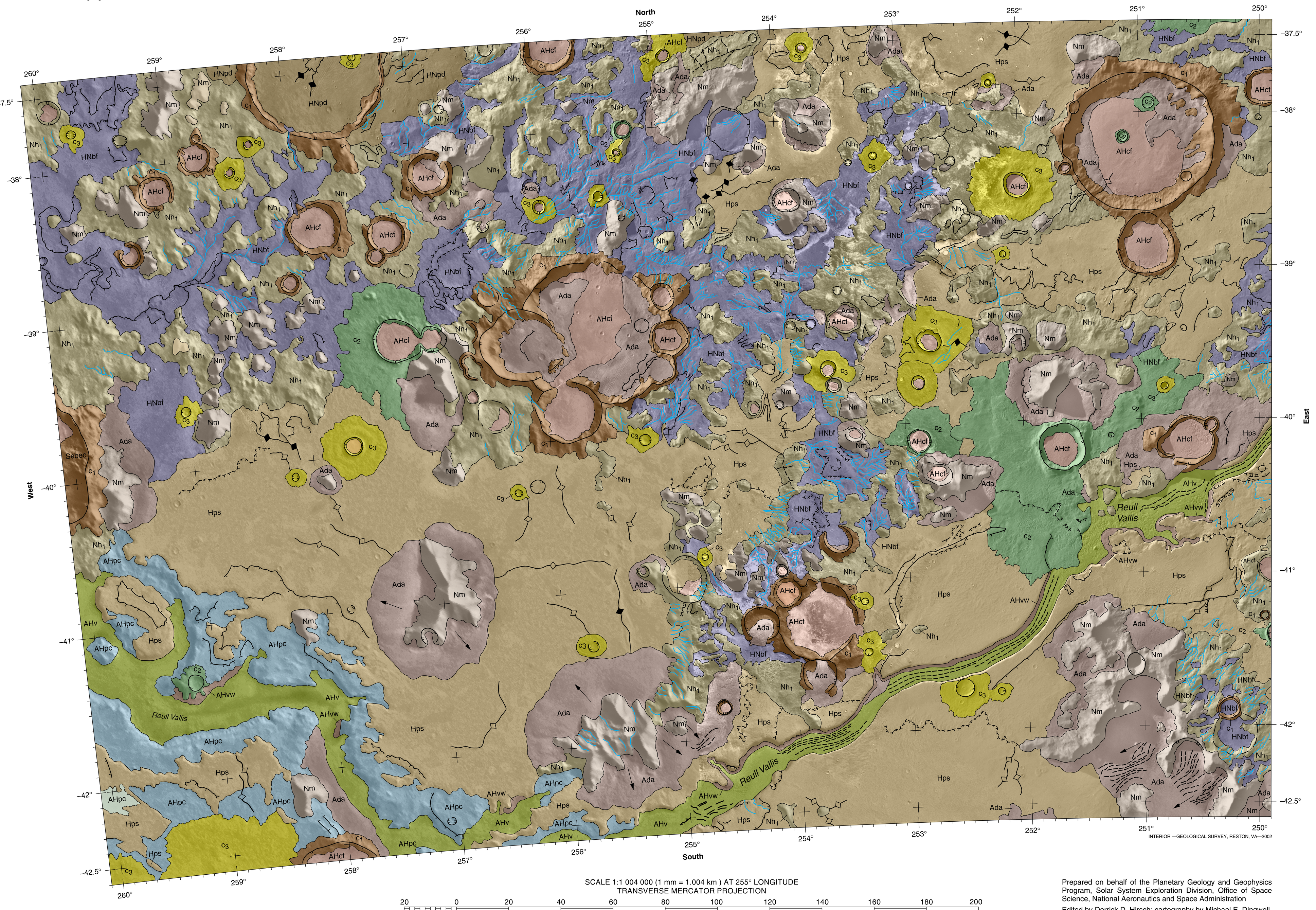
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEOLOGIC INVESTIGATIONS SERIES I–2730
ATLAS OF MARS: MTM –40252 AND –40257 QUADRANGLES



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

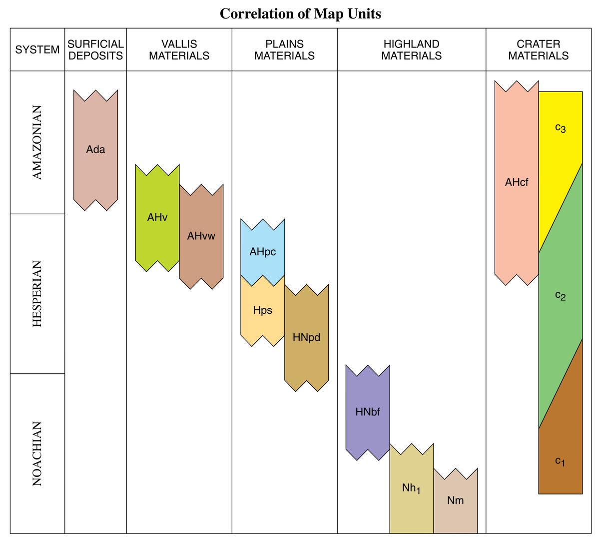
Edited by Derrick D. Hirsch; cartography by Michael E. Dingwell, Darlene A. Ryan, and Hugh F. Thomas

Manuscript approved for publication August 15, 2000

GEOLOGIC MAP OF MTM –40252 AND –40257 QUADRANGLES, REULL VALLIS REGION OF MARS

By
Scott C. Mest and David A. Crown
2002

Correlation of Map Units



DESCRIPTION OF MAP UNITS

[Unit descriptions and interpretations are based on morphology, texture, albedo, and stratigraphic position as observed in Viking Orbiter images]

SURFICIAL DEPOSITS

Ada — **Debris apron material**—Smooth, featureless (in low- to medium-resolution images) surfaces with lobate fronts, may exhibit pits and (or) lineations (that is, longitudinal ridges and grooves); borders highland massifs, crater rims, and vallis walls. *Type areas*: 40.2° S., 251° W. (pits) and 42.3° S., 251.1° W. (lineations). *Interpretation*: Deposits of unconsolidated material resulting from mass wasting of rugged highland massifs, crater rims, and vallis walls; mobility possibly due to incorporation of water or ice [for example, Squyres and Carr, 1986; Crown and others, 1992]; pits may be from partial collapse of volatile-rich debris; longitudinal ridges and grooves may indicate sorting of material within the flow or shearing of debris as it flowed [Squyres, 1978, 1979]

VALLIS MATERIALS

AHv — **Vallis floor material**—Deposits that form floor of Reull Vallis; lineated parallel to vallis walls; smooth or pitted. *Type areas*: 40.2° S., 250° W. (lineated), 42.4° S., 254.8° W. (smooth), and 40.7° S., 251° W. (pitted). *Interpretation*: Sedimentary material of surrounding units [Crown and others, 1992; Tanaka and Leonard, 1995] emplaced by a combination of collapse and fluid flow; modified by small-scale deflation and fluvial redistribution; pits may result from partial collapse of volatile-rich material; lineations may be related to flow of water through the canyon and/or from coalescing debris aprons [Squyres, 1978]

AHvw — **Vallis wall material**—Smooth deposits occurring at base of walls of Reull Vallis; typically overlain by vallis floor material. *Type area*: 40.5° S., 250.4° W. *Interpretation*: Materials eroded from highland and plains units deposited at the base of the walls of Reull Vallis, similar to talus

PLAINS MATERIALS

AHpc — **Channeled plains material**—Occurs in the southwest corner of MTM –40257 and along segment 3 of Reull Vallis. Smooth to irregular surface characterized by ridges having subdued morphologies and degraded craters; dissected by channels and scarps south and west of map area; fluted where exposed along Reull Vallis and in a large side canyon south of the main canyon of Reull Vallis (south of map area). *Type area*: 41.7° S., 258.5° W. *Interpretation*: Material deposited following erosion of surrounding highland and plains materials. Sinuous channels and scarps and degraded ridges and craters due to subsequent fluvial erosion of unit, possibly related to flooding from Reull Vallis. Mapped as smooth plains material (unit Hps) by Price [1998] and previously mapped as channeled plains rim unit (unit AHh_5) by Greeley and Guest [1987], Mest [1998], and Mest and Crown 2001

Hps — **Smooth plains material**—Occurs adjacent to Reull Vallis and in northern part of MTM –40252. Consists of smooth, relatively featureless materials embaying highland units; some occurrences have lobate margins; appears pitted adjacent to Reull Vallis (MTM –40252). Wrinkle ridges within unit have subdued morphologies. Also occurs as flat-topped, scarp-bounded mesas south of Reull Vallis (MTM –40257) within channeled plains material. Lightly cratered. *Type area*: 41° S., 256° W. *Interpretation*: Sedimentary deposits resulting from overflow of water from Reull Vallis; emplaced as sediment-rich flows and (or) from transient body of water; also may contain materials eroded from highland terrains [Mest and Crown, 2001]; subdued morphology of wrinkle ridges due to erosion and burial by plains material. Mapped as mesa material (unit AHm) by Price [1998] and previously included within smooth plateau unit (unit Hpl_3) by Greeley and Guest [1987]

HNpd — **Dissected plains material**—Occurs in the northern part of map area. Consists of smooth material that fills low-lying areas between knobs and massifs of highland materials. Majority of plains, especially in southwestern extent of unit (north of map area), dissected by sinuous scarps and small channels. Wrinkle ridges and craters within unit have subdued morphologies. *Type area*: 37.5° S., 254.1° W. *Interpretation*: Deposits of volcanic and (or) sedimentary materials modified by surface runoff. Previously mapped as ridged plains material (unit Hr) by Greeley and Guest [1987]

HIGHLAND MATERIALS

HNbf — **Intermontane basin fill**—Smooth to slightly hummocky deposits filling low-lying regions within highlands. In map area, unit contains numerous valley networks, dendritic to rectilinear in nature; less dissected in the western part of MTM –40257. Some occurrences, especially where adjacent to smooth plains, have scarp-bounded edges. *Type area*: 38.7° S., 253° W. *Interpretation*: Sedimentary deposits derived from highland materials; may also contain eolian deposits with non-local sources; most deposits eroded by fluvial processes forming channels

Nh_1 — **Basin-rim unit**—Material of Hellas basin rim; consists of rugged, mountainous terrains with small sections of smooth deposits; dissected by channels which may extend onto younger materials; typically embayed by younger plains; heavily cratered. *Type area*: 39° S., 253.3° W. *Interpretation*: Impact-generated unit of ancient martian crust modified by fluvial and eolian processes [Greeley and Guest, 1987]; channel formation due to combination of ground water sapping and runoff.

Nm — **Mountainous material**—Occurs throughout map area. Forms small to large, rugged, isolated massifs within basin-rim unit and younger units; typically embayed by younger plains; some surrounded by debris aprons. *Type area*: 41.4° S., 251.4° W. *Interpretation*: Ancient crustal material uplifted during formation of impact basins [Greeley and Guest, 1987]

CRATER MATERIALS

[Impact craters <4 km in diameter not mapped]

AHcf — **Crater fill material**—Forms smooth or pitted surfaces on crater floors; displays lobate margins against interior crater walls. *Type areas*: 38.3° S., 251° W. (smooth) and 40.1° S., 250.6° W. (pitted). *Interpretation*: Fluvial and (or) eolian sedimentary deposits and (or) coalesced debris aprons from crater rim materials that accumulate on crater floors; pitting may be due to partially collapsed volatile-rich materials. Mapped as smooth floor material by Greeley and Guest [1987]

c_3 — **Well-preserved crater material**—Characterized by pronounced, continuous crater rim elevated relative to surrounding materials and by well-defined, continuous ejecta blanket. *Interpretation:* Pristine crater material exhibiting little degradation; some crater floors may contain deposits emplaced by mass wasting, eolian activity, and (or) fluvial processes

c_2 — **Moderately degraded crater material**—Characterized by a crater rim that may exhibit only minor relief above surrounding materials and by discontinuous, poorly exposed ejecta. *Interpretation:* Impact craters with moderate degree of degradation; most crater floors contain deposits emplaced by mass wasting, eolian activity, and (or) fluvial processes

c_1 — **Highly degraded crater material**—Characterized by a degraded crater rim that may be discontinuous and exhibits little relief relative to the surrounding materials; no ejecta and smooth, featureless crater floors. *Interpretation:* Highly degraded impact crater material. Ejecta has been completely eroded or mantled by younger materials; rim has been modified by erosion. Most crater floors contain deposits emplaced by mass wasting, eolian activity, and (or) fluvial processes

Contact—Dashed where approximately located or gradational

Ridge

Subdued ridge

Lineament

Scarp—Hachures at top of scarp point downslope; dashed where inferred

Channel

Crater rim crest

Degraded crater rim crest

Apparent flow direction

INTRODUCTION

Mars Transverse Mercator (MTM) quadrangles –40252 and –40257 cover a portion of the highlands of Promethei Terra northeast of the Hellas basin (fig. 1). The map area consists of heavily cratered ancient highland materials of moderate to high relief, isolated knobs and massifs of rugged mountainous materials, extensive tracts of smooth and channeled plains, and other surficial deposits. Reull Vallis (fig. 2), an ~1,500-km-long outflow channel system, cuts through the southeast corner of the map area. Regional slopes are to the southwest, toward the Hellas basin, as indicated by martian topographic maps [U.S. Geological Survey, 1989; Smith and others, 1999] and the orientations of channels along the northeast rim of the Hellas basin. The martian highlands cover more than 60% of the planet's surface and are primarily in the southern hemisphere [Tanaka and others, 1992]. Most of the highlands consist of rugged, densely cratered terrains believed to represent the final phase of heavy bombardment in the inner solar system ~4.0 billion years ago [Murray and others, 1971; Schubert and others, 1992; Tanaka and others, 1992]. Parts of the martian highlands show evidence of extensive degradation and modification. The map area exhibits landforms created by numerous geologic processes, including tectonism, fluvial activity, and mass wasting. The occurrence of fluvial features, such as outflow channels and valley networks, has significant implications for past martian conditions. Determining the geology of the highlands northeast of the Hellas basin provides a better understanding of the role and timing of volatile-driven activity in the evolution of the highlands. Photogeologic mapping at 1:500,000 scale from analysis of Viking Orbiter images complements geomorphic studies of Reull Vallis and other highland outflow systems, of drainage networks, and of highland debris aprons and regional geologic mapping studies of the highlands at the 1:2,000,000 scale [Mest, 1998; Mest and Crown, 2001] and 1:1,000,000 scale [Mest and Crown, 2002]. Crater size-frequency distributions have been compiled to constrain the relative ages of geologic units and determine the timing and extents of the observed geologic processes.

REGIONAL GEOLOGY

Noachian materials are the principal components of the rugged highlands surrounding the Hellas basin and represent the oldest rocks on Mars [Murray and others, 1971; Tanaka, 1986; Tanaka and others, 1988, 1992; Schubert and others, 1992]. According to Greeley and Guest [1987], erosion of highland materials began during the Late Noachian Epoch and continued throughout the Hesperian Period, resulting in deposition of extensive plains materials in and around the Hellas basin. The units of the Hellas basin and its surrounding rim are grouped into the Hellas assemblage [Greeley and Guest, 1987]; these units range from the basin-rim unit, consisting of rugged highland plateaus and massifs dissected by channels and valley networks, to younger plains units, some of which contain channels, ridges, scarps, and mesas.

Highland volcanism began north and northwest of the map area in the Late Noachian/Early Hesperian Epochs with the formation of Hadriaca and Tyrrhena Paterae [Crown and others, 1992; Tanaka and Leonard, 1995; Crown and Greeley, 1993; Gregg and others, 1998], and northeast of the map area with emplacement of the ridged plains material of Hesperia Planum [Tanaka, 1986; Greeley and Guest, 1987]. The highland paterae are interpreted to be composed of pyroclastic deposits possibly resulting from phreatomagmatic eruptions [Greeley and Spudis, 1981; Greeley and Crown, 1990; Crown and Greeley, 1993]. However, the presence of an ~1000-km-long flank unit extending from Tyrrhena Patera that contains lava flows and a smooth deposit infilling the caldera of Hadriaca Patera suggests some effusive activity occurred late in the volcanoes' histories (presumably mid- to Late Hesperian/Early Amazonian) [Crown and others, 1992]. The ridged plains of Hesperia Planum is one of many areally extensive volcanic plains-forming units found on the surface of Mars [Scott and Tanaka, 1986; Greeley and Guest, 1987]. Ridged plains material exhibits wrinkle ridges, may contain lobate scarps (possibly flow fronts), and is interpreted to be composed of flood lavas which fill low-lying areas [Potter, 1976; King, 1978; Greeley and Spudis, 1981; Scott and Tanaka, 1986; Greeley and Guest, 1987].

Water is believed to have played a major role in modifying the martian highlands, and MTM quadrangles –40252 and –40257 exhibit extensive evidence of fluvial activity (see 'Fluvial Features'). Numerous well-developed valley networks appear to be the oldest fluvial features in the study area; they are found in rugged ancient highland terrains and are most likely Noachian to Hesperian in age [Crown and Mest, 1997]. The presence of several widespread plains units northeast of the Hellas basin provides evidence that extensive degradation and resurfacing occurred in the highlands. Subsequent erosion of these plains units is believed to have occurred in the Late Hesperian/Early Amazonian Epochs [Greeley and Guest, 1987]. Also during the Hesperian the highland outflow channels (Reull, Dao, Niger, and Harmakhis Valles) formed, depositing significant amounts of eroded material on their floors and along their banks, as well as on the floor of the Hellas basin. Recent studies of the four mid-Hesperian/Early Amazonian-aged outflow channels in the eastern Hellas region suggest an origin by subsurface flow and collapse of plains materials combined with fluvial processes, followed by modification by wall retreat [Crown and others, 1992; Tanaka and Leonard, 1995; Crown and Mest, 1997]. Each outflow channel heads within or adjacent to a major local volcanic feature: Dao Vallis cuts into the flank materials of Hadriaca Patera, Niger and Harmakhis Valles are located adjacent to the Tyrrhena Patera flank flow, and Reull Vallis begins in the ridged plains of Hesperia Planum. The fact that the outflow channels are in close proximity to these volcanic features suggests valles formation may be in part due to mobilization and release of subsurface volatiles by volcanic heat [Squyres and others, 1987; Crown and others, 1992]. Lastly, evidence of mass wasting has been observed in the form of debris aprons that extend from highland massifs, interior crater walls, and valles walls, and appear to be the youngest features observed [Crown and others, 1992; Crown and Stewart, 1995; Tanaka and Leonard, 1995; Crown and Mest, 1997; Crown and others, 1997].

STRATIGRAPHY

Relative ages of the geologic units mapped in MTM quadrangles –40252 and –40257 were determined using observed stratigraphic relations in combination with crater size-frequency distributions compiled in the regional study of the Reull Vallis region (table 1) [Mest, 1998; Mest and Crown, 2001]. Craters were counted on a Mars Digital Image Mosaic at 231 m/pixel (latitude –27.5° to –47.5°, longitude 245° to 270°). With a few exceptions, crater size-frequency distributions show relative ages that tend to be consistent with previous studies [for example, Greeley and Guest, 1987; Crown and others, 1992; Tanaka and Leonard, 1995].

Heavily cratered highlands contain the oldest materials exposed in the area. The oldest rock units visible are mountainous material (unit Nm) and the basin-rim unit of the Hellas assemblage (unit Nh_1) (fig. 3), previously mapped by Greeley and Guest [1987]. Mountainous material (unit Nm) forms large rugged, isolated or clustered massifs throughout the study area. Most massifs are found within exposures of the basin-rim unit or are surrounded by younger volcanic or sedimentary plains material. Numerous massifs of mountainous material in the area, especially near Reull Vallis, are surrounded by debris aprons derived from highland terrains [Crown and others, 1992; Crown and Stewart, 1995; Stewart and Crown, 1997]. The basin-rim unit forms the rugged, mountainous terrain of Promethei Terra. Most of the unit in the map area is north of Reull Vallis, but some is exposed to the southeast. Massifs within the basin-rim unit tend to be incised with small valleys and are more eroded than other highland materials in the area. In places, the basin-rim unit may also contain eolian mantling deposits derived from local materials. Mountainous materials and the basin-rim unit are interpreted to consist of ancient crustal materials (impact breccias and volcanics) uplifted during impact basin formation [Scott and Tanaka, 1986; Greeley and Guest, 1987].

Crown and others [1992] noted that intermontane regions within the basin-rim unit appeared to have smooth surfaces. The current study shows that these areas are filled with smooth material, called intermontane basin fill (unit HNbf), that was subsequently eroded by channels and well-developed valley networks (fig. 3). Exposures of intermontane basin fill in MTM –40252 and the eastern part of MTM –40257 are heavily dissected by valley networks and channels, whereas the remaining exposures in the region appear relatively smooth with only a few small channels and scarps. The difference in the amount of dissection may be due to the lower resolution images of western MTM –40257. The presence of highly eroded intermontane basin fill among highland massifs provides evidence of deposition and erosion by fluvial processes in the oldest parts of the map area. See the section entitled 'Fluvial Features' for a description and discussion of valley network morphology.

The basin-rim unit of the Hellas assemblage (unit Nh_1) and mountainous material (unit Nm) are some of the oldest materials exposed in the map area, but crater size-frequency distributions show ages slightly younger than other studies (Middle Noachian to Early Hesperian). These younger ages are most likely due to the degradational history of these units and their small areal extents in the Reull Vallis region. Also, intermontane basin fill (unit HNbf—not mapped in the regional studies of Mest [1998] and Mest and Crown [2002]) within the basin-rim unit would have buried small- and medium-size craters, giving the basin-rim unit a younger age than expected. Thus, the basin-rim unit proper is most likely Middle Noachian in age, and mountainous material Middle to Early Noachian. Although crater statistics were not compiled for intermontane basin fill, superposition relations place it between the basin-rim unit and smooth plains material (unit Hps), suggesting a Late Noachian to Early Hesperian age.

Dissected plains material (unit HNpd) is an extensive unit north of the map area nestled between the basin-rim unit and the ridged plains material (unit Hr) of Hesperia Planum and was previously mapped as the southwesternmost extension of Hesperia Planum [Greeley and Guest, 1987]. A small exposure of dissected plains material occurs in MTM –40252 along the north edge of the quadrangle, and a larger exposure occurs north of the basin-rim unit in MTM –40257. Dissected plains material is characterized by narrow sinuous channels, irregular scarps, and eroded ridges and is interpreted to consist of volcanic and (or) sedimentary materials modified by fluvial processes (fig. 4). Dissected plains material appears to have filled low-lying areas of the highlands, as numerous isolated knobs and hills of mountainous material (unit Nm) are embayed by the plains. The contact between the ridged plains and dissected plains materials is not well-defined and may be gradational; however, the mottled texture and the lack of high concentrations of cross-cutting pristine wrinkle ridges in dissected plains material allow it to be distinguished from ridged plains material.

Crater size-frequency distributions for dissected plains material (unit HNpd) show the unit to be Late Noachian to Early Hesperian in age and slightly older than the ridged plains material (unit Hr) of Hesperia Planum. Two possibilities exist for the origin of dissected plains material: (1) dissected plains material is an older part of Hesperia Planum (as mapped by Greeley and Guest [1987]) that underwent a period of fluvial erosion, or (2) dissected plains material is a discrete unit (volcanic or sedimentary) that predates the ridged plains and was subject to tectonic deformation and fluvial erosion.

Most exposures of smooth plains material (unit Hps) are immediately adjacent to Reull Vallis (Figs. 3, 5–8); smaller expanses are north of the basin-rim unit in MTM –40252. Smooth plains material appears to embay Noachian highland units (units Nh_1 and Nm) and exhibits lobate terminations in places where the plains meet the highlands (fig. 3). At moderate resolutions, smooth plains material displays relatively featureless surfaces except for a few wrinkle ridges with subdued morphologies, irregular scarps, and small valleys. At higher resolutions (~47 m/pixel), portions of smooth plains material adjacent to Reull Vallis contain pits or small-scale undulations (fig. 8). This surface texture could have resulted from minor erosion (scouring) of the plains as water drained from the area, localized collapse, and (or) mantling by wind-blown material forming dunes. Low-relief scarps and small channels within smooth plains material further suggest water eroded some surfaces after plains emplacement. An arcuate scarp-bounded trough north of Reull Vallis (MTM –40252) is interpreted to be a small channel that intersects Reull Vallis and is believed to have formed by fluvial processes. Two scarps, ~60 km and ~100 km long, are found south of the irregular basin and the main canyon of Reull Vallis in MTM –40252 (fig. 6). These scarps face away from the Reull Vallis and suggest that the canyon may have overflowed and deposited smooth materials in the surrounding region. Smooth plains material is interpreted to consist of sedimentary materials deposited from overflow of Reull Vallis and (or) materials eroded from the surrounding highlands during valley network formation.

Several flat-topped, scarp-bounded mesas occur just south of Reull Vallis within channeled plains material (unit AHpc — see below) [Crown and others, 1992] (fig. 7). These mesas have smooth surfaces and their scarps appear to have the same erosional characteristics as smooth plains material (unit Hps) seen along the northern edge of Reull Vallis. In addition, several degraded, infilled craters are present within channeled plains material [Crown and others, 1992] south and west of the map area; these craters have highly dissected rims, lack ejecta blankets, and are filled with smooth deposits. These craters may have been buried by smooth plains material and then re-exposed by fluvial erosion; the materials infilling the craters could have been protected by more resistant crater-wall materials.

Smooth plains material immediately adjacent to Reull Vallis appears to change in character where exposed along the walls of the different canyon segments (see fig. 2 and the section entitled 'Fluvial Features' for a complete description of the "segments" of Reull Vallis contained within the map area). Along the upper part of segment 2 (east of MTM –40252), smooth plains material shows a fluted scarp boundary and appears to have been laterally eroded. However, along the majority of the lower part of segment 2 (figs. 5, 6, and 8; in MTM quadrangles –40252 and –40257), smooth plains material shows no evidence of lateral erosion and extends to the canyon wall. As the lower part of segment 2 approaches segment 3 and the contact between channeled plains and smooth plains materials, the edge of the smooth plains again appears as a fluted scarp. Smooth plains material exposed north of segment 3, and mesas south of the canyon, also have a fluted appearance (fig. 7). These changes observed in smooth plains material may provide evidence for its formation. Flooding from Reull Vallis may have resulted in emplacement of smooth plains material; as floodwaters receded in the upper part of segment 2, lateral erosion of smooth plains material took place. Ponding also may have occurred at this time in the vicinity of the lower part of segment 2, resulting in a thicker, laterally extensive sequence of material being deposited around this portion of Reull Vallis. Subsequent outbursts of water appear to have occurred, forming the side canyon south of Reull Vallis, enlarging the canyon at segment 3, eroding smooth plains material north and south of segment 3, and eroding channeled plains material south and west of the canyon.

Smooth plains material also occurs as isolated patches within highland terrains in the northern part of the map area, separated from Reull Vallis by exposures of the basin-rim unit and mountainous massifs (fig. 3). These exposures of smooth plains material may have formed differently than those immediately adjacent to Reull Vallis. As stated earlier, some valley networks extend from the highlands onto the smooth plains but have subdued morphologies (fig. 3). These isolated exposures of smooth plains material may be composed of sediments eroded from the highlands and deposited in low-lying areas. A component of eroded highland material also may be included in the smooth plains material near Reull Vallis.

Crater size-frequency distributions show smooth plains material (unit Hps) to be Late Noachian to Late Hesperian in age. Most exposures of smooth plains material in the map area were previously mapped as smooth plateau material (unit Hpl_3) by Greeley and Guest [1987], which show an age of Upper Noachian to Lower Hesperian. Cross-cutting relations between smooth plains material and Reull Vallis, and superposition relations between smooth plains material and channeled plains (unit AHpc) and dissected plains materials indicate smooth plains material is most likely Early Hesperian in age.

The channeled plains rim unit (unit AHh_5 — defined by Greeley and Guest [1987] and mapped in Mest [1998] and Mest and Crown [2001]) is here subdivided into channeled plains material (unit AHpc) and smooth plains material (unit Hps — as discussed above). Price [1998] subdivided portions of the channeled plains rim unit into hummocky plains material (unit HNh), smooth plains material (unit AHps), and mesa material (unit AHm), retaining the channeled plains rim unit closer to the Hellas basin and adjacent to Dao, Harmakhis, and the terminus of Reull Valles (west of the current map area). Channeled plains material (unit AHpc) and smooth plains material (unit Hps) in the current study correspond to smooth plains material (unit AHps) and mesa material (unit AHm), respectively, in Price [1998]. Channeled plains material (AHpc) occurs immediately adjacent to the Hellas basin along its northeast rim and extends into the highlands of Promethei Terra. Exposures of channeled plains material occur in the southwest corner of MTM –40257 and along segment 3 of Reull Vallis (fig. 7). Channeled plains material typically has a smooth to irregular surface heavily dissected by sinuous channels and scarps; most channeling occurs south and west of the map area, but several scarps can be seen just north of Reull Vallis in MTM –40257. Channels and scarps immediately south of the map area tend to be orientated perpendicular to Reull Vallis, suggesting some water flowed toward and into Reull Vallis. However, channels and scarps west of the map area are oriented roughly radial to the Hellas basin, indicating some flow of water toward the basin, which is consistent with the regional topography [U.S. Geological Survey, 1989; Smith and others, 1999]. Channeled plains material contains numerous degraded ridges and craters and, in some places, has a fluted appearance where it is exposed along Reull Vallis, especially in a large side canyon south of the map area. Channeled plains material is interpreted to be a sedimentary unit deposited following removal of smooth plains material to the southwest of Reull Vallis. Channeled plains material most likely consists of sediments eroded from the smooth plains and sediments transported in the floodwaters associated with Reull Vallis. Channels, scarps, and degraded ridges and craters suggest large volumes of water (possibly from Reull Vallis) flowed over the surface toward Reull Vallis and the Hellas basin. The floodwaters redistributed sedimentary materials, left mesas of smooth plains material, exposed impact craters and ridges which may have been at least partially buried, and scoured the plains.

The stratigraphic position of channeled plains material (unit AHpc) is based on superposition relations and crater densities for the channeled plains rim unit (unit AHh_5) obtained in Mest [1998] and Mest and Crown [2001]. Channeled plains material is interpreted to be a sedimentary unit deposited in conjunction with erosion of smooth plains material and overflow of water from Reull Vallis. The current surface contains some large craters, which may have been exhumed from an older underlying unit. The N(2) and N(5) crater densities for channeled plains material suggest formation during the Late Hesperian to Early Amazonian Epochs, consistent with ages determined by Greeley and Guest [1987] and Crown and others [1992].

Vallis wall material (unit AHvw) occurs along the base of the walls of Reull Vallis (fig. 5); these deposits are apparently overlain partially by vallis floor material (unit AHvw). Vallis wall deposits are interpreted to consist of materials shed from adjacent highland and plains units deposited at the base of the canyon walls and are possibly similar to talus or colluvial deposits. Vallis floor material (unit AHv) is believed to consist of unconsolidated material infilling Reull Vallis emplaced by a combination of fluvial deposition and mass wasting. In MTM –40252 the surface of vallis floor material in the narrow section of segment 2 and in the basin exhibit pitting and lineations that parallel the canyon walls (figs. 6, and 8) These lineations are similar in appearance to those seen on lineated valley fill and are interpreted to have formed as interstitial ice/water caused unconsolidated materials to undergo shear during motion [Squyres, 1978, 1979; Squyres and Carr, 1986], similar to flow in terrestrial rock glaciers [Wahrhaftig and Cox, 1959]. Debris entering the canyon from a small tributary appears to have flowed onto the surface of the vallis floor material; flow lineations on the surface of this debris appear to be deflected in the direction in which the main mass of vallis floor material is moving. Several collapse features/slump blocks also occur along the south wall of Reull Vallis (fig. 8 Vallis floor material in segment 3 (MTM –40257) appears hummocky in Viking Orbiter images (fig. 7). Several debris aprons are seen along the walls of Reull Vallis in segment 3, so some component of the infilling vallis floor material consists of debris mass-wasted from the canyon walls. A combination of intercanyon deposition and infilling by wall materials can reasonably explain the morphology of vallis floor material within these segments of Reull Vallis.

Few craters are observed within vallis floor material (unit AHv), and previous studies have shown these deposits to be Late Hesperian [Greeley and Guest, 1987] to Early Amazonian [Crown and others, 1992] in age. Crater statistics determined for vallis floor material for Reull, Dao, Niger, and Harmakhis Valles in the regional studies of Mest [1998] and Mest and Crown [2001] show the unit to be Early Hesperian to Early Amazonian in age. However, relations between vallis floor and smooth plains materials constrain the range to Late Hesperian to Early Amazonian. Older ages for these deposits are most likely due to the inclusion of the entire canyon of Reull Vallis; the study by Crown and others [1992] only measured a portion of segment 3 of Reull Vallis near its terminus. If individual segments of Reull Vallis are considered separately, differences in age are evident. Vallis floor material in the upper part of segment 2 contains more craters than the lower part of segment 2 and segment 3 of Reull Vallis and floor material in Dao, Niger, and Harmakhis Valles. This relation suggests that the upper part of segment 2 of Reull Vallis could have a floor that is older than the other segments (Lower Hesperian versus Upper Hesperian to Lower Amazonian) or that it has not been affected by wall collapse and infilling to the same degree as the lower part of segment 2 and segment 3. On the basis of crater statistics, the formation of Reull Vallis would have begun in the Lower Hesperian and is an older system than Dao, Niger, and Harmakhis Valles. Crater counts for vallis wall material (unit AHvw) in Reull Vallis were not determined in the regional study [Mest, 1998; Mest and Crown, 2001] due to their limited exposure but are believed to be Upper Hesperian to Lower Amazonian based on superposition relations with vallis floor material.

Many craters in the region have smooth floors and have been infilled with crater fill material (unit AHcf) (fig. 9). This material varies morphologically among craters in the map area, which indicates multiple origins of crater fill material. Crater fill material observed in some craters presumably consists of materials eroded from the crater walls by fluvial processes and deposited on the crater floor. Crater fill material observed in other craters has pitted surfaces and lobate edges, similar to local debris aprons, and may be composed of coalescing volatile-rich debris mass-wasted from crater rims. Other occurrences of crater fill may consist of material deposited from external sources. Some craters in the map area, especially within the basin-rim unit, have discontinuous rims and may have been infilled with material eroded from the highlands, similar to intermontane basin fill. Craters found in channeled plains material with continuous, well-defined rims (outside of map area) appear to be filled with smooth deposits similar to nearby flat-topped mesas and smooth plains material. These craters may provide evidence that floodwaters were deep enough to flow over and deposit material inside craters. Also, some crater fill material could be composed of eolian deposits.

Mass wasting appears to have formed the youngest deposits in the map area. Debris apron material (unit Ada) occurs throughout the region, extending from massifs of Noachian mountainous material (unit Nm) (figs. 6–8), crater walls (fig. 9), and vallis walls (fig. 7) [Crown and others, 1992; Crown and Stewart, 1995; Stewart and Crown, 1997]. They are interpreted to consist of unconsolidated material. Most of the debris aprons in the area are associated with mountainous material (unit Nm). Debris aprons associated with isolated highland massifs frequently completely surround their parent massifs, spreading laterally and extending for distances up to ~40 km, whereas debris aprons in craters and within Reull Vallis tend to be confined and therefore relatively small [Crown and Stewart, 1995; Stewart and Crown, 1997]. Debris aprons around highland massifs have uniform or mottled albedoes and may exhibit lineations on their surfaces parallel and (or) perpendicular to the direction of motion; those in craters and within Reull Vallis have mottled albedoes, relatively featureless surfaces, and arcuate to lobate fronts. Some massif-related aprons, especially the largest deposits, have lobate frontal morphologies and appear to be composed of multiple coalescing lobes [Crown and Stewart, 1995; Stewart and Crown, 1997]. Pitting is seen on the surfaces of massif-, crater-, and canyon-related debris aprons, especially close to Reull Vallis.

Lineations parallel to the direction of flow occur on the surfaces of large debris aprons and suggest shearing of materials facilitated by interstitial water and (or) ice [Squyres and Carr, 1986; Zimbelman and others, 1989; Crown and others, 1992], similar to lineated valley fill [Squyres, 1978, 1979]. This type of ice creep appears to be a dominant process in middle to high latitudes on Mars, causing landforms to undergo "terrain softening" and forming concentric crater fill and debris aprons [Squyres and Carr, 1986]. The fretted terrain in the northern hemisphere (30°–50° north) displays landforms produced by creep-related processes, in which ice-rich materials flowed downslope [Squyres, 1978, 1979; Squyres and Carr, 1986]. Here, valley floors contain lineated valley fill, characterized by lineations parallel to the valley walls, and debris aprons with lineations parallel to the apparent direction of flow, both indicating slow movement of volatile-rich debris [Squyres, 1978, 1979].

Debris apron (unit Ada) and crater fill (unit AHcf) materials contain few craters on their surfaces and are not areally extensive, and therefore show low crater densities. Crater size-frequency distributions of these materials suggest they are some of the youngest deposits in the study area, ranging from Late Hesperian to Middle Amazonian for debris apron material, and Late Hesperian to Early Amazonian for crater fill material. Crater fill material is found in craters within units of various ages and is interpreted to have several different origins (for example, eroded from crater walls and rims, coalescing debris aprons, and external sources such as fluvial and eolian deposits). Mest [1998] and Mest and Crown [2001] observed in the regional study that crater fill material resulting from erosion of crater walls and rims contained more craters on their surfaces than crater fill material formed by coalescing debris aprons or eolian deposits; thus a range of ages for crater fill material is expected.

Crater materials within the map area display various states of preservation, indicating degradation of these materials has been a continuing process throughout the evolution of this region. Well-preserved crater material (unit c_3) shows the least amount of degradation and is characterized by pronounced, continuous crater rims that are elevated relative to the surrounding materials, and also by well-defined, continuous ejecta blankets. Many of these crater types, especially in the smooth plains near Reull Vallis, display rampart morphologies that suggest impact in volatile-rich materials [Squyres and others, 1992]. Moderately degraded crater material (unit c_2) shows moderate amounts of degradation and is characterized by crater rims (in places discontinuous) exhibiting minor relief above the surrounding materials, and by discontinuous and (or) poorly exposed ejecta blankets. Highly degraded crater material (unit c_1) shows the most degradation, with discontinuous crater rims exhibiting little to no relief above the surrounding materials and ejecta blankets that have either been completely eroded or mantled by younger materials. Many craters of all types (units c_3, c_2, and c_1) appear to have smooth, flat floors, containing crater fill material (unit AHcf) though still retaining their other characteristic morphologies. The fact that crater fill material may have various origins, and therefore ages, makes the presence (or lack) of this deposit an inappropriate method of characterizing craters within the map area.

FLUVIAL FEATURES

Fluvial processes appear to have played a major role in the geologic evolution of the map area. Numerous valley networks and channels are observed within many of the geologic units in the map area, including the basin-rim unit, intermontane basin fill, and dissected plains, smooth plains, and channeled plains materials. The presence of Reull Vallis also indicates large quantities of water may have assisted in removing copious amounts of materials from the highlands of Promethei Terra, depositing as well as eroding the surrounding plains materials.

Valley Networks

Valley networks in intermontane basin fill consist of narrow channels (<1 km wide) several tens to hundreds of kilometers long. They exhibit well-developed dendritic to rectilinear patterns (terminology from Mars Channel Working Group [1983]) (fig. 3), similar to other networks observed in the cratered highlands of Mars [Carr, 1995, 1996]. The drainage basins that contain the networks are 80 to 240 km wide and 80 to 640 km long; the largest drainage systems typically consist of two or more basins connected by individual channels that have breached their divides. Several of the valleys in MTM –40252 have a subdued appearance where they emerge from the highlands onto smooth plains material. These valleys could have been partially buried by smooth plains material, indicating that at least some plains material emplacement postdates valley network formation, or the erosive ability of these valleys decreased as water flowed from the steeper highlands onto the relatively flat plains.

Valley networks observed in the highlands of the map area, although small compared to other martian networks, clearly show dendritic to rectilinear patterns and have well-developed tributaries. Martian valley networks closely resemble terrestrial networks formed by runoff from rainfall [Carr, 1995, 1996; Craddock and Maxwell, 1993; Craddock and others, 1997], however some researchers [for example, Pieri, 1976, 1980] suggest martian valley morphologies more closely resemble terrestrial valleys produced by sapping or seepage-fed runoff [Mars Channel Working Group, 1983]. Pieri [1976, 1980] showed that, unlike terrestrial valleys, martian valley networks lack dendritic patterns and tributaries, showing reticulate patterns (indicating structural control), and that valley morphologies (steep-walled, U-shaped cross sections, and theater-headed terminations) appear similar to valleys on the Colorado Plateau where sapping processes dominate valley formation [Carr and Clow, 1981; Mars Channel Working Group, 1983; Carr, 1995, 1996]. However, in a study by Goldspiel and others [1993] topographic profiles across highland valleys were shown to have "smoothly curved" cross sections and lack the steep walls typical of terrestrial sapping valleys; these characteristics are similar to other martian valleys suggested to have been formed or modified by surface runoff. Therefore, these highland valley networks may have been affected by both runoff and sapping processes.

Outflow Channels

The Reull Vallis outflow system (fig. 2) extends nearly 1,500 km through materials of various types and ages, and displays a complex morphology indicative of multiple styles and episodes of formation and modification [Crown and Mest, 1997]. Reull Vallis can be separated into three morphologically distinct segments. Segment 1 of Reull Vallis, which contains its source area, is in the ridged plains of Hesperia Planum and is oriented roughly north-south. Segment 2 (oriented northeast-southwest) winds through the highlands of Promethei Terra and can be separated into a sinuous, v-shaped upper part and a less sinuous, steep-walled lower part. In segment 3, the main canyon alters its course northwestward through channeled plains material and terminates near the source basin of Harmakhis Vallis. Portions of the lower part of segment 2 are in MTM –40252 and MTM –40257, and part of segment 3 is in MTM –40257.

The lower part of segment 2 of Reull Vallis (fig. 5) begins where a narrow (1 to 2 km wide), shallow (~100 m deep) gully downcuts into vallis floor material (east of MTM –40252) [Mest, 1998; Mest and Crown, 2001]. This part of segment 2 extends for roughly 70 km through degraded highlands and smooth plains before opening into a large (20 km wide by 60 km long) basin (seen in MTM –40252). The irregular nature of the basin and the occurrence of slumped materials along the basin rim suggest its formation may have been influenced by collapse of volatile-rich materials. From this basin, segment 2 continues southwest for ~300 km where it joins with segment 3. The lower part of segment 2 has steep walls and a flat floor. The sections of segment 2 surrounding the basin (fig. 6) are narrower (6 to 18 km) and shallower (140 to 350 m) than the remainder of segment 2 (8–24 km wide; 150–800 m deep) [Mest, 1998; Mest and others, 1998]. The irregular nature of the remainder of segment 2 suggests that its shape was influenced by several preexisting craters breached during vallis formation and subsequent collapse of the vallis walls. Unlike segment 1 and the upper part of segment 2, the lower part of segment 2 shows no features on its floor indicative of surface runoff; however, the canyon displays some layering along its walls near the junction with segment 3. A tributary canyon (MTM –40257; fig. 5) joins segment 2 near its junction with segment 3. The tributary canyon heads near a large massif of mountainous material (unit Nm) and consists of a 40-km-long scarp-bounded trough, which enters the main canyon of Reull Vallis from the north.

Segment 3 of Reull Vallis (~600 km long) begins at the junction of segment 2 and a large side canyon, south of MTM –40257 (fig. 6). Segment 3 is noticeably wider (13 to 55 km) and deeper (200 to 2800 m) [Mest, 1998; Mest and others, 1998] and appears more heavily eroded along its walls than segment 2. The side canyon may have been a secondary source region for water, which resulted in enlargement of segment 3. Segment 3 dissects channeled plains material (south and west of the canyon), smooth plains material (northeast of the canyon), and the basin-rim unit (north of the canyon). Meanders in segment 3 (MTM –40257) appear to be angular, and the formation of Reull Vallis in this area may have been structurally controlled.

Dao, Niger, and Harmakhis Valles (1,200, 230, and 800 km long, respectively) are three outflow channels west of the map area. These valles are morphologically less complex than Reull Vallis, but provide a basis for comparison to Reull Vallis as their origins are believed to be similar. Dao, Niger, and Harmakhis Valles exhibit evidence for subsurface flow, collapse of plains, and surface flow. Large steep-walled basins head each canyon and are connected to the main canyons by areas of collapsed plains, presumably resulting from subsurface erosion of material and release of subsurface volatiles [Crown and others, 1992]. Subsequent erosion by surface flow is evident by the occurrence of scour marks in Niger Vallis and gullies in the collapse area of Harmakhis Vallis. As for Reull Vallis, slumping and scarp retreat are believed to have enlarged Dao, Niger, and Harmakhis Valles and contributed debris to vallis floor material. Debris flows extend from the walls of the Harmakhis Vallis source basin and a large oblong basin (~180 km long by 30 km wide) in the upper part of the main canyon of Dao Vallis.

STRUCTURAL FEATURES

Direct and indirect evidence for tectonic activity occurs within the map area. The most abundant features are wrinkle ridges, which consist of a broad arching rise topped with a narrow crenulated ridge, and are interpreted to be folded and (or) thrust-faulted strata resulting from compressional stresses [Lucchitta, 1976, 1977; Chicarro and others, 1985; Plescia and Golombek, 1986; Sharpton and Head, 1988; Watters, 1988, 1991, 1993; Golombek and others, 1990, 1991; Zuber, 1995]. Wrinkle ridges occur in a variety of units in the map area and display pristine, degraded, and subdued morphologies. Within channeled plains and dissected plains materials, wrinkle ridges show degraded morphologies suggesting erosion by fluvial processes. Wrinkle ridges within the smooth plains, dissected plains, and channeled plains materials also show subdued morphologies, indicating burial by plains material. Some pristine wrinkle ridges in the plains materials suggest (1) formation coeval or subsequent to the depositional and erosional events, (2) they were more resistant to erosion, or (3) some ridges were not buried.

Several lineaments, believed to have tectonic origins, are found in Noachian mountainous material and the basin-rim unit in the western part of MTM –40252. These lineaments are interpreted to be faults or fractures most likely developed during emplacement of these materials (as Hellas impact ejecta) or resulting from other impact events. The orientation of Reull Vallis (radial to the Hellas basin) and the angular morphology of segment 3 of Reull Vallis suggest vallis formation may have been influenced by faults and fracture patterns that resulted from the Hellas impact event [Crown and others, 1992; Mest, 1998; Mest and Crown, 2001].

GEOLOGIC HISTORY

The geologic history of the highlands region contained in MTM quadrangles –40252 and –40257 northeast of the Hellas basin was determined from analysis of Viking Orbiter images. Crater size-frequency distributions, compiled in the regional studies of Mest [1998] and Mest and Crown [2001], were used to support the relative ages of units identified and to constrain the evolution of the region. The following sequence of geologic events was documented by identification of the various types of geologic materials, analysis of the geomorphic characteristics of those materials, and determination of their apparent stratigraphic relations.

1. The Hellas impact event resulted in uplift of the mountainous material and basin-rim unit in the Early Noachian Epoch. Exposures of these materials occur as isolated knobs and massifs, as well as heavily cratered terrain, which contains the remnants of larger crater rims from subsequent impacts.

2. Erosion of the rugged Noachian highland materials began in the Middle to Late Noachian Epochs. Eroded materials were emplaced in low-lying areas between massifs of highland materials forming intermontane basin fill, which was subsequently dissected by valley networks and channels. Eroded materials were deposited around highland massifs forming some of the smooth plains.

3. Emplacement of an extensive volcanic and (or) sedimentary plains unit north of the map area occurred in the Late Noachian to Early Hesperian Epochs forming the pre-eroded dissected plains material surface.

4. During the Early Hesperian Epoch, emplacement of ridged plains material (northeast of the map area) was followed by collapse and release of water, possibly due to melting of ground ice in underlying volatile-rich material. This water eroded the highlands of Promethei Terra and the surface of the dissected plains material, in addition to forming the main canyon of Reull Vallis. An irregular basin in the lower part of segment 2 shows portions of the main canyon were formed by collapse presumably due to release of subsurface fluids. Floodwaters from Reull Vallis deposited material adjacent to the canyon forming extensive exposures of smooth plains material.

5. Enlargement of Reull Vallis (at segment 3) occurred during the mid- to Late Hesperian Epoch, as water was released from a large side canyon south of MTM –40257. Floodwaters were believed to have flowed to the southwest toward the Hellas basin, eroding and scouring smooth plains material south and west of segment 3 and deposited channeled plains material. The widespread occurrence of flat-topped, scarp-bounded mesas within channeled plains material represents the minimum extent of this flooding activity. Drainage of water from smooth plains material adjacent to segment 2 of Reull Vallis also formed scarps and small channels in the plains.

6. From Late Hesperian to Early Amazonian, emplacement of vallis wall material and vallis floor material occurred after water drained from Reull Vallis; interstitial water and (or) ice facilitated shear within vallis floor material causing it to flow downcanyon. Scarp failure and retreat of the walls of Reull Vallis continued throughout the Amazonian causing further canyon widening, especially in segment 3, where debris aprons can be seen on the canyon floor.

7. Beginning in the Late Hesperian and continuing into the Amazonian, mass wasting of debris from highland knobs and massifs and interior crater walls deposited debris aprons, and some crater fill material.

8. In the Amazonian Period, eolian activity has presumably modified the surfaces of most units in the map area.

REFERENCES CITED

Carr, M.H., 1995, The martian drainage system and the origin of valley networks and fretted channels: Journal of Geophysical Research, v. 100, p. 7479–7507.
———1996, Water on Mars: New York, Oxford University Press, 229 p.
Carr, M.H., and Clow, G.D., 1981, Martian channels and valleys: Their characteristics, distribution, and age: Icarus, v. 48, p. 91–117.
Chicarro, A.F., Schultz, P.H., and Masson, P., 1985, Global and regional ridge patterns on Mars: Icarus, v. 63, p. 153–174.
Craddock, R.A., and Maxwell, T.A., 1993, Geomorphic evolution of the martian highlands through ancient fluvial processes: Journal of Geophysical Research, v. 98, p. 3453–3468.
Craddock, R.A., Maxwell, T.A., and Howard, A.D., 1997, The early history of Mars as told by degraded highland impact craters, *in* Conference on Early Mars: Geologic and Hydrologic Evolution: Physical and Chemical Environments, and the Implications for Life; Lunar and Planetary Institute Contributions No. 916, p. 20–21.
Crown, D.A., and Greeley, Ronald, 1993, Volcanic geology of Hadriaca Patera and the eastern Hellas region of Mars: Journal of Geophysical Research, v. 98, p. 3431–3451.
Crown, D.A., and Greeley, Ronald, 2000, Geologic map of MTM quadrangles –30262 and –30267: Hadriaca Patera region of Mars: U.S. Geological Survey, in review.
Crown, D.A., and Mest, S.C., 1997, Dao, Harmakhis, and Reull Valles: The role of outflow channels in the degradation of the circum-Hellas highlands of Mars, *in* Abstracts of papers submitted to the Twenty-eighth Lunar and Planetary Science Conference, Houston, March 17–21, 1997: Houston, Lunar and Planetary Institute, p. 269-270.
Crown, D.A., Mest, S.C., and Stewart, K.H., 1997, Degradation of the martian cratered highlands: The role of circum-Hellas outflow channels and constraints on the timing of volatile-driven activity, *in* Conference on Early Mars: Geologic and Hydrologic Evolution, Physical and Chemical Environments, and the Implications for Life: Lunar and Planetary Institute Contributions No. 916, p. 22–23.
Crown, D.A., Price, K.H., and Greeley, Ronald, 1992, Geologic evolution of the east rim of the Hellas basin, Mars: Icarus, v. 100, p. 1–25.
Crown, D.A., and Stewart, K.H., 1995, Debris aprons in the eastern Hellas region of Mars, *in* Abstracts of papers submitted to the Twenty-sixth Lunar and Planetary Science Conference, Houston, March 13-17, 1995: Houston, Lunar and Planetary Institute, p. 301–302.
Goldspiel, J.M., Squyres, S.W., and Jankowski, D.G., 1993, Topography of small martian valleys: Icarus, v. 105, p. 479–500.
Golombek, M.P., Plescia, J.B., and Franklin, B.J., 1991, Faulting and folding in the formation of planetary wrinkle ridges, *in* Proceedings of the Twenty-first Lunar and Planetary Science Conference, Houston, March 12-16, 1990: Houston, Lunar and Planetary Institute, p. 679–693.
Golombek, M.P., Suppe, J., Narr, W., Plescia, J.B., and Banerdt, W.B., 1990, Does wrinkle ridge formation on Mars involve most of the lithosphere?, *in* Abstracts of papers submitted to the Twenty-first Lunar and Planetary Science Conference, Houston, March 12-16, 1990: Houston, Lunar and Planetary Institute, p. 421–422.
Greeley, Ronald, and Crown, D.A., 1990, Volcanic geology of Tyrrhena Patera, Mars: Journal of Geophysical Research, v. 95, p. 7133–7149.
Greeley, Ronald, and Guest, J.E., 1987, Geologic map of the eastern equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1802–B, scale 1:15,000,000.
Greeley, Ronald, and Spudis, P.D., 1981, Volcanism on Mars: Reviews in Geophysics, v. 19, p. 13–41.
Gregg, T.K.P., Crown, D.A., and Greeley, Ronald, 1998, Geologic map of the Tyrrhena Patera region of Mars (MTM quadrangle –20252): U.S. Geological Survey Miscellaneous Investigations Series Map I–2556, scale 1:500,000.
King, E.A., 1978, Geologic map of the Mare Tyrrhenum quadrangle: U.S. Geological Survey Miscellaneous Investigations Series Map I–910, scale 1:5,000,000.
Lucchitta, B.K., 1976, Mare ridges and related highland scarps--Results of vertical tectonism, *in* Proceedings of the Seventh Lunar and Planetary Science Conference, Houston, March 15-19, 1976: New York, Pergamon Press, p. 2761–2782.
———1977, Topography, structure, and mare ridges in southern Mare Imbrium and northern Oceanus Procellarum, *in* Proceedings of the Eighth Lunar and Planetary Science Conference, Houston, March 14-18, 1977: New York, Pergamon Press, p. 2691–2703.
Mars Channel Working Group, 1983, Channels and valleys on Mars: Geological Society of America Bulletin, v. 94, p. 1035–1054.
Mest, S.C., 1998, Geologic history of the Reull Vallis region, Mars: M.S. Thesis, University of Pittsburgh, 217 p.
Mest, S.C., and Crown, D.A., 2001, Geology of the Reull Vallis region, Mars: Icarus, v. 153, p. 89–110.
———2002, Geologic map of MTM –45252 and –45257 quadrangles, Reull Vallis region of Mars: U.S. Geological Survey Geologic Investigations Series I–2763, 1:1,000,000 scale [in press].
Mest, S.C., Crown, D.A., Craddock, R.A., and Zimbelman, J.R., 1998, Topographic characteristics of outflow channels in the martian southern highlands, *in* Abstracts of papers submitted to the Twenty-ninth Lunar and Planetary Science Conference, Houston, March 16–20, 1998: Houston, Lunar and Planetary Institute, Abstract #1334 (CD-ROM).
Murray, B.C., Soderblom, L.A., Sharp, R.P., and Cutts, J.A., 1971, The surface of Mars: 1. Cratered terrains: Journal of Geophysical Research, v. 76, p. 313–330.
Pieri, D.C., 1976, Martian channels: Distribution of small channels in the martian surface: Icarus, v. 27, p. 25–50.
———1980, Martian valleys: Morphology, distribution, age and origin: Science, v. 210, p. 895–897.
Plescia, J.B., and Golombek, M.P., 1986, Origin of planetary wrinkle ridges based on the study of terrestrial analogs: Geological Society of America Bulletin, v. 97, p. 1289–1299.
Potter, D.B., 1976, Geologic map of the Hellas quadrangle of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–941, scale 1:5,000,000.
Price, K.H., 1998, Geologic map of the Dao, Harmakhis, and Reull Valles region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2557, scale 1:1,000,000.
Schubert, G., Solomon, S.C., Turcotte, D.L., Drake, M.J., and Sleep, N.H., 1992, Origin and thermal evolution of Mars, *in* Mars, Keiffer, H.H., Jakosky, B.M., Snyder, C.W., and Matthews, M.S., eds.: Tucson, University of Arizona Press, p. 147–183.
Scott, D.H., and Tanaka, K.L., 1986, Geologic map of the western equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1802–A, scale 1:15,000,000.
Sharpton, V.L., and Head, J.W., 1988, Lunar mare ridges: Analysis of ridge-crater intersections and implications for the tectonic origin of mare ridges, *in* Proceedings of the Eighteenth Lunar and Planetary Science Conference, Houston, March 16–20, 1987: Houston, Lunar and Planetary Institute, p. 307–317.
Smith, D.E., Zuber, M.T., Solomon, S.C., Phillips, R.J., Head, J.W., Garvin, J.B., Banerdt, W.B., Muhleman, D.O., Pettengill, G.H., Neumann, G.A., Lemoine, F.G., Abshire, J.B., Ahronson, O., Brown, C.D., Hauck, S.A., Ivanov, A.B., McGovern, P.J., Zwally, H.W., and Duxbury, T.C., 1999, The global topography of Mars and implications for surface evolution: Science, v. 284, p. 1495–1503.
Squyres, S.W., 1978, Mars fretted terrains, flow of erosional debris: Icarus, v. 34, p. 600–613.
———1979, The distribution of lobate debris aprons and similar flows on Mars: Journal of Geophysical Research, v. 84, p. 8087–8096.
Squyres, S.W., and Carr, M.H., 1986, Geomorphic evidence for the distribution of ground ice on Mars: Science, v. 231, p. 249-252.
Squyres, S.W., Clifford, S.M., Kuzmin, R.O., Zimbelman, J.R., and Costard, F.M., 1992, Ice in the martian regolith, in Mars, Keiffer, H.H., Jakosky, B.M., Snyder, C.W., and Matthews, M.S., eds.: Tucson, University of Arizona Press, p. 523–554.
Squyres, S.W., Wilhelms, D.E., and Moosman, A.C., 1987, Large-scale volcano-ground ice interactions on Mars: Icarus, v. 70, p. 385–408.
Stewart, K.H., and Crown, D.A., 1997, Geomorphology of debris aprons in the eastern Hellas region of Mars, *in* Abstracts of papers presented at the Twenty-eighth Lunar and Planetary Science Conference, Houston, March 17-21, 1997: Houston, Lunar and Planetary Institute, p. 1377–1378.
Tanaka, K.L., 1986, The stratigraphy of Mars, *in* Proceedings of the Seventeenth Lunar and Planetary Science Conference, Houston, March 10–14, 1986: Part 1, Journal of Geophysical Research, v. 91, Supplement, p. E139–E158.
Tanaka, K.L., and Leonard, G.J., 1995, Geology and landscape evolution of the Hellas region of Mars: Journal of Geophysical Research, v. 100, p. 5407–5432.
Tanaka, K.L., Scott, D.H., and Greeley, Ronald, 1992, Global stratigraphy, *in* Mars, Keiffer, H.H., Jakosky, B.M., Snyder, C.W., and Matthews, M.S., eds.: Tucson, University of Arizona Press, p. 345–382.
Tanaka, K.L., Isbell, N.K., Scott, D.H., Greeley, Ronald, and Guest, J.E., 1988, The resurfacing history of Mars: A synthesis of digitized, Viking-based geology, *in* Proceedings of the Eighteenth Lunar and Planetary Science Conference, Houston, March 16–20, 1987: New York, Cambridge University Press, p. 665–678.
U.S. Geological Survey, 1985, Shaded relief map of the eastern equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1618, scale 1:15,000,000.
———1989, Topographic map of the eastern equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2030, scale 1:15,000,000.
Wahrhaftig, C., and Cox, A., 1959, Rock glaciers in the Alaska range: Geological Society of America Bulletin, v. 70, p. 383–486.
Watters, T.R., 1988, Wrinkle ridge assemblages on the terrestrial planets: Journal of Geophysical Research, v. 93, p. 10,236–10,254.
———1991, Origin of periodically spaced wrinkle ridges on the Tharsis plateau of Mars: Journal of Geophysical Research, v. 96, p. 15,599–15,616.
———1993, Compressional tectonism on Mars: Journal of Geophysical Research, v. 98, p. 17,049–17,060.
Zimbelman, J.R., Clifford, S.M., and Williams, S.H., 1989, Concentric crater fill on Mars: An aeolian alternative to ice-rich mass wasting, *in* Proceedings of the Nineteenth Lunar and Planetary Science Conference, Houston, March 14–18, 1988: New York, Cambridge University Press, p. 397–407.
Zuber, M.T., 1995, Wrinkle ridges, reverse faulting, and the depth penetration of lithospheric strain in Lunae Planum: Icarus, v. 114, p. 80–92.

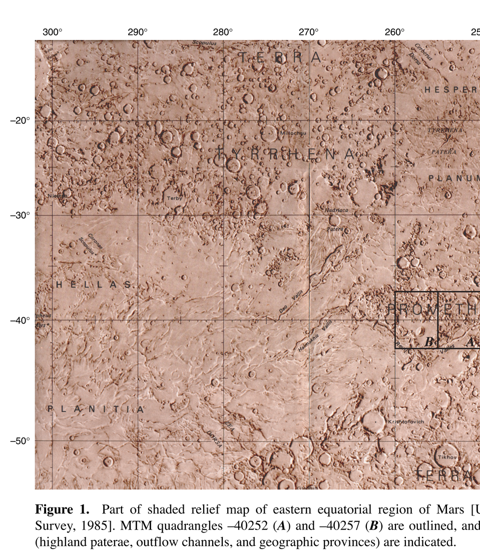


Figure 1. Part of shaded relief map of eastern equatorial region of Mars [U.S. Geological Survey, 1985]. MTM quadrangles –40252 (*A*) and –40257 (*B*) are outlined, and major features (highland paterae, outflow channels, and geographic provinces) are indicated.

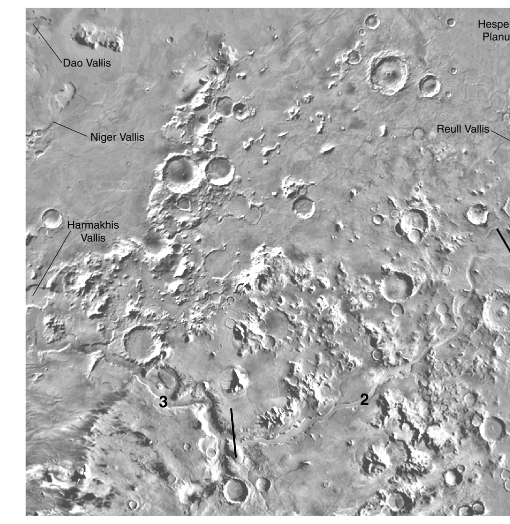


Figure 2. Mars Digital Image Mosaic of latitude –27.5° to –39°, longitude 245° to 260° showing a portion of Reull Vallis region [Mest, 1998; Mest and Crown, 2001]. Main canyon of Reull Vallis is subdivided into three segments; here segments are separated by a heavy black line. Segment 1 of Reull Vallis (**1**), oriented north-south, is in Hesperia Planum, and segments 2 (**2**) and 3 (**3**), oriented northeast-southwest and northwest-southeast, respectively, erode highlands of Promethei Terra. North is at top of mosaic.

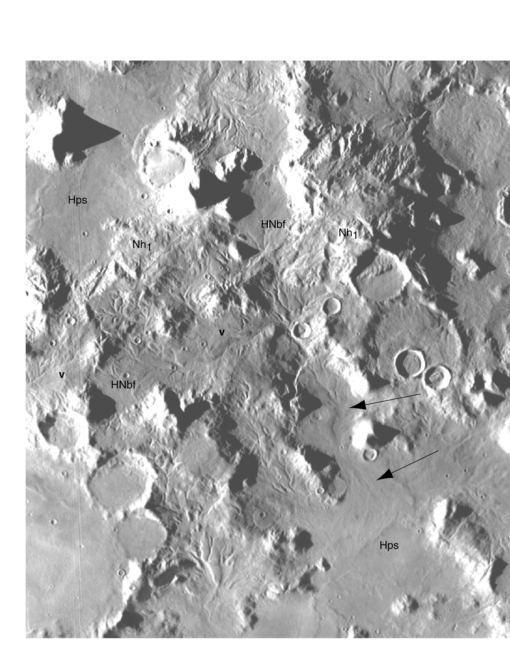


Figure 3. Viking Orbiter image 411S18 showing highlands in MTM quadrangles –40252 and –40257. Intermontane basin fill (unit HNbf) covers low-lying areas within basin-rim unit (unit Nh_1); most exposures of intermontane basin fill are dissected by well-developed valley networks (**v**) and channels. Some valleys (arrows) have subdued morphologies as they extend onto smooth plains material (unit Hps); smooth plains material in this area appears to embay highland materials. Resolution is 99 m/pixel; centered at 39° S., 254° W.

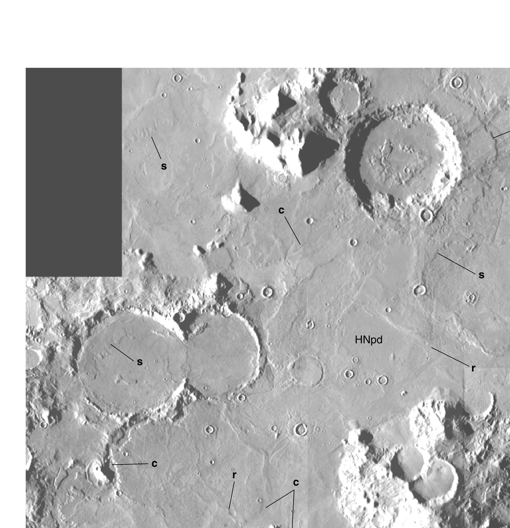


Figure 4. Dissected plains material (unit HNpd), in northern part of map area, is characterized by narrow channels (**c**), sinuous scarps (**s**), and wrinkle ridges (**r**) with morphologies that suggest erosion by fluvial processes. Viking Orbiter images 411S12–16; resolution is 100 m/pixel; centered at 37° S., 256° W.

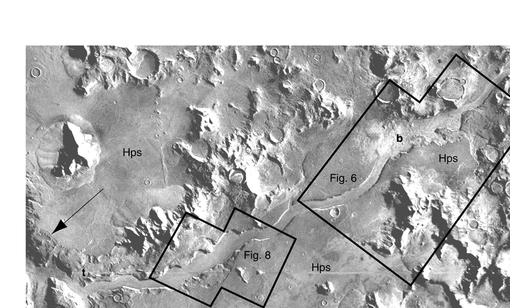


Figure 5. Mars Digital Image Mosaic of latitude –37.5° to –47.5°, longitude 245° to 260° showing lower part of segment 2 (see fig. 2) of Reull Vallis. This part of Reull Vallis extends for ~430 km through Promethei Terra, consists of a 6- to 24-km-wide and 140- to 800-m-deep, steep-walled, flat-floored canyon [Mest, 1998; Mest and Crown, 2001], and contains a 20-km-wide by 60-km-long basin (**b**). Along the majority of this part of Reull Vallis, smooth plains material (unit Hps) forms part of canyon wall, whereas downcanyon, smooth plains material shows a fluted scarp and appears to have been laterally eroded (arrow). A small tributary canyon (**t**) enters Reull Vallis from the north. Areas shown in figures 6 and 8 are indicated. North is at top of mosaic.

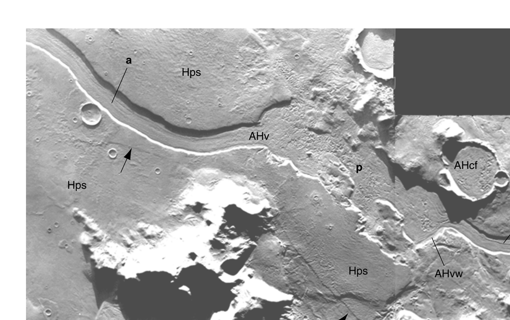


Figure 6. Lower part of segment 2 (see figs. 2, 5) of Reull Vallis, surrounding irregular basin, contains vallis floor material (unit AHv) with lineated and pitted surfaces. Lineations (**a**) may indicate shear as unconsolidated debris flowed downcanyon, and pitting (**p**) may result from collapse of volatile-rich debris. Vallis wall material (unit AHvw) is also seen along base of canyon walls. Scarps (arrows) south of Reull Vallis within smooth plains material (unit Hps) provide evidence that Reull Vallis may have flooded its banks and deposited portions of smooth plains material adjacent to canyon. Debris aprons (unit Ada) extend from highland massifs and show lineated and pitted surfaces; some crater fill material (unit AHcf) adjacent to basin also shows pitted surfaces. Viking Orbiter images 411S22 and 413S52; resolutions are 99 and 94 m/pixel, respectively; centered at 41° S., 250° W.

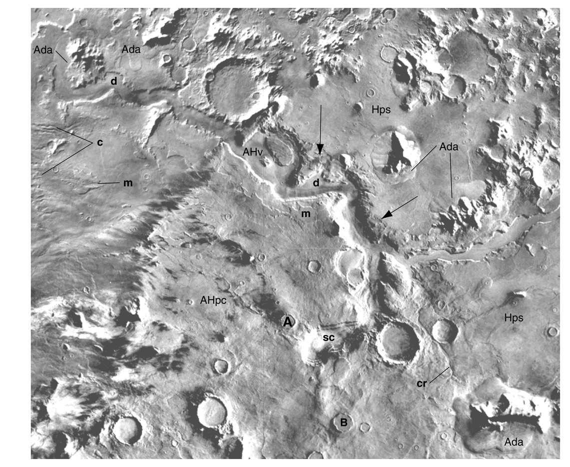


Figure 7. Segment 3 (see fig. 2) of Reull Vallis begins at junction of segment 2 and a large theater-headed side canyon (**sc**). Side canyon contains fluted layers along its walls and is believed to be a secondary source for water, which enlarged segment 3. Segment 3 exhibits layering (arrows) along its walls exposing channeled plains material (unit AHpc), which appears as a less erodible unit adjacent to smooth plains material (unit Hps). Channeled plains material south and west of segment 3 of Reull Vallis contains features indicative of erosion by surface flow, including channels radial to Hellas basin (**c**), channels perpendicular to Reull Vallis (**cr**), and craters (**A** and **B**) that have been filled and their ejectas removed and (or) mantled. Flat-topped, scarp-bounded mesas (**m**) composed of smooth plains material also are found within channeled plains material. Debris aprons (unit Ada) are observed to extend from highland massifs throughout map area; some vallis floor material (unit AHv) in segment 3 may consist of debris aprons (**d**) extending from canyon walls. Mars Digital Image Mosaic of latitude –37.5° to –47.5°, longitude 255° to 270°. North is at top of mosaic.

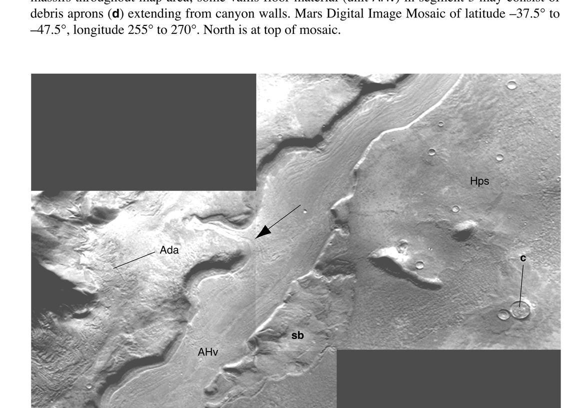


Figure 8. High-resolution Viking Orbiter images (584B22 and 23) showing portion of lower part of segment 2 (see figs. 2, 5) of Reull Vallis and smooth plains material (unit Hps). Vallis floor material (unit AHv) clearly shows lineations parallel to canyon walls. Debris entering Reull Vallis from small tributary (arrow) appears to have flowed onto surface of infilling vallis floor material; flow lineations on surface of this debris appear to be deflected downcanyon. Large slump block (**sb**) occurs along south wall of Reull Vallis indicating enlargement of canyon may result from collapse and scarp retreat. At this resolution, smooth plains material is observed to contain small undulations possibly resulting from fluvial and (or) eolian processes, and small craters (**c**) within smooth plains are filled with pitted materials. Debris aprons (unit Ada) extend from highland massifs north of Reull Vallis; aprons have pitted surfaces and show lineations perpendicular to direction of flow.

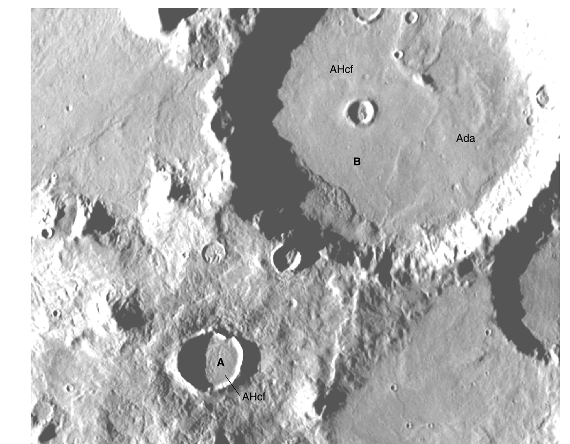


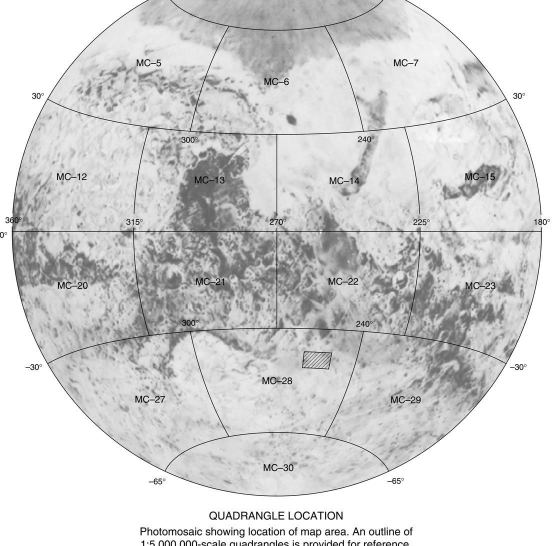
Figure 9. Crater fill material (unit AHcf) occurs in craters of various sizes in highlands of Promethei Terra. Crater **A** is filled with materials having a pitted surface and lobate terminations along interior crater wall, suggesting emplacement of volatile-rich debris. Crater **B** contains smooth deposits on its floor, presumably composed of materials shed from interior crater walls by fluvial processes and (or) mass wasting. Debris aprons (unit Ada) also are observed within crater **B** extending from crater walls onto crater fill material. Viking Orbiter image 411S19; resolution is 100 m/pixel; centered at 38.5° S., 251.5° W.

Table 1. *Crater Size-Frequency Data and Time-Stratigraphic Determinations†*

[N(2), N(5), and N(16) represent the cumulative number of craters >2, 5, and 16 km in diameter/10^6 km^2. Error = ±[($N^{1/2}$)/A] x 10^6 km^2, where A = area. Series ranges are based upon crater counts using the crater-density boundaries determined by Tanaka [1986], MA = Middle Amazonian, LA = Lower Amazonian, UH = Upper Hesperian, LH = Lower Hesperian, UN = Upper Noachian, MN = Middle Noachian, and LN = Lower Noachian. Series designations are based upon superposition relations and crater counts. See text for names of geologic units and unit subdivisions (for example, units AHh_5 and Nh_1)]

Unit	Total craters	Craters used (>.72 km)	Area (km^2)	N(2)	N(5)	N(16)	Series range	Series designation
Ada	53	52	35,282	227 ± 80	57 ± 40	0	UH-MA	LA or above
AHcf	71	67	17,974	445 ± 157	0	0	UH-LA	UH or above
AHv	66	65	68,463	307 ± 67	132 ± 44	0	LH-LA	UH-LA
AHpc‡	342	341	315,493	406 ± 36	27 ± 20	16 ± 7	LH-LA	UH-LA
Hps	196	196	83,276	901 ± 104	144 ± 42	36 ± 21	UN-UH	LH
HNpd	380	380	156,207	845 ± 74	218 ± 37	83 ± 23	LN-LH	UN-LH
Nm	132	132	63,169	1235 ± 140	427 ± 82	63 ± 32	MN-LH	MN-UN
Nh_1	491	490	186,203	935 ± 71	414 ± 47	150 ± 28	MN-LH	MN

†Data from regional study of Mest [1998]; craters contained within Mars Digital Image Mosaic (latitude –27.5° to –47.5°, longitude 245° to 270°) of Reull Vallis region; areas are total unit exposures within this region.
‡Crater size-frequency data for AHh_5 from regional study of Mest [1998] used for AHpc (see text for discussion).



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

Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

For sale by U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225, 1–800–ASK–USGS

ISBN 0-607-97507-5
9 780607 975079

Printed on recycled paper