FORMATION OF INLET VALLEYS INTO CRATER-HOSTED LAKES ON MARS.

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Introduction: Mars is a prime candidate for astrobiological investigation, with ample evidence of past liquid water. Analysis of impact crater-hosted lakes that have one or more inlet valleys has helped constrain early Mars' hydrology and habitability [1-3]. However, the timescales and intensity of fluvial activity in inlet valley formation and lake filling remain poorly constrained.

Many studies have shown that craters initially form with a high standing rim [4]. For a 40 km diameter crater such as Jezero, initial rim relief at crater formation would be on the order of 500m [4,5]. Given that craters are initially bounded by an area of high topography, it requires substantial geomorphic work to form inlet valleys across the crater rim. How did fluvial systems on Mars surpass the high relief of crater rims? Little attention has been paid to this question despite the fact that most identified paleolakes on Mars are hosted within impact craters [1-3] and the fact that crater inlet valley(s) would have acted as a key control on lake level, sediment and nutrient supply, and overall lake evolution.

Analogy to Transverse Drainage: The question of how fluvial systems were integrated across rim topography is analogous to the formation of transverse drainage systems on Earth [e.g., 6]. However, on Earth transverse drainage across mountain and fault belts is characterized by erosion competing with uplift over thousands to millions of years, while impact generated relief is generated within minutes to hours, in a geomorphologically destructive event [7], ruling out transverse drainage via antecedence as a mechanism (i.e., incision keeping pace with uplift). This leaves three possible mechanisms of establishing transverse drainage on Mars [Figure 1B-D]; however, we also consider that the rim relief may have been significantly, or entirely removed prior to inlet incision during crater degradation [e.g. 8, 9], allowing any fluvial system to readily integrate the basin [Figure 1A]. Note that we do not specify the source of water in fluvial systems for any of these scenarios, as there remain many unknowns on Mars' climate and whether fluvial activity was driven by rain, snowmelt, or subglacial melt [8, 10, 11]. The source of water may, however, become evident from our analysis.

Approach: The geomorphic features of a crater-hosted paleolake, particularly the presence or absence of significant rim relief, is expected to indicate the dominant mechanism(s) at play for inlet formation. Comparison of crater and inlet morphometry for different types of basin may also elucidate any spatio-temporal trends in inlet formation mechanisms. Here we present morphometric measurements and morphological observations for a subset of 34 martian crater-hosted paleolakes using remotely-sensed elevation data and images. We utilised Context Camera (CTX) [12-14] and High Resolution Stereo Camera (HRSC) [15, 16] digital elevation models (DEMs) to extract topographic profiles along the inlet(s) and rim, and 10 equally-spaced radial profiles across the crater rim [Figure 2] from which we obtained measurements of rim relief and crater morphometry (i.e., depth/diameter relationships).

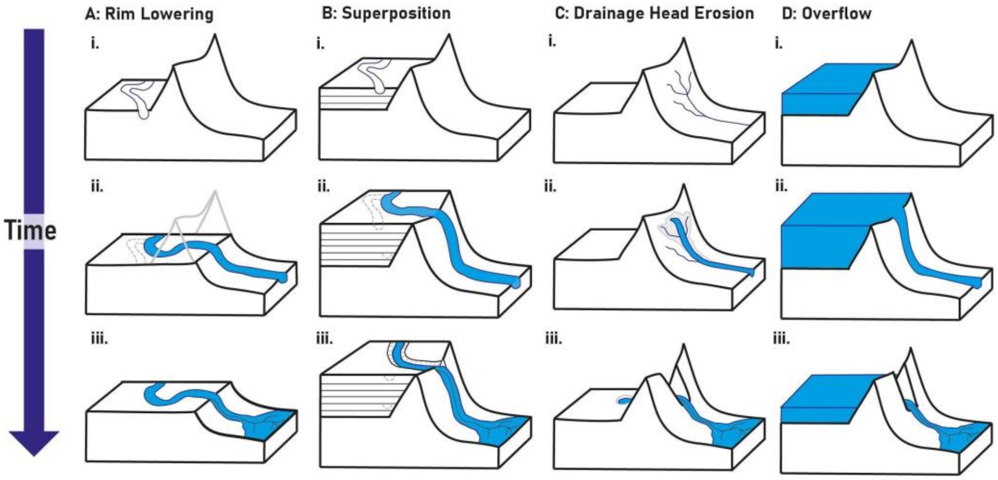

Figure 1: Schematic diagram outlining four hypothesized mechanisms of inlet valley formation (A-D), with successive stages illustrated from a stage prior to inlet formation (i), through the initial incision or event (ii), and the final resulting landscape (iii)

Figure 2 illustrates the measurements made, including: (i) the inlet longitudinal profile (blue line) from which we measured slope (S) and concavity. (ii) The rim topography (red line) from which we measured inlet width (W) and inlet depth (D). (iii) The average topography along 10 rim profiles (green line) shown with the standard deviation (grey shaded region), from which we have measured crater depth (CD), crater radius (R), and rim height (Hr).

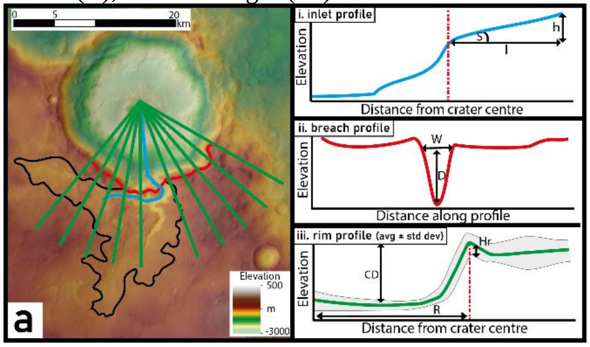

Figure 2: Example of measurements at each crater (a) Closed-basin paleolake at 16.2'N, 53.2'W with mapped profiles (i)-(iii), and a closed contour immediately upstream (black line). (i) Inlet profile, (ii) Breach profile (iii) Average of the 10 rim profiles with the standard deviation. *(in (i) and (iii), vertical dashed red line = rim location).*

Findings: *Inlet Incision Mechanisms:* Given that rim lowering and superposition both yield a similar topographic expression (i.e., the absence of significant rim relief), although achieved by different geomorphic processes, we describe both these mechanisms under the umbrella term of *rim relief removal*. We identify 17 inlets that fit observations for the *rim relief removal* processes. We identify 9 inlets where headward erosion appears to have been the dominant mechanism of drainage integration across the rim, and we identify 11 inlets as candidates for overflow from upstream. 13 paleolake inlets were not classified due to conflicting evidence possibly indicative of multiple mechanisms. We suggest these may represent cases where the dominant landscape and fluvial processes may have changed over space and/or time or acted in conjunction, e.g. rim lowering and headward erosion due to fluvial activity that both lead to upstream piracy.

Crater Degradation: In our subset of basins, there are 21 inlets into 12 hydrologically open basins (with an outlet), and 26 inlets into 22 hydrologically closed basins (without an outlet). All of the open-basin lakes are fed by a well-integrated valley network system, as reported in [17], while 6 of the closed basins are also fed by valley networks. Other basins are fed by isolated fluvial systems that are interpreted to be younger in age than the valley networks [17]. We find the valley-network fed craters have, on average, smaller depths relative to their diameter and smaller rims relative to a fresh crater of the same diameter, indicating that they are more degraded than the crater basins fed by younger fluvial systems.

Inlet Morphometry: We use inlet depth relative to crater depth (D/CD) to compare the inlet morphometry among basins. We find that the distribution of D/CD for both valley network fed basins (mostly open basins) and isolated inlet fed basins (all closed basins) are similar (mean of 0.322 and 0.316, respectively), indicating inlet depth is not affected by valley age nor hydrologic type. However, the D/CD ratio for inlets identified as candidates for integration by the overflow mechanism (i.e., inlets into basins with a closed contour immediately upstream) is 0.4, above the mean for all other mechanisms (~0.3), indicating inlet depth may be greater where valleys were incised by overflow.

Discussion: Identification of 11 inlets formed via overflow from upstream (perhaps in a single catastrophic event), indicates more paleolakes on Mars than previously recognized. The greater valley depth of crater-hosted lakes fed by overflow attests to the great geomorphic power held in lakes, consistent with observed catastrophic erosion during outlet canyon formation on Earth and Mars [18, 19].

The greater degradation of valley network fed craters supports widespread degradation on early Mars [8, 9] and indicates that the mechanism of rim lowering (Figure 1 A) may have been most important on early Mars, and primed impact craters for fluvial integration. Surprisingly, over half of crater paleolakes fed by 'late-stage' isolated inlets retain high rim relief, requiring some mechanism of transverse drainage to explain their formation. This implies young episodes of significant valley incision to integrate across crater rims, at least locally.

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