REVISITING NOACHIAN-HESPERIAN CRATER DEGRADATION: PROCESSES AND POTENTIAL EFFECTS.

J. W. Head[1], B. D. Boatwright[1], A. M. Palumbo[1], D. K. Weiss[1], M. K. Kreslavsky[2], J. L. Fastook[3], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 20912 USA, [2]Earth and Planetary Sciences, University of California, Santa Cruz, CA, USA, [3]School of Computing and Information Science, University of Maine, Orono, ME 04469 USA. (james_head@brown.edu).

Introduction: On Earth, landforms and their degradation are one of the most critical witnesses to climate and its evolution. Landforms produced by dynamic processes (tectonic, volcanic, impact) are "out of equilibrium" with the integrated processes that tend to cause erosion and planation. What are the key processes that modify these "out of equilibrium" landforms and how do we model them quantitatively? There is a rich history of investigation and development of sophisticated landscape evolution models for Earth.

These same approaches have been successfully applied to Mars, particularly in reference to the most common landform, impact craters and their degradation [1-8]. Craters formed in the Amazonian-Late Hesperian display generally fresh and pristine morphological characteristics (distinctive ejecta deposits, raised rim crests, wall terraces and slumps, deep interiors with central peaks, typical depth-diameter (d/D) relationship, etc.). Craters dating from the Noachian-Early Hesperian (Fig. 1) showed fundamental morphological differences from younger craters (e.g., general absence or subdued nature of ejecta, elevated crater rim crests being low or missing, much shallower flat floors than equivalent fresh craters, missing central peaks, and often textured, grooved walls). These differences were interpreted to be due to relatively higher erosion rates in the Noachian, rates that were generally attributed to landform degradation by rainfall (pluvial activity), in a warmer and wetter climate with a Late Noachian "climate optimum" resulting in fluvial erosion and formation of abundant valley networks [1-8]. Indeed, "Degraded craters are one of the main lines of evidence for a warmer climate on early Mars" [9]. Further analysis of 281 >20 km craters of all ages in two highland regions [9] confirmed these earlier findings, revealing three classes of craters: Type III: Fresh craters with ejecta and central peas; Type II: Gently degraded, often with a central peak, and fluvial landforms, including alluvial fans; Type I: Strongly degraded, without ejecta or central peak, with fluvial erosion. Type I strongly degraded craters were formed and degraded during the Noachian, Type II craters between the Early Hesperian and the Early Amazonian, and Type III formed subsequently. A sharp transition is seen between Types I and II, interpreted to indicate a rapid change in climate conditions [9].

A significant number of subsequent events (e.g., new mission, discoveries, models and data analysis) make it an opportune time to revisit and explore crater degradation and landscape evolution on Mars. In this contribution we highlight several of these new developments and outline some remaining outstanding questions.

Perspectives on Noachian Geologic Sequence and History: A synthesis of the sequence and timing of conditions on early Mars (Fig. 2) [10] showed 1) the distinctive separation of the EN basin-forming period (Hellas, Isidis, Argyre) from the MN-LN during which no basins formed, 2) the LN-EH during which the valley networks (VN) formed [11], earlier hypothesized to be related to basin formation cause and effect [12], 3) the lack of correlation between phyllosilicate weathering and VN formation, and 4) the relationship between these events and the cessation of the magnetic field.

Role and Legacy of Impact Basin Formation: Recent studies of the effect of impact basins on the climate and modification of the surface of Mars in the EN has shown that the threshold diameter for impact features having a radical effect on the atmosphere lies in the basin size range [13-14]; Assessment of the collective effects of such basin-scale impact cratering atmospheric/surface effects (ICASE) are: 1) globally distributed rainfall characterized by very high temperatures; 2) extremely high (~2 m/yr) rainfall rates with correspondingly high runoff rates; 3) such conditions will contribute significantly to degradation of crater rims, filling of crater interiors, regional smoothing of terrain, and imply vast resurfacing and resetting of crater ages following basin-scale impacts; 4) the high temperatures of impact-induced rainwater and the pervasive penetration of heat into the regolith substrate are predicted to have a significant influence on the mineralogical alteration of the crust [14]. These major events impart a global legacy into the surface nature and morphology, influencing later events.

Models of Noachian Climate: New estimates of Noachian ambient climatic condition have been derived from atmospheric general circulation models with a faint young Sun [15-16] suggesting mean annual temperature (MAT) of ~225 K, a distinctive alternative to the generally warm and wet/arid pluvial climate [1-8] with >273 K MAT implied by earlier models [1-8]. The adiabatic cooling effect predicted for denser Noachian atmospheres also suggests a "cold and icy highlands" [16] with snow and ice accumulating in the highlands above about a +1 km elevation. VN, open and closed basin lakes are attributed to transient heating and melting of the snow and ice in the "icy highlands" [17-18]. The predicted influence of a snow and ice substrate on impact cratering and crater degradation [19-20] included: 1) craters analogous to Amazonian double-layered ejecta and pedestal craters; 2) shallower cavities in the underlying target rock, and lower rims subsequent to removal of the ice; 3) additional modification by backwasting of rim-crest material, insolation-induced top-down melting of proximal rim-crest surface ice, melting of ice and fluvial erosion due to contact with hot ejecta, and basal melting of ice (enhanced by overlying low thermal conductivity ejecta). Removal of surface snow and ice in a subsequent climate regime could preferentially eliminate smaller craters that formed exclusively within the surface ice deposits -, and could drastically modify the observed crater size-frequency distribution by reducing the apparent diameters of larger craters.

In addition, [21] analyzed a "warm and wet" climate (MAT ~ 275 K) with a 3-D global climate model to determine how common and where rainfall activity would occur under these conditions, finding that rainfall is limited in abundance and areal distribution, precipitation is dominated by snowfall, and highlands temperatures are <273 K for the majority of the year. They concluded that, 1) valley networks and lakes could not have formed through rainfall-related erosion, 2) crater degradation by rainsplash and runoff is not predicted, and 3) the presence of a rainfall- and overland flow-fed northern ocean is improbable.

New Observational Data: The global distribution of the steepest slopes on crater walls was recently used to assess the magnitudes of degradational processes with latitude, altitude, and time [22], finding that the total amount of crater wall degradation in the Late Noachian is very small in comparison to the circumpolar regions in the Late Amazonian, an observation interpreted to mean that the Late Noachian climate was not characterized by persistent and continuous warm and wet conditions. Recent studies with Mars Reconnaissance Orbiter CTX image data [23] reveal evidence for crater wall cold-based glaciation, top-down glacial melting, fluvial crater floor meltwater drainage and endorheic crater lake formation modifying the crater floor. The criteria developed in [23] can be used to search for other examples of Noachian highland degradation.

Outstanding Questions: A full understanding of Noachian crater degradation clearly requires addressing the following questions: 1) What is the magnitude of the role of the impact flux and its effect on crater degradation and diffusional processes, and how does this change with atmospheric pressure? 2) In a warm and wet/arid climate, what was the intensity of the rainfall required for infiltration and what is the rate transition to runoff? How does this vary with atmospheric pressure and substrate? 3) What causes the abrupt change from highly degraded craters to much less degraded craters at the end of the Noachian? 4) What role do EN basin-related torrential rainfall processes have [24] on setting the stage for LN crater formation and degradation? 5) What role do explosive [25] and effusive [26] volcanism play in the resurface of craters and filling of crater floors? 6) How widespread is the evidence for Noachian glaciation [23] and what are the implications for crater modification and degradation state? 7) How do eolian processes vary with atmospheric pressure and how does this influence crater degradation with time? 8) Can the observed fluvial activity and open and closed-basin lake degradation and filling be explained by transient heating phenomena in an otherwise cold and icy climate?

References: 1. Craddock & Maxwell, 1990, JGR 95, 14625; 2. Craddock & Maxwell, 1993, JGR 98, 3452; 3. Craddock et al., 1997, JGR 102, 13321; 4. Craddock & Howard, 2002, JGR 107, 5111; 5. Forsberg-Taylor et al., 2004, JGR 109, E05002; 6. Howard et al., 2005, JGR 110, E12S14; 7. Irwin et al. 2005, JGR 110, E12S15; 8. Howard, 2007, Geomorphology 91, 322; 9. Mangold et al., 2012. JGR 117, E04003; 10. Fassett & Head, 2011, Icarus 211, 1204; 11. Fassett & Head, 2008, Icarus 195, 61; 12. Toon et al., 2010, Ann Rev 38, 303; 13. Turbet et al., 2019, Icarus 335, 113419; 14. Palumbo & Head, 2018, MAPS 53, 687; 15. Forget et al., 2013, Icarus 222, 81; 16. Wordsworth et al., 2015, Icarus 222, 1; 17. Head & Marchant, 2014, Antarctic Science, 26, 774; Fastook &Head, 2015, Icarus 106, 82; 18. Palumbo et al., Icarus 300, 261; 19. Weiss and Head, 2015, PSS 117, 401; 20. Weiss and Head, 2016, Icarus 280, 205; 21. Palumbo and Head, 2018, GRL 45, 10249; 22. Kreslavsky & Head, 2018, GRL 45, 751; 23. Boatwright and Head (this volume); 24. Palumbo & Head, this volume; 25. Kerber et al., 2013, Icarus 223, 149; 26. Whitten and Head, 2013, PSS 85, 24.

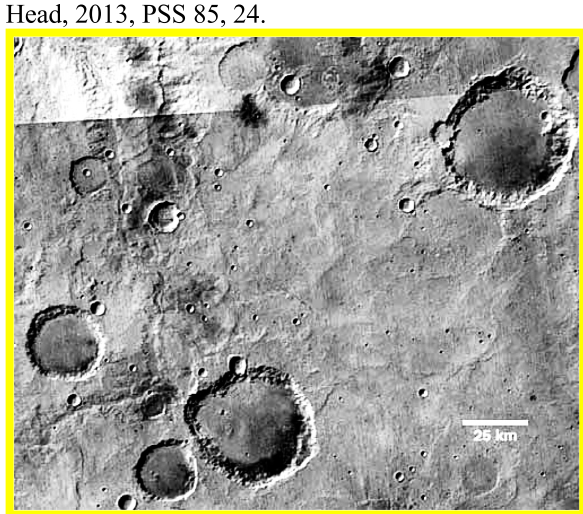

Fig. 1. Typical Noachian degraded craters. [4]

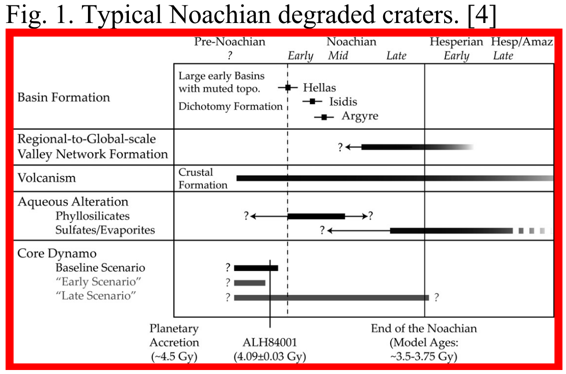

Fig. 2. Early Mars timeline and major events. [10]