IMPLICATIONS OF FLUVIO-LACUSTRINE LANDFORMS TO THE CLIMATE EVOLUTION OF MARS.

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Introduction: Nearly 50 years of exploration has given us more information about Mars than any other planet, yet many uncertainties remain about the evolution of its surface environment. Here we review both the known and enigmatic aspects about climate and surface processes of Mars from the earliest Noachian into the Amazonian We highlight with bullets some of the outstanding unresolved issues.

Earliest Mars: The surface environment between the formation of the crust and the crustal dichotomy until the end of the major basin-forming impacts at about 4 Ga is highly uncertain. Broad, >300 km diameter basins (QCDs) are putatively scattered throughout the cratered highlands and are much shallower and more muted than fresh craters. The processes that degraded these QCDs are uncertain but may include crustal relaxation and mantling by airfall deposits, lava, and ejecta from major basins. The degree of involvement of fluvial and lacustrine processes is uncertain.

Mid to Late Noachian: The style of crater modification during this epoch is very different than that modifying the QCDs. Craters of this age are generally strongly degraded and infilled, lack ejecta textures and raised rims, but retain sharply-defined interior rim slopes. These characteristics are most consonant with fluvial erosion being the dominant degradation process. Craters in the 20-50 km diameter range are generally infilled with 0.5-1 km of sediment (and locally perhaps by lava). Despite the intense crater degradation, drainage systems appear to have mostly been confined within local to regional basins rather than exhibiting integrated drainage. This suggests an arid climate. Phyllosilicate minerals occur in isolated exposures on the cratered highlands, particularly on crater rims and central peaks, suggesting a subsurface origin.

- *Weathering products.* Is the paucity of upland phyllosilicate mineral exposures due to the lack of a vegetation cover discouraging deep chemical weathering except within sedimentary basins despite a wet surface environment? Is it simply the function of preservation or exposure?

The Late Noachian-Early Hesperian Transition. Crater-count dating indicates that the erosion of the major valley networks ceased at about the Noachian-Hesperian (LN-EH) boundary. The sharp incision of the valley networks 50-300 meters below broad upland surfaces suggests that most of the erosion forming the networks occurred during a relatively brief time period of a climate considerably wetter than that of the Mid Noachian.

Because of the widespread occurrence and integration of the networks, their extension nearly to divides, and the need for appreciable discharges to erode the valleys and transport the eroded sediment through networks up to several thousand kilometers in length, runoff from precipitation was required. This runoff could have resulted directly from overland flow or more indirectly from snowmelt or groundwater discharge. Scaling of discharges from the dimensions of channels locally exposed in valley bottoms indicates that formative discharges were probably equivalent in magnitude (but not necessarily in frequency) to mean annual floods in terrestrial rivers of equivalent contributing area. The occurrence of exit-breaches in craters and the runoff necessary to form large networks indicates that the climate had to be at least as wet relative to evaporation (perhaps intermittently) as that that occurred in the southwestern Great Basin US during the late Pleistocene, when large lakes occupied the major depressions.

Although the majority of the well-defined valley networks occur in the equatorial region, valley neworks extend well into the high latitudes, at least partially underestimated in inventories because of post-Noachian modification. Erosion of the valley networks would have required only a few hundred thousand to a few million years if runoff occurred as result of occasional storms and annual snowmelt events as is characteristic of terrestrial landscapes.

- *Climatic environment.* Because only ~1 Ma of terrestrial equivalent semi-arid climate was required to accomplish erosion of valleys occurring from the Mid-Noachian to Early Hesperian (>200 Ma), was the Martian climate very arid or were there brief interspersed epochs of fluvial activity?
- *Water inventory and distribution.* Precipitation requires appreciable surface water/ice storage as an evaporative source and an active hydrologic cycle. Hydrologic modeling suggests that ~20% of the highlands may have hosted lakes during the excavation of valley networks. But this accounts for only a few meters of water globally averaged. Argyre and Hellas

probably hosted deep lakes, but the depth, extent, and hydrologic involvement of a northern ocean is uncertain.

- *Rarity of depositional landforms in basins.* The well-known Martian alluvial fans and deltas appear to have been formed well after the main period of valley network erosion (see below). Obvious alluvial fans and deltas of LN-EH age are rare to non-existent in the obviously highly infilled craters and basins of this age. Degraded crater floors commonly slope ~0.5 degrees toward their centers, but this could be the result of sediment consolidation. Some crater floors (e.g., Dawes) are very flat despite intricately dissected crater walls. Lava infilling may account for some of these flat floors. If most large craters hosted shallow lakes, as suggested by the hydrologic modeling, redistribution of sediment could create very flat floors as in the possible terrestrial equivalents of lakes Bonneville and Lahontan. Abundant fine sediment carried in suspension and varying lake levels could also smooth out depositional landforms.
- *Lack of glacial landforms.* If the Noachian environment were barely warm enough to support precipitation, higher latitudes and higher elevations might have hosted thick ice accumulations as sinks for much of the global water inventory. But Noachian and LN-EH glaciation has not been conclusively identified.
- *Paucity of fluvial activity in northern Arabia.* This region, below -1.5 km elevation, is strikingly deficient in valley networks compared to the highlands. A few enigmatic fluvial landforms occur in this region, including Mawrth Valles; an unbranched, constant-width channel with an undulating profile; and an early outflow channel. Possible reasons for the paucity of valley networks are a deep early ocean or the presence of a mantling of ash, sediment, or ice subsequently removed. Regional topographic control on precipitation is an additional possibility. The Noachis Terra region similarly contains few fluvial landforms.

Late Hesperian/ Amazonian (LH-A). Crater counting using small craters in high-resolution images indicates that most of the striking alluvial fans and deltas identified in previous studies as LN-EH actually date to the LH-A time period. In addition, the mid-latitudes contain numerous shallowly incised valleys in scattered locations (mid-latitude valleys, or MLV's) that are generally short compared to the valley networks and often have few to no tributaries. The major outflow channels formed during this time period and the south polar region hosted a large ice cap.

- *Global or local water sources.* Two end-member scenarios have been proposed about the timing and water sources for the LH-A fluvial features. The first is that there were several local to regional runoff events during the LH-A period resuting from spatially-limited causes such as the direct and indirect effects of large nearby impacts and local but intense precipitation from evaporation and convection from short-lived open water sources. The other end-member is one or a few global runoff episodes, perhaps occasioned by redistribution of water from ouflow channel floods as short or long-term accumulation of snowfall in the Martian highlands, followed by epochal or annual meltwater runoff.
- *Hydrologic and geologic environment of alluvial fans.* A host of unresolved issues surround the alluvial fans. Why are the fans only found in relatively large, deep (LN-EH age) impact craters (orographic effects on precipitation? Minimum steepness and size of source areas on crater interior rims?). Why do the fans only source from limited areas on host craters? The fans clearly record a history of multiple flows over an extended period of time. Flows were sufficiently intermittent and short-lived that deep lakes did not form in the host craters. Large fans are limited to the equatorial regions, suggesting a climatic control. Wind has scoured the surface of some fans, creating inverted relief, indicating that the at least some of the fan sediments are dominantly granule size and smaller. HiRISE images also show few meter-scale boulders on the fans.
- *Delta formative environment.* The relatively few deltas are fed by more extensive source areas than the fans. Some may have been deposited by reactivation of LN-EH valley networks. Although deltas such as Eberswalde could have been formed by constant discharges over a span of a few tens of years, as long as water could efficiently drain (evaporate?) from the crater, a more likely scenario is intermittent discharges over a period of several thousand years. Discharges to the deltas were apparently large and continuous enough to have caused lakes in their hosting basins.
- *Mid-latitude valley environment*. MLVs in Newton Crater are up to tens of kilometers in length but appear to have been sourced from the crater headwalls. Although sourcing of the flows from snowmelt has been suggested, hydrologic analysis suggests that flows were of a magnitude that is hard to explain from smowmelt. It is uncertain whether flows in MLVs were single or multiple events. Flows in Newton were not sustained long enough to create a deep lake. Some MLVs appear to have flowed over low topographic divides.