

# U.S. Department of the Interior U.S. Geological Survey



Prepared for the National Aeronautics and Space Administration

# **CORRELATION OF MAP UNITS AND MAJOR EVENTS** [Query at ends of unit boxes shows beginning and (or) end of unit activity is uncertain] PLATEAU AND CRATER, VALLEY, AND CHANNEL UNITS HIGHLAND UNITS MAJOR EVENTS $\longrightarrow$ End of volcanic and chaotic activity End of fan activity Holden crater formed Uzboi-Ladon-Morava flooding begins Crater degradation Uzboi basin impact Ladon basin impact

in yellow. EXPLANATION Elevation, meters 3,140 -4.79050 100 150 200 KILOMETERS

### Scientific Investigations Map 3525 Pamphlet accompanies map

## Figure 1. Topographic map of the Ladon and Holden basin region derived from Mars Orbiter Laser Altimeter (MOLA) and High **Resolution Stereo Camera (HRSC)** digital elevation model (DEM) blended topography at 200-meter-per-pixel resolution (Fergason and others, 2018) merged to Thermal Emission Imaging System (THEMIS) daytime infrared mosaic. White boxes indicate boundaries of Mars Transverse Mercator (MTM) -15032 and -20032 quadrangles (map area). Approximate locations of prominent basin rings of Ladon and Holden impact basins (Cartwright and Seelos, 2019) and diameter of each basin ring shown

0 50 100 MILES

# **DESCRIPTION OF MAP UNITS**

[Unit descriptions and interpretations based on morphology, albedo, brightness temperature, stratigraphic position, and superimposed crater populations as seen in available orbital imaging and topography. These data include Mars Odyssey Thermal Emission Imaging System (THEMIS, infrared and visible), Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HIRISE) and Context (CTX) cameras, and 128-pixel-per-degree Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Record (MEGDR). Derived products from MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) were used, where available, to identify mineralogical differences within and between mapped geologic units. See pamphlet for details and references. Abbreviations: IR, infrared; m, meter; km, kilometer; %, percent]

UNIT SYMBOL	UNIT NAME AND DESCRIPTION	ADDITIONAL CHARACTERICS	INTERPRETATION
		CRATER UNITS	
AHc <sub>3</sub>	<b>Crater 3 unit</b> —Continuous crater rim and well-defined continuous ejecta blanket that are elevated relative to surrounding materials. <i>Type locality</i> : lat –13.39° N., long 326.07° E.	Age variable, but locally crosscuts all other units. Craters exhibit simple crater morphologies (typically <15 km in diameter). Lineaments and sinuous striations common on ejecta lobes. Layered and lobate ejecta morphologies are well preserved and pervasive	Rocks emplaced by impact-related ejection and deformation of target units. Crater material exhibits little erosion. Some crater floors may contain deposits of impact melt and (or) impact-generated fine-grained materials
Hc <sub>2</sub>	<b>Crater 2 unit</b> —Characterized by crater rim that may exhibit only minor relief above surrounding materials and by discontinuous, subdued, and buried and (or) mantled poorly exposed ejecta. <i>Type locality</i> : lat –14.77° N.,	Somewhat more rugged texture than terra 1 ( $Nt_1$ ) and 2 ( $Ht_2$ ) units, which it overlies. Also overlies crater fill unit (Hcf), mountainous unit ( $Nm$ ), basin fill 1–3 units ( $HNb_1$ , $HNb_2$ , $HNb_3$ ). Underlies basin fill 5 unit ( $AHb_5$ ) and fan unit ( $Af$ ). Disrupted	Rocks emplaced by impact-related ejection of target units that have experienced moderate degrees of erosion, deformation, mantling, and burial



**Crater 1 unit**—Degraded, incomplete or remnant crater rims that exhibit little or Slumping of crater walls mapped as part of this unit. Crosscuts mountainous unit Highly degraded impact crater material. Ejecta is almost completely no relief relative to surrounding materials. Displays little to no discernible (Nm). Underlies crater fill unit (Hc<sub>2</sub>), and light-toned crater floor eroded or mantled by younger materials, rim has been heavily ejecta materials that only extend <1 crater diameter in distance and may not unit (AHIc). Disrupted by Holden secondary cratering modified by erosion and gravity, and crater floor contains younger materials

#### **VOLCANIC UNITS**

Only found in southern Ladon basin. Superposes basin fill 3 unit (HNb<sub>3</sub>)

CHAOTIC UNITS

- Rim regions are generally more disrupted than the crater centers as seen in CTX image D01 027471 1604 XN 19S032W. Displaced knobs and mesas composed of materials in terra 2 unit  $(Ht_2)$  and crater fill unit (Hcf)
  - subice lake (Roda and others, 2017)
- Densely fractured, uplifted, and (or) partially collapsed surfaces of unit Ht<sub>2</sub> and Hcf owing to localized inflation and (or) deflation of the surface. Collapse of an infill layer within a crater could be from drainage of either a surface lake (Sato and others, 2010) or a buried

Constructional vents and associated lava flows deposited by effusively

Alternatively, could be interpreted as mud diapirs and mud flows

by Ladon Valles and deposited within southern Ladon basin

erupted lava along grabens or fissures at the south edge of Ladon basin.

(Skinner and Mazzini, 2009) produced by water and sediments carried

### **BASIN FILL UNITS**

Overlies basin fill 3 unit (HNb<sub>3</sub>), basin fill 4 unit (AHb<sub>4</sub>), light-toned layered basin Lithified eolian materials, volcanic flows, or late-stage sediments unit (AHlb), channel 2 unit (HNch<sub>2</sub>), and Holden secondary craters. Appears darker from Ladon Valles toned in CTX data relative to other basin fill and channel units. Margins frequently defined by low-relief scarps as seen in CTX image J02\_045484\_1622

> Fine-grained clay-bearing, lacustrine and (or) distal alluvial sediments from water flow and ponding within Ladon Valles and Ladon basin. in CTX and HiRISE images, with HiRISE images showing individual beds are 1–5 m Variations in layer brightness may result from heterogeneities in the source regions upstream of Ladon Valles over time or variable beds. Overlain by dark-toned, more resistant capping layer that preserves small craters discharge orientation into Ladon basin (Weitz and others, 2022)

3.8<sup>+0.08</sup>\_-0.2 Ga Mountainous (Nm) Neukum (2010) not applied. 3.9<sup>+0.02</sup> Ga D range 10–40 km Estimated absolute-model ages and associated epochs after 100 Michael (2013) in table 1. Gray 0.01 0.1 10 100 0.01 0.1 1 10 1 Crater diameter, in kilometers Crater diameter, in kilometers lines are isochrons showing idea production-function curves for each of the resulting modeled Fan (Af) Basin fill 5 (AHb<sub>5</sub>) ages. Crater size–frequency 2.5 <sup>₊0.6</sup> Ga 3.3<sup>+0.1</sup><sub>-0.3</sub>Ga distributions of the following units Light-toned layered were determined: A, volcanic (Av), Light-toned layered highland (AHIh) basin (AHIb) chaotic (Act), terra 2 (Ht<sub>2</sub>), terra 1 2.2<sup>+0.8</sup> Ga 3.3<sup>+0.1</sup><sub>-0.5</sub>Ga (Nt<sub>1</sub>), and mountainous (Nm); *B*, ▲ Light-toned crate basin fill 3 (HNb<sub>3</sub>), basin fill 2 floor (AHIc) (HNb<sub>2</sub>), basin fill 1 (HNb<sub>1</sub>) (D 2.5<sup>+0.5</sup> Ga range is best-fit crater diameter range, in kilometers [km]); C, basin fill 5 (AHb<sub>5</sub>), light-toned layered basin (AHIb), and basin fill 4  $(AHb_4)$ ; and *D*, fan (Af), light-toned layered highland (AHIh), light-toned crater floor (AHIc) crater fill (Hcf), channel 2 (HNch<sub>2</sub>), and channel 1 (Nch<sub>1</sub>). 10<sup>-4</sup> + Crater fill (Hcf) 3.6<sup>+0.05</sup><sub>-0.07</sub>Ga Combined areas and diameter ranges used to produce estimated Channel 2 (HNch<sub>2</sub>) model ages in table 1. 3.8<sup>+0.06</sup><sub>-01</sub> Ga Basin fill 4 (AHb.) Channel 1 (Nch1) 3.3 <sup>₊0.08</sup> Ga 3.9<sup>+0.07</sup>Ga 10 0.01 0.1 100 Crater diameter, in kilometers Crater diameter, in kilometers



Figure 4. Image showing graben (black arrows) disrupting Ladon basin fill 2 unit (HNb<sub>2</sub>). Scarp that defines the geologic contact between basin fill 1 unit (HNb<sub>1</sub>) and basin fill 2 unit  $(HNb_2)$  is clearly visible. Small, dark valleys (white arrows) along terra 1 unit (Nt<sub>1</sub>) coalesce into one arger valley that extends into unit HNb<sub>1</sub>. Excerpt of Context Camera (CTX) image D08\_030161\_1611 (6.4 meters per pixel), centered at lat -17.56° N., long 326.83° E. North toward top.

Ridges are typically aligned north-south. In CTX images, ridges are brighter than the Moderately to strongly indurated volcanic, sedimentary, and (or) darker lows. Unit overlies basin fill 3 unit (HNb<sub>3</sub>) and underlies basin fill 5 unit eolian fill materials. Undulating terrain may have resulted from (AHb<sub>5</sub>). Disrupted by Holden secondary cratering depositional or erosional processes Where CRISM data exist, the surface and ejecta from craters within unit exhibit Moderately to strongly indurated volcanic, sedimentary, and (or) Fe/Mg-smectite signatures (Weitz and others, 2022). Small, superimposed craters in eolian fill materials that were locally aqueously altered to form clays CTX images are commonly well-preserved in surface layer. Overlies basin fill 1 (HNb<sub>1</sub>) and 2 (HNb<sub>2</sub>) units, underlies basin fill 5 unit (AHb<sub>5</sub>). Disrupted by Holden secondary cratering. Same unit as HNb<sub>2</sub> in Irwin and Grant (2013) and Wilson and others (2022) Disrupted by numerous grabens. Dissected by gullies along the steeper slopes at the Moderately to strongly indurated volcanic and (or) sedimentary contact with HNb<sub>3</sub>. Underlies crater 2 unit (Hc<sub>2</sub>) and basin fill 3 unit (HNb<sub>3</sub>), and materials. Possibly a slightly younger and smaller fluvially derived overlies basin fill 1 unit (HNb<sub>1</sub>) and terra 1 unit (Nt<sub>1</sub>). Disrupted by Holden deposit relative to HNb<sub>1</sub> from a second pulse of water and sediments through Ladon Valles into Ladon basin. Arcuate scarp could have formed as a flow margin or by tectonic activity Disrupted by valleys and grabens and has fewer wrinkle ridges relative to the terra Moderately to strongly indurated volcanic and (or) sedimentary units (Nt<sub>1</sub> and Ht<sub>2</sub>). Underlies crater 2 (Hc<sub>2</sub>) and 3 (AHc<sub>3</sub>) units and basin fill 2 materials. Arcuate scarp could be a flow margin from fluvially derived (HNb<sub>2</sub>) and 3 (HNb<sub>3</sub>) units, and overlies terra 1 unit (Nt<sub>1</sub>) and mountainous unit sediments during initial pulse of water and sediments through Ladon Valles into Ladon basin or tectonic activity (contraction) after deposition of the sediments within the basin

#### **CRATER, VALLEY, AND CHANNEL UNITS**

- Alluvial deposits emplaced by fluvial sediment transport and gravity Overlies crater 2 ( $Hc_2$ ) and crater 3 ( $AHc_3$ ) units and crater fill unit (Hcf). Same unit Spatially associated with dissected interior of crater walls. *Type locality*: as AHf in Wilson and others (2022) driven processes with little to no evident contribution from debris flows. Distributary paleochannel networks sometimes preserved in negative or (more commonly) positive relief. Youngest fluvial
  - Where CRISM data exist, the deposits contain Fe/Mg smectites (Weitz and others, 2022). Medium- to light-toned layers visible in CTX and HiRISE images. HiRISE images show individual layers are 1–5 m thick. Overlain by dark-toned, more resistant capping layer that is mapped as part of AHIh, where light-toned beds are IR images, but shade is variable due to different thicknesses of overlying observed beneath. Some deposits postdate and occur within Holden secondary craters
    - Alluvial and fluvial sediments containing clays that were deposited by water into blocked valleys and basins along the western Ladon-basin highlands. Likely contemporaneous with Eberswalde deltaic sediments to the south

Thinner deposits of AHIh and AHIb, or preexisting crater floor

Moderately to strongly indurated volcanic or eolian fill materials.

later veneered by smooth fluvial sediments during waning flow

Surfaces eroded by confined flooding along central Ladon Valles and

Surfaces eroded by early catastrophic flooding and thinly veneered

that underwent resurfacing sufficient to partially remove ejecta

blankets and crater rims and smooth topography, possibly by

by fluvial sediments during waning flow

materials

the Tharsis rise

Origin and composition may vary among individual craters

material altered by water ponding along the floors of some craters

deposits in map area





Figure 5. Image showing smoother and darker basin fill 5 unit (AHb<sub>5</sub>) overlying older, rougher, and slightly brighter basin fill 3 unit (HNb<sub>3</sub>). Unit AHb<sub>5</sub>



Figure 2. Topographic map of Mars Transverse Mercator (MTM) –15032 and –20032 projection. **EXPLANATION** Elevation, meter 0 25 50 KILOMETERS

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

quadrangles derived from Mars Orbiter Laser Altimeter (MOLA) Terra 2 unit—Relatively smooth over kilometer scale; moderately cratered data (463 meters per pixel) and variably dissected surfaces. North-south-oriented wrinkle ridges merged to Thermal Emission and Holden secondary craters are commonly present, but valleys are Imaging System (THEMIS) not. *Type locality*: lat –13.22° N., long 328.12° E. laytime infrared mosaic (see fig. 1 or regional context). Approximate Terra 1 unit—Widespread, smooth to rolling, cratered, and variably dissected CTX image G06 020746 1615 shows craters range from well-preserved to highly locations of prominent basin rings surfaces between degraded impact craters. North-south-oriented wrinkle of Ladon and Holden impact ridges and Holden secondary craters are commonly present. Radial basins indicated by yellow circles valley systems flowing downslope into Ladon basin occur throughout, (from Cartwright and Seelos, including Arda Valles. Type locality: lat -17.11° N., long 325.75° E. 2019). Transverse Mercator Nm rings. Mountains can be steep and variably eroded or subdued and long 326.78° E. Secondary crater chain ------ Contact—Solid where location is accurate; dashed where location is

location is approximate

329.86° E.

lat -20.80° N., long 329.85° E.

Channel 1 unit—Smooth to hummocky surfaces along sloping terrain

related to early incision of Ladon Valles. *Type locality*: Ladon Valles at

Mountainous unit-Mountains and other promontories along impact basin Deeper Noachian bedrock outcrops, exposed during Ladon and Oldest unit in map area. Overlain and embayed by terra units ( $Nt_1$  and  $Ht_2$ ), crater Holden impact-basin formation, that are locally deformed by mass units (AHc<sub>3</sub>, Hc<sub>2</sub>, and HNc<sub>1</sub>), crater fill unit (Hcf), and basin fill 1 (HNb<sub>1</sub>) and 2 smooth. Shedding debris and aprons from mountains are mapped as part (HNb<sub>2</sub>) units. Disrupted by Holden secondary cratering. Same unit as Nm in Irwin wasting of this unit. *Type locality*: Ladon impact-basin inner ring at lat –16.86° N., and Grant (2013) and Wilson and others (2022) **EXPLANATION OF MAP SYMBOLS Groove**—Graben modified by flowing water to produce jagged Impact basin ring—Approximate location of structural ring related to formation of an ancient basin. Location based on margins like those seen in valleys topographic remnants centered around impact basin **Crater rims**—Impact craters >5 km in diameter approximate. Internal contacts within crater units of the same age Depressions **Crest of crater rim**—Rim of crater is topographically exposed were used to show age relationships between overlapping ejecta Graben trace—Linear to curvilinear flat-floored depression and well defined. Hachures point inward toward center of crater where clear superpositioning or embayment relationships exist <1 km in width. Solid where location is accurate; dashed where depression Scarp crest—Designates topographic inflection, line placed at crest location is approximate ----- Crest of buried or degraded crater rim—Rim of crater is of scarp. Barb points downslope Channel (fluvial)—Line follows channel thalweg buried, subdued, or degraded Ridges Pitted cone Wrinkle ridge—Solid where location is accurate; dashed where

(Weitz and others, 2022). Disrupted by Holden secondary cratering. Dissects and overlies terra 1 unit (Nt<sub>1</sub>) and channel 1 unit (Nch<sub>1</sub>). Underlies light-toned layered basin

unit (AHlb) and basin fill 5 unit (AHb<sub>5</sub>). Same unit as HNch<sub>2</sub> in Irwin and Grant (2013)

Dissects terra 1 unit (Nt<sub>1</sub>) and dissected by channel 2 unit (HNch<sub>2</sub>). Disrupted by

Holden secondary cratering. Same unit as HNch<sub>1</sub> in Irwin and Grant (2013)

Overlies crater 1 unit ( $HNc_1$ ), terra 1 unit ( $Nt_1$ ), and mountainous unit (Nm).

Same unit as HNt in Irwin and Grant (2013) and Wilson and others (2022)

Underlies chaotic unit (Act), crater fill unit (Hcf), and crater 2 (Hc<sub>2</sub>) and 3 (AHc<sub>3</sub>)

PLATEAU AND HIGHLANDS UNITS

units

**— Trough**—Rounded depression >1 km in width; line follows trough rim

> Figure 7. Images showing layering in lightmouth of these valleys. Black polygon is ocation of image *B*. Approximate contact

xnibits snarp edges with topographic relief, characteristic of lithified material, such as a volcanic flow or lithified eolian debris. Smaller than map scale <1 kilometer) exposures of unit AHb<sub>5</sub> can be found inside impact craters on unit HNb<sub>3</sub>. Approximate contact between units HNb<sub>3</sub> and AHb<sub>5</sub> indicated by white line. Portion of Context Camera (CTX) image J02\_045484\_1622 (6 meters per pixel), centered at lat –18.3° N., long 328.2° E. North toward top.



3 MILES

1 2

exposure of ~60-meter-thick, lightand medium-toned layered strata in the light-toned layered basin unit (AHIb), which is clay bearing. Middle strata dominated by medium-toned beds; lower and upper strata dominated by bright beds (black arrows). Above unit AHIb is dark capping material weathered into eolian ripples, which we included in unit AHlb. Unit AHIb overlies channel 2 unit (HNch<sub>2</sub>), which in turn has a mantle of dark eolian bedforms such as debris and ripples in this image. Unit HNch<sub>2</sub> is a relatively flat, heavily fractured surface that sometimes exhibits clay signatures in Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data. Part of High **Resolution Imaging Science** Experiment (HiRISE) image ESP\_024728\_1595 (25 centimeters per pixel), centered at lat -20.39° N., long 329.95° E. North toward top.



Figure 8. Image showing two pitted cones (white arrows) in southern Ladon basin mapped as volcanic unit (Av). Linear fractures (black arrows) associated with each cone suggest fractures provided a conduit for volcanic material to erupt at the surface. Subframe of Context Camera (CTX) image B05\_011621\_1592 (6 meters per pixel), centered at lat -19.6° N. long 328.9° E. North toward top.

Geologic Map of MTM –15032 and -20032 Quadrangles, Western







Bv

2025

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should be aware that, because of diffe and pixel resolution, some slight distortion of scale may occur when viewing the online version on a computer screen or when printing it on an electronic plotter, even when it is viewed or printed at its intended publication scale For sale by U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225, 1–888–ASK–USGS Digital files available at https://doi.org/10.3133/sim3525 Printed on recycled paper Suggested citation: Weitz, C.M., Wilson, S.A., Grant, J.A., and Irwin, R.P., 2025, Geologic map of MTM -15032 and -20032 quadrangles, ISSN 2329-1311 (print) western Ladon basin, Mars: U.S. Geological Survey Scientific ISSN 2329-132X (online) Investigations Map 3525, pamphlet 14 p., scale 1:1,000,000, https://doi.org/10.3133/sim3525 https://doi.org/10.3133/sim3525.

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