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Substrate controls on valley formation by groundwater on Earth and Mars

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ABSTRACT

Valleys with amphitheater-shaped headwalls on Mars have been used to constrain early martian hydrology and, importantly, have been interpreted as eroded from groundwater-fed springs, which might have constituted hospitable environments for life on ancient Mars. Groundwater-fed springs have carved valleys in rare examples on Earth; however, these valleys are in loose sandy sediments and weakly cemented sandstones, and it is unclear whether groundwater is also an effective erosion agent in the basaltic bedrock and boulders within martian valleys. Here we develop a theoretical model for the efficiency of valley formation by groundwater-seepage erosion, and we show that valley formation by groundwater is limited to narrow ranges in aquifer permeabilities and sediment sizes that are characteristic of loose or weakly consolidated sand. The model is validated against groundwater-carved valleys in loose sand in physical experiments and natural valleys on Earth. Applied to valleys near Echus Chasma, Mars, our model precludes a formation by seepage erosion due to the inferred basaltic bedrock; instead, the model implies that surface flows of water were required to form the valleys, with significant implications for the hydrology, climate, and habitability of ancient Mars.

INTRODUCTION

The decline of hydrologic activity at the surface of Mars from the late Noachian to the early Amazonian is one of the most dramatic examples of climate change known in the solar system (Bibring et al., 2006), and it appears to be genetically related to the loss of a once-thicker CO_2 atmosphere (Wordsworth, 2016). Although the precise timing of atmospheric thinning and the loss of surface-water activity remains unclear (e.g., Hu et al., 2015; Lapotre et al., 2016a; Wordsworth, 2016), liquid water flowed throughout the Hesperian and into the early Amazonian period, at least through the episodic input of liquid water from the subsurface to the surface (Sharp and Malin, 1975; Harrison and Grimm, 2005). In particular, amphitheater-headed valleys have been interpreted as indicators of an increased relative contribution of groundwater to erosion from the late Noachian into the Hesperian period (Harrison and Grimm, 2005). These valleys, pending a rigorous understanding of their formation mechanism, thus represent a prime target to temporally resolve the fate of surface liquid water on early Mars.

Although groundwater might play a role in river network geometry (Seybold et al., 2017), only a few valleys on Earth (e.g., Schumm et al., 1995) are thought to be eroded exclusively from seepage erosion (e.g., Lamb et al., 2006). These valleys have steep amphitheater heads and roughly uniform widths. The planform geometry of valleys is readily observable from satellite imagery and thus often used to constrain hydrologic regimes; in particular, amphitheater-headed valleys are commonly assumed to be a signature of groundwater-seepage erosion (Sharp and Malin, 1975). However, valley morphology is not a unique indicator of formation process (Lamb et al., 2006). Groundwater seepage (Schumm et al., 1995), overland flow (Lamb et al., 2008), and combinations of the two (Laity and Malin, 1985; Pelletier and Baker, 2011; Amidon and Clark, 2015) have all been proposed to explain the formation of amphitheater-shaped valleys on Earth and Mars (Fig. 1), and they have distinct astrobiological implications. Specifically, spring environments have been proposed as possible refugia for martian life and are thought to have high organic-preservation potential (Farmer and Des Marais, 1999). Thus, there is a need to incorporate erosion mechanics into paleohydraulic reconstructions to better infer the formation process of amphitheater-headed valleys (Lapotre et al., 2016b) and assess their potential as exploration targets of astrobiological significance.

Following Higgins and Osterkamp (1990), we distinguish seepage weathering (the breakdown and detachment of material at the seepage face) from seepage erosion (the transport of weathered material away from a groundwater-fed spring), which together can lead to the formation of valleys through undermining and upslope retreat of the valley headwall (Dunne, 1990; Lamb et al., 2006). Although previous studies have formulated mechanistic models for seepage erosion in loose sediment (Howard and McLane, 1988; Lobkovsky et al., 2004), there is not yet a model to predict the necessary conditions for seepage erosion to carve a valley, and whether groundwater can carve valleys in sediment of different grain sizes or in different rock types, such as the basaltic rock and boulder rubble that are common to martian landscapes (Tanaka et al., 2014). Moreover,

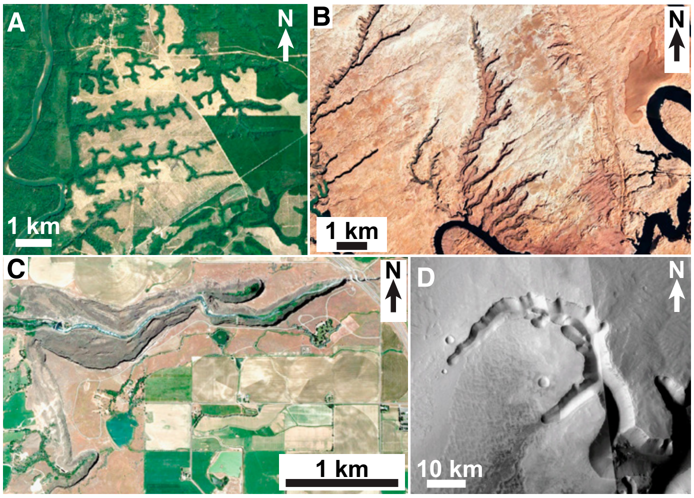

Figure 1. Amphitheater-headed valleys on Earth and Mars. A–C: Landsat satellite mosaics of (A) seepage-erosion valleys along the Apalachicola River, Liberty County, Florida, USA (30.484°N, 84.963°W); (B) valleys carved in Navajo Sandstone near Escalante River, Utah, USA (37.393°N, 110.851°W); and (C) Malad Gorge valleys, Idaho, USA (42.860°N, 114.869°W). D: Mars Reconnaissance Orbiter Context Camera mosaic of valleys near Echus Chasma, Mars (1.194°N, 82.098°W).

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models for martian valleys commonly assume that seepage erosion rates are proportional to groundwater discharge (Howard et al., 1987; Abrams et al., 2009; Pelletier and Baker, 2011)—an assumption that has been verified only for loose sand (Howard and McLane, 1988; Marra et al., 2014).

An alternative hypothesis is that floods of surface water formed the martian amphitheater valleys in basalt; floods have been argued to deliver sufficient water to entrain blocks of basaltic rock, transport boulders downstream, and form amphitheater-shaped headwalls through flood-flow focusing and block toppling at waterfalls (Lamb and Dietrich, 2009; Lamb et al., 2006, 2007, 2008, 2014; Irwin et al., 2014; Lapotre and Lamb, 2015; Lapotre et al., 2016b; Larsen and Lamb, 2016). Although numerical models have been used to argue that amphitheater headwalls are diagnostic of seepage erosion (Pelletier and Baker, 2011), these models do not include the physics of waterfall erosion that have been found to produce amphitheater headwalls. Still, the morphologic similarity between the large bedrock valleys on Mars and those produced by seepage-erosion experiments in sand, and the lack of a physics-based model to demonstrate the feasibility of seepage erosion in basalt, has led to the persistence of the assumption that amphitheater-headed valleys are diagnostic of seepage erosion (e.g., Sharp and Malin, 1975; Harrison and Grimm, 2005; Pelletier and Baker, 2011).

NECESSARY CONDITIONS FOR VALLEY FORMATION BY SEEPAGE EROSION

To investigate the feasibility of seepage erosion in a wide range of substrates, including basaltic rock and granular material of different grain sizes, we formulate a conservative theoretical model that couples equations of groundwater flow and sediment transport. We focus on quantifying the necessary conditions for valley formation by seepage erosion—even if sediment was readily weathered and detached from the seepage face by groundwater discharge, spring flow must be able to evacuate sediment from the valley head to allow valley formation (Lamb et al., 2006). In particular, for sediment substrates, we seek to characterize how grain size influences permeability and sediment transport, which leads to tradeoffs in seepage-erosion potential. Likewise, for bedrock, we expect certain combinations of substrate permeability and sizes of collapsed blocks at the seepage face to be required for valley formation.

Building on previous studies (Howard et al., 1987; Howard and McLane, 1988; Goldspiel and Squyres, 2000; Lobkovsky et al., 2004), we consider a one-dimensional (1-D) drainage basin of length L, with a constant topographic slope S, upstream of a vertical seepage face of height H_c. The latter defines the headwall of a valley of bed slope S_b (Fig. 2). All groundwater is transmitted through the seepage face, as would be the case with an impermeable rock unit at the base of the seepage face (e.g., as in certain regions of the Colorado Plateau, USA; Fig. 1B). We define the seepage-erosion efficiency factor, f, as

$$f = \frac{h_n}{h_{im}}, \tag{1}$$

where h_n is flow depth at the valley headwall and h_{im} is the critical flow depth for incipient sediment motion. When $f \geq 1$, eroded material can be transported, and valley formation by seepage is possible. Conversely, when $f < 1$, seepage is not sufficient to transport sediment and cannot carve a valley. We couple Darcy's law to equations of surface flow hydraulics and sediment transport (see the GSA Data Repository[1]), and we derive an equation that relates f to subsurface flow, aquifer and valley geometry, open-channel flow hydraulics, and sediment transport regime:

$$f^{3/2} = \frac{1}{2}\mathrm{DaRe_p}\frac{H^*}{L^*}\frac{C_f^{1/2}S_b}{R^2\tau_{*c}^{3/2}}\left[\left(1+SL^*\right)^2 - \left(\frac{\tau_{*c}R}{\phi S_b H^*}\right)^2 f^2\right], \tag{2}$$

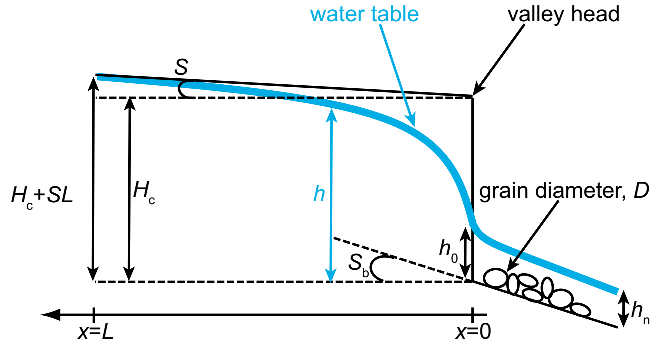

Figure 2. Conceptual longitudinal section of seepage face at valley head. Drainage basin of length *L* drains toward vertical seepage face of height H_c. Topographic slopes upstream and downstream of seepage face are *S* and S_b, respectively. Water table upstream of seepage face, defined by its height *h* above base of seepage face, breaks land line near drainage divide and emerges at height h_0. Sediment of diameter *D* forms by seepage erosion and is mobilized when flow depth in valley, h_n, exceeds critical depth for sediment transport.

where $\mathrm{Da} = \kappa_{eff}/D^2$ is the Darcy number of the flow (κ_{eff} is aquifer permeability and D is sediment-grain diameter), $\mathrm{Re_p}$ is the particle Reynolds number, $H^* = H_c/D$ is a dimensionless valley depth, $L^* = L/H_c$ is a dimensionless basin length, C_f is a bed-friction factor, S and S_b are the upstream and downstream bed slopes, respectively, R is the submerged specific density of the sediment, τ_{*c} is the critical Shields stress for incipient motion of the sediment, and ϕ is porosity of the aquifer (see the Data Repository). The particle Reynolds number, critical Shields stress, and bed-friction factor are parameterized as a function of grain diameter (see the Data Repository), and the other parameters can be estimated from field observations or remote sensing (Table DR1 in the Data Repository).

MODEL VALIDATION WITH EXPERIMENTAL AND NATURAL VALLEYS

We solve Equation 2 for permeability (κ_{eff}) as a function of grain diameter (D) at $f = 1$ to characterize the onset of valley seepage-erosion feasibility. To validate our model, we make predictions using input parameters typical for valleys whose origin is known: (1) physical experiments of seepage erosion in loose sand (Howard et al., 1987; Lobkovsky et al., 2004, 2007; Schorghofer et al., 2004) (Fig. 1A); (2) valleys carved in loose sand by groundwater-seepage erosion in the Florida Panhandle, USA (Schumm et al., 1995) (Fig. 1A); and (3) valleys carved by large-scale floods in fractured basaltic bedrock on Earth (Lamb et al., 2008, 2014; Lapotre et al., 2016b; Larsen and Lamb, 2016) (Fig. 1C). We also compare the model to valleys carved in sandstones of the Colorado Plateau (Laity and Malin, 1985; Howard et al., 1987), for which the relative importance of groundwater-seepage erosion versus surface water is debated (Lamb et al., 2006) (Fig. 1B). Through a sensitivity analysis, our results are found to constitute robust limits on seepage-erosion efficiency despite the 1-D framework and simplified theory, owing to the conservative assumptions made in deriving Equation 2 (see the Data Repository; Figs. DR1–DR6). Finally, because not all grain-size and permeability combinations are found in natural granular materials, we compare model results with empirical relationships between permeability and grain size, using loose well-sorted and weakly consolidated sediment as conservative upper and lower bounds, respectively (see the Data Repository). Because competent rock such as fractured basalt does not follow this relation, we also compiled grain-size and permeability bounds for various locations on Earth to provide insight on realistic parameter combinations (see the Data Repository) (Figs. 3A–3C).

Model results show that seepage erosion for loose, unconsolidated sediment is only possible for sediment sizes within the range of coarse

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[1] GSA Data Repository item 2018174, supplemental text, Table DR1, and Figures DR1–DR6, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org

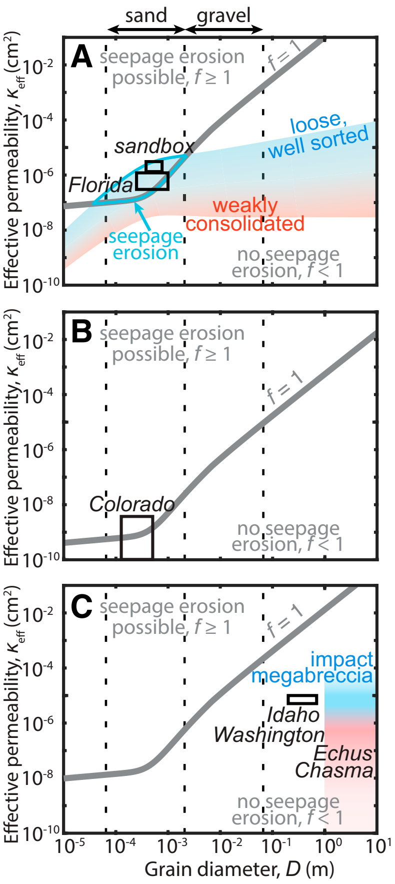

Figure 3. Seepage erosion efficiency: Onset of seepage-erosion feasibility ($f = 1$) as a function of grain diameter and aquifer permeability for physical experiments (sandbox) and Florida Panhandle (USA) valleys in loose sand (A), Colorado Plateau (USA) valleys in sandstone (B), and basaltic valleys on Earth (Idaho and Washington, USA) and Mars (Echus Chasma) (C). Boxes outline reported grain diameter and permeability values (Table DR1 [see footnote 1]). In A and C, we report known permeabilities of weakly consolidated and loose well-sorted sediment as conservative bounds for natural granular substrates, and estimated range of martian aquifer permeabilities with impact megabreccia as upper bound (Clifford, 1993), respectively (see the Data Repository). Line $f = 1$ is at lower permeabilities in B due to steep bed slopes upstream and downstream of the seepage face, which increase hydraulic head and facilitate sediment transport.

silt to very fine gravel. Despite large differences in scale, we find the $f = 1$ boundary for kilometer-scale Florida Panhandle (USA) valleys to roughly coincide in (D, κ_{eff})-space with meter-scale valleys produced in physical experiments (Fig. 3A). For poorly sorted or consolidated sediment, seepage erosion is limited to sand sizes only (Fig. 3A). In general, finer grains are easier to transport, but seepage discharges are insufficient to mobilize the grains due to low permeabilities. Seepage discharges are larger for coarser sediment due to large permeabilities, but they remain below the threshold needed for sediment transport owing to heavier grains. These predictions are in agreement with the independently determined groundwater-seepage origin of both experimental and Florida Panhandle valleys.

For competent rock, seepage erosion is predicted to occur only for very limited grain-size and permeability combinations that are characteristic of unconsolidated or weakly consolidated sand. In the weakly cemented sandstones that contain valleys within the Colorado Plateau, we find that grain sizes and permeabilities place valleys near the onset of seepage-erosion feasibility (Fig. 3B). This result is consistent with the argument that despite efficient salt weathering and enhanced groundwater discharge at the Kayenta Formation–Navajo Sandstone lithological contact (Utah, USA), episodic flash floods are required to flush eroded material away from valley heads (Laity and Malin, 1985; Howard et al., 1987; Lamb et al., 2006). In contrast, and despite some of the largest aquifer permeabilities on Earth (Meinzer, 1927), amphitheater-headed valleys of the basaltic Snake River plain (Idaho, USA) and the Channeled Scabland (Washington, USA) clearly fall within the $f < 1$ regime, inconsistent with a seepage-erosion mechanism, but consistent with field evidence of valley formation by large-scale flooding in those regions (Bretz, 1969; Lamb et al., 2008, 2014; Lapotre et al., 2016b; Larsen and Lamb, 2016) (Fig. 3C). Thus, our new theoretical model is independently validated by experimental and field data, and we next apply it to martian valleys.

APPLICATION TO HYDROLOGY ON EARLY MARS

Groundwater-seepage erosion was shown to be effective in loose sand even in cold martian surface conditions (Goldspiel and Squyres, 2000). However, the steep walls of many amphitheater-headed valleys on Mars appear to consist of competent rock (e.g., Lapotre et al., 2016b). For example, tributary valleys of Nanedi Valles and Nirgal Vallis, Mars, are often cited as evidence for groundwater-seepage erosion solely based on morphology (Harrison and Grimm, 2005), but they are most likely incised into layered volcanic bedrock. Similar tributary valleys near Echus Chasma (Mangold et al., 2008; Lapotre et al., 2016b) (Fig. 1D) consist of Hesperian-age basaltic lava flows, with sub-vertical fractures similar to cooling joints, that break down to meter-scale boulders (Lapotre et al., 2016b). Dendritic channel networks upstream of Echus Chasma valleys are evidence for overland flow, possibly acting in concert with groundwater-seepage weathering and erosion (Mangold et al., 2008), although it is unclear whether channel-network and valley formation were coeval. Using orbiter-based topographic measurements (Table DR1), we find that $f = 1$ for Echus Chasma valleys coincides with that for terrestrial valleys in Idaho and Washington, and that observed block sizes and estimated permeabilities (see the Data Repository) do not permit a groundwater-seepage origin near Echus Chasma (Fig. 3C). Forming these valleys by seepage erosion would require permeabilities approximately ten-thousand-fold greater than those of some of the most permeable basaltic aquifers on Earth, and one-thousand-fold greater than estimates for impact megabreccia (Clifford, 1993). Thus, the formation of valleys near Echus Chasma, as well as valleys in similar rock types on Mars, most likely required surface flows of water.

Weathering could aid seepage erosion (e.g., Luo and Howard, 2008). However, observations of steep walls shedding large boulders indicate that most martian valleys formed in competent bedrock (e.g., Harrison and Grimm, 2005). Erosion mechanics preclude groundwater from eroding valleys in rock unless weathering can render the rock permeability and particle sizes to be similar to loose sand, which may be unlikely on Mars. For example, chemical weathering is slow, and in basalt produces cohesive clays (e.g., Hausrath et al., 2008; Bishop et al., 2018) with low permeabilities that do not permit seepage erosion; freeze-thaw exploits preexisting weaknesses (flow boundaries and cooling joints in basalt) and would thus primarily generate boulders that are too large to transport by seepage; and salt growth would require an unlikely succession and repetition of events (see the Data Repository).

CONCLUSIONS

Most analytical and numerical models (Howard et al., 1987; Abrams et al., 2009; Pelletier and Baker, 2011) for valley formation by groundwater-seepage erosion assume that headwall-retreat rate is proportional to seepage discharge regardless of whether the substrate is loose sand or competent rock. This relation between seepage discharge and erosion is needed to drive a feedback that results in flow focusing at valley heads and valley formation (e.g., Howard et al., 1987). Our analysis indicates that valley formation by seepage erosion can only occur in sand because of its relatively unique mobility and permeability properties, consistent with experimental observations (Howard and McLane, 1988; Marra et al., 2014). In competent rock, we find that a more plausible scenario for large valleys is erosion by overland water flows. Valley erosion by surface flow, rather than by groundwater, has significant implications for the ancient hydrology, climate, and habitability of Mars. Although both valley-formation mechanisms may require similar water volumes, they may involve different water sources, radically different flow discharges, and thus different hydrologic pathways and timescales over which liquid water was thermodynamically stable at the martian surface. By exploiting valley morphology, lithology, and erosion mechanics, our model supports the case for active valley-carving overland flows during the decline of hydrologic activity at the surface of Mars.

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