THE ENVIRONMENT OF EARLY MARS AND THE TIMING OF KEY CONDITIONS.

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Introduction: Spacecraft data indicate that the early environment of Mars differs from recent conditions in a variety of important ways. Mars appears to have had an intense magnetic dynamo [1], a wetter surface [2], neutral-pH aqueous weathering [3,4], a denser atmosphere [5], and higher impact and volcanic fluxes [6,7]. Moreover, direct evidence strongly favors the existence of lakes on the early surface, some of which were quite large [8]; more speculatively, there may have been an ocean in the northern hemisphere [9]. Each of these factors (with the possible exception of a higher impact flux) is broadly consistent with planet more habitable early in its history than today. This has helped motivate an exploration strategy predicated on examining materials from this early period.

Given these different conditions inferred to exist on early Mars, it has been common to assume that there is a discrete geological period (perhaps of some length) when all of these conditions were met simultaneously. Although such a scenario is possible, timing constraints suggest that it may not be the most probable scenario. Here we review constraints on when these conditions existed and describe possible scenarios for the changes in the environmental conditions that may have occurred on Mars.

Valley Network Timing and Activity: In a recent study [10], we assessed when 26 valley network-incised regions in the highlands terminated fluvial activity. In every instance, the superposed crater population resulted in a best fit age in the Noachian or Early Hesperian, with most ages clustering around the Noachian/Hesperian boundary in the Late Noachian. (Note that certain valley systems, usually at small scales, are universally accepted as much younger [see discussion in 10]). The statistical nature of these results leads to some ambiguity in how they should be interpreted. One possible interpretation (which was favored in [10]) is that all of the variability is a result of counting statistics, and that valleys ceased activity at essentially a single point in time. In this interpretation, valley activity terminates at or near the Noachian/Hesperian boundary (best fit Hartmann and Neukum ages respectively of A_H=3.53 Gyr or A_N=3.75 Gyr, with a cumulative number of craters ≥5 km per 10^6 km^2 of N(5)=214 (N(5)=200 is the definition of the Noach/Hesp. boundary [7]).

An alternative interpretation of these data is that some of the valleys that have Early Hesperian best fit ages are in fact younger than the Noachian/Hesperian boundary, and that the spread in crater frequencies reflects the persistence of valley formation into the Early Hesperian (perhaps to N(5) of ~>150). This interpretation is supported by two observations: first, some of the valley networks with Early Hesperian best fit ages are the densest, most well-preserved systems, as would be expected, (e.g., Margaritifer Sinus: Parana/Loire has A_H=3.49 Gyr or A_N=3.73 Gyr, with N(5)=188), and (2) in some instances, valleys with young ages also have stratigraphic evidence suggesting Early Hesperian activity (e.g., Naktong Vallis [11]). These factors lead us to now prefer this second interpretation.

Some workers have continued to argue that *even* younger ages are possible [e.g. 12] for some large valleys. However, these interpretations rely on craters with comparatively small sizes (<1-2 km) for age interpretation. On Mars, such small craters are subject to resurfacing processes, which can systematically lead to young crater retention ages. To us, these data seem unlikely to relate to the period of fluvial activity rather than the modification time. In some cases, these data are inconsistent with counts on larger, harder to remove craters on the same valleys.

Thus, our interpretation is that regional-to-global scale valley formation on Mars persisted until the Early Hesperian. The rate and nature of earlier activity are hard to determine using crater statistics alone, since earlier fluvial activity greatly modified the surface. Some workers have hypothesized that the widespread Late Noachian/Early Hesperian valleys observed across Mars today represent a terminal climatic optimum, where valley formation became more important than earlier periods [13]. Nonetheless, there is strong evidence that significant earlier erosion did occur during the Noachian, including: (1) thick, layered sequences of sedimentary rock which under reasonable deposition rates implies an extended period of sedimentation [14]; (2) crater profiles, which have been interpreted to require fluvial erosion [15], (3) craters that clearly disrupted and changed the drainage network in a given drainage basin [16], and (4) different erosion and filling states for the large basins on the martian surface [17].

Basin Formation and Timing: Both published crater counts and our counts on the best preserved rim regions of Argyre, Isidis, and Hellas [18] suggest that the sequence of the large, well-preserved impact basins was Hellas, Isidis, and then Argyre. These data imply that Hellas and Isidis formed in the Early Noachian, and Argyre is Mid-to-Early Noachian.

All of these basins have been incised by valley networks on their interior or immediate exterior, implying that intense fluvial activity took place after their formation, consistent with our crater counting of valley networks [10]. However, Argyre appears to have the best preserved basin-related facies [17]; thus, the inferred sequence of basins from crater statistics is also supported by the preservation state of the basins. Crater counting data suggest that the period between the formation of Argyre (the last basin larger than 500 km) and the end of the wet conditions allowing formation of valley networks on a regional-to-global basis was >50 Myr and possibly ~300 Myr, depending on the absolute timing of the Late Noachian and Early Hesperian. This difference in crater populations between the fresh large basins and the end of valley network activity precludes a causal relationship between the formation of these basins and the terminal period of valley network formation.

Timing of Magnetic Field: Observations from the Mars Global Surveyor magnetometer experiment demonstrated that there are crustal magnetic anomalies observed over much of the surface, with the strongest anomalies concentrated in the southern highlands [1]. These crustal anomalies likely imply an early core dynamo and global magnetic field, (though see [19, 20]); the existence of this magnetic field may have played an important role in arresting the loss of an early martian atmosphere by solar wind sputtering, as well as shielding the surface from energetic cosmic rays [5].

The most important age constraints on the timing of the Mars magnetic field is the demagnetization (or non-magnetization) of certain basins and volcanoes. Magnetic anomalies are largely absent in Hellas, Argyre, Isidis, and Utopia, as well across most of Tharsis and volcanic edifices, with the exception of Hadriaca Patera [21]. The easiest explanation for the lack of magnetization on these basins and volcanoes is that much they post-date the cessation of the magnetic field (although such an explanation is not satisfactory for the lack of magnetic remnance in the northern hemisphere). If this interpretation is correct, the core dynamo must have ended during the Early Noachian, before the formation of Hellas. [22]. This is radically earlier than the end of valley network formation and the shift in weathering style on early Mars; this suggests that if a magnetic dynamo was playing an important shielding role for the surface and/or atmosphere, the shield may have been removed well before water stopped was playing an important geomorphic role on the martian surface.

Weathering Environments and Timing: The early weathering history of Mars has been revolutionized by observations in the last decade across the electromagnetic spectrum [3,4]. These data have resulted in the recognition of at least ~10 environment types where minerals which are the result of aqueous weathering processes are observed [4]. In some instances, these aqueous minerals are in situ (found where they formed); in other instances, they may have been transported and concentrated by depositional processes.

The materials that remain in situ are the most reliable for making inferences about the timing of the geochemical environments that these represent. These data suggest that until the Late Noachian, moderate-to-alkaline pH weathering environments were common. Later in the Hesperian, certain regions had abundant emplacement of layered sediments with sulfate minerals and hematite [3]. However, MRO data make clear that this low-pH weathering environment was not ubiquitous, as minerals (such as carbonate) that would be readily destroyed in such environments persisted in certain locations [4]. Because many of the late aqueous minerals on Mars seem to reflect groundwater interactions with the upper crust or surface evaporates, these minerals may not require a stable late hydrosphere or habitable surface conditions.

Thus, current data suggest that neutral-pH weathering on Mars was an important process until approximately the end of the Noachian. Although evidence for such weathering is ubiquitous, it hard to constrain how transient or persistent such conditions were. It is now clear that the transition to sulfate weathering that has been observed to occur later in Mars history was not universal, although it does demonstrate the continuation of some aqueous weathering into the Hesperian.

Summary: It has been hypothesized that the period when valley networks were formed early in the history of the planet is coincident with an early magnetic field that protected the atmosphere and that removal of this early shield ended clement surface conditions. As we describe here, this scenario appears unlikely. A causal relationship [23] between basin formation and valley network is also not favored. If cratering helps contribute to valley formation smaller craters must be invoked [10]. Formation of valleys by catastrophic events is not favored by the extended period of activity implied by network properties [24].

What does the timing of events described in this abstract mean for the prospects of exploration and the search for habitability on early Mars? If the magnetic field of Mars was necessary for protecting life at Mars' surface, valley sediments and even phyllosilicates which date to the Late Noachian or Early Hesperian (such as those in Holden and Eberswalde craters [25]) may have been emplaced in conditions that had already become less favorable, as the dynamo likely terminated hundreds of millions of years before these sediments were deposited. Thus, although these sites may provide invaluable information about surface hydrology and have the advantage of a clear stratigraphic context, sites with more ancient materials may give us the best hope for finding traces of life from early Mars.

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