameter are missing). This dearth of larger impact craters could have been caused by volcanism or impact-related processes. Various formation mechanisms have been proposed for the inter-crater plains, including volcanic eruptions and basin ejecta emplacement [1, 5–10].

The major difficulty with mapping the intercrater plains is the diversity of its morphology. USGS geologic maps produced using the Mariner 10 data used a variety of geologic unit names to describe the same materials, most frequently intercrater plains, cratered plains materials, and intermediate plains. An example of the confusion surrounding materials with an intercrater plains morphology, the Kuiper (H-6) quadrangle contains both an intercrater and crater plains materials unit [11]. Victoria quadrangle (H-2) also contains both units, so that along the border with H-6 intercrater plains are mapped as cratered plains materials and the rest of this morphologic unit is mapped as intercrater plains; in H-2 cratered plains materials are interpreted as intercrater plains. Cratered plains materials have also been interpreted as intermediate plains [12], bringing this unit definition full circle. Clearly, there was and continues to be little agreement about the definition of intercrater and intermediate plains.

It appears that previous researchers were looking for a way to divide up the massive intercrater plains unit by mapping an intermediate unit. This seems like a good idea, however, there was no quantitative measure or definitive characteristic used to divide the intercrater plains from the intermediate plains. Qualitatively, these two geologic units differ in their density of secondary craters and their morphology. Intermediate plains have a more muted appearance and have been interpreted as older smooth plains [13]. All of the plains units on Mer-cury appear gradational with one another in many locations on the surface (more often the smooth plains have distinct boundaries).

More recently, researchers have used the higher resolution MErcury Surface, Space ENvironment, Geo-chemistry, and Ranging (MESSENGER) datasets, to assess the intercrater plains [10]. Despite the higher resolution data, there are still no characteristics in spectral data (MDIS color, VIRS) that can be used to qualitatively subdivide the intercrater plains. The global resolution of topographic data is 64 ppd and the MLA track data are sparse and spaced far apart in the southern hemisphere, which leads to measures of roughness not being very useful. Areal crater density measurements of Mariner 10-mapped intercrater and intermediate plains N(10) and N(20) values [see 14] are completely intermixed, meaning that at the larger crater diameters (i.e. >10 and >20 km in diameter) there is no distinct age

Figure 1. View of the Derain (H-10) quadrangle. Red boxes show the location of mapped sub-regions used to define intercrater plains unit. The bold red region (rightmost box) map is shown in Figure 2. Smooth plains mapped by [7] are in yellow. Craters ≥30 km in diameter are shown in white and those >150 km are also outlined in blue. MDIS monochrome (750 nm) 166 m/pixel global mosaic.
differences that correspond to a coherent area of the surface of Mercury [10]. Thus, we have to look to the smaller-scale morphologic differences to subdivide the intercrater plains.

Here, we discuss an in-progress 1:5M USGS map of the Derain (H-10) Quadrangle of Mercury (Figure 1) as a means to assess whether the intercrater plains unit can be meaningfully subdivided and what it can reveal about the importance of impact melt and other ejecta materials on the resurfacing history of Mercury.

Data: MESSENGER mission image data are the primary dataset being used to produce the H-10 quadrangle map, specifically the Mercury Dual Imaging System (MDIS) monochrome mosaic at 166 m/pixel. Mapping is being done at a map scale of 1:1.25M. Supplemental datasets include the MDIS color mosaic (665 m/pixel), and MDIS East and West Illumination mosaics (166 m/pixel).

Approach and Current Progress: The intercrater plains boundary is typically difficult to define because in many locations on Mercury the morphology can transition from smooth plains to muted hummocky plains to plains with a high density of secondary craters (Figure 3). In H-10 we map the least complicated materials first, such as the smooth plains and crater materials (e.g., Figure 2). The remaining materials are almost all intercrater plains, having a variable morphology across the map area. Co-Is Ostrach and Fassett have identified an ‘intermediate’ plains unit that has a more muted hummocky appearance than mapped intercrater plains and is generally located between smooth and intercrater plains. Their mapped units generally overlap, so there is some consistency between mappers. The challenge that remains is to subdivide the intercrater plains in a consistent way, either as two separate units or one unit with two or more different facies (depending on how many distinct intercrater plains morphologies can be identified across H-10).

Two subsets of the H-10 quadrangle (Figure 1) have been mapped by the proposal team (e.g. Figure 2). This mapping effort was conducted in order to assess how each team member defines the intercrater plains. From these efforts it is clear that subdividing the intercrater plains is favored, but the exact method is not yet agreed upon. A preliminary Description of Map Units has been assembled.

Introduction: A 1:4M global geologic map of dwarf planet (1) Ceres was completed by the science team from NASA’s Dawn mission, derived from images obtained during the Low Altitude Mapping Orbit (LAMO, 35 m/px). The map was published on the cover of *Icarus*, volume 316, December 2018 issue, along with a series of papers describing the geology within Ceres quadrangles. In this abstract we present the final map (Figure 1) and summarize our findings.

Ceres Mapping Campaign: The geologic mapping campaign for Ceres using Dawn Framing Camera images is described in [1]. In summary, we conducted an iterative mapping campaign using images with increasing spatial resolution from Dawn’s Survey orbit, High Altitude Mapping Orbit (HAMO), and LAMO. The first Survey map was published in *Science* [2]. The HAMO map with the chronostratigraphy and geologic timescale for Ceres is currently in review. The 15 individual LAMO quadrangle geologic maps of Ceres are published with links included in the References [1, 3-13].

The objectives for geologic mapping using the LAMO mosaics were to investigate geologic features/topics identified from the initial global mapping in more detail and to refine the geologic history. As discussed in [1], there were challenges with this approach, most significantly coordination of 14 individual mappers and their mapping styles and objectives relative to efforts by other Dawn Science Team members. In the end, for the final published maps and mapping papers, individual quadrangles were combined when needed based on the distributions and extents of geologic units and features on the cratered surface. For example, the Urvara and Yalode quadrangles were combined because of the proximity of these two large basins and overlap of their deposits and structures [13]. In all, eleven papers were published that discuss important geologic features and processes, including the north polar cratered terrain [3]; the smooth impact melt-like deposits in Ikapati crater in Coniraya quadrangle [4]; the complex crater materials in Dantu crater; water ice-based lobate flows in Ezinu quadrangle [5]; six possibly cryovolcanic tholi (domes) in Fejokoo quadrangle [6]; the bright rayed and complex ejecta materials of Haulani crater [7]; the nature of the smooth material around Kerwan, Ceres’ oldest impact basin [8]; the ancient rim of the putative Vendemia Planitia basin in Nawish quadrangle [9]; the nature of floor fractures in craters in Occator quadrangle [10]; the interplay of cryovolcanic domes (e.g., Ahuna Mons), Yalode and Haulani ejecta in Rongo quadrangle [11]; the wide diversity of crater morphology found in the Sintana quadrangle [12]; and the complex stratigraphy of crater materials in the adjacent large basins Urvara and Yalode [13]. These eleven papers along with an introductory paper discussing the Ceres mapping campaign can be accessed at links below, or in the December 2018 special issue of *Icarus*.

Figure 1a. Final LAMO-derived global geologic map of dwarf planet (1) Ceres (Plate Carree projection, center long. = 180°, IAU-approved Dawn Kait coord. system). This map was produced using ArcGIS™ software through integration of 15 individual quadrangle maps produced by the coauthors. For citation of the Dawn Ceres LAMO-based map, please use this abstract. For a poster-sized version of the final map, please contact David Williams (David.Williams@asu.edu).

Figure 1b. Legend for Ceres unified LAMO geologic map. After [2].
HIGH-RESOLUTION GEOLOGIC MAPPING OF TERRACED FANS IN XANTHE TERRA, MARS. Jeannette M. Wolak, Natalie N. Robbins, Allison M. Bohanon, and Hannah E Blaylock, Department of Earth Sciences, Tennessee Tech University, 1 William L Jones Drive, Cookeville, TN, 38505; jwolak@tntech.edu.

Introduction: The Xanthe Terra region of Mars hosts a variety of fan-shaped features, including terraced fans, a subset characterized by their small aerial footprint (<10km diameter) and concentric, alternating zones of steep and shallow slopes. To date, approximately 84 such features have been identified on the global martian surface [1], and plausible interpretations for formation range from fluid-poor models, i.e. alluvial fan deposition [2], to fluid-rich models, i.e. deltaic deposition or sustained overland flow [3, 4]. Most terraced fans occur in late Noachian to Hesperian geologic units [1, 5]; however, recent work demonstrates that the fans themselves may be significantly younger than surrounding terrains [6].

The purpose of this project is to create a series of high-resolution geologic and geomorphic maps of terraced fans in the Xanthe Terra region and use these maps to test competing formative models of deposition. Prior mapping efforts provide valuable context [4, 6, 7]; however, most published geologic maps of terraced fans are low resolution and do not provide information about the abundance or distribution of small-scale features such as boulders, incised valleys, distributary channels, narrow levees or barforms. Many of these observations can be linked to sedimentological process; thus, high-resolution mapping provides a valuable framework for interpretation.

Study Locations: A recent global survey of approximately 1,300 fan-shaped features on Mars categorized geometries as either semi-conical alluvial fans, terraced or stepped fans, or low gradient deltas [1]. Approximately 6% of the surveyed features were identified as terraced or stepped fans, including many fans previously documented in the Xanthe Terra region [3, 4, 6]. Most fans in Xanthe Terra are associated with feeder channels that cross Noachian to Hesperian highland units, incise steep crater walls, and result in classic point-source deposition adjacent to the crater rim. Examples of terracing can be seen in fans located at the debouchements of Tyras Vallis (8.45°N, 310.27°E) and Subur Vallis (11.73°N, 307.07°E) as well as in Camichel Crater (2.69°N, 308.33°E) and Dukhan Crater (7.59°N, 321.02°E). The latter two locations have adequate Context Camera coverage and high-resolution stereo pair imagery from the High Resolution Science Experiment (HiRISE) to support detailed mapping efforts, shown here in Figure 1.

Geologic Mapping: Given that individual terraces may range from several meters wide to less than a meter wide, high-resolution mapping parameters were designed to capture as much detail as possible and facilitate sedimentological interpretations. The scale of mapping is 1:18k, comparable to recent mapping of structurally-complex regions in Candor Chasma [8]. Line work follows standardized mapping procedures outlined in the 2018 Planetary Geologic Mapping Protocol [9], and mapping is conducted at a scale of 1:4k, four times the proposed publication scale. Vertex spacing for line work is 4m, and geologic units are defined based on visual characteristics including tone, terrain roughness, abundance of boulders, and stratigraphic position. Mapping of multiple terraced fans shows a general stratigraphy that appears to be common to fan systems and includes, from oldest to youngest: (1) crater floor and wall terrains; (2) distal (lower) fan terraces; (3) proximal (upper) fan terraces; (4) feeder channel infill deposits; and (5) aeolian deposits.

Camichel Crater Fan Mapping: The fan located in Camichel Crater measures approximately 6.5km across the broadest terraces. The most distal deposits associated with fan deposition are 1km from the fan apex, the point at which flow parameters changed from confined within the feeder channel to unconfined adjacent to the rim of Camichel Crater. General measurements of fan thickness using Mars Orbital Laser Altimeter (MOLA) data show that the thickest parts of the proximal fan are 340-380m thick; however, this estimate assumes that terraces are subparallel to the underlying crater floor, and the crater floor has not subsided due to loading of fan material.

Two crater floor units are identified in Camichel Crater, and cross-cutting relationships suggest that these terrains are significantly older than fan units, a conclusion that is consistent with crater counts documented in Hauber et al. [6]. Six terraced fan units are defined based on subtle changes in texture and tone of the base orthoimage. These record changes in depositional process from older, distal terraces to younger, proximal deposits. Although aeolian features are visible on the surface of the Camichel Crater fan, they do not generally obscure geologic contacts, and thus they are not mapped as a different unit.

Dukhan Crater Fan Mapping: The Dukhan Crater fan is located approximately 800km east-northeast of Camichel Crater, on the eastern edge of the Xanthe highlands unit. The dimensions of the fan are similar to the Camichel Crater fan: 8.5km in diameter and 10.5km from fan apex to the most distal fan deposits. Fan thickness estimated from global MOLA topographic data is 530-550m; however, the rim of the Dukhan Crater dips...
to the northwest, parallel to the fan axis, and thus, fan thickness may be overestimated.

Although similar stratigraphic trends are observed on both terraced fans, geologic contacts on the Dukhan Crater fan are masked by thick, widespread dune deposits. Dune fields and sand sheets are therefore mapped as a separate unit (Figure 1). With respect to older terrains, two crater floor units are identified as well as a highlands unit that includes the crater rim and walls of an incised feeder channel [10]. Six units are defined that characterize fan deposition, and these are best exposed on broad terraces between younger dune deposits (Figure 1).

**Future Work:** Next steps include detailed documentation of map units and development of a correlation of map units for each fan. Additional geomorphic maps have been generated that show the abundance and distribution of dunes and boulders, which can be used to determine depositional process and the likelihood of fluid-rich versus fluid-poor development.


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**Figure 1.** High-resolution 1:18k geologic mapping of terraced fans located in Xanthe Terra: the Camichel Crater fan (left image, 2.69°N, 308.33°E) and Dukhan Crater fan (right image, 7.59°N, 321.02°E). Both features show a similar general stratigraphy of older crater floor units (greens) and terraced fan deposits (purples and blues); however, contacts on the Dukhan Crater fan are masked by extensive aeolian deposition (yellow).
GEOLOGIC MAPPING OF BOTH ALTERATION MINERALOGIES AND SHOCK STAGES OF EJECTA LOBES AT LONAR CRATER, INDIA USING GPS, LAB SAMPLE ANALYSES, AND HIGH RESOLUTION IMAGERY  S.P. Wright1 and S.A. Goliber2; 1 swright@psi.edu; Planetary Science Institute, Tucson, AZ; 2University of Texas, Austin, TX

Introduction: Lonar crater is an ~1.8 km diameter impact crater (Fig. 1) located in Maharashtra state, India [1]. This well-preserved impact crater is emplaced in the basaltic Deccan Traps, which makes it a good Earth analog for studying post impact modification of craters on Mars. The approximate crater age is 570 ka [2].

The formation of gullies and drainage patterns on and around Lonar crater help to constrain post-impact modification processes of a more hydrologically active Mars. Surface runoff most likely controls the formation of the drainage channels of Lonar crater, which originated at the crater rim and extend radially [3,4].

Figure 1. ASTER false color composite image of Lonar Crater using band ratios. Iron bearing minerals are shown in red, vegetation in green, and OH-bearing minerals such as clays in blue. Water, vegetation and urban have been masked out.

Goals: Planetary analog fieldwork at Lonar is in the near future concerning both rovers and astronauts. We aim to create a high-resolution geologic map that will compare well with Shoemaker’s geologic map of Meteor Crater, AZ [5]. Where mapping lithic breccia and suevite breccia, it was decided to field map the extent of lithic ejecta lobes and their precise aleration mineralogy, as several alteration types were found. These include: fresh basalt, gray basalt, hematite basalt, zeolite basalt, green amygdule basalt, iddingsite basalt, chaledony basalt, baked zones or “bole”, and others. The altered basalts represent the earliest ~65 Ma basalt flows that were aqueously altered by groundwater before impact. Figure 3 focuses on just one alteration mineralogy shown in red: “Gray Basalt Red Matrix” (GBRM).

Methods: A ~1 m/pixel resolution Quickbird image [7] was georectified in ArcGIS 10 using a Landsat 8 image as the base. The georectified Quickbird was used as an overview image as well as for mapping drainages.

Using the Quickbird image and a Digital Elevation Model from [7], the drainage patterns mapped by [6] were expanded. Channels in the interior walls of the crater were mapped if they appeared to have a visual hydrological connection to exterior drainages.

An ASTER Band math false color composite image (Fig. 1) was created using ENVI Classic 5.0. The band ratios are as follows: Red = B4 (1.6-1.7 μm) / B3 N (0.78-0.86 μm); Green = B3 (0.78-0.86 μm) / B2 (0.63-0.69 μm); Blue = B4 (1.6-1.7 μm) / B5(2.145-2.185 μm). The red highlights iron-bearing minerals, blue highlights OH- and clay bearing minerals, and the green is vegetation. The image was equalized to increase the contrast between the ejecta and surrounding farmland. Attempts to mask pixels corresponding the farmlands, vegetation, a reservoir, the lake, and the lakeside are ongoing. The goal is to quantitatively compare pixels of ejecta preserved by the Indian Department of Forest.

GPS points from previous field work obtained using a hand-help GPS were overlain on Quickbird and ASTER images were used in mapping a ejecta distribution, drainage and notable features on and around the
crater. Extensive farming activity in the surrounding area make the exact boundary of the ejecta blanket using satellite imagery difficult to determine.

Field Data: Whereas the Department of Forest has called for the preservation of near-rim ejecta, the uppermost surface and mostly all of the edges of the continuous ejecta blanket (CEB) have been destroyed by farming over the last thousand years. Further, the largest blocks of impact breccia clasts have been removed by ancient man (Dravidians ~1100 years ago) to build temples and other man-made structures.

The fine, red matrix of the impact breccia that is found with ~50% of Gray Basalt lobes is likely due to their pre-impact stratigraphic relation, as red boil or baked zone overlies Gray Basalt in outcrops 5 to 30 km away from Lonar. The boil is pulverized to become the matrix of the lithic breccia with nondescript Gray Basalt being the clasts. Another common “lithologic association” seen in lithic ejecta lobes include clasts of basalt containing (separately) iddingsite, hematite, and green amygules. We suggest these pre-impact alterations were mixed as ejecta lobes.

Figure 3 (above) 10 categories of altered basalt have been labelled/categorized for this study, but only one is focused on here and shown in the field on the lower left. “Grey Basalt Red Matrix” is shown in red on the table, the ASTER image, the 1-m “Google-Maps” image of the west ejecta, and the spectral plot. All other “Alteration Lithologies” are shown as blue.

Results: An integrated map of remote sensing and field data such as Figure 3 will be presented following the synthesis of the additional field data collected. This will include the location of ejecta types in the field and the distribution of channels and gullies surrounding Lonar crater. Remote multispectral spectra of Fe-bearing and OH-bearing pixels will be compared to laboratory VNIR-SWIR spectra of variously altered basalt described here, including those high in hematite, augite, and clays.

GEOLOGIC MAPPING METHODS FOR SMALL, ROCKY BODIES: THE VESTA EXAMPLE.
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Introduction: Defining criteria for mapping the boundaries of material units on airless, rocky bodies can be challenging because the primary geologic process is commonly impact cratering. Additionally, surface morphology is muted by the regolith’s physical and mechanical properties. Thus, the traditional mapping approach of using morphology as the primary criterion of unit definition can be problematic, because the differences in morphological characteristics among the various cratered surfaces can be subtle to absent.

We are constructing a global geologic map of Vesta at 1:300,000-scale using the Dawn Framing Camera (FC) images as a basemap, while DTM-derived slope and contour maps yield the shape of the surface. Our map also incorporates color (visible wavelength) and spectroscopic data; previous maps were not able to fully utilize these data as they were not yet calibrated [1-3]. As we map, we evaluate how much weight each dataset should be given in defining criteria for unit boundaries, and what the consequences of those choices are. Using Vesta as a test case, our ultimate goal is to explore best practices for geologic mapping with multiple, disparate datasets, under the challenges presented by an airless, rocky body.

Background: Vesta is an ellipsoidal asteroid of approximately 286 km long axis [4]. Earth-based and Hubble Space Telescope data suggested it had sustained large impacts, including one that produced an enormous crater at the south pole. Measured and inferred mineralogy results indicated that Vesta has an old, differentiated surface, with spectrally-distinct regions that can be geochemically tied to the HED meteorites [5-7]. Dawn data confirmed that Vesta has a heavily-cratered surface, with large craters evident in numerous locations. The two largest impact structures resolved are the degraded Veneneia crater (~395 km diameter), and the younger, larger Rheasilvia crater (505 km diameter), both located near the south pole. Vesta’s surface is also characterized by a system of deep troughs and ridges.

Data: The Dawn Framing Camera (FC) Low-Altitude Mapping Orbit (LAMO) images constitute the basemap. The Digital Terrain Model (DTM), derived from High-Altitude Mapping Orbit (HAMO) FC stereo data of 93 m/pixel horizontal resolution [8], provides topography, while DTM-derived slope and contour maps yield the shape of the surface and assist in evaluating the extent of geologic materials and features. Color data provided by the FC, and high-resolution, calibrated spectroscopic data by the VIR and Gamma Ray-Neutron Detector Spectrometer (GRaND), allow compositional and elemental information about Vesta’s surface materials to be evaluated. VIR provides spectral data in the visible and near infrared wavelengths. GRaND yields abundances for rock-forming elements (O, Si, Fe, Ti, Mg, Al and Ca), radioactive elements (K, U and Th), trace elements (Gd and Sm), and H, C and N (major constituents of ices).

Mapping Procedure: Our initial approach was to follow the methods developed and described by [10-13]. Units were initially defined and characterized based on morphology, surface textures, and albedo, as well as traditional methods of relative age dating (e.g., crater size-frequency distribution, superposition relationships). Color data from the FC (and VIR) were examined as an overlay on the first draft of units, to refine unit boundaries where the morphologic characteristics provided more than one possible interpretation, or the interpretation of the unit type was ambiguous. Where unit boundaries were obscured by subsequent geologic activity (through emplacement of impact ejecta, or through vertical or lateral mixing of the surface regolith), ejecta from craters that post-date the activity were used as a proxy for the unmodified composition of the unit (e.g., lunar dark halo craters [14]). However, we found that this method did not provide sufficient ability to assess and interpret the spectroscopic and color data on its own merits. As a result, the color and morphologic data were not being incorporated synergistically into interpretations.

Recently we have begun a different approach, one that has been used to map the lunar Aristarchus plateau region [15]. Initially used to test how the availability (or lack thereof) of various types of datasets affects mapping results, this method requires creating a GIS map based on each available dataset in isolation, then comparing the resulting maps to assess what information is unique to each dataset, and of that, what best summarizes the geologic history of the region.

Progress and preliminary lessons learned: Using the initial mapping workflow based on the FC albedo/DTM basemap [16], we chose several small areas on which to test the method of parallel mapping, using compositional (e.g., color, VIR) data as the basemap (e.g., Figure 1). This has revealed some key points. Firstly, and not surprisingly, boundaries defined by compositional data tend to be gradational rather than discrete. While this is also true for some geomorpho-
logic boundaries, it is the rule rather than the exception when using color. Spectroscopy in the shorter wavelengths (UV-VIS-near IR) can only sample the upper few μm of the surface, and it takes very little unique material to affect the signal of a regolith in particular. This should not necessarily be seen as “contamination” however; compositional boundaries may still indicate genetically distinct material, such as is often the case with crater ejecta.

Secondly, and related to this point, we have confirmed that compositional data provides unique insight into pre-impact stratigraphy. On an airless body, the ejecta of an impact event can persist relatively unchanged, potentially over geologic timescales. Thus, even the upper microns of the surface can contain records of the vertical composition of the rock body. On the Moon, in particular, this fact has been used to identify mare material that has been obscured by regolith maturation [14]. On Vesta, certain spectral features can be interpreted to indicate composition at depth (eucrite/diogenite differences being most pronounced).

There are a number of colors in the FC visible wavelength data (e.g., light teal ejecta, darker mantling, orange surface material) that may indicate unique subsurface lithologies important to reconstructing Vesta’s geologic history. It is currently unclear, however, how the compositional map based on these “colors” should be used in a consistent manner to define or refine unit boundaries on a map that utilizes all datasets. Craters deep enough to excavate through the overlying regolith to the layer in question are distributed in more or less random locations, rather than in locations where they would reveal the extent of a subsurface layer; in other words they occur without respect to our convenience in interpreting vertical layering. This issue will be a key one to address as we continue our work.

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Figure 1. Justina crater. (a) FC albedo overlaid with topographic data (top) with cool to warm tones indicating low to high topography respectively, and FC color (bottom). (b) Maps created using basemaps of albedo (top) and color (bottom). (c) Map created by combining unique aspects of both maps in (b).