CHARACTERIZING THE RECORD OF PALEOLAKE OUTLET CANYON INCISION ON MARS.

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Introduction: Mars has >200 documented paleolakes drained by an outlet canyon (**Fig. 1**) [*1, 2*]. Development of these hydrologically open lakes requires that water within the basins ponded to a level sufficient to overflow the basin-confining topography (typically a crater rim) and that the resultant flood incised an outlet across the drainage divide (**Fig. 1B**) [e.g., *1*].

Lake overflow events include some of the largest floods in Earth's geologic history, and have the ability to do significant amounts of geomorphic work in short periods of time [e.g., *3–5*]. Studies of lake overflow floods for individual basins on Mars have similarly concluded that these events had very high discharges and involved rapid outlet canyon incision [e.g., *6–10*]. Alternate hypotheses for outlet canyon formation include incision from multiple lake overflow floods [e.g., *11*] or incision from long-term outflow [e.g., *12*]. Here we present a study of the geometry of paleolake outlet canyons on Mars to test these competing hypotheses.

Methods: We measured the geometry of 24 paleolake outlet breaches and canyons from the catalog of [*1, 2*]. Geometries were measured using stereo-derived DEMs from HRSC [*13, 14*] and CTX [*15*] images, the latter produced using the NASA Ames Stereo Pipeline [*16–18*]. These data were supplemented with global gridded and point shot topography from the MOLA instrument [*19*]. We used CTX images and the THEMIS [*20*] 100 m/pixel global daytime infrared mosaic [*21*] to assess the geomorphology of the basins, outlet breaches, and outlet canyons.

The outlet breach cross-sectional area was estimated from a profile across the basin-confining topography (**Fig. 1C**). We estimated the pre-breach paleolake water surface elevation as the intersection level of the breach profile and manually mapped outlet canyon rims (**Fig. 1B,C**). The post-breach water surface elevation was estimated as the highest closed contour contained within the basin (**Fig. 1A**) [*1*]. The volume of water drained from the lake during progressive breach incision was calculated as the volume contained between the pre- and post-breach contours. We estimated the outlet canyon volume from profiles along the canyon length.

Results: Measured basins and outlets span several orders of magnitude in size: 7 for drained volume, 4 for breach cross-sectional area, and 6 for outlet canyon volume. Both breach cross-sectional area and outlet canyon volume vary systematically with respect to drained volume, and the data are well fit by power law functions (**Fig. 2**). The exponent for the outlet canyon volume best-fit power law is near unity, and the data are also well fit by a linear relationship with a leading coefficient of ~0.06 (OV = 0.06V; $R^2 = 0.988$).

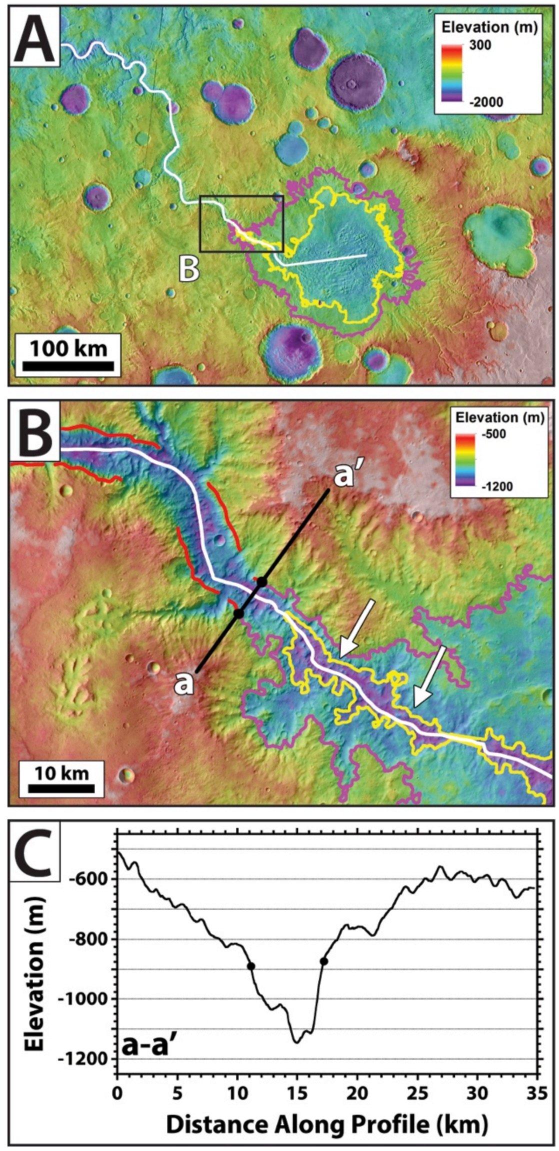

Fig. 1. *Parana basin paleolake (-21.7°N, -12.3°E; [1]). White line indicates outlet canyon (connected to the lowest point in the basin). Pre- and post-breach contours shown in magenta and yellow, respectively. North is up in both images.* ***(A)*** *Overview of basin. Mosaic of HRSC DEMs h4090_0000 and h4101_0000 and MOLA gridded topography overlain on the THEMIS daytime IR mosaic.* ***(B)*** *Outlet breach. Canyon rims mapped in red. Note incision in the basin interior (white arrows). Mosaic of HRSC DEMs h4090_0000 and h4101_0000 overlain on CTX image G06_020653_1608.* ***(C)*** *Profile a-a' of breach topography. Black circles indicate intersection level of profile and canyon rims. Profile extracted from HRSC DEM h4090_0000.*

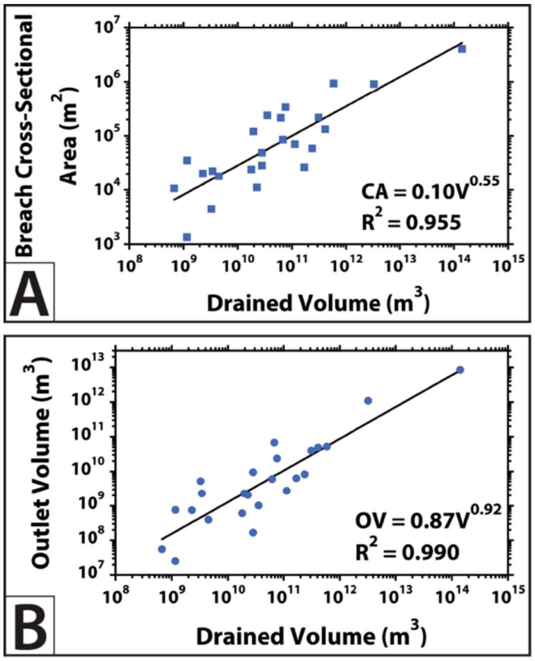

Fig. 2. *Breach cross-sectional area **(A)** and outlet canyon volume **(B)** versus drained volume. Black lines are best-fit power laws, with equation and R^2 value shown.*

Discussion: The total amount of potential energy available to be expended during lake overflow floods is proportional to the mass (and thus volume) of water drained [*22*]. The geometry of dam breaches formed during lake overflow floods on Earth is typically well correlated with drained volume [e.g., *23*]. The strong correlation between drained volume and both paleolake breach and outlet canyon geometry (**Fig. 2**) is thus consistent with the hypothesis that outlet canyon incision was the result of a single lake overflow flood.

Alternatively, it is possible that outlet canyon incision was driven by multiple overflow flooding events. This formation scenario is commonly invoked for outlet canyons formed by catastrophic flooding on Earth, where flights of terraces within the canyon record each successive flood [e.g., *3, 24*]. We find no evidence for terraces, or other indications of multiple floods, in the majority of outlets studied here; however, there are a small number of outlet canyons (3 of 24) that do appear to have interior terraces that record complex evolutions, potentially involving multiple floods [e.g., *11*].

A third alternative is that the outlet canyon was significantly incised by long-term outflow, to balance inflow to the basin, subsequent to the initial overflow flooding. In this scenario, the geometry of the outlet breach and canyon would be dependent on additional variables, primarily the timescale of lake outflow and the outlet discharge (controlled by the inlet discharge and basin size) [*12*]. Since there is no reason to expect these variables to vary systematically with drained volume, basin-to-basin variations in timescale and outlet discharge would add scatter to plots of geometry versus drained volume. While there is some scatter in our data (**Fig. 2**), they are remarkably well fit by power-law functions given the other potentially confounding variables (e.g., slope of the exterior terrain, eroded lithology, regional hydrology, etc.). We therefore suggest that our results provide no supporting evidence for the hypothesis that outlet canyon incision was driven by long-term outflow. However, we note that this conclusion is consistent with both short-lived and long-lived paleolake activity, and simply suggests that post-breach outflow did not significantly contribute to erosion of the outlet. This is also physically intuitive, as the energy stored in the lake that is available for incision pre-breach vastly exceeds what can be generated by slower, post-breach outflow, which is bounded by inflow to these lakes.

For these reasons, we conclude that the studied paleolake outlet canyons were primarily incised during single episodes of lake overflow flooding. The coefficient of 0.06 on the linear fit for outlet canyon volume versus drained volume indicates that time-averaged bulk sediment-to-water ratios during the canyon forming floods were ~6%, although instantaneous ratios were likely both higher (e.g., during the flood peak discharge) and lower (e.g., during the flood falling limb).

A striking indication of the power involved in these floods is evidenced by significant incision on the interior of many basins (**Fig. 2B**). Numerical modeling supports the hypothesis that this erosion was caused by the focusing of flow at the basin outlet as water drained at very high discharges [*10*]. We also note that the record of numerous large open-basin lakes on Mars [*1, 2*] implies that rapid canyon incision from catastrophic lake overflow flooding may have been an important process for shaping the early martian landscape.

References: [1] Fassett, C., and Head, J. (2008), *Icarus, 198*:37. [2] Goudge, T., et al. (2016), *Geology, 44*:419. [3] Bretz, J. (1969), *J. Geol., 77*:505. [4] O'Connor, J., and Baker, V. (1992), *GSA Bull., 104*:267. [5] O'Connor, J., and Beebee, R. (2009), in *Megaflooding on Earth and Mars,* pp. 128–177, Cambridge Univ. Press. [6] Irwin, R., et al. (2002), *Science, 296*:2209. [7] Irwin, R., et al. (2004), *JGR, 109*:E12009. [8] Coleman, N. (2013), *JGR, 118*:263. [9] Coleman, N. (2015), *Geomorph., 236*:90. [10] Fassett, C., and Goudge, T. (2017), *LPSC 48,* #1145 [11] Goudge, T., and Fassett, C. (2017), *4th Conf. Early Mars,* #3025 [12] Holo, S., and Kite, E. (2017), *4th Conf. Early Mars,* #3007 [13] Neukum, G., et al. (2004), *ESA Spec. Pub, ESA SP-1240*:17. [14] Gwinner, K., et al. (2010), *EPSL, 294*:506. [15] Malin, M., et al. (2007), *JGR, 112*:E05S04. [16] Broxton, M., L. Edwards (2008), *LPSC 39,* #2419. [17] Moratto, Z., et al. (2010), *LPSC 41,* #2364. [18] Shean et al. (2016), *ISPRS J. Phot. Rem. Sens.*, *116*:101. [19] Smith, D., et al. (2001), *JGR, 106*:23,689. [20] Christensen, P., et al. (2004), *Space Sci. Rev.*, *110*:85. [21] Edwards, C., et al. (2011), *JGR, 116*:E10008. [22] Costa, J., and Schuster, R. (1988), *GSA Bull., 100*:1054. [23] MacDonald, T., and Langridge-Monopolis, J. (1984), *J. Hydraul. Eng., 110*:567. [24] Baynes, E., et al. (2015), *PNAS, 112*:2355.