HYDROLOGIC ANALYSIS OF THE BIRTH OF ELAVER VALLIS, MARS BY CATASTROPHIC DRAINAGE OF A LAKE IN MORELLA CRATER.

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Introduction: Elaver Vallis, located south of Ganges Chasma, was carved by catastrophic drainage of a transient Hesperian lake in 70-km-wide Morella Crater (Fig. 1). The lake dimensions and the water volume drained can be accurately reconstructed because an early overflow channel was preserved on the crater rim. We analyze the Elaver Vallis megaflood and estimate the following: (1) minimum time for groundwater to fill the crater lake, (2) minimum water volume drained from the lake during two stages of flow, (3) peak discharge rate during the flood, (4) minimum elevation of the groundwater potentiometric surface, and (5) local cryosphere thickness, groundwater depth, and crustal heat flux at the time of the flood.

Source of Water: Elaver Vallis begins at a gap in the eastern rim of Morella Crater. This morphology reveals that a paleolake was present in the crater prior to crater rim breachment. There is only one outlet from this crater, and no channels enter it, so groundwater must have risen into the crater via Ganges Cavus – a 3-km-deep pit in the southern part of Morella – the only plausible source for the lake waters (Fig. 1). We interpret this easternmost cavus of Ophir Catena (see [2] for a regional map) as a subsidence feature produced mainly by dilational faulting [1]. This faulting likely increased the aquifer permeability parallel to the catena. We previously proposed that the inception of Ganges Cavus ruptured the cryosphere, permitting confined groundwater to rush upward into the crater [3,4]. Water discharged from the cavus onto the adjacent crater floor at an elevation of 1080 m.

Lake Level: The paleolake surface would have risen in elevation until the pressure of the lake water column equaled the pressure in the subcryosphere aquifer system. The crater acted, in effect, like an enormous standpipe that filled with groundwater. The water level in the paleolake did not rise as high as the regional potentiometric surface because the crater rim was overtopped and rapidly breached as the water level was rising, leading to a catastrophic outflow that eroded a water gap. We deduce that water in the lake rose, however, at least as high as 1780 m above the MOLA datum because a small channel at this elevation – which formed during the initial overflow – is preserved as a high-water mark on the crater rim just south of the water gap (Fig. 2). This small channel was abandoned and preserved high on the crater rim as a hanging valley while a deeper channel eroded at the water gap and captured all remaining flow.

Water Volume Drained: We subtract the channel floor elevation just east of the water gap (i.e., 1250 m) from the 1780 m high-water mark elevation and thereby determine that *at a minimum*, a 530-m-deep water column catastrophically drained through the breach in the rim of Morella Crater. Given that the crater has an average inner diameter of 70 km, we

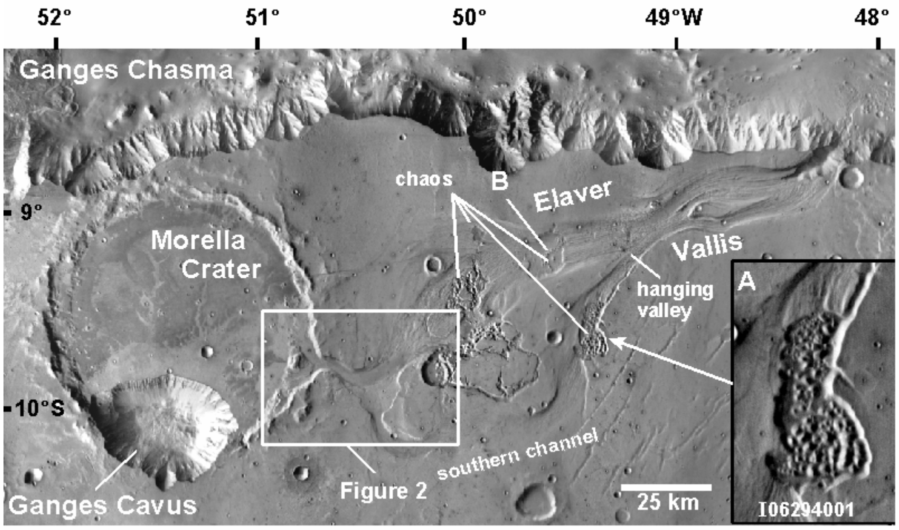

Figure 1. Morella Crater, Ganges Cavus, and Elaver Vallis. The channel complex consists of two main channels—a deeper northern channel and a southern channel that is hanging on both ends. The channels converge to the east and abruptly terminate at the southern margin of Ganges Chasma. White box is location of Fig. 2. "B" marks chaos discussed in text. Inset A: unnamed chaos on south channel floor. Image credit: [5].

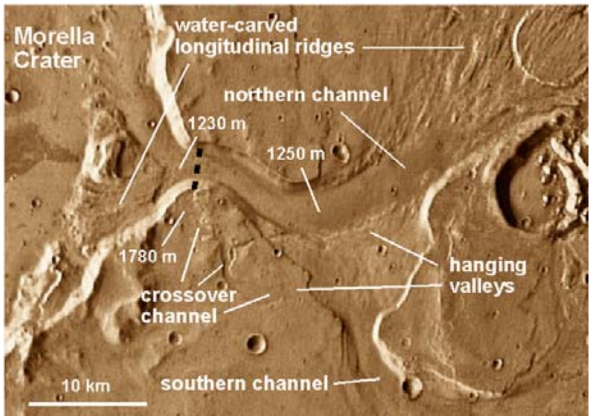

Figure 2. Location of gap in wall of Morella Crater where Elaver Vallis begins. Elevation of crossover channel marks the level at which lake overtopped the crater rim. The black dotted line shows location of Fig. 4. Image centered at 9.8°S, 50.5°W. Image credit: [5].

calculate a minimum lake volume of 2 × 10^{12} m^3. This lake volume is well defined because most of the floor of Morella Crater lies at elevations <1250 m, meaning a residual lake 170 m deep (1250 to 1080 m, excluding cavus depth) remained after the flood. As the lake level dropped 530 m, the overlying pressure at Ganges Cavus would have diminished by 2 MPa, inducing an increase in the groundwater outflow rate. This water flowed up into the water column of the residual lake, which explains why the discharge did not erode a channel across the floor of Morella Crater toward the outlet. Subsequent outflow would have continued at declining rates until the potentiometric surface fell below the channel floor elevation of 1250 m (Fig. 2).

Time to Fill Morella Crater: The paleolake in Morella Crater provides remarkable insights about Martian floods. In this special case the groundwater outflow accumulated in a gigantic reservoir of known volume. This basin is so large that the Mississippi river at high flood stage (~30,000 m^3/s) would require >770 days to fill the crater. Overtopping of the crater rim verifies that flow was continuing even after the crater holding capacity was reached. Clearly the aquifer system was extraordinarily productive.

Carr [6] used the Jacob-Lohman [7] method for free-flowing wells to evaluate massive groundwater discharges from chaos. He later commented [8] that the earlier analysis may have erred by calculating very large permeabilities (up to 3000 darcies). We agree such calculations have no meaning for aquifers that are disrupted by chaos or cavus formation.

The initial breakout at Ganges Cavus was controlled by massive groundwater overpressure that ruptured the cryosphere and destroyed the aquifer at the outflow zone. This *early-time* flow was unconstrained by aquifer properties and cannot be analyzed with traditional methods. However, *mid- to late-time* conditions are readily analyzed because they represent flow from *intact* aquifers around Ganges Cavus. We estimate a minimum time to fill Morella Crater using Jacob-Lohman's method [7] and hydraulic properties that likely overestimate the actual discharges, i.e., permeability ~1000 darcies, aquifer thickness ~2.5 km, transmissivity ~5.2 m^2/s, storativity ~0.005, radius of flow opening ~10 km, and a confined aquifer pressure head of 1400 m (assuming an initial potentiometric surface at 2480 m, similar to the outflow elevation at Ophir Cavus 200 km to the west [4]). We further assume that the first 27 days of outflow (*early time*) rapidly filled Morella Crater to an elevation of 1250 m. Subsequent flow constrained by the given aquifer properties had to fill the remaining crater volume of ~2 × 10^{12} m^3 to reach overflow. We account for the reduction in discharge caused by rising pressure at the outflow zone as the lake rose an additional 530 m. We calculate that >2880 days of gradually declining flow were needed to fill and overtop the crater (Fig. 3).

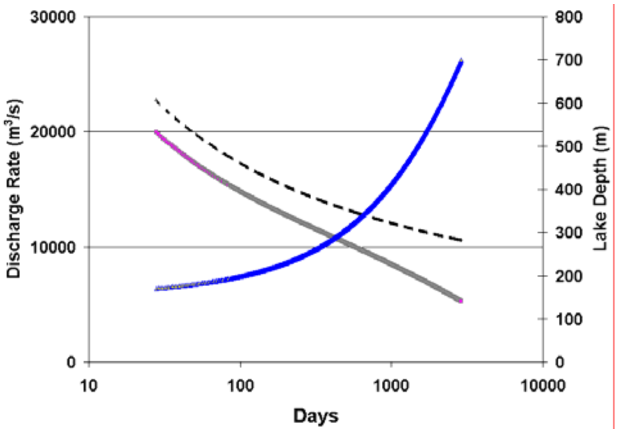

Figure 3. Semi-log plot of groundwater discharge and lake level with time. Dashed line is discharge uncorrected for rising lake waters. Gray line shows corrected discharge. Blue line is lake depth, with an overflow level at 700 m.

Lake Ice: We estimate the maximum thickness of ice that could have formed on the paleolake using equation 1 of Kreslavsky and Head [9]. Using a 55 K temperature difference between the freezing point of water and the mean surface temperature, we find that ice ~14.4 m thick could form in ~2880 days. The equation provides upper limits for the rate of ice growth because it assumes no heat is added beneath the ice. Groundwater influx at Ganges Cavus would have inhibited ice growth over the southern part of the lake, and fluid convection would have thinned the ice layer elsewhere. Dissolved salts in the water would also have reduced ice thickness. It is unclear whether enough ice was present to form ice jams at the outlet during the catastrophic release. Ice jams would significantly influence peak discharge rates. In any event, rafting of ice toward the outlet would have enhanced lateral erosion of the breach.

Elaver Vallis Morphology: The morphology of the Elaver channels is consistent with two stages of flooding. The initial outflows from the breached Morella Crater produced broad, 65-km-wide scabland flooding (Fig. 1). Two main channels comprise the Elaver Vallis complex – a deep channel to the north and a shallower channel to the south that forms a long, oxbow meander with hanging valleys at both ends. The southern branch is 200 m higher in elevation than the northern channel. The presence of this hanging valley demonstrates that flow persisted in the northern branch after flow ceased in the southern channel. Elaver Vallis abruptly terminates at the southern rim of Ganges Chasma, showing that Ganges continued to grow southward after the fluvial episode.

Chaos Morphology and Interpretation: At least four unnamed chaos exist on the channel floors (Fig. 1). The chaos in the southern channel (Fig. 1, inset A) has floor elevations ~400 to 420 m deeper than the high ground on its eastern side. This chaos is relatively pristine, suggesting that little flow from upstream occurred after this chaos formed. In the northern channel, the chaos marked “B” is ~500 m deeper than the terrain flanking it. MOLA data downstream from “B” reveal that the channel was further deepened over a width equal to that of the chaos. Therefore flow occurred along the entire downstream margin of the chaos. The relatively smooth floor of chaos “B” suggests that the knobs typical of chaos formation were eroded away by continuing flow in the northern channel after this chaos formed.

Based on the assumption that the maximum depth of a flood-induced chaos approximates the local cryosphere thickness, and the theory that fluvial incision can initiate secondary release of groundwater through chaos like these (cf. [10]), we estimate the cryosphere thickness east of Morella Crater at the time of the flood was >400 to 500 m. We calculate a crustal heat flux of >100 mW/m^2 using equation (1) [11],

$$Q = k\,\frac{T_{mp} - T_{ms}}{z} \qquad (1)$$

where Q = mean crustal heat flux (mW/m^2), k = mean thermal conductivity (1.5 W/m·K), T_{mp} = melting point (252 K), T_{ms} = mean surface temperature (218 K), and z = cryosphere thickness (>0.4 to 0.5 km).

The estimated crustal heat flux is consistent with the Elaver flooding having occurred during the mid- to late-Hesperian era (note also that the channels are incised in lower Hesperian strata, unit Hpl$_3$, of the Plateau Sequence [12]). The crustal heat flux is twice that calculated at Ravi Vallis (>50 mW/m^2) [10].

Water Gap Geometry: Because of a hole in MOLA coverage in the center of the Morella gap we reconstruct the topographic profile across Morella gap (Fig. 2) by measuring the channel width at its base and from one upper bank to the other. The top and bottom elevations of the gap (Fig. 4) were obtained from MOLA data that reflect the high-water mark elevation of 1780 m and the channel floor elevation of 1250 m just downstream and to the east of the Morella gap. Although the geometry of this cross-section may have changed somewhat over the 3 Gyr since the flood, the dimensions are suitable for order of magnitude calculations. Polygon elevations and widths in Fig. 4 yield 35° slopes for sides of the post-flood gap.

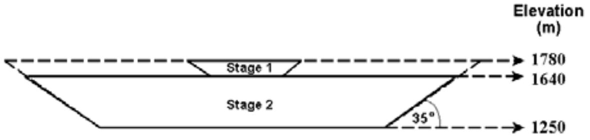

Figure 4. Topographic profile of water gap in Morella Crater. There is no vertical exaggeration. Top of polygon is 3.8 km wide; bottom is 2.3 km wide. Note change in polygon size from Stage 1 to Stage 2 flooding (see text).

Factors Influencing Peak Discharge: The plain east of Morella Crater has a relatively high preflood topography as estimated from the elevation of terrain flanking the Elaver channels. Where the Elaver channels converge to form a single channel more then 100 km east of Morella Crater, the eroded margin of the southern bank stands at an elevation of approximately 1640 m, marking the elevation of initial overland flooding. Extensive ponding could have occurred in lower areas to the west, resulting in backwater effects where water discharged through Morella’s gap. We subtract 1640 m from the 1780 m high-water mark elevation to obtain an estimate of 140 m for the lake water column that *easily and rapidly* drained before ponding and backwater effects arose. We refer to this as “Stage 1” flooding (Fig. 4). Our peak discharge analysis is based on Stage 1 parameters and represents a plausible peak discharge through the gap. Further deepening of the gap would have been regulated and constrained by the erosion rate of the channels to the east and backwater effects, significantly influencing the discharge rate at the gap and extending the duration of lake drainage. We refer to this protracted flooding period as “Stage 2” (Fig. 4). An additional lake depth of 380 m was drained during Stage 2, which corresponds to a volume of 1.5 × 10^{12} m^3.

Peak Discharge and Gap Erosion Rate: We apply the methods of Walder and O’Connor [13] for the failure of earthen dams to estimate the peak discharge

Table 1. Parameter definitions and resulting values from analysis of catastrophic release of water from Morella Crater paleolake.

Parameter	Value
Q_p (peak discharge rate)	1.1×10^6 m^3/s to 3×10^7 m^3/s (?)
g (gravitational acceleration)	3.71 m/s^2
D (drop in lake level during flood)	140 m (Stage 1) 530 m (Stage 1+2)
D_c (height of overtopped crater rim relative to channel thalweg)	140 m (Stage 1) 530 m (Stage 1+2)
V_o (water volume drained)	5.3×10^{11} m^3 (Stage 1) 2.0×10^{12} m^3 (Stage 1+2)
k (estimated erosion rates at breach for Stage 1)	0.014 to 0.028 m/s (50 to 100 m/hr)
$\eta = k \cdot V_o / g^{0.5} \cdot d^{3.5} = k \cdot 8500$	~120 to 240
r (ratio of breach bottom width to breach depth)	600/140 = 4.3 (Stage 1) 2300/530 = 4.3 (Stage2)
Time required to fill Morella Lake	>2880 days
Time required to drain initial 140 m of lake depth—Stage 1	~5000 sec (1.4 hrs)
Time required to drain additional 380 m of lake depth—Stage 2	To be further evaluated by future work

for Elaver Vallis. Table 1 lists values of parameters used in their equations. The parametric approach of [13] assumes that the cross-sectional shape of a dam breach is trapezoidal and that the breach shape does not change with time. Factors such as lake and breach shape and details of the breach-forming process usually have minor influence on the peak discharge and the flood hydrograph. The method [13] must be used with some caution here because, as previously discussed, flooding occurred in two stages. We use equation 20b of [13] (modified to reflect a larger r value) to calculate peak discharge from the Morella gap within an order of magnitude and assuming 140 m was the initial depth to which the gap rapidly eroded,

$$Q_p = 2.5 g^{0.5} d^{2.5} \left(\frac{D_c}{d} \right)^{0.75} \qquad (2)$$

where Q_p = peak discharge (m^3/s), g = gravitational acceleration (3.71 m/s^2), d = 140 m drop in lake level during Stage 1, and D_c = 140 m height of overtopped crater rim relative to surrounding terrain. We estimate a peak discharge, Q_p, of ~1.1×10^6 m^3/s. An important question remains. How rapidly were the Elaver channels east of Morella Crater eroded by the flooding? If this incision occurred quickly, then backwater effects would have been minimal, permitting the breach to rapidly erode to its full depth of 530 m. In that case equation 2 would yield an upper limit for the peak discharge of 3×10^7 m^3/s. Equation (2) is appropriate for scenarios where dimensionless $\eta = k \cdot V_o / g^{0.5} \cdot d^{3.5} >> 1$, which corresponds to large lake volumes with large erosion rates – conditions by which a dam breach fully develops before the lake level is significantly drawn down. Our estimate of gap erosion rates considers the large magnitude of the discharge (compared to terrestrial dam breaches) and assumes that the crater rim material was likely poorly consolidated as a result of the original impact event.

Conclusions: Due to the special condition that a castrophic flood issued from a well-defined source region, we have been able to present a detailed analysis for the Elaver Vallis megaflood. We estimate that the lake in Morella Crater took >2880 days (7.9 years) to form. The megaflood achieved a peak discharge of ~1.1×10^6 m^3/s during Stage 1, and may have reached ~3×10^7 m^3/s. A minimum water volume of 2×10^{12} m^3 rushed out of Morella through the water gap, with additional discharge continuing from Ganges Cavus after the lake drained. The water gap eroded to a total depth of ~530 m. East of Morella, secondary chaos were initiated on channel floors by fluvial incision of the cryosphere. We estimate a cryosphere thickness (and groundwater depth) of >400 to 500 m and a crustal heat flux >100 mW/m^2 at the time of this flood.

The abrupt termination of Elaver Vallis at the rim of Ganges Chasma confirms that the chasma continued to grow southward after the flood event. Finally, from the evidence of an elevated groundwater potentiometric surface we conclude that deep canyons probably did not exist north and south of Morella Crater at the time of the Elaver Vallis flooding because, if they had, high groundwater overpressures would have been more likely relieved by breakouts in those canyons.

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