IMPACT CRATER LAKES AND FLUVIAL VALLEY INCISION ON EARLY MARS. T. A. Goudge[1,2], E. R. Bamber[1], M. Coholich[1,3], C. I. Fassett[4], A. M. Morgan[5,6], G. R. Osinski[7], and G. Stucky de Quay[8], [1]Dept. of Geological Sciences & Center for Planetary Systems Habitability, The University of Texas at Austin, Austin, TX; [2]CIFAR Azrieli Global Scholars Program, Toronto, Ontario; [3]Dept. of Geological Sciences, Stanford University, Stanford, CA; [4]Johns Hopkins Applied Physics Laboratory, Laurel, MD; [5]Planetary Science Institute, Tucson, AZ; [6]Center for Earth and Planetary Sciences, National Air and Space Museum, Smithsonian Institution, Washington, DC; [7]Dept. of Earth Sciences, University of Western Ontario, London, Ontario; [8]Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA (Contact: tgoudge@jsg.utexas.edu)

Introduction: The surface environment of early Mars, >3.5 Ga, was much different than that of today, with networks of fluvial valleys and standing bodies of water [*1–7*]. The vast majority of lakes on Mars were hosted in basins defined by an impact crater, or multiple coalesced craters [*1,3*] (**Fig. 1**). This aspect of martian topographic structure, unique in comparison to lake systems on Earth, presents several interesting research questions. Here we summarize some of our recent work on this topic, considering how impact crater lake evolution and fluvial valley incision interacted on early Mars.

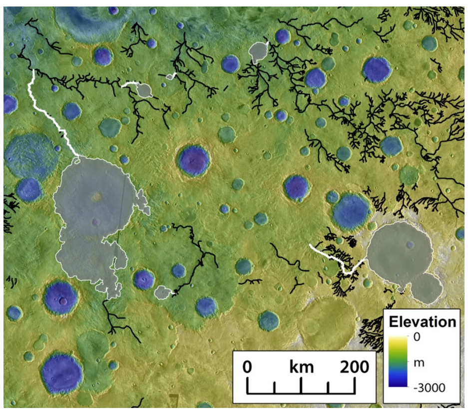

Fig. 1. *Paleolake basins (transparent polygons), outlet canyons (white), and valley networks (black) on the cratered early Mars landscape. MOLA global topography [8] overlain on the THEMIS daytime IR mosaic [9,10]. Image centered at −9.1°N, −2.1°E.*

Inlet Formation; or, how do crater lakes exist in the first place? The mere fact that crater lakes with inlets existed at all on Mars is interesting given that a defining characteristic of impact craters is an uplifted rim [*11,12*], which should inhibit flow into the basin interior.

Recent work by Bamber et al. [*13*] to address this problem evaluated three potential mechanisms for inlet valley formation, based on analogy with transverse drainage formation on Earth (**Fig. 2**): (A) Rim Relief Elimination, where the topographic relief of the rim is removed, by erosion and/or upstream deposition, before an inlet forms; (B) Drainage Head Erosion, where fluvial erosion on the interior of a crater wall progresses headward, incising through the rim and capturing any upstream drainage; and (C) Overflow, where the rim ponds a temporary lake upstream, which overflows into the crater, forming an inlet in the process. For the latter two mechanisms, the geomorphic work responsible for inlet formation is accomplished by coeval fluvial activity, while in the former, it is accomplished by crater degradation (which may also involve fluvial activity [e.g., *14–16*]) prior to inlet formation [*13*].

Examining orbital topography and image data for 39 paleolake inlet valleys, Bamber et al. [*13*] found that all three mechanisms likely occurred on Mars. For early Mars lakes, formed during the period of peak valley network activity (herein referred to as the 'VN-era'), Rim Relief Elimination was the dominant mechanism [*13*]. This suggests that widespread, early crater degradation [*14–16*] likely 'pre-conditioned' impact crater basins to become lakes during the VN-era.

This then raises a second interesting question – why are only some, not all, degraded impact craters breached by inlet valleys given how common they are on the early Mars landscape (**Fig. 1**)? This question was recently addressed by Bamber et al. [*17,18*], who found that the most important factor was regional hydrology, such as the potential catchment area or how much of a regional sink the basin is on the landscape. This latter aspect is often set by whether a given crater exists within a larger topographic low, typically a large impact basin [*17,18*].

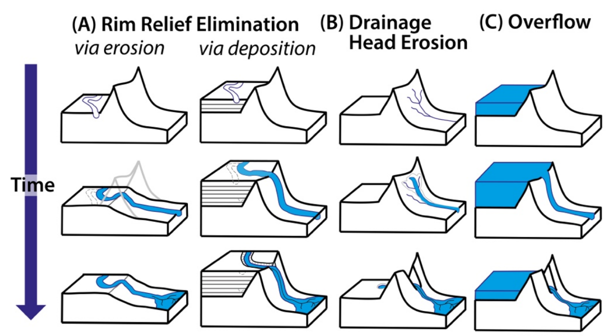

Fig. 2. *Schematic illustration of three proposed mechanisms of inlet formation for crater-hosted lakes [13].*

Outlet Formation; or, what happens when crater lakes fill up? In many cases, impact crater lakes that were breached in the upstream by an inlet valley also filled up with water completely (e.g., to the point of overflow), thus causing breaching in the downstream [*1–3*]. This formation of an outlet breach would establish a hydraulic connection between the lake interior and exterior terrain, and resulted in the rapid, catastrophic incision of outlet canyons on the early Mars landscape [*19–21*].

Although paleolake outlet canyons only account for ~3% of the total length of early Mars fluvial valleys, we have recently shown that they account for ~24% of the total eroded volume of valley systems due to the deep incision accomplished by catastrophic lake breach flooding [*22*]. This outsized importance of lake breach flooding for fluvial erosion on early Mars means that the filling and breaching of crater lakes played a key role in shaping the martian landscape, influencing valley incision in the process. Most notably, deep paleolake outlet canyons routinely disrupted regional, surface runoff-fed valleys, often leading to the formation of hanging tributaries [*19, 21*]. This helps to explain observations of immaturity commonly noted for valley networks on Mars [e.g., *5,6, 23*], as the systems were constantly forced to respond to perturbations by large, catastrophic incision events [*22*].

Lake breach floods are also likely under-recognized in the geologic record in cases where the lake was temporary or when the lake completely drained, exposing the basin floor to further valley incision [*22*]. Instead, the >250 breached open-basin lakes identified on Mars are all incompletely drained, indicating that at some point after initiation, the catastrophic breach flood shut off [*24*]. The completeness of draining can be quantified by the *Drained Fraction*, a ratio of the water volume drained by the breach flood to the initial water volume of the lake.

To explore the controls on what promoted complete versus incomplete lake draining, we recently conducted a study using a numerical model of the lake breach process [*25*] compared with observations of martian open-basin lakes. We found that the strongest control on the *Drained Fraction*, in both model and observational results, is the height of the crater rim, where taller crater rims promote more complete draining (**Fig. 3**) [*24*].

This result is especially interesting when compared with the hypothesis that rim degradation pre-conditioned craters for inlet breaching [*13*]. While rim relief removal allowed lakes to fill up with water from inlets in the first place, this also likely prevented the lakes from fully draining and completely eroding their confining topography. The persistence of these local (lake) basins would have buffered the routing of surface runoff within valley systems [*24*], contributing to the lack of widespread network integration on early Mars [e.g., *5,6,23,26*].

Summary: The topography of Mars' southern highlands is dominated by relief created by impact craters, so it is no surprise that these landforms played an important role in water routing during the early Mars VN-era [e.g., *26*]. At large scales, the topography created by impact basins dictated which craters developed inlets [*17,18*], allowing them to fill with water and create lakes [*13*].

This ponding of water also led to the storage of potential energy that was released as catastrophic lake breach floods [*21*], which carved deep canyons on the martian surface that broadly affected valley incision [*19,22*]. Degradation of impact craters, and specifically

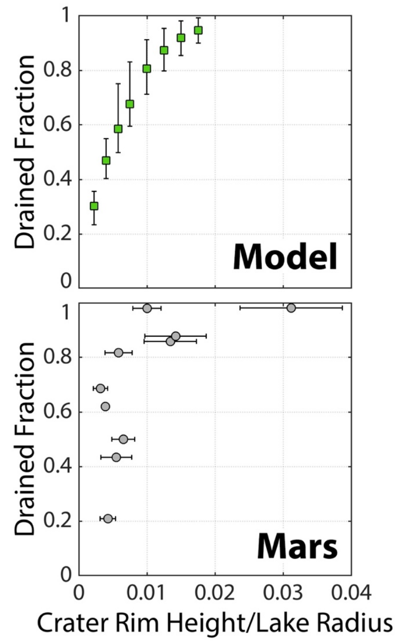

Fig. 3. *Drained fraction vs. crater rim height (normalized to the lake size, i.e., area-equivalent circle radius) for a series of numerical experiments (top) and from 10 open-basin lakes on Mars (bottom) [24].*

the removal of rim relief, allowed inlet formation for many early Mars crater lakes [*13*]. However, these lowered rims likely then prevented the lakes from completely draining [*24*], thus leaving martian lake basins on the landscape to act as a buffer of standing water keeping valley systems from becoming well integrated.

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