INEFFICIENT FLUVIAL EROSION AND EFFECTIVE COMPETING PROCESSES: IMPLICATIONS FOR MARTIAN DRAINAGE DENSITY.
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Introduction: Widespread valley networks in the Martian highlands are the most definitive evidence that running water modified that surface during the Noachian and early Hesperian periods [1] (>3.5 billion years ago [2]), although the implications of these valleys with regard to a warmer paleoclimate are uncertain. Supported by difficulty in modeling a warm atmospheric greenhouse [3], analogy with terrestrial box canyons has been used to support groundwater sapping rather than runoff from precipitation as the headward erosion process [4,5]. Alternatively, we show here that low drainage densities and poor tributary development are an inherent characteristic of past runoff erosion on Mars. Per unit precipitation, fluvial erosion would be at least 25–50% less efficient on Mars than on Earth, particularly in Martian headwater regions where runoff erosion competed with efficient cratering, infiltration, mass wasting, and sediment transport by wind.

Inefficient Fluvial Erosion: Fluvial processes have been modeled empirically and theoretically on the Earth [6–9] and can be scaled for Martian gravity (0.38 of Earth). Fluvial channels can erode either bedrock or poorly consolidated sediments (alluvium), so here we examine erosion processes for both consolidated and unconsolidated materials.

In alluvial channels, erosion occurs when flows impart a critical shear stress τ_{cr} (N/m^2) to the surface,

$$\tau_{cr} = \rho g H S, \tag{1}$$

where ρ is fluid density (kg/m^3), g is gravity (m/s^2), H is fluid depth (m), and S is slope (m/m). For channels where width W (m) is much greater than depth, discharge Q (m^3/s) can be calculated as:

$$Q = HWV = H^{5/3} S^{1/2} g^{1/2} W K_n n^{-1}, \tag{2}$$

where V is mean velocity (m/s), K_n is a constant, and n is the Manning roughness coefficient. As a Martian flow would be 1.3 times as deep and would have 25% lower velocity than a terrestrial flow of the same discharge per unit width (Q/W), τ is 50% lower on Mars for the same discharge ($\tau \propto g^{0.7}$). The lower shear stress suppresses the sediment transport rate q_s (m^3/ms) for a variety of flow conditions, as given by Yalin [8]:

$$\Phi = \frac{q_{sb}(1-\mu)}{g^{1/2} d^{3/2} (S_s - 1)^{1/2}} = \left(\frac{1}{\Psi} - \frac{1}{\Psi_{cr}} \right)^P,$$

$$\text{where } \frac{1}{\Psi} = \frac{\tau}{\rho_f g (S_s - 1) d}. \tag{3}$$

In equation (3), Φ and Ψ are dimensionless parameters, μ is alluvium porosity, d is the sediment grain size (m), S_s is the specific gravity of the sediment, and P is a scaling coefficient. The sediment transport rate scales with gravity as $q_s \propto g^X$, where $X \approx 0.26$–0.64 depending on flow conditions, yielding transport rates that are ~25–50% lower for Mars for the same discharge. Unconsolidated sediment becomes mobile and suspended on Mars given slightly lower discharges than on the Earth [9], but for small Martian valleys, 1.3–2.0 times more water is required for the same amount of erosion.

In channels floored by bedrock or boulders from any source, including impact ejecta, erosion requires the antecedent chemical or mechanical breakdown of the bed material. The erosion rate E (m/s) is related to to slope and drainage basin area A (m^2) as:

$$E = K_e (K_a^{(1-b)} K_w^{-1} \rho A^{e(1-b)} (gS)^f - \tau_c) \tag{4}$$

where K_e is the efficiency of the incision process, K_a relates discharge to area, K_w relates discharge to channel width, and b, e, and f are variable scaling exponents [6]. The fluvial erosion rate for bedrock also scales with $g^{0.7}$ and would be 50% lower on Mars, because the lower shear stress and flow or particle velocity on Mars impart less energy to the channel bed. The critical shear stress for bedrock erosion could also limit development of headwater valleys. Equation (4) also holds that the bedrock fluvial erosion rate decreases with more resistant geologic materials (low K_e), higher infiltration rates and/or low precipitation intensity (low K_a), and lower area or slope. For ephemeral streams in terrestrial drylands, K_w and b are typically higher, and K_a and e are lower than in humid regions [10], all of which would further inhibit the erosion rate (beyond the effect of gravity) on an unvegetated, arid (but wetter than present), early Mars.

Effect on Drainage Density: Inefficient (at most 50–75% of terrestrial efficiency) fluvial processes would suppress Martian drainage density D (m/m^2), which depends heavily on small headwater valleys. Most studies have reported D on the order of ~0.01 to 0.3 for eroded surfaces on Mars [e.g., 11–13], which is less than values commonly observed in terrestrial humid settings dominated by runoff erosion [14]. Vegetation does not impede aeolian deflation on Mars, so sand produced by weathering processes would be transported into fluvial valleys by wind. Headwater valleys with small contributing area and low discharge would be less able to remove this added sediment load, particularly given the general inefficiency of fluvial erosion on Mars. Duneforms would impede development of headwater valleys, and the many smaller craters would preferentially disrupt smaller valleys. Competing processes would be particularly effective in a climate with only seasonal or episodic precipitation. For these reasons, undissected interfluves are an expected and observed feature of all but the most efficient (steepest) Martian valley networks.

In addition to inhibiting fluvial erosion rates, climatic influences also directly affect drainage density [15]. To incise a channel, adequate water must be collected from a critical contributing area A_{cr} (m^2) to transport the substrate particles [7]:

$$A_{cr} = \frac{(HS)_{cr}^{\ 5/3}}{(R-I)nS^{7/6}}, \tag{5}$$

where $(HS)_{cr}$ is the critical product of depth and slope necessary to move a given particle, R is precipitation intensity (m/m^2), and I is infiltration capacity (m/m^2). Drainage density is inversely related to A_{cr}. From equation (5) we see that A_{cr} is greater (D is lower) given lower precipitation intensity, higher infiltration capacity, shallow slopes, and/or a coarse-grained or cohesive material. The terms R and I are unknown for early Mars, but precipitation intensity is generally lower for cooler climates owing to less atmospheric convection and water vapor capacity. Infiltration capacity is high for physically weathered surfaces such as impact crater ejecta. We can therefore qualitatively expect that the term (R–I) was low on early Mars relative to much of the Earth, and that A_{cr} was correspondingly higher than in terrestrial warm, humid climates.

For ancient valley networks to be included in modern drainage density measurements, the valleys must also have been large enough to remain preserved against 3.5 billion years of subsequent impact gardening and aeolian infilling processes [12,15]. The Martian surface has become saturated with small craters of <40 m diameter since the Noachian, reworking a layer ~10 m deep [16], so Martian valleys would have to be incised >10 m deep to remain preserved against this process alone. Noachian valleys smaller than ~20 m deep and ~100 m wide would not be preserved in any recognizable form, consistent with observations from high-resolution imaging [5].

Post-Noachian processes severely limit the area on Mars that could exhibit high D. From equation (5), as S approaches 0, the critical area and/or water depth approach infinity and fluvial channel incision and sediment transport do not occur. Modern terrestrial flow paths are observed where $S \approx S_{cr}$ for a given H (e.g., on depositional surfaces or drainage basins that have been regraded by the fluvial network), whereas preservable valleys on Mars would require higher slopes or larger contributing areas that would support deep channel incision. As the Martian highlands contain many enclosed basins from prior cratering [12], a relatively large area would experience net deposition from fluvial processes, and deep valleys could not be incised in those areas without late-stage increase in discharge or gradient. These requirements hold that valleys should (and do) appear clustered and a large area of the Martian surface should have low or zero drainage density relative to the Earth. As expected from equations (4) or (5), deep Martian valley networks with small contributing areas and high drainage density occur primarily as steep gullies on degraded crater walls or other slopes [12,15].

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