**THE GEOLOGIC HISTORY OF MARS: UNANSWERED QUESTIONS.** M. Carr[1] and J. W. Head[2], [1]United States Geological Survey, Menlo Park, CA 94025 USA, [2]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA.

**Introduction:** On the basis of decades of spacecraft exploration and data analysis, the analysis of martian meteorites, and the context of the nature and evolution of other terrestrial planetary bodies, the general processes and broad themes contributing to the geologic history of Mars have become more clear [1]. Nonetheless, critical outstanding questions remain, and require a robust Mars exploration to address. Here we outline the broad themes in the geologic evolution of Mars and highlight a list of outstanding questions that need to be addressed by future exploration and analysis.

**Geologic History of Mars [1]:** Mars accumulated and differentiated into crust, mantle and core within a few tens of millions of years of Solar System formation, and most subsequent geologic activity was confined to the first 1. 5 billion years of its history (Fig. 1). Formation of Hellas, which has been adopted as the base of the Noachian period, occurred around 4.1 to 3.8 Gyr ago. Little is known of the pre-Noachian period except that it was characterized by a magnetic field, and was subject to numerous large basin-forming impacts, probably including one that formed the global dichotomy. The Noachian period, which ended around 3.7 By ago, was characterized by high rates of cratering, erosion, and valley formation. Most of Tharsis formed during or prior to this period. Surface conditions were at least episodically such as to cause (or cause to be exposed from the subsurface) widespread hydrous weathering products such as phyllosilicates. Extensive sulfate deposits accumulated late in the period and into the Hesperian. Average erosion rates, though high compared with later epochs, fell short of the lowest average terrestrial rates and though valley networks are common, they form an immature system that had only a modest effect in shaping the landscape. The record suggests that warm, wet conditions necessary for fluvial activity were met only occasionally, particularly late in the Noachian, such as might occur if caused by large impacts, volcanic eruptions, or spin-axis/orbital induced climate change. A major change occurred at the end of the Noachian. The rates of impact, valley formation, weathering, and erosion all dropped precipitously (Fig. 1). On the other hand, volcanism continued at a relatively high average rate in the Hesperian, particularly in the first half, resulting in the resurfacing of at least 30% of the planet. Large water floods formed episodically, particularly in the latter parts of the Hesperian, possibly leaving behind large bodies of water in the northern lowlands. The canyons formed. The observations suggest that the change at the end of the Noachian suppressed most aqueous activity at the surface other than large floods, and resulted in growth of a thick cryosphere. However, the presence of discrete sulfate rich deposits and sulfate concentrations in soils suggests that water activity did not decline to zero. After the end of the Hesperian, around 3 Gyr ago the pace of geologic activity slowed further (Fig. 1). The average rate of volcanism during the Amazonian was approximately a factor of ten lower than in the Hesperian and confined largely to Tharsis and Elysium. The main era of water flooding was over, although small floods appear to have occurred episodically until geologically recent times. Canyon development was largely restricted to formation of large landslides. Erosion and weathering rates remained extremely low. The most distinctive characteristic of the Amazonian is formation of features that have been attributed to the presence, accumulation, and movement of ice. Included are the polar layered deposits, latitude-dependent ice-rich veneers at high latitudes, glacial deposits on the flanks of tropical volcanoes, and a variety of landforms in the 30–55° latitude belts indicative of the accumulation of ice and glacial flow, including lobate debris aprons, lineated valley fill and concentric crater fill. Gullies on steep mid-latitude slopes formed in the latest Amazonian. The rate and latitude of formation of the ice-related features and the gullies varied as changes in orbital parameters affected ice stability relations.

In summary, the advent of the international Mars exploration program during the last two decades has brought untold new knowledge of, and perspectives on, the geologic history of Mars. It has also raised important new questions [1, 4], which form the basis for future research and robotic/human exploration planning.

**Fundamental Outstanding Questions:** Among the many outstanding questions are:

-What were the factors that lead to the initial size, composition and density of Mars, and how do these relate to early Solar System formational models?

-What is the current configuration of the internal structure of Mars? What is the average crustal thickness and how and why does it vary?

-What is the thermal evolution of Mars? What were the heat sources and sinks, how did these change with time, and what was the level of thermal homogeneity, heterogeneity with time? What is the history of the elastic lithosphere? How did the hydrosphere and cryosphere interact with heat production and dissipation?

-What is the cratering history of Mars, particularly in its early history? Was there a late heavy bombardment and, if so, what were its consequences? How did the cratering history influence crustal formation (heating, melting), crustal evolution (excavation, modification and redistribution), the atmosphere and hydrosphere?

-What is the origin and history of the magnetic field? How did it cease and over what time period? When and how were the crustal magnetic anomalies emplaced?

-What is the history of water on Mars, its total abundance, and its acquisition (accretion, degassing) and loss with time? What was the nature of the hydrological cycle with time? How was water partitioned into the atmosphere, surface water, altered minerals, cryosphere and groundwater, and how did this change with time?

-What was the nature of the Noachian climate? Was it warm and wet, cold and icy, or some combination with time? What was the influence of impact cratering events on the presence and nature of the atmosphere, and how did this vary with impactor size? What other factors caused changes in the Noachian climate?

-What were the sources and fluxes of greenhouse gases? How did they change with time? Were greenhouse gases ever sufficiently abundant to warm the atmosphere significantly, and if so, for how long?

-Was Late Noachian valley network formation episodic or continuous? Did it occur throughout the Noachian? What is the history and residence time of water in open-basin and closed-basin lakes?

-Were there oceans in the northern lowlands in the Noachian? When, why and for how long?

-How did the seemingly pervasive aqueous formation of Noachian crustal rocks occur and over what time scales? Did it occur at the surface, in the subsurface due to groundwater, in both environments? What are the implications for the hydrological cycle and system?

-What caused the change in surface chemistry and water flux at the end of the Noachian?

-When did the major canyons of Valles Marineris form and how, and at what rate did they evolve? Are the sediments on the floor of the canyons Noachian, or younger, in age, and how did they originate? Were there extensive lakes in the canyons and if so, how were they related to outflow channel formation?

-How much water and sediment was emplaced by outflow channels in the northern lowlands (ponds, lakes or seas)? What was the fate of the outflow channel effluent? What were the sources of water that carved the outflow channels, and how were the reservoirs resupplied?

-What caused the change from phyllosilicate to sulfate deposits around the Noachian–Hesperian boundary?

-When did Mars become characterized by a global cryosphere and how much groundwater remains today in the subsurface? How has the thickness and latitudinal distribution of the cryosphere changed with time?

-What was the flux of volcanism during the Hesperian? Was it a steady decline from the Noachian, or a peak related to the emplacement of Hesperian ridged plains?

-Why was volcanism centralized to the Tharsis and Elysium regions?

-What is the spin-axis/orbital parameter history of Mars and how has this controlled the distribution of volatiles in the surface and subsurface? Did true polar wander ever occur?

-Under what atmospheric and astronomical conditions do tropical mountain glaciers, mid-latitude glaciers, and large circumpolar ice caps form and what do these deposits tell us about the climate history of Mars?

-What is the age of the current polar ice deposits and why do they apparently differ? How long does it take to form the individual polar layers and what processes of deposition and sublimation are involved? What is the origin of the north polar basal unit? Is there evidence for ancient polar deposits and where and from what era do they date?

Answering these fundamental questions requires a sophisticated, multi-disciplinary approach in order to develop an in-depth understanding of the geologic history of Mars. Reaching this new understanding requires a robust future Mars exploration program, including sample return and human exploration.

**References:** [1] M. H. Carr & J. W. Head (2010) Geologic history of Mars, *Earth Planet. Sci. Lett., 294,* 185-203, doi:10.1016/j.epsl.2009.06.042. [2] W.K. Hartmann & G. Neukum (2001) Cratering chronology and the evolution of Mars. Space Sci. Rev. 96, 165–194. doi:10.1023/A:1011945222010. [3] J.W. Head (2006) Interplanetary correlation: Themes in the geological history of terrestrial planetary bodies. Vernadsky–Brown Microsymposium, vol. 46, p. 24. Abstract. [4] J.W. Head (2007) The geology of Mars: new insights and outstanding questions. In: Chapman, M. (Ed.), The Geology of Mars: Evidence from Earth-Based Analogs. In Cambridge University Press, pp. 1–46.

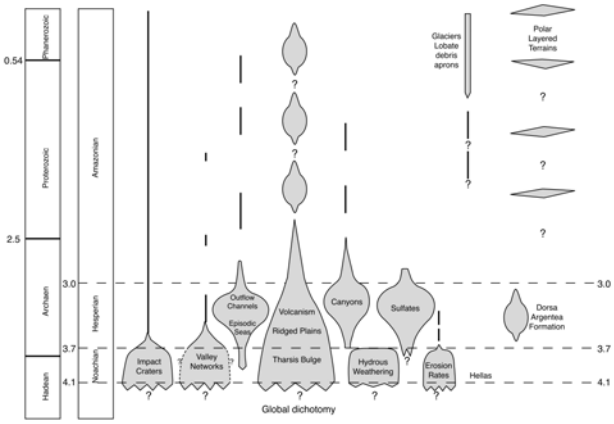


Fig. 1. Geological activity as a function of time on Mars. Shown are the relative importance of different processes (impact cratering, volcanism), the time and relative rates of formation of various features and units (valley networks, Dorsa Argentea Formation), and types and rates of weathering, as a function of time. The approximate boundaries of the major time periods of Mars history are shown [2], and are compared to similar major time subdivisions in Earth history [3].