2 Acquisition and history of water on Mars

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2.1 Introduction

The purpose of this chapter is to summarize the geologic history of Mars and the role water has played in the evolution of the surface so that subsequent chapters on more specific topics can be viewed in a broader context. It focuses mainly on surficial processes such as erosion, sedimentation, and weathering, rather than on primary terrain-building processes such as impact, tectonism, and volcanism since surficial processes provide more information on surface conditions under which lakes could have formed. The role of liquid water in the evolution of Mars is puzzling. With a mean annual temperature of 215 K and a mean surface pressure of 6.1 mbar (Haberle et al., 2008) liquid water can exist at the surface only locally and temporarily under anomalous conditions. Yet geologic evidence for the widespread presence of liquid water is compelling, particularly for early Mars, and claims have also been made of present-day water activity. One of the outstanding unsolved problems of Martian geology is how conditions necessary for liquid water could have been so sustained at the surface on early Mars as to result in pervasive aqueous weathering and widespread formation of valley networks and lakes.

Martian surface features have been divided into three age groups—Noachian, Hesperian, and Amazonian—on the basis of intersection relations and the numbers of superimposed impact craters (Scott and Carr, 1978; Tanaka, 1986). Noachian terrains survive from the early heavy bombardment era. The era was named for the heavily cratered Noachis region, following the long-established terrestrial practice of naming eras after type localities. The rest of Mars’ history was divided into two eras, the Hesperian named for Hesperia Planum and the Amazonian named for the younger Amazonis Planum. From estimates of Martian cratering rates as a function of time (Ivanov, 2001), Hartmann and Neukum (2001) estimated that the Noachian era ended around 3.7 Gyr ago and that the Hesperian era ended around 2.9–3.3 Gyr ago. The date of the end of the Noachian is unlikely to be grossly in error, but the date for the Hesperian–Amazonian boundary could incorporate significant errors. Dating younger (<1 Gyr) terrains, where small craters must be used, is even more uncertain because of the nonuniform distribution of secondary craters (McEwen et al., 2005) and the possibility of a long-term decline in impact rates (Quantin et al., 2004).
The geologic records of Mars and the Earth are very different. Most of the Martian geologic record, particularly that relating to liquid water, dates back to the Noachian and Hesperian, prior to 3 billion years ago, close to the middle of the terrestrial Archean. The record of liquid water from the Amazonian, which constitutes two-thirds of Mars’ geologic history, is very sparse, although not absent, and restricted mainly to gullying of slopes, rare groundwater eruptions, and melting of ice. In contrast, most of the geologic record on Earth dates from after 3 billion years ago, the earlier record having been destroyed as a result of the much higher rates of geologic activity on Earth and surface conditions that enabled high rates of erosion and weathering.

2.2 Acquisition and retention of water

Excess $^{182}$W in Martian meteorites indicates that Mars’ core formed remarkably quickly, within 20 million years of Solar system formation, and the 4.53 Gyr age of ALH84001 shows that at least some crust formed within a few tens of millions of years (Borg et al., 1997; Lee and Halliday, 1997). Rapid core formation and estimates of present average crustal thickness of several tens of kilometers (Zuber et al., 2000) place constraints on thermal evolution models. According to Hauck and Phillips (2002), heat flows would have peaked at 60–70 $\text{mW m}^{-2}$ around 4.4 Gyr ago and then declined almost linearly to a present value of not more than 10–20 $\text{mW m}^{-2}$, and possibly much lower, as suggested by the lack of flexure of the lithosphere under the present polar loads (Johnson et al., 2000; Phillips et al., 2008). According to the Hauck and Phillips model, by 4 Gyr ago over 70% and possibly considerably more of the crust would have accumulated. They also conclude that the mantle must have been wet and that delivery of water and other volatiles such as sulfur to the surface by volcanism during and subsequent to this early era could have affected surface environments.

One of the more surprising results of the MGS mission was the discovery of large magnetic anomalies, mostly in the southern highlands (Acuna et al., 1999; Connerney et al., 1999). Anomalies are mostly absent around the large, easily recognizable impact basins. The simplest explanation is that pre-Noachian Mars had a magnetic field that left large anomalies that were subsequently destroyed in and around impact basins such as Hellas, Utopia, Argyre, and Isidis (Solomon et al., 2005 and references therein). Some of the anomalies in the southern uplands are striped, drawing comparisons with terrestrial seafloor features (Connerney et al., 1999), although there is no geomorphic evidence for plate tectonics. Nimmo (2000) alternatively suggested that the anomalies may be due to the presence of deep dike swarms.

The amount of water acquired during accretion and subsequently outgassed and retained at the surface to participate in geologic processes is very uncertain. It depends, among other things, on the mix of meteorites and comets that accreted to form the planet, which has been estimated from modeling the mix of meteoritic materials required to reproduce the global composition of Mars inferred from the
chemistry of Martian meteorites (Dreibus and Wanke 1987) and from dynamical modeling of planet formation and isotopic studies (e.g., Lunine et al., 2003). Estimates of the amount of water originally accreted range up to an amount equivalent to a global layer of many tens of kilometers deep. But we just saw that the core formed very early, within no more than 20 million years of the start of accretion. During global differentiation to form the core water would have outgassed, possibly forming a steam atmosphere (Matsui and Abe, 1987), and would have reacted with metallic iron in the originally accreted material to form FeO and H, which would have outgassed (Dreibus and Waenke, 1987). The early atmosphere probably suffered a massive loss of hydrogen by hydrodynamic escape driven by extreme ultraviolet radiation from the early Sun (e.g., Pepin, 1994; Zahnle et al., 1988). The outflow of hydrogen to space would have carried other atmospheric gases with it, including CO2, N2, and most of the noble gases lighter than xenon (Pepin, 1994). The hydrodynamic phase was over within 200 MY of the start of accretion at which time the Sun’s output of extreme ultraviolet was no longer sufficient to drive the flow. A major uncertainty is the extent to which water incorporated into the planet during accretion was retained after these massive degassing and atmospheric losses. It has been argued that most of the early water was lost and that most of the present inventory of water on both Earth and Mars was delivered mainly by comets and carbonaceous chondrites late during heavy bombardment after the hydrodynamic phase was over (Chyba, 1990; Owen and Bar-Nun, 2000). Dreibus and Waenke (1987) argued against addition of such a late volatile-rich veneer for Mars because of the lack of excess siderophiles in Martian meteorites. However, there are other plausible explanations for the lack of a siderophile anomaly, such as a poorly mixed Martian mantle due to a lack of plate tectonics (Carr and Waenke, 1992). D/H enrichment of water in Martian meteorites provides some support for late cometary additions since comets have a higher D/H ratio than asteroids, the source of most of the original accreted materials (Baker et al., 2005); however, high D/H ratios also result from preferential loss of H from the upper atmosphere.

After the hydrodynamic phase was over, the atmosphere would have been supplemented by further outgassing from the interior and depleted by various processes including erosion by large impacts (Melosh and Vickery, 1989) and losses by weathering to form carbonates and other minerals. Losses from the upper atmosphere would have been largely restricted to hydrogen until the magnetic field turned off, which is estimated to have been around 4 Gyr ago (Connerney et al., 1999). After this time, impingement of the solar wind on the upper atmosphere would have resulted in enhanced losses of heavier species such as O and N as a result of ion pickup and sputtering. These losses continued for the rest of the planet’s history (Jakosky and Jones, 1997).

Preferential loss of hydrogen over deuterium from the upper atmosphere can, in principle, be used to estimate the size of the water reservoir that was originally present in the Noachian and exchanging with the atmosphere ever since. Lammer et al. (2005), for example, estimate that 3.5 Ga ago this reservoir was the equivalent of 35–115 m spread over the entire planet. Unfortunately we have no way of estimating the size of the reservoir, such as deep ice and groundwater, which is not
equilibrating with the atmosphere. Nor do we know whether present loss rates of hydrogen are representative of the last 3.5 Ga. The average obliquity over the last 3.5 Ga is 40°, significantly higher than the current 25° (Laskar et al., 2004). At 40° obliquity, the water content of the atmosphere could have been higher than the present by a factor of 100 (Mellon and Jakosky, 1995), thereby leading to enhanced hydrogen losses from the upper atmosphere and the possibility of enriching a larger reservoir.

In view of all the uncertainties outlined above, we must conclude that modeling of accretion and atmospheric evolution does not place strong constraints on the amount of water available for geologic processes. In an alternative approach, Carr (1986) estimated that a global equivalent of roughly 500 m of water was required to transport the material eroded away to form the outflow channels, but this figure also has large uncertainties.

### 2.3 Early geologic events

How deep into the era of heavy bombardment can the geologic record be discerned from the surface topography is unknown. Part of the uncertainty stems from the cratering history: whether there was a late spike in basin formation around 3.9 Gyr ago (Tera et al., 1974) or a steady decline after accretion (Stöffler et al., 2006). Assuming a steady decline and using the Hartmann and Neukum (2001) estimates of the cratering rate in the late heavy bombardment period, Frey (2003) estimated that Hellas formed around 4.1 Gyr ago from the number of basin-like features superimposed on its rim. This number should, however, be viewed with considerable caution because of all the assumptions involved. Frey also suggested that Hellas be taken as the base of the Noachian and that the era from 4.55 to 4.1 Gyr ago be referred to as pre-Noachian.

Possibly the earliest geologic event recorded in the topography of the surface is the formation of the global dichotomy (Carr, 2006; Nimmo and Tanaka 2005; Solomon et al., 2005). The dichotomy is expressed in three ways that do not coincide everywhere: as differences in elevations, as differences in crustal thickness, and as differences in crater densities. The dichotomy results in a bimodal distribution of elevations, with a difference of 5.5 km between the two hemispheres (Aharonson et al., 2001). Neumann et al. (2004) estimate that the thickness of the crust averages roughly 30 km north of the dichotomy boundary and roughly 60 km to the south. As expected, the differences in crater densities across the boundary may be only a superficial difference for a densely cratered surface that is present at depths below the present Hesperian–Amazonian surface north of the dichotomy as indicated by remnants of old craters that poke up through the younger plains and by vague circular outlines in both the Mars Orbiter Camera (MOC) images and Mars Orbiter Laser Altimeter (MOLA) data. The low-lying, heavily cratered Noachian surface, north of the dichotomy boundary, is simply covered by younger deposits. A distinction must also be made between the time of formation of the depression and the time of formation of the fill. The number of craters superimposed on the fill yields little information about the age of the
depression itself. From the geologic evidence the dichotomy could have formed at any
time between the formation of the crust 4.5 Gyr ago and the formation of the oldest of
the clearly superimposed impact basins, such as Utopia and Chryse, around 4.1 Gyr
ago according to the Frey (2003) chronology.

The mode of formation of the dichotomy is also uncertain. One possibility is that
the dichotomy is the result of one or more large impacts (Andrews-Hanna et al., 2008;
McGill and Squyres 1991; Wilhelms and Squyres 1984). The outline of the basin is
roughly circular except in Tharsis where younger volcanics are superimposed on the
boundary and in Chryse where there may be a younger superimposed basin. Zuber
et al. (2000) and Neumann et al. (2004) expressed skepticism that the northern
lowlands could be an impact scar because there is little evidence for extreme thinning
of the crust as there is within Hellas and Isidis, nor is there a perceptible rim around
the basin. They prefer an early internal origin, tied to global mantle convection (Wise
et al., 1979; Zuber et al., 2000; Zhong and Zuber 2001; Solomon et al., 2005).
However, the thicker crust and absence of a rim around the proposed impact basin
may simply reflect an extremely old age, and Andrews-Hanna et al. (2008) have
recently attempted to reconcile the geophysical data with an impact origin. If the basin
formed very early, soon after formation of the crust, it would have experienced
erosion, sedimentation, isostatic rebound, and volcanic filling for hundreds of millions
of years, an era almost as long as the terrestrial Phanerozoic, before a more complete
geologic record emerged after the formation of the Hellas basin at the start of the
Noachian.

Surface conditions in this early era prior to the formation of Hellas are very
uncertain. One certainty is that the surface was episodically disrupted by very
large, basin-forming impact events. Formation of these large (>500 km diameter)
craters and basins would have resulted in the ejection of large amounts of rock
vapor and rock melt into and beyond the atmosphere, evaporated any oceans that
might have been present, and raised the surface temperatures to several hundred
kelvin (Segura et al., 2002; Sleep and Zahnle 1998). Despite the low solar
luminosity, surface temperatures could have remained above freezing for years
after each large impact event. Water that was injected into the atmosphere during
the initial impact and during the subsequent warming of the surface and subsurface
could rain out over years, the time depending on the size of the impact. Conditions
during the long (possibly millions of years) periods between basin-forming events
would have depended on the effects of smaller impacts and on the ability of the
atmosphere to provide significant greenhouse warming during this era of low solar
luminosity, which in turn would have depended on the thickness of the atmosphere
and its composition, particularly the abundance of trace greenhouse gases such as
CH$_4$ and SO$_2$.

In summary, the geologic record of the pre-Noachian era extending from the time
of formation of the planet 4.5 Gyr ago to the time of formation of Hellas estimated at
around 4.1 Gyr ago is sparse. The planet differentiated into crust, mantle, and core
within a few tens of millions of years of planet formation, the global dichotomy
probably formed early, and the planet had a magnetic field. Large impact craters and
basins that formed episodically would have had devastating environmental effects.
However, the nature of the atmosphere, the surface inventory of volatiles, and surface conditions between large impact events are all unknown.

### 2.4 The Noachian era

If the above chronology is correct, the Noachian era extends from approximately 4.1–3.7 Gyr ago, roughly coincident with the upper Hadean on Earth. Its most distinguishing features compared with later times are high rates of cratering, erosion, and valley formation, the accumulation of most of Tharsis, and surface conditions that enabled the widespread production of weathering products such as phyllosilicates. This is the era for which we have the best evidence for widespread water erosion. The density of visible craters larger than 100 km in diameter in Noachian terrains is roughly $2 \times 10^{-6}$ km$^{-2}$ (Strom et al., 1992), or 300 such-sized craters planet-wide, implying that one 100 km diameter crater formed every million years. The impacts would have ballistically distributed ejecta around the planet, caused hydrothermal activity around the impact sites, comminuted surface materials thereby enabling them to be moved by wind and water, and brecciated the near-surface materials thereby increasing their porosity, and so affecting groundwater movement and storage. Noachian craters with diameters between 500 and 1000 km would have deposited roughly 300 m of ejecta planet-wide (Segura et al., 2002). Hellas alone would have deposited 500 m. The coarser fraction from all these impacts would have formed bedded deposits with thicknesses depending on the size of the impact events and their proximity to the resulting craters. The fate of the finer ejecta was likely more complicated. Large areas of the Noachian terrain have an etched appearance (Greeley and Guest, 1987; Malin and Edgett, 2001; Scott and Tanaka 1986) as though parts of the surface had been formerly covered with easily erodible, horizontally layered deposits that had been partly removed by the wind. Fine-grained impact ejecta are likely a significant component of these deposits, along with volcanic ash, as well as the products of weathering and erosion as discussed below. Correlations between gravity and topography suggest that the densely cratered terrain of the southern highlands has surface densities of 2500–3000 kg m$^{-3}$ (McGovern et al., 2004), significantly lower than the density of the Tharsis volcanics and Martian meteorites (3100–3300 kg m$^{-3}$), and consistent with a crust that has been modified by impacts, erosion, and sedimentation.

While volcanism likely occurred almost everywhere, Tharsis was particularly active, resulting in a volcanic pile roughly 5000 km across and 9 km high by the end of the Noachian (Phillips et al., 2001). Large impact basins and the northern basin may also contain significant amounts of Noachian volcanic fill that is buried by younger deposits. Almost everywhere else, the rates of volcanic resurfacing were low compared with the impact rate so that what is preserved in the morphology is an impact-cratered surface on which almost all traces of Noachian volcanic morphology have been destroyed. Despite the scarcity of geomorphic evidence for volcanism, most of the materials exposed in the cratered uplands are probably primarily volcanic rocks or volcanic rocks reworked by impacts. They are mainly basalts rich in low calcium pyroxene, with variable amounts of olivine (Bibring et al., 2006; Poulet et al.,
2007). The Columbia Hills (Squyres et al., 2006) may be typical of the cratered Noachian uplands in general. They comprise mostly basaltic rocks of various types, including pyroclastic flows and impact breccias. Many of the rocks have undergone aqueous alteration, suggestive of circulation of hydrothermal fluids. Detection of primary igneous minerals, particularly olivine, in much of the Noachian terrain (Bibring et al., 2006) may indicate limited weathering after the deposition of the uppermost layers. However, the widespread presence of hydrated silicates deeper in the section and in alluvial fans indicates widespread aqueous alteration prior to deposition of the upper olivine-rich units.

Formation of Tharsis deformed the Martian lithosphere on a global scale to create a trough around the rise, an antipodal high, and gravity anomalies, as predicted by loading of a spherical elastic shell with the Tharsis topography (Phillips et al. (2001). That Tharsis was largely in place at the end of the Noachian is demonstrated by slope indicators such as valley networks and lava flows. Roughly $3 \times 10^8$ km$^3$ of rock accumulated to form Tharsis, the equivalent of a global layer 2 km thick. If the magmas contained amounts of water similar to the Hawaiian basalts, the global equivalent of a layer of water 120 m deep would have been outgassed, together with significant amounts of sulfur. If all of Tharsis accumulated in the Noachian, the extrusion rate would have been 0.75 km$^3$ year$^{-1}$, roughly equivalent to the Hesperian extrusion rate estimated by Greeley and Schneid (1991) for the entire planet. For comparison, the extrusion rate for the Earth is 4 km$^3$ year$^{-1}$ (Crisp, 1984). Another possible site of large accumulation of Noachian volcanics is the northern basin, including Utopia.

### 2.4.1 Erosion rates

The Noachian terrains are clearly more eroded than younger terrains. While Hesperian craters as small as a few kilometers across generally preserve all their primary impact features, even delicate textures on their ejecta, Noachian impact craters hundreds of kilometers across mostly have highly eroded rims and partly filled interiors. However, even though average Noachian erosion rates were 2–5 orders of magnitude higher than they were subsequently, they still appear to have been close to or well below terrestrial rates (Carr, 1992; Golombek and Bridges, 2000; Golombek et al., 2006). The number of fresh appearing craters with well preserved ejecta patterns on Noachian terrains is comparable to the number on Hesperian terrains, which suggests that high erosion rates persisted until the end of the Noachian and then rapidly declined (Craddock and Maxwell, 1993).

Low average rates of erosion in the Noachian compared with the Earth are consistent with preservation of the planet’s larger features. The Noachian era is roughly equivalent to the time on Earth from the end of the Silurian to the present day. On Earth, during this time, continents assembled and disassembled, the present-day ocean basins opened, and numerous mountain chains formed and were eroded away. The fact that the Hellas basin is preserved gives an indication of the average Noachian erosion rates. The denudation rate for the continental United States is roughly $50 \text{ m} 10^{-6}$ years (Judson and Ritter, 1964), or 20 km in 400 Myr, the
estimated length of the Noachian. Clearly the rim of Hellas has not been eroded by 20 km. We do not know how much fill is in Hellas, but with a depth of over 9 km, it is unlikely to contain more than a few kilometers. If we assume the floor of the basin \((2.5 \times 10^6 \text{ km}^2)\) has 2 km of fill derived from the surrounding drainage area \((17 \times 10^{-6} \text{ km}^2)\), we derive a denudation rate of 0.75 m \(10^6\) years, almost 2 orders of magnitude lower than the US rates. Thus, the data from crater preservation and the paucity of filling within Hellas are consistent. Average Noachian erosion rates, while orders of magnitude greater than the rates for subsequent eras, still fell short of terrestrial rates.

### 2.4.2 Valley networks

Valley networks provide compelling evidence of former conditions that enabled sustained flow of liquid water across the Martian surface. Much, but not all, of the Noachian terrain is dissected by valley networks. Most drain into local lows and are only up to a few hundred kilometers long, particularly in Cimmeria and Serinum where there is no strong regional slope. However, between Syrtis Major Planitia and Argyre several valleys thousands of kilometers long drain northwest down the long regional slope from the high ground around Hellas toward the Chryse–Acidalia low. Stream profiles are poorly graded and closely follow the regional slopes (Howard et al., 2005). There is little indication that formation of the presently identifiable valleys resulted in a general lowering and grading of the landscape as occurs with long-lived terrestrial rivers. The result is low basin concavities (Aharonson et al, 2001), poorly graded stream profiles, and poor correlation of basin circularity with elevation within the basins (Stepinski and O’Hara, 2003). Drainage densities vary considerably with location, up to the low end of the terrestrial range (Craddock and Howard, 2002; Hynek and Phillips, 2003). The apparent low drainage densities, amphitheater heads of tributaries, and rectangular cross-section suggested to many early workers that groundwater sapping had played a major role in the formation of many of the valleys (Baker, 1990; Carr and Clow, 1981; Gulick, 1998, 2001; Pieri 1980), although all acknowledged that precipitation and/or hydrothermal circulation were/was needed to recharge the groundwater system to enable sustained or episodic flow. Better imaging and altimetry now show that dense, area-filling networks are common throughout the Noachian terrains (Figure 2.1, see also Chapter 10). They indicate that precipitation followed by surface runoff, coupled with infiltration and groundwater seepage, must have occurred at least episodically in the Noachian (Carr, 2006; Howard et al., 2005; Hynek and Phillips 2003; Irwin and Howard, 2002). Major uncertainties are how persistent conditions necessary for precipitation and surface runoff were sustained and how such conditions were achieved.

Many lows, such as craters having inlet and outlet valleys, indicate that lakes formerly occupied lows in the dissected terrains, as expected for a poorly graded landscape undergoing fluvial erosion (Cabrol and Grin, 1999, 2001, 2002, 2005; Fasset and Head, 2008) (Figure 2.2). Deltas or alluvial fans are commonly observed where valleys enter the lows. Particularly striking examples of deltas are in Eberlswalde crater, Holden Crater (Chapter 12), and in the Nili Fossae (Fassett and
Figure 2.1  The Warrego Valles at 42° S, 267° E. The dense drainage network strongly suggests precipitation and surface runoff (THEMIS).

Figure 2.2  Possible site of former lakes at 4° S, 111°E. Near the center of the figure, Tinto Vallis breaches the southern rim of the crater Palos. The northern rim is also breached, suggesting flow into the crater from the south and out to the north. Several other craters nearby have similarly breached rims. If the valleys are fluvial, water must have pooled in all the breached craters (THEMIS).
Head, 2005). The dimensions of the channel remnants on the Eberswalde delta suggest that the discharges were comparable to terrestrial streams draining similar-sized basins (Moore et al., 2003) and that the deltas and fans may have taken only decades to form (Jerolmack et al., 2004). Chlorine-rich deposits found in local lows within the Noachian uplands may be the result of evaporation of lakes (Osterloo et al., 2008). Some of the sulfate-rich deposits found in Meridiani may have been deposited in transient inter-dune lakes, and subsequently altered as a result of oscillations in the local groundwater table (Grotzinger et al., 2005; McLennan et al., 2005). The Meridiani deposits are discussed more in detail below under the Hesperian.

Howard et al. (2005) suggested that the more pristine valleys incised into the highland terrains are the result of a late Noachian to early Hesperian episode of incision. They make a distinction between the general degradation of the landscape and formation of the incised valley networks. They suggest that during most of the Noachian there was widespread fluvial erosion of crater rims and other high ground and partial infilling of lows such as craters, but that formation of the incised networks was fundamentally different. They were incised into a degraded landscape, but contributed little to that degradation. They form an immature drainage system in which individual valleys are poorly graded and basin development by erosion and alluviation barely occurred. Some support for the late incision model in which the more pristine, more easily detected valleys contribute little to the general landscape degradation is the observation that areas that appear only sparsely dissected, such as the region between Hellas and Argyre, are just as degraded as the highly dissected areas.

Degradation of the Noachian landscape must have produced large amounts of erosional debris. The partial to nearly complete filling of Noachian craters of all sizes is a significant possible sink for erosional products. Malin and Edgett (2000) conclude that much of the crater fill consists of layered, sedimentary rocks. They also point out the common presence of layered rocks in intercrater areas, canyons, and areas of chaotic terrain. On the basis of their erodibility, the presence of steep scarps, and the lack of boulders at the bases of scarps, they conclude that most of these layered Noachian deposits are indurated, fine-grained sediments rather than coherent volcanic rocks. Unknown amounts of fill could also be hidden under younger deposits in the low-lying northern plains.

One of the most striking characteristic of these sediments, irrespective of their age, is their rhythmic layering, which in many cases is remarkably regular (Malin and Edgett, 2000) (Figure 2.3). The layering could result from a variety of causes such as successive impacts and volcanic events or changes in the erosional regime as a result of climate changes. While all these three processes likely contributed to the sediments, the extreme regularity of some of the layering argues against volcanism and impacts as a primary cause, at least in these cases. The rhythmic depositional patterns suggest an astronomic cause such as changes in erosion rates brought about by climate changes, which in turn result from periodic changes in the orbital and rotational motions of the planet (Laskar et al., 2004).

Many of the fluvial features found on post-Noachian terrains were formed by large floods. However, despite widespread dissection during the Noachian, large floods appear to have been rare. Ladon Vallis is one example. It may be part of a large ancient
Figure 2.3  Finely layered sediments with unconformities within Galle crater at 52.3° S, 329.9° E. The mode of deposition, whether by water or wind, is unknown, but the regular rhythmic layering suggests that deposition was modulated by changes induced by astronomic motions (MOC).

waterway extending from close to the rim of Argyre into the northern plains. It has been attributed to overflow of a lake in Argyre (Parker et al., 2000), although that interpretation has been challenged (Heisinger and Head, 2002). Another possible Noachian flood feature is Ma’adim Vallis, which Irwin et al. (2002) plausibly argue was formed in part by rapid drainage of a large lake upstream from the main valley.

The widespread dissection of Noachian terrains coupled with surface runoff patterns indicates at least episodic precipitation and temperature and pressure conditions that stabilized water at the surface. Nevertheless, there is considerable uncertainty as to how sustained such conditions were and whether there was ever a global hydrologic system in which precipitation, infiltration, runoff, and groundwater flow were in quasi-equilibrium with evaporation and sublimation from large bodies of water and ice. Despite considerable relief along the dichotomy boundary and around Hellas, large drainage basins analogous to the Mississippi and Amazon did not develop. Seemingly, the cumulative effects of erosion, alluviation, and stream capture were insufficient to result in integration of drainage over large areas and growth of large drainage basins before being destroyed by impacts. There are, for example, no significant valleys draining into Hellas from the north and west despite several kilometers of relief and despite the area having experienced 300–400 My of erosion during the Noachian. Even if Hellas were filled with water to the –3.1 km level as suggested by Moore and Wilhelms (2001) (Figure 2.4, see also Chapter 7), there are still 5 km of relief from the rim crest down to the proposed sea level to enable
drainage. If the observed degradation of craters superimposed on the rim was due to fluvial erosion, then most of the drainage was likely local with the water accumulating in local lows to be lost by infiltration or evaporation. Such a scenario is also consistent with the apparent failure to transport large amounts of sediment from the Hellas drainage basin into the central depression. The sediment eroded from the highs must simply have accumulated in local lows.

Whether there were ever oceans on Mars is one of the planet’s most controversial issues (Carr and Head, 2002; Clifford and Parker, 2001; Head et al., 1999; Parker et al., 1989, 1993, see also Chapters 9 and 10). Discussion has focused mainly on the possibility of post-Noachian oceans because they could have resulted from the large post-Noachian floods discussed later and because any evidence for oceans would be better preserved for the post-Noachian than that for the Noachian. However, the Noachian is the time for which we have the best evidence for conditions under which oceans might be present. Clifford and Parker (2001) argue from estimates of the global inventory of water and the thermal conditions implied by the valley networks that possibly one-third of the planet was covered by oceans during parts of the Noachian. Moore and Wilhelms (2001) identify two possible Noachian shorelines within Hellas (see Chapter 7), and Howard et al. (2005) proposed that the absence of valleys in the Noachian of northwest Arabia resulted from burial by sediments, along the periphery of a northern ocean. Despite these suggestions, the prospect for finding compelling geomorphic evidence of former Noachian oceans is poor, since such
evidence, if it ever existed, would be vulnerable to erasure by burial and erosion. Nevertheless, if during the Noachian, Mars had a large inventory of water and if ever warm condition prevailed, as is indicated by the valley networks, then bodies of water would have accumulated in lows such as the northern basin and Hellas.

### 2.4.3 Weathering

A distinguishing feature of the Noachian as compared with later eras is the widespread presence of phyllosilicates, such as nontronite, Fe-rich chlorites, saponite, and montmorillonite (Bibring et al., 2006; Murchie et al., 2008), minerals that all form by the aqueous alteration of basalts (e.g., Zolotov and Mironenko 2008). Weathering to form these minerals probably also occurred in the pre-Noachian but the evidence has been largely destroyed. In some places the phyllosilicates appear to be excavated from below the surface or are overlain by unaltered, olivine-rich rocks. Mustard et al. (2007) show, for example, that olivine-rich rocks overlie phyllosilicates in the Nili Fossae and suggest that they formed from impact melts produced by the event that formed the Isidis basin. The relations suggest that prior to the uppermost Noachian, conditions were such that phyllosilicates could form, but conditions changed toward the end of the era such that rocks that formed at the end of the Noachian retain their primary mineralogy. The presence of phyllosilicates in Noachian terrains and their absence in younger terrains suggest that near the end of the Noachian, surface conditions changed from warm wet conditions under which hydrous weathering could occur, at least occasionally, to colder, drier conditions under which hydrous weathering was suppressed.

### 2.4.4 Noachian Climates

The geomorphic evidence for lakes and rivers, the widespread presence of phyllosilicates in Noachian terrains, and the evidence for groundwater movement and surface water at Meridiani (Grozinger et al., 2005) all suggest at least episodic warm conditions during and at the end of the Noachian. Greenhouse models indicate that it is very difficult to raise global temperatures sufficiently to allow widespread precipitation on early Mars with only a CO$_2$–H$_2$O atmosphere because of Mars’ distance from the sun, the expected low energy output of the Sun, and formation of CO$_2$ clouds (Haberle, 1998; Kasting, 1991). In addition, we saw above that a thick CO$_2$ atmosphere is difficult to sustain against impact erosion and weathering. Although some carbonate rocks have been detected from orbit (Ehlman et al., 2008), failure to detect widespread carbonate deposits (Bibring et al., 2006) argues against a thick (>1 bar) CO$_2$ atmosphere during and particularly at the end of the Noachian, when the most prominent valleys formed. If surface conditions on Mars were at least episodic such as to stabilize liquid water near the end of the Noachian, some mechanism other than, or in addition to, warming by a CO$_2$–H$_2$O greenhouse seems to be required. Possibilities include the presence of other greenhouse gases such as SO$_2$ and CH$_4$, or large-scale climatic perturbations resulting from large impacts or large volcanic events. Segura et al. (2002) suggest that large impacts would warm the surface and inject significant
amounts of water into the atmosphere that could precipitate out over decades to form the valleys. They estimate, for example, that formation of 600, 1000, and 2500 km craters would result, respectively, in global precipitation of 2, 9, and 16 m of water. Some possible difficulties with the model are (i) the modest amounts of precipitation that result from these very large impacts, which are few in number; (ii) all the Noachian craters with the above sizes are highly eroded and must be much older than the valley networks that we observe, particularly the more pristine ones; and (iii) the two best preserved impact basins, the 200 km diameter Lowell and the 220 km diameter Lyot, are only minimally dissected by valley networks. Thus, while the mineralogic and geomorphic evidence for warm conditions near the end of the Noachian are convincing, how such conditions were achieved remains obscure. This discrepancy is one of the most puzzling aspects of Mars’ evolution.

2.5 Hesperian era

The Hesperian era was initially invoked to distinguish old post-Noachian plains such as Hesperia Planum and Lunae Planum from younger plains such as those in Tharsis and Amazonis (Scott and Carr 1978). It was subsequently defined more quantitatively according to the number of superimposed craters (Scott and Tanaka 1986). The crater densities suggest that the period extends from the end of heavy bombardment around 3.7 Gyr ago to around 3 Gyr ago (Hartmann and Neukum, 2001), roughly coinciding with the lower Archean on Earth. The main characteristics of the Hesperian era are continued possibly episodic volcanism to form extensive lava plains, low rates of valley formation compared with the Noachian, formation of the canyons, formation of the largest outflow channels and their terminal lakes or seas, extremely low rates of erosion, a steep decline and possibly cessation of rock alteration to form phyllosilicates, and accumulation locally of sulfate-rich deposits, particularly in the western hemisphere (Figure 2.5). The steep decline in rates of erosion, weathering, and valley formation strongly suggests that surface conditions favorable to aqueous erosion and

![Figure 2.5 Sulfate-rich layered deposits — gypsum (CaSO₄·2H₂O) overlying Kieserite (MgSO₄·H₂O) — in Juventae Chasma at 3° S, 297° E. Their origin is controversial. Alternate suggestions are that they are remains of the materials into which the canyon is cut, or that they were deposited by water or wind on the canyon floor after the canyon formed (HRSC).](image-url)
weathering, seemingly common in the Noachian, were rare in the Hesperian. Thus, while the main era of local lake formation that accompanied formation of the valley networks was over by the start of the Hesperian, the main era of flooding and consequent formation of very large bodies of water was in the Hesperian.

Hesperian volcanism is evident mainly in the form of ridged plains. In the western hemisphere Hesperian lava plains occur mainly around the eastern periphery of Tharsis. In the eastern hemisphere, they form Hesperia Planum, Syrtis Major Planum, Male Planum, and part of the floor of Hellas. Hesperian ridged plains, present in local lows throughout the cratered uplands of both hemispheres, may also have a significant volcanic component. Partly buried craters and subdue ridges in Vastitas Borealis suggest that the northern plains are underlain by Hesperian volcanics that are continuous with the volcanic ridged plains further south (Head et al., 2002) and Hesperian plains almost certainly underlie the younger Amazonian plains of central Tharsis and Elysium. The large Tharsis shields, including Olympus Mons, probably started to accumulate in the Hesperian, or even earlier despite the young ages of the present surfaces. Thus volcanism was widespread in the Hesperian, continuing at a rate of \( \sim 1 \text{ km}^3 \text{ year}^{-1} \), comparable to the Noachian (Greeley and Schneid, 1991). It resulted in resurfacing roughly 30% of the planet, if we assume that in central Tharsis and Elysium Hesperian volcanics underlie the younger Amazonian (Tanaka et al., 1986).

### 2.5.1 Valleys and Channels

The rate of formation of valley networks declined precipitously at the end of the Noachian. Despite the decline, there are examples of Hesperian, and even Amazonian valley networks, particularly on volcanoes (e.g., Alba Patera and Ceraunius Tholus). A rare example of a heavily dissected Hesperian plain is that adjacent to southern Echus Chasma (Mangold et al., 2004). Within the uplands are numerous examples of valleys cutting, or having deposited sediments, upon what appears to be Hesperian plains in local lows. Thus, although a change in conditions resulted in the dramatic drop-off in valley formation at the end of the Noachian, conditions were occasionally such that fluvial erosion to form small valleys was enabled, at least locally.

In contrast, most of the large outflow channels formed in the Hesperian, particularly the upper Hesperian (Tanaka et al., 2005). The most important question concerning outflow channels is whether or not they were carved by liquid water. Some outflow channels have features in common with lunar and venusian rilles, including abrupt beginnings, streamlined islands, inner channels, anastomosing reaches, and terraces (Leverington et al., 2004). Lava flows are clearly visible in some outflow channels (e.g., Marte Vallis, Athabasca Valles), and the source of some outflow channels (e.g., Cerberus Fossae) are also sources of lava flows. Boulders, omnipresent in the low-lying northern plains at the ends of the large Chryse channels, suggest lava flows at the surface rather than fluvial sediments (McEwen et al., 2007). Despite these observations, a fluvial origin for most of the large outflow channels seems secure. The lunar and venusian rilles are only a few kilometers across as compared with tens of kilometer widths of Kasei, Ares, Mangala, and others. Most of the rilles are simple in form and lack the rich array of landforms that are common to both the
Martian outflow channels and large terrestrial flood features (Baker and Milton, 1974). In addition, the floors of several rubble-filled channel sources (e.g., Juventae Chasma and Aromatum Chaos) are at a much lower elevation than the outgoing channels and yet show no evidence of former lava lakes such as draping of the source depressions by lava. An aqueous origin is also supported by sulfate-rich deposits in several source depressions such as Juventae chasma (Gendrin et al., 2005) (Figure 2.6). Although some of the simpler, rille-like channels, such as Hrad Vallis, may be cut by lava, the following discussion will assume that the larger, more complex outflow channels such as Kasei, Tiu, Simud, Ares, Mangala, and Maja were cut by large floods of water. If this assumption is correct then large bodies of water must have been left in the lows at the ends of the channels when the floods were over.

The abrupt start of outflow channels indicates that they are formed not by surface drainage immediately following precipitation but by the rapid release of large volumes of stored water. The storage medium could be an aquifer, or a lake, as with the Channeled Scablands of Eastern Washington, or ice, as with Icelandic jökulhlaups. All three possibilities may be represented on Mars: (i) several large channels that emerge from rubble-filled depressions south of the Chryse basin, and others elsewhere that start at graben, appear to have formed by eruptions of groundwater (Carr, 1979) (Figure 2.6); (ii) drainage of lakes in the Valles Marineris is suggested by eroded sections of Ganges, Eos, and Capri Chasmas and the mergers of Kasei Vallis with Echus chasma and of Maja Vallis with Juventae Chasma (Luchitta et al., 1992;
McCaulay, 1978; see also Chapters 5 and 6); and (iii) Chasma Boreale may have formed from meltwater from the north polar cap (Clifford, 1980; Fishbaugh and Head, 2002).

Numerous estimates have been made of peak discharges and the volumes of water involved in the floods. The main difficulties are knowing the flood depth and how long the floods lasted. Channel depths can be measured but they give only an upper limit for the stream depth. Most estimates of peak discharges for the largest channels range from $10^6$ to $10^8$ m$^3$ s$^{-1}$ depending on the channel and the assumed depth (Baker, 1982; Leask et al., 2007; Robinson and Tanaka 1990). If the floods formed by water, then a groundwater source appears almost inescapable for channels such as Shalbatana, Tiu, Maja, and Ares that originate in chaos-filled depressions and for those such as Mangala and Athabasca that originate at graben. The sources are likely extensive aquifers trapped below a thick cryosphere. The discharges from such aquifers would be restricted by the dimensions of the aquifers, their permeability, the hydrostatic head, and the dimensions of the conduit to the surface (Carr, 1979; Manga, 2004). Andrews-Hanna and Phillips (2007), by modeling the eruption of groundwater from an overpressurized aquifer trapped below a kilometers thick cryosphere, estimated that for a typical Ares flood peak discharge ranged from $10^6$ to $10^7$ m$^3$ s$^{-1}$ and that $10^3$–$10^4$ km$^3$ of water were erupted. The volume of Ares Vallis is roughly $8 \times 10^4$ km$^3$, so many floods may have been needed to erode it, according to this model. The high discharges require that the aquifer be pressurized. This could result simply from the aquifer topography and supply of water from highs such as Tharsis and Elysium (Carr, 1979; Harrison and Grimm, 2005a, 2005b) or from tectonic pressurization, particularly for channels such as Mangala and Athabasca that start at faults (Hanna and Phillips, 2005). Emplacement of dikes may also have contributed to water release, by melting of ground ice and creating fractures that act as both horizontal and vertical conduits (Head et al., 2003).

The apparent scarcity of groundwater eruptions to form large floods in the Noachian may have resulted from the lack of a thick cryosphere. Their repeated occurrence in the Hesperian may be another consequence of a change in surface conditions at the end of the Noachian that is implied by the decline in the formation of valley networks and hydrated weathering products. The change led to the growth of a thick cryosphere, thereby enabling the trapping of water and large groundwater eruptions. The decline in groundwater eruptions toward the end of the Hesperian could result from a variety of causes such as depletion of water below the cryosphere, growth of the cryosphere to engulf most of the high-porosity megaregolith, and declining tectonic and volcanic activities.

### 2.5.2 Valles Marineris

The Valles Marineris present some of the most puzzling issues of Martian geology, including how and when they formed, the origin of their interior layered deposits, whether the canyons ever contained lakes, and if so how the lakes formed and dissipated (Chapters 5 and 6). The primarily structural origin by movement along faults radial to Tharsis was recognized early (Blasius et al., 1977; Sharp, 1973).
NNE–SSW extension to form the rifts may have occurred over hundreds of millions of years, and thinned the crust under the canyons (Anderson and Grimm, 1998). Extension may also have been accompanied by dike intrusions (McKenzie and Nimmo 1999; Mège and Masson 1996). East of roughly 310 E structural control by Tharsis radials is much less obvious as the roughly E–W canyons merge with more northerly trending outflow channels.

The age of the canyons is difficult to determine precisely. Since Tharsis appears to have largely been formed by the end of the Noachian, it is likely that the canyons started to form in the Upper Noachian, although we have no observational evidence. Side canyons and gullies on the canyon walls cut Hesperian plains and are themselves cut by faults. There is little if any evidence of alluvial fans on the canyon floors. The canyon floors were probably still subsiding when erosion occurred, and the fans that resulted were either eroded away or buried by younger deposits. In contrast, the landslides, the youngest features that cut the adjacent plains, accumulated on the canyon floor and are rarely cut by faults. Most of the landslides are Amazonian but some may be as old as upper Hesperian (Quentin et al., 2004). The floors of Coprates and Ganges are continuous eastward with the Upper Hesperian-aged Tiu and Simud Valles. These data collectively suggest that canyons started opening in the Noachian and that faulting, subsidence of the floor, and erosion of the walls continued through the upper Hesperian, after which faulting and subsidence was minor and widening was largely restricted to landslides.

Mounds of layered sediments are widespread within the canyons, at elevations that range from under −3000 m in Melas to over 3000 m in west Candor. Most are rich in hydrated, mainly Mg and Ca, sulfates (Bibring et al., 2006; Gendrin et al., 2005). For the last 30 years the favored origin for the sediments is that they were deposited in intra-canyon lakes (Komatsu et al., 1993; Lucchitta et al., 1992; McCauley et al., 1978; Nedell et al., 1987; Weitz and Parker, 2000; see Chapters 5 and 6). Such an origin is consistent with the eastward merger of the canyon floors with large outflow channels, the fine layering of the sediments, superposition relations across the Ophir–Candor divide, the marked contrast in erosional styles between the sediments and the canyon walls, and the presence of sulfates. The only plausible shoreline so far identified within the canyons, however, is one in Coprates Chasma at an elevation of roughly −3500 m (Harrison, 2007), 6500 m below the top of the sediments in Candor. The lake hypothesis does not necessarily imply deep lakes. The sediments, together with evaporitic minerals, may have accumulated over many millions of years by repeated episodes of evaporation and/or sublimation following injections of water into the canyons as a result of climatic events, faulting, or other causes. As indicated above, outflow channels commonly start at faults, so it is not unreasonable to conclude that the huge faults that created the canyons could have been conduits that supplied groundwater for lakes within the canyons. If climatic conditions were similar to today’s, the lakes would have frozen and been hindered from draining away by a thick cryosphere.

Even if the canyons did at times contain lakes, the origin of the layered deposits still remains puzzling. One possibility is that they are a mixture of subaqueous and subaerial deposits, the materials having been brought in by the wind and deposited in water when lakes were present and subaerially when lakes were not present. Such an origin is
consistent with the common presence of mounds of sediments in upland craters, mounds that resemble those in the canyon (Carr, 2006, figure 2.7, 2.9). Other suggestions are that the canyon internal deposits are young pyroclastic deposits (Hauber et al., 2006), or products of sub-ice or subaqueous volcanism (Chapman and Tanaka, 2001).

Malin and Edgett (2000) and Catling et al. (2006) suggest a very different origin for the sediments. They argue that the sediments do not postdate the canyons but are instead simply remnants of the Noachian–Hesperian materials into which the canyons are cut. By this hypothesis, the layering, the contrasting erosional styles, and the superposition relations are inherited from the original pre-canyon materials. Lakes may still have been present at times but they did not result in the deposition of kilometer-thick stacks of sediments, and the apparent young age of the sediments is an exposure age and not a depositional age.

### 2.5.3 Oceans

If the outflow channels were formed by floods, as is likely, then large bodies of water must have been left at their termini, which are mostly in the northern plains. Evidence for such bodies of water remains equivocal. Several possible shorelines have been tentatively identified in and around the northern plains (Clifford and Parker, 2001; Parker et al., 1989, 1993; see Chapters 9 and 10) and Hellas (Moore and Wilhelms 2001; see Chapter 7) but they remain controversial. Supporting evidence for the presence of former bodies of water of Hesperian age in the northern plains are partly buried ridges and craters, interpreted as the result of burial by sediments carried by the large floods (Head et al., 2002). The burying unit, part of the Vastitas Borealis Formation (Tanaka et al., 2005), covers an area of $1–2 \times 10^7 \text{km}^2$ and has a minimum volume of $3 \times 10^5 \text{km}^3$ (Kreslavsky and Head, 2002). The boundary of the unit is roughly coincident with the Deuteronilus shoreline identified by Parker and coworkers (Chapter 9). Its enclosed volume is more than adequate to account for even the largest flood volumes estimated by Andrews-Hanna and Phillips (2007) and Leask et al. (2007). Also supporting the former presence of bodies of water in the northern plains are numerous features that suggest that stagnant ice sheets could have been left behind when the bodies of water froze (Kargel et al., 1995, see also Chapter 10). Most of the features (e.g., thumbprint terrain, polygonal ground) are found around the edge of the Vastitas Borealis formation (Tanaka et al., 2005). Arguing against the former presence of large bodies of water in the northern plains are the lack of detection of evaporites (Bibring et al., 2005) and the presence of large boulders up to 2 m in diameter in low areas where fine-grained sediments would be expected by the flood hypothesis (McEwen et al., 2007).

### 2.5.4 Erosion and weathering

Both orbital and surface observations (summarized in Golombek et al., 2006) indicate that average erosion rates dropped 2–5 orders of magnitude at the end of the Noachian. The low rates were sustained for the rest of the planet’s history. The rates of $0.02–0.03 \text{nm year}^{-1}$ estimated for the uppermost Noachian or Hesperian lava
plains of Gusev and the Pathfinder landing site are many orders of magnitude below
the lowest rates ($10^4$–$10^5$ nm year$^{-1}$) for the Earth. However, despite the extremely
low average rates, extensive post-Noachian erosion has occurred locally, causing
some post-Noachian units, such as the Medusae Fossae Formation and the polar
layered deposits, to be deeply eroded. The higher rates appear to occur mainly as a
result of local events such as floods, or where rock properties are such that wind and
sublimation are effective removal agents. In addition, steep slopes, particularly in
midlatitude craters, are commonly gullied (see Section 2.6).

The widespread detection from orbit of olivine (Putzig et al., 2005) on post-Noachian
surfaces indicates persistently low weathering rates throughout much of Mars’ history
(Hoefen et al., 2003), olivine being a mineral particularly susceptible to breakdown
under moist conditions. Low weathering rates are also implied by alteration of the
basalts in Gusev. The basaltic flows on the floor of Gusev crater have a crater retention
age of 3.6 Gyr (Greeley et al., 2005) and although individual boulders analyzed by the
Spirit rover cannot be dated they are likely also to be billions of years old. The rocks
have a thin alteration rind in which S, Cl, and Br are enhanced, but the primary minerals
olivine, plagioclase, and magnetite are retained. Chemical patterns in the soils indicate
migration of soluble elements, thereby implicating liquid water. However, the alteration
rinds and soil patterns are likely to be mainly the result of interactions at low water/rock
ratios such as that might result at low rates from acid clouds or local melting of frost
under present or higher obliquity conditions (Haskin et al., 2005).

### 2.5.5 Sulfates

Abundant sulfates have been observed in the soils at all the landing sites so far visited;
many of the rocks in the Columbia Hills have been pervasively altered by sulfate-rich
fluids. Sulfates are a major component of the sediments at Meridiani, and thick sulfate
deposits have been detected from orbit at several locations mainly in the western
hemisphere, but also around the north pole. The sulfate-rich deposits sampled by
Opportunity in Meridiani are part of a unit roughly 600 km across and several hundred
meters thick, which overlies typical Noachian cratered terrain. It appears etched in
orbital images (Arvidson et al., 2003). The Mars Exploration Rover (MER) science
team interprets the composition of the deposits analyzed by the rovers as the result of a
mixture of roughly equal parts of a sulfate end member and altered basalt that has been
depleted of roughly 50% of its original Fe, Mg, and Ca. Jarosite, the only sulfate mineral
detected by the rovers, has the same sulfur content as the hypothesized sulfate end
member. Kieserite has been detected elsewhere in the etched unit by CRISM (Wiseman
et al., 2007) as have phyllosilicates (Poulet et al., 2008). The MER science team
interprets the section at Meridiani to result largely from eolian deposition of sand-
sized grains of the two end members to form dunes and sand sheets. Sedimentary
structures indicative of aqueous deposition in the upper part of the section in Endurance
crater suggest ephemeral, inter-dune playas, which are interpreted as acid because
jarosite precipitates under very acid conditions. Mineral casts and incrustations together
with variations in Cl and Br in the section probably result from groundwater oscillations
(McLennan et al., 2005).
The sulfates at Meridiani appear to have formed elsewhere and been transported to Meridiani, mainly by the wind. The same may be true for sulfate deposits that occur at other locations, particularly those in the north pole. For the bulk of the sulfate deposits at Meridiani, the MER science team favors a playa-like source, similar to that inferred for the upper part of the Endurance section, but no extensive sources have been identified. Because of the large volume of the etched Meridiani unit (roughly $10^{5}$ km$^3$), a playa source, fed either by surface runoff or by groundwater, would imply the processing of large amounts of water. Evaporation of waters from the large floods appears to be ruled out because of timing and failure to detect evaporites in the northern plains. Another possibility is that the sulfates do not form by evaporation but are instead primary weathering products. By this scenario, acid fogs or other forms of acidic precipitation form easily erodible, sulfate-rich weathering rinds that are eroded by the wind and ultimately accumulate in eolian sedimentary deposits. By this mechanism discrete bodies of water are not required.

Much of the discussion above on Meridiani applies equally well to other sulfate-rich deposits such as those in Valles Marineris. We saw above that faulting could have caused groundwater eruptions into the canyons, where the water could have been contained. Evaporation of successive groundwater eruptions could have led to the accumulation of the thick sequences of sulfates observed, or the sulfates could have been brought in by the wind. Jarosite has not been detected in the canyons so the case for acid conditions is weaker than that at Meridiani, as would be expected if the groundwater was buffered by a reaction with basalt. Nevertheless, the evaporative origin of the sulfate deposits in the canyons is not proven. We have compelling evidence of movement of sulfur-rich particles by the wind in Meridiani and around the north pole, and the Valles Marineris deposits could similarly have been deposited by the wind.

While the precise ages of the sulfate-rich deposits are uncertain, most (although not the north polar deposits) are upper Noachian or Hesperian in age. Where the deposits occur in Noachian terrain, as in Meridiani, they are at the top of the section. Although phyllosilicates are detected in Noachian terrains where craters have ejected materials from deeper in the section, sulfates are not. There appears to be a transition from a mainly phyllosilicate-producing era in the middle and lower Noachian to a sulfate-producing era in the upper Noachian and Hesperian. Bibring et al. (2006) suggested that the transition was due to massive eruptions of sulfur that accompanied the formation of Tharsis, an origin that may be at odds with the conclusions of Phillips et al. (2001) that Tharsis was largely built by the end of the Noachian. Another possibility is that the enhanced sulfur activity is the result of the eruptions that formed the widespread Hesperian lava plains. Yet another possibility is simply that sulfate-rich deposits become more visible in transitioning from the Noachian to the Hesperian because as the pace of processes such as impacts, volcanism, and fluvial erosion slows, the results of evaporation and eolian activity become more evident.

Thus, the planet underwent a major change in transitioning from the Noachian to the Hesperian. Rates of impact and erosion declined dramatically. The rate of valley formation also steeply declined although not to zero. Surface conditions changed such that the rate of weathering to produce phyllosilicates declined but sulfate-rich deposits became more evident. In contrast the rate of formation of large floods increased,
which likely resulted in the episodic and temporary presence of large bodies of water, particularly in the northern plains. The Valles Marineris, which appear to have largely formed by the end of the Hesperian, may have episodically contained lakes that drained to the east to form outflow channels. Many of the changes suggest a climate change at the end of the Noachian and start of the growth of a thick cryosphere, although the magnitude of the change and its cause remain unclear.

2.6 Amazonian era

The Amazonian Period extends from roughly 3 billion years ago, the middle of the terrestrial Archean, to the present, encompassing two-thirds of the planet’s history. Despite the long time represented by the period, only a modest amount of geologic activity occurred, compared with earlier periods, and the extremely low erosion and weathering rates that typified the upper Hesperian continued (Golombek et al., 2006). Particularly as a consequence of the low rates of terrain building, the effects of some surficial processes such as those involving ice and wind are more evident than those for earlier eras and perhaps the most distinguishing feature of the Amazonian is the abundant evidence for the action of ice, particularly at mid-to-high latitudes. Processes driven by obliquity variations are also more evident for this era although such processes likely occurred throughout all of Martian history.

2.6.1 Volcanism

Volcanic activity in the Amazonian was largely in, and peripheral to, Tharsis and Elysium, where the large shields continued to grow and lava plains continued to accumulate. However the eruption rate appears to have declined significantly. The eruption volumes estimated by Greeley and Schneid (1991) and the chronology of Hartmann and Neukum (2001) suggest that average eruption rates dropped from roughly 1 km$^3$ year$^{-1}$ in the Hesperian to roughly 0.1 km$^3$ year$^{-1}$ in the Amazonian. Most of the Amazonian volcanic plains are distinctively different from the earlier Hesperian plains. The earlier plains (e.g., the Lunae, Solis, Chryse, Hesperia, Syrtis Major, Hellas Plana) typically have numerous wrinkle ridges but few primary flow structures. In contrast, most of the Amazonian plains have few wrinkle ridges but numerous primary volcanic structures such as flow fronts, lava channels, and lines of skylights at the crests of lava ridges. Crater ages of tens of millions of years for volcanic surfaces in Tharsis and Elysium (Neukum et al., 2004; Berman and Hartmann, 2002) and crystallization ages as young as 150 MY from Martian meteorites (McSween, 2002) suggest that Mars is still episodically active, although at very low rates.

2.6.2 Ice

Ice likely played a significant role in modifying the landscape throughout much of Mars’ history but its effects are most evident for the Amazonian. The possibility that extensive ice deposits were left in low areas after large Hesperian floods was
mentioned above. In addition, there are indications of pervasive near-surface ice at mid-to-high latitudes, widespread, ice-rich veneers cover most the surface also at mid-to-high latitudes, and glaciation may have occurred locally. Also, much of the ice presently at the poles appears to have accumulated late during the Amazonian.

At mid-to-high latitudes ice is unstable at the surface because summer daytime temperatures rise above the frost point. However, daily temperature fluctuations damp out rapidly with depth, and modeling suggests that water ice is stable a few tens of centimeters below the surface, the depth depending on the latitude and the thermal inertia of the materials overlying the ice (Farmer and Doms, 1979). As expected, at latitudes higher than 60°, neutron and gamma-ray spectrometer measurements detected large fractions of ice at depths of tens of centimeters below a dehydrated layer (Feldman et al., 2004), and the presence of an ice table centimeters below the surface was confirmed by the Phoenix lander. Comparably large fractions of ice are not detected by orbiter spectrometers at latitudes much lower than 60° although geologic indicators of ground ice, such as debris aprons, are present down to latitudes as low as 30°. The observations suggest that significant amounts of near-surface ice may be present down to latitudes as low as 30°, but at depths too deep to be detected by the spectrometers.

The stability of ice at the surface is sensitive to the obliquity cycle. During periods of high obliquity ice tends to be driven from the poles to be deposited at lower latitudes (Jakosky and Carr, 1985; Mellon and Jakosky, 1995). The reverse occurs at low obliquities. During the current epoch, the obliquity oscillates between 15° and 35° about a mean of 24°, but Laskar et al., (2004) estimate that the average obliquity over geologic time is 40° and that there is a 63% probability that the obliquity reached 60° in the last 1 Gyr. At the current obliquity, ground ice should not be present at latitudes lower than 40° latitudes. Indicators of ice at latitudes as low as 30° may indicate that the ground ice has equilibrated with the more common higher obliquity conditions.

Most of the terrain in the 30–55° latitude belts is covered with a thin (∼10 m) veneer of material that forms a smooth surface where still intact and finely pitted surfaces were partly removed (Mustard et al., 2001). Head et al. (2003) suggested that it is an ice–dust mixture deposited during a recent era of higher obliquities 0.4–2 Myr ago and that it is now in the process of being removed. Much thicker, possibly ice-rich deposits occur preferentially on pole-facing slopes at midlatitudes (Carr, 2001). If thick enough, such deposits could flow to form glaciers. They have been invoked as a source of water that cut the gullies that commonly occur on steep slopes, as discussed below (Christensen, 2003).

Lobate debris aprons adjacent to most steep slopes in the 30°–55° bands in both hemispheres (Squyres, 1979) are compelling indicators of the presence of ice (Figure 2.7). They typically have convex-upward surfaces, are roughly 500 m thick adjacent to the slope at their origin, and extend about 20 km away from the slope. Their radar properties are identical to those of the polar layered terrains, strongly suggesting large fractions of ice (Plaut et al., 2008). Numerous surface textures indicate flow away from the slopes, with the aprons commonly wrapping around obstructions or converging on gaps in obstacles to the flow. Similar features are not found at latitudes less than 30° where talus normally simply accumulates on slopes at the angle of repose. Mangold et al. (2002) suggested on the basis of experimental
work that, if the debris flows are mixtures of rock and ice they must contain at least 28% ice. Lucchitta (1984) proposed that the ice was shed from the slopes at the head of the debris flows, which implies that the ground ice is pervasive in the 30°–55° latitude belts to depths of tens to hundreds of meters, consistent with flow of the near-surface materials to produce a general softening of the terrain (Squyres and Carr 1986). In contrast, Head et al. (2003, 2006) and Dickson et al. (2008) have emphasized the role of glaciation, suggesting that many of the features observed in these latitude belts could be the result of glaciation caused by precipitation of ice during periods of high obliquity (Figure 2.8). Counts of all craters, irrespective of preservation, indicate ages of several hundred million years, whereas counts of small fresh craters give ages of a few million years (Mangold et al., 2003). The counts indicate that the debris flows began forming at least several hundred million years ago and that the superimposed craters have been episodically or continually undergoing degradation by sublimation, shear, and other processes ever since. Degradation rates are such that small (<0.5 km) craters are preserved for millions of years.

Glaciers may have formed outside the 30°–55° latitude belts. On the northwest flanks of Olympus Mons and other large Tharsis volcanoes, several features, including lobate flows and fan-shaped formations with finely striated margins, strongly suggest that former glaciers modified the volcanic surfaces and left extensive moraines on the adjacent plains (Head and Marchant, 2003; Lucchitta, 1981; Shean et al., 2005). A glacial origin is supported by modeling studies of the atmosphere, which indicate that...
the northwest volcano flanks are preferred sites for precipitation of ice during periods of high obliquity (Forget et al., 2006).

While the geologic evidence for large fractions of near-surface ice at high latitudes (>60°) is compelling, and confirmed by direct observations, numerous issues remain. Geomorphic indicators of flow, such as lobate debris aprons, lineated valley fill, and concentric crater fill, suggest large (>30%) fractions of near-surface ice may also be present under a dehydrated layer down to latitudes as low as 30°. The thickness of the ice-rich layer is however undetermined. It could fill bedrock pores to substantial depths (hundreds of meters to kilometers) or be restricted to the interstices of the uppermost fragmental materials. Also unclear is when the ice accumulated. Crater counts indicate that ice-abetted flow has been occurring for at least several hundred million years. Some of the ground ice could have accumulated as early as in the late Hesperian, a consequence of the large floods, or even earlier, the result of the changes in surface conditions at the end of the Noachian. Alternatively it may have accumulated entirely during the Amazonian as a consequence of deposition during obliquity highs.

2.6.3 Fluvial activity

Although the main era of outflow channel formation was over by the end of the Hesperian, a few younger outflow channels have been identified, and more will likely
be discovered as high-resolution imaging accumulates. The most prominent examples of young outflow channels are the Athabasca, Grjota, Rahway, and Marte Valles in southeast Elysium. These have crater ages that range from 2 to 140 Myr, according to Burr et al. (2002), and some cut plains with crater ages of 10 Myr (Berman and Hartmann, 2002). All the young outflow channels start at fault-created fissures. If formed by water, they imply that in places liquid water is present at depth, below the cryosphere, and can be released to the surface by tectonic activity, even in the present epoch. They also imply the occasional presence of young lakes.

Very few demonstrably Amazonian valley networks have been identified. Unusually young valley networks occur in Melas Chasma and to the west of the south end of Echus Chasma (Mangold et al., 2004) and in the crater Lyot (Dickson et al., 2009). While the units they dissect are late Hesperian (2.9–3.4 billion years old), the valleys could be Amazonian. Similarly, some of the valleys on densely dissected volcanoes such as Ceraunius Tholus and Hecates Tholus could be Amazonian. However, the most prominent unambiguously Amazonian valley networks are on Alba Patera. The origin of these valleys is unclear. Some form hierarchical networks that resemble those formed by terrestrial drainage systems, but interspersed among such networks are channels that are clearly formed by lava, so that the role of precipitation in forming these valleys remains obscure. If formed by precipitation, then one possibility is that they formed by melting of ice deposits that accumulated during periods of high obliquity (Forget et al., 2006).

Gullies are by far the most common fluvial-like features that formed in the Amazonian (Figure 2.9). They typically consist of an upper theater-shaped alcove that tapers downslope to converge on one or more channels that extend further downslope to terminate in a debris fan (Malin and Edgett, 2000). They are mostly

![Figure 2.9](image_url) Gullies a few meters across in the south-facing wall of Newton crater at 41° S, 192° E. The gullies cut though several ledges and extend almost up to the crater rim (MOC).
meters to tens of meters wide, hundreds of meters long, and are common on steep slopes in the 30–60 latitude belts, particularly in the south. They have a slight preference for pole-facing slopes, at least at midlatitudes (Balme et al., 2006; Bridges and Lackner, 2006). Their origin is controversial. Although initially attributed to groundwater seeps, this origin now seems unlikely given the probable thick cryosphere during most of the Amazonian and the common presence of gullies at locations where groundwater is unlikely, as on slopes around mesas and central peaks and at crater rim crests. Dry mass-wasting may contribute to their formation but this also seems to be an unlikely primary cause since many of the gullies cut through bedrock ledges. Erosion by wind or ice appears ruled out by their morphology, and erosion by liquid or gaseous CO₂ appears ruled out by stability relations (Stewart and Nimmo 2002). All the morphologic attributes are consistent with water erosion, and the broad consensus is that that is their cause.

In the southern highlands at midlatitudes, where most of the gullies occur, average daily summer temperatures are in the 220–230 K range and surface pressures are below the triple point of water. While small amounts of liquid water might temporarily exist today under such conditions, particularly in the presence of salts, accumulation of sufficient liquid to erode gullies is unlikely, and although newly formed light-toned slope streaks starting at gullies have been attributed to liquid water (Malin et al., 2006), spectral data and closer examination have failed to find evidence that the recent bright deposits were deposited by water (McEwen et al., 2007). They may simply be dust avalanches. A plausible possibility is that the gullies result from the temporary presence of water produced by the melting of snow and ice deposited at midlatitudes during periods of high obliquity (Christensen, 2003; Costard et al., 2002; Lee et al., 2001). Such an origin is supported by modeling studies (Costard et al., 2002) and by observations of gullies emerging from beneath what appear to be ice deposits on steep slopes (Christensen, 2003). The age of the gullies cannot be accurately determined but they probably have been forming episodically, when obliquities were high throughout the 3-billion-year length of the Amazonian, and possibly longer (Schon et al., 2009). They appear fresh because of the extremely low erosion rates, but are unlikely to have been forming continuously since there is little evidence that they have caused significant backwearing of crater walls and filling of the craters despite the long times over which they probably have been forming. Thus, fluvial activity during the last 3 billion years of Mars’ history has been minor and restricted mainly to rare groundwater eruptions, very rare valley network formation of unknown causes, and the gullying of steep slopes, probably from melting of ice during high obliquities.

### 2.6.4 Poles

The finely layered deposits at the poles provide the most complete record of geologically recent events on the planet. The deposits in the north form a mound roughly centered on the pole and reaching up to 3 km above the surrounding plains of Vastitas Borealis. Crater counts indicate that the average age of the surface is of the order of 10⁵ years (Herkenhoff and Plaut, 2000). The deposits can be divided into two distinct units: (i) a basal, platey, low-albedo unit, up to 1 km thick, that rests directly on the
much older, extensive fill of the Borealis basin and (ii) the overlying, finely layered deposits that constitute the bulk of the 3-km-high mound (Byrne and Murray, 2002). The layered deposits extend out to roughly the 80° latitude and are surrounded by a vast dune field that is in places rich in gypsum (Langevin et al., 2005). Radar sounding shows that the layers in the upper unit form four distinct packets and individual layers can be traced large distances across the entire cap both in the radar returns (Phillips et al., 2008) and in the images (Milkovich and Head, 2005). The southern deposits are more complicated. A 3-km-high central mound extending roughly 5° from the pole is partly surrounded by thinner, older deposits that extend several degrees further out, where a much older layered unit, the Dorsa Argentea formation, is exposed. Crater counts on the central mound indicate an age of the order of 10^7 years. Herkenhoff and Plaut (2000) attribute the difference in ages between the two caps to differences in the persistence of the residual CO_2 cap at the two poles. If composed mostly of water ice, the total volume of the water in the layered deposits is roughly equivalent to a 20-m-deep global layer, far short of the volume of water needed to cut the Hesperian flood channels.

The layering has long been attributed to accumulations of dust and ice modulated by orbital and rotational motions (Murray et al., 1972) and this is still the prevailing theory. Phillips et al. (2008) suggest that the weakest radar reflectors detected by SHARAD could contain as little as 2% dust, the rest being ice; the strongest reflectors could contain as much as 30% dust. Variations in obliquity would affect deposition and removal of ice at the poles and the incidence of dust storms and hence the deposition of dust (Toon et al., 1980). While attempts have been made to correlate specific layers with recent obliquity variations (Milkovich and Head, 2005), the correlations will remain uncertain until samples are available for dating. Nevertheless, the layering appears to reflect geologically recent events. The absence of an older record is consistent with the interpretation that many features at midlatitudes result from removal of ice at high latitudes and deposition at lower latitudes during periods of high obliquity. Accumulation and removal of layered deposits at the poles probably have been occurring repeatedly throughout the history of the planet. At the north pole we have only a recent record, but a partial record of older polar events may be preserved in the south.

2.7 Summary

Mars accumulated and differentiated into crust, mantle, and core within a few tens of millions of years of Solar System formation. The global inventory of near-surface water available to participate in a geologic process is poorly constrained because of large uncertainties in the amount of water originally accreted and subsequently lost during the first 0.5 Gyr of the planet’s history. The Noachian period (4.1–3.7 Gyr ago) was characterized by the presence of a magnetic field, high rates of cratering, erosion, and valley formation. Most of Tharsis formed and surface conditions were at least episodic such as to cause the widespread production of hydrous weathering products such as phyllosilicates. Erosion rates, though high compared with later epochs, fell
short of the lowest terrestrial rates. Water-worn valley networks are common, but the best preserved valleys form an immature system that has had only a modest effect in shaping the landscape. The record suggests that warm, wet conditions necessary for fluvial activity were met only occasionally, such as might occur if caused by large impacts or volcanic eruptions. A major change occurred at the end of the Noachian. The rates of impact, valley formation, weathering, and erosion dropped precipitously. On the other hand, volcanism continued at a relatively high rate throughout the Hesperian, resulting in the resurfacing of at least 30% of the planet. Large floods formed episodically, possibly leaving behind large bodies of water. The canyons formed. The observations suggest the change at the end of the Noachian suppressed most aqueous activity at the surface other than large floods, and resulted in the 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. The rate of volcanism during the Amazonian was roughly a factor of 10 lower than that in the Hesperian and confined largely to Tharsis and Elysium. The main era of flooding was over, although small floods appear to have occurred episodically until geologically recent times. Canyon development was largely restricted to the formation of large landslides. Erosion and weathering rates remained extremely low. The most distinctive characteristic of the Amazonian is the formation of features that have been attributed to the presence, accumulation, and movement of ice. Included are the polar layered deposits, glacial deposits on volcanoes, ice-rich veneers at high latitudes, and a variety of landforms in the 30–55° latitude belts, including lobate debris aprons, lineated valley fill, and concentric crater fill. Most of the gullies on steep slopes also formed during this era. The rate of formation of the ice-related features and possibly the gullies probably varied as changes in obliquity affected the ice stability relations.

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