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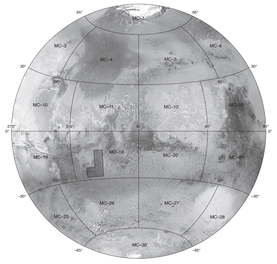
U.S. Department of the Interior
U.S. Geological Survey

Prepared for the
National Aeronautics and Space Administration

Scientific Investigations Map 3209
Pamphlet accompanies map



QUADRANGLE LOCATION

Photomosaic showing location of map area. An outline of 1:5,000,000-scale quadrangles is provided for reference.

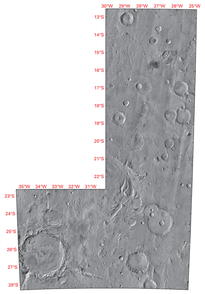


Figure 2. Base mosaic of THEMIS DIR images of map area at 100 m/pixel resolution, transverse Mercator projection, planetographic latitude and longitude coordinate system.

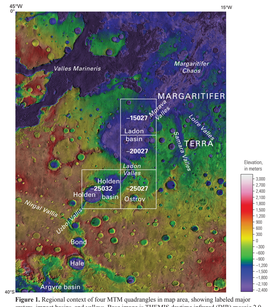


Figure 1. Regional context of four MTM quadrangles in map area, showing labeled major craters, impact basins, and valleys. Base image is THEMIS daytime infrared (DIR) mosaic 2.0 with gores filled by Viking Orbiter Mars Digital Image Mosaic (MDIM) 2.1, colored with Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Record (MEGDR) topography at 128 pixels/degree. Projection is simple cylindrical.

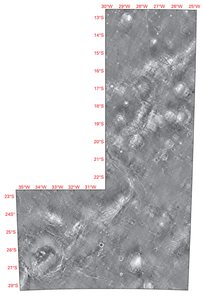
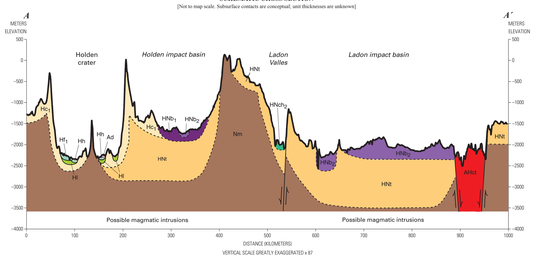
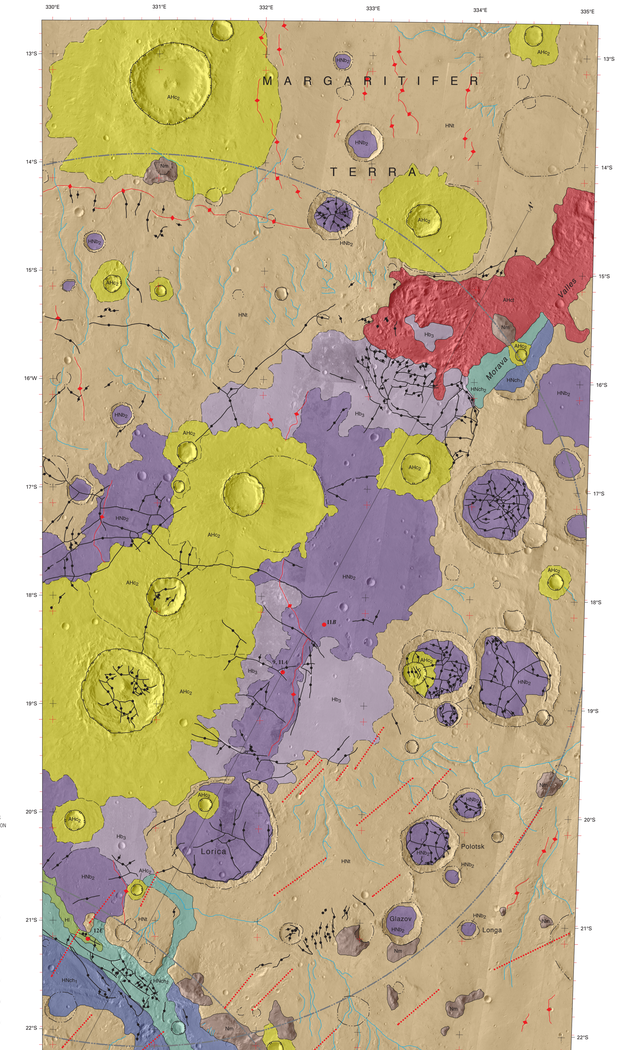


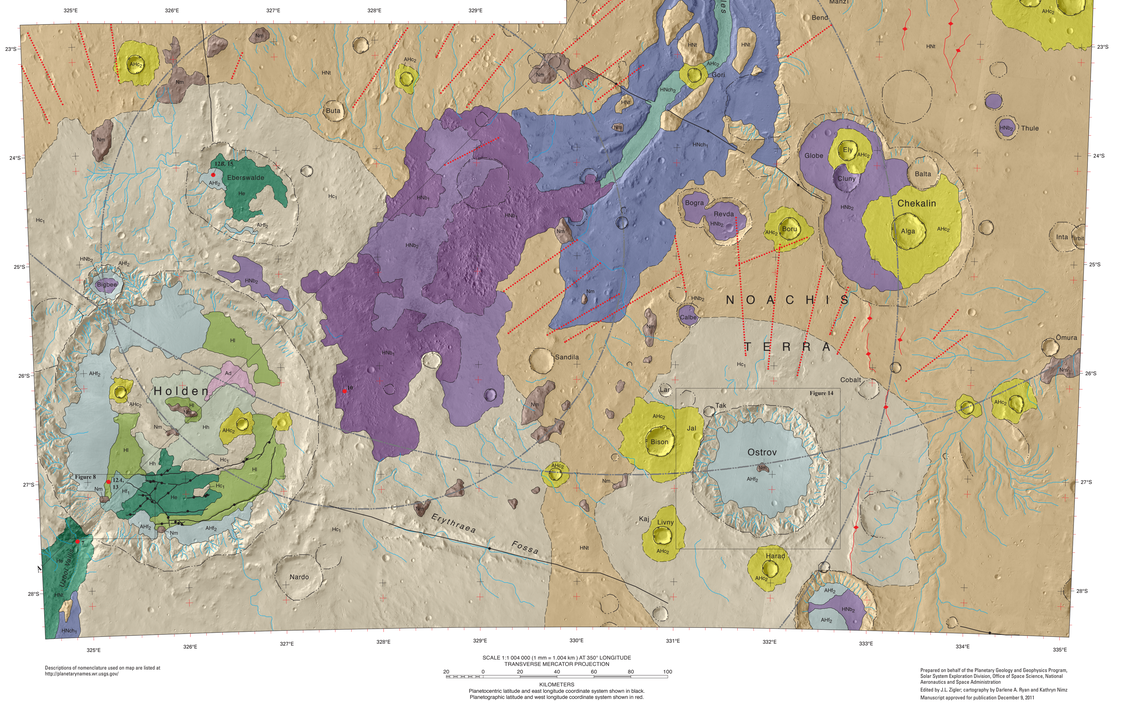
Figure 3. THEMIS nighttime infrared 2.0 mosaic of map area (256 pixels/degree), transverse Mercator projection, planetographic latitude and longitude coordinate system.

SCHEMATIC CROSS SECTION

[Not to map scale. Subsurface contacts are conceptual; unit thicknesses are unknown]







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

SCALE 1:1 004 000 (1 mm = 1 004 km) AT 350° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

KILOMETERS

Planetocentric latitude and east longitude coordinate system shown in black.
Planetographic latitude and west longitude coordinate system shown in red.

Prepared on behalf of the Planetary Geology and Geophysics Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration
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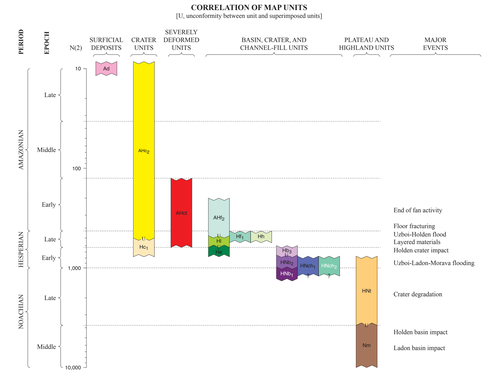
CORRELATION OF MAP UNITS

[U, unconformity between unit and superimposed units]



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 Global Surveyor (MGS) Mars Orbiter Camera (MOC, narrow-angle), Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) and Context (CTX) cameras, and 128-pixel/degree MGS Mars Orbiter Laser Altimeter (MOLA) Mission Experiment Gridded Data Record (MEGDR). Derived products from MRO Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) used, where available, to identify mineralogical differences within and between mapped geologic units. See pamphlet for details and references]

Unit label	Unit name, age, description, and type locality	Additional characteristics	Interpretation
	SURFICIAL DEPOSITS		
Ad	**Dune unit (Late Amazonian)**—Concentration of typically dark-toned bedforms. *Type locality:* Holden crater floor at lat 25.65° S., long 33.5° W. (CTX image P16_007125_1530_XN_27S033W)	At type locality, size of barchan dunes increases and spacing decreases from north to south. Subjacent Hesperian Holden central (Hfh) and crater 1 (Hc_1) materials exposed between dunes	Recent aeolian dunes, likely composed of chemically unaltered basaltic sand. At type locality, barchan to barchanoid dune form reflects limited sand supply and transport from north to south
	CRATER UNITS		
AHt_2	**Crater 2 unit (Late Amazonian to Late Hesperian)**—Floor, rim, and continuous ejecta of morphologically fresh impact craters little modified by rim erosion and (or) infilling. *Type locality:* Unnamed crater at lat 18.5° S., long 29.3° W. (CTX P13_006281_1607_XN_19S029W)	Age variable, but AHt_2 locally overlies all other units but Ad	Interior materials, fractured rim, and continuous ejecta of Hesperian and Amazonian impact craters. Rocks emplaced or exposed by impact typically have older crystallization ages and reflect composition of target material
Hr_1	**Crater 1 unit (Late to Early Hesperian)**—Rims of Holden and Ostrov craters and area thickly mantled by their ejecta. *Type locality:* Highlands east of Holden crater at lat 27° S., long 30.5° W. (CTX B05_011410_1534_XI_26S030W)	Somewhat more rugged texture than terra unit (HNt), which it overlies. Possibly coeval with base of etched unit (Hte). Underlies layered unit (Hl), fan units (Hf_1, AHf_2), and Holden central unit (Hh)	Moderately degraded crater rim and impact ejecta from Hesperian Holden and Ostrov craters
	SEVERELY DEFORMED UNITS		
AHt	**Chaotic unit (Early Amazonian to Late Hesperian)**—Discrete areas of severe structural disruption, resulting in dense fracturing, vertical movement, and some rotation of variably sized blocks. Less than 50% of original surface intact. Slope failures common on block margins. *Type locality:* Near head of Morava Valles at lat 15° S., long 26° W. (CTX P19_008509_1619_XN_18S025W)	Recent sand infilled some low areas between blocks. Displaced knobs and mesas composed of materials crosscut by chaotic unit. Crosscuts mountainous unit (Nm), terra unit (HNt), channel units ($HNch_1$, $HNch_2$), and basin fill 3 unit (Hb_3)	Densely fractured, uplifted, and (or) partially collapsed surfaces due to localized inflation and (or) deflation of the surface in Late Hesperian to Early Amazonian. Topographic relations with fluvial surfaces suggest that uplift from volcanic intrusion, hydraulic pressure (less likely), or processes related to ground ice (unlikely) preceded and created space for subsequent collapse. Possible temporal and causal relation with wetlike floor fractures in nearby impact basin and crater floors
	BASIN, CRATER, AND CHANNEL-FILL UNITS		
AHf_2	**Fan 2 unit (Early Amazonian to Late Hesperian)**—Sloping or cone-shaped deposits. Distributary paleochannel networks preserved in negative or (more commonly) positive relief. *Type locality:* Holden crater at lat 26.1° S., long 34.9° W. (CTX B04_011397_1534_XI_26S035W; HiRISE PSP_008193_1535)	Cone-shaped deposits derived from deeply dissected impact crater walls coalesced into broad bajada along western wall of Holden crater and around entire circumference of Ostrov crater. In Eberswalde crater, coarse-grained, sinuous distributary paleochannels and deflated interchannel fines concentrated on west margin of crater in deposit with distal scarp. Overlies terra unit (HNt), crater 1 unit (Hc_1), and crater floor deposits (Hm, Hl, HNb_2). Youngest fluvial deposits in map area	Late Hesperian to Early Amazonian alluvial deposits composed primarily of gravel and fines, emplaced by fluvial sediment transport with little to no resident contribution from debris flows. Low abundance of boulders visible at HiRISE scale at type locality. Relief inversion of distributary paleochannels due to selective aeolian erosion of granule- to sand-sized material originally deposited between channels. In Eberswalde crater, similar material composition to Holden crater fans deposited in lower-energy deltaic environment. Separate lobes of Eberswalde deposit indicate multiple water levels, and lateral migration of paleochannels that formed meander loops and cutoffs suggests periods of base-level stability during aggradation
Hf_1	**Fan 1 unit (Late Hesperian)**—Dark-toned, coarse-grained to bouldery, low-relief, multi-lobed deposit containing megaripples, subaqueous dunes, and crude bedding where exposed. Bedding commonly includes low-angle truncations near mouth of Uzboi Vallis, from which deposit was derived. More parallel and continuous bedding toward center of crater. Deposit locally entrains large clasts eroded from subjacent layered unit (Hl). *Type locality:* Holden crater floor at lat 26.6° S., long 34.5° W. (CTX B01_009841_1528_XI_27S034W, HiRISE PSP_002721_1530)	Overlies light-toned strata of layered unit (Hl), but potentially coeval with Hl unit's dark-toned capping layer. Potentially contemporary with Holden central unit (Hh)	High-energy flood deposit, composed of chemically unaltered to weakly altered plateau and highland units bedrock (HNt, Nm), deposited when Hesperian paleolake impounded in Uzboi Vallis overflowed and breached Holden crater rim
Hh	**Holden central unit (Late Hesperian)**—Moderately dark toned, low-thermal-inertia, smooth material surrounding etched or rugged outcrops of underlying rocks. Poor crater preservation and retention on both smooth surfaces and outcrops, but particularly on former. *Type locality:* Holden crater floor at lat 26.2° S., long 33.9° W. (CTX B06_011964_1544_XI_25S034W)	Located primarily inside central rim structure of Holden crater. Some small outcrops of underlying materials emplaced during Holden crater impact (crater 1 unit, Hc_1). Possibly contemporary with fan 1 unit (Hf_1)	Hesperian sedimentary deposit, subsequently etched by wind and mostly mantled by recent aeolian sand sheet
Hl	**Layered unit (Late Hesperian)**—Medium- to light-toned, phyllosilicate-bearing beds with meter to submeter thickness and lateral continuity to kilometers, overlain by dark-toned, more resistant capping layer that preserves small craters. Lower light-toned layers typically deeply eroded, exposed as scarps, and largely devoid of small craters where capping layer removed. Polygonal fractures observed in some beds. *Type locality:* Holden crater floor at lat 26.65° S., long 34.78° W. (figs. 12*A*, 13)	In Holden crater, light-toned beds include three members (undifferentiated at map scale, see fig. 13). Lower member: strongest phyllosilicate signature of the three, poorly expressed bedding, and darker tone. Middle member: brighter in tone but weakly expressed bedding. Upper member: most widespread exposure, well bedded, with higher albedo and weaker phyllosilicate signature than underlying members. In Holden crater, unit overlies etched unit (Hte) and crater 1 unit (Hc_1) and underlies fan units (Hf_1, AHf_2). In Ladon Valles, unit overlies channel materials ($HNch_1$, $HNch_2$)	Hesperian fine-grained, phyllosilicate-bearing, lacustrine and (or) distal alluvial deposits overlain by coarse-grained alluvial sediments and (or) indurated aeolian sand sheets of likely basaltic mineralogy. Capping layer possibly coeval with and laterally equivalent to fan 1 unit (Hf_1), particularly near entrance breach of Uzboi Vallis, but typically thinner and finer grained
Hte	**Etched unit (Early to Late Hesperian)**—Erosionally resistant material on Holden crater, Eberswalde crater, and Uzboi Vallis floors exposed where aeolian deflation selectively removed layered unit (Hl). Varied outcrops of (moving upsection) widespread and unsorted bouldery deposits, polygonally fractured materials, light-toned layered deposits, elongated and locally sinuous gravel deposits, and sand sheets. Light-toned strata commonly thinly bedded and exposed as scarps beneath more resistant, darker-toned capping layers. *Type locality:* Eberswalde crater floor at lat 23.9° S., long 33.3° W. (fig. 12*B*; HiRISE ESP_012610_1560 and ESP_011542_1530)	Small size of varied outcrops prohibits subdivision at map scale. Basal materials of etched unit possibly coeval with crater 1 unit (Hc_1). Smaller outcrops higher in section possibly coeval with layered unit (Hl) and fan 2 unit (AHf_2). Underlies Holden central unit (Hh) and fan 1 unit (Hf_1)	Deflated crater-fill deposits overlying Hesperian Holden crater ejecta or crater fill. Includes fine-grained, phyllosilicate-bearing, lacustrine and (or) distal alluvial deposits overlain by coarse-grained alluvial sediments (stripped over much of area) and recent aeolian sand sheets of likely basaltic mineralogy. Megabreccia and possible impact melt appear related to Holden crater impact, and unit may include early, coarse-grained sedimentary deposits
Hb_3	**Basin fill 3 unit (Early to Late Hesperian)**—Plains-forming unit in Ladon impact basin with high thermal inertia and generally well preserved populations of small, superimposed impact craters. *Type locality:* Floor of Ladon impact basin at lat 18.75° S., long 27.4° W. (CTX P20_008720_1610_XN_19S027W, HiRISE PSP_008720_1610)	At type locality, unit overlies and embays moderately indurated, etched deposits and subjacent layered deposits composed of or weathering into boulders (HNb_2)	Late Noachian to Early Hesperian deposits composed of resistant indurated sediments and (or) thin lava flows
Hb_2	**Basin fill 2 unit (Early Hesperian to Late Noachian)**—Relatively smooth, low-relief plains confined to impact crater and basin floors. Small superimposed craters commonly well preserved in surface layer, but some basin fill 2 surfaces with exposed underlying layers have etched appearance and relatively poor crater retention. *Type locality:* Floor of Ladon impact basin at lat 18.4° S., long 27.8° W. (figs. 9, 11)	Unit may include materials contemporary with channel units ($HNch_1$, $HNch_2$). Overlies basin fill 1 unit (HNb_1) and terra unit (HNt). Underlies basin fill 3 unit (HNb_3) and fan 2 unit (AHf_2)	Moderately to strongly indurated alluvial, volcanic, or aeolian fill materials; origin and composition may vary within and between individual basins. Type locality interpreted as underlying flood deposits from Ladon Valles, medium- to light-toned sedimentary deposits associated with later infilling, and darker-toned capping layer
Hb_1	**Basin fill 1 unit (Early Hesperian to Late Noachian)**—Prominent knobby outcrops embayed by fruitle, wind-eroded layered deposits. Aeolian infill material common in deflated surfaces and topographic lows. *Type locality:* Holden impact basin floor at lat 25.8° S., long 32.3° W. (fig. 10)	Where exposed, some layered deposits between knobs resemble basin fill 2 (HNb_2) unit. Overlies terra unit (HNt) and underlies basin fill 2 unit (HNb_2)	Knobby outcrops of Hesperian Holden crater ejecta and older channel deposits with interspersed sedimentary deposits and recent aeolian infill. Development of knobby texture postdates Holden impact
$HNch_2$	**Channel 2 unit (Early Hesperian to Late Noachian)**—Smooth floor of main outlet valley from Holden impact basin (part of Ladon Valles) and deepest channel of Morava Valles. *Type locality:* Ladon Valles floor at lat 22.1° S., long 28.65° W. (CTX P02_001890_1572_XN_22S028W)	Overlies terra unit (HNt). Contemporary with channel 1 unit ($HNch_1$). Locally buried by light-toned deposits (Hf)	Surfaces deeply eroded by Late Noachian to Early Hesperian catastrophic flooding and veneered by coarse fluvial sediments during waning flow
$HNch_1$	**Channel 1 unit (Early Hesperian to Late Noachian)**—Eroded surfaces related to early incision of Uzboi, Ladon, and Morava Valles. Streamlined outcrops of terra and mountainous units common. *Type locality:* Ladon Valles at lat 23.5° S., long 28.9° W. (fig. 2; CTX P15_006993_1576_XN_22S029W)	Overlies terra unit (HNt). Contemporary with channel 2 unit ($HNch_2$)	Surfaces eroded by Late Noachian to Early Hesperian catastrophic flooding and thinly veneered by coarse fluvial sediments during waning flow
	PLATEAU AND HIGHLAND UNITS		
HNt	**Terra unit (Early Hesperian to Late Noachian)**—Widespread, smooth to rolling, cratered, and variably dissected surfaces between degraded impact craters. *Type locality:* East of Ostrov crater at lat 27° S., long 25.5° W. (CTX P18_008074_1536_XN_26S025W)	Overlies mountainous unit (Nm). Underlies all other units	Noachian geomorphic surface resulting from impact cratering, ejecta emplacement, prolonged weathering, and erosion primarily by water and wind
Nm	**Mountainous unit (Middle Noachian)**—Bedrock promontories including impact crater central peaks and mountain chains along impact basin rings. Mountains typically steep and variably eroded depending on age. *Type locality:* Holden impact basin inner ring at lat 22.2° S., long 32.75° W. (CTX B05_011687_1567_XI_23S032W)	Oldest unit in map area	Deeper Noachian bedrock outcrops exposed during impacts and overlain by terra unit

EXPLANATION OF MAP SYMBOLS

- **Contact**—Dashed where approximately located
- **Normal fault**—On map, line follows center of fracture or graben. On cross section, arrows show relative movement
- **Reverse fault**—Line follows crest of wrinkle ridge
- **Chain of secondary craters**—Approximately located
- **Small valley**—Line follows valley thalweg
- **Small entrenched channel**—Line follows channel thalweg
- **Fresh crater rim crest (class C1)**—Hatchures point into crater
- **Degraded crater rim crest (classes C2 and C3)**—Current location reflects rim retreat during crater degradation
- **Impact basin ring**
- **Figure location and number**

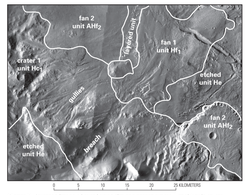


Figure 8. Enlarged image of overflowed rim and breach where Uzboi Vallis enters Holden crater. Gullies in west side of image formed when a lake in Uzboi Vallis overtopped the crater rim. Flow coalesced into a single breach and formed lobate fan 1 unit (Hf_1) deposits in upper right. Mosaic of THEMIS visible imaging at 18 m/pixel, centered at lat 26.8° S., long 325.2° E. See map for image location.

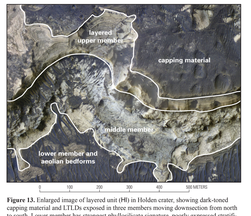


Figure 13. Enlarged image of layered unit (Hl) in Holden crater, showing dark-toned capping material and LTLDs exposed in three members moving downsection from north to south. Lower member has strongest phyllosilicate signature, poorly expressed stratification, and darker tone. Middle member is brighter in tone but also has weakly expressed stratification. Upper member has most widespread exposure, is well-stratified, and has higher albedo and weaker phyllosilicate signature than underlying members. HiRISE PSP_002088_1530, centered at lat 26.6° S., long 34.8° W. See map for image location.

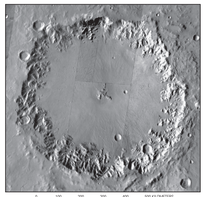


Figure 14. Enlarged image showing deeply eroded interior wall and alluvial fans in Ostrov crater. Mosaic of THEMIS DIR imaging at 100 m/pixel, centered at lat 28.5° S., long 331.9° E. See map for image location.

Figure 4. Hartmann (2005) isochron plot for all fresh and degraded craters in map area, except for Ladon and Holden impact basins. Crater count indicates resurfacing about Middle to Late Noachian boundary and ongoing crater degradation into Early Hesperian.

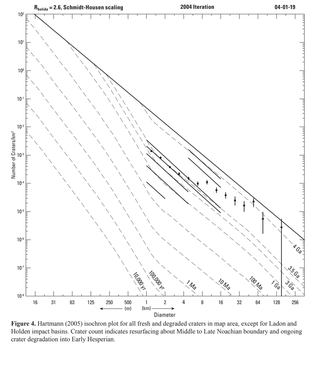


Figure 7. Enlarged image of etched unit (Hte) in floor of Uzboi Vallis southwest of Holden crater. Near top of image, darker-toned material overlies medium-toned stratified (layered) and lighter-toned fractured materials. Toward bottom of image, lighter-toned fractured materials are exposed on valley floor. Patchy, darker-toned aeolian bedforms and sand sheets partially cover these outcrops; otherwise, stratigraphy is exposed downsection from north to south. Subset of HiRISE ESP_011608_1525, centered at lat 27.1° S., long 35.2° W. See map for image location.

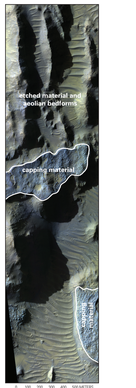


Figure 10. Enlarged image of basin fill 1 unit (HNb_1), showing dark-toned capping material and medium-toned, wind-eroded materials exposed on floor of Holden impact basin, just east of Holden crater. Recent aeolian bedforms occupy corridors between knobs of capping material. Subset of HiRISE PSP_010197_1540, centered at lat 25.8° S., long 32.3° W. See map for image location.

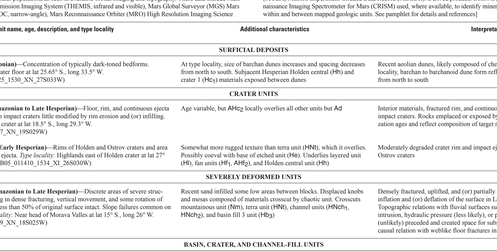


Figure 5. Hartmann (2005) isochron plot for fresh craters superimposed on terra unit. Crater count indicates Early Hesperian age for waning of crater degradation in map area.

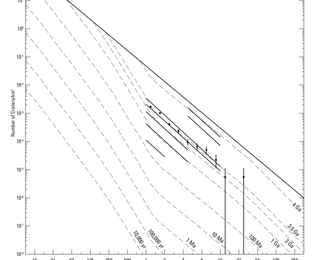


Figure 11. Enlarged image of basin fill 2 unit (HNb_2), showing erosional expression of stratigraphy shown in figure 9. See map for image locations. *A*, Stratigraphic section exposed downsection from north to south, including dark-toned capping material and weakly resistant, medium- to lighter-toned materials (etched surface). Subset of HiRISE ESP_013045_1615, located south of figure 9. *B*, Closeup of outcrops similar to *A* moving downsection from south to north. Subset of HiRISE ESP_015946_1620, centered at lat 17.9° S., long 332.6° E. Compare to stratigraphy exposed in Holden impact basin to the south (fig. 10).

Figure 6. Hartmann (2005) isochron plot for craters superimposed on crater 1 unit (AHc_1) surrounding Holden crater. Crater count indicates a Hesperian age for Holden impact.

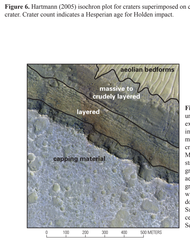


Figure 9. Enlarged image of basin fill 2 unit (HNb_2), showing stratified outcrop exposed in graben on floor of Ladon impact basin. Dark-toned capping material preserves a population of small craters and disaggregates into boulders. Medium-toned, stratified to crudely stratified (layered), apparently finer-grained materials underlie it. Recent aeolian bedforms cover the floor of the graben at the top of the image; otherwise, the stratigraphy is exposed downsection from south to north. Subset of HiRISE ESP_013045_1615, centered at lat 18.4° S., long 27.8° W. See map for image location.

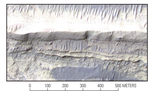


Figure 15. Enlarged image of fan 2 unit (AHf_2), showing stratigraphy exposed in an inverted paleochannel of Eberswalde crater delta, moving downsection from north to south. HiRISE PSP_001534_1560, centered at lat 23.8° S., long 33.6° W. See map for image location.

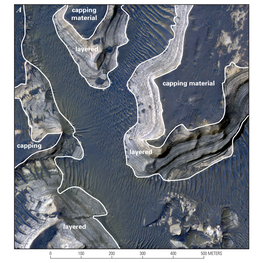


Figure 12. Images comparing light-toned, layered deposits (LTLDs) in map area. See map for image locations. *A*, Layered unit (Hl), showing LTLDs and dark-toned capping materials exposed on floor of Holden crater. Four stratal packages are exposed in outcrop in right half of image. Stratification is laterally continuous through scene. Subset of HiRISE ESP_016276_1535, centered at lat 26.4° S., long 34.8° W. *B*, Fan 2 unit (AHf_2) at north margin of Eberswalde delta, showing dark-toned aeolian bedforms and capping material, lighter-toned subjacent strata (layered), and blocky material exposed to north, moving downsection from south to north. HiRISE PSP_001336_1560, centered at lat 23.8° S., long 33.6° W. *C*, Layered unit (Hl), showing darker-toned capping material and LTLDs in Ladon Valles, moving downsection from north to south. HiRISE PSP_006637_1590, centered at lat 20.9° S., long 29.7° W.

Geologic Map of the MTM –15027, –20027, –25027, and –25032 Quadrangles, Margaritifer Terra Region of Mars

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