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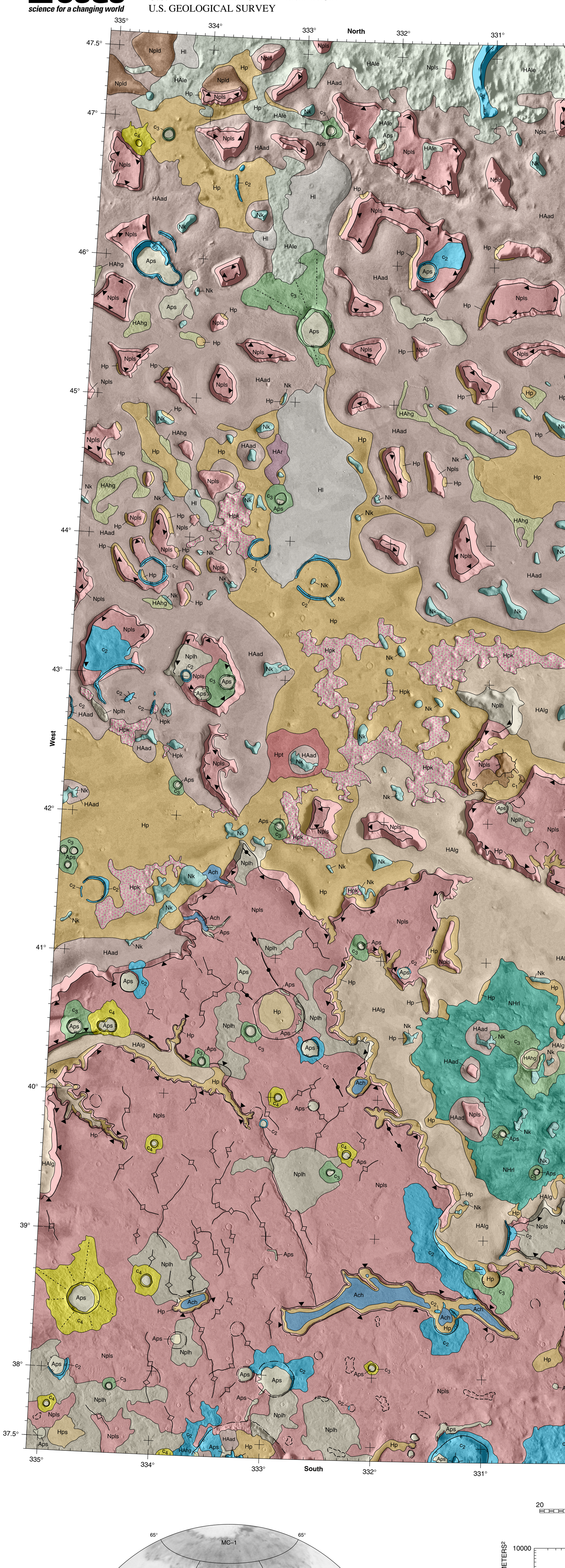

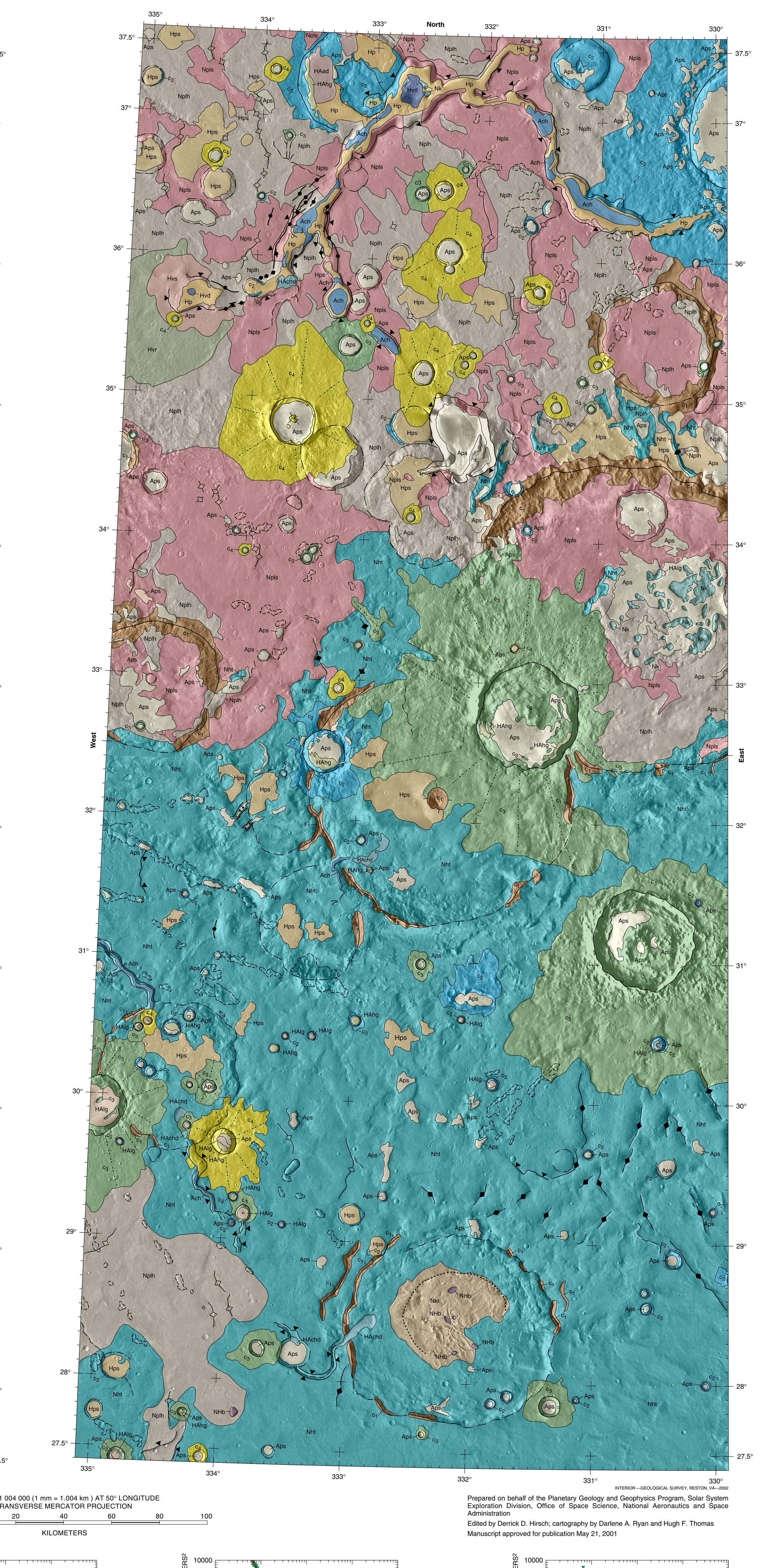

SCALE 1:1 004 000 (1 mm = 1.004 km) AT 50° LONGITUDE
TRANSVERSE MERCATOR PROJECTION
20 0 20 40 60 80 100
KILOMETERS

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 Darlene A. Ryan and Hugh F. Thomas
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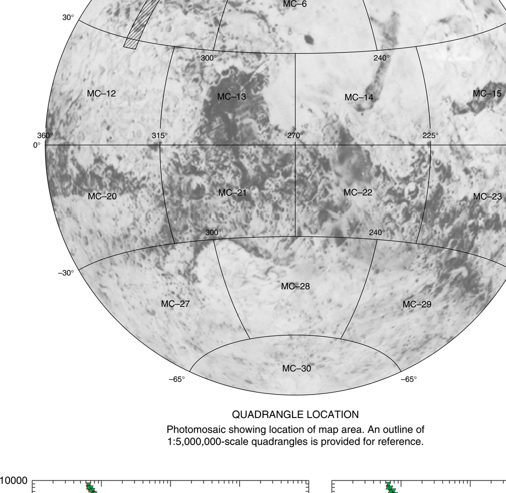


QUADRANGLE LOCATION
Photomosaic showing location of map area. An outline of 1:5,000,000-scale quadrangles is provided for reference.

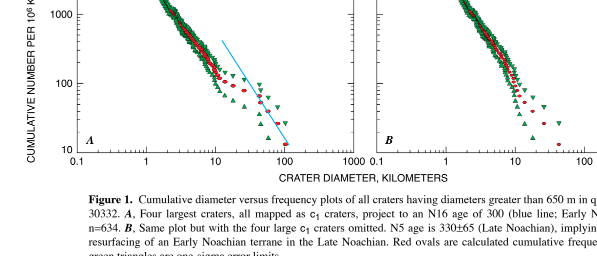


Figure 1. Cumulative diameter versus frequency plots of all craters having diameters greater than 650 m in quadrangle 30332. ***A***, Four largest craters, all mapped as c_1 craters, project to an N16 age of 300 (blue line; Early Noachian). n=634. ***B***, Same plot but with the four large c_1 craters omitted. N5 age is 330±65 (Late Noachian), implying a major resurfacing of an Early Noachian terrane in the Late Noachian. Red ovals are calculated cumulative frequencies and green triangles are one-sigma error limits.

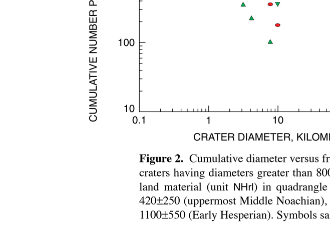


Figure 2. Cumulative diameter versus frequency plot of 12 craters having diameters greater than 800 m on rough lowland material (unit NHrl) in quadrangle 40332. N5 age is 420±250 (uppermost Middle Noachian), whereas N2 age is 1100±550 (Early Hesperian). Symbols same as figure 1.

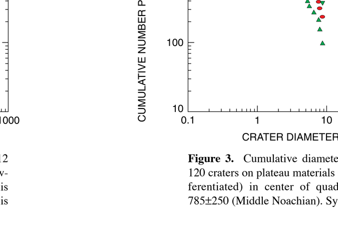


Figure 3. Cumulative diameter versus frequency plot of 120 craters on plateau materials (units Npls and Nplh, undifferentiated) in center of quadrangle 40332. N5 age is 785±250 (Middle Noachian). Symbols same as figure 1.

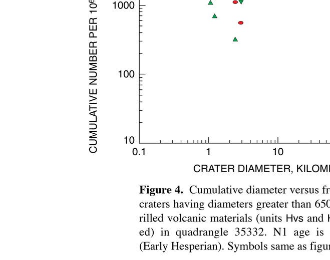


Figure 4. Cumulative diameter versus frequency plot of 10 craters having diameters greater than 650 m on smooth and rilled volcanic materials (units Hvs and Hvr, undifferentiated) in quadrangle 35332. N1 age is about 3400±1400 (Early Hesperian). Symbols same as figure 1.

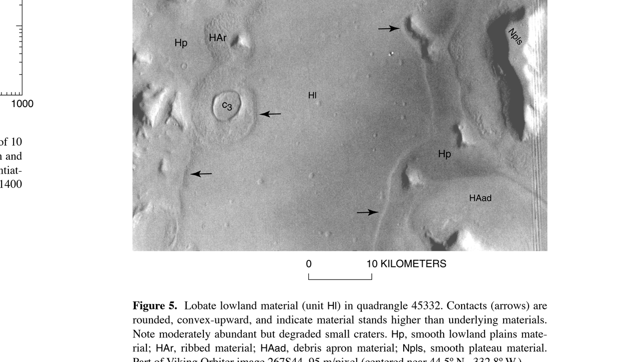


Figure 5. Lobate lowland material (unit Hl) in quadrangle 45332. Contacts (arrows) are rounded, convex-upward, and indicate material stands higher than underlying materials. Note moderately abundant but degraded small craters. Hp, smooth lowland plains material; HAr, ribbed material; HAad, debris apron material; Npls, smooth plateau material. Part of Viking Orbiter image 267S44, 95 m/pixel (centered near 44.5° N., 332.8° W.).

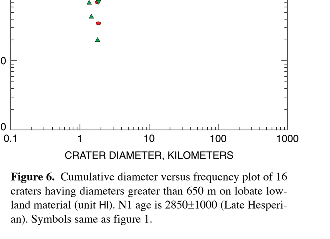


Figure 6. Cumulative diameter versus frequency plot of 16 craters having diameters greater than 650 m on lobate lowland material (unit Hl). N1 age is 2850±1000 (Late Hesperian). Symbols same as figure 1.

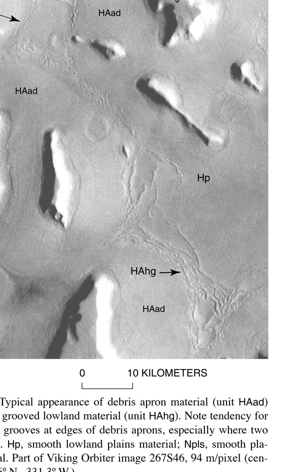


Figure 7. Typical appearance of debris apron material (unit HAad) and heavily grooved lowland material (unit HAhg). Note tendency for pronounced grooves at edges of debris aprons, especially where two aprons abut. Hp, smooth lowland plains material; Npls, smooth plateau material. Part of Viking Orbiter image 267S46, 94 m/pixel (centered at 44.6° N., 331.3° W.).

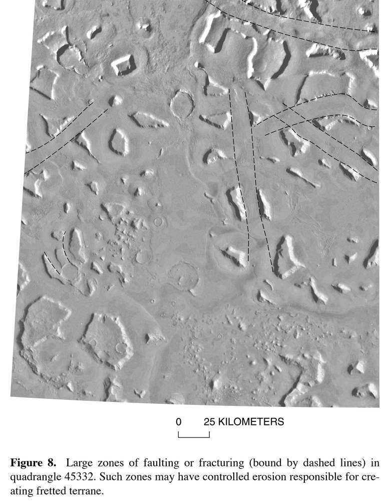


Figure 8. Large zones of faulting or fracturing (bound by dashed lines) in quadrangle 45332. Such zones may have controlled erosion responsible for creating fretted terrane.

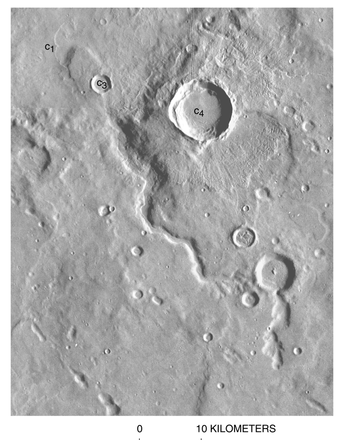


Figure 9. Example of small channel in quadrangle 30332, showing delta where channel debouches into large crater (c_1). Parts of Viking Orbiter images 231S06, 07, and 08, 60 m/pixel (centered at 29.3° N., 334.1° W.).

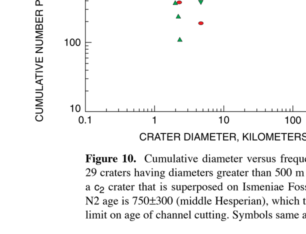


Figure 10. Cumulative diameter versus frequency plot of 29 craters having diameters greater than 500 m on ejecta of a c_2 crater that is superposed on Ismeniae Fossae channel. N2 age is 750±300 (middle Hesperian), which thus is upper limit on age of channel cutting. Symbols same as figure 1.

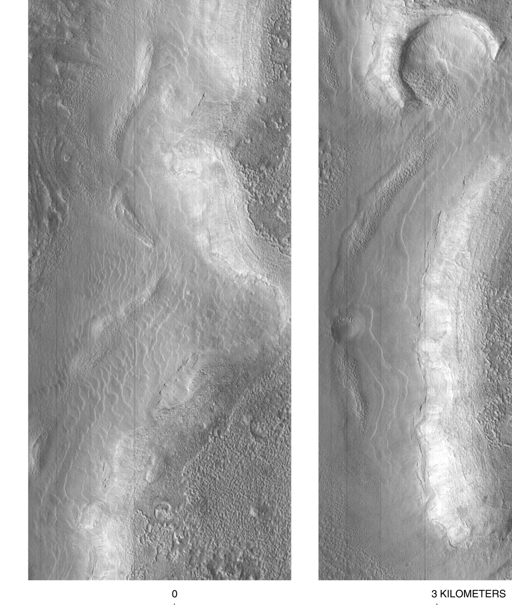
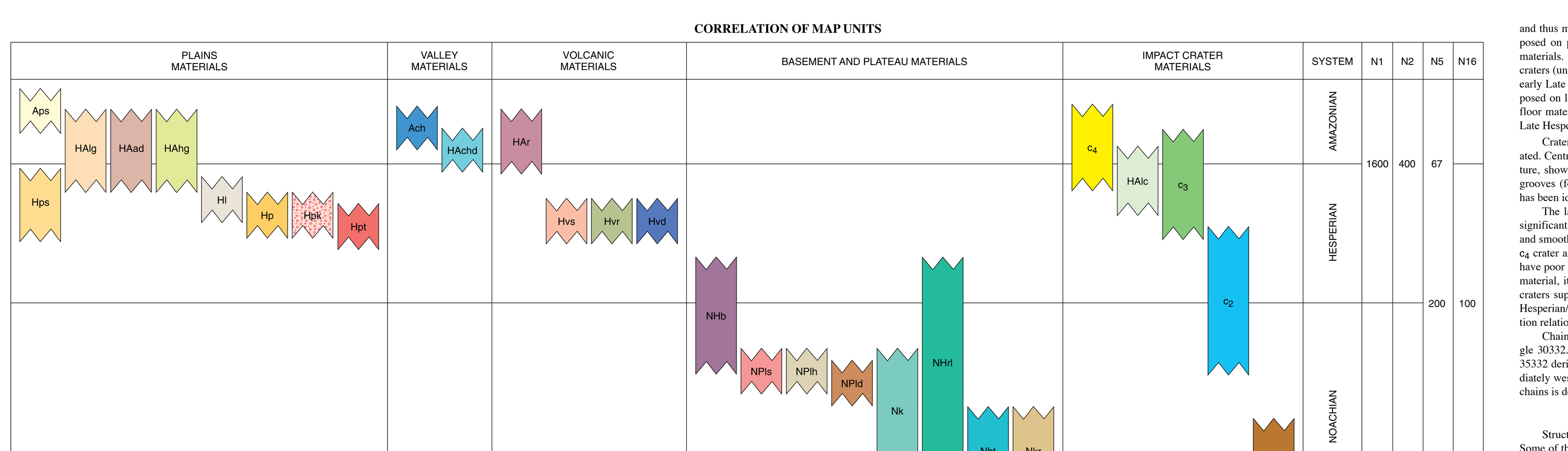


Figure 11. Parallel "bands" along west flank of mesa centered at 46.65° N., 334.85° W. in quadrangle 45332. Sun is to left, and north is approximately up. Bands appear to be ridges, because they are brighter toward sun than away from sun. Mars Orbiter Camera (MOC) image M01-000232 is divided into north (left) and south (right) halves. Width of image strip is 3 km. Resolution of original MOC image is 6 m/pixel.

GEOLOGIC MAP TRANSECTING THE HIGHLAND/LOWLAND BOUNDARY ZONE, ARABIA TERRA, MARS: QUADRANGLES 30332, 35332, 40332, AND 45332

By
George E. McGill
2002

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

PLAINS MATERIALS

Aps **Younger smooth plains material**—Appears smooth and featureless at mapping resolution; albedo slightly higher than most other materials; essentially devoid of superposed impact craters; commonly occurs on floors of craters, including the youngest craters present, and in other depressions, primarily in the highlands. *Interpretation*: Probably of diverse origins, but mostly eolian

HAlg **Lightly grooved material**—Smooth to faintly lineated at mapping resolution; albedo variable; superposed impact craters very rare; locally exhibits convex-upward contacts with older surface along bases of scarps; primarily present on lowland floor adjacent to plateau scarps, but locally present as crater fill in uplands; gradational with debris apron material. *Interpretation*: Thin debris-flow material, most likely derived from adjacent elevated terrain, such as plateau scarps or crater walls

HAad **Debris apron material**—Smooth to faintly lineated at mapping resolution; albedo variable and commonly blotchy; superposed impact craters very rare; generally present as distinctly convex upward aprons around isolated knobs and mesas in the lowland; aprons locally coalesced into a continuous deposit that resembles lightly grooved material. *Interpretation*: Debris-flow material derived from erosion of large knobs and mesas

HAhg **Heavily grooved material**—Similar to lightly grooved material but grooves very pronounced; commonly occurs adjacent to or between deposits of debris apron material; locally present on highland crater floors. *Interpretation*: Debris-flow material

Hl **Lobate lowland material**—Smooth at mapping resolution; albedo slightly blotchy; superposed small craters present but uniformly degraded; contacts with older materials are convex upward. *Interpretation*: Debris-flow material derived from unknown source

Hp **Smooth lowland plains material**—Smooth at mapping resolution; albedo highly variable and commonly streaky; scattered superposed small impact craters; occurs between and stratigraphically beneath debris apron and grooved materials in lowlands, and along margins of lowland embayments and fretted channels cut into highlands; locally indistinguishable in appearance from smooth plains materials (units Hps and Aps). *Interpretation*: Enigmatic, but likely a mix of volcanic, eolian, and debris-flow deposits

Hpk **Knobby lowland plains material**—Similar to smooth lowland plains material except unit includes abundant knobs too small to map separately at mapping scale. *Interpretation*: A hybrid unit consisting of interspersed smooth lowland plains and erosional knobby inliers of older material

Hpt **Textured lowland plains material**—Surface appears rough at about the limit of local image resolution (85 m/pixel); albedo variable and similar to that of smooth lowland plains; small impact craters appear to be more abundant than on other lowland materials; single locality at 42.4° N., 333° W. *Interpretation*: Enigmatic, but probably of similar origin as younger smooth lowland plains material

Hps **Older smooth plains material**—Similar to young smooth plains material except superposed impact craters moderately common; fills irregular depressions in plateau and highland materials. *Interpretation*: Possibly of diverse origins, but most likely eolian

VALLEY MATERIALS

Ach **Lineated valley floor material**—Occurs on floors of fretted valleys and associated deep, closed depressions; lineated and grooved parallel to valley walls; albedo variable, but commonly brighter than adjacent smooth lowland materials; essentially devoid of superposed impact craters; generally separated from channel and depression walls by smooth lowland materials. *Interpretation*: Debris flow materials partially filling older valleys and depressions

HAchd **Delta material**—Smooth at mapping resolution; forms small, irregular, elevated deposits at mouths of small valleys debouching into larger valleys or into craters. *Interpretation*: Deltas formed in ephemeral lakes

VOLCANIC MATERIALS

HAr **Ribbed material**—Small, lobate, convex upward deposit on the lowlands of quadrangle 45332; characterized by irregular ribs and grooves defining a "cracked shell" pattern; intermediate albedo; appears superposed on all surrounding lowland materials. *Interpretation*: Extrusive dome (tholoid)

Hvs **Smooth volcanic material**—Smooth at mapping resolution; albedo relatively light; occurs on upper slopes surrounding deep, irregular depression. *Interpretation*: Pyroclastic deposit, possibly due to phreatomagmatic eruption

Hvr **Rilled volcanic material**—Occurs on lower slopes, peripheral to smooth volcanic material; similar to smooth volcanic material but with abundant rille-like grooves radial to the deep depression. *Interpretation*: Pyroclastic deposit eroded by water from central depression, possibly related to a phreatomagmatic eruption

Hvd **Dome material**—Smooth to radially rilled; forms steep-sided domical features on floors of deep depressions. *Interpretation*: Volcanic (resurgent?) dome on floor of phreatomagmatic crater

BASEMENT AND PLATEAU MATERIALS

NHrl **Rough lowland material**—Surface characterized by irregular hillocks and ridges at tens of kilometers scale; albedo variable, but generally much darker than surrounding lowland materials; occurs on floor of large lowland embayment into highland plateau within quadrangle 40332. *Interpretation*: Exhumed highland terrane, possibly of volcanic origin

NHb **Butte material**—Surface very smooth; albedo higher than surrounding highland materials; occurs as small, isolated buttes in the southern part of quadrangle 30332. *Interpretation*: Erosional remnants of once more widespread deposit of uncertain origin

Npls **Smooth plateau material**—Surface moderately smooth and planar to gently rolling; albedo somewhat variable but generally intermediate; superposed impact craters common and locally large (D>20 km); crater abundance declines significantly from south to north; separated from lowland materials by pronounced scarps; gradational with hummocky plateau and highland materials; locally deeply incised by fretted valleys and valleylike closed depressions; commonly deformed by wrinkle ridges, which become less abundant from south to north. *Interpretation*: Flood lava, possibly with interbedded sediments or pyroclastic material

Nplh **Hummocky plateau material**—Similar to smooth plateau material but surface characterized by hummocks and ridges at kilometer to tens of kilometers scale; gradational with smooth plateau and highland materials. *Interpretation*: Flood lava, possibly with interbedded sediments or pyroclastic material

Npld **Dark plateau material**—Similar to smooth plateau material except albedo much darker; occurs at a lower elevation than smooth plateau material in mesa remnants of plateau in the northwest corner of quadrangle 45332. *Interpretation*: Exhumed surface of flood lava or other material stratigraphically beneath smooth plateau material

Nk **Knob material**—Forms knobs large enough to map; albedo uncertain because all surfaces are relatively steep slopes. *Interpretation*: Erosional remnants of plateau material, basement material, or old crater rims

Nht **Highland terrane material**—Irregular surface locally characterized by large ridges, large formless depressions, hilly and hummocky topography, or flat to gently rolling terrane; probably about coeval with the largest and oldest craters; gradational from south to north into plateau materials. *Interpretation*: Mostly ancient crater and basin ejecta, but some intermixed volcanic materials may also be present

Nkr **Knobby and ridged material**—Occurs in the center of an old impact basin at the southern boundary of quadrangle 30332; complex topography, with abundant small knobs and anastomosing narrow ridges. *Interpretation*: Remnant of floor material within inner ring of ancient impact crater

IMPACT CRATER MATERIALS

c_4 **Material of well-preserved craters**—Undifferentiated central peak, floor, wall, rim, and ejecta materials of craters with complete and undegraded rims and ejecta

c_3 **Material of slightly degraded craters**—Undifferentiated central peak, floor, wall, rim, and ejecta materials of craters with complete but somewhat degraded rims and ejecta

c_2 **Material of moderately degraded craters**—Undifferentiated central peak, floor, wall, rim, and ejecta materials of craters with partial to complete rims that are moderately degraded, and with incomplete and very degraded ejecta

c_1 **Material of highly degraded craters**—Undifferentiated central peak, floor, wall, rim, and ejecta materials of craters with discontinuous remnants of very degraded rims and with very degraded and incomplete ejecta

HAle **Crater Lyot ejecta material**

Contact—Dashed where approximately located
Graben
Wrinkle ridge
Large ridge
Scarp crest—Barbs point downslope
Small valley
Depression
Crater rim—Showing crest. D ≥ 5 km; dashed where degraded
Crater rim—Showing crest. 3 km < D < 5 km
Radially grooved ejecta (schematic)
Secondary crater chain and cluster
Central peak
Basin ring
Rimless crater

INTRODUCTION

Arabia Terra is a large region of cratered terrane extending from about 20° W. longitude eastward across the prime meridian to about 300° W. longitude for an average east-west width of about 5,000 km. The northern boundary ranges from 40° N. to 45° N.; the southern boundary is a poorly defined zone at about 0° N. Thus, the north-south width is about 2,500 km. Except for the westernmost part, Arabia Terra has an albedo higher than surrounding terranes. The four quadrangles mapped (30332, 35332, 40332, 45332) provide a north-south strip from highland terrane in the south to lowland terrane in the north.

The northern portion of Arabia Terra is the type region for both fretted terrane and fretted valleys (Sharp, 1973; Sharp and Malin, 1975) and, along with the immediately adjacent northern plains, is also the site of some of the best examples of putative flow deposits present as aprons around isolated knobs and mesas or as deposits on the floors of fretted valleys and on the lowland surface (Squyres, 1978, 1979). Mass wasting, eolian erosion or deposition, glacial scouring, fluvial or shoreline erosion, deposition from an ocean, hydrovolcanism, plateau volcanism, and faulting all have been proposed to account for the topography and crater characteristics in northern Arabia Terra (Sharp, 1973; Lucchitta, 1978; Greeley and Guest, 1987; Maxwell and McGill, 1987; Parker and others, 1989; Dimitriou, 1990; Moore, 1990; Grant and Schultz, 1990, 1993; Craddock and Maxwell, 1993; Edgett and Parker, 1997; Carruthers and McGill, 1998; Tanaka, 2000; McGill, 2000). Although underlain by what appears to be typical highland terrane, Arabia Terra is anomalously low, with elevations generally below the planetary reference (Smith and others, 1999).

Probably the most important question concerning the global-scale tectonic history of Mars is the origin of the crustal dichotomy. The northern lowland is not only several kilometers lower than the southern highland, it also is surfaced by materials that are significantly younger than surface materials in the southern highland (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987). The young surface materials in the lowland rest unconformably on basement material having an age comparable to the exposed ancient highland terrane to the south (Scott, 1978; Maxwell and McGill, 1987; McGill, 1989; McGill and Dimitriou, 1990; Schultz and Frey, 1990). The age of the dichotomy continues to be controversial, as is the mechanism for its formation, as reviewed by McGill and Squyres (1991), although gravity and topography data from Mars Global Surveyor appear to favor early formation due to internal processes (Zuber and others, 2000). Because complex depositional and erosional events affected the boundary since its formation, the cause and history of these events must be unraveled before we can directly attack the fundamental question of the reason for the dichotomy.

METHODS AND DATA USED

Mapping was based on both digital and hardcopy Viking images, most with resolutions between 40 and 100 m/pixel. These images are available in raw form on CD-ROM's prepared by the U.S. Geological Survey and were processed on a SUN SPARCstation 2 through Integrated Software for Imagers and Spectrometers (ISIS) level 1 to remove reseaux and artifacts, to correct shading, and to despike. During mapping, both hard and digital versions of these images were used. The map bases are sinusoidal equal-area mosaics of Viking images at a scale of 1:500,000 prepared by the U.S. Geological Survey. These bases also were used in both digital and hardcopy versions. The actual drawing of contacts, symbols, and lettering was done digitally using Adobe Illustrator. However, spot mapping of particularly difficult regions was done initially on acetate overlaid on base mosaics or on individual Viking images. Stratigraphic material units were defined primarily by distinctive surface textures and albedos, but the definition of some units also included association with a specific topographic feature, such as an impact crater or a plateau. Crater abundance and superposition relations were used to determine the stratigraphic sequence but were not generally instrumental in the original definition of these units. Units were placed within the standard Mars time-stratigraphic scale (Tanaka, 1986) by means of crater diameter versus frequency plots, superposition, and cross-cutting relations. Mars Orbiter Laser Altimeter (MOLA) data were useful in providing quantitative data on slopes and relief. The few Mars Orbiter Camera (MOC) images available during mapping did not influence the definition of mapping units, but they did provide useful data concerning surface texture of several units, and they provided the only clues concerning the geology beneath the surfaces of the plateaus and mesas by resolving relations exposed on plateau and mesa flanks.

STRATIGRAPHY

The stratigraphic units within the four quadrangles are grouped into five broad categories, three of which are defined by topography and geography (plains, highlands, valley floors), and two by inferred origin (volcanic, impact). Twenty-eight units have been defined: eight basement and plateau units, nine plains units, two valley-floor units, four volcanic units, and five impact crater units. Unit symbols are based on feature association or textural characteristics (lower-case letters) preceded by an upper-case modifier (N, H, or A) indicating the time-stratigraphic assignment (Noachian, Hesperian, and Amazonian, respectively) for the unit.

BASEMENT AND PLATEAU MATERIALS

Basement Materials

Most of quadrangle 30332 and a small portion of quadrangle 35332 are underlain by highland terrane material (unit Nht), which exhibits a relatively high albedo and is characterized by a rolling to hummocky topography and scattered large ridges. Most of this material is inferred to be degraded ejecta from ancient basins and large craters, but little or no direct evidence for this origin has survived. Applying the crater-dating scheme of Tanaka (1986), the crater diameter versus frequency plot (fig. 1*A*) for all of quadrangle 30332 exhibits a clear duality. Extrapolating from the four largest craters, all mapped as ancient c_1 craters, yields an N16 age of about 300 (Early Noachian), whereas a plot with these four craters omitted (fig. 1*B*) yields an N5 age of 330±65 (Late Noachian). These data suggest that highland terrane material is of Early Noachian age, but that the surface was extensively modified by erosion or deposition later in the Noachian. Highland terrane material grades smoothly northward into hummocky and smooth plateau materials such that the contact between basement and plateau materials is difficult to map and thus somewhat arbitrary.

The central region of the double-ringed basin near the south border of quadrangle 30332 consists of knobby and ridged material (unit Nkr), which is generally similar to highland terrane material but also includes abundant small knobs and anastomosing ridges. This unit is inferred to be highly degraded floor material within the inner ring of the basin.

On the floor of a large lowland reentrant into the highland plateaus of quadrangle 40332 is a large (65 km by 85 km) patch of rough lowland material (unit NHrl) centered at 40.2° N., 330.8° W. Rough lowland material has an albedo much lower than most of the surrounding plains and plateau materials, and its surface is characterized by irregular ridges and depressions at scales of several kilometers. Within this patch are several mesas capped by smooth plateau material (unit Npls) and knob material (unit Nk). A diameter versus frequency plot of the 12 craters larger than about 800 meters in diameter (fig. 2) yields an N5 age of 420±250 (uppermost Middle Noachian), suggesting that this is a patch of ancient basement showing through the surrounding younger plains. However, the N2 age is 1100±550 (Early Hesperian). The presence of plateau mesas within the rough lowland material indicates that this material may once have been buried by plateau materials. If so, no craters could have accumulated on it between about mid-Noachian and mid-Hesperian. Thus, the rough lowland material is likely mid Noachian or older in age, but because of the uncertainties, the age range for this unit is unusually large on the correlation chart. Lucchitta (1989) and Carruthers (1996) suggested that this material could be volcanic, based in part on its low albedo and in part on the irregular morphology of some craters.

Throughout parts of quadrangles 35332, 40332, and 45332 scattered clusters of rounded knobs apparently project through overlying plains materials. Although elsewhere on Mars knob clusters projecting through younger plains commonly define the rims of large degraded and buried craters (Maxwell and McGill, 1987; McGill, 1989; McGill and Dimitriou, 1990), this is not the case here. Nevertheless, most of them probably represent eroded remnants of highland terrane material. Where large enough, individual knobs are mapped as knob material (unit Nk); where abundant small knobs are present within the plains a hybrid knobby lowland plains unit has been mapped (see "Plains Materials" section).

Plateau Materials

The topography of most of quadrangle 35332 and more than half of quadrangle 40332 is characterized by nearly horizontal plateaus that are separated from adjacent valley and lowland floors by relatively steep (15° to 25°) flank slopes that are typically 1,500-2,000 m high. The materials exposed on the surfaces of these plateaus are mapped as plateau materials. Several MOC images show what appears to be a line of rough, irregular outcrops about midway down these scarps at some locations. Above this level, the material appears structureless; below this level, the slope exhibits features that suggest it is underlain by talus. A possible, but not provable, hypothesis is that the top of this line of putative outcrops represents the contact between plateau materials and underlying Early Noachian basement. Abundant scattered mesas in quadrangles 40332 and 45332 represent remnants of these plateau materials presumably isolated by erosion. Three plateau units (smooth, hummocky, and dark) are defined based on differences in surface texture and albedo.

In the northwest corner of quadrangle 45332 three small areas of plateau material are characterized by a much lower albedo than is typical of plateau surfaces elsewhere in the region. These small areas, mapped as dark plateau material (unit Npld), are present on larger mesas where they are at a lower elevation than those parts of the mesas underlain by smooth plateau material. This relationship indicates that dark plateau material is stratigraphically beneath smooth plateau material in at least the northwestern part of quadrangle 45332, where it has presumably been exposed by erosion of the overlying smooth plateau material.

Smooth plateau material (unit Npls) and hummocky plateau material (unit Nplh) exhibit similar intermediate albedos and are apparently the same age; they differ only in surface texture, as their names imply. Wrinkle ridges commonly deform both units. A count of 120 craters larger than 650 meters in diameter in the center of quadrangle 40332 (fig. 3) yields an N5 age of 785±250 (Middle Noachian) for combined smooth and hummocky plateau materials. Hummocky plateau material is more common than smooth plateau material in quadrangle 35332, but it becomes progressively rarer northward across quadrangle 40332 and is present in quadrangle 45332 only as three small patches near the south border. The hummocky appearance is due to ridges, hillocks, and grooves at a scale of a few kilometers or smaller. At MOC resolution (3-6 m/pixel), all plateau surfaces appear rough, but the surface roughness of hummocky plateau material is typically at a scale of hundreds of meters (for example, MOC image M00-02140, 35.67° N., 334.91° W.), whereas that of smooth plateau material is typically at a scale of meters to tens of meters (for example, MOC image SP2-50005, 39.76° N., 334.83° W.), that is, much too small to be resolved by the Viking images. In quadrangle 35332 and the southern part of quadrangle 40332 the two plateau units are so intimately intermingled that the textural difference between them is almost certainly primary. However, the progressive northward increase in smooth plateau material at the expense of hummocky plateau material in the northern part of quadrangle 40332 and in quadrangle 45332 is accompanied by a progressive loss of small craters, suggesting that post-plateau erosion that increased in intensity northward also may have contributed to the surface smoothness of smooth plateau material.

Near the south margin of quadrangle 30332, several small occurrences of butte material (unit NHb) are smooth and featureless and have albedos higher than the surrounding highland terranes. These buttes are superposed on both hummocky plateau material (unit Nplh) and knobby and ridged material (unit Nkr) and are most likely small erosional remnants of the mantling deposits that are more widespread both east and west of the area mapped (Grant and Schultz, 1990, 1993; Edgett and Parker, 1997; Tanaka, 2000). The Noachian to Hesperian age inferred for this unit is based on age estimates given in these cited references.

VOLCANIC MATERIALS

Materials of volcanic and probable volcanic origin are present in quadrangles 35332 and 45332. At the western source (35.7° N., 334.6° W.) of the large fretted valley (part of Ismeniae Fossae) within quadrangle 35332 and also some distance downstream (37.2° N., 332.7° W.), are large, irregular, deep depressions that have been interpreted to be of hydrovolcanic origin (Carruthers, 1996; Carruthers and McGill, 1998). Three material units believed to be of primary volcanic origin are associated with the large depression forming the western source of the fretted valley. The proximal portion of the gently sloping flanks of the depression is underlain by very smooth, featureless material mapped as smooth volcanic material (unit Hvs). This unit grades outward and down slope into rilled volcanic material (unit Hvr), which is characterized by straight, apparently flat floored, radial troughs. Rilled volcanic material is superposed on both smooth and hummocky plateau materials. Ten craters larger than 650 meters in diameter on smooth and rilled volcanic materials combined (fig. 4) yield an N1 age of 3400±1400 (Early Hesperian). On the floor of the depression is a steep-sided, dome-shaped feature mapped as dome material (unit Hvd). This feature most likely is analogous to the domes that occur locally as a late stage of hydrovolcanic eruptions. A somewhat larger and steeper dome (also mapped as unit Hvd) is characterized by radial troughs and is present within the second deep depression, about 150 km downstream. MOLA track 10199 indicates that this dome is about 200-250 m high. The volcanic materials associated with Ismeniae Fossae are more completely described elsewhere (Carruthers, 1996; Carruthers and McGill, 1998).

Near the center of quadrangle 45332 two small (8–12 km diameter) convex upward patches of material characterized by irregular ribs and grooves resemble the texture shown by some tholoids and rhyolite lava domes (Green and Short, 1971, plates 62B and 63B), although an origin by mass wasting processes is possible. These patches are mapped as ribbed material (unit HAr). Because the edges of the two convex patches abut each other, they are mapped as a single unit. The age is based on the total absence of superposed craters and by superposition of this unit on Late Hesperian lobate lowland material.

VALLEY MATERIALS

At four localities in quadrangle 30332 (31.7° N., 332.9° W.; 29.8° N., 334.3° W.; 28.2° N., 333.4° W.; 28.3° N., 332.8° W.) and at one locality in quadrangle 35332 (35.8° N., 333.8° W.), smooth materials form irregular, flat-topped, steep-sided deposits mapped as delta material (unit HAchd). All of the localities in 30332 are where small valleys debouch into impact craters; the locality in 35332 is where a small valley debouches into the major Ismeniae Fossae fretted valley. With one exception, superposed impact craters are not present on these deposits.

The floors of fretted valleys are commonly characterized by material that is corrugated into long, narrow grooves and ridges, generally oriented about parallel to the walls of the valleys. This material, mapped as lineated valley floor material (unit Ach), has a varied albedo, but most commonly it is brighter than immediately adjacent lowland and plateau materials. No impact craters large enough to be resolved in the Viking images are superposed on lineated valley floor material. The edges of the lineated valley floor deposits appear to be rounded and convex-upward on the Viking images, but this morphology is difficult to verify with MOLA profiles because the horizontal scale of the apparently rounded edges is less than the MOLA shot spacing. Between the edges of the lineated valley floor deposits and the bases of the valley walls are narrow strips of smooth lowland plains material (unit Hp) on a surface that slopes very gently toward the valley center (Parker and others, 1989). These characteristics support the inference that lineated valley floor material is superposed on smooth lowland plains material.

PLAINS MATERIALS

Nine plains units have been mapped: Older smooth plains material (unit Hps), younger smooth plains material (unit Aps), textured lowland plains material (unit Hpt), knobby lowland plains material (unit Hpk), smooth lowland plains material (unit Hp), lobate lowland material (unit Hl), heavily grooved lowland material (unit HAhg), debris apron material (unit HAad), and lightly grooved lowland material (unit HAlg). The two smooth plains materials (units Hps and Aps) are mostly local fill within depressions in the highlands; the other seven units are present predominantly in the lowland parts of quadrangles 40332 and 45332. The contacts between the four youngest lowland units (units Hl, HAhg, HAad, HAlg) and the three older ones (units Hpt, Hpk, Hp) are rounded and convex-upward, with the younger materials standing slightly higher than the older materials.

Textured lowland plains material (unit Hpt) is present in one locality along the border between quadrangles 40332 and 45332. Albedo is about the same as for surrounding smooth lowland plains material. The surface appears rough at about the limit of local image resolution (85m/pixel), and small impact craters appear to be more abundant than on other lowland materials. Knobby lowland plains material (unit Hpk) is a composite unit consisting of smooth lowland plains material and abundant small knobs that are too small to map separately. The knobs probably are inliers of an older underlying unit. A less likely interpretation is that they represent remnants of a younger lowland material that has been almost completely eroded away. Smooth lowland plains material (unit Hp) is apparently the oldest plains material over most of the lowland area mapped. It appears smooth at mapping resolution and at MOC resolution (for example, MOC image M02-02164, 39.70° N., 334.58° W.) and is characterized by a highly varied, commonly streaky albedo; the streakiness is clearly visible in low-resolution images of this lowland region. There are scattered superposed small impact craters. Smooth lowland plains material generally is found between and beneath the widespread debris aprons surrounding isolated knobs and mesas and along the margins of lowland reentrants and fretted valleys cut into the highlands. Locally, in areas between the scattered superposed impact craters, this material is similar in appearance to younger smooth plains material (unit Aps); it is mapped as a separate unit because in most places it is demonstrably older than both c_3 and c_4 craters, whereas young smooth plains material covers the floors of c_3 and c_4 craters.

The four remaining lowland materials form deposits having characteristics suggestive of the involvement of fluid flow in their emplacement. Lobate lowland material (unit Hl) is present as a deposit having an overall form similar to that created by pouring a highly viscous liquid on a flat surface (fig. 5); that is, the top of the deposit is smooth and very flat, but the edges are rounded, convex upward. This morphology is clearly seen on MOLA profile, which indicates that the relief across the rounded edge is about 100 m. The albedo is varied and patchy. Superposed small craters are present and yield an N1 age of 2850±1000 (early Late Hesperian; fig. 6). Lightly grooved lowland material (unit HAlg) is smooth to faintly lineated at mapping resolution and has a varied albedo. Superposed impact craters are rare, and most of them are less than 1 km in diameter. Unit HAlg primarily covers the lowland surface within reentrants into the highlands, where it commonly is separated from the reentrant walls by smooth lowland plains material on surfaces that slope very gently away from the base of the reentrant wall. At these localities, the lightly grooved lowland material is slightly elevated above the smooth lowland plains material, and the edge of the lightly grooved lowland material is rounded, convex upward. MOLA profiles indicate that this rounded edge is only about 10 meters high. Debris apron material (unit HAad) forms broad, convex upward, gently sloping aprons surrounding isolated knobs and mesas and locally at the bases of plateau scarps (fig. 7). The albedo is similar to that of lobate lowland material. The surface is smooth to very faintly lineated. No superposed impact craters are visible at Viking resolution. In places, individual aprons coalesce into a continuous deposit that is difficult to distinguish from lightly grooved lowland material. Heavily grooved lowland material (unit HAhg) is similar in appearance to debris apron and lightly grooved lowland materials except the grooves and ridges are very pronounced, rather like the case for lineated valley floor material. Most commonly, this material is present at the periphery of or between debris aprons (fig. 7). MOLA track ap00023k indicates that the grooves and ridges have a relief of about 25–35 m, and slopes about 2.5° to 5° (McGill, 2000). Locally, material mapped as this unit is present on the floors of highland craters.

Most depressions, including most impact craters, are floored with smooth plains materials. Two units are mapped: Older smooth plains material (unit Hps) and younger smooth plains material (unit Aps). Both have surfaces that appear smooth and featureless at mapping resolution, and both have albedos slightly higher than most other materials in these quadrangles. The only distinction between the two units is that small impact craters are always present on older smooth plains material, whereas younger smooth plains material is almost totally devoid of superposed craters large enough to be seen at the resolution of the available Viking images. The absence of superposed craters on younger smooth plains material supports an Amazonian age for this unit, as does its presence inside even small c_4 craters. A crater age of Early Hesperian was determined by combining counts on eight separate but close patches of older smooth plains material in the northwest corner of quadrangle 35332. This age can represent the true age of the unit only if all of the patches are approximately the same age, which must be assumed a priori.

IMPACT CRATER MATERIALS

Impact craters are classified into four categories by morphology, as summarized in the Description of Map Units. The material of highly degraded craters (unit c_1) is older than the plateau materials, and thus must be of Noachian age. Material of moderately degraded craters (unit c_2) is mostly superposed on plateau materials and, where in contact, is buried by Hesperian and Amazonian lowland materials. Thus, c_2 craters must be of Noachian or Early Hesperian age. Material of slightly degraded craters (unit c_3) is superposed on and superposed by lowland materials, and thus is inferred to be about early Late Hesperian to Early Amazonian in age. Material of well-preserved craters (unit c_4) is superposed on lowland materials and thus is probably largely Amazonian in age. However, lineated valley floor material appears to be younger than some large c_4 craters, and thus some c_4 craters may be of Late Hesperian age.

Crater materials are mapped as central peak, floor, wall, rim, and ejecta materials, undifferentiated. Central peaks and crater rims are indicated by symbols. Some crater ejecta exhibit a radial structure, shown on the map as a line pattern. MOC images indicate that the radial lineations consist of grooves (for example, MOC image M03-01117, 29.28° N., 334.19° W.). No radially lineated ejecta has been identified around c_1 or c_2 craters.

The large crater Lyot is north of quadrangle 45332, but its ejecta material (unit HAle) covers a significant area in the northern part of that quadrangle. This material is superposed on smooth plateau and smooth lowland plains materials and on at least one c_3 crater, but it is superposed by ejecta from a c_4 crater and appears to be embayed by debris apron material. Because Viking images covering Lyot have poor resolution (~190 m/pixel) and because the crater appears to be partially mantled by younger material, it is difficult to obtain a reliable count of craters superposed on it. However, a count of 12 craters superposed on the inner part of Lyot ejecta yields a poorly constrained age that straddles the Hesperian/Amazonian boundary, which is in good agreement with the age determined by superposition relations (Tanaka, 1986).

Chains and clusters of secondary impact craters are locally very abundant, especially in quadrangle 30332. Most of the secondary crater chains in 30332 and in the southwest corner of quadrangle 35332 derive from the 120-km-diameter crater Cerulli, which is centered at 32.5° N., 338° W., immediately west of the boundary between quadrangles 30332 and 35332. A smaller set of secondary crater chains is derived from the 43-km-diameter c_3 crater in the northern part of quadrangle 30332.

STRUCTURAL GEOLOGY

Structural features present in the area mapped include large ridges, wrinkle ridges, and grabens. Some of these structures appear to have influenced the geomorphic evolution of the region, and thus a brief discussion is in order.

Large ridges of various orientations are about 3 km wide and up to 50 km long and locally characterize the highland terrane material (Nht). Most of these are in the east-central part of quadrangle 30332. These ridges probably represent topography created by faulting, most likely of the thrust or reverse type (Watters, 1993), but an origin by local folding is possible.

Wrinkle ridges are abundant on plateau materials, particularly in quadrangle 40332. Most are about 1 km wide and 20–30 km long, but a single, large wrinkle ridge, which is 2 km wide and 75 km long, is present in about the center of quadrangle 40332. The wrinkle ridges define an anastomosing pattern, with most trending within 30°–40° of north; east-west trends are very rare. As discussed in the literature (for example, Plescia and Golombek, 1986; Watters, 1991), these ridges most likely formed by contractional strains oriented approximately normal to ridge trends. Wrinkle ridges become less abundant on plateau materials northward of the center of quadrangle 40332 and are completely absent in quadrangle 45332 even though large areas of plateau materials remain as mesas.

Arabia Terra was inferred to be the site of subduction during a Late Noachian or Early Hesperian episode of plate tectonics, as proposed by Sleep (1994). However, no significant contractional structures are near the dichotomy boundary in Arabia Terra, and no volcanic rocks are the appropriate age (the possibly volcanic materials of the plateaus are too old). Thus, the specific plate-tectonic model proposed by Sleep is not supported by the areal geology of Arabia Terra.

Small grabens are present but not abundant, and they do not define any coherent trends or patterns. Most of these grabens are areally associated with the deep fretted valleys cut into the plateau materials.

In quadrangle 45332 the shapes and distributions of the mesas strongly suggest structural control. Many mesas have straight sides with sharp corners, which suggests faults or joints controlled erosion (Kochel and Peake, 1984). Furthermore, some mesas with straight sides occur as parallel pairs, and locally more than one such pair is lined up in a way to suggest the presence of a large graben or zone of concentrated fracturing that presumably controlled erosion and defined the alignment. At least seven such alignments are visible in quadrangle 45332, defining at least seven straight to gently curved structures ranging between 5 and 15 km wide and as much as 150 km long (fig. 8). Immediately east of the area mapped, a set of northwest-trending faults and scarps defines the dichotomy boundary (Dimitriou, 1990), and there has been little or no development of fretted terrane. The faulting or fracturing that defines the dichotomy boundary was possibly more extensive in the area of quadrangle 45332 than to the east, and this faulting or fracturing likely controlled the erosion responsible for fretted terrane. Few, if any, similar large structures are present on the little eroded or uneroded highland plateau surfaces, suggesting a correlation of fretted terrane with relatively abundant large structural zones. The fretted valleys and depressions seem to have trends controlled more by old crater and basin structures than by large grabens or fracture zones of the type presumably present within the fretted terrane itself. Thus, the southern limit of the erosion that created fretted terrane probably occurred where major structural disruption of the crust ceased.

If these structural zones are grabens, then the missing plateau materials are probably present beneath lowland materials, and thus it is not necessary to infer extensive removal of material by erosion. If, on the other hand, these are zones of concentrated fracturing, then the missing plateau materials must have been removed by erosion and transport away from the fretted terrane.

GEOMORPHOLOGY

The craters, other landforms, and materials present in these four quadrangles provide a record of the surficial processes that have acted on the crust in this region. This record can be read and interpreted with varying degrees of certainty, as is always the case in geomorphological studies, on Earth as well as on other terrestrial bodies. Probably the primary contribution of detailed mapping is in deciphering the chronology of events, which in turn provides important constraints on models of process and crustal history. The following discussion is organized around feature types; the inferred sequence of events will be presented in the Geological History section of the text.

CRATER MORPHOLOGY AND SIZE DISTRIBUTION

The craters in quadrangle 30332 provide strong evidence for a major event during Middle to Late Noachian that destroyed or buried all but the largest ancient (Early Noachian) impact craters. The distinct bend in the diameter/frequency plot in the diameter range 10–40 km (fig. 1*A*) implies the loss of virtually all old craters in this size range and smaller. Only four c_1 craters are mapped in this quadrangle, and they are the largest four on figure 1*A*. A few shallow, rimless depressions with diameters in the 10–30 km range are present, but no definite impact craters. Nothing suggests the presence of any c_1 survivors with diameters less than 10 km. Evidence for significant resurfacing of highland regions during the Noachian has been presented and discussed in the past, and a number of processes have been suggested, including erosional modification of craters by fluvial processes (Craddock and Maxwell, 1993; Grant and Schultz, 1990, 1993), infilling of craters by airfall deposits or lava flows (Moore, 1990; Wilhelms and Baldwin, 1989; Tanaka, 2000), and mantling by deposits from an ocean (Edgett and Parker, 1997). The absence of any evidence for concentrated runoff on the rims of ancient craters argues against running water from rainfall or sapping as the cause of resurfacing, and the rather rough topography of the highland terrane material argues against burial by lava or sediment thick enough to mask this rough topography. A sedimentary mantle is consistent with the total loss of small craters but does not fit the nature of the degradation of the surviving large craters. These large craters appear partially filled in, and their ejecta blankets can no longer be discerned, characteristics that could be due to mantling. However, a sedimentary mantle could not obliterate part or most of the rims while leaving remnants with significant relief. A combination of running water partially destroying the rims of large craters followed by an airfall blanket, a sequence proposed by Grant and Schultz (1990), could explain the crater population, as could a combination of running water and ocean deposition. No unequivocal evidence is present in this area to support either of these hypotheses.

Small craters, with diameters less than the mapping cutoff diameter of 3 km, are very abundant on most of the area underlain by highland terrane and plateau materials. However, from the northernmost part of quadrangle 40332 northward into quadrangle 45332 these small craters are rare and are essentially absent over most of quadrangle 45332. Either an erosional or a depositional event (or both) must have taken place after emplacement of the plateau materials, and this event must have increased in intensity northward. The apparent local erosional loss of the uppermost plateau materials to expose the underlying layer of dark plateau material in the northwestern corner of quadrangle 45332 and the northward decline in relief between plateau and mesa surfaces and adjacent lowland surfaces support erosion rather than deposition as the process modifying the surface of the plateaus. Although speculative, a possible explanation for this event is deposition from an ocean or coastal erosion during recession of the inferred ocean (Edgett and Parker, 1997).

Small craters are very rare on most lowland materials. In part this must be due to the very young ages of these materials, but that explanation probably does not entirely account for the paucity of craters. As shown in figure 5, the craters superposed on lobate lowland material (unit Hl), and used to determine its crater age, are all degraded in appearance. Craters of the same size on highland materials are mostly fresh and crisp. Because many of the lowland plains materials exhibit characteristics suggestive of flow, it is possible that small craters were rapidly degraded if flow continued after crater formation.

VALLEYS

Small, somewhat sinuous valleys are present but not abundant in areas underlain by highland terrane and plateau materials. This paucity of small valleys and valley networks is a regional characteristic of the entire Arabia Terra area (Carr, 1996). Most of the small valleys present in the area mapped are on highland terrane (unit Nht) in quadrangle 30332, and the remainder are on plateau materials in quadrangle 35332 and the southernmost part of quadrangle 40332. Typically, the valleys range in width from about 3 kilometers down to the limit of resolution and in length from a few tens of kilometers to about 100 kilometers. At their sources, most of the valleys consist of one or more narrow, roundheaded troughs, but some appear to begin in craters. Most valleys widen downstream, and all have few or no tributaries. Valleys eroded into highland terrane material generally drain into impact craters, whereas all valleys eroded into plateau materials drain into large fretted valleys. Locally, small deltas (fig. 9) are present at the mouths of these valleys, strongly implying the presence of lakes within some of the old craters. The time of formation of these small valleys is difficult to estimate. Valleys cut into highland terrane must be Late Noachian or younger, otherwise they would have been obliterated by the process that destroyed most of the c_1 craters. Those valleys that cut into plateau materials and that drain into fretted valleys must be the same age or younger than the fretted valleys, placing an old age limit on those valleys of Early to early Late Hesperian (see below). Estimating young limits is generally not possible, but one of the valleys (fig. 9) is clearly older than a 3.5-km-diameter c_3 crater and a 10-km-diameter c_4 crater, and thus is most likely of Hesperian age.

Fretted valleys have been explained as due to running water (Lucchitta, 1978), sapping (Sharp, 1973; Sharp and Malin, 1975), or one or more mass wasting processes (Lucchitta, 1984; Carr, 1995, 1996). The morphology of the Ismeniae Fossae fretted valley segment present in quadrangle 35332 has been described in detail by Carruthers (1996) and Carruthers and McGill (1998). Both sources of this fretted valley coincide with deep, irregular depressions, the floors of which are significantly lower than the floors of the valley branches flowing out of them. Regardless of the origin of these deep depressions, this topographic evidence points to the presence of lakes in the depressions, and that in turn indicates an important role for running water in cutting the fretted valley. As discussed elsewhere (Carruthers, 1996; Carruthers and McGill, 1998), evidence exists for a hydrovolcanic origin for at least one of these deep depressions, which also supports the presence of liquid water.

The depth of the Ismeniae Fossae fretted valley within quadrangle 35332 indicates a complex formation and modification history. From the western source to the irregular, possibly volcanic, depression at 37.2° N., 332.7° W. the valley is 600 to 1000 m deep. Within the putative volcanic depression the depth is 1800 to 2000 m. Downstream from this depression the valley shallows to a depth of 450 m and then deepens again to 1000 m before leaving the area of the quadrangle. Within this area, the elevation of the bounding plateau surface varies by only about 300 m, and thus the valley depths represent real differences in floor elevation.

The age of the Ismeniae Fossae fretted valley can be constrained rather well. It must be younger than the plateau materials it cuts, which places a Middle Noachian old age limit on formation. In the northeast corner of quadrangle 35332 and in the adjacent quadrangle to the east, a large c_2 crater is superposed on this valley, completely burying a short section of it (McGill, 2000). The crater population (fig. 10) superposed on the ejecta blanket of this crater yields an N2 age of 750±300 (middle of the Hesperian). Thus the valley must be older than middle Hesperian. The putative volcanic deposits around the deep depression at the western source of the fretted valley yield an Early Hesperian age (fig. 4), and thus if one accepts a genetic association between the formation of the depression and the cutting of the valley, the most likely time of fretted valley cutting is Early Hesperian.

The floor of the fretted valley is characterized by grooved and lineated material (unit Ach) that has been interpreted as due to mass wasting, most likely some form of debris flow (Squyres, 1978, 1979; Lucchitta, 1984; Carr, 1995, 1996). This material is essentially devoid of superposed impact craters. Furthermore, even though the large Hesperian c_2 crater in the northeastern part of quadrangle 35332 is clearly superposed on the valley, the valley floor materials are equally clearly superposed on crater ejecta. These observations lead to the conclusion that valley floor material is young, most likely Amazonian in age, and thus very much younger than the age of formation of the valley itself. Mass wasting processes almost certainly have modified the fretted valley, but no evidence exists to suggest that they actually formed the valley.

FLOW DEPOSITS

The materials inferred to have formed by some process of viscous flow have been thoroughly studied (Squyres, 1978, 1979; Lucchitta, 1984; Kochel and Peake, 1984; Carr, 1995, 1996; Colaprete and Jakosky, 1998). These authors envisage unconsolidated materials flowing under the influence of gravity because of interstitial water or ice, analogous to slow debris flows and rock glaciers on Earth. The use of the term "debris flow" here to encompass all of these mapped materials is a matter of convenience and does not imply any preference for ice versus water as the interstitial material. Generally, past studies have concentrated on the lineated valley floor and debris apron materials. The debris aprons surround most knobs and mesas in the lowland and are present adjacent to the scarps that rise to the highland plateau surface. In the northwest corner of quadrangle 40332, MOLA track ap00023k crosses a debris apron and the plateau scarp. The apron exhibits the anticipated gentle, convex-upward slope, which averages about 1.9° (McGill, 2000). The slope of the plateau scarp is about 15°, and other scarps in this area have slopes of 15° to 25°, similar to values determined by Parker and others (1989).

The grooves and ridges that characterize most of these materials can form either parallel to the flow direction or normal to it (Squyres, 1978). Squyres (1978) favored formation normal to flow in most instances because the most pronounced grooves and ridges are found at the convergence of debris aprons or where flow is confined by scarps, an observation verified by detailed mapping here. He argues that the lineated valley floor material is due to converging flow from opposite walls of the valley and that the major flow direction is transverse to the valley itself. However, Lucchitta (1984) notes examples of grooves and ridges that enter a valley normal to its length and then curve into parallelism, suggesting dominant flow parallel to the valley. Detailed mapping indicates that the lineated valley floor material is generally separated from the valley walls by an older surface that slopes gently toward the valley center (Parker and others, 1989) and that the contact of the lineated material is rounded, convex upward. This relation also argues for dominant flow parallel to the valley. However, the presence of heavily grooved lowland material (unit HAhg) at the edges of debris aprons and where aprons are in contact with each other is consistent with formation of the grooves and ridges normal to the flow direction. Furthermore, the formation of valley-parallel grooves and ridges by valley-parallel flow in completely enclosed valleys is difficult to understand.

In addition to the valley and apron deposits, areally extensive deposits of ungrooved and lightly grooved lowland materials (units Hl and HAlg) are neither confined to valleys nor found as convex-upward aprons surrounding knobs and mesas. The sources of the materials making up these deposits are not apparent.

All of the debris flow deposits are younger than the smooth lowland plains material (unit Hp) and its local variants textured and knobby lowland plains materials (units Hpt and Hpk). Whatever its genesis, the apparent presence of smooth lowland plains material along the edges of valleys and erosional re-entrants into the highlands provides further evidence for the completion of the erosion that formed fretted terrane and fretted valleys before the onset of demonstrable mass wasting on a large scale.

KNOBS AND MESAS

Abundant knobs and mesas that range in size from features near the resolution limit of the images to large mesas many tens of kilometers across characterize the lowland portions of the area mapped. The large mesas are almost certainly erosional remnants of highland plateaus. Smaller features also have been mapped as plateau remnants if they are mesas; that is, if they preserve a remnant of a flat top. The implication is that these mesas are capped by materials younger than the Early Noachian basement that most likely underlies the northern plains materials. Knobs do not have flat tops, so their origin is less certain. Some of the largest knobs are probably plateau remnants that have eroded enough to be all in slope; that is, no flat top is preserved. Other knobs, especially the abundant small ones, are probably inliers of pre-plateau materials, as seen at other lowland localities on Mars (Maxwell and McGill, 1987; McGill, 1989; McGill and Dimitriou, 1990). Because separating knobs according to origin is not possible, their age range overlaps most other Noachian materials on the correlation chart.

Between the plateau edge in the northwest corner of quadrangle 40332 and the north border of quadrangle 45332 the elevations of the mesa tops decline very gently. As measured on two MOLA tracks (ap00023k and ap00372k) this elevation change of the plateau surface is about 500 m over a horizontal distance of about 375 km, for an average slope of about 0.08°.

Bands on Mesa Flank

MOC image M01-000232 provides a detailed view of the west flank of a small mesa centered at 46.65° N., 334.85° W. Narrow bands characterize this flank along most of its length (fig. 11). These bands are especially clear near the north end of the mesa, where two bands maintain uniform spacing for at least 7 km along the flank of the mesa. Farther south, a possible third band is less continuous and not as clearly defined. The bands appear to be caused by narrow ridges, because their west (sunward) flanks are bright and their east flanks are dark. These bands possibly represent stratigraphic contacts within the mesa, but the ridgelike morphology does not seem consistent with this interpretation. Alternatively, they could represent beach ridges left by a lowland ocean, such as proposed by Parker and others (1989). MOLA track 10042 indicates that the top of the mesa lies at an elevation of about –3100 m and that the adjacent lowland floor lies at about –3800 m, indicating that the bands must lie in the interval –3100 to –3800 m. The bands appear to be closer to the top than to the base of the mesa flank and thus are most likely closer to –3100 m than to –3800 m. This elevation coincides very closely with the elevation of contact 2 of Parker and others (1989) as determined by MOLA data (Head and others, 1998). Thus, the bands probably represent shorelines. However, none of the small number of other MOC images of mesa flanks within the area mapped exhibits similar evidence for shorelines.

GEOLOGIC HISTORY

The oldest processes recorded by the rocks in this region are those responsible for the creation of the Lower Noachian highland terrane, including all c_1 craters. Impact cratering was clearly an important process, and the only one for which any evidence exists. Coeval volcanism was certainly possible, but there is no surviving evidence. Plateau materials were emplaced in the Middle Noachian (fig. 3), possibly by large-scale flood volcanism (for example, Greeley and Guest, 1987), although no definitive evidence for a volcanic origin is present in these quadrangles and other models have been proposed (for example, Sharp, 1973). Except for a single c_2 crater in quadrangle 45332 that appears to be stratigraphically beneath knob remnants of plateau materials, all c_2, c_3, and c_4 craters are younger than these plateau materials; all c_1 craters are older. A major resurfacing of the Lower Noachian terrane also took place later in the Noachian, but the crater distributions (fig. 1) suggest that this occurred in the Late Noachian rather than at the same time as emplacement of plateau materials in the Middle Noachian. This is a curious result, because it is difficult to understand how craters on a Middle Noachian plateau could survive a significant Late Noachian resurfacing unless the process was local in nature. The plateau materials also experienced a resurfacing, but only in the northern part of the area mapped where wrinkle ridges and small craters evidently were destroyed and where the relief between mesa tops and adjacent lowland is less than it is farther south. This resurfacing must have occurred after the emplacement of the plateau materials but before the erosion that formed fretted valleys and fretted terrane. Therefore, this resurfacing is constrained to be Middle Noachian or younger, definitely middle Hesperian or older, and probably Early Hesperian or older.

The presence of several small buttes resting on highland and plateau materials near the south boundary of quadrangle 30332 suggests that the area may have been mantled by sedimentary materials at some time in the Noachian or Hesperian.

A major erosional event formed the fretted valleys and fretted terrane, most probably in the Early Hesperian but certainly between Middle Noachian and middle Hesperian (figs. 3, 4, 10). In the area mapped, some large c_2 craters are incorporated into the Ismeniae Fossae fretted valley or were eroded during fretted terrane formation, other c_2 craters are superposed on the valley or on isolated mesas of plateau material. The dominant process responsible for the fretted valleys remains uncertain, but evidence favors some combination of sapping and running water. Hydrovolcanism very likely aided these processes. What seems to be clear from the stratigraphy is that there is no evidence that mass wasting played a major role in cutting the valleys. Small valleys probably formed at the same time or later than the fretted valleys and likely remained active into the Amazonian. Excellent evidence confirms the existence of several lakes within deep, irregular depressions at the sources of the Ismeniae Fossae valleys and within old impact craters where deltas formed at the mouths of small valleys. The lakes associated with Ismeniae Fossae were most likely of Early Hesperian age; other lakes could be Hesperian or Amazonian.

Lowland materials are present between the mesas in the fretted terrane, in large reentrants eroded into the highland terranes, and on the floors of fretted valleys. All of these materials are younger than c_2 craters, some are younger and some older than c_3 craters, and almost all are older than c_4 craters. The oldest lowland materials (units Hpt, Hpk, Hp) were deposited after the formation of fretted terrane and fretted valleys was complete. From superposition relations, these materials appear to be entirely of Hesperian age, but they cannot be dated any more precisely. The youngest lowland materials (units Hl, HAad, HAhg, and HAlg) all exhibit morphological evidence indicating formation by a process similar to that which forms rock glaciers or slow debris flows on Earth. The oldest of these materials (unit Hl) is Late Hesperian (fig. 6); the others are probably mostly Amazonian in age because superposed craters are very rare or absent. Some uncertainty remains because the absence of craters could be due to destruction of older craters by ongoing flow. Material (for example, unit Ach) similar to grooved lowland material is present on the floor of the Ismeniae Fossae fretted valley, indicating relatively recent mass wasting activity there as well.

The youngest unit in the region is younger smooth plains material (unit Aps), which is present on the floors of virtually every crater, including the smallest c_4 craters. Most likely these smooth crater floor deposits are eolian in origin. Light and dark streaks throughout this general region of Mars suggest ongoing eolian activity.

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