IMPACT CRATERING AS THE CAUSE OF CLIMATE CHANGE, ATMOSPHERIC ALTERATION, AND LATE NOACHIAN VALLEY NETWORK FORMATION ON MARS: AN ASSESSMENT

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Introduction: The martian valley networks (VN) [1] and associated open- and closed-basin lakes (e.g. [2,3]) are related fluvial features indicative of the flow of liquid water in the southern highlands and adjacent areas during the Late Noachian and Early Hesperian [4]. Also, highland impact craters from this period are highly degraded, possibly due to fluvial activity. In the Amazonian, liquid water is unstable in the atmosphere [5] and metastable on the surface [6], but the LN-EH climate was potentially much different.

However, due to a younger and 25% less luminous Sun [7], recent climate models show that the mean annual temperature (MAT) of LN-EH Mars was unable to reach the triple point of water solely by incoming solar radiation [8,9], even with additional greenhouse gases in the atmosphere [8-15] when considering reasonable source, sink, and atmospheric pressure constraints. Additionally, the formation of the fluvial features observed on Mars may not require continuous clement conditions throughout the Noachian, suggesting that transient warming could be responsible for runoff and subsequent VN formation. This conundrum has led to two candidate end-member early climate scenarios: 1) "warm and wet" [16], during which MATs were consistently high enough to permit rainfall, or 2) "cold and icy" [9] during which the southern uplands of Mars were dominated by snow accumulation, mean annual temperatures were significantly <273 K, and transient melting was required to form the VNs.

In a "cold and icy" climate, MAT is ~225 K, so it is likely that external forcing would be required to produce transient conditions >273 K. A major candidate for periodically raising atmospheric and surface temperatures is impact cratering [17-20].

One can anticipate the importance of impact cratering in the Noachian: the intense kinetic energy transfer from the projectile collision is predicted to cause vaporization, melting, and ejection of all of the projectile and some of the target material, heating the atmosphere and surface to produce conditions appropriate for significant rainfall and runoff [17,18,20]. The higher impact cratering flux in early planetary history not only increased the frequency of events, but also increased the number of large-magnitude (basin scale) events. The abundance and diversity of Noachian impact craters coupled with their intense, punctuated, and widespread effects makes this mechanism an attractive candidate for temporarily inducing climate change throughout the history of Mars.

Regardless of the background climate, impact cratering would lead to rainfall and runoff, contributing to surface fluvial activity. An in-depth understanding of the implications of impact cratering on the Noachian climate is critical to the overall climate scenario, but the process has not been sufficiently studied in detail.

Analysis of the impact cratering mechanism: In this work, we explore the effects of impact cratering on the atmosphere and surface, documenting the "Impact Cratering Atmospheric/Surface Effects" (ICASE) scenario as originally put forth by [17-18]. We highlight the important steps in the mechanism to create an illustrative timeline for qualitative understanding of the sequence (Fig. 1) while discussing the geological implications predicted by ICASE at each step. We illustrate the schematics of these steps and discuss the global or regional implications through a series of descriptive diagrams (Fig. 2). The critical contributions of this work are (1) putting the climatic effects of impact cratering in the Noachian into geologic context, then (2) analyzing the predictions from previous workers [17,18] with respect to our geologic understanding to draw conclusions about the role of impact cratering on martian fluvial and lacustrine activity and VN formation.

Important Factors: Previous work has used 1-dimensional column models to interpret the effects of impact cratering on the atmosphere and surface with respect to formation of the VNs [17,18]. Parameters which should be considered when modeling ICASE include impactor size, impacting velocity, and angle of incidence because they correlate directly with the amount of energy transferred by the impacting event, influencing the amount of vaporized projectile and target material and, thus, the amount of water vapor available for subsequent rainfall.

Understanding ICASE: In Figs. 1 and 2, we highlight the important climate-related steps in ICASE and make predictions on the geologic effects of each step, including impact-induced rainfalls.

Expansion of the vapor plume (Figs parts A and B). Immediately following the impact, the vaporized material, comprised mostly of silicate and water, expands as a plume releasing no heat until the plume cools through expansion to transparency temperature of the surrounding atmosphere. The amount of water vapor in the plume increases with increasing amount of water in the impactor.

Vapor plume growth (global/regional/none) will depend directly on the amount of energy transferred by the impact event. Previous work [e.g. 17-20] using 1-dimensional models has assumed global growth of the plume under all circumstances. However, a major limitation of 1-dimensional modeling is the inability to determine lateral motion. Additionally, smaller, less energetic impacts will likely produce regional effects, local effects, or vaporize no material at all. We suggest that 3-dimensional modeling of plume growth is necessary to quantify this variable and make reliable predictions on an impactor size to global plume growth relationship under early Mars atmospheric conditions.

The final size of the plume is directly correlated to the distribution of impact related effects. However, our initial analysis of plume growth as a function of impactor size implies that global plume growth [17-20] is an overestimate of the distribution of plume effects, including impact-induced rainfall.

Cooling of the plume (Figs parts B and C). Upon reaching transparency temperature, the plume continues to grow and release heat through expansion and thermal radiation, decreasing temperature within the plume and increasing temperature in surrounding areas in the atmosphere and on the surface. The plume will cool sufficiently for the vaporized rock silicate to condense and rain down at extreme temperatures, possibly ~1600 K [17,18]. At this point, the water vapor will still be in the atmosphere due to the much lower condensation temperature.

The condensed rock silicate material will produce a layer at the surface by following ballistic trajectories from the atmosphere to the surface, implying a global layer regardless of final plume size. The geomorphology of regions adjacent to craters can provide insight into the nature of the rock silicate layer. The material may rain down in a molten state, forming a solid layer, trapping heat underneath and forcing the heat to escape through specific conduits. Alternatively, the material may rain down in spherules, creating a porous layer and allowing buried heat beneath the layer to escape to the atmosphere. In either case, we expect geomorphological effects from this layer. Interactions between the rock silicate material and surface should be considered in future studies.

Rainfall (Figs parts D-G). Following the global rock silicate fallout, the plume will cool to the condensation temperature for water, producing global [17,18] or regional rainfall, surface runoff, and a temporary hydrologic cycle (for impacts above a certain size threshold). The hydrologic cycle is described through the following steps (see Fig. 2 part F): (1) rain falls onto and seeps into the hot rock layer; (2) water vaporizes from buried thermal energy in the layer; (3) water vapor is injected back into the atmosphere; (4) the atmosphere cools through radiation and the water rains back down on the surface. This process repeats until the rock silicate layer cools below an average 373 K or the thermal energy is buried inaccessibly deep in the layer. At this point, the climate returns to its ambient state and the ICASE process has been terminated.

Previous predictions on rainfall totals that do not account for a hydrologic cycle have found a total 0.5-6 km GEL of water from all Noachian impacts [18], which is much higher than the predicted 3-100 m GEL required to form the VNs [22]. Additionally, a temporary hydrologic cycle introduces the possibility for the impact-induced water to interact with the surface multiple times, increasing the water total and producing more erosion.

The nature and distribution of the rainfall and hydrologic cycle is not well constrained. Previous workers [17-20] have assumed global effects, but it is likely that this assumption would not hold true for smaller, less energetic, impacts. A better understanding of ICASE requires further studies regarding the rainfall, hydrologic cycle, and interactions between the water and surface. Future work should introduce a water vapor profile of correct concentration and lateral extent into a 3-dimensional general circulation model to study the rainfall patterns, rainfall distributions, and duration of the induced hydrologic cycle.

Relationship to VN Formation: Could ICASE be responsible for the correct magnitude of erosion and fluvial/lacustrine activity responsible for the formation of the VN and OBL?

The rainfall events proposed by the ICASE scenario predict (1) rainfall quantities much higher than what was necessary to form the VNs and (2) average global rainfall rates equivalent to that of Earth in tropical rainforests, approximately 2 m/year, at much higher temperatures and with no plant life to naturally absorb water. The hotter water will likely promote higher erosion rates. Additionally, large-scale impact events will induce a hydrologic cycle, allowing the intense rainfalls to continue for hundreds of years after large impacts, permitting multiple water-surface interactions and more erosion.

For all aforementioned reasons, ICASE water totals imply a significant deluge effect. We conclude that the water from the initial rainfall and subsequent hydrologic cycle predicted by ICASE would produce too much erosion and surface runoff to carve the VNs, likely by an order of magnitude. Regardless of the background climate, impact cratering during this period was clearly a significant process, and the effects may have contributed to smoothing of plains and degradation of crater rims, but the effects seem too global (for large impacts) and intense to produce the delicate and widely-spaced VNs. The conditions produced are in contrast with the transient, moderate warming required to form snow melt, subsequent surface runoff, and VN formation in a “cold and icy” climate.

Argyre as a Reference for ICASE: A study of geomorphological effects and surface features related to impact cratering is required for a complete analysis of ICASE. We must consider regions of Noachian terrain that were likely last modified by a single event to avoid later Noachian resurfacing. Specifically, we can map and analyze correlations between a single, relatively young Noachian crater and nearby VNs, attempting to further constrain ICASE effects and validate our prediction that impact cratering cannot be responsible for VN formation. Additionally, understanding ICASE through a single impact permits further extrapolation and scaling to understand all Noachian impacts.

We propose that Argyre basin offers an interesting perspective into martian geologic history, being the youngest of the large Noachian-era impact basins. Most of the area surrounding Argyre in the southern highlands dates to the late Noachian, coinciding with the time of Argyre basin formation. It is possible that the resurfacing of this region was caused by the aftermath of the impact event, specifically the fallout and rainfall from the vapor plume. Thus, Argyre is an excellent candidate to study the possible relationship between VNs and impact cratering. In this portion of the work, we map and analyze the craters within the ejecta deposit of Argyre to determine which surrounding craters are most likely to pre-date and post-date Argyre, allowing for an assessment of the relationship between VNs proximal to these craters produced before and/or after the Argyre-forming event. We answer questions including: do all VNs in the region appear to post-date Argyre, implying either a broad-scale resurfacing by the impact and subsequent, unrelated fluvial activity or, in contrast to our hypothesis, a correlation between the event and the formation of VNs? This work also helps constrain whether the VNs were formed intermittently or from one global fluvial event.

Conclusions: We have undertaken a detailed review and analysis of the pioneering work of [17-19], which we describe as the ICASE scenario. We clarify the steps in the process and describe the potential geologic implications of each step to permit testing and refining of the ICASE model. We have also tested the applicability of the ICASE scenario as a mechanism to explain the VNs, as proposed by [17-20]. We provide a geologic context and understanding for the impact cratering process and apply our intuition to a specific study site, Argyre basin, to reconcile our hypotheses.

Relationship to VN Formation: Revisited. As predicted by ICASE, we find that impact cratering is a mechanism which brings heat to the atmosphere and surface to transiently raise temperatures far above the triple point of water and produce conditions that permit rainfall and surface runoff. However, we predict that the extreme energy transfer typical of larger impacts and increase in temperature by hundreds to thousands of degrees will produce rainfall rates typical of a tropical rainforest on Earth (~2 m/yr) for hundreds of years after large impacts. Fluvial erosion is predicted to be more of a near-global deluge for large impacts, rather than the local to regional and moderate fluvial activity that appears to characterize the VNs. Additionally, rainfall totals previously proposed [17,18] are far too high in comparison to geologic observations of necessary VN-forming water totals. We suggest that impact-induced deluge conditions may be related to degradation of crater rims or smoothing of plains.

"Warm and wet" versus "cold and icy" conditions. Despite the fluvial and lacustrine surface features, uncertainty exists as to the nature of the Noachian climate. In the case of a "warm and wet" early Mars, rainfall and runoff would occur under ambient conditions, not only subsequent to impacts, implying continuous physical and chemical weathering. For a "cold and icy" early Mars, however, impacts may be the driving force for surface and near-surface physical and chemical weathering, implying transient weathering. Regardless of the background climate, however, impact cratering will contribute a significant amount of rainfall and runoff. Understanding the nature of weathering can help constrain the background climate. For example, does the observed physical and chemical weathering require continuous water-rock interaction as predicted for a "warm and wet" climate or transient interaction, potentially through impact cratering, as predicted for a "cold and icy" climate?

Future work. It is clear that the ICASE model must have been operative at various scales throughout the Noachian, and that the effects could have ranged from regional to global, depending on the size of the impact and the nature of the ambient atmosphere. We have introduced a physical and geologic understanding of this process, highlighting that there is likely not a relationship between VNs and impact cratering-induced rainfalls.

In order to improve understanding and further develop ICASE, we highlight several productive avenues of future research in the following areas: (1) An improved assessment of the relationship between impact energy and final plume diameter; (2) More refined predictions concerning geomorphological

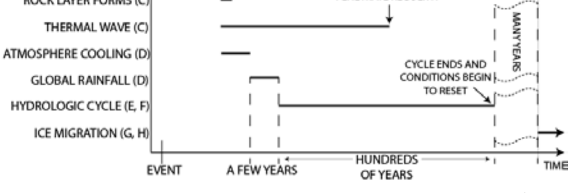

Fig. 1 (above). ICASE sequence timeline expressing steps of ICASE as described by [18]. Letters next to the time step names correspond to the diagram in Fig. 2 which illustrates these steps.

effects that might be caused by the immediate post-impact ~1600 K global condensed-silicate-rock layer; (3) An improved understanding of the impact-induced rainfalls through the use of 3-dimensional GCMs to predict the nature of the rainfall and distribution of resultant ponding; (4) Continuation of a geomorphologic assessment of individual Noachian impact craters and basins as models for studying the global/regional effects of large impacts.

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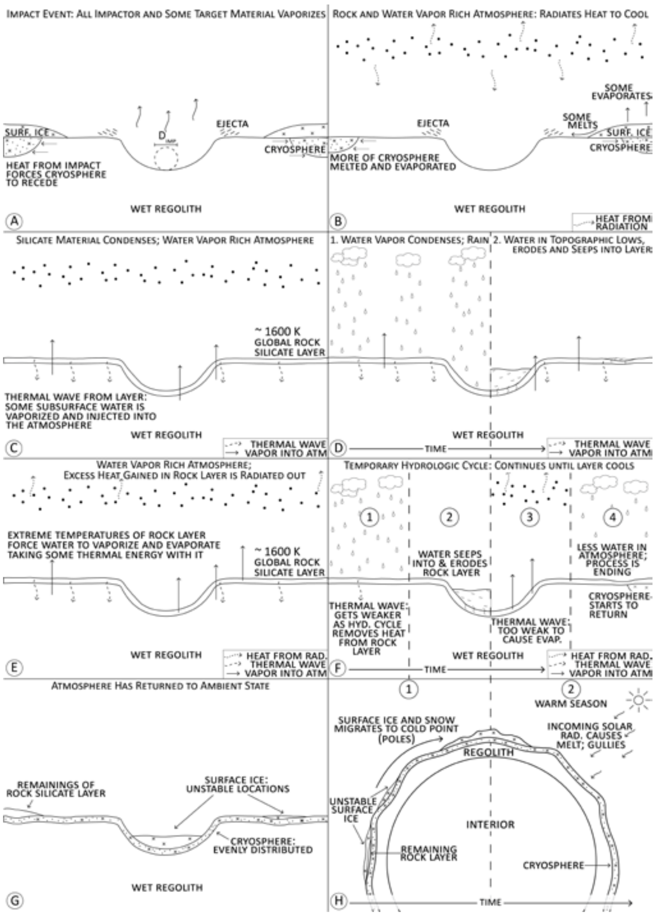

Fig. 2 (above). ICASE sequence diagram. (A) impact event; the cryosphere recedes from the impact site from high thermal input, material is pulverized, melted, and vaporized. (B) extremely hot rock and water vapor rich atmosphere radiates heat to cool, melting surface ice. (C) atmosphere cools to condensation temperature for silicate, forming a global ~1600 K layer [20]; thermal wave from layer penetrates beneath it, melting ice and potentially vaporizing water. (D) the water vapor condenses and rains; the thermal wave continues to liberate water from the subsurface into the atmosphere; the global rain layer seeps into the porous silicate rock layer and erodes it. (E) the extreme temperatures of the rock layer vaporize the water, further cooling the layer. (F) the hydrologic cycle for large impacts begins and continues until the rock layer has cooled. (G) the atmosphere returns to its ambient state and ice is on the surface in unstable locations. (H) unstable ice migrates back to stable locations, e.g. the poles under low obliquity conditions.