Mars Global Surveyor observations of Martian fretted terrain

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Abstract. The Martian fretted terrain between latitudes 30° and 50°N and between 315° and 360°W has been reexamined in light of new Mars Orbiter Camera (MOC) and Mars Orbiter Laser Altimeter (MOLA) data from Mars Global Surveyor. Much of the terrain in the 30°–50° latitude belt in both hemispheres has a characteristic stippled or pitted texture at MOC (1.5 m) scale. The texture appears to result from partial removal of a formerly smooth, thin deposit as a result of sublimation and deflation. A complex history of deposition and exhumation is indicated by remnants of a former, thicker cover of layered deposits. In some hollows and on some slopes, particularly those facing the pole, are smooth textured deposits outlined by an outward facing escarpment. Throughout the study area are numerous escarpments with debris flows at their base. The escarpments typically have slopes in the 20°–30° range. At the base of the escarpment is commonly a deposit with striae oriented at right angles to the escarpment. Outside this deposit is the main debris apron with a surface that typically slopes 2°–3° and complex surface textures suggestive of compression, sublimation, and deflation. The presence of undeformed impact craters indicates that the debris flows are no longer forming. Fretted valleys contain lineated fill and are poorly graded. They likely form from fluvial valleys that were initially like those elsewhere on the planet but were subsequently widened and filled by the same mass-wasting processes that formed the debris aprons. Slope reversals indicate that downvalley flow of the lineated fill is minor. The ubiquitous presence of breaks in slope formed by mass wasting and the complex surface textures that result from mass wasting, deflation, and sublimation decreases the recognizability of the shorelines formerly proposed for this area.

1. Introduction

The term “fretted terrain” was first used by Sharp [1973, p. 4073], in reference to terrain “characterized by smooth, flat, lowland areas separated from a cratered upland by abrupt escarpments of complex planimetric configuration.” He was referring mainly to the plains-upland boundary between 30°N and 50°N and from 280°W westward to 360°W, but the term has also been applied to the plains-upland boundary near the equator between 180° and 240°W [Parker et al., 1989]. Our main concern here is with the northern fretted terrain in which broad flat-floored, steep-walled valleys reach from the northern plains deep into the upland, and the uplands transition northward into numerous mesas separated by plains. The mesas become smaller and more widely spaced to the north and ultimately merge with the knobby terrain of the northern plains. The transitional region is several hundred kilometers wide, across which surface elevations fall ~2 km [Smith et al., 1999].

The terrain is of interest for a variety of reasons. First, it lies astride the plains-upland boundary, one of the most fundamental and least understood features of the planet. Second, many of the stratigraphic contacts, terraces, and other linear features of the fretted terrain have been interpreted as shorelines of a former ocean [Parker et al., 1989, 1993], so the area can be viewed as a test bed for the ocean hypothesis. Third, the wide, flat-floored, steep-walled, fretted valleys with their lineated fill are very different from valleys elsewhere and have been attributed to a wide variety of processes [e.g., Sharp, 1973; Lucchitta, 1984; Carr, 1995]. Fourth, the terrain lies at the latitudes where debris aprons [Squyres, 1979] and terrain softening [Squyres and Carr, 1986] are most common. Finally, within the fretted area are several discontinuous channels that could plausibly be interpreted as having been caused by mass-, channelized, subsurface flow. Thus a wide variety of phenomena can be observed in a small area.

This reassessment of the characteristics of the fretted terrain is based mainly on the Mars Global Surveyor Mars Orbiter Camera (MOC) and Mars Orbiter Laser Altimeter (MOLA) data. The main emphasis is on the western part of the fretted terrain, that between 30° and 47.5°N and from 315°W westward to 0°W (Figure 1). It is the area covered by the U.S. Geological Survey (USGS) 1:2,000,000 charts MC-5 SW and MC-5 SC. At the time of writing, roughly 200 MOC narrow-angle frames were available of the area. These were mostly taken from the mapping orbit with resolution of 1.5 m/pixel. Mapping frames are identified by three symbols that indicate the mapping phase followed by five digits to indicate the sequence in that phase. Thus frame M02-00123 is frame 123 of mapping phase 2. MOC frames taken before the mapping phase are identified by various designators such as SP1, for the first science-phasing orbit [Albee et al., 1998], followed by the five-digit number indicating the sequence during that phase. The MOLA data used were those on the CD-ROMs PDS_MGSL_2001 through 2004 released by the Planetary Data System.

The main purpose of the paper is to describe what MGS has recently revealed about the area. Much of the paper is descriptive. The new data are puzzling, and much of what is in the imaging cannot be readily explained. Although a new hypothe-
Figure 1. Index map of the study area showing figure locations.
esis for the formation of fretted channels is outlined, no new unifying theory is presented that explains everything seen in the fretted terrain. The main intent here is to present some of the new data and discuss some of the relations and possible implications in the hope of stimulating new ideas.

The very high resolution and small size of the MOC frames cause problems in presentation. The format size of the MOC frames is typically so large that only a fraction of a frame can be displayed in a figure if the resolution is to be preserved. Hundreds of figures would be required to adequately display the roughly 200 MOC frames in the area. Since typically a journal can display only 10–20 figures, only a minute fraction of the information available can be displayed to support the arguments in the text. In addition, it is difficult to present an integrated picture because the frames normally cover only a small area (4 × 12 km, for example) and are widely separated. Only a minute fraction of the area of concern has actually been imaged by the MOC. A further complication is that the contrast in resolution between the MOC frames and the previously acquired Viking frames is so large that some of the MOC frames cannot be confidently located in the Viking frames used for context.

The study area is similar to that discussed by Parker et al. [1989]. Heavily cratered Noachian terrain is exposed in the southern half of the area. Although morphologically these cratered uplands resemble those elsewhere on the planet, they are at a lower elevation than typical upland, being mostly at elevations of −0.5 to −2 km as compared with the more typical 0 to +3 km [Smith et al., 1999]. In addition, the crust under the cratered terrain is thinner than that under typical cratered uplands and more like that under the northern plains [Zuber et al., 2000]. The plains upland boundary, as defined by the surface morphology, runs through roughly the middle of the area. In the southern half of the area the uplands are mostly continuous, whereas in the northern half the uplands are broken up into numerous flat-topped mesas, each surrounded by a steep cliff at the base of which is a debris flow. Between the mesas and their surrounding debris flows are plains. Many, although not all, of the rounded knobs, common on the plains, are probably upland remnants, like the mesas. In the northwest

Figure 2. (a) Cratered uplands at 30.13°N, 324.4°W. A thin deposit with a stippled upper surface appears to be draped over the preexisting terrain. Illumination is from the left (SP2-51906). (b) Similar deposit on plains at 48.3°N, 343.9°W. Illumination is from the right (SP2-49907).
corner of the area, typical thumbprint terrain [Guest et al., 1977] occurs between the upland remnants. Clearly identifiable upland remnants disappear northward at ~50°N, beyond which are mostly mottled and knobby plains.

The plains-upland boundary runs through the middle of the area, but the concern here is not with the origin of the boundary but how the boundary has affected the geomorphological evolution of the area. The depression filled by the northern plains has been attributed to one or more large impacts [Wilhelms and Squyres, 1984; McGill, 1989]. However, Zuber et al. [2000] point to several inconsistencies between the impact hypothesis and the new Mars Global Surveyor (MGS)-derived gravity and topography. While acknowledging the likely impact origin for features such as the Isidis and Utopia basins, they prefer an internal origin for the global upland-plains dichotomy.

Crater counts indicate that the uplands are Noachian in age [McGill, 2000]. They are, however, atypical of most other Noachian terrains in that they are almost undissected by valley networks. It is possibly the most sparsely dissected area of Noachian age on the planet [Carr, 1995]. There are, however, two prominent systems of fretted channels in the area. Mamers Vallis starts near the rim of the crater Cerulli at 32.5°N, 339°W and winds northwards between 340° and 345°W, cutting across several craters. Near Cerulli it is 2 km across and 400 m deep, but it widens and deepens downstream such that it is 30 km wide and 2 km deep at 39°N. The other system of channels is informally referred to as the Ismeniae channels after the Ismeniae Fossae. It is a complex network centered on 37°N, 327°W and consists of numerous connected and disconnected segments. In addition, an unnamed outflow channel starts close to 35°N, 350°W and extends northward to the crater Semeykin at 41°N, 351°W.

2. Regional-Scale Surficial Deposits

Although a comprehensive global survey of all the available MOC images has not yet been made, a preliminary survey of several hundred narrow-angle images from all over the planet indicates that much of the surface in the 30°–45° latitude belts of both hemispheres has a characteristic stippled or granular appearance. This is true of these latitude bands irrespective of the underlying geology, whether it be uplands (Figure 2a), plains (Figure 2b), high on the flanks of a volcano such as Alba

Figure 3. Deposits similar to those in Figure 2, except at southern midlatitudes. (a) SW of Gorgonum Chaos at 40.1°S, 171.8°W (M00-03091). (b) West of Hellas at 41.5°S, 257.3°W (FHA-00443). Illumination is from the top left in both images.
Patera [Carr and Malin, 2000, Figure 11], or whether it be the northern (Figure 2) or southern (Figure 3) latitudes. Most commonly, the surface appears to be composed of closely spaced pits and low hills tens of meters across. When seen in section as in craters (Figures 2a and 3a) or in channel walls, the pitted material is revealed as a thin deposit draped over the underlying topography. Commonly, it can be seen that the pitted surface has formed at the expense of a former smooth surface (Figure 4a). More complete removal of the draped deposit leaves closely spaced hills and ridges as in Figure 4b, or a scabby texture. These remnants of the former cover were likely those most resistant to removal. The linear ridges (Figure 4b), for example, may indicate where the cementation along joints caused resistance to removal. The scabby texture is reminiscent of that seen at a much coarser scale north of Isidis [Greeley and Guest, 1987] and around the periphery of the Medusae Fossae Formation in Memnonia, both of which are areas where a former thick cover has been largely removed.

In some places, there are remnants of layered deposits that are much thicker than the almost ubiquitous stippled deposit just discussed (Figure 5). These layered remnants are few in number in this area, although they are not uncommon throughout the uplands. More extensive deposits resembling these remnants were mapped as etched deposits by Scott and Tanaka [1986] and Greeley and Guest [1987]. They indicate that the uplands in general have had a complex history of burial and exhumation.

Squyres and Carr [1986] noted a general muting of the terrain between the 30° and 45° latitudes in both the northern and southern hemispheres. The muting or softening was visible only in the Viking images with resolutions better than 50 m/pixel. They attributed the softening to flow of the surface materials due to the presence of ground ice. This interpretation was subsequently challenged by Zimbelman et al. [1989], who pointed out both theoretical and observational problems with creep of ice-rich ground being the cause of the softening. They suggested eolian blanketing as a more likely explanation of the muting and associated concentric structures in craters. The new MOC observations appear to support the Zimbelman et al. interpretation, for the muting of at least the smaller features (<1 km across). Loss of definition of craters in this size range is clearly due to partial covering of the craters by the surficial deposit.

The pitted deposit is draped over the topography and clearly was deposited from the atmosphere. It is likely another manifestation of the wind-blown materials that are almost universally present at the Martian surface. The relations in Figure 4a suggest that at least part of the deposit originally had a smooth texture and that the pitting is a secondary process. However, the process of partial removal of the deposit to form the pitted and scaly surface texture is unlikely to be the result of wind alone. The texture in most areas shows no directional anisotropy as would be expected if wind were controlling the removal. One possibility is that volatiles played a role in cementing and stabilizing the surface of the original deposit and that a change in the thermal regime resulted in loss of the volatiles, thereby leaving the surface materials vulnerable to removal by the wind. Although in general the stippled surface shows no preferred elongation of the texture-forming elements, in some locations such as within valleys and adjacent to steep slopes,
strongly lineated textures have formed, probably as a result of mass wasting, as will be described in section 3.

The cratered terrain in this area appears to have accumulated in layers. In many places (e.g., Figure 6), fine layering can be seen in cliff faces, and the upper, partly stripped layer just discussed appears to be simply the uppermost of many layers that continue to depths of over a kilometer. Deposition of layered deposits appears to have started deep within the Noachian, as has already been noted from layering in the walls of the canyons [McEwen et al., 1999]. It is not possible to determine what caused the layering or whether the uppermost surface layer formed as a consequence of the same processes that operated earlier within the Noachian. Possible causes include episodic deposition by volcanism, water, wind, or large impacts.

In some areas, particularly in the Cydonia region around 40°N, 10°W, many of the upland outliers have smooth or faintly lineated deposits draped on slopes, particularly on those that face north (Figures 7 and 8). Similar deposits are also seen in some local hollows or craters, as in the top half of Figure 8a. The most distinctive feature of the deposits is that the upslope edge of the deposits is generally marked by a sharp upslope-facing escarpment. The deposits either merge downslope with the surrounding plains or are overlapped by the surrounding

Figure 5. Scattered remnants of layered deposits (black arrows) superimposed on the preexisting terrain suggest that extensive areas of the present surface have been exhumed from beneath the layered deposits. (a) In the bottom left corner, striae on floor deposits within a shallow valley extend away from the valley walls and curl downstream as though material had flowed away from the walls and down the valley (M07-04897 at 33.8°N, 347.6°W). (b) M022-01519 at 39.3°N, 343.0°W.
Figure 6. Layering in the walls of a channel incised into the highlands at 35.7°N, 347.2°W. Note also that the layers on the lower parts of the valley wall are covered with a deposit with a faintly striated or smooth surface. The deposit is similar to those in Figures 7 and 8 (M04-03989, 35.7°N, 347.2°W).
plains materials. In this area the deposits show a strong preference for north facing slopes. Similar deposits are found on south facing slopes at similar latitudes in the southern hemisphere (e.g., M04-01255). Although there is no obvious connection, the seeming preference of these deposits for poleward facing slopes is similar to the preference for the groundwater seepages described by Malin and Edgett [2000b]. The preferential location of the deposits on slopes facing away from the Sun strongly indicates that the formation and/or stability of the deposits is affected by illumination. At these latitudes (30°–50°), ice is expected to be stable typically at depths greater than about a meter [Farmer and Doms, 1979]. However, ice could be stable nearer the surface under certain circumstances [Paige, 1992], particularly where illumination is reduced by the steeply sloping ground. These smooth deposits on poleward facing slopes may be mostly ice or eolian deposits cemented by ice that has accumulated on unusually cold surfaces by freezing from the atmosphere.

3. Debris Flows Adjacent to Escarpments
The local boundary between the uplands and the plains commonly has three distinct, clearly defined components (Figure 9): (1) a steep upper slope on which the layers of upland bedrock may be visible, (2) an intermediate unit with a more shallow slope and a surface that may appear smooth or have faint striae that extend downslope, and (3) the main debris apron [Squyres, 1979] with a highly textured surface that may

Figure 7. Smooth deposits in hollows or pasted onto slopes around mesas and hills in the Cydonia region. The deposits appear to be preferentially located on cold, north facing slopes: (a) M04-1292 at 41.2°N, 2.0°W and (b) M08-00546 at 41.4°N, 347.9°W.
Figure 8. Same as Figure 7, but for (a) M03-04566 at 40.1°N, 9.74°W and (b) M044-00576 at 42.0°N, 10.8°W.
extend up to 20 km away from the escarpment. Within the fretted valleys, debris aprons from opposing walls merge to form lineated valley fill [Lucchitta, 1984]. In many places the intermediate unit is absent, and the debris aprons abut against the steep valley walls. Slopes on the escarpments are typically in the 20°–30° range; the surfaces of the debris aprons mostly slope 1°–3° out to a flow front with slopes up to 6° (Figure 10).

Closely spaced subparallel ridges form the linear texture of the intermediate unit (Figure 9). The ridges are normally oriented at right angles to the slope, but in some places, especially in narrow, linear depressions and alcoves, the ridges curl downslope (Figure 5a) [Lucchitta, 1984, Figure 3]. The intermediate unit transects the textures of the debris apron, and commonly faint traces of the surface texture of the debris apron can be traced into the intermediate unit, as though the latter had partly buried the former. The relationships indicate that the intermediate unit is younger than, and in places overlies, the debris apron and the lineated valley fill.

The surface of the debris apron itself generally appears smooth in all but the highest-resolution Viking scale images but is highly textured at MOC scales. The textures differ significantly according to whether the outer boundary of the unit is unconfined, and the unit has been able to spread over the adjacent plains to form a debris apron, or whether the material has been confined within a channel. The more confined, the more markedly linear is the surface texture. Figures 9 and 11 and Figure 2 of Malin and Edgett [2000a] give an indication of the variations in surface textures encountered on debris flows that are poorly confined. The surface typically has a pitted or granular texture, and local hollows have formed, presumably by a combination of deflation and sublimation. Impact craters are common and are not sheared by movement of the debris flow, which suggests that the debris flows are not forming today. The pattern of etching to form deep irregular hollows (Figures 11b and 11c) suggests a process in which there is a resistant layer at the surface and less resistant material below, and once the resistant layer is penetrated, more rapid erosion ensues. One possibility is that surface materials are made more resistant to erosion than the underlying materials by an ice cement.

The lineated fill within valleys (Figure 12) has been discussed extensively in the past [Squyres, 1978; 1979; Lucchitta, 1984; Kochel and Peake, 1984; Carr, 1995; Hamlin et al., 2000]. Most authors envisage viscous flow of ice-laden debris away from the valley walls. Issues have been the extent to which the debris then continues to flow down the valley and whether the

**Figure 9.** Three examples of the contact between the uplands and the plains. Commonly, there are three components: a steep bedrock face, an intermediate unit with a surface that is either smooth or striated at right angles to the bedrock escarpment, and the main debris flow with a highly textured surface: (a) M08-01091 at 32.8°N, 342.2°W, (b) M03-00119 at 36.6°N, 335.0°W, and (c) M00-02013 at 38.5°N, 339.4°W.
lineations form at right angles to the flow or parallel to the flow. As noted above (Figure 9), the lineations in the intermediate unit, adjacent to the bedrock escarpment, are oriented at right angles to the escarpment and in places curl downstream (Figure 5). The lineations appear to be parallel to the flow of debris away from the escarpment and down the valley. However, the lineations on the bulk of the valley fill appear to be oriented at right angles to the flow. They appear to form as flow away from the valley walls meets resistance from preexisting fill or from flow from the opposing wall. The fill commonly has fine-scale crenulations, inconsistent with down valley flow, and the lineations are present even in completely enclosed depressions where downstream flow is impossible. Moreover, as shown below, many of the fretted valleys are poorly graded, with many reversals in slope. Unless the slope reversals were caused by later tectonic deformation, which is improbable [Phillips et al., 2001], the sections with slope reversals would have been barriers to downvalley flow, thereby restricting downstream flow to no more than a few tens of kilometers and probably to considerably less. Thus, while some downvalley flow clearly occurs, as is indicated from Figure 5a and other examples given by Lucchitta [1984], slope reversals demonstrate quite conclusively that most of the fill within the valleys is derived not from material that has flowed down the valley from further upstream but from materials that have flowed across the valley from the nearby walls.

The debris aprons require that material shed from escarpments flow for up to 20 km. Squyres [1979] and Lucchitta [1984] both suggested that the presence of ice in the debris enabled the flow and that the lack of similar aprons at low latitudes was

Figure 10. Two Mars Orbiter Laser Altimeter (MOLA) profiles across a debris flow centered at 42°N, 341°W. Vertical exaggeration is 10.7 times.
due to the instability and absence of ice at low latitudes. As noted above, the surface textures seen in the some of the MOC images of some of debris aprons suggest sublimation and the presence of ice. Squyres [1979] suggested that the ice was incorporated in the debris flows after it was shed from the escarpments as a result of deposition of winter frosts, whereas Lucchitta [1984] suggested that the terrain itself has abundant ground ice that became incorporated into the debris aprons when shed from escarpments.

Not all valleys in the area have lineated fill. Some small valleys have smooth fill that commonly laps up onto the valley walls, the outer boundary of the fill being marked by an outward facing escarpment. The fill resembles the smooth deposits described in the last paragraph of section 2. In some rare cases (Figure 13), crevasses have formed close to the junction between the floor material and the valley wall, similar to the way crevasses develop in glaciers.

4. Fretted Channels

The general characteristics of fretted channels have been discussed in detail elsewhere [Sharp, 1973; Squyres, 1978; Lucchitta, 1984; Carr, 1995; Carruthers and McGill, 1998; McGill, 2000] and are summarized here only briefly. Like valley networks at lower latitudes, the fretted valleys typically follow a meandering path and have few tributaries. They differ from...
Figure 12. Lineated valley fill. (a) SP2-43104 at 33.9°N, 296.5°W. Scabby remnants of the stippled unit described under section 2 are clearly visible on the uplands adjacent to the valley. Layers pasted on the walls of the valley may also be remnants of the same unit. Illumination is from the right. (b) SP2-41204 at 35.6°N, 303.0°W. The characteristic subparallel ridges and swales on the surface of the valley fill are thought to be the result mainly of flow of material away from the valley walls toward the center of the valley. Illumination is from the left.
most valley networks in that they widen considerably down-
stream such that they may be tens of kilometers wide where
they meet the northern plains. Mass-wasted debris typically
forms the flat valley floors, as described in section 3. In con-
trast, most valleys at lower latitudes maintain a 1–2 km width
for most of their length, and eolian deposits commonly form a
flat floor [Carr and Malin, 2000]. Several fretted valley are
closed depressions with no outlet or with an outlet at a higher
elevation than the floor of the depression (Figure 14). Other
sections appear to have formed by collapse into a void [Luc-
chitta, 1984]. Some of the closed depressions contain the typ-
ical lineated valley fill described in section 3, emphasizing that
the linear fill is not the result of downvalley flow. Transection
relations indicate that the valley fill and the present valley walls
may be younger than the time of initiation of the valleys them-
selves. In other words, the valleys continued to widen and fill
over a long period of time, during which other local events
occurred. This is clearly demonstrated in Figure 6 of McGill
[2000], in which ejecta from a crater completely fills a section
of a fretted valley, yet where the valley is not filled, there is no
trace of draping of the ejecta over the valley walls and floor.
Instead, the valley walls transect the ejecta, and lineated fill is
present on the valley floor. Although the valley was at one time
buried by ejecta from the crater, the partly buried sections
must have continued to widen and fill. Mass wasting continued
after crater formation, thereby causing the valley walls to erode
into the ejecta and producing fill that buried the ejecta within
the valley.

Figure 13. Fretted valley tributaries with smooth fill, which appears to lap up onto the valley walls. In Figure
13a, crevasse-like features can be seen in places within the fill adjacent to the valley wall, and layered deposits
similar to those in Figure 5 are present at the heads of the valleys. (a) M02-02164 at 39.4°N, 334.3°W and (b)
SP2-042705 at 39.8°N, 334.8°W, with illumination from the right.
Figure 14. Part of the fretted terrain centered at 32°N, 332°W, showing interconnected closed depressions (white arrows) and areas where fractures indicate that the surface has collapsed (black arrows) to form a linear depression (Viking Mars digital image maps (MDIM)).
Some of the characteristics of fretted valleys are exemplified by Mamers Vallis. The crater Cerulli is superimposed on the upper reaches of the valley (Figure 15). In the unburied sections adjacent to Cerulli, ejecta is found on the plains into which the valley is cut, but not in the valley, unless the peculiar deposits seen there are remnants of the ejecta (Figure 16). West of Cerulli at 31°N 341°W the valley crosses two craters as though superimposed from above. One possibility is that the area, including the two transected craters, was formerly covered by layered deposits of which only a few remnants remain.

Figure 15. Viking MDIM showing Upper Mamers Vallis. At A the valley is superimposed across two impact craters. At B an impact crater is superimposed on the valley, but ejecta is absent on the fill adjacent to the crater (see Figure 16). The white line around the crater indicates the extent of the ejecta (see Viking frame 204S12). At C the valley crosses an old rimless impact crater, but the crater is much deeper than the valley upstream and downstream (see Figure 17), and the valley cannot be traced across the crater floor.
Figure 16. Mamers Vallis just northwest of the crater marked C in Figure 15. Ejecta from the crater is clearly visible on the terrain adjacent to the valley but is not obvious in the main valley or its tributary to the north. The lineated fill in the center of the valley is more cratered than the rest of the fill and could be remnants of the fill that was in the valley when the crater to the east formed. This is SP2-46306 at 32.4°N, 341.8°W (illumination from the right). For a higher-resolution view of the same area, see M07-01448.
(Figure 5). The original Mamers Vallis formed on these deposits and later became superimposed over the craters when the layered deposits were removed. At B in Figure 15 a crater is superimposed on the valley. Ejecta from the crater is present on the plains adjacent to the valley, but little evidence of ejecta is present in the valley or its tributaries (Figure 16). Valley widening and formation of valley fill seemingly continued after superposition of the crater, despite complete blockage of the valley by the crater. About 150 km downstream, at 34°N, 343°W, the valley crosses and appears to be superimposed on another crater, this one 50 km in diameter, although the valley cannot be traced across the crater.

An elevation profile of the valley from its source near Cerulli downstream to where it merges with the plains at 40°N, 339°W was determined from MOLA data (Figure 17) by finding the lowest point in the MOLA tracks that crossed the valley. The profile shows numerous reversals in slope, indicating that any downstream flow of the valley fill is minor compared with cross valley flow. The particularly deep point 300 km from the source is the within the 50 km crater crossed by the valley. The depth of the crater and the absence of the valley within the crater suggest that deepening of the crater continued after formation of the valley, such as by sublimation or deflation.

These characteristics together with the discussion in section 3 and analogy with valleys at lower latitude indicate a possible sequence of events in forming the fretted valleys. Because of the scarcity of surface runoff at the time of their formation, most Martian valleys appear to have initially had a triangular cross section, with the width of the valley being controlled by the depth of incision and the angle of repose of material on the valley walls [Carr and Malin, 2000]. Flat floors developed later as wind-blown materials accumulated in the valleys. A similar process may have operated in the fretted terrain. During the main valley-cutting era (Noachian-Lower Hesperian), valleys such as Mamers Vallis formed in the fretted region. They initially resembled valleys elsewhere in having a roughly triangular cross section, but the lower reaches were deeply incised because of the steep regional slope along the plains-upland boundary. Once water erosion ceased, the valleys started to fill with material mass wasted from the walls. Mass wasting was more efficient in the fretted latitudes as compared with lower latitudes because of the presence of ground ice. Movement of material was mostly away from the walls to create linear valley fill; downstream flow was minor. This process could have continued at a very slow rate, giving the fill a young age despite the old age of the original valley, as is demonstrated by absence within some valleys of ejecta from superimposed craters. However, the process did not continue to the present day, since almost all the valley fill is cratered and the craters show little evidence of shear or compression. The process requires that a slope be maintained from the walls to the center of the valley so that flow away from the walls could continue. Widening and filling of the valleys may have stopped earlier in upstream sections because the original valley would have been narrower and shallower and filled with mass-wasted debris more quickly than the downstream sections.

By this hypothesis the age relations in Figure 16 and Figure 6 of McGill [2000] are simply explained. The crater ejecta partly filled the original water-cut valley. Subsequently, retreat of the walls of those parts of the valley not completely filled by ejecta cut into the crater ejecta and supplied the fill for the valley floor, thereby erasing evidence of the former presence of ejecta. The scenario also explains the presence of lineated fill in closed depressions since downstream flow of the valley fill is not required. The disconnected fretted valley segments are explained by a combination of surface and subsurface flow in the original valley, possibly enabled by the presence of abundant ground ice. Similar evidence for subsurface flow, seen in several places elsewhere, has been compared with terrestrial karst [Carr, 1996; Malin and Carr, 1999; Carr and Malin, 2000].

While the mechanisms just described may explain some of the fretted valley characteristics, they do not explain them all. Some other processes must have been responsible for formation of the northern plains and for filling between the mesas in the northern part of the fretted terrain, where the spacing between the mesas exceeds the distance over which debris aprons can spread. Whatever process resulted in the filling of the northern plains may also have contributed to the filling of

**Figure 17.** MOLA elevations of the deepest part of Mamers Vallis as a function of distance from its start near the crater Cerulli. The deepest point is within the crater marked C in Figure 15. The numerous reversals in slope indicate that the texture on the present fill is not the result primarily of movement downstream.
the lower reaches of the fretted channels. In addition, some positive relief features within the fretted valleys themselves (Figure 16) are not adequately explained.

5. Possible Shorelines

The northern plains extend into the northern part of the study area. Several types of plains are present [Parker et al., 1989]: (1) polygonally fractured ground with polygons ranging from tens to hundreds of meters across, (2) thumbprint terrain [Guest et al., 1977], on which parallel, arcuate strings of bright, cratered cones against a dark background form the characteristic thumbprint texture, (3) mottled plains, in which bright craters and their ejecta, together with clusters of secondaries, create the characteristic mottled texture, and (4) smooth plains, almost featureless except for superimposed craters. Parker et al. [1989, 1993] discuss the relations among these units and between the units and the uplands and suggest that some of the contacts may be shorelines of a former ocean that filled the northern basin. They identified two major contacts: an outer contact 1 and an inner contact 2. In this region the two contacts almost merge. Head et al. [1999] showed that the inner contact 2 is at an almost constant elevation, and could plausibly be interpreted as a shoreline. The outer contact 1, however, has a wide range of elevation and is less likely to be a shoreline, although in their preliminary assessment Head et al. did not trace in detail elevations along the intricate boundary between upland and plains in this area.

The new high-resolution imaging of the area sheds little light

Figure 18. Two pieces of MOC image M02-02055 showing close-ups of the boundary between a high-standing, bright plateau and low-lying, dark “thumbprint terrain” at 45.3°N, 353.0°W: (a) southern boundary of the thumbprint terrain and (b) the northern boundary. This boundary was suggested as a possible shoreline by Parker et al. [1989]. The location and elevation profile across the boundary are given in Figure 19. The dark streaks are thought to be paths of dust devils.
Figure 19. Elevation profile across the boundary seen in Figure 18. The thick white line shows the approximate location of the MOC image. The entire line shows the path of the elevation profile.
on the shoreline controversy. There are sharp curvilinear contacts between the various plains and upland units (Figures 18, 19, and 20), and most of the steep slopes in the area have benches or terraces (Figure 9), as discussed by Parker et al. [1989]. There is, however, little basis for confirming or excluding a marine origin for any of these features. The surficial geology of the area is complex and has resulted in numerous textural and albedo boundaries. There is evidence of burial and exhumation of the terrain. Mass wasting, not marine erosion, is clearly the cause of terrace-like features on many slopes (Figure 9). Other sharp breaks in slope (Figures 7 and 8) delineate slope deposits unique to these latitudes. Moreover, the breaks

Figure 20. Another “shoreline” proposed by Parker et al. [1989]. The shoreline is the ridge and escarpment seen in the bottom left half of Figure 20a. It continues down the center of the top half of Figure 20b (SP2-44403 at 46.8°N, 346.2°W; illumination from the right). While the feature mapped by Parker et al. [1989] is clearly visible, there is little in the images to support or deny the shoreline interpretation.
in slope are at a wide range of elevations that appear to depend more on local spacing between mesas and massifs than on any regional cause, such as a shoreline. Even if shorelines were at one time present in the area, identifying them and distinguishing them from the effects of all these surficial processes will be extremely difficult. Thus, while many of the features presented by Parker et al. [1989] as possible evidence for shorelines are from this area, closer examination by MOC has failed to deny or confirm a marine origin for the features. Moreover, such confirmation may not be possible because of the complex interplay of so many other processes. Similar results were reported by Malin and Edgett [1999] for other areas.

6. Summary and Conclusions
A small portion of the fretted terrain, that from 30° to 50°N and 280° to 360°W, has been reexamined in light of the new MOC and MOLA data. The area is almost completely covered by water ice. The area is almost completely covered by water ice.

The presence of shorelines formerly proposed for this area cannot be confirmed or denied. The complex surficial geology and the presence of numerous terraces formed by mass wasting would tend to mask any shorelines if they were present. Their detection will probably require careful tracing and correlation of breaks in slope across the region. They are unlikely to be detected from imaging alone.

References

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