# Generation of recent massive water floods at Cerberus Fossae, Mars by dike emplacement, cryospheric cracking, and confined aquifer groundwater release

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[1] Previous studies noted the close association of geologically very recent lava flows and fluvial channels emanating from Cerberus Fossae. To assess these relationships, we outline a model of magmatic dike emplacement that involves 1) surface fractures and localized volcanic eruptions, 2) attendant cryospheric cracking to fracture the surface and release pressurized groundwater confined beneath the cryosphere, 3) effusion of water along a segment of the fracture to form Athabasca Valles, and 4) heating of the regions adjacent to the dike to cause melting and subsequent subsidence of the surface, forming late-stage pits and depressions. Previous estimates of the aqueous discharge were ~1–2 × $10^6$ $m^3$ $s^{-1}$. Our models show that this flux could be readily accommodated by flow through adjacent dike-related cryospheric fractures at water rise speeds of ~60 m/s. The required aquifer permeability, however, is far larger than commonly encountered over similar depths and scales on Earth. This suggests that water may be transported in the subsurface by mechanism more efficient than porous flow, and/or that the previously proposed volume flux values are overestimates. *INDEX TERMS:* 1823 Hydrology: Frozen ground; 1821 Hydrology: Floods; 6225 Planetology: Solar System Objects: Mars; 5480 Planetology: Solid Surface Planets: Volcanism (8450). **Citation:** Head, J. W., L. Wilson, and K. L. Mitchell, Generation of recent massive water floods at Cerberus Fossae, Mars by dike emplacement, cryospheric cracking, and confined aquifer groundwater release, *Geophys. Res. Lett.*, *30*(11), 1577, doi:10.1029/2003GL017135, 2003.

## 1. Introduction

[2] The Cerberus Plains of Mars have long attracted attention as a site of geologically recent volcanic and fluvial activity [e.g., *Plescia*, 1993]. *Berman and Hartmann* [2002] conclude that fluvial channels (Figure 1) associated with Athabasca Valles [*Burr and McEwen*, 2002] give a model age of fluvial activity of less than 20 Myr. *Burr et al.* [2002a, 2002b] concluded that water carving the fluvial channels of Athabasca Valles emanated from Cerberus Fossae, that flow rates (assuming bank-full flow) were 1–2 × $10^6$ $m^3$ $s^{-1}$, and that water must have collected in the subsurface in a liquid state (groundwater) in order to flow at their estimated discharge rates. Due to the lack of broad collapse in the vicinity of the source region, they inferred the source of this groundwater to be at least several kilometers deep, and concluded that it was released along extensional faults due to flexural loading.

[3] In this contribution we address the fundamental issues raised by earlier works concerning 1) the role of regional tectonic forces versus dike emplacement processes, and 2) the mechanisms of lateral and vertical transport of subsurface water to the surface to form Athabasca Valles and Cerberus Fossae. We conclude that dike emplacement processes can explain the vast majority of features observed.

## 2. Dike Emplacement and Cryospheric Cracking

[4] The propagation of magma-filled cracks (dikes) from magma source regions often culminates in the dike reaching the surface to cause eruption of magma and the production of lava flows (Figure 2a). Commonly, however, dikes or portions of dikes approach the surface but do not reach it, setting up an extensional near-surface stress field that can produce surface fractures and graben (Figures 2a and 2b).

[5] Long graben systems are evidence for giant lateral dike swarms radiating from major volcanic centers, with the upper tips of the dikes being trapped at shallow depths by the combined effects of magma density and regional stress field. *Wilson and Head* [2002] summarized work by *Rubin* [1992] to show that if the formation of a graben is induced by dike injection, the mean width of the dike, $W_d$, is approximated by (1.25 Y) and the depth to the dike top, $Z_d$, is approximated by (0.29 B), where B is the width and Y is the depth of the fracture/graben. Analysis of the topography of the fractures and graben at Cerberus Fossae (Figure 2b) using MOLA data and shadow measurements yield estimates of the dike width of ~150–250 meters and depth to the top of the dike of ~50–225 meters, if the structures are caused entirely by extension due to dike intrusion. Thus, dike emplacement is a reasonable process for producing near-surface stress fields and fractures capable of cracking the cryosphere and providing conduits for subsurface groundwater to reach the surface.

[6] Evidence for this scenario comes from MOC images and MOLA altimetry, which show lines of candidate volcanic spatter vents along the strike of the fossae and spatter-fed lava flows emerging from these vents (Figure 2a), fractures and narrow flat-floored graben along the same strike (Figure 2b), and collapsed linear segments with ridges on their floors interpreted to be the tops of dikes (Figure 2c).


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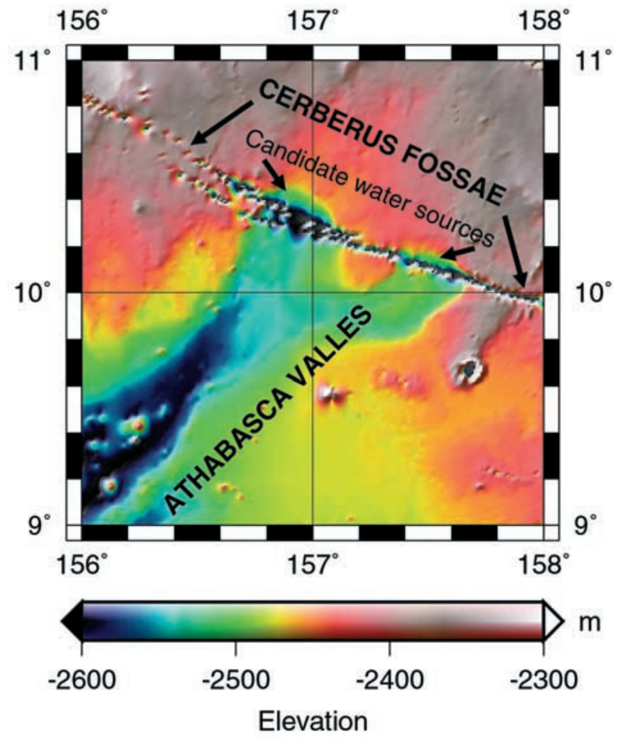


**Figure 1.** MOLA topography showing the Athabasca Valles source along Cerberus Fossae and the channel carved by the water outflow. One degree equals ~ 60 km.

[7] The topography in the Athabasca Valles source area (Figure 1) [*Burr et al.*, 2002b] shows that the water eroding the channels emerges from a pair of fractures closely aligned with one another along a strike of ~N65°W and totaling ~30–40 km in length. Surrounding the sources is a broad shallow depression, ~50 m deep, ~10–20 km wide and ~30 km along strike. The fissures strike approximately at right angles to the ~0.07° regional slope, and the depression extends uphill for ~4 km. We infer that the high speed of the water emerging from the fracture caused water to flow uphill for this distance before spreading sideways and back downhill around the ends of the active fractures, eroding the depression in the process.

[8] Let the vertical rise speed of the water in the fracture of width $W$ be $V$. Also let the initial speed of the water flowing away from the fracture be $U$ and its initial depth be $\Delta$. Water rises in a fountain over the fracture and descends again to feed a flow on both sides of the fracture. Conservation of energy implies $U = V$, and continuity requires $(2\,V\,\Delta) = (V\,W)$ so that $\Delta = (0.5\,W)$. Water can be considered incompressible over the small range of pressure changes involved, and so in flowing uphill against the regional slope until it comes to rest after the distance $D = {\sim}4$ km, it trades decrements in its kinetic energy ($V\,dV$) against increments in its potential energy ($g \sin\alpha\, dX$) and work done against basal friction ($[(f_s V^2)/(2\,\Delta)]\, dX$), where $X$ is distance measured along the ground surface, $g = 3.74$ m s$^{-2}$ is the acceleration due to gravity, $\sin\alpha = \sin 0.07° = 1.2 \times 10^{-3}$, and $f_s$ is the basal friction factor. Equating these components and integrating

$$W = (2 f_s D)/\ln\left\{1 + \left[\left(f_s V^2\right)/(W g \sin\alpha)\right]\right\} \quad (1)$$

where $W$ has been substituted for $(2\,\Delta)$ using the above continuity relationship. The dynamics of water with density $\rho = 1000$ kg m$^{-3}$ rising turbulently through the fissure under a pressure gradient $dP/dz$ in excess of the static weight of the water leads to

$$V = [(W\,dP/dz)/(f_w \rho)]^{1/2} \quad (2)$$

where $f_w$ is the wall friction coefficient. Using (2) to eliminate $V$ from (1) gives

$$W = (2 f_s D)/\ln\{1 + [(f_s\,dP/dz)/(f_w \rho g \sin\alpha)]\}. \quad (3)$$

The friction factors $f_w$ and $f_s$ must be obtained recursively using the formulae for fully turbulent flow [*Schlichting*,

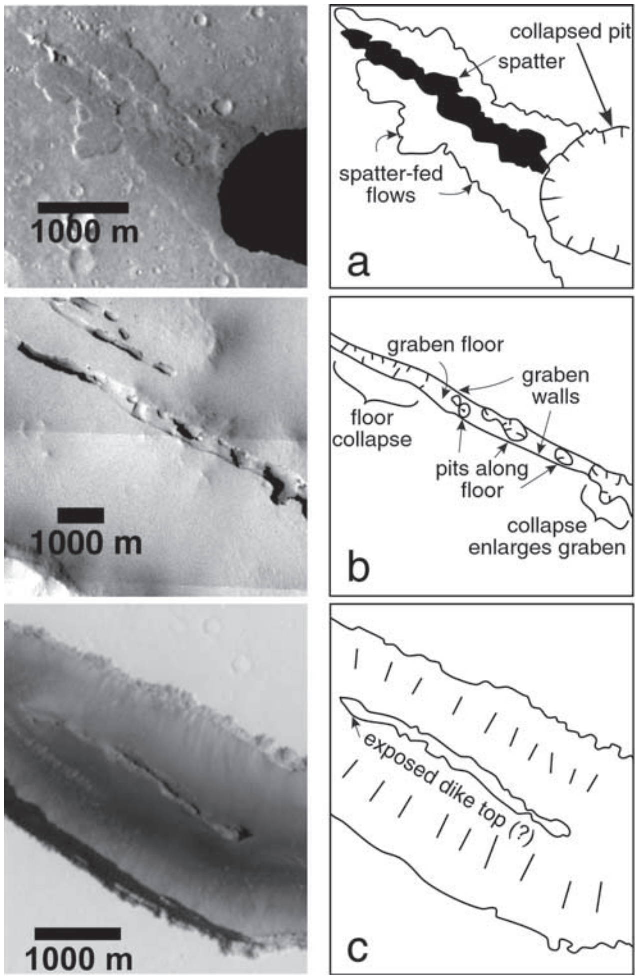


**Figure 2.** MOC and THEMIS images, and sketch maps showing key relationships in the Cerberus Fossae system. a) Fissure with associated rough spatter-like material and adjacent spatter-fed flows. The large depression along strike to the southeast cuts and thus postdates the fracture and flows. MOC image MO201973. b) Relationships between fractures and graben interpreted to be the product of near-surface dike emplacement, and subsequent collapse attributed to late-stage melting adjacent to the dike followed by subsidence and collapse. THEMIS image VO1355006. c) Ridge on the floor interpreted to be the surface manifestation of the top of the dike, exposed by subsidence and drainage (see Figure 3c). MOC image MO201973.

1968], $f_w^{-1/2} = 2.28 + 4\log_{10}(2\ W/E)$ and $f_s^{-1/2} = 2.28 + 4\log_{10}(W/E)$, where $E$ is the scale height of surface roughness, here taken as 1 mm. To estimate d$P$/d$z$ we assume that the aquifer feeding the fracture extends for a depth $Z = \sim 5$ km from the bottom of a trapping cryosphere of thickness $C$ = 3 km [*Clifford*, 1993]. The water in the aquifer is pressurized by the water table of the topographically higher Elysium Rise and the Elysium Mons complex to the northwest, which we assume extends to a height $S = \sim 5$ km (one quarter the height of the volcano) above the level of the breakout point. Then d$P$/d$z$ is $\sim \rho\ g\ \{[(S + C + Z)/(C + Z)] - 1\}$ = $\sim$2338 Pa m$^{-1}$. Solving the above two equations we find $W = \sim 2.8$ m and $V = \sim 44$ m s$^{-1}$. The corresponding friction factors are $f_s = 0.0039$ and $f_w = 0.0033$. The height of the water fountain over the source fracture would have been $[V^2/(2\ g)] = \sim 260$ m, and the total water flux from the $\sim$30–40 km long fracture would have been $\sim 4.4 \times 10^6$ m$^3$ s$^{-1}$, comparable to the range $\sim 1-2 \times 10^6$ m$^3$ s$^{-1}$ estimated by *Burr et al.* [2002a]. The implied $\sim$28 m fracture would be almost impossible to detect using current image data.

[9] Previous workers have noted that along many segments of Cerberus Fossae both lava flows and water floods end abruptly at fossae margins (Figure 2a), strongly suggesting that the present margins postdate lava and water flow. Also, *Burr et al.* [2002b] and *Berman and Hartmann* [2002] propose that some fractures postdate (cut) the lava flows emanating from the fissures, suggesting that the fossae and fractures are largely due to later regional tectonic stresses, rather than dike emplacement and associated processes.

[10] In the dike emplacement scenario, however, these features and structures are a natural consequence of the associated processes following dike emplacement, cryospheric cracking, and water flooding. Thus, we interpret the large steep-walled depressions along the strike of Cerberus Fossae (Figures 2a and 2b) to be due to late-stage melting of the ice-saturated cryosphere adjacent to the dike, drainage, and subsequent collapse of the fracture and the floor of the graben to enlarge the trough and destroy evidence of the initial vent (Figures 3b and 3c). Heat conducted from the dike would melt ice out to about half the dike width on either side, i.e. the melting zone width would be double the dike width. If ice occupies pore space amounting to 25% of the volume of the crustal rocks, then to cause the 300–400 m subsidence observed it would be necessary to remove the ice from a $\sim$2400–3200 m vertical extent of crustal rock, assuming that only half of the pore space was compacted during ice removal. This vertical distance is sufficiently close to estimates of the cryosphere thickness that we regard this as a viable mechanism.

[11] The steps in our model are illustrated in Figure 3. First, the crust in the Cerberus Fossae/Elysium Planitia area consists of a lava flow substrate overlying a megaregolith, which in turn overlies fractured crustal bedrock. The upper part of this column ($\sim$3 km) is predicted to be water-ice saturated cryosphere [e.g., *Clifford*, 1993]. Underlying this is a pressurized groundwater-saturated zone. Emplacement of a dike to the shallow subsurface (Figure 3a) cracks the cryosphere, causing magma to rise to the surface in a few places, creating local surface eruptions, curtains of fire and spatter-fed flows. Concurrently, the crack to the surface provides a path for groundwater in the pressurized water-saturated zone. Water courses to the surface mainly along two $\sim$15–20 km long portions of the crack (Figure 1), creates fountains and ponds which extend $\sim$4 km upslope from the cracks, and drain around the ends of the active crack segments to carve the channels of Athabasca Valles (Figure 3a). At the same time, the dike intruding into the ice-saturated cryosphere is losing heat conductively into the surrounding substrate, causing melting of the ice (Figure 3b). This causes drainage of material adjacent to the dike and collapse of the overlying substrate to produce the irregular troughs (Figure 3c), destroying the details of the fracture and near-vent lava and water flow textures (Figures 2a and 2b). Thus, in our model, this process is simply a consequence of the terminal phases of the dike emplacement event rather than being due to later tectonic activity as suggested by *Burr et al.* [2002a, 2002b] and *Berman and Hartmann* [2002].

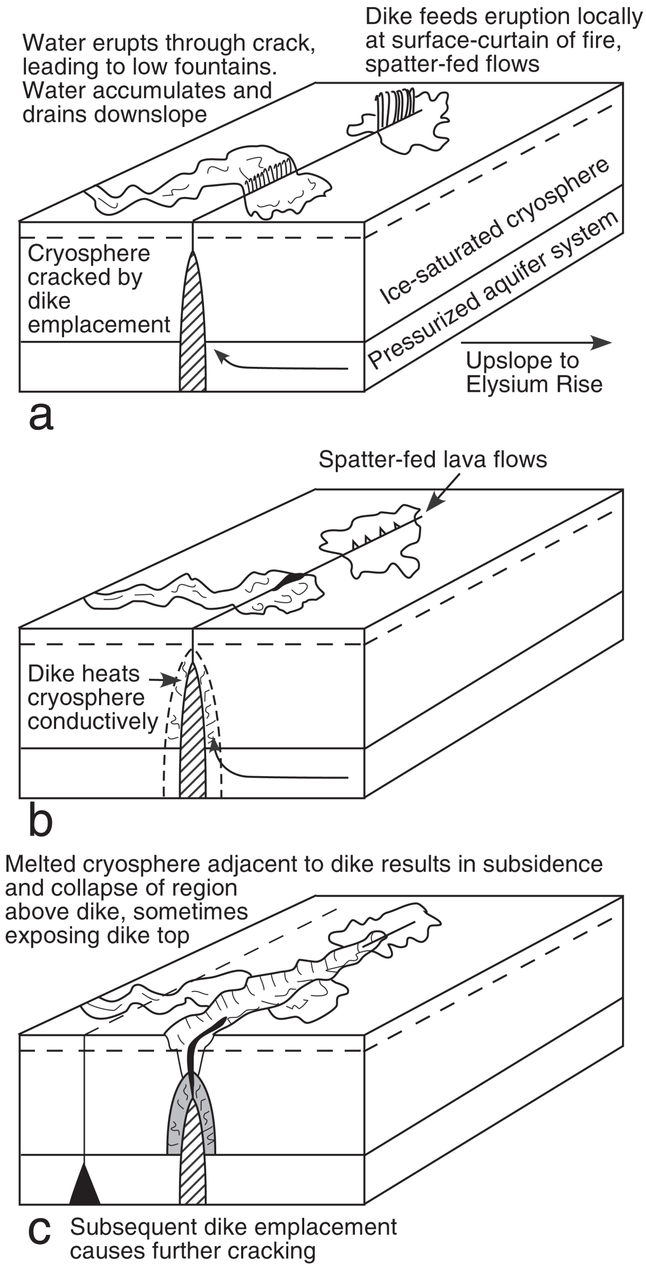


**Figure 3.** Sequence of events in the model.

[12] We can relate the discharge up the vertical crack fed by the aquifer to the aquifer properties using Darcy's law. The water volume flux per unit area (i.e. the Darcy velocity), $u_i$, is given by

$$u_i = (k/\eta)(\mathrm{d}P/\mathrm{d}x) \tag{4}$$

where $k$ is the intrinsic permeability of the aquifer medium, $\eta$ is the dynamic viscosity of water, $\sim 1.5 \times 10^{-3}$ Pa s, and d$P$/d$x$ is the lateral pressure gradient (e.g., *Carr* [1979]) in the aquifer. The main source of the pressure gradient is the 5 km water head in the Elysium Rise complex 700 km away, so that d$P$/d$x$ = [$\rho$ $g$ (5 km/700 km)] = $\sim$27 Pa m$^{-1}$. The common rock types in the source area are geologically recent basaltic lava flow units that are underlain by megaregolith grading down into fractured bedrock which may have a high permeability [*Clifford*, 1993]. To illustrate a likely maximum estimate of the available water flux we assume that the aquifer has properties similar to that of porous gravel, with $k$ up to $\sim 10^{-7}$ m$^2$ [*Turcotte and Schubert*, 2002]. Then $u_i$ = 1.8 mm s$^{-1}$. The total discharge from the aquifer into the vertical crack is this velocity multiplied by the inferred 30–40 km total horizontal crack length and the assumed 5 km vertical extent of the aquifer, i.e. $\sim 3 \times 10^5$ m$^3$ s$^{-1}$. This value is nearly an order of magnitude smaller than the estimate by *Burr et al.* [2002a, 2002b] despite the fact that we are using maximum estimates.

[13] If the fissure length were greater than our estimated 30–40 km total length, this would influence the flux. However, even doubling the fissure length would still result in a shortfall by a factor of $\sim$2. To obtain a flux of $10^6$ m$^3$ s$^{-1}$ (the lower end of the range estimated by *Burr et al.* [2002a, 2002b]) into the $\sim$35 km horizontal length of active fracture from an aquifer assumed to be 5 km thick, the Darcy velocity (i.e. the water volume flux per unit area) would have to be $\sim$10 mm s$^{-1}$, implying an aquifer permeability of $\sim 5.6 \times 10^{-7}$ m$^2$, which is several times larger than the largest permeability commonly encountered on Earth, $\sim 10^{-7}$ m$^2$. In fact, typical permeabilities on Earth for regional scale Darcy flow are $\sim 10^{-14}$ m$^2$ [*Clifford*, 1993], several orders of magnitude smaller. An alternative explanation is that water is not flowing by porous flow, but via some other mechanism such as a large-scale, horizontally-interconnected fracture system. Another possible explanation is that the volume flux estimates by *Burr et al.* [2002a, 2002b] are too large. In their original estimates, *Burr et al.* [2002a] used MOLA topography of the channel, Manning's equation modified for martian gravity, and assumed bankfull flow, acknowledging that the estimate may thus be "erroneously large". The assumption that the presently-observed channels were bank-full would overestimate the flux if any channel floor erosion had taken place during the flood event.

## 3. Conclusions

[14] In our model, dike emplacement produces 1) surface fractures and localized volcanic eruptions, 2) attendant cryospheric cracking to fracture the surface and release pressurized groundwater confined beneath the cryosphere, 3) effusion of water along an observed 30–40 km-long segment of the fracture to form Athabasca Valles, and 4) heating of the regions adjacent to the dike to cause melting and subsequent subsidence of the surface, forming the observed late-stage pits and linear depressions. Although it is plausible that most or all of the key observed features occurred in a single intrusive and eruptive phase, it is highly likely that multiple intrusive phases would have occurred in this environment, as is typical on the Earth [e.g., *Rubin*, 1992]; such repeated events often lead to locally complex stratigraphic relationships (e.g., Figure 3c).

[15] Our model shows that previously estimated aqueous discharge fluxes for Athabasca Valles fluvial channels ($\sim 1$–$2 \times 10^6$ m$^3$ s $^{-1}$) can be readily accommodated by flow through a dike-related cryospheric fracture $\sim$2 m wide, at water rise speeds of $\sim$60 m/s. However, these values require aquifer permeability that is far larger than commonly encountered on Earth, suggesting that subsurface mechanisms more efficient than porous flow may be involved, and/or that the previously proposed volume flux values are overestimates.

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