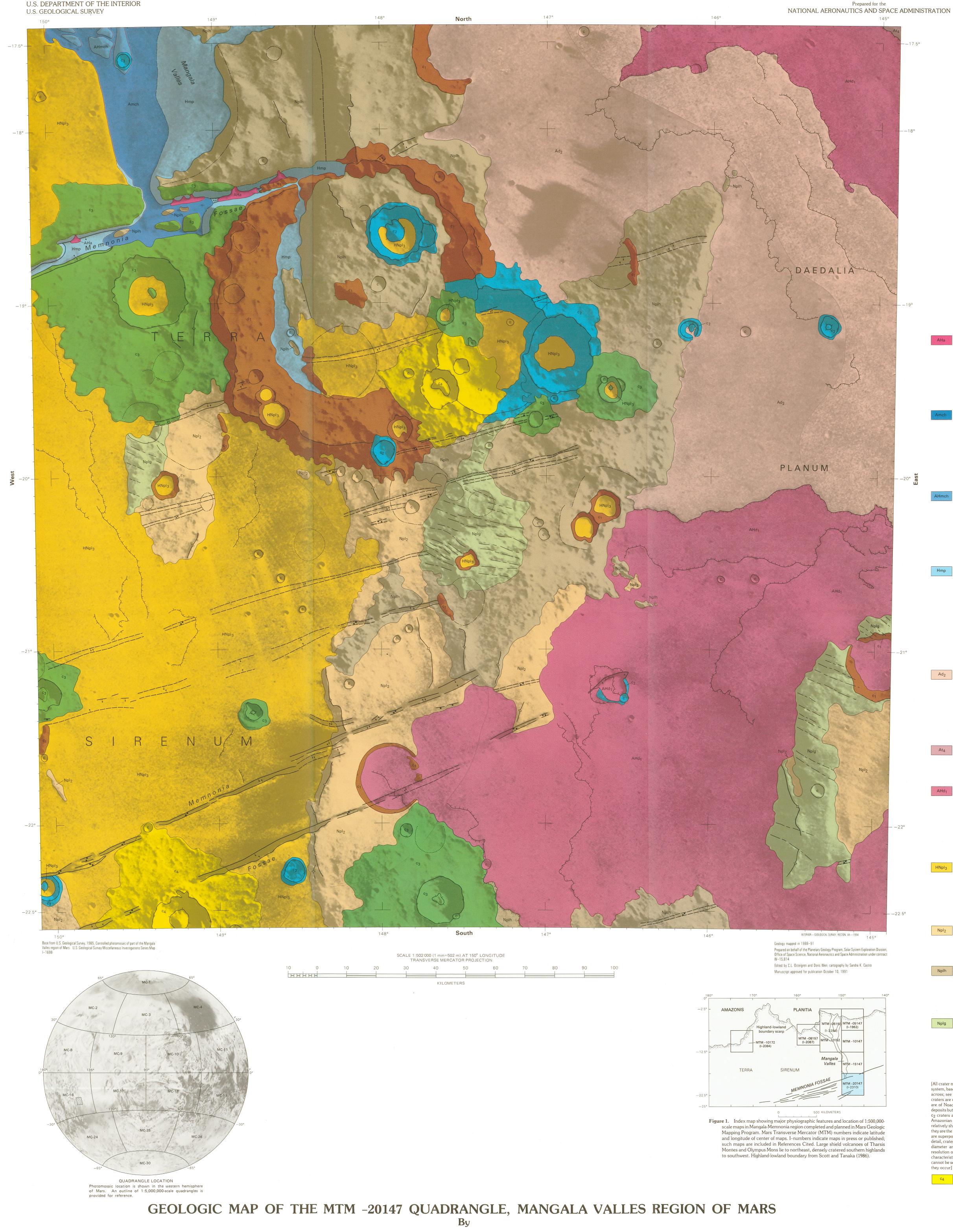
I-2310



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HIGHLAND TERRAIN MATERIALS LOWLAND TERRAIN MATERIALS CRATER MATERIALS SERIES Surficial deposit Mangala Valles Western volcanic Highland assemblage assemblage UPPER AMAZONIAN MIDDLE AMAZONIAN LOWER AMAZONIAN UPPER HESPERIAN LOWER HESPERIAN NOACHIAN MIDDLE NOACHIAN

CORRELATION OF MAP UNITS

DESCRIPTION OF MAP UNITS Crater material, subdued—Relatively sharp rim crests. Con-SURFICIAL DEPOSIT tains small, irregular central peaks on crater floors. Apron terrain material—Occurs along Memnonia Fossae as Ejecta are hilly, undulatory, rarely lobate, and irregularly smooth, fan-shaped aprons that extend from southcentered. Ejecta centered at lat 19.0° S., long 149.4° are facing walls; may be present along north-facing walls but dissected by channels and appear to be embayed by is not seen due to limited emission angles at which smooth highland material; unit possibly caps blocks in available images were acquired. Occurrence at lat 18.40° Memnonia Fossae. Unit at lat 22.50° S., long 147.65° is S., long 149.15° appears to consist of several aprons that partly embayed by Daedalia Planum material, unit 1 have coalesced; occurrence at lat 18.30° S., long 148.60° (Viking Orbiter images 637A81 and 639A13). Unit at lat appears to be controlled by eroded crater material (unit 21.35° S., long 148.80° appears to be embayed by smooth c<sub>1</sub>) at its base (Viking Orbiter image 637A82). Interpreta-

tion: Landslides caused by failure of weak unit(s) exposed

along graben wall. Height of western occurrences may be

and lack of craters greater than 2 km in diameter.

Interpretation: Alluvial deposits from late-stage flooding

of Mangala Valles, scoured floor with few or no alluvial

younger age. (See text.) Forms isolated mesas within

lined shapes, some of which indicate flow direction other

direction inferred from adjacent streamlined "islands."

Interpretation: Alluvium from early flooding of Mangala

Valles deposited on stoss side of obstructions, material

sufficiently competent to withstand peak flood velocities,

(1986) flood-plain material (unit Hchp). Forms broad,

planar area east of younger and older channel units and

west of hilly highland material. Partly fills large crater

truncated by valley at lat 18.4° S., long 148.5° and buries

small local graben at lat 19.3° S., long 148.55° (Viking

Orbiter image 627A82). Margin of northern occurrence is

lobate and stands in relief above younger channel

material. Streamlined features within 10 km of lobate

margin are normal to flood-plain margin rather than

oriented toward source of Mangala floods. Texture of

flood-plain material is smooth at all scales down to 46

capped by lava flows (suggested by lobate pattern of

some margins and greater resistance to erosion than

other channel materials); associated with earliest and

Daedalia Planum material, unit 2—Broad, smooth material

of uniform albedo separated from Daedalia Planum

material, unit 1 by east- and south-facing lobate scarps.

Contains several sets of discontinuous lobate scarps,

most of which extend southeast from lat 17.8° S., long

146.6° in map area. Embays highland materials and

craters to west. Lineated patches of low-albedo streaks in

some areas. Stratigraphic relations and crater statistics

indicate Early Amazonian age. Interpretation: Late-stage

volcanic flood lavas erupted from fissures associated with

formation of Memnonia Fossae and possibly Mangala

Valles. Material appears to have erupted from fissure

1986)—Consists of overlapping light-colored flows with

dark wind streaks. Flows are elongate on steep upper

slopes, broad on gentler lower slopes. Only a small

occurrence in northeast corner of map area. Interpreta-

tion: Early flood eruptions associated with formation of

Tanaka's (1986) member 3 of Tharsis Montes Formation

(unit AHt3). Exposures are smooth, containing many

discontinuous lobate scarps; grades to east and northeast

outside map area into narrow lobate occurrences. Embays

highland materials to west. Contains extensive low-

flood eruptions associated with isostatic adjustment of

deep-seated faults from Daedalia basin (Craddock and

others, 1990), flood eruptions from formation of Tharsis

Montes, or possibly fissure eruptions associated with

Smooth unit—Corresponds to smooth unit of plateau sequence

(unit Hpl3) of Scott and Tanaka (1986), but crater size-

equency data (table 1, fig. 2) indicate age is in part

Noachian. Sparsely cratered, generally flat unit occurring

chiefly in low-lying areas in southwestern part of map

area; moderate to high albedo; contains scarps that are

subdued to sharp and well defined. Covers or embays

floors of some craters. Typical locality: lat 21.0° S., long

149.0° (Viking Orbiter image 637A81). Interpretation:

Thin deposits of eolian or fluvial origin formed concur-

sparsely cratered unit containing some subdued lineations; stands at higher elevation than surrounding volcanic

units. Interpretation: Thin lava flows, eolian deposits, or

deposits derived from surrounding, topographically

higher highland materials that mantle remnants of ancient

upland unit; heavily cratered; embayed in places by volcanic materials. Small blocks occur throughout map

area. Interpretation: Ancient crustal material consisting

of volcanic flows and ejecta from local and distant

craters. Small blocks at lat 18.45° S., long 149.2° may be

S., long 148.0° may be ejecta materials, or may be uplifted

crust along fault trending north at about long 148.38°

parallel to subparallel, narrow troughs oriented generally

northwest; embayed in places by volcanic materials.

Type locality: lat 21.5° S., long 145.4° (Viking Orbiter

image 637A84). Interpretation: Ancient crustal materials

scoured by large impact basin. Groove orientation sug-

gests basin centered in Daedalia Planum at lat 26.0° S.,

long 125.0° (Craddock and others, 1990). Mass wasting

may have enlarged grooves on steep slopes

CRATER MATERIALS

[All crater materials are interpreted to be of impact origin. A four-fold classification

system, based on crater degradation, is employed (except for craters less than 5 km

they occur

Grooved unit—Moderately rugged upland unit with many

erosional remnants resistant to floods. Block at lat 18.7°

Subdued unit (Scott and Tanaka, 1986)—Gently undulatory,

Hilly unit (Scott and Tanaka, 1986)—Rugged, undulatory

albedo patches east of map area. Interpretation: Volcanic

AHd<sub>1</sub> Daedalia Planum material, unit 1—Subdivision of Scott and

HIGHLAND ASSEMBLAGE

extending from source graben of Mangala Valles

Tharsis Montes Formation, member 4 (Scott and Tanaka,

most widespread flooding

Arsia Mons

Memnonia Fossae

rently with faulting

highland crust

WESTERN VOLCANIC ASSEMBLAGE

m/pixel resolution. Interpretation: Alluvial fill, perhaps

Flood-plain material—Subdivision of Scott and Tanaka's

Older channel material—Subdivision of older channel mate-

controlled by thickness of subdued crater ejecta

Crater material, degraded—Continuous crat MANGALA VALLES ASSEMBLAGE isolated, small, irregular central peaks on crater floors. **'ounger channel material**—Smooth, flat material that Interpretation: Erosionally resistant impact crater mateextends northward along Mangala Valles from lat 18.6° S., long 149.4°. Lateral extent controlled by smooth Crater material, eroded—Hilly, undulatory unit forming rim highland material (unit HNpI3) to west and flood-plain of highly degraded crater; embayed by channel and plains material (unit Hmp) to east. Streamlined forms evident at materials and buried by other crater units. Forms one lat 17.45° S., long 149.85°; other streamlined forms may large, irregular hill on floor of eroded crater at lat 18.95° be represented by slight changes in albedo (Viking S., long 148.20° (Viking Orbiter image 637A82). Inter-Orbiter image 637A82). Subdivision of older channel pretation: Erosionally resistant rims and central peaks of material (unit Hch) of Scott and Tanaka (1986), but ancient impact craters that have been highly modified. assigned younger age because of superposition relations

——— Contact—Dashed where approximately located Fault or narrow graben—Dashed where partly buried; ball on rial (unit Hch) of Scott and Tanaka (1986), but assigned downthrown side of fault Lobate scarp—Interpreted as volcanic flow front. Ticks in younger channel material. Many small knobs have streamflow direction; dashed where uncertain or partly buried ——— Ridge—Intrepreted as fold or thrust-fault structure than what appears to be that of regional slope. Surface also exhibits subtle linear features too small to be resolved clearly but consistent in orientation with flow

and embayed by other materials

highland material (Viking Orbiter image 637A81). Inter-

pretation: Impact crater material modified by erosion

Unit typically resembles hilly highland material (unit

NpIh); the two units are roughly the same age

Crater rim crest—Dotted where buried Eroded crater rim crest—Dotted where buried Small crater rim crest—Age not determined Crater central peak

This map is one in a series of 1:500,000-scale geologic maps prepared to investigate areas on Mars of high scientific interest. The quadrangle contains the source area for Mangala Valles, one of the largest outflow channel complexes on Mars (Sharp and Malin, 1975). Preliminary mapping by Masursky and others (1986), Zimbelman (1988), and Chapman and others (1989, 1991) showed that several episodes of channel formation and deposition may have occurred in association with Mangala Valles. To elucidate the complex history of Mangala Valles and the general geology of the area surrounding their source, the detailed photogeology of the MTM -20147 quadrangle is presented here. The area has been studied previously through reconnaissance photogeologic mapping. Using Mariner 9 data, Mutch and Morris (1979) derived a

1:5,000,000-scale geologic map of the Memnonia quadrangle and recognized six units within the MTM -20147 quadrangle. These units include three cratered plains materials, smooth plains material, mountain material, and materials associated with Mangala Valles. At 1:2,000,000 scale, Scott and Schaber (1981) and Scott and others (1981) simplified the geology within the quadrangle by recognizing only four units: a lava flow from Arsia Mons, ancient cratered (terra) material, a smooth plains unit, and a deposit from Mangala Valles. More recently, at 1:15,000,000 scale, Scott and Tanaka (1986) recognized two lava flows from Arsia Mons, three ancient cratered (terra) materials, a smooth plains unit, and two separate deposits from

Our map was compiled by analysis of Viking Orbiter images (average image resolution of  $\sim$ 270 m/pixel) supplemented by the study of two adjacent quadrangles to the north (MTM -10147 and MTM -15147; fig. 1) and pertinent Mariner 9 images. We used conventional planetary photogeologic mapping techniques (Wilhelms, 1972). We also drew upon results from the Viking infrared thermal mapper (IRTM) to assess the physical properties of surficial materials (Craddock and others, 1987). PHYSIOGRAPHY

The quadrangle includes part of the boundary separating the old, densely cratered Martian highlands typical of the southern hemisphere from ne plains materials originating near the Tharsis Montes to the northeast. The Terra Sirenum highlands within the map area are characterized as rugged, heavily cratered terrains, which have been modified by a wide variety of processes including eolian and fluvial activity. In places, the highlands consist of widespread plateaus. The plateaus and the highlands are cut by a series of east-trending grabens of the Memnonia Fossae (fig. 1). The large, primary channel of the Mangala Valles complex appears to have originated from a breach in one such graben centered at about lat 18.5° S., long 149.5°. The main channel continues northward for about 850 km until it separates into smaller channels that debouched into Amazonis Planitia. The eastern part of the quadrangle includes part of the vast lava plains of Daedalia Planum in the Tharsis region. One of the large Tharsis Montes volcanoes, Arsia Mons, is about 1,700 km northeast of the map area. STRATIGRAPHY

as part of their 1:25,000,000-scale geologic map. Three stratigraphic systems, the Noachian, the Hesperian, and the Amazonian, were named from regions containing representative, widespread exposures of the materials used as referents. These systems were further subdivided by Tanaka (1986) and applied to the 1:15,000,000-scale geologic map of the western hemisphere of Mars (Scott and Tanaka, 1986). The geologic units derived by Scott and Tanaka (1986) provide the stratigraphic framework for the present map. NOACHIAN SYSTEM

The oldest recognized geologic units in the map area are highland materials, which consist of the hilly (unit NpIh), grooved (unit NpIg), subdued (unit NpI<sub>2</sub>), and smooth (unit HNpI<sub>3</sub>) units. These materials are a subdivision of Scott and Tanaka's (1986) plateau and high-plains assemblage. The hilly unit has rugged, undulatory surfaces and contains many impact craters, most of which are extremely eroded. Grooves in the grooved unit may be impact features somewhat analogous to Imbrium sculpture on the Moon. Their orientation on Mars suggests an origin from a postulated buried impact structure centered at lat 26.0° S., long 125.0°, southeast of the map area (Craddock and others, 1990). Downslope mass movement has modified and enlarged the grooves in some areas. These two units are interpreted to be ancient materials composed of volcanic flows and uplifted

Subdued highland material (unit NpI<sub>2</sub>) has a gently undulatory surface

and sparse craters, many of which are heavily eroded or partly buried. This

unit is interpreted as highland material buried by thin lava flows, eolian deposits, or deposits eroded from surrounding, topographically higher highland materials. Smooth highland material (unit HNpI<sub>3</sub>) is characterized by a lack of relief and is present chiefly in low-lying areas (Zimbelman, 1989). The unit is sparsely cratered, has moderate to high albedo, contains subdued lobe fronts and crater rims, and is superposed on some faults and crosscut by others. These observations suggest that the unit is an eolian mantle, fluvial material deposited coevally with the faulting, or a series of thin lava flows possibly erupted in association with the formation of the Memnonia Fossae. The unit has about the same age as the plains material of the Mangala Valles assemblage (described below), perhaps suggesting a relation between the

smooth material and the formation of Mangala Valles (fig. 2).

across; see below). Craters range in age from c1 (oldest) to c4 (youngest). The c1 HESPERIAN AND AMAZONIAN SYSTEMS craters are characterized as extremely degraded rim and central peak deposits and Hesperian and Amazonian materials include flood-plain material (unit are of Noachian age; c2 craters, of Hesperian and Noachian age, have degraded Hmp) and older and younger channel materials associated with Mangala deposits but are superposed on c1 crater materials. The ejecta deposits of both c1 and Valles (units AHmch, Amch). Volcanic materials constitute the remaining c<sub>2</sub> craters are eroded or are buried by younger materials; c<sub>3</sub> craters, considered Amazonian and Hesperian in age, have extensive preserved ejecta deposits and principal units in the map area (units AHd<sub>1</sub>, At<sub>4</sub>, and Ad<sub>2</sub>). Because of their relatively sharp rim crests. Craters mapped as c4 are considered Amazonian in age; many streamlined features, Mangala Valles are thought to be the result of they are the freshest craters, have sharp rim crests and extensive ejecta deposits, and catastrophic flooding (Milton, 1973; Baker and Milton, 1974; Sharp and are superposed on c3 craters and all other materials. To avoid uneven portrayal of Malin, 1975). Masursky and others (1986) suggested that Mangala Valles are detail, craters less than 2 km in diameter were not mapped. Craters less than 5 km in the result of multiple episodes of channel formation, but only two episodes, diameter are assumed to be relatively young; however, because of the limited or stages, of flooding are represented in the map area. The first stage, resolution of available photographs (typically about 270 m/pixel), the morphologic forming the flood-plain material (unit Hmp), was much more widespread characteristics necessary for determining the age of craters 2 to 5 km in diameter cannot be seen. These small craters are colored the same as the materials on which than the second and appears to have completely flooded the inferred source graben. A channel breached the source graben wall and flooded a large crater at lat 18.4° S., long 148.5°, partly filling it with plains material. The older channel material (unit AHmch) may have been deposited on the stoss side of craters and other features of positive relief as flood velocities subsided. The younger channel material (unit Amch) was emplaced by subsequent flooding that appears to have been confined to a small section of the source graben and is represented by the deepest part of the channel. An

c<sub>4</sub> Crater material, fresh—Sharp rim crests. Contains small, irregular central peaks in center of crater floors. Ejecta smooth to undulatory, consists of overlapping, discontinuous lobes concentric to crater center; lobes typically become less extensive toward crater rim. Superposed on all other materials. Interpretation: Material from young Amazonian age is inferred for these units because of the lack of craters impacts. May have been deposited as fluidized flow due greater than 2 km in diameter; however, the small areal extent of the units to presence of an atmosphere or due to incorporation of may result in misleading crater counts. Mangala Valles may have formed in a subsurface volatiles during emplacement single, catastrophic event that became more confined with time. The ated with higher flood velocities in the middle of the channel or tapering velocities in floods that covered the lowest lying surfaces. The oldest of the three volcanic units is unit 1 of the Daedalia Planum material (unit AHd<sub>1</sub>), which corresponds to member 3 of the Tharsis Montes Formation mapped by Scott and Tanaka (1986). Unit 1 consists of broad, smooth materials of uniform albedo. This unit contains several sets of discontinuous lobate scarps in the map area. The most likely interpretation of its origin is that it represents late-stage, mare-style volcanism that infilled the Daedalia basin (Craddock and others, 1989, 1990). Unit 2 of the Daedalia Planum material (unit Ad2) is separated from unit

youngest unit of the assemblage may represent substantial erosion associ-

1 by east-facing lobate scarps. The two Daedalia Planum units resemble each other morphologically; however, the lobate scarps associated with unit 2 appear to originate near lat 17.8° S., long 146.6° from an extension of the Mangala Valles source graben, now partly covered by volcanic materials. Although these materials may be flood lavas that ponded next to the highland boundary, unit 2 may have formed from eruptions associated with the formation of Mangala Valles. If so, the association is evidence for the correlation of volcanic activity and the formation of Martian outflow channels, as suggested by McCauley and others (1972) and Masursky and others (1977). Figure 3 shows the crater size-frequency curves for the two Daedalia Planum units and supports the age designations for these materials (table 1). A crossover of curves at crater diameters larger than 4 km suggests that craters larger than this diameter were not buried by unit 2. According to the rim-height equation for Martian craters (Pike and Davis, 1984), the thickness needed to bury a 4-km-diameter crater is about 145 m. Because 4-km-diameter craters are apparently not buried, unit 2 is probably about 100 m thick. Its surface area of approximately 5,300 km<sup>2</sup> (table 1) yields an eruption volume of about 530 km<sup>3</sup>, which is comparable with most of the eruption volumes composing the Saddle Mountain or Wanapum Basalts of the Columbia Plateau (Tolan and others, 1989). A small exposure of the Tharsis Montes Formation, member 4 (unit

At<sub>4</sub>) occurs near the northeast corner of the map area and is characterized by a mottled appearance and lobate scarps. This unit is interpreted to represent a change in volcanic styles associated with the formation of the Tharsis Montes/Daedalia basin infilling: early flood eruptions evolved to more channelized flows (Hawaiian-style eruptions), characterized by possible leveed channels northeast of the map area. The remaining unit of Amazonian-Hesperian age is apron material (unit AHa), which occurs along the south wall of the Mangala Valles source

graben as smooth, fan-shaped aprons. Although a crater-retention age cannot be determined because of its small extent, its relative age is inferred

from superposition relations. The height of the western occurrences

appears to be controlled by the thickness of the subdued crater material

centered at lat 19.0° \$., long 149.4°. The apron material is interpreted to be landslides caused by failure of one or more weak units exposed along the source-graben wall after channel formation. Surficial materials, such as thin mantles of windblown sediments, are not mapped. However, the occurrence of streaks and other albedo patterns associated with topography suggests the presence of dust that is subject to present winds. In addition, high-resolution Viking IRTM data show low thermal-inertia values near the source area of Mangala Valles, suggesting the presence of a thin veneer of windblown dust. Rock abundances derived through Christensen's (1982) model show that greater than 15 percent of the exposed surface material is composed of material effectively 15 cm in

diameter, which suggests that brecciated materials possibly related to channel formation are present in the source graben (Craddock and others,

## STRUCTURE Faults of the Memnonia Fossae system are widespread in the map area

and are part of the tectonic pattern radial to the Tharsis rise (Wise and others. 1979). Two orientations of faults in the Memnonia region have been recognized by Plescia and Saunders (1982). Through structural analysis, they demonstrated that faults oriented N. 60°-70° E. are radial to a center near Pavonis Mons (lat 1° N.; long 113°), whereas faults oriented N. 75°-80° E. are radial to a center in Syria Planum (lat 1°-20° S., long 97°-112°; Plescia and Saunders, 1982). Both sets of faults are contemporaneous with the emplacement of the subdued and the smooth units of the highland assemblage, as indicated by crosscutting relations. By comparing geologic maps with Earth-based radar data, several north-oriented faults within Noachian highland materials have been identified (Zimbelman, 1988, 1989); the vertical relief of their scarps ranges from 500 to 2,500 m. These faults are not related to Tharsis principal stresses (Schultz,

1985). Thermal stresses related to a cooling lithosphere have been suggested as their cause (Schultz, 1985; Zimbelman, 1988); however, compressional features such as wrinkle ridges are commonly associated with them (Craddock and others, 1989). The faults are also approximately concentric to a proposed Noachian impact basin in Daedalia Planum and may be related to an extended ring system for that basin (Craddock and others, 1990). The compressional features suggest that zones of weakness caused by the impact were reactivated during isostatic rebound following basin formation or crustal loading from mare-style volcanism (Craddock and others, 1989) represented by unit 1 of the Daedalia Planum material and member 4 of the Tharsis Montes Formation. An irregular crater about 10 km across occurs in the former at lat 21.2° S., long 146.6° at the end of a Memnonia Fossae graben; the crater may be a volcano-tectonic depression formed by collapse in association with the development of the graben and extrusion of volcanic materials.

## GEOLOGIC HISTORY

From an assessment of the physiography, stratigraphic relations, and structural features observed in the map area, the following geologic history 1. Early Noachian—Intense impact cratering and deformation of basement rocks; intense brecciation by impact; formation of large impact basin in Daedalia Planum, the ejecta of which produced the grooved highland unit (NpIg). North-trending faults result from the cooling lithosphere or the formation of the Daedalia basin. 2. Middle to Late Noachian—Terminal stages of heavy bombardment continued to fracture and brecciate ancient crust. Erosion of the uplands by wind and water to produce mantling deposits of the subdued highland unit. 3. Hesperian—Massive crustal deformation associated with the early stages of formation of the Tharsis plateau (fig. 1) produced northeast-trending faults in the highland plateau sequence of the Memnonia Fossae system. Eruption of lavas and continued degradation of older rocks by wind and water led to the emplacement of the smooth highland unit. 4. Late Hesperian-Early Amazonian—Release of water from the brecciated megaregolith of the highlands produced Mangala Valles; their source was associated with a graben whose formation may have triggered the release of water. Water release may have been episodic; two stages of flooding are recorded in the map area. Flood eruption of fluid lavas emplaced flows in western Daedalia Planum; vent areas were subsequently buried. 5. Amazonian—Late eruptions of flood lavas, possibly from local fissure vents associated with Memnonia Fossae.

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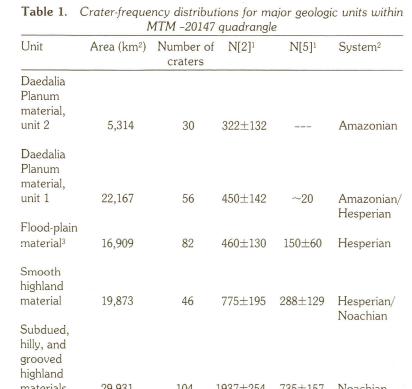
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materials 29,931 104 1937 $\pm$ 254 735 $\pm$ 157 Noachian  ${}^{1}N$  = number of craters greater than [x] km diameter/106 km<sup>2</sup>. <sup>2</sup>Crater-density boundaries from Tanaka (1986). <sup>3</sup>Data include craters in MTM -15147 quadrangle (Zimbelman and others, work in progress, 1991).

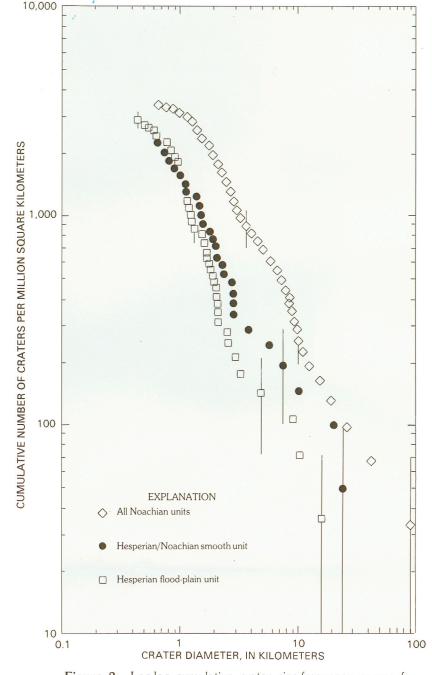


Figure 2. Log-log cumulative crater size-frequency curves for major units in map area other than units of western volcanic assemblage. Noachian hilly, grooved, and subdued cratered materials (units NpIh, NpIg, and NpI<sub>2</sub>, respectively) are grouped together to make counting area statistically significant. Curve for plains material was calculated using additional data from MTM -15147 quadrangle (Zimbelman and others, work in progress, 1991). One-sigma error bars are proportional to cumulative number of craters observed for a specified diameter.

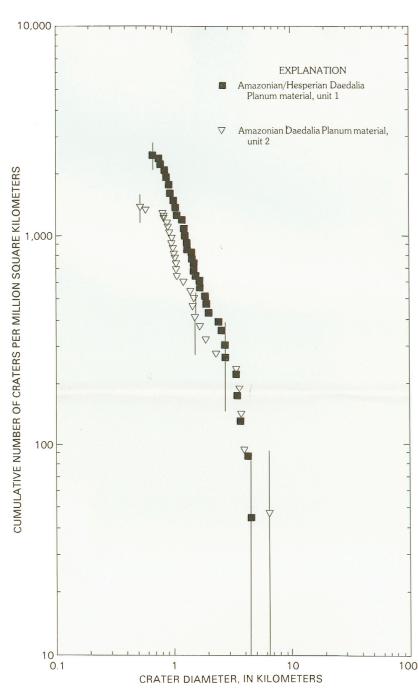


Figure 3. Log-log cumulative crater size-frequency curves for Daedalia Planum units in map area. Although crater-frequency distribution of unit 2 (N[2]=322 $\pm$ 132, table 1) is based on small areal extent, this value and stratigraphic relations suggest an Early Amazonian age for unit. Crossover of curves at crater diameters of 4 km indicates that these materials are about 100 m thick. Crater-frequency distributions of N[2]=  $450\pm142$  and N[5]~20 (table 1) indicate a Late Hesperian and Early Amazonian age for unit 1, the same age determined by Scott and Tanaka (1986). One-sigma error bars are proportional to cumulative number of craters observed for a specified