MULTIPLE GENERATIONS OF MARTIAN VALLEY NETWORKS: RECONCILING EXTENSIVE FLUVIAL EROSION WITH IMMATURE DRAINAGE SYSTEMS.

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Introduction: Most studies of martian erosion have focused on crater statistics, aeolian landforms and deposits, and valley network morphology. Previous workers have noted that the martian crater population is deficient in craters less than ~30 km in diameter, presumably due to erosion [1], and that ancient martian craters were subjected to different erosional processes than craters on airless bodies [2]. The martian record of craters that are visible in imaging is also deficient between 150-300 km diameter relative to the Moon [1], although many highly degraded or buried craters in this size range are now visible in Mars Orbiter Laser Altimeter (MOLA) topography [3] (Fig. 1). Extensive regions of the martian surface have been resurfaced by airfall deposits [4-7], although some areas retain 20-50 m deep valley networks and other small scale Noachian landforms [8]. Martian valley networks have a similar appearance to some terrestrial arid-zone counterparts. However, martian drainage densities are spatially variable and can be quite low [9], appearing highest on crater walls and other steeply sloping terrain [8].

MOLA topography and *Viking Orbiter* imaging also show numerous remnant highland massifs, with hundreds of meters of vertical relief and relatively steep sides (Fig. 1). These features and the degraded impact basins collectively suggest that the extant martian valley networks and impact craters represent only a small fraction of the total erosion and deposition that has affected the martian highlands. Here we describe evidence that martian highland erosion was accomplished by multiple generations of valley networks, which were disrupted and buried by cratering, airfall deposition, and basin infilling. This interpretation reconciles observations of extensively eroded terrain with the limited development of valley networks.

Extensive fluvial erosion: Observations of valley networks in the Terra Cimmeria/Terra Sirenum constrain our understanding of erosional processes:

1) Erosional processes could be focused at specific locations, rather than representing ubiquitous delamination or burial. Crater rims are landforms with known original geometries, and are often widely breached on the side that is downslope relative to pre-crater topography [8] (Fig. 1). This suggests that crater degradation was accomplished by a through-flowing fluid rather than by a process local to the crater.
2) Slopes on the order of ~1° magnitude controlled the erosional processes, such that sediments were transported down these slopes from elevated areas and deposited on basin floors. It is unlikely that aeolian erosion would deeply mantle only basin floors without ramping onto this gently sloping dissected terrain. Neighboring basin floors commonly do not occupy similar levels, as might be expected for equipotential volcanic flooding [8].
3) Ancient impact basins hundreds of km in diameter were significantly modified, which requires a through-flowing transport medium that is much more voluminous than the transported materials. A parent rock cannot be transported in its entirety by interstitial water, unless the material is largely ice-supported with intermixed sediments.
4) Erosional processes resulted in gradation or planation of the landscape without generating collateral constructional features, such that impact craters were degraded, filled, sometimes exhumed, and ultimately removed from the surface record [1]. These processes created the gently sloping "intercrater plains," which appear unrelated to volcanic constructs.

These observations probably require fluvial erosion as the dominant process during the interval when extensive erosion was taking place. The Noachian period on Mars may have been ~800 Ma long [10], so ample time was available for the observed erosion, even if a relatively arid climate (by terrestrial standards) prevailed.

Burial and disruption of ancient valleys: Is the limited extent and discontinuous nature of the martian valleys the result of precipitation on the surface and later disruption, or of groundwater emerging along subsurface channels? While the answer to this question has severe climatic inferences, the high resolution geologic record that is now available seems to favor the first hypothesis. Valley networks on Mars have variable drainage densities, and although some drainage basins are dissected by valleys to the full extent of the drainage basin, this may not be the case in all regions. The extensive degradation of Noachian impact craters and other high-standing terrain is ubiquitous throughout the highlands, however. Basin deposits are similarly widespread, although they are of discrete size and separated by dissected terrains.

As valley network activity was concentrated during the period of heavy meteorite bombardment [2,8,11], one important process affecting valley networks may have been cratering (Fig. 2). In analysis of drainage basin topography in two study areas in Terra Cimmeria and Terra Sirenum, covering ~5 million km^2 total, we have identified craters that disrupted older through-flowing watersheds [8, in prep.]. These older drainage basins, defined topographically, are dissimilar in form to lunar cratered terrain or martian volcanic regions. In some cases, drainage basins were re-integrated by infilling of the basin by sediment (Fig. 2), ponding of water and overflow of the basin divide, or headward growth of groundwater-fed valleys [8]. The resulting re-integrated valley networks, as well as any networks forming atop the crater or its ejecta, indicate a second stage of fluvial dissection despite occupying part of an older drainage basin. This observation and the occurrence of craters at variable states of degradation suggest that valley networks were continually forming and being destroyed by the cratering process.

Over the longer term, sediment would ultimately be transported to the larger depositional impact basins, despite temporary impounding behind crater-related obstructions. This deposition of extensive plains materials would be expected to bury or aggrade the floors of valley networks that provided the sediment, providing a second loss mechanism.

A third possibility is that episodes of airfall deposition buried valley networks, as suggested by some workers for the Arabia Terra and mid-latitude Terra Sirenum regions on Mars [4,5], as well as parts of the dichotomy boundary [7]. Airfall deposits appear most concentrated in low-standing cratered terrain or at middle to high latitudes, where they can be meters to kilometers thick.

Multiple generations of valley networks: Our observations of martian highland drainage basins suggest that multiple episodes of fluvial erosion occurred in the Terra Cimmeria/Terra Sirenum region. The first generation of valley networks was responsible for the extensive degradation of highland impact basins, removal of small craters from the surface record, gradation of formerly steep slopes, and formation of wide breaches in formerly continuous drainage divides. Although we refer to this erosion as a single generation of networks, the development of that ancient landscape was the result of a continuous process of erosion, disruption, and re-integration of drainage basins. These networks were continually being disrupted by impact cratering globally, as well as spatially and temporally variable contributions from airfall and basin deposition. The second generation of valleys are evident over much of the Noachian highlands, but are spatially more limited than earlier valley networks. These valleys have been degraded by aeolian activity, mass wasting, and impact gardening, but remain visible. A third generation of flow features is of recent origin and of very limited extent, including fresh-appearing intra-crater and intercrater gullies [12].

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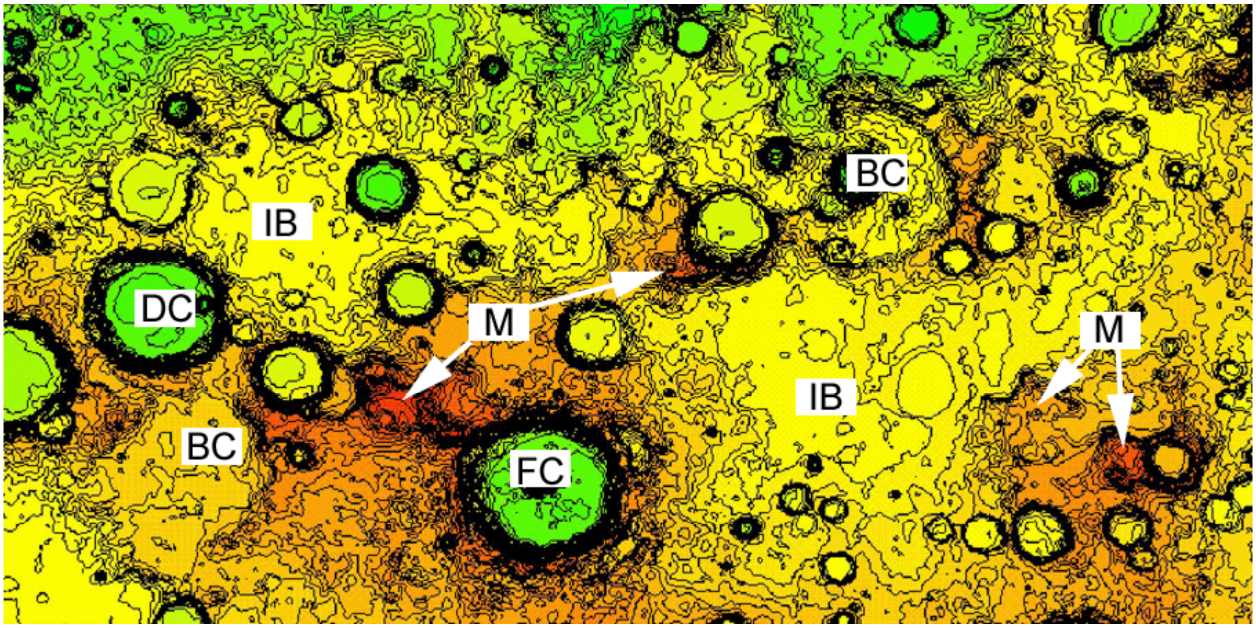

Figure 1. MOLA contour map (100 m interval, 60 cells/degree) of a region in Terra Cimmeria, bounded by 161°E, 173°E, 20°S, and 26°S. The area has been deeply eroded, particularly along its northern margin, where valley network development is extensive. Remnant massifs (M), highly degraded impact basins (IB), impact craters with wide breaches in the rim (BC), degraded craters (DC), and fresh craters (FC) are labeled as examples. This extensive erosion of large craters represents the earliest stage of fluvial erosion and gradation on Mars.

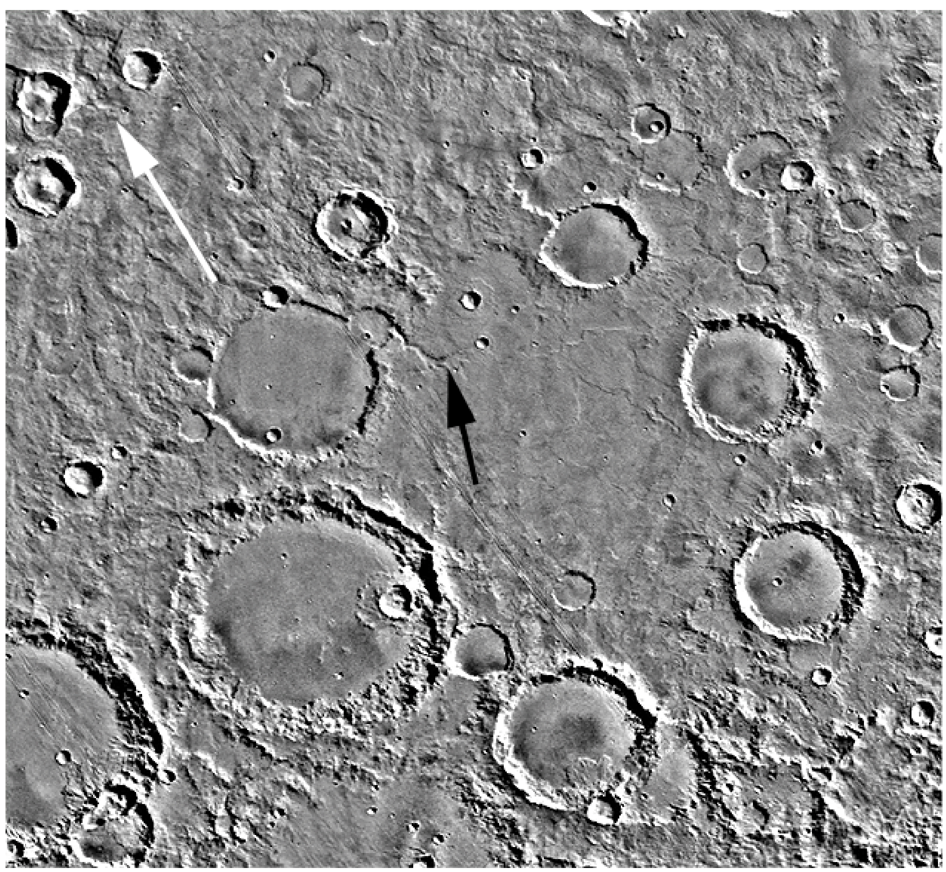

Figure 2. Viking Orbiter MDIM of the northwestern corner of the area shown in Figure 1. Valley networks flowing to the northwest (white arrow) are part of the Al-Qahira Vallis drainage basin. These networks have been disrupted by fresh craters and their ejecta, as valley networks were probably disrupted during heavy bombardment. If flows continued, these valleys would reorganize to accommodate the new obstacles to flow. A highly degraded impact basin floor drained into a superposed degraded crater floor (black arrow). The headward growth of this valley is an example of the reintegration of drainage basins after divides were eroded.