Timescales for Terminal Groundwater Drainage from the Southern Highlands on Mars. M. A. Hesse[1,2,3,‡], M. A. Shadab[2,3,4,†] and E. Hiatt[1,3,4,*], [1]Department of Geological Studies, Jackson School of Geosciences, [2]Oden Institute for Computational Engineering and Sciences, [3]Center for Planetary Systems Habitability, [4]Institute for Geophysics, The University of Texas at Austin, Austin TX ([‡]mhesse@jsg.utexas.edu, [†]mashadab@utexas.edu, [*]eric.hiatt@utexas.edu,).

Introduction: Several lines of evidence indicate that Mars once supported surface hydrology in the form of rivers and lakes on the southern highlands [1-3]. Less certain is the existence of a large ocean in the northern lowlands [4, 5]. There is also evidence for a deep globally connected groundwater aquifer beneath the southern highlands that reached the surface at Arabia Terra [6]. However, today all surface water has disappeared and the existence of water in the deep subsurface is uncertain.

Whatever the mechanism of surface water loss [7, 8], it should have led to a slow terminal drainage of any groundwater from beneath the southern highlands into depressions such as deep impact basins and the northern lowlands. Currently, it is not clear how long the subsurface beneath the southern highlands could have retained groundwater after the disappearance of the surface water. Here we develop a simple model for the drainage of an unconfined aquifer in spherical cap geometry to provide first-order estimate of these drainage timescales.

Aquifer Model: We use the transient Dupuit-Boussinesq model to describe the drainage of an unconfined aquifer beneath the southern highlands. We assume the aquifer has uniform thickness, d_{max}, beneath the surface. The drainage timescales are strongly affected by the decay of permeability with depth and here we follow [9] and assume a power-law decay of permeability and porosity with depth, so that $\phi = \phi_0 z^m$ and $k = k_0 z^n$, where z is the height above the base of the aquifer, ϕ_0 and k_0 are constants and m and n are power-law exponents.

We determine ϕ_0 by setting a surface porosity, ϕ_s, and matching the commonly used exponential porosity decay with depth [2] at $z = d_{max}/2$. The resulting power-law exponent is $m \approx 2.5$ and the resulting porosity profile is shown in Fig. 1a. Similarly, we fit the permeability power-law to the commonly used crustal permeability data of [10] scaled to Mars gravity. The resulting vertical property variation in the aquifer is shown in Fig. 1b.

With these parameterizations the azimuthally averaged 1D governing equation for the head, h, on a spherical cap is given by

$$\phi_0 h^m \frac{\partial h}{\partial t} - \frac{1}{R\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{\sin\theta}{R}\frac{K_0 h^{n+1}}{n+1}\frac{\partial h}{\partial\theta}\right) = 0,$$

where R is Mars' mean radius, $K_0 = k_0 \rho g_{Mars}/\mu$ is the hydraulic conductivity coefficient and θ is the southern co-latitude. We consider a domain from the south pole

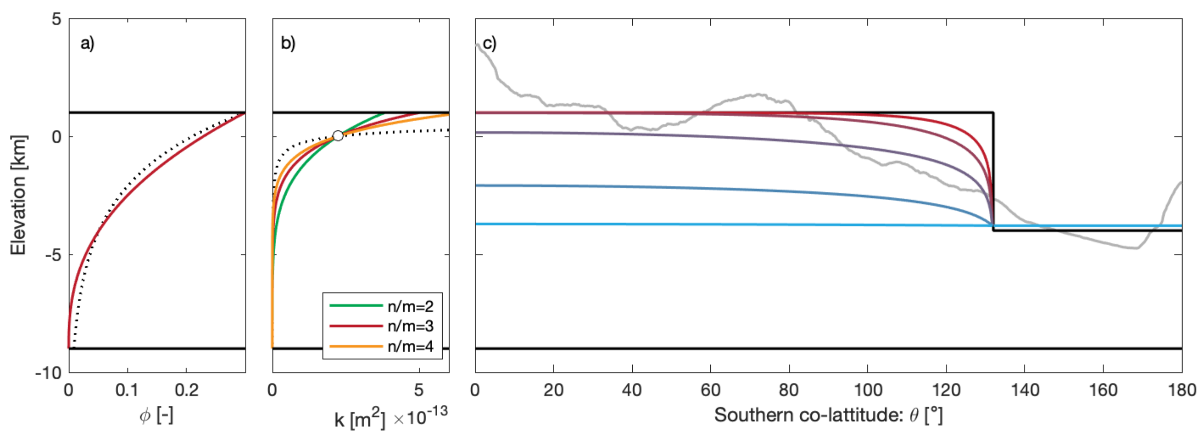

Figure 1: Transient simulation of terminal groundwater drainage from the southern highland's aquifer on Mars after the end of recharge. a) Vertical porosity variation in aquifer. Dotted line shows commonly used exponential porosity decay [2]. b) Vertical permeability variation in aquifer for three values of the ration of the power-law exponents n/m. Dotted line shows commonly used correlation for crustal permeability [10]. c) Groundwater table in spherical cap aquifer with dimension of the mean Deuterolinus shoreline and n/m=3. Gray line is azimuthally averaged Martian topography. Black lines are simplified step-function topography and base of aquifer.

to the dichotomy, which is assumed to be the mean of one of the proposed Deuteronilus shoreline [5]. The initial water table is assumed to be the steady solution for a uniform recharge [11] and the boundary condition is the head equivalent to Deuteronilus sea level elevation along the dichotomy boundary.

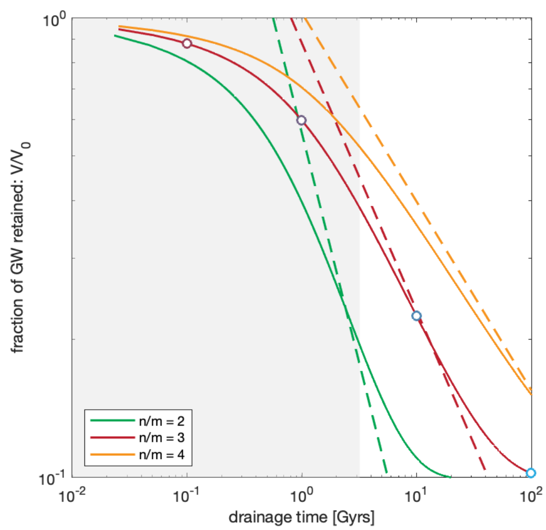

Figure 2: Decay of the groundwater volume in the southern highland's aquifer as function of time. Full lines show numerical simulation results for the three *n/m* values shown in Figure 1b. The dashed lines show the corresponding theoretical scaling laws [9]. The gray shaded area is 3.2 Ga corresponding to the duration of the Amazonian period. Time here is since the end of recharge not absolute time. The dots along the red line correspond to the profiles shown in Fig. 1c.

Results: The dynamics of an idealized 1D draining unconfined aquifer are self-similar and following the scaling analysis of [9] we can show that the volume of groundwater remaining is expected to decline as

$$V \sim \frac{1}{t^{\frac{m+1}{n-m+1}}}$$

at late time. Here we show that this power-law is also valid for an aquifer on a spherical cap (Fig. 2), where the theoretical prediction is shown together with numerical simulations of the decline of groundwater volumes.

At late time our simulations deviate from the predictions. This is because the theory assumes that the entire aquifer drains, i.e., that the head at the boundary is zero. In our case we have a finite head at the boundary that prevents full drainage of the aquifer (Fig. 1c). As such, the theory gives a guide to the drainage dynamics at intermediate timescales, i.e., the time after the entire aquifer begins to drain and before the groundwater level approaches the assumed Deuteronilus sea level. For the three cases of permeability decline in shown in Fig. 1b we expect the groundwater volume decay to follow power-laws with t^{-1}, $t^{-0.58}$ and $t^{-0.41}$, respectively. Figure 2 shows these theoretical predictions together with numerical simulations of the decline of groundwater volumes. The simple scaling correctly predicts the increasingly slower drainage rates are permeability declines ever more rapidly with depth as n/m increases.

For all cases investigated the terminal drainage of the groundwater from beneath the southern highlands takes several billion years (Gyrs). The process is slow, because the horizontal transport distances are large and the hydraulic gradients driving the flow are small and decline with time. Not all groundwater drains from the aquifer, because the base of the aquifer is well below the assumed sea level and hence cannot drain. For the porosity profile (Fig. 1a) and the Deuteronilus shoreline, chosen here, the remaining water is approximately 10% of the initial volume.

Discussion: We have presented a simple analysis of the terminal drainage timescales of Martian groundwater from beneath the southern highlands after change in the Martian climate ends groundwater recharge. Despite uncertainties about the aquifer properties the drainage times scales are so long that the process may still be ongoing.

Our analysis assumed a simple spherical cap aquifer and ignores the complex shoreline and large impact basins that likely improve drainage. As such our estimated likely provide an upper bound. Investigating the effect of complex geometries will require numerical simulation in 2D spherical shell geometry [12] and is the logical next step.

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