Martian floods at Cerberus Fossae can be produced by groundwater discharge

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[1] Young flood channels emanate from Cerberus Fossae, Mars. In order to determine whether subsurface aquifers can discharge water sufficiently fast to explain these flood features, I develop a model that couples groundwater flow in a sub-cryosphere aquifer with flow through a fissure that penetrates from the surface to the aquifer. The model is constrained by estimates of peak discharge, and the distance water flowed uphill from the fissure. Aquifer permeabilities similar to those of young basalt aquifers on the Earth, $\sim 10^{-9}$ m^2, can produce inferred discharges of 10^6 m^3/s [*Burr et al.*, 2002a] but probably require multiple floods to create the channels. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 5499 Planetology: Solid Surface Planets: General or miscellaneous; 6225 Planetology: Solar System Objects: Mars. **Citation:** Manga, M. (2004), Martian floods at Cerberus Fossae can be produced by groundwater discharge, *Geophys. Res. Lett.*, *31*, L02702, doi:10.1029/2003GL018958.

1. Introduction

[2] The presence and size of Martian channels provide the most compelling evidence for the existence of a hydrologic cycle and large amounts of water on Mars, respectively. The processes by which water arrived in the channels provides insight into the nature and evolution of the Martian hydrologic cycle [*Clifford and Parker*, 2001], and hence some of the boundary conditions for life.

[3] Channel-forming floods are often attributed to the rapid release of water stored in aquifers that are confined beneath the cryosphere [e.g., *Carr*, 1979]. The existence of such aquifers, however, is speculative, and no evidence for abundant deep groundwater is obvious within impact craters [*Russell and Head*, 2002]. Nevertheless, a subsurface origin of flood waters still offers the most satisfying explanation for the surface features seen in the headwaters of outflow channels [*Baker*, 2001].

[4] The channels within Athabasca Valles in the Cerberus Plains, while smaller than typical outflow channels, are of special interest because they are young, <20 Ma [*Berman and Hartmann*, 2002]. The source of the flood waters appears to be Cerberus Fossae (Figure 1), elongate eruptive fissures approximately radial to the the Elysium volcanic rise [e.g., *Burr et al.*, 2002a]. A temporal and spatial association with volcanic and magmatic activity is probably not a coincidence: dikes may allow pathways to form between deep aquifers and the surface by either melting pathways or cracking the cryosphere [*McKenzie and Nimmo*, 1999; *Gaidos*, 2001].

[5] Here I reexamine some of the surface features of, and estimated discharges from, Cerberus Fossae. I show that it is indeed possible for subsurface aquifers for discharge water sufficiently fast to explain flood-related features.

2. Model

[6] I assume, as in previous models [e.g., *Carr*, 1979; *Head et al.*, 2003], that the sources of flood waters are deep volcanic aquifers confined beneath the cryosphere. Once a fissure is created, water flows 1) through a subhorizontal aquifer, 2) through a subvertical fissure, and then finally 3) over the Martian surface. Figure 2 shows a cross-section perpendicular to the Fossae and the three regions in which flow occurs.

2.1. Subsurface Flow

[7] Flow in a confined aquifer is governed by the groundwater flow equation [e.g., *Domenico and Schwartz*, 1998]

$$\frac{\partial h}{\partial t} = \frac{k_h \rho g}{\mu S_s} \frac{\partial^2 h}{\partial x^2}, \tag{1}$$

where h is hydraulic head, k_h is horizontal permeability, g is gravity, ρ is density of water, μ is dynamic viscosity, and S_s is specific storage. Discharge from the aquifer (per unit width parallel to the fissure) is given by Darcy's equation

$$q = -\frac{k_h \rho g H}{\mu} \frac{\partial h}{\partial x} \quad \text{at } x = 0, \tag{2}$$

where H is aquifer thickness.

[8] Discharge and its evolution in time depend on head at the bottom of the fissure, h_0, which in turn depends on the ability of the fissure to transmit water to the surface. Discharge through the fissure (again, per unit width parallel to the fissure) is given by the equation describing flow between two rough plates [e.g., *Chow*, 1959]

$$q = \sqrt{\frac{2 h_0 g w^3}{f D}}, \tag{3}$$

where w and D are fissure width and length, respectively, and f is a friction factor. For the expected water velocities, the Reynolds number will be sufficiently large ($>10^6$) that flow will be in the fully turbulent limit. I use the same expression for friction factor as that used by *Head et al.* [2003].

[9] Equations (1)–(3) are coupled through the value of head at the bottom of the fissure (h_0), and the requirement that q in equations (2) and (3) are identical (i.e., mass is conserved). Equation (2) combined with equation (3) is a

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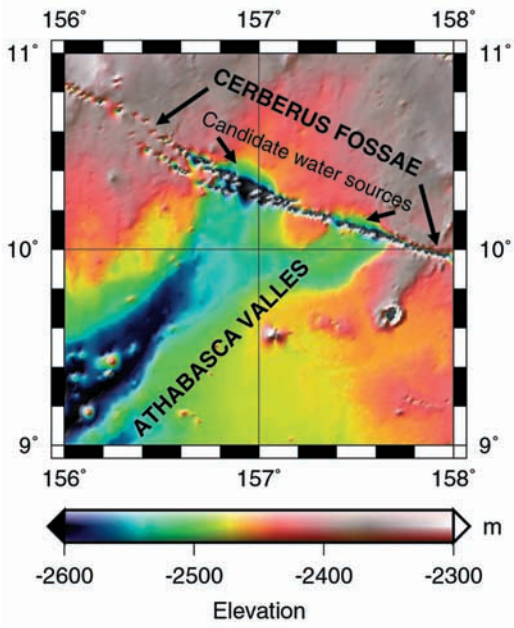

Figure 1. Topography of Athabasca Valles showing inferred water source [from *Head et al.*, 2003].

form of a radiation boundary condition for the diffusion equation, but because the boundary condition is nonlinear, analytical solutions cannot readily be found. Equations (1)–(3) are thus solved numerically using an explicit finite difference method.

2.2. Surface Flow

[10] Once water reaches the surface I assume that the depth and velocity of the flow can be calculated from Manning's equation [e.g., *Chow*, 1959], modified to explicitly include gravity,

$$q = \frac{0.32 g^{1/2} s^{1/2} R^{5/3}}{n}, \tag{4}$$

where s is the surface slope, R is the hydraulic radius (water depth, here), and n is an empirical coefficient called Manning's n (all units SI units). For all the discharges I compute (by solving equations (1)–(3)), the water depth R is sufficiently great that the surface flow is subcritical and I do not need to account for hydraulic jumps.

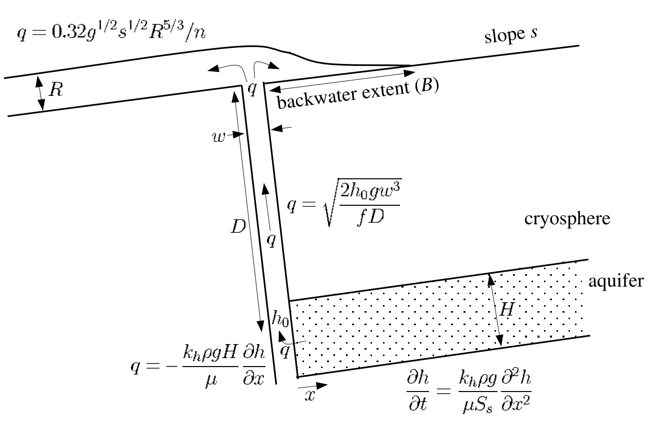

Figure 2. Geometry of model problem.

[11] At the surface, because R is finite, a fraction of the surface discharge will flow uphill until the head gradient becomes 0. *Head et al.* [2003] attribute the depressions that extend approximately 4 km uphill of Cerbereus Fossae to scouring by water forced uphill from the fissure. In the western part of the outflow source area, the depression extends approximately 7 km from the center of the fissure (Sakimoto, personal communication). *Head et al.* [2003] assume that this 4 km distance, denoted B, represents how far surface water ejected from the fissure has to flow before coming to rest. Because their calculated flow is supercritical (and would have dissipated a nonnegligible amount of its energy through a hydraulic jump), I ascribe a slightly different origin for these depressions.

[12] Water that flows uphill creates a backwater, a region of water trapped uphill behind the sheet of water flowing downhill. Scouring is presumed to occur (but is not modeled) during both the filling and draining of the backwater. The fraction of q that flows uphill is assumed to be $(R - Bs)/2R$, that is, it is proportional to the difference in water depths on either side of the fissure. The volume of water in the backwater is then obtained by integrating the uphill discharge over time. Note that as discharge from the aquifer decreases, the depth of water in the backwater will eventually exceed R obtained from equation (4), and water will then drain from the backwater.

2.3. Parameters and Constraints

[13] Table 1 summarizes model parameters and constraints. Most parameters are identical to those used by *Head et al.* [2003]. Of these parameters, only permeability deserves further discussion because it is both a critical parameter and the most uncertain.

[14] A substantial fraction of the subsurface in the Cerberus Plains and Elysium region is made up of lava flows [*Berman and Hartmann*, 2002]. Large volume (>1 m^3/s) cold springs that discharge water from young basaltic andesite aquifers in the Oregon and California Cascades provide a rare opportunity to determine regional scale permeability of formations comprised of lava flows. The regional scale permeability is 10^{-9} m^2 (Saar, M. O. and

Table 1. a) Model Parameters. Bold Properties are Varied b) Model Constraints[e]

a) Property	Value
Horizontal permeability[a] (k_h)	10^{-9} m^2
Specific storage[b] (S_s)	10^{-6} m^{-1}
Fissure width[c] (w)	2.0 m
Initial aquifer head[c] (h at t = 0)	5 km
Aquifer depth[c] (D)	5 km
Aquifer thickness[c] (H)	3 km
Fissure length[c] (L)	40 km
Slope[c] (s)	0.0012
Manning's[d] n	0.02
Kinematic viscosity (μ/ρ)	10^{-6} m^2/s
b) Constraint	**Value**
Peak discharge[d] (Q)	1–2 × 10^6 m^3/s
Backwater extent[c] (B)	4 km

[a]Measured for >10 km length basaltic aquifers [*Saar and Manga*, 2003].
[b]Fractured rock, *Domenico and Schwartz* [1998].
[c]*Head et al.* [2003].
[d]Smooth, straight channel [*Chow*, 1959].
[e]*Burr et al.* [2002a].

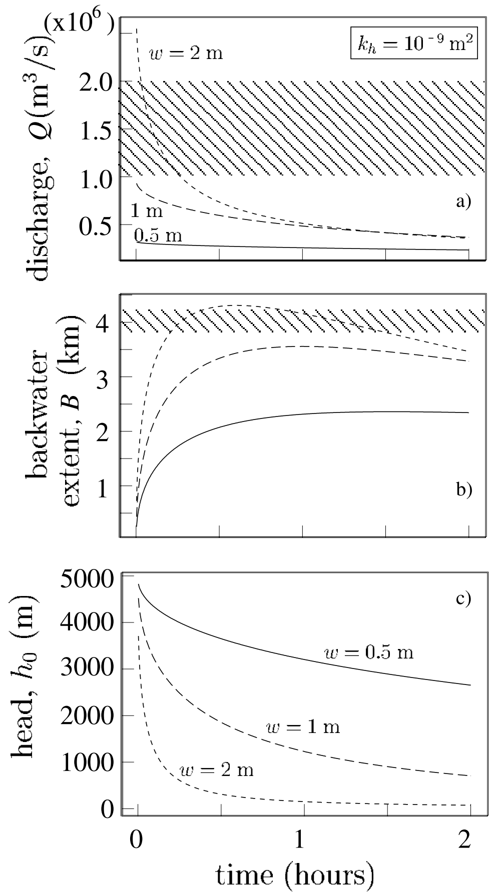

Figure 3. Evolution of a) Discharge, b) Backwater extent and c) Head at the base of the fissure. For all simulations, parameters are those in Table 1a and only fissure width is varied. Shaded area shows constraints from Table 1b.

M. Manga, Depth dependence of permeability in the Oregon Cascades inferred from hydrogeologic, thermal, seismic, and magmatic modeling constraints, submitted to *J. Geophys. Res.*, 2003; hereafter referred to as Saar and Manga, 2003), a value obtained from measurements of hydraulic diffusivity [*Manga*, 1997] and mean residence time of water in the aquifers [*James et al.*, 2000].

[15] Two details of this value require explanation. First, a regional scale estimate is essential because the relevant permeability values must average over the structures and scale appropriate for the problem of interest. In this case, aquifers extend over distances >10 km and thus include several flow units and the full range of permeable structures within lava flows.

[16] Second, in the Oregon Cascades permeability decreases to less than 10^{-14} m^2 quite rapidly (depths > few hundred m) as secondary minerals precipitate in pore spaces [*Ingebritsen et al.*, 1994]. These minerals form either by hydrothermal alteration or weathering as meteoric water reacts with the glass and crystalline phases in the basalt [*Keith and Barger*, 1988]. In order to scale the reduction of permeability to the Martian subsurface, I suggest that to zeroth order the water/rock ratio can be used as a proxy for the degree of alteration and hence permeability reduction. This may be a reasonable approximation because both groundwater systems are cold, though if the salinity of Martian groundwater is high, then reaction rates will be higher. In aquifers that discharge water at cold springs in the Oregon Cascades (the aquifers with permeabilities of 10^{-9} m^2), the water/rock ratio = age of the aquifer × mean recharge rate/aquifer thickness = 10^6 years × 1 m/year/100 m $\sim 10^4$. I assume that this water/rock ratio results in minimal weathering. Thus, for 4 Ga Martian aquifers of thickness 3 km, we expect that recharge rates less than 1 cm/yr should also result in minimal permeability reduction. Such a recharge rate is much higher than average rates over geological times scales [*Clifford and Parker*, 2001]. Moreover, the absence of abundant chemical weathering products on the surface [*Bandfield et al.*, 2000] and the preservation of old yet easily weathered minerals from the Martian subsurface [*Christensen et al.*, 2003; *Hoefen et al.*, 2003] suggest that permeability reduction at depth may be minimal. Furthermore, porosity and hence permeability reduction by viscous flow (self-compaction) is too slow over geological time scales to significantly change permeability at depths less than about 10 km. In summary, adopting terrestrial permeabilities for shallow aquifers comprised of basaltic lava flows may in fact be a good assumption for the Martian crust for depths of several km.

3. Results and Discussion

[17] Figure 3 shows the temporal evolution of discharge and backwater extent for the parameter values listed in Table 1a and fissure widths of 0.5, 1 and 2 m. Discharge decreases monotonically following the opening of the fissure. For wide fissures, w greater than about 2 m, the fissure offers little resistance to flow, head at the bottom of the fissure decreases rapidly and, consequently, discharge from the aquifer is greatest. Figure 3 also shows the discharge and backwater constraints from Table 1b. The listed parameters and a fissure width of 2 m allow both discharge and backwater constraints to be satisfied.

[18] Because permeability is highly uncertain, I also consider the influence of permeability on discharge and backwater extent. Figure 4 shows that smaller permeabilities do not permit sufficiently large discharges, whereas higher permeabilities should result in both larger discharges and backwaters that extend much further uphill. The larger backwater extent in the western part of the Fossae thus suggests that this region taps a more permeable aquifer.

[19] The discharge shown in Figure 4 is the average discharge over the time period during which the backwater fills. For large fissure widths w, the mean discharge is not linearly proportional to permeability k_h as might be anticipated from equation (2). Instead, because the evolution of h satisfies the diffusion equation, the length scale over which h varies in the aquifer scales with $\sqrt{\rho g k_h t / \mu S_s}$, and discharge at a given time t will thus scale with $k_h^{1/2}$.

[20] It is important to note that the peak discharge estimated by *Burr et al.* [2002a] is based on the morphology of features downstream of the fissure. It will thus be smaller than the calculated discharge at the fissure for two reasons. First, flood waves spread and dissipate as they move downstream. Second, some of the flood water will be lost back into the underlying permeable lavas.

[21] The total volume discharged is limited primarily by the volume of water stored in the aquifer, k_h, and the length

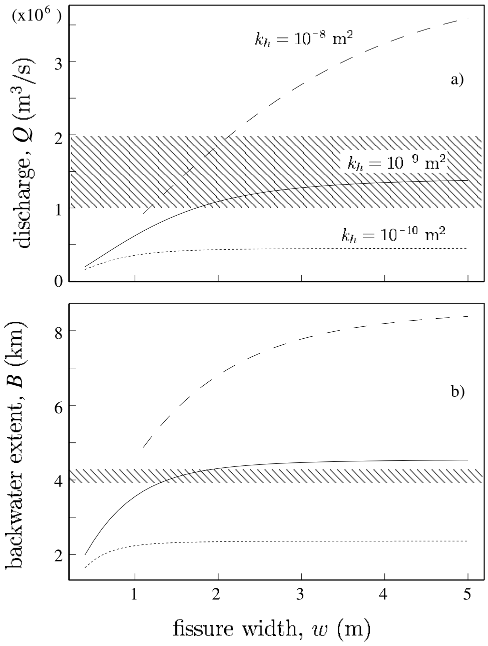

Figure 4. a) Average discharge while the backwater region is being filled and b) Maximum extent of backwater. All parameters values are listed in Table 1a and the aquifer permeability is varied. Shaded area shows constraints from Table 1b.

of time the fissure remains open. In more detail, for the parameters listed in Table 1 and w between 0.5 to 2 m, 44 to 46 km^3 of water is discharged during a 1 week period. During this time, t_{open} = 1 week, the decrease in head within the aquifer will have propagated up-aquifer a distance $\ell \sim \sqrt{\rho g k_h t_{\mathrm{open}}/\mu S_s} \approx 34$ km. The subsurface aquifer is probably large compared to the region (size ℓ) influenced by flow to the fissure [*Head et al.*, 2003]. Consequently, head within the aquifer will reequilibrate over a time comparable to t_{open} once the fissure seals, permitting repeated flooding over intervals much smaller than the age of the channel.

[22] How long the fissure remains open is probably limited by the eventual collapse and sealing of the fissure as the fluid pressure in the aquifer, and hence fissure, decreases. Refreezing of water in the fissure will probably not limit t_{open} because cooling and freezing is negligible if $Q \gg \kappa\ H\ L/w \sim 10^2$ m^3/s (cooling time much less than advection time). Such low discharges are reached after several years and after fluid pressures in the fissure are close to hydrostatic.

[23] The total predicted discharge for a single flood is similar to the tens of km^3 of sediment presumably removed from the Athabasca Valles [*Burr et al.*, 2002b]. Multiple floods may thus be required to remove this much sediment. *Burr et al.* [2002b] have argued for repeated flooding, though the multiple floods may not be required by the surface morphology [*Plescia*, 2003].

4. Conclusions

[24] A reasonable estimate of large-scale permeability for crust containing basaltic lava flows is probably 10^{-9} m^2. A sub-cryosphere aquifer a few km thick with this permeability can discharge water rapidly enough to satisfy the 10^6 m^3/s estimate for channels emanating from Cerberus Fossae. A deep groundwater origin for recent floods should thus be viewed as plausible, provided subsurface aquifers are many tens of km in lateral extent. No unusual physics or properties need to be invoked except perhaps repeated flooding.

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