

PERMEABILITY, RECHARGE, AND RUNOFF GENERATION ON MARS. J. Taylor Perron, Michael Manga, and Michael P. Lamb, Department of Earth and Planetary Science, University of California, Berkeley (perron@eps.berkeley.edu).

The dendritic valley networks dissecting the cratered southern highlands of Mars appear to have been eroded by surface runoff [e.g., 1,2]. Runoff could have resulted from liquid precipitation or from basal melting of snow or ice [3]. In either case, runoff generation implies that the rate of fluid delivery to the subsurface (hereafter referred to as the recharge rate, u_r , with units of $L T^{-1}$) exceeded the rate at which the subsurface could convey it away.

The rate of subsurface flow is controlled primarily by the permeability, k . The permeabilities of geologic materials span 15 orders of magnitude [4], whereas fluid properties and the forces driving fluid flow in typical geologic settings fall within much narrower limits.

Terrestrial landscapes illustrate the influence of substrate permeability on drainage network morphology. In the Western Cascades of Oregon (Figure 1), the altered Tertiary volcanic rocks are highly dissected by runoff-dominated streams. In the more permeable Quaternary volcanics of the High Cascades to the east, spring-fed streams with large contributing areas and few tributaries are common, and drainage density (the total length of channels per unit area) is lower [5]. Because discharge varies little with downstream distance in these spring-fed streams, channel geometry remains relatively constant. In eastern Idaho, the Big and Little Lost Rivers disappear entirely as they emerge from the Paleozoic sediments of the Lost River Range onto the highly permeable basalts of the Snake River Plain. These dramatic examples demonstrate that the potential for surface runoff is closely coupled to subsurface permeability.

If the valley networks were formed by surface runoff, estimates of the recharge rate and subsurface permeability must be mutually consistent and reasonable. The simple calculations below suggest that the geometry of drainage basins on Mars and the range of permeabilities expected for near-surface materials are consistent with recharge rates of the same order of magnitude as those in arid to semiarid regions on Earth. We assume that the ground was not frozen (this is possible as a transient case but seems unlikely as a long-term condition if frequent precipitation or basal melting of snow or ice were also occurring).

Given the topography of a region on Mars where surface runoff appears to have occurred and an estimate of the subsurface permeability, we can place constraints on the rate of recharge by precipitation or

snowmelt. Permeability is related to the specific flow velocity (u) of fluid through a porous medium by Darcy's equation:

$$u = -\frac{k\rho g}{\mu} \frac{dh}{dl} \quad (1)$$

where ρ and μ are the density and dynamic viscosity of the fluid (1000 kg m^{-3} and 10^{-3} Pa s for water), g is gravitational acceleration (3.7 m s^{-2}), and dh/dl is the hydraulic head gradient. As written here, Darcy's equation ignores any anisotropy in k .

Over short timescales (individual rainfall events), runoff will occur if u_r exceeds the rate of vertical infiltration ($dh/dl = 1$). If the shallow subsurface consists of silt-sized particles, k can be as small as 10^{-14} m^2 [4]. This implies $u_r > \sim 3.7 \times 10^{-8} \text{ m s}^{-1}$, or about 3 mm per Mars day. Over longer timescales, perennial runoff (baseflow) will occur if the time-averaged recharge rate to a drainage basin exceeds the rate at which water can leave the basin via subsurface flow. If all the recharge to a basin is focused at the outlet, the condition for baseflow at the outlet is $u_r > uh/A'$, where h is the

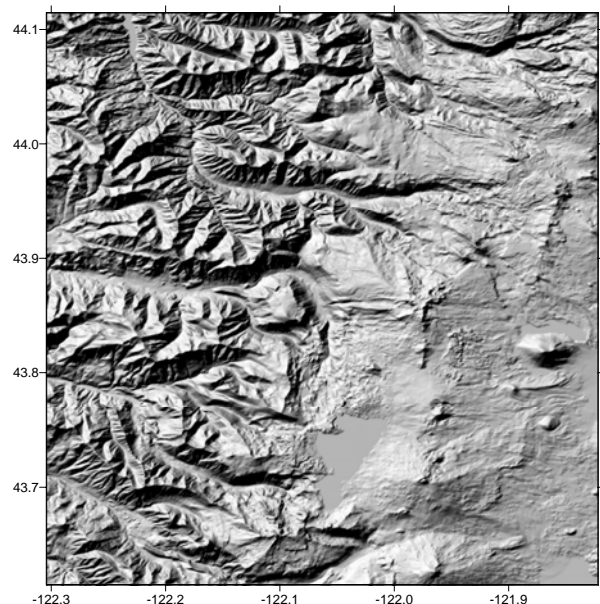


Figure 1. Shaded relief map showing the boundary between intensely dissected Tertiary volcanics of the Western Oregon Cascades and the more permeable, relatively undissected Quaternary basalts of the High Cascades to the east. Axis units are degrees. *Data source: USGS NED*

depth of the permeable layer and A' is the contributing area per unit width (perpendicular to the groundwater flow direction) at the outlet. We will assume $10 < h < 100\text{m}$. A permeable subsurface layer composed of young basalt could have a regional-scale k of up to 10^{-9} m^2 [6]. The heads of the tributaries in a valley network provide an estimate of the size of the smallest basins that experienced frequent runoff. For a tributary head with a drainage area of 100 km^2 , a slope of 0.01 [7], and an outlet width of 100-1000 m (estimated from MOLA topography), the required recharge rate is $\sim 0.02\text{-}2\text{ m}$ per Mars year. Both estimates of the recharge rate (time averaged and instantaneous) are comparable to precipitation rates in the western United States.

If we compare these recharge rates with the eroded volumes of the Martian valley networks, we can get a rough estimate of the length of time required to form the valleys. By analogy with terrestrial rivers eroding basalt, Gulick [8] argued for a (conservatively low) ratio of water volume to eroded rock volume of 1000. For a valley network with an eroded volume of 10^{12} m^3 and a drainage area of $5 \times 10^4\text{ km}^2$ [e.g., 9], a recharge rate of $0.02\text{ to }2\text{ m yr}^{-1}$ would imply at least 10^4 to 10^6 yr of erosion.

The range of permeabilities expected for near-surface materials on Mars suggests that if the valley networks were eroded by surface runoff, recharge rates would have been comparable to those in arid to semi-arid regions on Earth. The low drainage densities of the valley networks relative to terrestrial rivers could reflect high subsurface permeabilities, and the spatial clustering of valley networks [10] could be a consequence of spatially variable permeability rather than local differences in recharge or preservation.

References: [1] Craddock R. A. and Howard A. D. (2002) *JGR*, 107, 5111. [2] Hynek B. M. and Phillips R. J. (2001) *Geology*, 29, 407-410. et al. [3] Carr M. H. and Head J. W. (2003) *GRL*, 30, 2245. [4] Freeze R. A. and Cherry J. A. (1979) *Groundwater*, Prentice Hall, 604 pp. [5] Tague C. and Grant G. E. (2004), *Water Res. Res.*, 40, W04303. [6] Saar M. O. and Manga M. (2004) *JGR*, 109, B04204. [7] Rosenshein E. B., Greeley R. and Arrowsmith J. R. (2001) *LPS XXXII*, Abstract #1921. [8] Gulick V. C. (1993), Ph.D. thesis, Univ. Arizona, Tucson, 146 pp. [9] Gulick V. C. (2001) *Geomorphology*, 37, 241-268. [10] Carr M. H. (1996) *Water on Mars*, Oxford, 229 pp.