**MARS DURING THE PRE-NOACHIAN.** J. C. Andrews-Hanna\(^1\) and W. B. Bottke\(^2\), \(^1\)Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, jehanna@lpl.arizona.edu, \(^2\)Southwest Research Institute and NASA’s SSERVI-ISET team, 1050 Walnut St., Suite 300, Boulder, CO 80302.

Introduction: The surface geology of Mars apparently dates back to the beginning of the Early Noachian, at \(~4.1\) Ga, leaving \(~400\) Myr of Mars’ earliest evolution effectively unconstrained [1]. However, an enduring record of the earlier pre-Noachian conditions persists in geophysical and mineralogical data. We use geophysical evidence, primarily in the form of the preservation of the crustal dichotomy boundary, together with mineralogical evidence in order to infer the prevailing surface conditions during the pre-Noachian. The emerging picture is a pre-Noachian Mars that was less dynamic than Noachian Mars in terms of impacts, geodynamics, and hydrology.

**Pre-Noachian Impacts:** We define the pre-Noachian as the time period bounded by two impacts – the dichotomy-forming impact and the Hellas-forming impact. The latter has previously been used to define the boundary between the Noachian and pre-Noachian [1], and the former so profoundly changed the surface and interior of Mars as to make it a natural starting point for any study interested in early martian evolution. Isotopic and geochemical evidence supports the formation of the martian dichotomy by a giant impact at \(> 4.47 - 4.5\) Ga [2], while the crater retention age of the Hellas basin is \(3.97 - 4.06\) Ga [3]. Based on the similar preservation state of the rim of the Borealis basin as expressed in the dichotomy boundary, and the rims of the Noachian-aged basins Hellas, Isidis, Utopia and Argyre (HUIA), a similar preservation state is expected for any crustal-scale basins formed during the intervening pre-Noachian. The lack of evidence for similarly well-preserved pre-Noachian basins of this scale and the lack of evidence for excavation of the dichotomy boundary by basins other than Isidis suggest that no other basins formed during this time [2].

The formation of at least three crustal-scale basins (Hellas, Isidis, and Argyre) during a span of \(~200\) Myr during the Noachian [3] and at most one crustal-scale basin (Utopia, whose age is poorly constrained) during a span of \(~400\) Myr during the pre-Noachian indicates that the average impact flux during the pre-Noachian was \(<17\%\) of that during the Noachian. If Utopia is a Noachian-aged basin [4], the flux during the pre-Noachian would be lower still. At least one pre-Noachian basin, Ladon, has been confidently identified in the next size interval smaller than HUIA. The formation of one Ladon-sized basin during the 400 Myr pre-Noachian, and the four HUIA basins in the subsequent 200 Myr implies that the mean impact flux during the pre-Noachian was \(~10\%\) of that during the LHB. Consideration of the sawtooth-shaped exponentially declining impact fluxes both in the aftermath of planet formation and during the Late Heavy Bombardment [5] suggests that the impact flux during much of the pre-Noachian was even lower than indicated above. This bombardment history is consistent with a late heavy bombardment (LHB) of the inner Solar System [6] during which HUIA formed, which followed the planet formation era impacts during which the dichotomy formed.

**Pre-Noachian Tectonism and Volcanism:** The crust within each of the southern highlands and northern lowlands is remarkably uniform in thickness, aside from regions in which it has been thickened by volcanism (e.g., Tharsis, Elysium) or thinned by impacts (HUIA), both of which occurred dominantly in the Noachian. Furthermore, the path of the Borealis basin rim is within \(1\%\) of an ellipse, even where it has been buried beneath Tharsis [7], with no major deflections from this shape. These observations indicate that there were no large-scale changes to the crust of Mars during the pre-Noachian. This constraint effectively rules out a global plate tectonic cycle of lithosphere recycling akin to that currently operating on Earth. Similarly, no giant Tharsis-style volcanic rises formed during the pre-Noachian. In contrast, the incipient stages of Tharsis formation may have begun in the Early Noachian [8] with substantial construction continuing through the Hesperian [9]. However, smaller structures would be more easily destroyed during the LHB, and so neither localized rifting and tectonism, nor smaller shields and volcanic provinces can be ruled out during the pre-Noachian.

**Pre-Noachian Water and Climate:** Fluvial valley networks, lakes, and sedimentary deposits formed during the pre-Noachian would have been destroyed by impacts during the Noachian LHB. However, the preservation of the crustal dichotomy boundary does place some constraints on the pre-Noachian climate. The dichotomy boundary is a topographic step similar to that at the edges of many continents on the Earth (Fig. 1). Under a persistent Earth-like climate, such a step would be rapidly eroded to the local base level. On Earth the elevation of continents relative to sea level (the “freeboard”) is reduced to a value slightly above zero by erosion on timescales of hundreds of millions of years. The Appalachian mountains of North America experienced long-term erosion rates of 10-50
m/Myr [10], which was likely limited by the uplift rate rather than erosion. This freeboard concept applied under cold climate conditions as well, resulting in the relatively uniform elevation of the edge of the continental shelves from erosion during ice ages when sea level was lower. The concept of freeboard is applicable whether the high-standing topography was generated by tectonism or by impact. On Mars, Earth-like erosion rates would have drastically reduced the elevation of the southern highlands and reduced the dichotomy boundary to a gradual slope leading down to the lowlands. At the rate of erosion experienced by the Appalachians, the 8 km topographic step across the dichotomy boundary could have been reduced by 4-20 km during the 400 Myr pre-Noachian. Although erosion would have been accompanied by flexural uplift [11], the dichotomy boundary scarp itself would have been largely erased under these conditions and a more gradual slope would be expected. As a caveat, it is difficult to completely rule out the other extreme end-member interpretation — that the near constant elevation of the southern highlands is the result of high erosion rates coupled with a pre-Noachian sea level close to the average southern highlands elevation. However, in this scenario one might expect higher elevations further from the putative shoreline, in conflict with the similar elevations within the southern highlands over distances of up to ~5000 km from the dichotomy boundary.

Figure 1. Maps of the elevation of Earth (a; relative to sea level) and Mars (b), and profiles across North America (at 45°N) and the Martian dichotomy (at 150°E). Earth’s continents remain close to sea level (dashed red line in a) except in areas of active mountain building.

While the geophysical record effectively rules out Earth-like conditions being maintained throughout the pre-Noachian, the mineralogical record supports the presence of liquid water in the subsurface. Extensive Fe/Mg phyllosilicate deposits are found on Noachian surfaces, which may have formed at depth and later been exposed at the surface [12]. By this interpretation, these clays pre-date the Noachian surfaces in which they are found, and could have formed within surface-driven weathering sequences in the pre-Noachian. The pre-Noachian climate is thus inferred to be wet, but not persistently Earth-like, similar to some interpretations of the Noachian climate. Alternatively, if the Fe/Mg clays instead formed by hydrothermal processes [13] or from surface-driven weathering in the Noachian, combined with the lack of large-scale erosion of the dichotomy boundary, this leaves open the possibility of a cold and barren pre-Noachian with a stripped atmosphere waiting to be revived by Noachian-era impacts and volcanism.

Conclusions and Implications: The complete lack of a pre-Noachian geological record forces us to rely upon indirect inferences based on the geophysical and mineralogical records in an attempt to reconstruct the conditions during this substantial period of martian history. The preservation of the dichotomy boundary requires that there were no large-scale crustal rearrangements or modifications during the pre-Noachian. No basin-forming impacts occurred during this time period spanning between the Borealis and Hellas impacts. Impact rates during the pre-Noachian were <17% of those in the Noachian, and likely lower still. Neither plate tectonics nor regional volcanic rise construction were active during this time. Erosion of the newly formed dichotomy boundary scarp during the pre-Noachian occurred at rates substantially lower than is characteristic of recently generated high topography in terrestrial mountain belts, though widespread aqueous alteration of the crust suggests the presence of liquid water at shallow depths.

This interpretation of pre-Noachian conditions suggests that this epoch, spanning ~400 Myr of Mars’ earliest history, was a quiescent time relative to the Noachian in every respect. For this reason, this period has been dubbed the martian “doldrums”. However, the pre-Noachian may have had the greatest astrobiological potential of any time period on Mars. It was possibly wetter than the Hesperian and Amazonian epochs, but provided a more stable environment than the LHB-era Noachian.