**Introduction:** Mars has 29 km of topographic relief, much of it related to volcanoes, Noachian impact basins, and the pre-Noachian crustal dichotomy. Tectonic relief-forming processes have been much more localized on the single-plate planet Mars than on the Earth, leaving most of the highland crust intact (aside from cratering) throughout its visible geologic record. The long-term tectonic stability and aridity of Noachian Mars allowed expansive arid-zone geomorphic surfaces to develop over hundreds of millions of years. Here we describe the three major geomorphic features that have developed in the Noachian intercrater areas: escarpments, pediments, and plains; and we review how similar geomorphic surfaces form on Earth. The characteristics of these features place strong constraints on the ambient Noachian paleoclimate.

**Geomorphic Features:** Noachian intercrater surfaces present largely as escarpments, gently rolling terrain, and flat basin-filling plains, all of which are deficient in small craters relative to the Moon [1]. The early study by Malin [2] based on Mariner 9 imagery showed that many intercrater surfaces are layered. High-resolution datasets have shown that these plains are more complex than early data suggested [3].

Inselbergs or monadnocks are positive-relief bedrock outcrops, often remnants of old impact structures or volcanic features on Mars. The escarpments that surround many inselbergs and crater interiors formed mostly in regolith and are thus usually below the angle of repose. They tended to retreat linearly, rather than becoming deeply gullied and embayed. This pattern of erosion is consistent with the overall reduction of high-frequency relief in the Noachian landscape and suggests limits on fluvial and aeolian erosion.

Pediments are gently sloping, extensive erosional surfaces with low net erosion or deposition. Pediment Associations generally include an erosional highland portion, a pediment, and a depositional plain [4]. On Mars, they are typically underlain by regolith and have a net loss of small craters.

Depositional plains formed in craters and larger basins, many of which are more ancient buried craters. Sediment was preferentially moved toward these long-term depositional centers, and the burial of smaller and larger craters was more complete in these areas.

**Pediments and Plains:** On Mars, Noachian intercrater surfaces formed over a long period of time in a relatively stable tectonic setting. The Early Noachian highland surface contained many large craters, which were thickly mantled by ejecta from the Hellas, Isidis, and Argyre impacts in the Early and Middle Noachian Epochs. These ejecta blankets also became cratered. Crater degradation during the Noachian Period included radial retreat of interior wall escarpments, smoothing of ejecta surfaces, and loss of small craters, which led to an overall smoothing of intercrater surfaces. Bedrock outcrops were eventually reduced to inselbergs or knobs of regolith.

A careful application of the geomorphic concept of pediplaination to the Noachian-age intercrater plains is appropriate. Pediments are low-gradient, low-relief, erosional bedrock surfaces that often form through retreat of escarpments in arid regions. Pediplains are coalesced pediments. In contrast to peneplains, the term does not imply base level control. In even a weak fluvial regime, the lack of vegetation on Mars should have discouraged accumulation of thick sedimentary cover on uplands, leading to a strong contrast between gently sloping erosional pediments underlain by regolith and flat depositional plains with thick sediment. Pediments serve as long-term sources of sediment without becoming deeply dissected.

Pediments in the Martian highlands appear to have developed in a regime that was mostly below some intrinsic threshold for fluvial erosion, potentially due to low rates of rainfall (or snowmelt), high rates of infiltration, or some combination. An intrinsic threshold may be exceeded by deterioration of resistance (i.e., local mass wasting, chemical or textural weathering or pedogenesis) rather than an increase in driving forces [5], but the latter (i.e., channeling, fluviation) appears to have applied more preferentially on Late Noachian to Early Hesperian Mars. In general, erosional regimes with no corresponding uplift tend to generate more stable surfaces [6].

Pediment surfaces that degrade slowly are bounded by thresholds of erosion, those of channelized fluvial flow on the one hand or surface stability on the other (i.e., net input of sediment matches losses over time). Duricrusts, interstitial phyllosilicates, hydrated silica, and other secondary materials can form in these settings.

The Martian highlands are a multibasin landscape that does not appear to have experienced integrated drainage until around the Noachian/Hesperian transition, and then primarily on long regional slopes [7]. Liquid water accomplished little channeling (flows above a threshold for erosion) and perhaps more
sheetwash, infiltration, dissolution, recrystallization, and chemical weathering. Local aeolian redistribution of sand and fines may have helped to fill small craters.

Terrain Diversity: Libya Montes, the mountains in the southern periphery of Isidis basin, consist of high and rugged relief. Mesas and knobs are typically bounded by escarpments, and enclosed basins are common. This area represents early development of pediments and plains in a high-relief landscape.

Terra Cimmeria represents lower rolling relief and more extensive development of regolith. Slow weathering of materials in place, with weathering generally exceeding transport, produced sediment across swale surfaces. In landscape evolution modeling by Matsubara et al. [8], the intercrater surfaces aggrade over time due to uplift of crater rims and deposition of ejecta blankets, which are never completely removed. Low areas accumulate thick sedimentary deposits. Very slow erosion preferentially moves fine materials toward regional basins, infilling craters and producing local deposits.

Noachis Terra represents lower relief and regional slope. Slow Noachian physical disintegration, chemical weathering, and erosion formed regolith pediment surfaces and depositional plains. Most of the processes for reduction of relief were long-term and extremely slow, remaining below thresholds of erosion most of the time.

Geologic and Climatic Implications: Impact cratering produced regolith including breccias and melt glasses, which served as the substrate for later geomorphic processes. Volatiles introduced by impacts and volcanism contributed to a thicker early atmosphere, but surface water is expected to have migrated to subsurface aquifers and polar cold traps. Evidence for an active water cycle at times appears to conflict with limited drainage density and other measures of the immaturity of fluvial networks, suggesting that the water cycle was variable. Polar storage and episodic release of volatiles due to variations in axial obliquity may explain the apparent pulses of fluvial activity in the geologic record.

The Martian highlands were apparently more arid during the Noachian Period than around the Noachian/Hesperian transition, as shown by the development of extensive geomorphic surfaces with little fluvial dissection [9]. There was, however, enough water and time to achieve significant cumulative weathering and erosion.


Noachis Terra Study Area: Showing bedrock in-selbergs (dark brown), lava flow (red), pediment areas (green and gold), and depositional plains (grey).