

Late Noachian to Hesperian Climate Change on Mars: Evidence from Crater Lakes and Thermokarst Terrain Near Ares Vallis. N. H. Warner¹, S. Gupta¹, S. Lin², J. Kim², J. P. Muller², J. Morley³ ¹Dept. Earth Science & Engineering, Imperial College London, South Kensington Campus, SW7 2AZ, UK, n.warner@imperial.ac.uk. ²Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St. Mary, Surrey, RH5 6NT, UK, ³Centre for Geospatial Science, Sir Clive Granger Building, University of Nottingham, University Park, Nottingham, NG7 2RD, UK.

Introduction: A significant transition in the climate of Mars may have occurred near 3.8 Ga to 3.5 Ga at the boundary of the Noachian and Hesperian [1]. This period of martian geologic time is marked by a distinct change in landform morphology and mineralogy, with a diminishing occurrence of well-developed valley networks [2-4] and an overall disappearance of phyllosilicates within layered deposits [5]. Currently, it is unclear whether this climate change was gradual, occurring throughout the Noachian and into the Hesperian, or punctuated by specific events at the Noachian-Hesperian boundary [6].

In this analysis we describe the surface and crater morphology of a region on Mars previously defined by crater statistics to have formed during this critical period of climate change. The equatorial highland surfaces of Xanthe Terra and Arabia Terra are heavily cratered Late Noachian to Early Hesperian-age terrain that contains numerous large catastrophic outflow channels [7]. Specifically, we focus our analysis on the regions of Xanthe Terra and Arabia Terra that immediately surround the Ares Vallis catastrophic outflow channel (Fig. 1). Here we have identified several previously undescribed crater basins and thermokarst depressions (Fig. 2) that exhibit small outlet channels. Importantly, these features lack inlets and suggest that water ponded at these locations at some point in the history of Mars.

Using complimentary data sets of MRO CTX images (6 m pixel⁻¹), CTX DTMs (18 m), HRSC DTMs (50 m – 75 m), HRSC ortho-images (12 m pixel⁻¹), THEMIS visible light images (18 m pixel⁻¹), and THEMIS thermal infrared images (100 m pixel⁻¹) (day and night) we describe the morphology of the impact craters that contain outlet channels and of the thermokarst terrains. Furthermore, we extend our observations to 75 large diameter ($D > 8$ km) craters in the study region to relate crater morphology to regional surface degradation and climate change. Crater statistics were obtained from the highland terrain, crater floors, and thermokarst terrains to constrain the timing of surface liquid water stability at these locations. The primary outstanding questions that we look to address are: (1) What was the regional extent of crater lakes in the highland terrain surrounding Ares Vallis and how do the morphologies of the water-filled craters compare to other craters that

lack evidence for infilling? (2) Do these crater lakes represent local occurrences of water infilling or do they represent a broader hydrologic cycle (precipitation, ground-water influx, infill from Ares Vallis floods). (3) What is the timing of water infilling and how does it relate to the timing of drainage? (4) What is the timing of formation of the associated thermokarst terrains, is the timing consistent with the formation of the nearby crater lakes, and what does the presence of thermokarst depression-connecting channels indicate about the stability of surface ice? (5) What are the broader implications regarding climate change at the Noachian-Hesperian boundary.

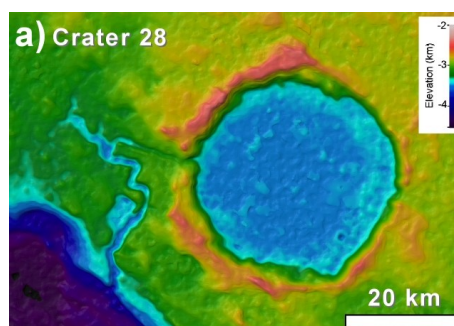


Fig. 1: Example 70 m HRSC DTM of an impact crater basin with an associated outlet channel near the margin of Ares Vallis.

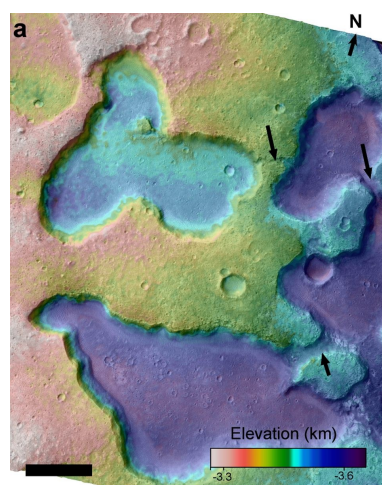


Fig. 2: Example 18 m CTX DTM of thermokarst depressions in Ares Vallis that exhibit connecting channels. Scale bar is 2 km.

Craters with Outlet Channels: The data indicate that 46 of the 75 measured large diameter impact craters in the Ares Vallis region have d/D ratios that are reduced by $>20\%$ from modeled ratios for pristine craters of equal diameter [8]. Additionally, the data reveal that the majority of impact craters in the region show some measurable reduction from modeled rim heights, indicating that erosive scour or embayment of plains material modified the craters. However, comparisons of the measured d/D ratios to the measured crater rim heights and observations of the crater floor materials with CTX images indicate that crater infill must account for a portion, if not most of the crater degradation.

Four of the highly degraded impact craters surrounding Ares Vallis contain obvious outlet channels with no morphologic evidence for inlets or gullying on the interior crater walls. Furthermore, there is no geologic evidence for modification of the outlet channel craters by Ares Vallis floods, indicating that these craters were not filled with water during the catastrophic outflow events. We therefore suggest that groundwater sapping into the crater basins is the most likely mechanism for infill of water. Furthermore, the infill material may be sediment that was derived from modification of the interiors of the crater rims. The presence of polygonal fractures on the surface of the crater infill material suggests that this material was formerly hydrated.

The cumulative crater density of the 75 impact craters provide an average Late Noachian model age of $3.82 \text{ Ga} +0.02, -0.03$ for the highland terrain in the study region. However, our analysis of crater d/D ratios indicates that 29 out of the 75 measured impact craters show a near pristine morphology. If we assume that the modification processes that operated to infill craters, subdue crater rims, and destroy ejecta blankets occurred at some time in the past over the entire Ares Vallis region, then the cumulative crater density of the near-pristine crater population is representative of the age since intense modification. The model age for the near-pristine crater class is $3.62 \text{ Ga} +0.05, -0.08$, approximately 200 Ma younger than the age determined for the highland terrain. This indicates that intense modification, including infill of the craters, occurred during a short 200 Ma interval between the formation of the highland terrain and formation of the near-pristine population.

The estimated range in thickness of the infill material in the craters with outlet channels is $\sim 300 \text{ m} - 600 \text{ m}$. We hypothesize that the infill was deposited during the modification events that dominated the Late Noachian. Crater statistics acquired from CTX images ($D > 100 \text{ m}$) of the floor of the craters indicate a consistent Late Noachian model age ($3.8 \text{ Ga} - 3.6 \text{ Ga}$) for all craters with outlets. Near pristine impact craters lack infill deposits indicating that the process of infill ceased in the Hesperian.

The presence of outlet channels indicates that water must have drained out of the crater basins at some time following the infill event(s). Superposition relationships between the younger drainage channels and older grooves associated with Ares Vallis and Hydapsis Chaos floods indicate that the crater outlets formed during the Hesperian-Early Amazonian from $3.5 \text{ Ga} - 2.9 \text{ Ga}$. This observation suggests a period of delay ($100 \text{ Ma} - 900 \text{ Ma}$) between the Late Noachian-age influx of water into the basins and drainage.

Thermokarst Terrain: The observation of Hesperian-age crater outlet channels implies that liquid water was at least transiently stable at the surface of Mars during this period. In support of this hypothesis we have identified several thermokarst-like depressions on the highland terrains and within the Ares Vallis outflow channel that are spatially associated with the craters with fluvial outlets. These thermokarst depressions may represent collapse structures that formed following sublimation or melting of near-surface ice [9]. However, we have identified several small depression-connecting channel-like features at multiple locations across the Ares Vallis region that suggest that the depressions formed from melting of near-surface ice, similar to terrestrial alpine lakes (Fig. 2). The regional occurrence of these features implies that the melting mechanism was also regional. Crater statistics and relative relationships with Ares Vallis outflow channels indicates that the depressions formed during the Hesperian, near $3.3 \text{ Ga} - 3.0 \text{ Ga}$.

Conclusions: We suggest that the presence of Hesperian-age crater outlet channels in association with Hesperian-age alpine-lake type thermokarst features requires climate conditions that were favorable for the transient occurrence of stable surface liquid water. We further hypothesize that infilling of the large crater lake basins, occurring in the Late Noachian, was followed by $100 \text{ Ma} - 900 \text{ Ma}$ of water/ice stability within the large crater basins before climate induced warming led to melting and drainage.

References: [1] Hartmann, W. K., and G. Neukum (2001), *Space Sci Rev*, 96, 165-194. [2] Carr, M. (1996), *Water on Mars*, Oxford University Press, New York. [3] Craddock, R. A., and T. A. Maxwell (1990), *JGR*, 95(B9), 14265-14278. [4] Fassett, C. I., and J. W. Head (2008), *Icarus*, 195(1), 61-89. [5] Mustard, J. F., et al. (2008), *Nature*, 454(7202), 305-309. [6] Howard, A. D., et al. (2005), *JGR*, 110(E12), E12S14, DOI: 10.1029/2005je002459. [7] Nelson, D. M., and R. Greeley (1999), *JGR*, 104(E4), 8653-8669. [8] Garvin, J. B., et al. (2000), *Icarus*, 144(2), 329-352. [9] Warner, N., et al. (2010), *Geology*, 38, 71-75.