THE NATURE OF MODIFIED IMPACT CRATERS ON MARS. Robert A. Craddock[1], Ramses M. Ramirez[2], Rossman P. Irwin, III[1], and Alan D. Howard[3], [1]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560 craddockb@si.edu, [2]Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan, [3]Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ, 85719.

Introduction: Valley networks have been described as the best evidence that liquid water was once stable on the surface of Mars [e.g., *1*]. However, some investigators continue to argue that valley networks are simply the result of periodic melting of a thick ice deposit covering the highlands [*2*]. This "icy highlands" scenario does not support rainfall or, presumably, any direct interaction between precipitation and the surface [*2*]. There are many arguments against such an interpretation. Here we discuss how the icy highlands scenario fails to explain the population of modified impact craters that are ubiquitous features found throughout the Noachian highlands of Mars, including higher latitudes [*3*].

Previous Work: One of the earliest observations made by the Mariner missions to Mars was the unique population of modified impact craters that are morphologically distinct from fresh martian craters or craters seen on the Moon [*4*]. Instead of possessing sharp, raised rims, obvious ejecta deposits, or a central peak or pit, modified impact craters lack discernable ejecta deposits, have missing or poorly defined rims, and are typically flat floored [*5*]. Initial suggestions of aggradational processes, such as airfall deposits [*6*] or lava flows [*7*], are incapable of explaining such morphology, because crater rim height increases with crater diameter, and lava flows or aeolian deposits usually have a finite thickness. Instead, erosional processes best explain the morphology of the modified impact craters. Importantly, modified impact craters are preserved in various stages of degradation that is unrelated to crater diameter [*3,5,8,9*]. This indicates that craters were being modified as they were forming throughout the Noachian. Importantly, morphologic analyses indicate that these craters were eroded by a combination of diffusional transport processes associated with rain splash and advective transport processes associated with surface runoff [*3,9*]. The icy highlands scenario completely fails to explain these characteristics.

Icy Highlands Alternatives: The most direct attempt at explaining modified impact craters in the icy highlands scenario suggest that Noachian craters formed in ice that subsequently "evolved" and melted [*10*]. There are many reasons why this model fails. Similar to problems with aggradational models, the ice deposit is a finite thickness, so the effect on craters forming in the deposit is different at increasing diameters. This is not what is observed, however. Instead, craters are preserved at different stages of modification across a range of diameters (5 km to 100 km+). To erode the crater ejecta that superposes the ice deposit, additional ice accumulation is needed, and melting of this new ice is supposed to be driven by the heat from the ejecta itself. However, this is completely ad hoc as it requires eroding the hot ejecta that is supposed to be driving the erosion. The "top down" melting of ice from hot ejecta would be short-lived and would not be capable or eroding larger ejecta blocks or transporting the ejecta or sediment away from the crater. Ultimately in this model, all modified craters reach the same general morphology, and again, that is not what is observed.

Other investigators have focused on the interpretation that rain splash is responsible for the diffusional erosional characteristic of modified impact craters [*3,9*]. Alternatives include liquefaction [*11*] or "seismic shaking" [*12*]. Such processes are demonstrably wrong and are easily dismissed. For example, such interpretations imply that liquefaction or seismic shaking is a natural process accompanying impact crater and, as such, it should be observed on all planetary surfaces. Obviously, however, it is not. The morphology of modified impact craters is unique to Mars—and also Earth where rainfall regularly occurs. In addition, if liquefaction or seismic shaking occurred during the Noachian under climate scenarios similar to those observed today on Mars, then why did it stop? It should be an ongoing process modifying martian craters up to the present, and that is not the case. Modification ceased during the Hesperian [*5,8*]. There are also problems with scaling in that smaller craters should be more heavily modified than larger craters through liquefaction or seismic shaking, and that is not observed. In addition, liquefaction does not explain the amount of backwasting and enlargement that has occurred—the advective component that is observed [*3,5,8,9*]. Liquefaction or seismic shaking would result in widespread slump blocks and landslides originating from crater walls, and this is not observed.

The Nature of Rainfall on Mars: In addition to modified impact craters, the physical characteristics of valley networks [*13,14*], evidence for a past ocean [*15*], highland seas [*16*] and crater lakes [*17*]. alluvial fans [*18*] and deltas [*19*], and fluvial sedimentary deposits analyzed by the Mars Pathfinder, Opportunity, and Curiosity landers [*20,21,22*] indicate that rainfall and surface runoff occurred throughout most of the early history of Mars. However, there are temporal differences in geologic processes that modified martian impact craters, which occurred throughout the Noachian, and the formation of valley networks, which occurred during the Noachian/Hesperian transition [*23*]. One possibility for explaining these differences is related to the changing nature of rainfall as the primordial atmospheric pressure on Mars waned through time [*24*]. To test this possibility, we calculated the terminal velocity and resulting kinetic energy from raindrops >0.5 mm in diameter impacting the surface of Mars in a CO_2-rich atmosphere ranging from 0.5 to 10 bars [*25*]. Theses analyses indicated that the primordial atmosphere of Mars could not have exceeded ~4.0 bars as raindrop sizes would have been limited to <3 mm, which would have limited surface erosion from rain splash and crater. At pressures between ~3.0 and 4.0 bars, sediment transport from rain splash could occur, but surface runoff would have been limited, which could explain the modification of impact craters during the Noachian. Once atmospheric pressures waned to ~1.5 bars during the Hesperian, rainfall intensity could begin to exceed the infiltration capacity of most soils, which could initiate martian valley network formation. Due to the lower gravity, a storm on Mars that occurred in a 1 bar atmosphere could generate raindrops with a maximum diameter of ~7.3 mm compared to 6.5 mm on the Earth. However, rainfall from such a storm would be only be ~70% as intense on Mars, primarily due to the lower martian gravity and resulting lower terminal velocities of the rain drops.

This analysis was challenged recently by advocates of the icy highlands scenario [*26*]. In their manuscript, they calculate a terminal velocity of a raindrop falling through the martian atmosphere as well as a separate "breakup" velocity where the shear stress of the atmosphere exerted on the raindrop causes it to burst. Because their presented "breakup" velocities are always greater than the any terminal velocities a raindrop could obtain (their Table 1), they conclude that the "…maximum possible raindrop size does not depend on atmospheric pressure and, as a result, simple parameterized relationships suggest that rainfall intensity (rainfall rate) does not depend on atmospheric pressure." Basically, according to their calculations a raindrop would never fall fast enough through the martian atmosphere to break apart regardless of pressure. However, the values presented for terminal velocity (v_t) and breakup velocity (v_b) in their Table 1 are *reversed*. It is their calculated "breakup" velocities that should be the lower values. A raindrop would always breakup due to the forces exerted on the drop by the atmosphere, and the diameter at which this occurs is, in fact, a function of atmospheric pressure. Their maximum drop size (10.797 mm) was calculated incorrectly by equating terminal velocity and breakup velocity to one another. This cannot be done as only their breakup velocity accurately describes the behavior of a *liquid* particle passing through an atmosphere while their terminal velocity equation only accounts for atmospheric drag.

Regional Variations in Modified Crater Morphology: We analyzed the depth, crater wall slope, crater floor slope, the curvature between the interior wall and the crater floor slope, and the curvature between the interior wall and surrounding landscape of modified impact craters in the Margaritifer Sinus, Sinus Sabaeus, Iapygia, Mare Tyrrhenum, Aeolis, and Eridania quadrangles to assess whether there were any regional variations in crater morphology [*27*]. A statistical analysis of these parameters showed that fresh impact craters have consistent morphologic parameters regardless of their geographic location, which is expected. Modified impact craters both in the initial (Type 3) and terminal stages (Type 1) of modification also have statistically consistent morphometric parameters. This would suggest that the processes that operated in the late Noachian were globally ubiquitous, and that modified craters eventually reached a stable crater morphology. However, craters preserved in advance (but not terminal) stages of modification (Type 2) have morphometric parameters that are not consistent across the quadrangles. Potentially these differences reflect spatial variations in the types and intensity of geologic processes that operated during the Noachian and imply that there were regional differences in the ancient martian climate.

Influence of the Climatic Optimum and Valley Network Formation: To further explore the possibility of regional or temporal variations in crater modification processes, we have begun an analysis of craters in the Margaritifer Sinus and Sinus Sabaeus quadrangles, where there is a dense concentration of valley networks, to craters in the Noachis quadrangle, where there are few valley networks. In particular, we are trying to evaluate the influence of valley network development on crater morphology. Although this analysis is ongoing, craters in Margaritifer Sinus and Sinus Sabaeus tend to be slightly shallower while the floor and wall slopes tend to be steeper potentially reflecting infilling and backwasting by fluvial processes in the Hesperian.

Conclusions: The icy highlands scenario is not supported by any empirical evidence. Interpretations of "top-down melting" or degradation of martian impact craters from ice layers [*10*] are motivated completely by theoretical climate models that suggest that early Mars was always cold and dry [*2*]. However, these climate models have now become antiquated as our understanding of the geologic and geochemical conditions of early Mars have advanced. Analyses of the martian meteorites indicate that the early Martian mantle was extremely reduced, approaching the iron-wustite buffer, if not lower [*28*]. It follows that volcanic outgassing would favor reducing gases, such as H_2, resulting in percent levels of or higher of the gas [*29*]. Multiple climate models by a variety of investigators [e.g., *30, 31*] now confirm that under such conditions a warm early Mars could have had a large northern ocean sustained by a thick carbon dioxide and hydrogen atmosphere. Nevertheless, modified impact craters remain enigmatic features that record the entire geologic and climate history of Mars and suggest that the Noachian represents a semi-arid to hyper-arid environment. Our continued analyses are attempting to unpack this history.

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