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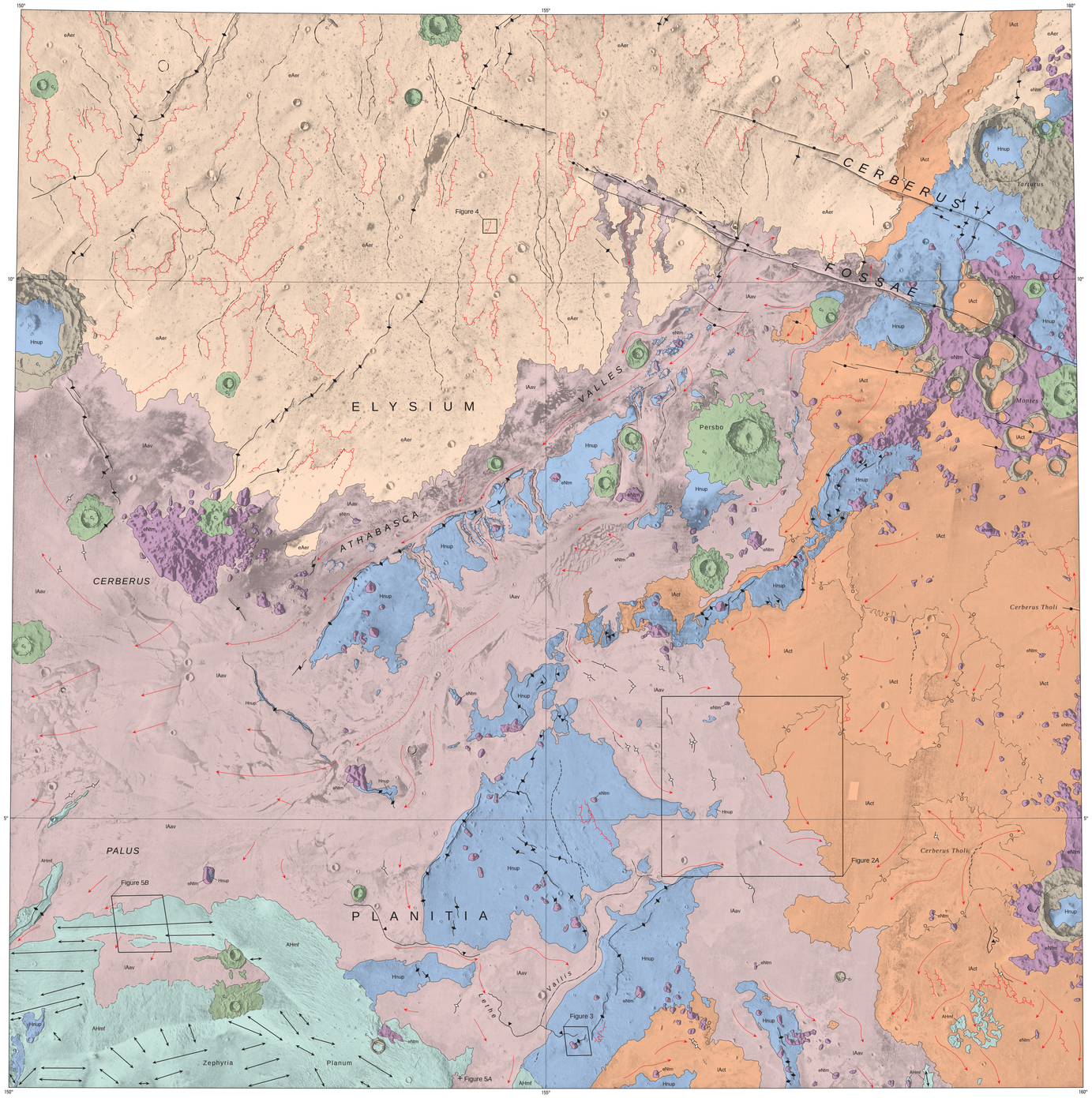
Prepared for the
National Aeronautics and Space Administration

Scientific Investigations Map 3477
Pamphlet accompanies map



Descriptions of nomenclature used on map are listed at https://planetarynames.wr.usgs.gov/

Elevations are based on topography derived from the Mars Orbiter Laser Altimeter (MOLA) experiment data set. For more information on the MOLA data, see Smith and others, 2001

SCALE 1:1 000 000 (1mm=1 km)
TRANSVERSE MERCATOR PROJECTION
25 0 25 50 75 100 MILES
25 0 25 50 75 100 KILOMETERS
PLANETOCENTRIC LATITUDE AND EAST LONGITUDE COORDINATE SYSTEM

Prepared on behalf of the Planetary Science Division, Planetary Mission Directorate, National Aeronautics and Space Administration

Edited by J.M. Brigham and J.L. Zigler; digital cartographic production by Katie Sullivan

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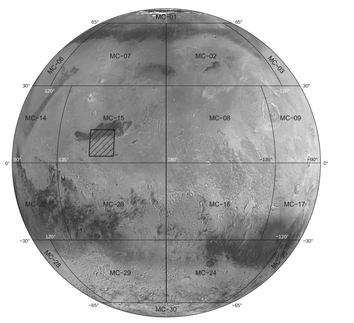
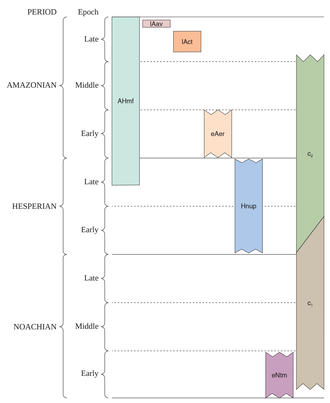


MAP LOCATION
Photomosaic showing location of map area (hachured rectangle). An outline of 1:5,000,000-scale Mars Chart quandrangles is provided for reference.

CORRELATION OF MAP UNITS



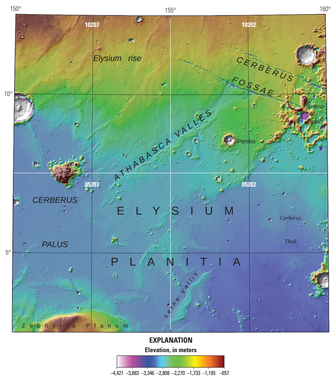


Figure 1. Topographic map showing the map area, the surrounding region, and the geographic feature names approved by the International Astronomical Union (IAU). The informal "Elysium rise," which is widely used in previous publications, is also labeled. Topography is from the Mars Orbital Laser Altimeter (MOLA) visualized with shaded relief and colored elevation. Mars Transverse Mercator (MTM) quadrangles are delineated with white lines and identified with white text.

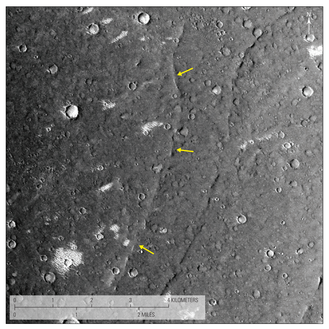


Figure 4. Image showing the typical surface of unit eAer. At the center of the image, the solar azimuth is 92.513° true, the incidence angle is 50.2°, and the emission angle is 1.3°, giving a phase angle of 51.5°. Degradation by impact craters and infilling by aeolian materials has largely obscured hectometer-scale features. The kilometer-scale and larger features are mapped selectively at 1:1,000,000 scale to provide an accurate representation of the surface without excessive clutter. For example, the scarp indicated by the arrows is shown on the map but the parallel scarp about 1 kilometer to the east is not. The unit is interpreted as lavas associated with the Elysium rise, but detailed volcanological interpretations are hampered by the poor state of preservation of smaller-scale features diagnostic of emplacement style. Image K04_05491_1917 of Mars centered at lat 10.532° N., long 154.472° E. acquired by the Context Camera (CTX) instrument onboard the National Aeronautics and Space Administration (NASA) Mars Reconnaissance Orbiter spacecraft. Map projected using Transverse Mercator projection with center latitude 11.811° N., center longitude 154.435° E. at a pixel scale of 5.482 meters.

DESCRIPTION OF MAP UNITS

[Unit groups and labels are discussed in pamphlet. Unit definitions, based on Mars Odyssey Thermal Emission Imaging System (THEMIS) Day Infrared (IR) observations, include diagnostic characteristics (for example, morphology, size, tone, and contact relations) and site coordinates for center of type area. Additional characteristics include observations from THEMIS Night IR, Mars Orbital Laser Altimeter (MOLA), Context Camera (CTX), and (or) High Resolution Imaging Science Experiment (HiRISE) images about secondary and local texture and contact morphologies diagnostic for unit distinction and correlation; image numbers cited where relevant. Interpretations derived from unit descriptions, additional characteristics, and published literature to state probable and possible geology. See Geologic History in pamphlet for further discussion of map units. Abbreviations: km, kilometer; m, meter; %, percent]

UNIT LABEL	UNIT NAME (AGE) AND DESCRIPTION	ADDITIONAL CHARACTERISTICS	INTERPRETATION	PREVIOUSLY PUBLISHED MAP UNIT (UNIT LABEL; SOURCE)
AHmf	**Medusae Fossae Formation (Late Amazonian to Late Hesperian)**—Grooved mounds/lobes, 10-km-scale. Abundant yardangs. Each mound/lobe preserves yardangs with consistent orientations, but these orientations vary from mound to mound. Impact ejecta relatively resistant to erosion, leading to pedestal craters. Exposure limited to the southern part of the map area as a 100-km-scale undulating plateau in the southwest with isolated outliers. Smooth at a 10-km wavelength but rough at the kilometer scale with local slopes exceeding the angle of repose and sometimes approaching vertical. Stratigraphically above unit Hnup but no contact with unit eAer. Commonly below the Late Amazonian lavas but above unit IAav in one area. *Type locality:* lat 2.75° N., long 150.75° E.	CTX: Specific contacts with units IAav and Hnup generally grade as the formation thins into a zone of increasingly isolated outcrops. In these locations, contact mapped as "approximate," where the terrain is ~50% unit AHmf and ~50% the adjacent unit (CTX image numbers: P08_004049_1859; P14_006472_1830)	Indurated but friable aeolian deposits, perhaps reworked and altered pyroclastic rocks and sediments. Each lobe appears to have formed independently in a series of similar but temporally distinct events over the Amazonian and perhaps even the Hesperian. The lobe that overlies unit IAav may be redeposited pyroclastic materials from the eruption that formed unit IAav	Rolling plains material (pr; Scott and Allingham, 1976) Medusae Fossae formation, Lower member (Aml; Greeley and Guest, 1987) Medusae Fossae formation, Lower member (Aml; Tanaka and others, 1992) Medusae Fossae unit (Aam; Tanaka and others, 2005) Cerberus Fossae 1 unit (A_{HC_1}; Tanaka and others, 2005) Hesperian transition undivided unit (Htu; Tanaka and others, 2014) Amazonian and Hesperian transition undivided unit (AHtu; Tanaka and others, 2014)
IAav	**Athabasca Valles Basalt (Late Amazonian)**—Young platy-ridged plains with lobate flow margins. Platy-ridged textures in most medial parts of the flow, exhibiting kinematic indicators (such as flow directions). Widespread across the central, western, and southern portions of the map area as one contiguous exposure and one 10- x 30-km outlier within unit AHmf. Drapes Athabasca Valles with a thin layer, produces a flat surface elsewhere. Flows downhill except immediately adjacent to the Cerberus Fossae where unit extends ~15 km against a very shallow slope. Stratigraphically overlies all other units except unit AHmf. No impact craters younger than unit IAav are mappable at this scale. *Type locality:* lat 6.0° N., long 151.5° E.	THEMIS Night IR: Northern valley of Athabasca Valles is brightest at Cerberus Fossae and darkens to the southwest with tonal streaks oriented northeast-southwest parallel to flow direction. Southern valley and Cerberus Palus are darker and have connected elongate, irregular polygons of bright material oriented perpendicular to flow direction HiRISE: Contacts are distinct with clear superposing embayment relations. In Athabasca Valles, the high lava marks are up to 100 m above the valley floor. Buried craters and other features suggest the deposit can be as thin as a few meters. The medial section is dominated by plates and ridges and the distal end of the lava transitions to sheets with inflation and meter-scale lobes. The 100-m-scale cratered mounds are arranged along buried topographic highs common within Athabasca Valles (HiRISE image numbers: ESP_011825_1895; ESP_012814_1895)	Fissure-fed, platy-ridged flood lavas. This dominant morphology is formed by the disruption and movement of large pieces of the upper crust of the sheet flow. Much of the length of Athabasca Valles was filled to overflowing and then the lava drained away. The pattern of filled basins and exploited spillways suggests the flow thickness is ~15 m in Cerberus Palus and beyond. Cratered mounds are phreatomagmatic rootless cones. Features most consistent with mafic to ultramafic compositions (Jaeger and others, 2010)	Cerberus Fossae 3 unit (A_{HC_3}; Tanaka and others, 2005) Late Amazonian volcanic unit (IAv; Tanaka and others, 2014) Younger channel and floodplain material, undivided (Achu; Greeley and Guest, 1987) Rolling plains material (pr; Scott and Allingham, 1976) Plains material (p; Scott and Allingham, 1976) Elysium flood-plains material (Ache; Tanaka and others, 1992)
IAct	**Cerberus Tholi Basalt (Late Amazonian)**—Young lobate plains and low shields. Surface very sparsely cratered; no kilometer scale (or larger) impact craters. Occurs on the east side of the map area as one large exposure with isolated 10-km-scale outliers filling craters in unit eNtm and cut off by unit IAav. Extremely shallow slopes and lobate scarps only a few meters tall. Fissures or closed depressions located at the summit of 20- to 100-m-tall low shields. Stratigraphically below unit IAav but above all other units. Contacts and superposition relations within the unit allow the formation to be subdivided into 13 members. *Type locality:* lat 6.75° N., long 158.75° E.	CTX and HiRISE: Contacts generally sharp and distinct but locally obscured by aeolian deposits in the northeastern part of the map. Platy-ridged lava textures with distinct downslope flow indicators are clearly visible (CTX image numbers: P01_001474_1878; P15_006775_1897; P15_006986_1850) HiRISE: Flow margins are generally crenulated masses of meter-scale lobes at the limit of HiRISE resolution (HiRISE image number: ESP_038844_1855) MOLA: Slopes ≤0.1%, low shields ≤100 m tall	Intercalated lavas from low shields and fissure vents formed by plains volcanism (Greeley, 1982). Lava textures, vent structures, and general morphometry are consistent with mafic to ultramafic compositions	Cerberus Fossae 3, 2, 1 units (A_{HC_3}, A_{HC_2}, A_{HC_1}; Tanaka and others, 2005) Late Amazonian volcanic field unit (IAvf; Tanaka and others, 2014) Smooth plains material (Aps; Greeley and Guest, 1987) Younger channel and floodplain material, undivided (Achu; Greeley and Guest, 1987) Smooth plains material (ps; Scott and Allingham, 1976) Elysium flood-plains material (Ache; Elysium Region)
eAer	**Elysium rise Formation (Early Amazonian)**—Lobate flows oriented radial to Elysium Mons. Abundant flow margins and infrequent impact craters and wrinkle ridges. Flow margins generally a few tens of meters tall and define simple lobes tens of kilometers wide and >100-km-long. Morphologic features indicative of lava channels or tubes rare. Distributed as one continuous exposure covering the northwest portion of the map and a few 10-km-scale outliers as kipukas within units IAct and IAav. Gently slopes to the southeast with scarps that locally exceed the angle of repose. Stratigraphically below the Late Amazonian units and above unit eNtm. *Type locality:* lat 10.5° N., long 152° E.	CTX and HiRISE: Contacts generally sharp but commonly obscured by thin aeolian mantle in the northeastern portion of the map (CTX image numbers: P04_002437_1875; P07_003650_1989O) MOLA: The unit has a 0.2% slope over a 100-km baseline, which is much higher than any of the other units	A low broad shield of large mafic lava flows that were mostly emplaced in a manner consistent with aa. Intercalated with an indeterminate amount of aeolian sediments	Elysium rise unit (AHre; Tanaka and others, 2005) Amazonian Hesperian volcanic unit (AHv; Tanaka and others, 2014) Elysium formation, Member 1 (A_{el_1}; Greeley and Guest, 1987) Streaked plains material (pst; Scott and Allingham, 1976) Elysium formation, Member 2 (A_{el_2}; Tanaka and others, 1992)
eNtu	**Nepenthes undifferentiated plains (Late Hesperian to Early Hesperian)**—Elevated smooth plains. Sparse wrinkle ridges and impact craters; infrequent ridges and scarps similar to features common in unit eAer. Distributed across the map area as isolated kilometer-scale kipukas in younger lavas to 100-km-scale sloping plateaus associated with wrinkle ridges. Slopes are generally less than 0.1%. Stratigraphically below all units except unit eNtm. *Type locality:* lat 4.5°N., long 155° E.	CTX: Contacts gradational with unit eNtm, which it often surrounds. Contacts gradational with AHmf; sharp with other units (CTX image numbers: P01_001474_1878; P14_006472_1830)	Origin uncertain, but perhaps largely consists of colluvium from the erosion of unit eNtm. Some outcrops, especially near the center of the map, may be remnants of distal Elysium rise lavas that are older than unit eAer	Utopia Planitia 2 unit (H_{Nu_2}; Tanaka and others, 2005) Hesperian and Noachian transition unit (HNt; Tanaka and others, 2014) Late Hesperian transition unit (IHt; Tanaka and others, 2014) Knobby plains material (Apk; Greeley and Guest, 1987) Smooth plains material (Aps; Greeley and Guest, 1987) Knobby material (k; Scott and Allingham, 1976) Rolling plains (pr; Scott and Allingham, 1976) Smooth plains material (Aps; Tanaka and others, 1992)
eNtm	**Tartarus Montes Formation (Early Noachian)**—Intensely cratered rugged massifs and knobs 0.5–2 km in relief. Impact craters, crater ejecta, and mass-wasting features pervasive. Occurs across the map area, including the southwest end of the Tartarus Montes, as isolated knobs to 100-km-scale regions of overlapping impact craters up to 50 km in diameter. Slopes often exceed the angle of repose. Stratigraphically the lowest unit. *Type locality:* lat 9°N., long 159° E.	CTX and HiRISE: Contacts gradational with unit Hnup; sharp with other units (CTXimage number: P01_001474_1878)	Remnants of heavily cratered ancient (Noachian) highlands with significant modification by impacts, erosion, and burial that possibly extend into the Early Hesperian. Likely to consist of a wide variety of lithologies including significant amounts of megabreccia	Nepenthes Mensae Formation (HNn; Tanaka and others, 2005) Hesperian and Noachian transition unit (HNt; Tanaka and others, 2014) Undivided material (HNu; Greeley and Guest, 1987) Knobby material (k; Scott and Allingham, 1976) Undivided materials (HNu; Tanaka and others, 1992)
eNhc2	**Crater 2 unit (Late Amazonian to Early Hesperian)**—Sharp to subdued, continuous to semicontinuous asymmetric ridge that roughly encircles a bowl to semi-bowl-shaped basin with radial material that is a semi-continuous or fully continuous blanket around the exterior of the ridge. The ridge is circular to semicircular and infrequently scalloped. The interior basin commonly has a central peak and is not infilled by other units. Occurs throughout the map area. *Type locality:* lat 8.56° N., long 156.89° E.	Blanket material pervasively embayed or buried by younger units; infrequently forms isolated outcrops of ramparts	Moderately degraded impact crater material	Crater unit (AHc; Tanaka and others, 2005) Material of sharp-rimmed craters (c_2; Scott and Allingham, 1976) Central peak material (cp; Scott and Allingham, 1976) Amazonian crater material, moderately fluidized (Acf; Tanaka and others, 1992)
eNhc1	**Crater 1 unit (Early Hesperian to Early Noachian)**—Discontinuous asymmetric ridge that fully or partially surrounds a basin and rarely has visible radial material blanketing the exterior of the ridge. The ridge is frequently flattened relative to adjacent terrain. The basin does not have a central peak and is pervasively infilled by younger units; semi-bowl-shaped basins rare. Predominantly occurs within or adjacent to unit eNtm. *Type locality:* lat 9.79° N., long 159.31° E.		Intensely degraded impact crater material altered by erosion and deposition processes of adjacent terrains	Crater unit (AHc; Tanaka and others, 2005) Material of subdued craters (c_1; Scott and Allingham, 1976) Crater chain or cluster (cc; Scott and Allingham, 1976) Noachian crater material (Nc; Tanaka and others, 1992)

EXPLANATION OF MAP SYMBOLS

[For each feature type, typical morphologies and origin processes are indicated]

Contact—Solid where location certain; dashed where location approximate

Internal Contact—Boundary between different events within one unit, showing relative age where known: Y, younger; O, older

Positive-Relief Features

Ridge crest, type 1—Linear to sublinear, positive-relief feature with an echelon wrinkles and symmetric or asymmetric topographic profiles tens of meters high. Origin: tectonic compression

Ridge crest, type 2—Sinuous linear to sublinear, positive-relief feature with symmetric or asymmetric topographic profiles <10 m high. Origin: tectonic or volcanic compression

Flow front—Volcanic flow margins. Lobate scarps. Hatchures point downscarp

Terrace scarp—Scarp margin. Hachures point downscarp. Origin: volcanic or fluvial

Scarp base—Inflection axis at base of linear, sharp to muted scarps. Teeth point downslope. Origin: tectonic, volcanic, or erosional

Negative-Relief Features

Narrow fissure—Linear depression bounded on both sides by sharp to subdued scarps. Origin: volcanic

Channel, volcanic—Linear to curvilinear depression. Bounding lobate margins rare. Origin: volcanic

Lineament—Linear to curvilinear depression with irregular topographic expressions, lacking well-defined scarp boundaries. Origin: unknown

Orientation Features

Yardang—Parallel, narrow, linear ridges. Origin: eolian erosion

Flow direction—Flow direction as inferred from kinematics of surface features. Origin: volcanic flow

Crater Features—For all impact craters >5 km in diameter

Crater rim, sharp—Impact crater rim. Pointed to rounded scarp bounding interior depressions

Crater rim, degraded or buried—Older impact crater rim. Asymmetrical scarp bounding interior depression or scarp similar to crater rim; sharp

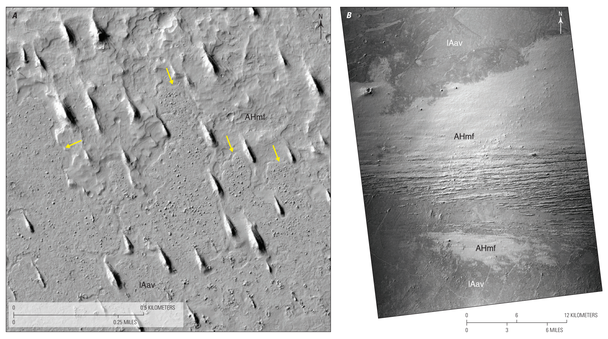


Figure 5. Images showing superposition relations between the Medusae Fossae Formation (AHmf) and Athabasca Valles Basalt (IAav). *A*, Image showing an example of unit IAav lavas emplaced atop unit AHmf. At the center of the image, the solar azimuth is 119.113° true, the incidence angle is 48.3°, and the emission angle is 0.1°, giving a phase angle of 48.2°. Arrows point to contact. *B*, Image showing an example of unit AHmf over unit IAav. The rafted plates and other features of the lavas continue uninterrupted underneath both thin patches and yardangs of unit AHmf. This relation is evident all along the northern side of Zephyria Planum. At the center of the image, the solar azimuth is 115.161° true, the incidence angle is 48.1°, and the emission angle is 0.1°, giving a phase angle of 48.1°. Image *A* of Mars spanning lat 2.615° to 2.638°, long 154.214° to 154.225° acquired by the High Resolution Imaging Science Experiment (HiRISE) instrument onboard the Mars Reconnaissance Orbiter. Map projected using the Equirectangular projection with center latitude 0.0° and center longitude 180.0° at a pixel scale of 0.5 meters (m). Image *B*, P18_008041_1841 of Mars centered at lat 4.005° N., long 151.208° E. acquired by the Context Camera (CTX) instrument onboard the National Aeronautics and Space Administration (NASA) Mars Reconnaissance Orbiter spacecraft. Map projected using the Transverse Mercator projection with center latitude 4.128° N., center longitude 151.197° E. at a pixel scale of 23.295 m.

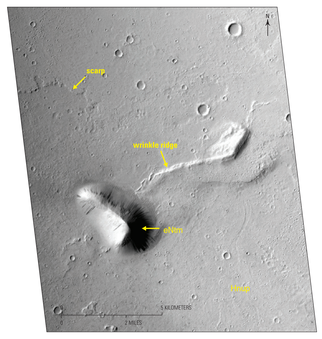


Figure 3. Image showing geographic features in units eNtm and Hnup. At the center of the image, the solar azimuth is 108.297° true, the incidence angle is 41.7°, and the emission angle is 1.5°, giving a phase angle of 43.0°. Superposition of unit Hnup plains material around the topographically higher knob of unit eNtm is somewhat obscured by talus shed from the knob. Similarly, any deformation of the knob during wrinkle-ridge formation has been removed by the mass wasting of the knob. Degraded hectometer- to kilometer-scale channels, mesas, and scarps are common in the plains but are generally impractical to represent on a 1:1,000,000-scale map. The labeled scarp near the top of the figure is one of the few larger features that we are able to include in our map. The scarp may be the margin of a lava flow, but the nature of the crenulation of the margins and the surface of the plains above the scarp are more consistent with a sedimentary deposit. Image G18_025064_1832 of Mars centered at lat 2.940° N., long 155.298° E. acquired by the Context Camera (CTX) instrument onboard the National Aeronautics and Space Administration (NASA) Mars Reconnaissance Orbiter spacecraft. Map projected using the Transverse Mercator projection with center latitude of 3.231° N., center longitude of 155.257° E. at a pixel scale of 10.765 meters (m).

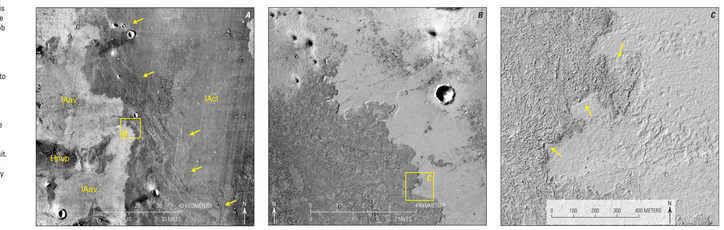


Figure 2. Images showing how prominent features in the 100 meter per pixel (m/pixel) Thermal Emission Imaging System Infrared (THEMIS IR) basemap are misleading when mapping the very young lavas in our map area. We identified unit contacts using High Resolution Imaging Science Experiment (HiRISE) images (<1 m/pixel) and then mapped them using Context Camera (CTX) <10 m/pixel data. *A*, Image showing a part of the controlled mosaic of Mars spanning lat 4.528° to 6.215° N., long 156.086° to 157.773° E. The prominent boundary between bright (warm) and dark (cold) surfaces might be presumed to be the contact between the lavas of units IAav and IAct. However, the contact is actually at the locations indicated by the arrows where there are no discernible features in the THEMIS basemap. Box shows location of figure 2*B*. *B*, Image showing a part of image P19_008489_1852 of Mars centered at lat 5.297° N., long 156.809° E. At the center of the image, the solar azimuth is 117.274° true, the incidence angle is 49.575°, and the emission angle is 8.130°, giving a phase angle of 56.378°. The prominent boundary seen in THEMIS IR (fig. 2*A*) is caused by a prominent change in surface texture and tone. The darker material on the west stands higher than the brighter material to the east, consistent with this being a boundary with younger lavas from unit IAav moving from west to east over older lavas from unit IAct. Box shows location of figure 2*C*. *C*, Image showing a part of image PSP_008489_1850 of Mars spanning lat 5.243° to 5.260° N., long 156.827° to 156.844° E. At the center of the image, the solar azimuth is 117.466° true, the incidence angle is 49.672°, and the emission angle is 8.133°, giving a phase angle of 56.453°. Yellow arrows highlight locations where it is evident that the higher-standing, platy-ridges lavas on the west are embayed by smooth pahoehoe sheet flows encroaching from the east, which is opposite from the relation inferred from THEMIS and CTX. Further examination of these lavas at HiRISE scale shows that the pahoehoe lobes on the east are a later breakout from the same platy-ridged sheet that is on the west, making these medial and distal facies of the same unit (IAav). The actual contact between IAav and IAct is >20 kilometers (km) further to the east. This illustrates how the HiRISE data were essential to determine the nature of contacts that were mapped on the CTX data. Image *A* was constructed from data acquired by the THEMIS IR instrument onboard the National Aeronautics and Space Administration (NASA) Mars Odyssey spacecraft. Map projected using the Simple Cylindrical projection at a pixel scale of 100 meters (m). Image *B* was acquired by the CTX instrument onboard the NASA Mars Reconnaissance Orbiter spacecraft. Map projected using the Transverse Mercator projection with center latitude 5.118° N., center longitude 156.832° E. at a pixel scale of 5-498 m. Image *C* was acquired by the HiRISE instrument onboard the NASA Mars Reconnaissance Orbiter spacecraft. Map projected using the equirectangular projection with center latitude 5.000° N. and center longitude 180.000° E. at a pixel scale of 0.25 m.

Geologic Map of the Athabasca Valles Region, Mars

By
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2021

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