EROSIONAL HISTORY OF THE MARTIAN HIGHLANDS DURING THE NOACHIAN AND HESPERIAN.

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Introduction: The environment and erosional history of Mars early in its history has been a subject of debate since the first global imaging from Mariner 9. We present a synthesis that reflects our conclusion that fluvial erosion was widespread and intensive throughout the Noachian, extending into the Hesperian.

Earliest Noachian: Frey and colleagues [*1*, *2*] have identified numerous muted basins in the highlands and lowlands constituting a population of highly degraded earliest Noachian impacts. They interpret the basins to be buried by later deposits, with much of the extant relief due to differential compaction [*3*]. In the Terra Cimmeria – Terra Sirenum region (including such basins as Gorgonum, Atlantis, Ariadnes) these muted basins often appear to be composed of multiple impacts, but which lack the usual septa rims between adjacent impacts. Adjacent larger basins similarly often lack inter-basin rims. Simple burial and compaction would not suffice to eradicate such rims while retaining well-defined basins. Fluvial erosion, however, can destroy inter-basin rims through a combination of erosion of crater rims and deposition in basin centers [*4*] We conclude that extensive fluvial erosion began very early in Martian history.

Early to Mid-Noachian Fluvial Features: MOC, THEMIS, and MOLA data support suggestions (e.g., [*5*]) that extensive fluvial erosion and deposition occurred throughout the highlands during the Noachian (e.g., [*4*]). Sediment yields were high, infilling >10 km diameter craters with several hundred meters of sediment and creating alluvial ramps at the foot of highland relief, thus implying active chemical or physical weathering. Erosion of massifs and inner and outer crater wall slopes reached close to divides, and drainage densities locally approached terrestrial values (e.g., [*6*]). Integrated drainage networks 100's to 1000's km long were formed were regional slopes existed [*6-9*]. Erosion of highlands may have averaged several hundred meters [*4*, *10*], although rates should have varied with regional slope and local climatology. Estimates derived from depth of incision or basin infilling are probably conservative because continual impact cratering reset the topography and disrupted drainage networks [*6*]. Both during and subsequent to their formation these fluvial features were highly degraded by impacts, eolian transport, mass wasting [*11*], and in many areas by extensive airfall mantling by dust, large-impact ejecta, or volcanic ash (e.g., [*12*]). The statistics of degraded crater infilling and crater counts in the highlands are consistent with degradation primarily by fluvial processes at a rate that was proportional to the rate of new impacts [*13*], implying a gradual decline in fluvial activity.

Noachian environment. The environment that supported such intensive erosion during the Noachian erosion is controversial [*4*], but the prevailing interpretation is that widespread, although episodic, precipitation (as snow or rain) occurred with associated runoff and groundwater seepage. The abundance of alluvial plains at the base of crater walls and the small number of breached crater rims suggests an arid climate, with ephemeral lakes in the larger craters [*4*]. Noachian erosion amounts and rates appear to have been much less than terrestrial values in active tectonic settings and humid temperate landscapes, but may have been commensurate with terrestrial values in hot and cold desert landscapes (e.g. [*4*]). This suggests either an arid climate during the Noachian, or, alternatively, precipitation may have been limited to climatic optima produced by volcanic eruptions [*14*] or large impacts [*15*].

Late Noachian – Hesperian landforms: During this time period a distinct suite of water-related landforms were superimposed upon the earlier Noachian landscape of the highlands.

Fluvial features: Based upon Viking images, [*16*] distinguished between older, 'degraded' valley networks on the equatorial Martian highlands and younger, 'pristine' networks restricted to downstream reaches. Recent MOC and THEMIS images confirm this distinction [*17*, *18*]. Relatively unmodified fluvial features are found widely in the equatorial highlands. Sparse, arroyo-like networks incise 20-200 m into onto earlier Noachian fluvial deposits. The incised channels seldom extend headward onto crater walls or upland slopes, but they can extend far downstream, rejuvenating the Noachian drainage paths. Although [*16*] described the channels as 'pristine', MOC NA images show that they were modified by cratering, mass wasting, and eolian deposition, but to a lesser degree than the Noachian network [*11*].

In contrast to Noachian fluvial activity, the runoff incising the 'pristine' channels required larger source areas to collect sufficient discharge to erode. Sediment loads from headwater areas were low, allowing channel incision into earlier fans. MOC NA and Odyssey Thermal IR imaging of the incised valleys commonly reveals a light-colored, high thermal inertia layer that caps the tops of the valley walls bordering the incised valleys. This suggests that resistance of the capping unit may also have contributed to limiting the areal extent of the late incision. Flows were large and long-lasting enough to permit up to 200 m of incision into presumably resistant materials of the Isidis rim massifs. Deltaic sediments deposited by this upland incision record continuous or recurrent flows of moderate magnitude [*19, 20*]. The volume of the deltas appears to be commensurate with the volume of incised valleys eroded during this time period [*19*]. The 'pristine' fluvial features are the last major fluvial erosion event throughout the highlands, and probably date to latest Noachian and early Hesperian (e.g., [*16*]).

The walls of some deep, late Noachian craters feature deep, incised reentrants and fan complexes presumably of equivalent age [*18, 21*]. These are similar to, but much larger than, the modern gully systems on some mid-latitude crater walls [*22*].

The morphology and possible climatic environment of this suite of late stage fluvial features, and possible climatic environments, are more fully presented in [*17, 18*].

Correlative features: The early outflow channels appear to date to this time period. In particular, Ma'adim Valles and associated deposits in Gusev Crater may be Late Noachian-Early Hesperian [*23*], although [*24*] place the valley-forming flows later in the Hesperian. [*23, 25*] hypothesize that this valley originated by overflow of a large highland lake basin. It this interpretation is correct, a strong hydrologic cycle characterized this time period. More restricted ice-covered lakes may have persisted in this region well into the Hesperian [*26*].

Thick deposits of layered sediments of approximately early Hesperian age occur in a number of crater basins surrounding the north and east side of Hellas Basin, including Millochau [*27*] and Terby Craters. [*28*] suggest that the Hellas Basin hosted a deep, ice-covered lake at this time.

Noachian-Hesperian transition environment. The contrast in erosional style between the widespread Noachian erosion and the more limited 'pristine' channels indicates different climatic regimes. [*17, 18*] examine several scenarios for this change of erosional style, including headward migration of knickpoints by sapping (favored by [*16*]), low intensity but continuous precipitation, and basal melting beneath a thick ice cover [*29*]. [*17*] concluded that the limited headward extent of channel incision was best explained by runoff from snowmelt, with development of duricrusts as a contributing factor. Alluvial fans formed during this time period appear to lack the secondary drainage that occurs on most terrestrial alluvial fans that results from post-depositional runoff erosion. This suggests that the source of water for these fans was restricted to the contributing basins on the crater headwalls. Such headwall alcoves might be natural traps for snowfall. A cold climate with relatively abundant snowfall is also consistent with the possible occurrence of large, possibly ice-covered lakes on the highlands and in Hellas at this time. Runoff might have occurred during favorable obliquity conditions. In addition, the Hesperian marked a peak in volcanic activity (e.g., [*30*]), possibly contributing to greenhouse warming and water inventories [*31*]. Although impact-induced climate optima [*15*] might aid either enhanced precipitation or snowmelt, the presence of long-lived deltas suggests volcanism or orbital mechanics controlled the Noachian-Hesperian climate or else prolonged the effects of impact-produced climate excursions.

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