NOACHIAN EVOLUTION OF MARS.

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Introduction: The Noachian era on Mars is distinguished by the development of the Tharsis rise and the widespread creation of terrain types that likely required the involvement of running water. Here we review both aspects as well as possible interrelationships between Tharsis evolution and global geomorphic signals of fluvial activity.

Origin and Evolution of Tharsis: Following the development of the global crustal dichotomy, the tectonic and volcanic history of Noachian Mars was dominated by the development of the Tharsis rise. The construction of Tharsis was largely complete by the end of the Noachian [1, 2, 3] and upwards of 3×10^8 km^3 of magmatic material may have been involved [1], equivalent to a global average thickness of 2 km. The volatiles associated with Tharsis magmas may have perturbed the climate in a significant way. Tharsis deformed the global lithospheric shell and induced major fault structures across the western hemisphere. The global warping of the lithosphere strongly influenced the orientations of many subsequent valley networks.

There have been a number of competing models for the origin of the Tharsis rise. Models employing a plume origin of Tharsis were proposed early [4, 5]. A long-standing issue with such models is the difficulty of numerically creating a single large plume (or two, if Elysium is considered). A single-plume structure might be generated in conjunction with the spinel to post-spinel endothermic phase change deep in the mantle [6,7], although the existence of a pressure sufficiently high for the phase change is questionable.

The major alternative to a plume model proposes that Tharsis is a region of weak (thin) lithosphere early in martian history, favoring localization of intrusive and extrusive magmatism [8]. Conceptually, heating associated with magmatism maintains a thin lithosphere in this passive model. Compensation of the load is isostatic early in Tharsis history, and flexural later due to thickening of the lithosphere.

Both types of models require buoyant uplift of the lithosphere, as does a third type of model that requires a low-density melt residuum in the upper mantle [9]. The passive model must maintain a hot, thus positively buoyant, upper mantle in order to maintain a thin lithosphere. Evidence for uplift is provided by circumferential graben in the Claritas Fossae region, first noted in [9], and supported by analyses [10] of more recent tectonic mapping [11].

Evidence for a mantle buoyant component in the creation of Tharsis might be found in a residual positive buoyancy in the present-day interior structure. Buoyancy structures due to plumes presently do not contribute more than 10% to the Tharsis geoid when considering the viscoelastic rheology of the mantle [12]. The consideration of simultaneous top (lithospheric) loading and bottom (mantle buoyancy) loading when constrained by the degrees 2 and 3 geoid-to-topography ratios indicates that a thermal plume could account for < 15% of the geoid and < 25% of the topography [13]. This then does not rule out a mantle plume (or more generally a mantle buoyant) contribution to the origin of Tharsis, but indicates that presently lithospheric loading, presumably by igneous masses, accounts for the majority of the geoid and topography. Further, pervasive Noachian tectonic structures can be explained by lithospheric loading models using the present-day high-fidelity geoid and topography fields obtained by MGS [2]. This indicates that the types and distributions of the loads have changed little since the end of the Noachian, i.e., any plume component was no longer dominant by then. The simplest explanation for the orientation and structural type of the majority of tectonic features in the western hemisphere remains that of flexural/membrane loading of a thin elastic spherical shell [2]. However, dike emplacement could have had an important influence on tectonic fabric [14, 15].

Recent analysis of magnetic field data indicates crustal anomalies high on the Tharsis rise, with the strongest anomalies associated with Noachian terrain and lesser anomalies associated with younger volcanic areas [10]. The Hesperian and Amazonian volcanics on Tharsis are a thin veneer (< a few km) covering a Noachian substrate [1], so it is likely the magnetic anomalies there are also Noachian in origin. There are two possibilities for the origin of the high-elevation magnetic anomalies: (*i*) Magnetic anomalies in uplifted Noachian basement survived, which is plausible [16]. (*ii*) The magnetization was acquired as Tharsis magmas themselves cooled through the Curie temperature, and this magnetization subsequently survived erasure by later igneous activity. We note that it is possible that the uplift inferred structurally at Tharsis could have taken place merely by crustal thickening due to igneous intrusion, regardless of the nature of the origin of upper mantle buoyancy.

Thus, with the aid of MGS data, we can draw reasonably firm conclusions that (*i*) There is a strong igneous constructional component to Tharsis that was nearly complete by the end of the Noachian, though lesser volcanism in the Hesperian and Amazonian indicates the continued presence of a warm, though diminished mantle source. (*ii*) An upper mantle buoyancy anomaly existed beneath Tharsis as it was forming. This anomaly had a large thermal component, which was responsible for extensive partial melting that created the bulk of the Tharsis melts. (*iii*) It is not possible at this time to assign the relative proportions of active and passive components to this buoyancy.

Noachian Fluvial Geomorphology: The formation of ubiquitous valley networks and extensive erosion during periods in the Noachian has led to the idea that fluvial erosion was an important process on Noachian Mars [17]. However, the occurrence of olivine, highly weatherable in the presence of water, and the lack of any significant accumulations of carbonates at the surface [18] argues against long-standing bodies of water during Noachian times. Additionally, climate models cannot produce, to the community's overall satisfaction, clement conditions for Noachian Mars [19, 20].

Recent analyses of MGS data show that valley network geomorphology is much more Earth-like than previously thought in terms of stream order and density [21]. Figure 1 shows an example region in Arabia Terra, where the valley system is 6th order and the drainage density is 6.5×10^{-2} km^{-1}. Measured at roughly the same resolution, this drainage density approaches the low end of terrestrial values [22]. Moreover, many of the valleys reach up to drainage divides.

MGS and earlier data sets provide information on widespread Noachian erosion [23, 24, 25]. Documented in the Tharsis trough [1] from the Margaritifer Sinus region to northwestern Arabia Terra is a dramatic late Noachian denudation of the landscape that left behind inliers containing valleys predating the denudation [25] (Figure 2). It is estimated that $\sim5\times10^{6}$ km^{3} of material was stripped away, and water is the most likely agent of erosion. Earlier erosion events, chiefly documented by crater degradation [23], indicate that erosion was an on-going, though possibly episodic, phenomenon throughout much of the Noachian.

Geomorphic indications that sapping was a dominant process in valley network formation does not obviate the need for precipitation, particularly as valleys extend to drainage divides. Infiltration of highly permeable near-surface stratigraphy and recharging of ground water systems may have enabled long-term sapping [26, 27].

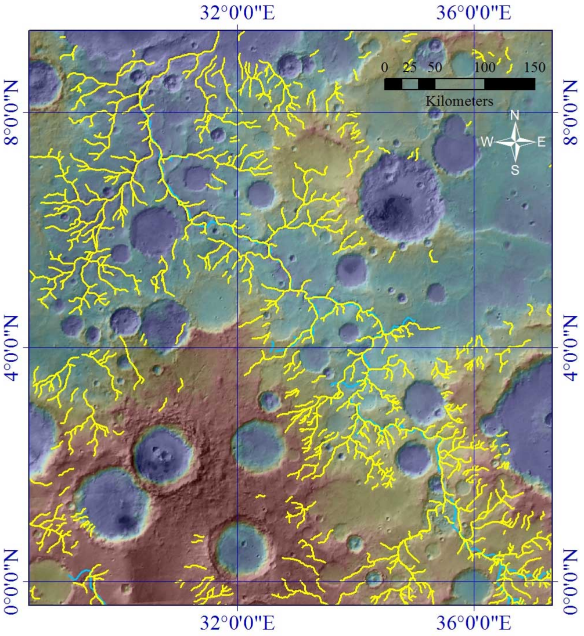

Figure 1. Valley networks (yellow segments) mapped in Arabia Terra using a combination of the MOC wide angle global image mosaic and MOLA elevation data [21]. Blue segments show valley networks mapped earlier using Viking images [37].

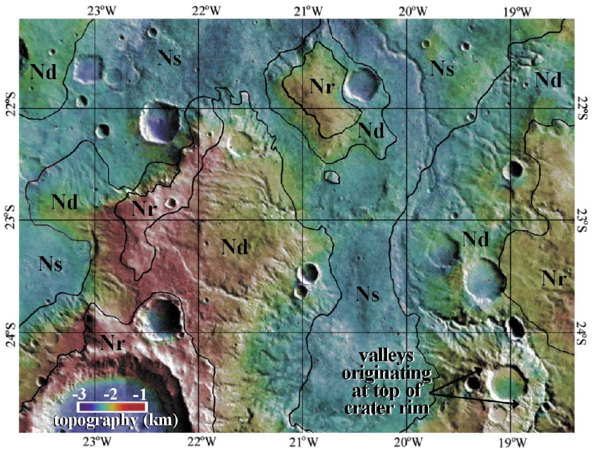

Figure 2. Combined Viking imagery and MOLA elevations in the Margaritifer Sinus region show relationships between undissected Noachian inliers (Nr), portions of the inliers that were dissected by middle to late Noachian valley networks (Nd), and a depositional unit derived from erosion of older Noachian terrain (Ns). The erosional event stripped and/or buried valleys. From [25].

Noachian Climate: Given the difficulty of creating models that produce a sustained warm and wet Noachian period, there are additional possibilities that might explain the formation of valley networks, widespread erosion, and the development of extensive layered deposits, some of which may have an aqueous origin [28]. Water is the most likely agent to produce both valley formation and substantial erosion. Temperatures could have been sub-freezing and precipitation in the form of snowfall, with subsequent basal melting percolating downwards into the ground. This process may operate in the current martian climate [29], but with less vigor.

It is also possible that there were episodic perturbations to the Noachian climate that created, for short periods of geological time, conditions favorable for rainfall or snowfall. Basin-forming impacts may have increased surface and interior temperatures significantly, delivered large quantities of water vapor to the atmosphere, and provided a transient climate favorable for valley formation and erosion [20]. However, valley network formation and widespread erosional events occur to the end of the Noachian (and beyond), past the formation dates of the largest impact basins. This model would have to fashion similar conditions with relatively numerous but less energetic impact events.

Episodic volcanism is another possible mechanism for perturbing the climate, as recognized for Earth [30]. The construction of Tharsis can deliver substantial quantities of water and CO_2 to the atmosphere. A global equivalent layer of 120 m of water and a 1.5 bar CO_2 atmosphere have been estimated [1], and preliminary modeling has explored the climatic implications of Tharsis outgassing [31]. We have little information on the level of episodicity of Tharsis construction. The rate at which volatiles were supplied to the atmosphere versus the rate at which they were removed [e.g., by carbonate deposition (little observed), solar wind stripping, thermal escape, and impact erosion] would dictate the role of Tharsis in perturbing the climate sufficiently to carve valley networks and foster widespread erosion events.

Noachian Evolution: Early Noachian tectonic evolution was dominated by the development of the crustal dichotomy and formation of major impact basins. Subsequently, the construction of Tharsis dominated Noachian volcanic and tectonic processes. The main features of Noachian volatile and climate evolution have been summarized in [32]. Climate was controlled by the volatile history, which involved competition between sources (primordial, comet/asteroid delivery, and volcanism) and sinks, as mentioned above. The magnetic field played a crucial role in protecting the atmosphere from the solar wind loss processes of pick-up-ion sputtering and hydrodynamic collisions. Thus, understanding the history of the magnetic field [33] is crucial for understanding the climate history.

It is clear that by the end of the Noachian, the bulk of the valley networks had formed and the erosion rate was steeply declining [17]. Isotopic evidence in martian meteorite ALH84001 suggests that the atmosphere was largely unfractionated near the end of the Noachian [34, 35]. The geologic and isotopic information taken together suggests a relatively rapid loss of atmosphere as Mars entered the Hesperian era. Loss of a global magnetic field has been an attractive mechanism, but when the global field declined is a continuing matter of contentious debate.

Figure 3 is a diagram meant to place, in a relative temporal relationship, major events in the Noachian (and later). Most of the entities are discussed in this abstract and/or in [32]. Some of the major basins are shown; noteworthy is the Ares basin, which may have formed while a global field was still active [36], as evidenced by the presence of strong magnetic anomalies within the basin proper. The time span in the early Noachian between the formation of the Ares and Acidalia basins may mark the major decay period of a global field. This is difficult to reconcile with a substantial atmosphere existing until the end of the Noachian unless it was protected by regional remanent magnetic fields [32]. This may provide more weight to the argument that Tharsis, constructed almost exclusively during the Noachian [1], was at least partially responsible for maintaining the atmosphere through the release of large amounts of volatiles.

In summary, on Noachian Mars there was a strong interplay among geodynamic, atmospheric and geologic processes. Tharsis is largely a constructional phenomenon, although its origins can be traced to a warm, buoyant mantle in the western hemisphere. Valley networks and widespread Noachian erosion imply strongly that there were significant precipitation events, frozen and/or liquid, in the Noachian, even if the valleys formed dominantly by groundwater sapping. If temperatures never rose above freezing, there must have been a water supply available to produce sufficient snow to carve the valleys and denude the landscape. Some of this water may have been recirculated in the crust back to the atmosphere. Precipitation may have occurred in short bursts associated with major impact or Tharsis magmatic events. Lack of olivine weathering points to this as well as to generally subfreezing temperatures. Whatever conditions led to precipitation ceased to exist near the end of the Noachian; leading suspects are the loss of a global magnetic field and the waning of Tharsis magmatism.

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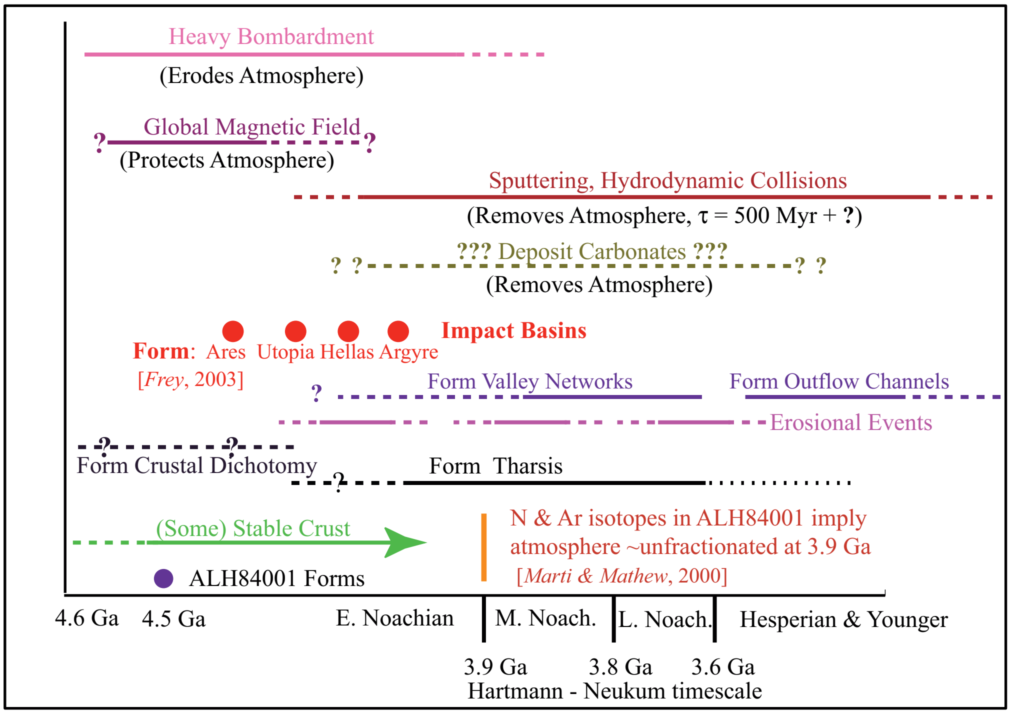

Figure 3. Major events and their interrelationships in the Noachian (and later). Diagram is intended as a thought tool and is thus subject to constant revision. The time axis is definitely not linear. *τ* is the characteristic timescale for atmospheric removal by solar wind processes.