Drainage basin evolution in Noachian Terra Cimmeria, Mars

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Received 6 November 2001; revised 5 February 2002; accepted 11 February 2002; published 31 July 2002.

Geomorphic mapping of a ~1 million square kilometer section of Terra Cimmeria on Mars (1:1M scale) indicates that prolonged, intense fluvial erosion occurred during the period of heavy bombardment. Crater counts date the termination of ubiquitous, intense erosion to the late Noachian, although some valleys may have continued downcutting into the early Hesperian. Stratigraphic and topographic relationships indicate that early erosional processes created large, integrated drainage basins, affected primarily by large impact basin structures and regional slopes. This terrain is not consistent with an origin purely by volcanic or impact processes. Cratering competed with drainage basin development, minimizing valley length, catchment area, and valley network integration. Drainage basin disruption resulted from impacts on valley thalwegs, or when the ejecta of large (usually >75 km) craters created low divides. Near-level upland intercrater plains are lightly dissected, in part because smaller craters could interrupt flow paths on gently sloping or flat terrain. Some closed drainage basins became integrated by continued erosion of drainage divides and stream capture, overflow of the divides, or headward growth of valleys fed by groundwater collected in closed basins. Drainage divide breaching was most effective on steeper (>0.5°) regional slopes, where observed drainage density is also highest. This is due to greater runoff volumes and velocity encouraging valley incision, as well as steep slopes allowing valleys to bypass or breach superimposed craters. Valley systems commonly extend nearly to the crests of sharp drainage divides, and spatially ubiquitous valley source points throughout the higher elevations suggest that runoff derived largely from precipitation.


1. Introduction

1.1. Overview

[2] Abundant small valley networks and degraded impact craters in the Noachian southern highlands of Mars record a time when the climate supported liquid water on the surface. Previous work indicates that rapid erosion and small valley development on Mars declined with reduced meteorite bombardment during the late Noachian/early Hesperian periods [e.g., Hartmann, 1973; Carr and Clow, 1981; Baker and Partridge, 1986; Barlow, 1990; Grant and Schultz, 1993; Craddock and Maxwell, 1993; Grant, 2000]. The intercrater plains deposits and the highly eroded profiles of large impact basins indicate that erosion (including fluvial, impact, eolian, volcanic, and possibly glacial processes, summarized by Tanaka et al. [1992]) was capable of reducing even large topographic features that formed earlier in the Noachian [Schultz et al., 1982]. The subsaturation population of degraded craters <30 km in diameter suggests that degradational processes were capable of removing features of that scale during the late Noachian [Strom et al., 1992]. The origin of surface water for fluvial degradational processes has been the subject of debate, with rainfall, hydrothermal circulation, and glacial melt as proposed mechanisms [e.g., Craddock and Maxwell, 1993; Carr, 1996; Gulick, 2001; Head and Pratt, 2001]. Furthermore, it is likely that the climate and water supply were spatially and temporally variable. Detailed mapping of fluvial features and drainage basin characteristics can help to resolve these uncertainties.

[3] Imaging and topographic data from the Mars Global Surveyor mission are used, in part, to support interpretation of the planetary environment during the Noachian [e.g., Carr and Malin, 2000]. As the polar regions of Mars and the northern lowland plains have been more recently degraded or resurfaced, geomorphic studies of ancient Martian climate concentrate on evidence preserved in the Noachian equatorial highland regions. This paper discusses the geologic history of part of the Terra Cimmeria, including the dynamic interaction of cratering and degradational processes during the Noachian. This interaction is evaluated...
in light of the topographic controls on fluvial dissection observed in the highlands. The first goal of this project is a thorough description of the source and flow regimes necessary to produce observed 100–1000 km scale topography and valley courses. Second, this study addresses whether the extant valley networks could be responsible for the observed erosion of large features throughout the Noachian. Third, we discuss the evolution of Martian drainage basins in the presence of a heavy impact flux, to describe the cause for the discontinuous pattern of the Martian valley net-

Figure 1. (a) Geomorphic map of the study area overlaid on Mars Digital Image Mosaic, Version 2. Drainage basins are labeled in Figure 4a. The area is 593 km across at the equator. (b) Contoured topographic map of the study area (100 m interval), based on the 32 pixel/degree (1.85 km/pixel) topographic grid derived from MOLA data. The area is 593 km across at the equator.
works. The map of this area (Figure 1a) is not a traditional geologic map, but a geomorphic map that emphasizes impact craters and the fluvial features of the region, including channel networks, drainage basin divides, and presumed depositional basins.

1.2. Previous Mapping in the Study Area

The study area is located in the Mare Tyrrenenum quadrangle (MC-22 NE and SE) in the Terra Cimmeria of Mars [U.S. Geological Survey (USGS), 1982a, 1982b]. The area is ~1,006,000 km², bounded on the east by 135°E (225°W), on the south by 30°S, on the west by 125°E (235°W), and on the north by the equator, using the 1999 RAND global control net [Kirk et al., 1999]. This area has not previously been mapped at a scale equal to or finer than the present 1:1,000,000 compilation. The 1:15,000,000 geologic map of the equatorial Eastern Hemisphere of Mars [Greeley and Guest, 1987] is the most recent geologic map covering the entirety of this project’s study area. They divided the area into four types of plains units: Hesperian ridged plains (Hr) and Noachian subdued cratered unit (Npl3), which are interpreted as volcanic, and the Noachian cratered unit (Npl1) and Noachian dissected unit (Npld), which are primarily erosional surfaces. Generally, the dissected unit is located in a more northerly position near the highland dichotomy in this area, while the inferred volcanic plains were largely confined to basins. Recent deposits include three subdivisions of crater materials where the crater was larger than ~100 km in diameter. These physiographic units broadly characterize the surface but do not necessarily indicate differences in lithology. For example, the dissected unit and cratered unit are of the same Noachian age, but the dissected unit contains more obvious valley networks. On inspection, small valleys are generally deeper and better preserved in the dissected unit, although drainage densities in the cratered unit can be locally higher than in the dissected unit.

Edgett [1991] mapped and interpreted the region immediately surrounding Herschel basin. The purpose of his writing was to characterize the heavily eroded ejecta and interior deposits of this basin, but not to describe other features of the landscape in detail. He dated the Herschel basin impact to the late Noachian and made general comments on stratigraphy in the immediate vicinity of the crater. Specifics of Edgett’s interpretations are discussed in section 4. This study area was mapped and described in detail by Irwin [2000], on which this paper is based.

The study area is located on the highland plateau approximately one crater diameter from the Hellas basin, and the elevated topography results in part from Hellas impact ejecta [Smith et al., 1999]. Recent Thermal Emission Spectrometer data suggest an exposed surface composition resembling terrestrial basaltic sand with <15% weathered materials [Christensen et al., 2000].

2. Methodology

Nearly global coverage of Mars was obtained at resolutions of 130–300 m/pixel by the two Viking Orbiter spacecraft between 1976 and 1980 [USGS, 1982a, 1982b]. Surface mapping relies predominantly on this image base. The 231 m/pixel base images covering the map area were taken from the Mars Mosaicked Digital Image Model (MDIM) version 2.0. The map boundary is only as accurate as the georeferencing of the MDIM, which has a published standard error of ~1 km for the control base [Eliason et al., 2001]. A simple cylindrical projection was applied to the MDIM, which is most appropriate for display of equatorial regions. Additionally, a series of 115 m/pixel images was taken of the southern part of the map area during the extended mission of the Viking Orbiter 1 spacecraft. The Mars Global Surveyor spacecraft is presently providing a set of individual high-resolution images (generally 1–10 m/pixel) from its Mars Orbiter Narrow-Angle Camera (MOC) [Malin et al., 1991], and images released through August 2001 were consulted during the mapping. The Mars Global Surveyor spacecraft has also returned topographic data using its Mars Orbiter Laser Altimeter (MOLA). The MOLA instrument returned elevation data with an absolute vertical accuracy of 10 m and along-track shot spacing of 330 m [Zuber et al., 1992]. MOLA data were used to determine slope gradients, drainage divides, and the locations of level areas. A 1/32° contoured MOLA grid (Figure 1b) facilitated mapping.

Quantitative data derived from the geographic information system (GIS), such as feature area and line length, are corrected for poleward convergence of the meridians by ESRI ArcView 3.2 software. Mapped features and units (detailed in the discussion below and shown in Figure 1a) were selected to reflect the important resurfacing processes, for example, cratering, fluvial erosion, eolian transport, or basin deposition. The appearance of these units in the images is indicated in Figure 2. The terrain units, which differ from those used in formal geologic mapping, are

![Figure 2](image-url)
described below, followed by mapped linear or structural features.

2.1. Terrain Units

2.1.1. Dissected plains

[9] The default “unit” in the study area is the dissected plains, which exhibit variable drainage densities. This map does not differentiate between the “dissected” and “cratered” units of Greeley and Guest [1987] as these units were defined by the subjective discriminator “more highly dissected by small channels and troughs.” The dissected plains include most of the upland terrain and are differentiated here from two types of smoother plains units that occupy basins.

2.1.2. Basin interior hills

[10] Basin interior hills are positive relief features such as central peaks, interior basin rings, or ejecta blankets surrounding by a basin plains unit.

2.1.3. Undissected basin plains

[11] Undissected basin plains are areas that appear to be smooth at 213 m/pixel resolution and are located at the downstream end of a fluvial drainage system. The drainage basin may be a degraded crater interior (the most common setting), a broader valley network debouching into a crater, or closed basins created by natural dams related to impacts. The plains themselves are distinct interior geologic units, and their borders were mapped independently from the crater rims that surround them in many cases. Crater walls are erosional surfaces not distinguished from surrounding dissected terrain, while the smooth plains are depositional surfaces, filled perhaps by fluvial or eolian debris or volcanics. Slopes on basin plains units in this area can reach 0.75° but are commonly <0.5°. These “smooth” basin units may be highly textured by pits, eolian dunes, etc., at the meter scale based on examination of MOC high-resolution images. All undissected basin plains mapped in the study area are at the termination of one or more valley networks, except for the interiors of some small, degraded impact craters, where the interior wall is too short to have visible, deeply incised gullies. For dissected craters the “rim” has evolved to become a drainage divide rather than a primary impact feature. The mapped crater rims, defined as the break in slope at the top of the inner crater wall, may not be congruent with the original rim location, due to preferential erosion of the crater wall and enlargement of the crater diameter by as much as 10% [Grant and Schultz, 1993; Craddock et al., 1997].

2.1.4. Intravalley basin deposits

[12] Where a valley enters and exits a breached crater or other largely enclosed basin, the floor is mapped as an intravalley basin deposit. These are smooth or dissected units, often located in degraded craters with obvious breaching of the rim by through-cutting valleys. The flat-floored cross-sectional profiles of these craters are consistent with crater infilling by sediment from the external source. When mapping these deposits, the crater rim is not necessarily a drainage divide, as the interior is incorporated into the external drainage system.

[13] In this paper the term “breached” is used for craters that receive drainage from outside the crater rim, but the crater is the terminal basin for the watershed. Craters having both an entering and exiting valley are termed as “cross-cut,” with an entrance and exit breach.

2.1.5. Continuous ejecta blankets

[14] Continuous ejecta blankets of fresh craters with diameters >10 km were mapped where evident. These units frequently overlie older features without completely obscuring them. Therefore the ejecta blankets on the geomorphic map frequently overlie mapped valleys or basin deposits. In dissected areas, ejecta deposits from fresh craters are frequently obscured by the texture of the surroundings, partly because surface flow of fluidized ejecta was interrupted by the roughness. Distinction was not made between ballistic or rampart ejecta blankets.

2.2. Linear or Structural Features

2.2.1. Drainage divides

[15] Drainage divides separate valley networks that do not eventually converge (either in the study area or outside) and were defined on the basis of image interpretation and MOLA-derived topographic maps. Several small valley networks drain across the highland dichotomy escarpment, and these are not subdivided except for the large watershed associated with Licus Vallis. Drainage divides are commonly associated with high ridges, impact crater rims, or the probable ejecta blankets of degraded craters. Appropriate to the map scale, degraded crater rims are mapped as drainage divides if they meet one of the following criteria:

1. The drainage basin is located entirely within a degraded impact crater >40 km in diameter.

2. Drainage was contributed from outside the original crater rim through a rim breach and the crater serves as a terminal basin for a watershed. The divide continues beyond the breach to encompass the whole contributing watershed.

2.2.2. Valleys

[16] Valleys can be subparallel, radial, or dendritic in plan and can have V-shaped or flat-floored morphologies. Occasionally, there is an obvious headwall to the valley, although these are generally restricted to near-level low plains. Most valleys in the study area originate near a sharp drainage divide and do not have obvious headwalls. Occasionally, flat-floored valleys will exhibit an inner valley or channel in high-resolution images. Division of valleys into separate classes was not practical for this mapping project, due to limited resolution and mantling by younger deposits. To illustrate the drainage systems, larger valleys were mapped where they can be traced over large areas and are shown in Figure 1a, and smaller valleys were mapped in selected areas to estimate drainage density.

2.2.3. Wrinkle ridges

[17] Wrinkle ridges are low ridges crosscutting other landforms, also called “lobate scarps” with analogy to Mercury [Dzurisin, 1978; Watters and Robinson, 1999]. They are usually interpreted to result from compressional stresses (see summary by Banerdt et al. [1992]). These are mapped both on basin floors and on dissected uplands, where evident, to distinguish these features from fluid-carved landforms. The texture of the upland surface typically makes them difficult to trace, so wrinkle ridges may be underrepresented there; however, the wrinkle ridges typically crosscut valleys and basin floor units. They are therefore among the youngest topographic features.
Table 1. Epoch Boundaries of the Martian Geologic Timescale Based on Crater Populations, as Defined by Tanaka [1986]

| Epoch    | N(2) | N(5) | N(16) | Absolute Age
|----------|------|------|-------|---------------
| Amazonian|      |      |       |               |
| Upper Amazonian | <40  |      |       | <1.8–3.5 Ga   |
| Middle Amazonian | 40–150 | <25  |       |               |
| Lower Amazonian | 150–400 | 25–67 |       |               |
| Hesperian |      |      |       | 3.8–3.55 or   |
|           |      |      |       | 3.5–1.8 Ga    |
| Upper Hesperian | 400–750 | 67–125 |       |               |
| Lower Hesperian | 750–1200 | 125–200 | <25  |               |
| Noachian  |      |      |       | >3.5–3.8 Ga   |
| Upper Noachian | >200–400 | 25–100 |       |               |
| Middle Noachian | >400  | 100–200 |       |               |
| Lower Noachian | >200  |      |       |               |

Table 2. Fresh Crater Counts on Herschel Crater Floor, on All Other Basin Floors, and on Dissected Upland Terrain

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Count &gt; Diameter</th>
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<tr>
<td>Herschel crater floor</td>
<td>35 &gt; 2 km</td>
<td>N(2) = 620 ± 105</td>
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<tr>
<td>All other basin floor deposits</td>
<td>110 &gt; 2 km</td>
<td>N(2) = 750 ± 71</td>
</tr>
<tr>
<td>Dissected upland terrain</td>
<td>745 &gt; 2 km</td>
<td>N(2) = 1012 ± 37</td>
</tr>
<tr>
<td>Dissected upland terrain</td>
<td>179 &gt; 5 km</td>
<td>N(5) = 243 ± 18</td>
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Table 3. Fresh Crater Counts on Herschel Crater Floor, on All Other Basin Floors, and on Dissected Upland Terrain, Where Only Craters >2 km and <3 km in Diameter Are Counted

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<th>Geologic Unit</th>
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<td>Herschel crater</td>
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2.2.4. Fresh craters

[18] Small fresh craters have bowl-shaped profiles, although some infilling may exist below the limit of map resolution. Large fresh craters have terraced or hummocky walls, visible central peaks, and rough or fluidized ejecta blankets and can be surrounded by chains of secondary craters. Only those craters >2 km (>9 pixels) in diameter were mapped. In contrast, degraded craters have flat floors, dissected or breached walls, and lowered rims, and the original texture of the ejecta is absent.

[19] Dunes in the study area are not apparent in the 231 m/pixel base images, but high-resolution MOC images show discontinuous low dunes scattered over much of the landscape. Thick eolian dune fields were found to correspond with low-albedo features in the floors of some large basins and valley floors, and these units occurred exclusively along the southern margins of the basin floors. Air fall deposits can be noted as dark areas on the base images but are not mapped.

[20] The density of fresh impact craters was determined from the digitized GIS database of rim crests, using the definition that the crater number N(x) is the count C of craters of diameter x or greater in area A, normalized to an area of 10^6 km^2 [Wise et al., 1979]. The total densities of >2 km and >5 km craters were determined. Drainage density was calculated using georeferenced images at 231 and 115 m/pixel resolution, and an ArcView shapefile of valleys overlaying that image.

3. Age and Dissection of the Study Area

3.1. Relative Ages of Highland Terrain Units

[21] For dissected areas the timing of the termination of intense erosion can be determined using fresh crater populations, relative to the Martian time-stratigraphic epochs defined by Tanaka [1986] and shown in Table 1. The study area was divided into four terrain types for crater counts. Previous mapping has established that the Herschel crater floor is the youngest unit in the map area, dating to the Hesperian [Greeley and Guest, 1987; Edgett, 1991]. The second category was the upland dissected terrain. To consider this as a single category, it was assumed that fluvial erosion ceased at the same time over the entire area, which was validated by occurrence of statistically similar crater counts in several divisions of the dissected uplands. The third terrain category included all undissected basin plains materials. If these plains are sedimentary units, then they should have similar fresh crater populations to the dissected terrain that provided the sediment [Maxwell and Craddock, 1995]. Alternatively, some process might have preferentially obscured fresh craters on basin floors (e.g., post-Noachian lava inundation or eolian infilling), resulting in lower crater populations on basin plains. Fresh craters occurring on the lowlands north of the dichotomy escarpment constituted the fourth group.

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*See discussion of absolute age by Tanaka et al. [1992].
in a post-Noachian infilling of parts of large basins by eolian material, which is consistent with the distribution of dune fields, or resurfacing of one or more of the basins by lava rather than sediment. Alternately, fluvial erosion may have continued into the early Hesperian at a reduced rate, allowing sediment transport in the valleys but not significantly eroding upland craters. Valley development has been observed in Hesperian units elsewhere, where valleys tend to be well-preserved, although the surfaces are poorly dissected (see summary by Carr [1996, pp. 72–74]).

There is a discrepancy in the age of the uplands surface when comparing N(5) and N(2) values. The N(2) value dates the surface to the early Hesperian, according to the stratigraphic scheme of Tanaka [1986]. For this reason we have compared N(5) crater numbers only to N(5), and similarly with other crater numbers. Tanaka’s locations of the Noachian/Hesperian boundary using N(2) values may represent a different absolute age than his location of the division using N(5) values, a trend that has been observed elsewhere on Mars (R. A. Craddock, personal communication, 2001). In this case, perhaps the estimation of the production rate of 2–5 km craters was overestimated.

### 3.2. Drainage Density

Small valleys dissect most of the study area and are particularly abundant on slopes >0.5°. MOLA data indicate that valley depths generally range from 20 to 50 m in this area. As on the Earth, deep incision of Martian valleys is not a constant feature of the landscape, but this is common where a valley crosses a divide or escarpment or some reduction in base level has occurred on a downstream reach. The abundance of valleys is defined by drainage density, which is the ratio of total valley length to area, with units of km⁻¹.

Drainage densities of 2–30 km⁻¹ are typically observed for terrestrial river basins. Higher-resolution images were utilized to identify the shallower degraded valleys in drainage basin 53, which may account for the somewhat higher observed drainage density there. The estimates in Table 3 are 3–7 times greater than values obtained in Margaritifer Sinus by Grant [2000] and ~2 orders of magnitude higher than values reported by Carr and Chuang [1997] for the same geologic units. For Npld units, their drainage density value was 7.405 E⁻³ km⁻¹ and Nplf units had a value of 2.816 E⁻³ km⁻¹. This large disparity occurs primarily because of their use of a smaller map scale (1:2,000,000) and use of the 1:15,000,000 units of Greeley and Guest [1987]. These geologic units incorporate diverse lithology, such as recent crater ejecta and basin deposits, into broad physiographic provinces. Most of these smaller recent units should not be classified as dissected at all, and gently sloping areas in older units are unlikely to have developed dissection to a depth that would make the valley obvious in the images. Further, an examination of Carr and Chuang’s [1997] valley coverage overlaid on the area mapped here suggests that their mapping was incomplete, even at 1:2,000,000.

The drainage density values derived in our study are similar to those mapped within the United States by Carr and Chuang [1997]. The U.S. drainage densities included currently active valleys mapped at 1:1,000,000 scale on base mosaics of four Landsat images covering areas of ~109,000 km² in each mosaic. Drainage densities in the United States ranged from 0.079 km⁻¹ in Nebraska to 0.209 km⁻¹ in Washington State. The maximum drainage density that can be portrayed at 1:1,000,000 is on the order of 0.5 km⁻¹, while larger map scales allow recognition of terrestrial drainage densities of 2–30 km⁻¹, 1–2 orders of magnitude higher than is possible with the 1:1 M map scale [Carr and Chuang, 1997]. Although recognition or portrayal of terrestrial drainage networks depends on map or image scale, drainage densities on Earth are not infinite. Thresholds of channel incision (e.g., Montgomery and Dietrich [1988, 1989] or the balance between diffusive and advective processes [e.g. Howard, 1994]) determine a true length scale for drainage networks. It is uncertain whether the true drainage density of Noachian Martian landscapes at the time of their formation can be ascertained, partly due to limitations in image resolution and coverage, but more fundamentally due to ~3.6 billion years of slow modification by eolian and mass wasting processes [Arvidson et al., 1979; Craddock and Maxwell, 1993], whereas terrestrial valleys are much younger and still active. Current incision, surface water, and vegetative cover would make small terrestrial valleys relatively easy to identify, and these tributaries provide the largest contribution to drainage density values.

### Table 4. Location, Measured Length of Valleys, Area, and Drainage Density for Subsets of Dissected Upland Units

<table>
<thead>
<tr>
<th>Catchment Number</th>
<th>Resolution, m/pixel</th>
<th>Total Valley Length, km</th>
<th>Area, km²</th>
<th>Drainage Density, km⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>231</td>
<td>644</td>
<td>3216</td>
<td>0.20</td>
</tr>
<tr>
<td>9</td>
<td>231</td>
<td>1031</td>
<td>5252</td>
<td>0.20</td>
</tr>
<tr>
<td>50</td>
<td>115</td>
<td>455</td>
<td>1533</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Indeed, MOC images (Figure 5) suggest that small impacts and eolian deposits mute the topography of small Martian valleys. This results in fragmented and unclear depressions that have been termed “pseudodrainage” by Carr and Malin [2000]. Hartmann et al. [2001] observed that the Martian surface is saturated with post-Noachian craters with diameters below ~40 m, which would result in 4–18 m of impact gardening. As valley depths are commonly on the order of 20–100 m, recent impacts would effectively degrade the topography of shallower valleys, leaving only the deepest valleys as continuous mappable features.

Another feature evident in Figure 5 is the presence of a narrow, shallow channel upstream from a deep, theater-shaped valley headwall. These features occur elsewhere on Mars, although they do not appear at all headwalls. These upstream channels suggest that some valley headwalls are knickpoints through resistant layers rather than sapping headwalls, and waterfalls would have been present in some of these locations. Observations of bedrock outcrops at the top of Martian valleys [e.g., Malin, 1976; Carr and Malin, 2000] suggest that the surface layer is consolidated, below the depth of more recent impact brecciation. If these knickpoints prove to be widespread in examination of the complete MOC data set, then we might expect two classes of Martian valleys. The ones visible in available Viking images have cut through the surface layer, while shallow, highly degraded networks of valleys are present on some Noachian watersheds in MOC imagery. Baker and Partridge [1986] noted this downstream change in morphology but attribute it to late stage sapping as an overprint on an older valley.

3.3. Herschel Crater

The interior of the 290 km Herschel crater (Figure 6) appears to be a younger surface than the rest of the study area, and it is treated independently from the forthcoming discussion of drainage basins. Edgett [1991] interpreted Herschel as one of the younger impact structures of this size on Mars on the basis of its state of degradation. It does not appear to have been breached, although the rim is nearly absent in two locations, and interior gully incision has widened the basin. Greeley and Guest [1987] mapped the floor of Herschel as Hesperian ridged plains (Hr). Edgett’s [1991] more detailed map divides the crater interior into wrinkle-ridged plains (equivalent to Hr) and hilly materials. The hilly materials (excluding impact ejecta) are oriented around a low plain in the center of the basin, and they probably represent an eroded inner basin ring with a diameter of 160 km [Tanaka et al., 1992]. The interior hills appear to be embayed by the ridged plains unit, which is interpreted by Edgett as volcanic due to its smooth surface and relatively young crater-retention age. The floor deposit must be sedimentary, however, at least in part, as the large basin is degraded by valleys. The floor of Herschel varies in elevation between about 1200 and 1500 m, similar to the elevation of Hesperia Planum to the west (1400–1600 m). MOLA data show that the rim of Herschel is not breached and that surrounding valleys channeled water away from the rim rather than into the interior. Interior eolian deposits are discussed in section 4.7.

4. Drainage Basin Development

4.1. Regional Topographic Controls on Drainage

Figure 1b is a contour map based on the 1/32° MOLA topographic grid, which illustrates regional topo-
Figure 4. (a) Valleys mapped for drainage density in catchment 1. The image is centered at 6.33°S, 128.5°E (231.5°W) and is 55 km across. (b) Valleys mapped for drainage density in catchment 9. The image is centered at 10.33°S, 127.8°E (232.2°W) and is 74 km across. (c) Valleys mapped for drainage density in catchment 50. The image is centered at 27.9°S, 125.75°E (234.25°W) and is 37 km across.

Figure 5. Breached crater with contributing valley networks, located due east of Knobel crater on the right side of Figure 3. Note interior channels and small tributary valleys upstream of apparent headwall (white arrow) and degradation resulting from numerous small impact craters. (Subset of MOC image SP2-38404, centered at 6.8°S, 134.6°E (225.4°W), 10.50 m/pixel.)
graphic patterns. The study area contains widespread ancient valley networks with sharp drainage divides, highly eroded impact craters, and basin plains units surrounded by convergent valleys. These areas are interspersed with intercrater plains having less or no visible dissection, which are associated with lower (<0.5°) slopes. In the following discussion we confine “drainage divides” to only those ridges that support valleys on either side; many ridges that are related to fresh craters were not mapped as such. Drainage was controlled by topographic gradients associated with the dichotomy boundary, crater rims, and high ridges apparently unrelated to cratering. Although the dichotomy escarpment is the greatest source of topographic relief (~2 km), a relatively small area drains across it (catchments 1 and 2 indicated in Figure 3; see discussion in section 4.6). Precrater ridges are drainage divides that are too high and/or broad to have been created by the craters in their vicinity. These ridges are significant controls on drainage patterns in some areas (Figure 7). Most drainage divides are associated with degraded impact crater rims and ejecta, and of these, Herschel crater is by far the largest. The rim of Herschel crater is mapped as a precrater divide because, although it is an impact structure, it predates other impact events in the area. Drainage divides are indicated in white in Figure 1a.

A precrater ridge at ~8°S separates valleys to its north, which drain to the lowlands, from northeast flowing valleys to its south. Drainage patterns are directed radially away from the Herschel crater rim to a distance of ~200 km. South and east of Herschel, the landscape is divided into large enclosed drainage basins. A westward draining region occurs at the southern and western ends of the mapped area.

The steepness and length of regional slopes are strong controls on drainage basin development. Basin floor units (yellow and green colors in Figure 1a) are located in the lowest points, and floor elevations commonly slope gently (gradients are generally <0.25° but can reach 0.75°) upward toward the edge of the basin. Valleys are most pervasive and evident where regional slopes are both long

Figure 6. The 290 km Herschel impact basin. Wrinkle-ridged plains in the north have a sharp contact with dark eolian dunes in the south. The hills at ~0.5 radii probably represent an inner basin ring. Fresh craters overlie the southern rim. The image is 399 km across.

Figure 7. Precrater ridges (blue lines) and the principal disrupting impact craters (black circles) overlaid on a MOLA topographic map of the study area and vicinity. Elevation scale is the same as Figure 1b. The white border is the study area boundary, and white circles represent the thick ejecta blankets that were deposited within 1 radius of the disrupting craters’ rims. The ejecta has been heavily eroded in most cases, but its topography is preserved even where texture is not. Although lower precrater ridges may be present, the high ridges shown here unequivocally predate their neighboring craters. The Herschel rim, and the drainage divide of the closed basin to its SSW, are clearly impact-related, whereas others are not. Compare the size of these ancient drainage basins to Figure 1, which shows the current divides. The image is 1185 km across at the equator.
and steep (~1°), which is consistent with a greater potential for fluvial incision due to the steep gradients and large contributing areas. Valley thalwegs generally have gradients between 0.25° and 1°. Mappable valleys are not as common on the nearly level enclosed intercrater plains basins to the southeast and west of Herschel. Shallow degraded valleys (<20 m deep) with rounded drainage divides dominate the southernmost part of the map area. Here the valleys are difficult to trace because of their degraded texture and shallow incision, especially on low-resolution images, although dense valleys appear in the 115 m/pixel images where slopes greater than ~0.5° occur.

4.2. Establishment of Ancient Large Catchments

[34] Most of the drainage divides on the highland plateau are related to large degraded craters or their ejecta; however, the ridges mapped in Figure 7 appear to predate extant degraded craters. These ridges delimit much larger drainage patterns that are not evident by examination of the Viking Orbiter MDIM alone. Younger craters frequently superimpose these ancient divides but are too small to be responsible for the length and height of the ridges. For example, the divide extending from 230° to 235°W along the 7.5°S parallel does not originate from any of the impacts in the area, including Herschel. Originally continuous drainage networks exist on both sides of this ridge. Catchment 1 debouches directly to the lowlands, while catchments 9 and 2a are disrupted by a 92 km impact crater, which is superimposed on the northeast side of the basin (8.5°S, 128.75°E (231.25°W), point B in Figure 8).

[35] Catchment 9 is located between the northern precrater ridge and Herschel crater to its south. Without the 92 km crater obstructing flow, the thalweg of this catchment would follow a continuous northeast flowing gradient to the lowlands. Figure 8 is a longitudinal profile of the valley from point A, through the disrupting crater at B, past a second disrupting crater at C, and over the dichotomy escarpment. As the crater floor is lower than the ancient valley thalweg, the stream profile steepens upstream of point B to accommodate the more recent base level. As the drainage divide at 7.5°S (between catchments 1 and 9) would have been largely unaffected by the Herschel impact, and as it is of comparable size to the impact basin rim, the high ridge controlling those networks must have predated Herschel. If the precrater ridge had been created by erosion subsequent to the Herschel impact, we would expect that the Herschel rim would be substantially more degraded than it is, owing to the parity of their sizes. This northern precrater divide is ~1000 m above the plateau in catchment 1 and 1300 m above the primary valley in catchment 9, but inspection of the immediate surroundings does not suggest an impact or structural origin for this ridge. It is therefore likely that well-developed drainage systems occurred on both sides of the ridge in advance of the Herschel impact and that the divide results from the longevity of these valleys. Similar high ridges exist throughout the highlands, including the southern half of this study area (Figure 7). On the highland plateau to the southeast of Herschel crater, there is no evidence that the ridge-bounded drainage basins were ever connected to the lowlands or to Hellas. This region appears to drain internally to several low points. A broad drainage basin follows a continuous westward gradient toward Hesperia Planum at ~30°S in the southwestern corner of the map, which is also bounded by high precrater ridges (see Figure 7). Numerous other large catchments can be easily identified on the MOLA topographic grid outside the area mapped here.

[36] These broad drainage patterns are among the most interesting features in the study area, as they record the earlier history of the Noachian landscape. The “primordial” surface of Mars, or the earliest landscape that can be discerned when more recent modifications are neglected, contained some relatively large catchments with continuous gradients. In most cases, relatively sharp-crested ridges delimit the catchments. This observation is not consistent with unmodified volcanic landscapes, which tend to be planar or sloping upward toward a central caldera and do not contain high ridges like those mapped here. Furthermore, the irregular pattern of these ridges is not suggestive of tectonic features. Nor is this ancient Noachian terrain dominated entirely by 100 km scale cratering, because craters in this size range would not create long continuous gradients even at subsaturation densities. The earliest discernable Martian landscape was, however, heavily influenced by basin-scale (>300 km) impacts [Schultz and Frey, 1990], many of which are so heavily eroded that they do not retain obvious characteristics of impact craters. The large impact basins also control broad drainage patterns, particularly in the interior of the upland plateau, where there is little regional slope.

[37] The large basins identified here would have collected water from larger areas than the current drainage divides (often crater-related) would allow. Assuming that heavy cratering occurred throughout the Noachian, rather than only at the end, large craters must have been eroded away throughout the period to account for the diverse states of degradation. This interpretation agrees with the observation that >300 km impact basins are in advanced states of degradation despite their size [e.g., Schultz et al., 1982], relative to the population of smaller craters. Below ~64 km diameter, Mars is deficient in craters relative to the Moon [Wilhelms, 1974; Hartmann et al., 2001]. For these reasons, crater degradation could not have occurred during a single postbombardment erosional episode. Erosional processes must have been adequate to overcome frequent large impacts, or the catchments would not have had the opportunity to develop to their observed extents, and large impact basins could not have been so extensively degraded. This early high erosion rate must have declined at some point during the late Noachian, with only the latest stage (involving many small disrupted drainage basins) represented by extant valleys and degraded craters. Some large catchments may not have contained continuous valleys at any time; rather, the watersheds could have collected water from larger areas than the current drainage divides (often crater-related) would allow. Assuming that heavy cratering occurred throughout the Noachian, rather than only at the end, large craters must have been eroded away throughout the period to account for the diverse states of degradation. This interpretation agrees with the observation that >300 km impact basins are in advanced states of degradation despite their size [e.g., Schultz et al., 1982], relative to the population of smaller craters. Below ~64 km diameter, Mars is deficient in craters relative to the Moon [Wilhelms, 1974; Hartmann et al., 2001]. For these reasons, crater degradation could not have occurred during a single postbombardment erosional episode. Erosional processes must have been adequate to overcome frequent large impacts, or the catchments would not have had the opportunity to develop to their observed extents, and large impact basins could not have been so extensively degraded. This early high erosion rate must have declined at some point during the late Noachian, with only the latest stage (involving many small disrupted drainage basins) represented by extant valleys and degraded craters. Some large catchments may not have contained continuous valleys at any time; rather, the watersheds could have developed in stages, with occasional local disruptions by impact craters.

[38] Within these catchments the valleys we observe today developed subsequently to the youngest degraded craters that control their flow patterns, and they therefore represent only the final stages of dissection and drainage basin development. For this reason, the density and morphology of late Noachian or Hesperian valleys is not
Figure 8. (a) Precrater valley network that has been disrupted by a 92 km crater at point B, which became the terminal basin for the upstream reach of the crater. Knobel crater, to the right of point C, also disrupted the valley, but basin infilling at C allowed the divide to be breached and the crater circumvented. The valley presently debouches across the dichotomy escarpment, and an alluvial fan has developed to the right of point D. Southwest of point B, small breached craters occur on the Herschel ejecta blanket. The image is 470 km across. (b) Longitudinal valley profile following the white line in Figure 8a from left to right. Points correspond to points in Figure 8a. Note steepening of the valley profile at A to accommodate the lower base level at B and also at the dichotomy escarpment. V.E. = 166×.
necessarily indicative of the extent, intensity, or type of erosional processes that occurred earlier in the period.

4.3. Disruption of Ancient Catchments by Impact Cratering

[39] The broad catchments are disrupted in many locations by impact craters (Figure 7), which themselves became degraded to varying degrees. By comparing drainage divides in Figures 1 and 7, the relative effect of <100 km craters appears to increase through time, or at the least, fluvial erosion was inadequate to reintegrate drainage systems subsequent to the youngest large impacts. The emplacement of an impact crater can have varying effects on a valley network depending on the crater’s position in the older drainage basin. If the crater is located on a precrater ridge, it will raise the preexisting divide and perhaps steepen the upstream reach of the watershed, promoting valley incision there. A crater superimposing a valley thalweg will dam a valley and cause deposition upstream of the crater. A valley can be dammed either by the crater rim or by the ejecta blanket, although damming by ejecta alone usually requires a relatively large crater (~75 km as observed here) to produce a sufficiently broad and thick ejecta blanket, relative to the horizontal and vertical scale of the watershed. Smaller craters (relative to the catchment width) are more likely to divert a valley than dam it, particularly when the crater is emplaced on a regional slope. For example, the courses of valley networks in catchment 2 are controlled by the topography of degraded craters, following courses that avoid the craters or beginning at local crater-related divides (Figure 9). The precrater slope in this area affords a more direct route toward the lowlands, so it is likely that the valley courses were modified near the impact craters.

[40] Many craters are located on precrater ridges. The drainage basins to the east and northeast of Herschel are situated on a prevailing northeast slope toward the dichotomy escarpment, which is supplemented by the ejecta blanket of Herschel and the craters on its northeast rim. The craters bordering the Licus Vallis watershed are all located on precrater ridges, as are several degraded craters in the southeast quarter of the map area (catchments 23, 34, 42, 45, 48, 53–56). All of these craters supplement the slopes that existed prior to the impacts. In these cases, craters did not significantly alter flow patterns, but they elevated the preexisting divides.

[41] To significantly affect flow patterns, impact at or near a valley thalweg was required. Precrater drainage basins are interrupted by crater ejecta in several locations. The ejecta of an unnamed 75 km crater (catchment 45) redirects a valley in catchment 43 such that it no longer follows its original course through a mapped precrater watershed (Figure 10). As shown in Figure 11, ejecta from

Figure 9. Valleys guided by impact crater topography (points A and B) on a precrater slope downward to the northeast in catchment 2, near the dichotomy escarpment (D). Note the relatively short, steep incised reaches near the escarpment (arrows) and dense contributing valley networks. As in Figure 3, a wrinkle ridge cuts the floor of a degraded crater SW of crater B, illustrating both the relative youth and difficulty in identifying these features on dissected units. The image is 177 km across.
the 130 km Knobel crater (catchment 8) disrupted the catchments 14 and 15, creating a low divide between them. The ejecta of 115 km Müller crater (catchment 48) divides catchments 41 and 33, and the ejecta of an unnamed 65 km crater to the southeast of Müller (catchment 51) divides catchments 52 and 50.

Direct impacts on valley thalwegs also disrupted more lengthy catchments, creating several closed drainage basins in the study area. In some cases the crater is breached and serves as a terminal basin, and elsewhere the intercepting crater creates a closed basin outside its rim. The terminal basin for catchment 17 is a degraded crater on the eastern boundary of the study area at 9.5°S. A spillway apparently connects this crater with a large valley on its northeastern side; however, the breach does not extend to the crater floor (Figure 11). This crater is a likely candidate for former impounding of water. Also in Figure 11, catchment 21 was possibly integrated with catchment 17 to its north at one time, but a smaller degraded crater (point C in Figure 11) overlies the likely original point of exit from 21 to 17. This crater may have dammed catchment 21 and caused deposition to occur in an elongated basin (point D in Figure 11), which is located at the edge of the crater’s continuous ejecta blanket.

Degraded craters superimposed on a regional slope are often breached and received drainage from small contributing areas, as in catchments 7, 10, 20, 24, 25, 29, 44, 53, and 54. These are distinct from craters that disrupted precrater catchments at the thalweg. When craters are emplaced on regional slopes, the original upslope rim of a crater is lower than the downslope rim in relation to the precrater surface. Breaching of these craters occurred readily because the sediment from upslope was transported toward the upslope rim and deposited, helping to further reduce the rim height relative to the sloping plain. Rim lowering and/or

Figure 10. A disrupted watershed in the southeastern quarter of the study area. Topography is shown in Figure 13. The mapped precrater watershed thalweg followed a course from A toward the terminal basin D (black arrow); however, ejecta from craters at B and C dammed the original valley. The valley presently follows a course (white arrow) through C from right to left and then drains to D. The breaches on both sides of crater C are above the crater floor elevation, suggesting a possible site for ponded water. The image is 217 km across.

Figure 11. Northeastern portion of the map area, characterized by integrated drainage networks that are disrupted by Knobel crater ejecta (catchment 8). The crater at point A receives drainage and has an elevated exit spillway on its northeast side. A valley headwall is located near a drainage divide at point B. A crater at C overlies the likely point of exit between catchments 21 and 17, causing sediment to accumulate at D. Breached small impact craters occur on the Herschel ejecta blanket near point E. The image is 293 km across.
sediment deposition on the uphill side of the crater resulted in early rim entrance breaching, and the interior was infilled by sediment. The smooth floor unit resembles that of degraded craters with closed rims. Given enough time, interior sedimentary infilling and rim lowering allowed exit breaching of the degraded downslope rim and capture of the whole drainage area by a downstream valley network. A good example of this is a crosscut crater at point F in Figure 12. The crater controlled the course of Licus Vallis to the west, and after entrance breaching, it received drainage from the slope above it. The crater collected drainage in its interior, and after infilling, the exiting valley downcut the floor deposit in one location, just upstream of its confluence with Licus Vallis. Conversely, breaching of a crater on a near-level surface would require a thicker sedimentary deposit around the entire circumference of the crater or an advanced state of rim degradation, so these craters would be reintegrated more slowly.

Steep slopes favored runoff and downcutting over infiltration, whereas level areas are deeply dissected only where they border a steep slope, and the channel was simply pursuing a stable gradient along its entire length. Development of long, stable valley courses is much more difficult with frequent cratering, particularly on near-level areas. On slopes, several craters can occur in a small area and a disrupted channel would pursue a path between them, as close as possible to the steepest path down the precrater gradient. On near-level surfaces, however, drainage basin disruption could be accomplished by smaller impacts, which were also more numerous. Where a channel has a low gradient and a small contributing area, a low divide of crater ejecta from a small crater would be adequate to block a flow path. In this situation, lengthy valley networks would not tend to develop.

4.4. Basin Sedimentation

All basin plains units in this study area received drainage from mapped valley networks. Most basins occupy floors of degraded craters, but intercrater basin plains are also common. Previous authors (see summary by Carr [1996]) have invoked intracrater drainage systems to support the hypothesis that Noachian valleys were carved primarily by runoff following precipitation. The interior gullies start very near the crater rims, and it is difficult to envision a groundwater flow model that would move water preferentially to these elevated locations through fractured materials. In MOLA crater profiles, the transition between the interior slope and flattened floor is typically abrupt and concave, suggesting that small fan deposits have accumulated near the base of the interior slopes or that sediment has been distributed throughout the impact basin interior. These observations support the interpretation that crater interiors contain deposits that result from erosion of interior slopes. Topographic profiles of degraded craters support this interpretation, suggesting that amounts of infilling closely match rim erosion, with minor eolian contributions [Craddock et al., 1997].

Mapping of drainage divides suggests that the steep crater interior valleys themselves were relatively long-lived. Degraded crater rims are frequently somewhat irregular in shape with respect to fresh craters, suggesting that the valley incision has led to wall backwasting by an amount greater than the valley depth. Where one gully grows relative to others, its rate of downcutting and headward extension is enhanced relative to other valleys, and the crater is widened in that location. Coupled with the modeled ~10% overall enlargement in the diameter of craters with complete rims due to backwasting [Grant and Schultz, 1993; Craddock et al., 1997], this observation suggests that interior valleys were active over a prolonged period and moved large quantities of material. Precipitation is the only reasonable source of water to support crater degradation in this manner, and short-lived impact-induced groundwater release [Brakenridge et al., 1985] is inadequate to explain the observed rim morphology, particularly the extension of valleys to the crater rim. Timing is also a problem when impact melting of ground ice is considered as the sole source of water, because many valley networks both predate and postdate (in different reaches of a long valley) some of the larger craters in the region.

Mare-type equipotential volcanic flooding cannot be invoked to explain all of the flat crater floors in the study area, unless each crater had its own unique source of magma with no communication to those of other infilled craters. To the contrary, MOLA data (Figures 1b and 7) show that crater floor elevations are variable, and they generally appear related to the precrater ground surface and states of degradation. For example, the floors of catchments 33, 40, and 42 have a similar elevation at 1500 m, but other terminal basin floors between and around them have sub-
stantially lower or higher elevations, in most cases dependent on their placement on the plateau or on precrater ridges. Level plains on the Earth do not necessarily indicate volcanism but generally result from other erosional or depositional processes. The presence of valleys incised into the surrounding uplands is more consistent with a fluvial explanation for many of these basin plains, rather than volcanism.

[49] In some areas, relatively large, near-level, poorly dissected intercrater plains occur that are surrounded in part by low drainage divides (see Figure 13). Catchments 27 and 49 are examples of intercrater depositional plains. Greeley and Guest [1987] interpreted catchment 23 as a thin volcanic deposit (Npl2), part of a wrinkle-ridged unit that occurs between this study area and Hesperia Planum. Emplacement of Hesperia Planum to the west and Elysium Mons to the northeast suggests that this region on Mars could have been volcanically active as late as the Hesperian. However, if both catchment 23 and the Herschel interior contain volcanic materials, then the materials likely resulted from different magmatic sources, as equipotential flooding from a common source never affected both areas simultaneously. Catchment 23 has modest local topography but little regional slope, maintaining an elevation of ~2300–2400 m, which is some 900 m above the Herschel crater floor. Furthermore, valleys surround catchment 23, which is itself dissected in some areas, so a sedimentary origin is likely. Small, numerous disrupting craters, a surface of impact breccia, and the facility of eolian transport could have favored infiltration over runoff on these near-level units, accounting for sparse visible dissection.

[50] Catchment 49 is encircled by precrater divides, except along its southern margin where a low divide was formed by impact craters and their ejecta. The basin floor is not deeply dissected by either the small valleys or the older, broad watersheds observed around catchments 1, 2, 9, 14, 15, 17, 43, and 50. However, even without abundant valley development, the large craters in catch-

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**Figure 13.** MOLA contour map (50 m interval) of the southern portion of the map area, bounded by 18°S, 28.5°S, 125°E (235°W), and 135°E (225°W). White lines are drainage divides, and blue lines are the major valleys. Catchment 33 is a large closed basin that is probably of impact origin, overlain by later craters at A and B, with a floor unit at 1500 m elevation. A precrater ridge occurs between catchments 33 and 49. Catchment 49 is a closed upland drainage basin at 2200 m elevation, consisting in part of sediments shed from the precrater ridge. Catchment 43 is the area shown in Figure 10. The scene is 546 km across.
ment 49 are degraded and <20 km degraded craters are largely absent. Infilling of this area by crater ejecta and materials eroded from the bounding ridge is the likely origin of the smooth plain, which has an elevation of 2000–2400 m (Figure 13).

[51] A large, highly degraded impact basin is located in catchment 33. This area is dominated by a large, irregularly shaped, smooth basin plains unit, which incorporates two embayed impact structures at its northern and southern ends (points A and B in Figure 13). Catchment 33 is surrounded by degraded impact craters (catchments 34, 40, 42, and 48 and smaller craters), but these craters do not divide the basin from potential outlets at lower elevation. The large central basin is probably of impact origin (although highly degraded), as at 1400–1600 m of elevation it is considerably lower than surrounding dissected plains. The slopes surrounding the smooth basin floor have gradients of 0.5°–1.0° and contain dense, radial valley networks. The basin floor is a likely sedimentary deposit, although it was mapped as Hr by Greeley and Guest [1987]. There are no apparent volcanic landforms or ridges on the basin floor, and the embayed impact craters control the course of nearby valleys. Thus the embayment could have been contemporaneous with basin floor sedimentation, and volcanism is not required. The interior valleys developed during the late Noachian (post-Herschel) largely on unconsolidated crater ejecta materials. The valleys are not well integrated due to their radial orientation and the short regional slopes.

[52] In terrestrial environments, closed drainage basins can develop extensive evaporite deposits where dissolved solutes cannot escape the basin through infiltration to groundwater. However, these deposits appear to be uncommon or absent in materials exposed on the Martian surface, despite the prevalence of impact craters and other closed drainage basins. Thermal emission spectrometer data from the Mars Global Surveyor indicates a basaltic sand composition for Terra Cimmeria. Weathering products, including carbonates, are minimal (<15%) [Christensen et al., 2000]. The absence of surface weathered products, carbonates, and evaporites on a highly eroded landscape is a likely condition in a relatively arid environment that is subject to cratering. Impacts fractured or brecciated the bedrock, supporting a high infiltration capacity that would allow trapped surface water to escape from crater floors. Short valley lengths provide little opportunity for physical and chemical weathering of sediment before the depositional basin is reached. Transport of sediment in terrestrial dry environments tends to be “flashy,” where the sediment is dry most of the year and is then transported en masse during seasonal floods [Reid and Frostick, 1997]. The sediment can therefore remain relatively coarse and unweathered through the valley system. Meteorite impacts, both during the Noachian and later, brought unweathered material to the surface and distributed it in widespread ejecta blankets. While the original bedrock is basaltic, cratering would minimize the surface expression of weathered materials even during the Noachian. There are also the issues of post-Noachian degradation of carbonates, burial by eolian deposits, selective removal and abrasion of evaporites by the wind, and burial of evaporites beneath more recent basin sediments. This issue may have several answers, including the one we present, and the Mars Odyssey 2001 mission may return relevant data.

4.5. Reintegration of Disrupted Drainage Basins

[53] On the Earth, closed drainage basins are inherently unstable features, as sedimentation typically fills the basin over time and/or surface outflow streams downcut an exit breach. In this way, closed catchments are integrated with drainage networks, eventually leading to an ocean basin. In the Basin and Range province of the southwestern United States, continuing tectonism plays an important role in maintaining enclosed basins against the inherent tendency for basin integration. In this study area on Mars, closed drainage basins are also common and integration appears to have been less efficient than disruption, at least at the terminal stage of fluvial erosion. Infilling sedimentation can be an efficient means of removing closed basins on both planets. By filling the basin to at least the level of the divide, surface water can overflow and downcut the divide, eventually dissecting the basin deposit itself (e.g., Figure 12, point F). High levels of standing water in a lake can also breach a divide, but basins subject to rapid and complete filling by water are likely to be short-lived due to overflow and rapid downcutting, and basin sediments are not likely to have a significant topographic expression. A likely scenario for lake overflow would have a crater located on the thalweg of a large valley, where the crater has a relatively pristine rim that is exit-breach ed in one location or crosscut. In this study area the prevalence of closed drainage basins with extensive floor deposits suggests that overflow of divides by ponded water was not an important process in basin reintegration. To the contrary, the absence of (observed) evaporite deposits suggests strongly that closed basin interiors tended to be well drained through groundwater flow or that the influx of unweathered granular sediment exceeded the influx of solutes (unless the evaporites are there and undetected). Thus exit breaching through a combination of internal sedimentation and rim lowering appears to have been more prevalent than via overflow of deep lakes.

[54] Several theater-headed valleys originate at low drainage divides (Figure 14), particularly in locations where the divides originated as crater ejecta. These headwalls suggest that some elevated, closed drainage basins were able to drain, in part, by directing groundwater to external valley networks. In a classic example, Hebes Chasma drained to Echus Chasma by this method [Carr, 1996]. In the process the valley would extend headward toward the closed basin, in some cases eventually breaching the divide without the necessity of surface overflow. One example of a valley that was likely fed by groundwater occurs at the low drainage divide between catchments 15 and 14. These are separated by a low (50–100 m) divide that is likely Knobel crater ejecta (see point B in Figure 11 and Figure 14b). Catchment 15 contains abundant channels that are well integrated, but most collectively debouch into a depressed area in the northeastern part of the unit. There is no smooth plains unit at this location, which suggests that the divide is relatively young. In catchment 14 the largest valley is also quite deep (~200 m) and originates at a headwall (Figure 14b), nearly coincident with the drainage divide with catchment 15. This valley grew generally toward the low point of catchment 15. In this area the divide is not breached, but groundwater from
Figure 14. (a) Sapping valley morphology between catchments 2 and 11. The valley headwall (arrow) was growing headward toward the closed basin plains unit immediately to its south. The image is centered at 8.5°S, 128.5°E (231.5°W) and is 119 km across, with north at top. (b) Sapping valley morphology between catchments 14 and 15. The valley headwall (arrow) was growing headward to the west. The image is centered at 9°S, 133.5°E (226.5°W) and is 119 km across, with north at top. (c) Sapping valley morphology between catchments 31 and 37. The valley headwall (arrow) was growing headward toward the closed basin plains unit immediately to its southwest. The image is centered at 17.5°S, 134°E (226°W) and is 119 km across, with north at top. (d) Subset of Viking Orbiter 1 image 421s27 (115 m/pixel resolution), centered at 28.5°S, 130.5°E (229.5°W). Just up from center, a theater-headed valley (arrow) is oriented toward a closed drainage basin to its northeast. Degraded valleys are present throughout the image. The image is 92 km across, with north at top.
the closed catchment 15 supported development of a large theater-headed valley.

[55] Catchment 11 drained to catchment 2a (the valley network illustrated in Figure 8) in a similar manner. The divide between catchments 11 and 2 is low (~100 m), and the primary valley in 2 appears to have been growing toward 11 when valley development ceased. The head of this valley (Figure 14a) is the best example of sapping valley morphology in the study area. The catchment 2 primary valley is inferred to have originally been contiguous with the valley in catchment 9 prior to interruption by the 92 km crater discussed above.

[56] The precrater catchment 50 is divided from its continuation in 52 by a low ridge of impact crater ejecta from 51. A valley with an obvious headwall in catchment 50 is oriented toward the enclosed catchment 52 at the mapped boundary (Figure 14d). This is a similar orientation of a sapping-type valley to those discussed in catchments 11 and 2. A fourth example is observed at the boundary of catchments 31 and 37, which are also separated by a low divide (Figure 14c). As it is difficult to determine whether sapping or overflow was important in drainage divide breaching after the fact, the importance of this process globally would have to be evaluated in a broader study of dissected basin plains.

[57] On the northern and eastern slopes of Herschel crater, small, misshapen craters have been breached by crosscutting tributary valleys (intravalley basins southwest of point B in Figure 8 and in Figure 11). As the impacts occurred on a thick unconsolidated unit, the craters were highly susceptible to this type of modification, which does not occur as commonly elsewhere in the map area. The elongate shape of the craters, with the long axes parallel to the crosscutting valleys, may be due to erosion, rather than an origin as secondary impact craters [Edgett, 1991].

[58] Several previously closed basins in the study area have been re integrated. Immediately to the east of Licus Vallis, two highly degraded impact craters have crosscutting valleys. These craters are strongly degraded and hence ancient relative to other features in the vicinity, as evidenced by the control that the western crater places on the course of Licus Vallis (Figure 12, points F and G). The likely cause for reintegration of the eastern crater (point G) is infilling, and this may hold true for the crater at point F as well. The 130 km Knobel crater (catchment 8) has an effect on the valley network profiled in Figure 8. A depositional plain occurs to the west of Knobel crater (see Figure 2), and immediately downstream of this basin the valley pursues a steep course into the lowlands. At the base of this slope an alluvial fan is evident in the base images. The likely scenario here is that Knobel crater interrupted the valley, resulting in the development of a depositional plain behind the new drainage divide. After some amount of infilling the divide was breached and downcutting into the depositional plain occurred, with the sediment redeposited in the alluvial fan. Again, sediment deposition behind the divide allowed for eventual breaching. At the crater illustrated in Figure 10, valley reintegration occurred when the valley was diverted through a nearby impact crater, creating another likely site for ponded water.

4.6. Effect of the Dichotomy Escarpment

[59] The dichotomy escarpment appears to have strongly affected the morphology of crosscutting valleys. The deep incision and terraced walls of Licus Vallis are unique in the study area, although fretted valleys elsewhere on Mars are similarly broad and deep [Sharp, 1973]. The main valley and its network of much smaller tributaries are separated by a plateau centered at 4.5°S at 1500 m elevation (Figure 12, point B). South (up-slope) from the plateau, small valley networks extend to the topographic divide at ~2500 m elevation. The depth of these headwater valleys ranges from 20 to 100 m on both the plateau and its contributing slope, and divides between individual small valleys are sharp. Licus Vallis and its tributaries from the east and west are incised up to 800 m near the dichotomy escarpment, where the valley debouches into the undifferentiated lowlands unit to the north [Greeley and Guest, 1987].

[60] The drainage divide between catchments 1 and 9 occurs at least 250 km from the rim of Herschel basin, so catchments 1 and 2 would not have received a thick ejecta deposit from this or other impacts in the area. Generally, the texture of catchment 1 suggests that erosion occurred over a prolonged period, as dense valley networks exist in the near absence of 20–40 km degraded craters. The large craters are in advanced states of degradation, with the exception of a 74 km crater (catchment 3) that is not as extensively modified. Degraded craters on the divides of drainage basins 1 and 2 (catchments 3, 5, 6, and 7 and smaller craters) are located on precrater ridges, so they did not disrupt flow toward Licus Vallis.

[61] The plateau at the head of the valley has a generally rounded plan, which may represent an older impact basin at the terminal state of degradation. The breach of the old basin’s rim, and capture by Licus Vallis of its internal valley networks, could have occurred by overflow of the divide (downcutting after basin infilling was complete) or headward growth by Licus Vallis (sapping fed by groundwater in the enclosed basin). A small, degraded crater near the middle of the plateau (point B) serves as the apparent source for Licus Vallis. The exit breach thalweg is near the floor elevation of the crater; however, there is no entrance breach in the crater wall. It is therefore unclear whether Licus Vallis in its final stages of excavation was fed by surface water in this upstream reach, and indeed an integrated valley system on the plateau is not evident in the images. Rather, the crater floor may have served as a discharge point for groundwater flow in the local area, since it is the topographic low point on the rounded plateau.

[62] The reach in Licus Vallis between this head crater and the possible old basin rim is V-shaped, while the central reach has a wider, flat valley floor with an incised central channel. The downstream section of the valley was also able to downcut, with its greater contributing area and proximity to the northern lowlands, until the impact of a 24 km crater occurred at a narrow section of the valley (point E in Figure 12). At this point the valley accumulated a flat floor deposit at ~500 m elevation, and the walls continued to widen. A rounded section of the valley wall (between points D and E in Figure 12) suggests an outline of another crater that intercepted Licus Vallis previously. Intravalley lakes have been suggested elsewhere as having been created by craters [Cabrol et al., 1996]. The longitudinal profile of the valley is somewhat convex, and a terrace with an incised central channel occurs near point C. These together suggest that late-stage
incision was occurring into an older fluvial deposit in the central and upstream reaches of the valley.

[63] We do not discuss the evolution of the undifferentiated terrain north of the dichotomy in this paper, except to note the unusual response of valleys to the escarpment. Most valleys in the study area (including Licus) become deeply entrenched as they approach the dichotomy escarpment, which has a total relief in this area of ~2 km. Catchment 2 is located in the northeast corner of the study area and includes north-flowing valleys that debouch across the dichotomy escarpment. The few valleys that crosscut the escarpment commonly exhibit a spur-and-gully morphology on their sideslopes, as does the escarpment itself. In addition, the valleys always steepen and assume convex longitudinal profiles near the dichotomy boundary. These observations are consistent with any of three possible explanations. First, if the escarpment in its present form dates to the late Noachian or earlier, then Noachian valleys did not flow across it, dissect it to saturation (such that sharp crests occur between crosscutting valleys), and reach an equilibrium profile. This would be difficult to explain given the highly eroded nature of the nearby Noachian landscape and high density of valleys. Second, the escarpment could have advanced rapidly southward during the late Noachian and early Hesperian, when few valleys were active, thereby explaining the poor dissection and poor compensation of valley profiles to this uniquely high topographic feature. This possibility seems most consistent with observed Hesperian fretting elsewhere, crosscutting valley density, and morphology of terrain to the north of the dichotomy. Third, and most controversially, valley convexity and incision can result from reduction in the level of a standing body of water, which in this case would have to entirely fill the lowlands. We have found no morphological evidence to permit discrimination between these alternatives in the mapped area, but it remains the subject of continuing investigations.

4.7. Post-Noachian Modifications

[64] The prevailing wind in the study area comes from the northeast, based on the orientation of barchan dunes on the floor of Herschel basin and elsewhere. Dark deposits on crater floors and other depressions in the study area prove to be eolian dune deposits where imaged by the MOC high-resolution camera. These deposits are commonly trapped against the southern interior walls of impact craters and valleys and are thin or absent on the northern half of plains units. For example, the dark streak across catchment 9 is an eolian deposit restricted to depressions on the southern (north facing) slope of the primary valley in that unit (Figure 8). Dark eolian deposits are most common in the north-facing slope of the primary valley in that unit. For example, the dark streak across catchment 9 is an eolian deposit restricted to depressions on the southern (north facing) slope of the primary valley in that unit (Figure 8). Dark eolian deposits are most common in the north-facing slope of the primary valley in that unit.

[65] Edgett [1991] suggested that small, subparallel ridges on the Herschel ejecta material were yardangs, developing in response to a westerly paleowind direction. However, comparison with similar features at the Mars Pathfinder landing site and eolian features on the floors of valleys suggests that these ridges are small transverse dune forms oriented perpendicular to the present wind direction.

[66] High-resolution MOC images commonly show that local surface depressions have been partly filled by eolian material, and impact “gardening” has resulted in diffusive movement of the top few meters of the surface, removing the highest-frequency features in the landscape. These processes have been sufficient to nearly obscure some craters and shallow valleys in the study area of <2 km in size. The infilling of most valley networks in the area has been minor, however, and even small tributary valleys in high-resolution images are generally not degraded enough to completely mask the features. Throughout the map area, post-Noachian eolian deposition has not been a significant resurfacing process, except on smooth plains, where the dark deposits are most common. Where eolian transport was unimpeded by surface roughness, sediment could be transported downwind, creating these thick eolian deposits on the southern end of some basin plains.

5. Summary and Conclusions

[67] MOLA data, along with Viking Orbiter and MOC images, were used to characterize drainage basin development in Terra Cimmeria, Mars. The most ancient landforms include high prerater ridges, highly degraded impact craters and basins, and relatively large, integrated catchments. These terrains do not exhibit the long-wavelength topography that would be consistent with a largely unmodified volcanic or cratered landscape, but contain extensively modified primary constructional features. During the early and middle Noachian, fluvial erosion successfully competed with cratering in creating the main topographic features of the highlands, as running water was the only reasonable cause for the broad, lengthy catchments. During the final, declining stage of fluvial erosion, cratering isolated numerous smaller drainage basins, which were never subsequently reintegrated. Watershed disruption occurred when impact craters or thick ejecta blankets overlaid a valley thalweg. The sudden emplacement of obstructions to regional surface flow limited both the length of individual valleys and the area drained by individual networks. Valley networks are therefore generally short, poorly integrated on 100–1000 km spatial scales, and isolated within small drainage basins.

[68] In the arid Noachian Martian climate (relative to terrestrial humid environments), small catchment areas generally did not collect adequate water to overflow the obstructions created by large craters. Drainage basins remained particularly poorly integrated in gently sloping and level areas, where the numerous smaller craters could effectively disrupt flow paths, thus favoring infiltration over runoff (and thus low drainage densities) in those areas. The possibility that evaporite deposits are absent, if true, would require that closed basin floors were well-dained by infiltration, perhaps supporting valley development by spring sapping on intercrater plains at lower elevations. Alternatively, the influx of clastic sediment from physical or primitive chemical weathering could have greatly exceeded the influx of solutes, as in a terrestrial desert or arctic/alpine sedimentary environment.

[69] Some impact craters or ejecta-related divides were breached by deposition of a plains unit upstream of the divide, headward growth of groundwater-fed valleys, or (less commonly) ponding of surface water and overflow of
the divide. Smaller (20–40 km) craters were more likely to divert valleys around them, while craters on thick unconsolidated deposits were more susceptible to being breached and misshapen. The extant valley networks represent the only final stages of erosion. The random, episodic disruption of valley courses by impacts would have frequently reset the topographic control of valley development. New valleys would originate with new topography, and the drainage basins would become integrated to the extent possible before disruption occurred again.

[70] The highly degraded profiles of the large highland crater basins, origin of valleys near sharp drainage divides, larger ancient catchments, diverse states of crater degradation, uniform age of the decline of fluvial erosion, and relatively high drainage densities on ancient sloping terrain all support the theory that Noachian erosion was primarily due to runoff resulting from precipitation. As with terrestrial environments, groundwater flow was probably important in draining undissected areas and maintaining fluvial discharges; but even so, the long duration and spatial ubiquity of fluvial erosion on slopes requires precipitation as the ultimate water source. Further support comes from the spatial relationship between valleys with headwalls and their likely sources of groundwater, which are elevated, closed basin floors and not volcanic features in this area. The orientation of headwall valleys toward possible sources of collected surface water suggests that the groundwater source was collected precipitation rather than geothermally liberated virgin water. The collection of surface water is the only interpretation that explains all of the surface features. Reemergence of infiltrated surface water in nearby headwall valleys is rare, however, as the basin floors (particularly crater floors) most often are the lowest points within their local areas. Flat crater basin floors and smooth intercrater plains may have been partially infilled by local volcanic eruptions of low-viscosity lava flows, but infilling by fluvial and (possibly) lacustrine sedimentation is an adequate explanation for the observed basin morphology. Furthermore, a volcanic origin for crater floor units would require many independent sources within a small area, which all operated without leaving volcanic primary constructional features. This possibility is inconsistent with analogy to known volcanic landforms on the Earth and Mars.

[71] Results from the Mars Global Surveyor spacecraft have raised questions and provided possible answers regarding the first-order tributaries to Martian valleys. Where ridge crests are bounded by steep slopes, valleys originate within several kilometers of the crest. In many areas on Mars, however, first-order valleys are not observed, or they take the form of “pseudodrainage.” Carr and Malin [2000] interpreted this as highly modified, poorly integrated, ancient small valleys. Alternately, this terrain may represent primitive integration of first- and second-order valleys in a landscape dominated by impact ejecta and small crater depressions, as an intermediate condition between undissected plains and well-integrated networks. The presence of a consolidated surface layer is widespread in the highlands, where it commonly outcrops at the top of valley walls [e.g., Malin, 1976; Carr and Malin, 2000]. This layer may divide deeply incised valleys from the shallower “pseudodrainage,” with the transition occurring in some cases at apparent headwalls (Figure 5, point F in Figure 12a). These headwalls may result from differences in the strength of subsurface strata, and the headwall would be a knickpoint rather than a sapping headwall. In areas where shallow slopes did not favor deep valley incision, eolian deposits and impact gardening could obscure the shallow upstream channels. These small tributary valleys would be a major contributor to the drainage densities on Mars, which are similar to terrestrial values for steeply sloping, deeply dissected terrain. In general, only small features (<1 km in valley or crater width) are extensively modified by eolian deposits, except perhaps in large dune fields created by trapping. Impact gardening was capable of reworking the top ~10 m of the Martian surface since the Noachian [Hartmann et al., 2001], which is enough to degrade the shallow valleys in concert with eolian transport.

[72] Widespread fluvial activity did not continue to the Noachian/Hesperian boundary in this area, as fresh crater numbers of \( N(5) = 243 \) suggest that intense erosion ceased during the late Noachian. Generally, Hesperian and Amazonian units elsewhere on Mars are poorly dissected by valleys, regardless of slope [Carr, 1996]. More pronounced local and/or regional slopes may have favored valley incision at higher elevations. Grant [2000] suggested that runoff was necessary to accomplish early erosion in the Margaritifer Sinus region (0°–45°W, 0°–30°S) but that infiltration and sapping dominated at the final stages of valley development. This transition would be caused by a reduction in precipitation amounts, and Grant’s interpretation is consistent with mapping of this area. The evidence in favor of precipitation is discussed by Craddock and Howard [2002].

[73] Valleys originating by sapping processes on Mars suggest that the near-surface strata were not frozen prior to desiccation of the aquifers [Carr and Malin, 2000]. If the ground were perpetually frozen at the water table, infiltration and sapping would not have been possible, and runoff valley morphology would dominate. Goldspiel and Squyres [2000] suggest that under precise modeled conditions, flow of water at sapping faces can persist at low temperatures due to advection of heat with the groundwater, even when a permafrost layer exists. However, an exclusive sapping model does not explain the widespread degraded valleys originating at ridge crests with pristine valleys forming later by sapping. The widespread fluvial erosion predates the more focused valley development, suggesting that some mechanism must have supplied water to the entire surface initially and that surface and groundwater flow must have remained possible after the available volume of water declined. This temporal sequence suggests that the temperature regime was at least periodically above freezing during the Noachian and early Hesperian periods in the equatorial highlands. Seasonal drops in temperature would have occurred only toward the southern end of this study area, with the climate remaining warm year-round near the equator. Sapping-type morphology therefore does not suggest a cold (always below freezing) early Mars, regardless of how dry it may have been. Hesperian groundwater flow requires that the late Noachian change in erosional intensity near the equator was due to a drying rather than a freezing event.
[74] Assuming that the temperature varied with elevation according to the Martian adiabatic lapse rate (4.5°C/km), temperatures within the study area may have varied over 12°C (between 1000 and 3700 m of elevation) at any point in time, with additional latitudinal and seasonal variations. This variability may have been adequate for snowfall at higher elevations, but the tropical latitudes and requirement of a thawed aquifer in basins suggest that rainfall was the most common type of precipitation in this area. Furthermore, it is possible that precipitation in the study area was derived from a hypothesized sea in the Utopia Basin to the north [e.g., Parker et al., 1989, 1993; Head et al., 1999]. If so, a change in the areal extent or surface cover of this body of water may have caused a reduction in precipitation amounts within the study area. Again, assuming that the surface was not frozen at 2000 m of elevation, a nearby location at ~3500 m would have been almost 25°C warmer on average, neglecting other influences on the surface temperature.

[75] The critical flaw in the “cold, dry” early Mars model is that there is no mechanism offered to explain the highly eroded state of large features, broad catchments, and the anomalously low populations of impact craters. In a landscape affected by ~700 Myr of cratering, the valleys we observe are only the most recent to develop, and these have been modified by ~3.8 Gyr of slower erosion by small impacts and eolian transport. Valley morphology alone should not be used to interpret Martian erosional processes during the period of heavy bombardment, although it may be a good indicator of early Hesperian conditions. Furthermore, the presence of highly degraded landforms of considerable size suggests that water volumes available for erosion cannot be constrained simply by measuring the volume of the most recent valleys. To interpret the late Noachian, we must rely on larger, better preserved features.

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Acknowledgments. Robert Craddock and Ted Maxwell provided an invaluable opportunity, insight on mapping techniques, and comments on the resulting text. Jeff Moore and an anonymous reviewer provided constructive comments on this manuscript, and Robert Davis and William Ruddiman reviewed an earlier version [Irwin, 2000]. Financial support was provided by NASA Planetary Geology and Geophysics Program grants NAG5-3931 and NAG5-3932.
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U.S. Geological Survey, Controlled photomosaic of the Mare Tyrrennum Southeast Quadrangle of Mars, scale 1:2M, Map I-1470, 1982b.


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