GEOLOGICAL AND CLIMATOLOGICAL HISTORY OF EARLY MARS: RECENT DEVELOPMENTS, UNKNOWNS AND DIRECTIONS FOR THE NEXT DECADE.

J. W. Head[1], R. D. Wordsworth[2], L. Wilson[3], M. A. Kreslavsky[4], A. M. Palumbo[1], H. Y. McSween[5]. [1]Brown Univ., Providence RI; [2]Harvard Univ., Cambridge MA; [3]Lancaster Univ., Lancaster UK; [4]UCSC, Santa Cruz CA; [5]Univ. Tenn., Knoxville TN.

Introduction: Mars is extremely fascinating due to its many similarities to Earth, its potential for life, and as a human exploration goal. For these and related reasons, Mars has been the destination for more than 40 robotic missions since 1960. Guided by a theme of "Follow the Water", the results of these missions and related research have transformed our perception of Mars. Emerging as a critical area of focus in understanding the evolution of Mars has been the Late Noachian (LN)-Hesperian (H) era [1], due to compelling evidence for fundamental changes in geodynamics, atmosphere, climate, geomorphology, volcanology, and the water and sulfur cycles. Here we assess the state of understanding at the end of the 1st decade of the 21st century, highlight findings of the 2nd decade, and raise important questions to address in the 3rd decade.

Knowledge circa 2010: This period marked the end of two decades of data gathering and global characterization (summarized in [2-9]): improved dynamical models of terrestrial planet formation showed that Mars was anomalously small; lunar magma ocean scenarios were applied to Mars to address the origin and evolution of the primary crust; ancient crustal magnetic fields were discovered; global gravity data provided crustal thickness; global topography ushered in an era of quantitative geomorphology; orbital remote sensing data showed that Mars is a dynamic planet with time-dependent mineralogical alteration (N-phyllosilicates, H-sulfates and A-anhydrous iron oxides) and local distinctive mineralogical and weathering environments; high resolution images revealed stratigraphic relationships and details of geologic processes (including evidence for N and H oceans); geomorphological, mineralogical, and isotopic ratio data suggested a significant N water inventory, widespread pluvial, fluvial and lacustrine activity, enhanced degradation, and warm and wet climate conditions in the LN-H; detailed models were developed for a vertically integrated N hydrological cycle and a colder horizontally stratified LH-A hydrological cycle; outflow channels were interpreted as catastrophic outbursts of huge volumes of pressurized groundwater (GW) beneath a thickening global cryosphere; the origin of the hemispheric dichotomy was attributed to a huge oblique impact; geological and geophysical data suggested that the Tharsis volcanic and tectonic province had largely formed by the MN, stabilizing Mars against further TPW; the role of spin-axis/orbital evolution in climate change became clear (leading to improved understanding of the global distribution of ice and the significance of non-polar glaciation); new findings from martian meteorites led to maturation of the field of astrobiology.

Syntheses near the end of these decades [2-9] raised fundamental questions about the: initial volatile inventory of a 'too-small' Mars; duration of the magnetic field; role of crater and basin formation in geological and climatological evolution; nature of a warm and wet early Mars and how it transitioned to its current state; location of the missing carbonates inferred from the loss of the early atmosphere; causes and implications of time-correlated mineralogical and geological evolution; rates and implications of atmospheric loss to space; meaning of the SNC meteorites in terms of mantle characteristics and processes, initial and changing fO_2, petrogenetic evolution, and volatile presence and abundance.

2010-2019: What did we learn in the last decade [e.g., 10-14] and how did this change the fundamental questions? Planetary accretion and dynamics models underlined the unusual nature of Mars and its bombardment history; newly developed global data sets enabled compilations, comparisons, and age dating of valley networks (VN), open and closed-basin lakes (OBL/CBL), deltas and fans, impact craters of all scales, outflow channels and buried ice deposits; improved crater statistics refined geological history and era boundaries; a global geologic map of Mars was published; new models linking interior evolution and surface geology/chronology emerged; the age of the demise of the magnetic field (and thus its shielding effect on atmospheric loss) was identified as prior to the formation of the last large basins; multidisciplinary modeling brought increased clarity to the effects of crater and basin formation on atmospheric blow-off, retention, volatile cycling, and climate; Mars meteorites provided new clues about ancient non-volcanic processes, atmospheric history and water budget; new and improved general circulation models (GCMs) of early Mars (with a water cycle) found that the climate was likely to have been characterized by an ambient mean annual temperature (MAT) of ~225K, liquid water was not stable, precipitation was in the form of snow, not rain, and if atmospheric pressure exceeded a few 10s of millibars, an adiabatic cooling effect resulted in surface H_2O being transported to the southern uplands and the south polar regions (the 'cold and icy highlands' model); among the implications of these GCMs are that a global cryosphere existed, the hydrological system/cycle was horizontally stratified, glacial accumulation in the uplands would have been cold-based, transient warming events of some type were needed to temporarily raise MAT to well in excess of 273K to produce VN/OBL/CBL; the duration of focused fluvial and lacustrine activity shortened to a phase in the LN-EH; the environment of surface phyllosilicate formation supporting an early warm and wet climate became less clear and increasingly removed in time from VN/OBL/CBL; alternative candidate environments of phyllosilicate formation associated with initial high-temperature accretional stages, subsurface GW hydrothermal circulation, and impact basin-related climate alterations emerged with more clarity; evidence for additional carbonates was found, but not in abundances thought necessary to account for 'missing' atmospheric CO_2; tracing of the surface-near surface water inventory back in time revealed much lower predictions for the Noachian water budget than thought previously; plausible sources of GW and recharge to pressurize the GW system, crack the cryosphere, and produce significant volumes of water to form the outflow channels remained elusive; climate modeling of the fate of water outbursts in outflow channels showed little influence on climate and no substantial ponding to form seas or oceans; Antarctic analog investigations showed that the "high" weathering rates typical of LN Mars still correspond to the lowest on Earth, being similar to those in terrestrial icy polar deserts with MAT <<273K; phyllosilicate and sulfate occurrences are interbedded and overlap in time, blurring the initial separation into eras; new insights into mantle state, evolution and petrogenesis underlined the close relationship of atmospheric pressure and release of H_2O and S species; improved volcanological models helped track the interaction and distribution of tephra and exsolved gases as a function of atmospheric pressure; the origin of sulfates and their detailed nature at several Mars rover sites and other sulfate occurrences was attributed to a vertically integrated hydrological system; recent data on atmospheric loss rates to space suggest that N atmospheric pressure did not exceed ~1 bar.

Fundamental Questions & Research Themes for the 2020s & Beyond: How do these results frame future questions? Ten themes and related sub-questions are emerging. The first four broadly address 'inheritance': *What were the initial conditions and events and how did they set the stage for the evolution of Mars?*

1. Origin: Size, location and growth rates; budget of volatiles; earliest bombardment history?
2. Solar State and Evolution: Solar state, radiance and temporal variability?
3. Crustal Formation and Evolution: Nature of magma ocean and its aftermath; primary and secondary crust formation; associated outgassing history and implications for the atmosphere?
4. Geodynamic Evolution and Petrogenetic History: Core formation, ensuring mantle convection patterns and changes with time; redox state(s) and petrogenetic evolution; timing and role of basins; changes in magmatic sources/styles/compositions with time; primary or fractionated magmas; timing of Tharsis, relation to TPW and tectonic activity?

The following six themes broadly address the question: *What was the nature and evolution of the early climate?*

5. Nature of Ancient Atmosphere and Climate: What were N "ambient conditions", 'warm and wet' or 'cold and icy'? How did species and quantities change with time; nature of primary and secondary atmospheres, their transition and evolution; nature and evolution of volcanic degassing and relationship to evolving atmospheric pressure; nature, scale and duration of ambient climate perturbations and influence on MAT?
6. Candidate Climate Perturbations: What events perturbed the ambient atmosphere? Role of seasonal, spin axis/orbital variations, impacts, greenhouse gas input, hydrolysis, clouds, and solar variability?
7. Water Cycle: What was the initial water budget, how did it change with time; Was the hydrological cycle ever vertically integrated; how was water partitioned (sources, sinks, D/H, rates of loss to space)?
8. Sulfur Cycle: What was the total S budget, how did it partition with time; nature of volcanic S exsolution as a function of evolving atmospheric pressure; S cycle (sources, sinks, evolution, relative roles of direct volcanic deposition and groundwater basalt leaching and evaporative deposition); origin of Valles Marineris ILDs?
9. Mineralogical and Geomorphological Evolution and Implications: What do detailed geological, mineralogical and temporal data tell us about the diversity of occurrences of phyllosilicates and sulfates? What is the distribution and origin of salts, carbonates and silica-rich deposits? What do these data tell us about LN-H climate and weathering processes and rates; how are crater degradation and VN/CBL/OBL origin linked to LN-H mineralogy, climate and GW/volcanic processes?
10. Environments for the Formation and Evolution of Life: New insights, terrestrial perspectives and evolving paradigms are leading away from a sustained 'warm and wet' early Mars, toward an ambient 'cold and icy' climate. What strategies/proxies are needed to explore potential biotic environments in Antarctic-like surfaces and a warmer, wetter and geochemically active 'Mars underground'?

Synthesis: Future exploration, guided by these questions and a focus on *Mars System Science*, will continue to revolutionize our thinking as we explore Mars with an additional triad of rovers, work toward sample return and pave the way for human exploration.

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