MARS BEFORE THE VALLEY NETWORKS: OUTSTANDING QUESTIONS ON NOACHIAN CRATER DEGRADATION AND EARLY CLIMATE. Benjamin D. Boatwright and James W. Head, Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI 02912 USA (benjamin_boatwright@brown.edu; james_head@brown.edu).

Introduction: Significant progress has been made in characterizing the nature and timing of the valley networks and crater lake basins in the southern highlands of Mars [1-4]. In recent years, a general consensus has emerged that these features formed during a relatively brief "terminal epoch" around the Noachian–Hesperian boundary, in which fluvial activity experienced a significant increase in intensity over previous background rates, followed by a sharp decline into the Hesperian [5-7]. The pre-valley network substrate has been heavily reworked by impacts, but evidence exists for fluvial erosion as well. Such evidence comes primarily from the morphometry of Noachian crater profiles in a range of degradation states [8-11] and their topographic relationships with the surrounding intercrater regions [12-14]. These studies have painted a picture of slow, steady erosion occurring in a warm and arid climate for hundreds of millions of years before the inception of the valley networks, but many key aspects remain uncertain. Establishing a more robust understanding of this earliest period of geologic history will provide important context for the later episodes of globally distributed fluvial activity on Mars. We provide a summary of the state of knowledge of pre-valley network geology and climate, and pose outstanding questions that could be addressed by ongoing and future Mars research.

Previous work: A body of research exists that has laid the groundwork for our understanding of landscape evolution on Mars in the era before the valley networks. Viking photoclinometry established a degradation sequence for martian craters ranging from pristine to almost completely erased ghost craters [8-11]. Unlike on the Moon, craters on Mars have a distinct style of degradation that suggests the influence of fluvial erosion derived from runoff, with lesser contributions from mass wasting and eolian infilling [8-11,15-16]. This was a major finding that has since been used as evidence for a warm and wet early Mars climate [17-18]. The pre-valley network intercrater regions have also played an important part in defining the regional topography of the highlands. The intercrater plains have been described as tectonically stable surfaces that experienced significant overall erosion despite minimal fluvial dissection during the Noachian [14]. This suggests that fluvial erosion was transport-limited, and rates of evaporation and infiltration were much higher than runoff [12,14].

Outstanding questions: The Noachian highlands of Mars have been characterized as fluvially degraded but in a style very distinct from the later valley networks. In this section, we pose some major outstanding questions that have been raised by these observations, and explain how we have begun to address them in our recent work.

1. What were typical erosion rates? Multiple early studies gave estimates of erosion rates during the Middle and Late Noachian, typically using a total reworked sediment volume to arrive at an average rate over a given timespan [8-10]. We have reanalyzed these estimates to account for differences in methods between studies [19]. Accordingly, when scaled over the Middle and Late Noachian, erosion rates are on the order of 10^{-4}–10^{-2} mm/yr [19]. This is in contrast to the terminal epoch of valley network formation, when erosion rates may have been as high as 2–10 mm/yr [19]. Thus, average erosion rates during the Noachian prior to the valley networks appear to have been significantly lower.

2. What transport processes were responsible? Geomorphic observations have been used to hypothesize that the style of erosion before the valley networks was transport-limited, i.e. fluvial discharge was generally not high enough to result in incision of the landscape despite water flowing over the surface [12,14]. The nature of transport-limited vs. weathering-limited erosion has been addressed extensively in the modeling literature [e.g. 20], and a recent study applies the same methods to the earlier period of Noachian crater degradation [16]. They find that the most arid conditions they tested result in the closest statistical match to the regional topography of the highlands, with evaporation rates 10-15x higher than runoff [16]. Our preliminary work has provided an improved framework for using numerical landscape evolution models in this context [21].

3. What was the climate, and what caused it to change by the time of valley network formation? If the major component contributing to the degradation of Noachian craters was fluvial erosion, then the climate supporting such erosion must have changed in a significant way to account for the difference in erosion rates and mechanisms between the earlier Noachian and the terminal epoch at the Noachian–Hesperian boundary. Canonical interpretations suggest that the climate was already warm and dry, then essentially humidified to form the valley networks [17-18]. However, recent climate modeling studies have demonstrated the difficulty of maintaining average temperatures above freezing on early Mars [22-25]. Various punctuated warming scenarios have been explored [26-28], but none have been conclusively proven to result in valley network formation. An alternative model suggests that an adiabatic cooling effect would cause preferential deposition of snow and ice in the southern highlands in a colder

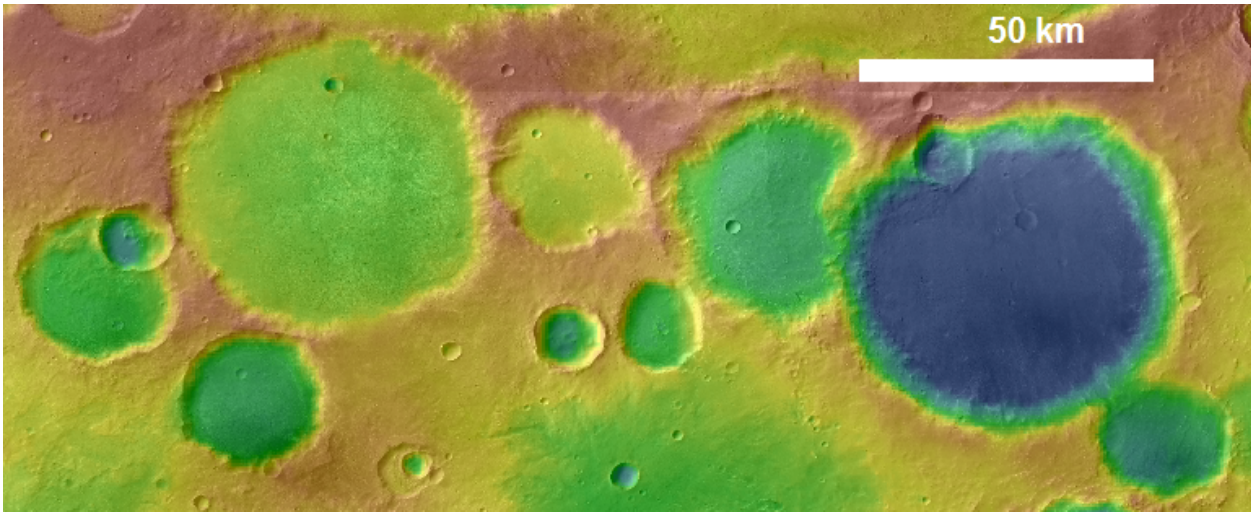

Fig. 1. CTX mosaic [37] with MOLA topography overlay showing a group of degraded craters in Terra Sabaea that has been used as an example of fluvial erosion in a warm and wet early Mars climate.

climate, forming an ice sheet whose equilibrium line altitude appears to be correlated with many of the valley networks and crater basin lakes [29]. Despite predictions that the ice sheet would be mostly cold-based, runoff could still be generated from top-down melting if local surface temperatures reached above freezing [30].

How does Noachian crater degradation fit into this climate picture? Our ongoing investigations into the hydrology of crater interiors in Terra Sabaea [31-32; Fig. 1] has revealed a plethora of geomorphic features that appear analogous to those described in craters that have undergone Amazonian glaciation in Newton basin [33-35]. Preliminary crater age dating suggests that these features are ancient, providing potential evidence for glacial activity within degraded craters in the Noachian. This could further imply that runoff, which is predicted to have been the primary driver of Noachian erosion, was sourced from snowmelt instead of rainfall. Analog studies of cold-based glaciation in the McMurdo Dry Valleys of Antarctica have shown that bedrock erosion rates there are ~10^{-3} mm/yr [36], comparable to estimates for Noachian crater degradation [8-10]. Further work will be necessary to determine the feasibility of these different models.

Ongoing research and future avenues: With modern high resolution global datasets, the types of analyses performed decades ago could be significantly improved today. A better understanding of the hydrologic conditions that prevailed for most of the Noachian will be key to completing the story of climate evolution and potential habitability on early Mars. The combination of geomorphic characterization and numerical modeling of climate and landform evolution will be critical to this effort. We plan to continue our own studies of Noachian crater degradation by testing theories relating to the generation of runoff through snowmelt and the potential interaction between fluvial and glacial processes, as observed in degraded craters in Terra Sabaea. Geomorphic studies of the Noachian period remain largely focused on the valley networks, which only represent a small fraction of the geologic history of the planet. While continued focus on early Mars science objectives will obviously be fruitful with the upcoming Mars 2020 and ExoMars rovers, digging deeper into the past may reveal even more fundamental insights, providing valuable context for future landed and orbital missions.

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