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Key Science Questions from the Second Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life

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ABSTRACT

In October 2004, more than 130 terrestrial and planetary scientists met in Jackson Hole, WY, to discuss early Mars. The first billion years of martian geologic history is of particular interest because it is a period during which the planet was most active, after which a less dynamic period ensued that extends to the present day. The early activity left a fascinating geological record, which we are only beginning to unravel through direct observation and modeling. In considering this time period, questions outnumber answers, and one of the purposes of the meeting was to gather some of the best experts in the field to consider the current state of knowledge, ascertain which questions remain to be addressed, and identify the most promising approaches to addressing those questions. The purpose of this report is to document that discussion. Throughout the planet's first billion years, planetary-scale processes—including differentiation, hydrodynamic escape, volcanism, large impacts, erosion, and sedimentation—rapidly modified the atmosphere and crust. How did these processes operate, and what were their rates and interdependencies? The early environment was also characterized by both abundant liquid water and plentiful sources of energy, two of the most important conditions considered necessary for the origin of life. Where and when did the most habitable environments occur? Did life actually occupy them, and if so, has life persisted on Mars to the present? Our understanding of early Mars is critical to understanding how the planet we see today came to be. Key Words: Early Mars—Noachian—Volatiles—Habitability—Water—Geologic evolution. Astrobiology 5, 663–689.

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INTRODUCTION

One hundred thirty-seven planetary and terrestrial scientists participated in the "Second Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life," which was held in Jackson Hole, WY, October 11–15, 2004 (see http://www.lpi.usra.edu/meetings/earlymars2004/). The scientific content of this conference derived from the enormous influx of new data from the Mars Exploration Rovers (MERs), Mars Express, and other recent spacecraft missions. It also stemmed from progress in early climate modeling, advances in the understanding of martian meteorites, growing evidence of the role of water in the planet's evolution, and the rapid pace of new discoveries about the origin and diversity of life on Earth. This progress has reinvigorated interest in both the conditions that prevailed on Mars during its first billion years of geologic history and their possible implications for the development of indigenous life. The conference sessions were structured to promote the identification, discussion, and debate of the key scientific questions relating to this era, a summary of which is presented here as the formal conference report.

Why focus on early Mars? Because during this period (whose duration is poorly constrained but believed to have extended from planetary formation at about 4.6 Ga to about 3.7 Ga), the planet accreted from the solar nebula, differentiated, developed a hemispheric crustal dichotomy, experienced significant volcanism and impact cratering, formed an atmosphere, developed an active hydrosphere (that included sizable bodies of surface water), and may have even given rise to life. Following this initial period of intense activity, the planet is believed to have transitioned to a less dynamic state, one that has persisted to the present day. The early Mars time period encompasses what is formally known as both the Noachian Period, when the earliest exposed rocks were formed, as well as the older "pre-Noachian" time (Table 1). The early Mars time period, at least as we are using it in this report, concluded in the Late Noachian and appears to have coincided with the decline in the heavy bombardment phase of the inner solar system (roughly 3.8–3.7 Ga), though whether these events were related is presently unclear.

TABLE 1. MARTIAN GEOCHRONOLOGY

Martian epoch	*Approximate age (Ga)*[a]
Late Amazonian	0.45–present
Middle Amazonian	1.75–0.45
Early Amazonian	3.1–1.75
Late Hesperian	3.6–3.1
Early Hesperian	3.7–3.6
Late Noachian	3.8–3.7
Middle Noachian	3.9–3.8
Early Noachian	4.1–3.9
Pre-Noachian	4.6–4.1

The geochronology here follows that of Tanaka (1986), Hartmann and Neukum (2001), Frey (2005), and Nimmo and Tanaka (2005).

[a]Absolute age of all boundaries is uncertain. Uncertainty of Noachian boundaries is probably <0.2 Ga, but increases to approximately ±0.35 Ga for the Early/Middle Amazonian boundary and is approximately ±0.15 Ga for the Middle/Late Amazonian boundary.

Perhaps the single greatest reason scientists find this early period of martian geologic history so compelling is that its dynamic character may have given rise to conditions suitable for the development of life, the creation of habitable environments for that life to colonize, and the subsequent preservation of evidence of those early environments in the geologic record. But beyond the question of life, understanding the conditions that prevailed on early Mars is also likely to provide important clues with regard to how the Mars we see today came to be. In this respect, Mars may also provide critical insight into understanding the nature of the early Earth. As much as 40% of the martian surface is believed to date back to the Noachian (Tanaka *et al.*, 1988), but this period is barely represented in the Earth's geologic record, as those few exposures that have been identified from that time are highly metamorphosed (*i.e.*, with uncertain preservation of original texture and chemistry). Since Earth and Mars are Solar System neighbors, they undoubtedly shared certain early (pre-3.7 Ga) processes, and studies of Mars may provide essential clues for our home planet.

KEY QUESTIONS

During the 2nd Early Mars Conference, many dozens of scientific questions, at many different levels of detail, were identified by the participants. After compilation, the organizers found that these ideas could be grouped into 12 relatively broad questions (Table 2). Obviously,

TABLE 2. TOP SCIENCE QUESTIONS RELATED TO EARLY MARS

A	What was the nature of the early martian planetary environment?
A1	How did the formation, initial composition, and differentiation of early Mars affect the evolution of its crust, mantle, and core?
A2	What was the cratering rate on Early Mars, and how did it evolve with time?
A3	What were the principal resurfacing processes and rates on Early Mars, and why did they later decline with time?
B	How did the early martian atmosphere and hydrosphere form, and what role did they play in the geologic and mineralogic evolution of the planet's surface?
B1	Was Mars volatile-rich at the time of its formation, especially with regard to the initial abundance of water and CO_2?
B2	What were the principal mechanisms (and associated magnitudes) of volatile loss on early Mars?
B3	Did oceans or large seas exist on early Mars, and, if so, what was their significance and ultimate fate?
B4	What was the nature of the early martian atmosphere and climate, and how did they evolve with time?
B5	What conditions and processes gave rise to the valley networks, and what were their discharge rates, durations, and continuity of flow?
B6	How was the chemistry and mineralogy of the early martian crust influenced by atmospheric, surface, and subsurface processes?
C	Did life arise on early Mars?
C1	Did life develop on early Mars, either through seeding by meteorite transport from Earth, or by an independent genesis?
C2	Were habitable environments present on early Mars?
C3	If life appeared on Mars, and has subsequently gone extinct, is its record preserved?

These questions are as identified by the participants of the 2nd Conference on Early Mars, held in Jackson Hole, WY, in October 2005. They are not in priority order.

within each of these more general questions, there is a wealth of interesting secondary questions, and these will be the focus of exciting scientific investigation for years to come. Although an attempt was made to place the 12 primary questions in a sequence of relative priority, it was not possible to achieve a satisfactory consensus—scientists from different subdisciplines see things differently, and with equal merit.

Broad-scale questions, like those identified in Table 2, are often difficult to address directly, but they can often be broken down into more specific questions that are amenable to investigation.

Group A. What was the nature of the early martian planetary environment?

A1. How did the formation, initial composition, and differentiation of early Mars affect the evolution of its crust, mantle, and core? Many of the questions about early Mars begin with the formation, differentiation, and initial igneous evolution of the planet. To date, the greatest insights into this evolution have come from study of the martian meteorites (of which about 30 are currently known), actual samples of the planet's crust that have given scientists the opportunity to apply a vast array of detailed analytical measurements. These studies are limited, however, by the fact that the martian meteorites are few in number and appear to represent only a portion of the planet's crust. Thus, the results of the meteorite studies should be viewed, when possible, in the more extensive geologic context of Mars inferred from orbital and *in situ* measurements (and *vice versa*).

Prior to the discovery that the Shergotty-Nakhlite-Chassigny (SNC) suite of meteorites were from Mars, questions with regard to the initial composition, differentiation, and formation of Mars were beyond our ability to address. Radiometric age determinations for these meteorites, primarily Rb-Sr analyses, yielded surprisingly young ages (~175 Ma) (*e.g.*, Nyquist *et al.*, 1979), a finding that was interpreted as evidence that they originated from impact metamorphism on a large terrestrial planet, such as Mars. Once the compositional similarities between the SNC meteorites and martian surface were recognized (*e.g.*, Bogard and Johnson, 1983), a wealth of information soon followed. The major and trace element systematics were examined in detail, and it was soon discovered that, relative to Earth and Moon, Mars is rich in moderately volatile elements such as the alkali metals and halogens (Dreibus and Wänke, 1985). It also became apparent that the source regions of the meteorites are characterized by elevated Fe and depressed Al abundances, which suggests fundamental differences in either the bulk composition of Mars or the existence of an, as yet, poorly understood fractionation process. As more Rb-Sr isotopic measurements were completed on the SNC meteorites, it became apparent that the source regions from which they were derived formed very early in the history of the planet (Shih *et al.*, 1982). However, the exact time at which these source regions formed and the mechanisms by which they formed, as well as the role that they played in the broader geochemical evolution of Mars, were not well understood.

A more coherent view of Mars began to emerge once it was suggested (Jones, 1989) and demonstrated (Borg *et al.*, 1997) that the radiometric ages of the martian meteorites represented crystallization ages. As noted previously, the current picture of Mars is one of a planet that had an early, short-lived dynamic history followed by a period of more modest activity. The discovery that young martian rocks have isotopic anomalies produced by the decay of now extinct nuclides (Harper *et al.*, 1995; Lee and Halliday, 1997) supports previous studies that required planetary geochemical reservoirs to form when these systems were still active. Short-lived chronometers, such as ^{182}Hf $\rightarrow$ ^{182}W ($t_{1/2}$ = 9 Ma) and ^{146}Sm $\rightarrow$ ^{142}Nd ($t_{1/2}$ = 103 Ma), are now interpreted to indicate that core formation occurred within 10 or so Ma (Foley *et al.*, 2005) of planetary accretion, whereas silicate differentiation occurred 20–60 Ma after planetary accretion (Borg *et al.*, 2003). This means that the geochemical reservoirs (core, mantle, and at least a primordial crust) were in place on Mars very early.

This dynamic early history of Mars is somewhat at odds with the abundance of martian meteorites with ages of 165–1300 Ma. Most of these meteorites are derived from compositionally distinct sources and therefore require numerous individual melting events to have occurred within the most recent past. This observation suggests that magmatic activity on Mars is almost certainly occurring at present. Interestingly, the observation that young martian rocks were produced from these reservoirs in the last 165 Ma requires them to have remained isolated from one another over most of martian history. Thus, large-scale mixing processes, such as plate tectonics and giant impacts, have not homogenized the martian mantle. Furthermore, mineralogical, geochemical, and isotopic differences between the meteorites suggest that they are derived from a range of sources. In general, these can be characterized, at one end, as reduced and depleted in incompatible elements, and, at the other, as oxidizing and relatively enriched in incompatible elements. Thus, these reservoirs are in many ways analogous to mantle and crustal reservoirs observed on the Earth and Moon.

Despite our having developed a fairly broad and cohesive picture of early martian geochemical evolution, many questions remain. These questions can be broken down into several broad categories. The first concerns the earliest period of martian history, focusing specifically on the mechanisms by which the crust, mantle, and core formed and evolved. Central to this question are the constraints that can be placed on the first 100 Ma of geologic history, the role of water during early planetary differentiation, the relative importance and extent of communication between water reservoirs in the mantle and the crust, determining whether Mars had a magnetic field, and whether plate tectonics was ever active.

The second category of questions addresses how and when the products of differentiation interacted. This includes assessments of the bulk composition of Mars and how elements were partitioned into various geochemical reservoirs, assessing how representative the martian meteorites are in constraining geologic processes, defining the oxidation state of the crust and mantle and determining whether it changed as a function of time and space, and constraining the processes by which planetary geochemical reservoirs interacted to produce the compositional variability seen in martian rocks.

The final category is concerned with the thermal environment of Mars. This includes the history of heat flow from the interior, the nature and variations of the heat sources for martian magmatism through time, and determining whether hydrothermal systems were present on Mars and, if so, what their basic characteristics (*e.g.*, temperature and composition) were.

A2. What was the cratering rate on early Mars, and how did it evolve with time? The relative age of an exposed surface on Mars can be determined by comparing the number of craters, with diameters greater than some minimum size, that are present per unit area. However, to translate this relative age to an "absolute" chronology, knowledge of the cratering rate, and its variation with time, is needed. This is necessary not only to establish when specific events (*e.g.*, like the Hellas impact) occurred, but also to quantify the rates of various processes, like erosion and deposition. However, our understanding of the present Martian cratering rate is not well constrained and even less so for the past.

Although it is generally accepted that the early cratering rate was much higher than the present, having undergone an exponential decline during accretion, its exact rate at any given time and how it changed over time are unknown. Therefore attempts to develop an absolute chronology for Mars have relied on the scaling of lunar crater counts and surface ages, as determined from the radiometric ages of rock samples returned by the Apollo astronauts. Such scaling assumes that the orbital dynamics and velocities exhibited today by Earth- and Mars-crossing asteroids are similar to what they were earlier in the Solar System's history. The most recent attempt to derive the correct scaling relationship between lunar and martian crater counts is reflected in the chronology proposed by Hartmann and Neukum (2001). This model has been used to determine "absolute" ages (Table 1) for the martian stratigraphic boundaries identified by Tanaka (1986). Based on this approach, the boundary between the Early and Middle Noachian has an age of 3.92 Ga, the boundary between the Middle Noachian and Late Noachian is 3.82 Ga (Nimmo and Tanaka, 2005), and the age of the boundary between the Late Noachian and Early Hesperian is about 3.70 Ga. These ages are uncertain by as much as ±0.2 Ga, a level of uncertainty that increases to as much as ±0.35 Ga for the boundary between the Late Hesperian and Early Amazonian (W.K. Hartmann, 2002, personal communication).

The discovery of a very large population of what appear to be buried impact basins (H.V. Frey *et al.*, 2002) has demonstrated several important, but previously unknown, things about early Mars: (1) Buried crust exists on Mars that is significantly older (in terms of crater retention ages) than the oldest Early Noachian surfaces exposed elsewhere on the planet (Frey and Frey, 2002; E.L. Frey *et al.*, 2002). (2) This "pre-Noachian" period (Frey, 2003, 2005; Nimmo and Tanaka, 2005) was a time of intense cratering, including the formation of very large (>1,000 km in diameter) impact basins, and substantial resurfacing, as evident from the fact that even the oldest surface units have a population of buried craters. The model absolute age for the boundary between the Early Noachian and pre-Noachian is ~4.1 Ga (Frey, 2005; Nimmo and Tanaka, 2005). This implies that the early cratering rate was substantially higher than previously believed, though it is impossible to say exactly how much higher because we are likely seeing only a portion of all the "pre-Noachian" craters that were formed. This is due to our inability to detect all buried craters and the likely possibility that the cratering record might have become saturated.

The discovery of a buried impact population, in addition to a visible crater population, has provided a more complete chronology of events on early Mars. But there seems to be no real prospect of determining the absolute ages of these events to an accuracy better than that already known until radiometric dating of actual surface materials can be done. It is hoped that the first opportunity to conduct such measurements will occur within the next decade, with the flight of the first sample return mission to Mars.

A3. What were the principal resurfacing processes and rates on early Mars, and why did they later decline with time? Resurfacing activity, dominated by impact, volcanic, fluvial, mass-wasting, and aeolian processes during the Noachian, modified the early crust to a much greater extent than occurred during all of subsequent martian history. This suggests a comparatively rapid decline in geologic activity, which was likely driven by the combined effects of a declining crustal heat flow, impact flux, and a possible change in climate at the end of this period (Tanaka *et al.*, 1988; Hartmann and Neukum, 2001; Craddock and Howard, 2002). Large exposures of stratigraphic layering observed in high-resolution Mars Orbiter Camera images of ancient cratered terrains demonstrate that the burial of Noachian surfaces was extensive (Malin and Edgett, 2001, 2003). High erosion rates during the Noachian are also supported by degraded crater morphologies (*e.g.*, Craddock and Maxwell, 1993) and the higher density of fluvial networks (Hynek and Phillips, 2003).

However, many aspects of the conditions and processes involved in Noachian resurfacing remain unresolved. Perhaps the most fundamental question is: How did the evolution and interaction of thermal, impact, and atmospheric processes drive resurfacing on early Mars?

What specific mechanisms were responsible for the high rates of erosion that apparently characterized this period? Among the leading candidates are snow and rain, which require a thicker and perhaps occasionally warmer atmosphere. However, hydrothermal circulation induced by magmatism and impacts may have been important as well. Numerous subordinate issues also need to be addressed. For example, what is the origin of the numerous exposures of Noachian layered materials? Can we identify sedimentary deposits that are more likely to preserve evidence of past life, such as carbonates, shales, or evaporites? Finally, how rapidly did resurfacing rates decline at the end of the Noachian? What processes were involved and how did they vary spatially? New data sets, geological and mineralogical mapping, modeling of potential processes and conditions, and laboratory and analog studies offer promising new approaches to these questions.

Group B. How did the early martian atmosphere and hydrosphere form, and what role did they play in the geologic and mineralogic evolution of the planet's surface?

B1. Was Mars volatile-rich at the time of its formation, especially with regard to the initial abundance of water and CO_2? What was the original volatile inventory of Mars? How did it compare with the inventories of Earth and Venus? And how did it evolve with time?

From the perspective of the origin and evolution of Mars' atmosphere and surface, the most important volatiles are water, carbon, nitrogen, and sulfur. The large depletion of noble gases on Mars relative to solar abundance indicates that when Mars formed it did not accrete gases directly from the solar nebula, but rather in the form of solids. For example, water would have been acquired in the form of water ice or water of hydration bound in silicate minerals, and carbon would have been acquired mainly as solid hydrocarbons.

But did Mars obtain volatiles mainly during planetary accretion or during subsequent impact bombardment from asteroids or comets? Simulations of the formation of planets suggest that Earth acquired much of its water from large "planetary embryos" that accreted in the asteroid belt between the orbits of Mars and Jupiter before they were ejected by the gravitational influence of Jupiter toward Earth or outward from the Sun. Comets are ruled out as the major source of Earth's oceans on isotopic and dynamical grounds (Zahnle, 1998). In contrast, explaining the relative smallness of Mars requires either that it accreted from a nebular region of unusually low density (Chambers, 2001) or that it suffered essentially no collisions with planetary embryos and grew through smaller asteroidal bodies that accreted later (Lunine *et al.*, 2003). If the latter is correct, Mars might be considered a remnant planetary embryo. This means that Mars may have started out with a much smaller fraction of volatiles than Earth did (Lunine *et al.*, 2003). However, an alternative school of thought argues that Mars and Earth acquired volatiles from local planetesimals in a cold nebula, which would argue that both bodies possessed a similar volatile fraction (Drake and Righter, 2002).

The earliest, primitive atmosphere of Mars may have been hydrogen-rich, but the duration of this hydrogen-rich atmosphere remains an open question. The source of hydrogen would have been volcanism, which would have been much more active than today because the early mantle had a higher content of radioactive elements. During the Early Noachian, the upper atmosphere was heated by high fluxes of extreme ultraviolet radiation from the young sun. (Although the young sun was fainter than today overall, astronomical observations and theory show that young stars have much greater output of extreme ultraviolet radiation.) Such an atmosphere would have been prone to hydrodynamic escape of hydrogen (see below), which would have dragged away heavier gases, such as CO_2 and N_2. The length of time that hydrodynamic escape persisted depends on the amount of hydrogen in the early atmosphere, which, in turn, depends on the timing of core formation. Very early core formation could have separated free iron from incoming volatiles, which would have allowed the latter to be released relatively slowly from the mantle and retaining H mainly as H_2O. However, later core formation, with incoming volatiles mixing with free iron, would have allowed water to oxidize iron, which would have released hydrogen to the atmosphere and produced several hundred million years of hydrodynamic escape. Exactly how long hydrodynamic escape could have lasted is important because, if it was for a significant period of time, comets arriving after the completion of hydrodynamic escape may have brought in most of the atmospheric volatiles in the current inventory. Hafnium-tungsten isotopes in meteorites suggest that the martian core formed within 7–15 million years of the formation of the oldest Solar System remnants (Kleine *et al.*, 2004), which are 4.567-Ga Ca-Al-rich inclusions in chondritic meteorites. Consequently, a hydrogen-rich atmosphere may have been more short-lived than usually assumed. On the other hand, if the mantle of Mars remained relatively reducing (Wadhwa, 2001), hydrogen-rich volcanic gases might have persisted long after core formation.

The initial inventory of H_2O on Mars is uncertain because we do not know how much water exists in the subsurface or how much has been lost over time. Estimates of the H_2O inventory have been derived based on both geochemical and geomorphological arguments. Dreibus and Wänke (1987) suggested that during the accretion of Mars, H_2O would have oxidized metallic iron, which would have released hydrogen into the atmosphere and space. At the end of accretion, they suggest that the only H_2O retained by Mars was the H_2O that was present in its mantle, which they estimated to be equivalent to a global layer of water ~130 m deep. They further estimated that, of this mantle inventory, only a small fraction—of the order of 10 m—was ever released to the surface. However, the regolith of present-day Mars could be much wetter if the reaction of H_2O with metallic iron was less than 100% efficient or if the planet gained a late veneer of water from impacts after core formation. Evidence for a large inventory of H_2O is provided by a long list of martian landforms whose morphology has been attributed to the existence of ground ice and groundwater (Carr, 1986; Squyres *et al.*, 1992). In particular, a larger inventory is supported by the existence of the outflow channels, whose distribution, size, and range of ages suggest that a significant body of groundwater has been present on Mars throughout much of its geologic history (Tanaka, 1986; Carr, 1986; Baker *et al.*, 1992). Based on a conservative estimate of the discharge required to erode the channels, and the likely extent of their original source region, Carr (1986) estimated that Mars may possess a crustal inventory of water equivalent to a global ocean 0.5–1 km deep. This compares with a terrestrial global inventory of ~2.6 km of water, contained primarily in the Earth's oceans and ice sheets.

Mars' initial bulk inventories of CO_2, N_2, and sulfur can be estimated on geochemical grounds. The Earth is estimated to have stored the equivalent of 60–90 bars of CO_2 in carbonate rocks. If this CO_2 were all released, Earth's atmosphere would be similar to that of Venus. Mars, scaling by its relative mass, may have had an original inventory of no more than ~9 bars of CO_2, assuming that its volatile fraction was similar to Earth's. However, most of Mars' initial endowment of CO_2 appears to have vanished. With a surface area of $\sim 10^5$ km^2 and a thickness between 1 and 100 m, the residual south polar cap contains no more than 0.6–60% as much CO_2 as the atmosphere. The regolith on Mars contains an unknown amount of adsorbed CO_2, but probably <0.04 bar (Kieffer and Zent, 1992). Martian meteorites contain <0.5% carbonate salts by volume, which, when scaled to the crust provide <0.25 bar of CO_2 equivalent/km depth (Bridges *et al.*, 2001). Also, taken at face value, there is no evidence from remote spectroscopy that even a single carbonate outcrop exists on Mars (Christensen *et al.*, 2001). Thus, the current CO_2 inventory of Mars is perhaps a few times 0.1 bar, which, to the nearest order of magnitude, is ~0.1% of the original estimated inventory.

Similarly, the current atmospheric N_2 inventory is merely 1.6×10^{-4} bar, compared with 0.78 bar and 3.3 bars of N_2 in the atmospheres of Earth and Venus, respectively. Nitrogen could perhaps exist on Mars as nitrate minerals. However, nitrates are largely absent from martian meteorites (Grady *et al.*, 1995), and the absence of any spectral evidence for nitrates on the surface does not lend much credence to the speculation that Mars has abundant nitrates. We can also consider the ratio of nitrogen to carbon. This ratio (~1–3%) is about the same for Earth, Venus, and Mars (assuming no hidden carbonate or nitrate reservoirs on Mars). But, whereas the ratio of the mass of the volatiles to the planetary mass is ~0.01% for Earth and Venus, it is only 0.000005% for Mars. The simplest explanation is that Mars has lost carbon dioxide and nitrogen with equal efficiency, so that the nitrogen to carbon ratio has remained the same, but the volatile inventory has been greatly diminished. Impact erosion and hydrodynamic escape (see below) are plausible loss mechanisms that would remove volatiles en masse.

The initial volatile inventory suggested above is corroborated by considering the stable and most abundant isotope of krypton, ^{84}Kr, which is an excellent volatile tracer because it should not be subject to fractionation by gradual atmospheric escape of the kind that occurs today for hydrogen, nitrogen, carbon, and oxygen (Owen and Barnun, 1995). Thus, krypton has probably been retained ever since the end of heavy bombardment around ~3.5–3.8 Ga. The ratio C/^{84}Kr is $\approx 4 \times 10^7$ for Earth and Venus, but $\approx (4.4–6) \times 10^6$ on Mars. This suggests that the amount of CO_2 that Mars had when heavy bombardment and impact erosion ended was 10 times greater than now (*i.e.*, a 90% loss, consistent with isotopic fractionation of nitrogen). Given that Mars has ~6 mbars of CO_2 now, the Kr abundance implies that around 3.5 Ga the atmosphere may only have had ~60 mbars of CO_2. In addition, the amount of ^{84}Kr/kg on Mars is only about 1% of that on Earth. This implies a factor of ~100 depletion (of both krypton and carbon) due to early atmospheric loss before 3.5–3.8 Ga, which is consistent with the predictions of impact erosion models. A primordial inventory of ≥6 bars CO_2 would be inferred, consistent with inferences about Mars' original endowment of volatiles on geochemical grounds.

One of the key volatiles mentioned above, sulfur, is unstable in a wet early martian atmosphere because its final form, SO_2, is soluble. Nonetheless, did sulfur play an important role in the early atmosphere of Mars because of a large flux to the atmosphere? Large amounts of sulfur are thought to have been introduced by volcanism, particularly when Tharsis was forming during the late Noachian and Hesperian. Martian meteorites are approximately five times as rich in sulfur as in water, and it is possible that martian volcanic gases are richer in sulfur than water, in stark contrast to terrestrial volcanic gases (Wänke and Dreibus, 1994). SO_2 might not be considered a viable greenhouse gas for warming early Mars with an active hydrological cycle because SO_2 is highly soluble and would rain out. However, if Mars were cold and dry, yet volcanically active, it is plausible that SO_2 could have poised the climate at subzero Celsius temperatures in a negative feedback with low temperature eutectic brines and acid-sulfate weathering. Any warming perturbation (for example, impact-generated warmth) would have produced H_2SO_4-rich brines and sulfate salts, consistent with abundant sulfate salts observed on Mars. Clearly, the role of sulfur in the early atmosphere warrants further study.

B2. What were the principal mechanisms (and associated magnitudes) of volatile loss on early Mars? Loss mechanisms for atmospheric volatiles can be divided into two groups: loss to space or loss to surface minerals. For Mars, both theory and isotopic evidence strongly suggest that there was significant escape to space, whereas the degree to which volatiles were lost into minerals remains an open question.

Martian volatiles can escape to space in the following ways: impact erosion, hydrodynamic escape, sputtering, thermal escape, and non-thermal escape. Impact erosion and hydrodynamic escape would have been important processes only on very early Mars. The other processes have likely dominated in the last 4 Ga or so.

Impact erosion occurs when the hot vapor plume from a large impact heats atmospheric molecules so that they exceed escape velocity. Modeling suggests that Mars was prone to atmospheric impact erosion and that this process alone could have reduced the mass of the early atmosphere by a factor of ~100 (Melosh and Vickery, 1989). Thus, if Mars started with a ~6 bar atmosphere after accretion, it may have been depleted to only 0.06 bar by ~3.8–3.5 Ga, when the early bombardment had subsided. Evidence for impact erosion comes from the martian $^{40}Ar/^{36}Ar$ and $^{129}Xe/^{132}Xe$ ratios. The primordial gases ^{36}Ar and ^{132}Xe appear to have been lost early in the planet's history, whereas the enrichment of ^{40}Ar and ^{129}Xe, which result from the decay of radioactive ^{40}K and ^{129}I, respectively, is consistent with accumulation of these radiogenic isotopes after early atmospheric loss.

Hydrodynamic escape applies to a hydrogen-rich primitive atmosphere, which likely existed from 4.5 Ga to some later time that is poorly determined (see Question B1 above). Hydrodynamic escape occurs when the typical thermal energy of a gas in the upper atmosphere becomes comparable to the gravitational binding energy and the atmosphere expands into the vacuum of space, analogous to the solar wind. Heavy atoms are dragged along through collisions with hydrogen atoms. This leads to the loss of heavy gases and isotope fractionation. The noble gases on Mars display isotopic patterns that are consistent with fractionation by early hydrodynamic escape [*e.g.*, Mars' $^{36}Ar/^{38}Ar$ ratio of <3.9, compared with a terrestrial ratio of 5.32 and the average carbonaceous chondrite value of ~5.3 (Bogard *et al.*, 2001)]. By inference, major gases, such as CO_2 and N_2, should have also been lost through this process. A key question is whether hydrodynamic escape was more important than impact erosion. This depends on how long hydrodynamic escape persisted on early Mars.

Sputtering, or stripping by the solar wind, occurs when ions in the upper atmosphere are "picked up" by magnetic fields generated by the flow of the solar wind around the planet. Solar wind stripping would have been prevented by the presence of a substantial global magnetic field on early Mars, which would have forced the solar wind to flow around the planet at a greater distance, without significant atmospheric interaction. Thus, sputtering would have only been important after Mars lost its global magnetic field. The field probably disappeared some time before ~4 Ga, but an important question is when.

Thermal escape is when atoms at the base of the exosphere (~230 km altitude) are warm enough to escape, *i.e.*, there is a sufficient population above the escape velocity in the tail of the Maxwell-Boltzmann velocity distribution so that atoms are easily depleted. This is important today for hydrogen. However, *non-thermal escape* allows oxygen, nitrogen, and carbon to escape also. Ionized molecules (*e.g.*, O_2^+) in the ionosphere combine with electrons in "dissociative recombination," which dissociates the molecules into atoms with enough kinetic energy to escape ($O_2^+ + e^- \rightarrow O + O$). Such loss mechanisms have probably been important in the last 4 Ga of martian history and can account for observed isotopic ratios on Mars (*e.g.*, $^{15}N/^{14}N$). Effectively, water escapes because hydrogen and oxygen are both lost. However, the rate of water escape is so slow that if it had been constant over the last 4.5 Ga, the loss would only be equivalent to a global layer of water ~2.5 m deep.

Isotopic enrichment in N and C combined with modeling indicates a loss of 50–90% of the atmospheric species to space since ~4 Ga due to sputtering and non-thermal processes (reviewed by Jakosky and Jones, 1997; Jakosky and Phillips, 2001). Atmospheric losses are cumulative. For example, if impacts and hydrodynamic escape removed 99% of the earliest atmosphere and sputtering removed 90% of the remainder, the total loss would be 99.9%.

Surface sinks occur mainly in the presence of liquid water. For example, CO_2 will dissolve to form carbonic acid, react with the surface through chemical weathering, and precipitate as carbonates (*i.e.*, $CO_2 + CaSiO_3 = CaCO_3 + SiO_2$). Similarly, SO_2 will react with water and rocks to form sulfates. While sulfates are clearly abundant on the surface of Mars, so far there is no spectral evidence of even a single carbonate outcrop. The amount of sulfate and carbonate that has been sequestered into the subsurface is also unknown.

Among the key questions to emerge from the above are: How important was hydrodynamic escape relative to impact erosion for volatile loss? When did Mars lose its global dipole field and become subject to sputtering loss? What is the ratio of volatile loss from escape to volatile loss to surface minerals? And, finally, where are the minerals that sequestered volatiles (carbonates, nitrates, and sulfates), and what is their total mass? The answers to these questions will require new modeling studies and the acquisition of paleomagnetic and compositional data from a variety of locations on the planet's surface.

B3. Did oceans or large seas exist on early Mars, and, if so, what was their significance and ultimate fate? Given the estimated size of the martian inventory of H_2O (equivalent to a global layer of water 0.5–1 km deep), the superficial resemblance of the planet's northern plains to an ocean basin, and the many large outflow channels that flow into the northern plains from the southern highlands, is there any evidence that oceans or other large standing bodies of water were ever present on the surface? Attempts to answer this question have relied on observations of martian landforms, regional topography, and geochemistry that have been cited as being analogous to large former standing bodies of water here on Earth. In this regard, plains boundaries and associated landforms around the northern lowlands (visible in Viking Orbiter images) have been described and variously interpreted as possible ice-sheet-related landforms at or near the margin of an ice-covered ocean (Lucchitta *et al.*, 1986), as wave-eroded shorelines (Parker *et al.*, 1989), or as frontal features associated with a catastrophically emplaced "mud ocean" (Jöns, 1990).

Although the question of as to whether an ocean even existed on Mars has not been settled, evidence in support of this possibility appears to be growing. Perhaps the most significant advance in addressing this question has been the global elevation measurements acquired by the Mars Orbiter Laser Altimeter (MOLA), which has provided a several orders of magnitude improvement in topographic accuracy and spatial resolution over what was known from Viking and Mariner 9. The MOLA data revealed that many of the suggestive landforms identified in earlier Viking-based studies as potentially indicative of shorelines fall within narrow ranges of elevation—possibly defining an equipotential surface, an observation that is consistent with erosion by a fluid in hydrostatic equilibrium (Head *et al.*, 1998, 1999; Webb, 2004). Additional evidence for an ancient ocean is hinted at by the presence of what appear to be broad, degraded erosional terraces around the highlands margin (Parker, 2005).

In many places, these terraces appear to be cut, not only into the sloping highland margin, but also into large craters along the margin. These craters exhibit infilling to the same elevation, despite the fact that they are otherwise unrelated.

If the presence of a former ocean on Mars can be established, during what period (or periods) of martian history did it occur? The landforms identified by Lucchitta *et al.* (1986), Jöns (1990), and Parker *et al.* (1989) lie entirely within the northern plains of Mars and, based on crater counting of the plains surfaces to either side of them, probably date to the Late Hesperian/Early Amazonian. Until recently, this observation led to the widespread belief that, if an ocean ever occupied the northern plains, it probably resulted from the discharge of the outflow channels and thus would have first appeared about midway through Mars's geologic history. However, Clifford and Parker (2001) have argued that the former presence of an ocean can be deduced independently by considering the hydraulic conditions required to explain the origin of the outflow channels, and extrapolating them backwards in time. This analysis suggests that an ocean on Mars (as on Earth) was almost certainly an initial condition, having condensed shortly after the planet formed.

The basis for this argument is that when the outflow channels were most active [during the Late Hesperian and Early Amazonian (Tanaka, 1986; Hartmann and Neukum, 2001)], their source regions in the southern highlands stood some 4 km above the lowest point in the northern plains. Thus, much of the planet's inventory of groundwater was stored at high elevations. Such a state is possible as long as the groundwater is confined beneath a thick layer of frozen ground, a natural consequence of the extremely cold climatic conditions that are thought to have characterized this period of time.

But earlier in Mars's history, a substantially higher geothermal heat flow would have resulted in a substantially thinner hydraulic barrier of frozen ground, which makes the confinement of an elevated water table highly unlikely. If the current crustal dichotomy dates back to this era, then it implies that a primordial ocean, up to several kilometers deep and covering as much as a third of the planet, would have occupied the northern plains. Indeed, there is some evidence that indicates that such an ocean may have covered as much as 50% of the planet's surface. This evidence consists of the tentative identification of higher-elevation terraces that lie tens to hundreds of kilometers further into the Late Noachian cratered highlands then the most extensive shorelines inferred from the earlier Viking-based investigations (Parker, 2005). If these interpretations are correct, then it suggests that many other low-lying areas, such as the Argyre and Hellas impact basins, must have hosted interior lakes and seas as well.

In response to the long-term decline in planetary heat flow, the progressive cold-trapping of H_2O into the polar regions and the pore volume of the growing thickness of frozen ground are expected to have created a large thermodynamic sink for any surface or groundwater—which potentially explains the eventual disappearance of the ocean and the apparent decline in outflow channel activity later in the planet's history.

B4. What was the nature of the early martian atmosphere and climate, and how did they evolve with time? The evidence for fluvial activity on the surface of early Mars is compelling. Valley networks, high erosion rates, and the recently discovered ancient sulfate deposits all argue for the presence of substantial quantities of liquid water. Thus, somehow the environmental and climatic conditions on early Mars must have been much different than they are today. But what were those environmental conditions? Specifically, was early Mars' continuously warm and wet conditions sustained by a long-lived greenhouse effect? Or were the necessary conditions produced episodically by impacts, volcanism, or a combination of the two?

A common approach to this vexing problem has been to invoke an early Mars atmosphere that generated a strong enough greenhouse effect to support an active hydrological cycle with rainfall and runoff. To appreciate the magnitude of the problem, however, consider what it would take to raise global mean surface temperatures on Mars to the melting point of water (273K) 3.8 Ga when solar luminosity was 75% of what it is today. A measure of the greenhouse effect is the difference between the planet's effective radiating temperature and its actual surface temperature. Today, this difference is ~5K. On early Mars, the atmosphere would have had to provide 77K of greenhouse warming to have raised global mean surface temperatures to the melting point of water. This means that the atmosphere would have had to absorb ~85% of the radiation emitted by the surface (for a review, see Haberle, 1998). This is a major challenge for greenhouse theories.

A popular view for the mass and composition of the early Mars atmosphere is that it consisted of CO_2 and H_2O with surface pressures as high as 5 bars. Such an atmosphere was initially thought to be capable of sustaining liquid water on the surface for extended periods of time (Pollack *et al.*, 1987), but the lack of any detectable carbonate outcrops from remote sensing observations is problematic. Furthermore, CO_2 ice clouds would form in such an atmosphere and limit the greenhouse effect by changing the thermal structure of the atmosphere through the release of latent heat (Kasting, 1991). This effect could be mitigated if the CO_2 clouds were global and the particles grew big enough to create an infrared scattering greenhouse (Forget and Pierrehumbert, 1997). However, the warming effect is limited by a negative feedback between cloud formation and surface temperature (Colaprete and Toon, 2003), and full three-dimensional general circulation models find it challenging, although not impossible, to create planet-wide surface temperatures above freezing (Forget *et al.*, 2004).

Alternative greenhouse gases are ammonia (NH_3), methane (CH_4), and sulfur dioxide (SO_2), but each has significant problems. NH_3 is rapidly and irreversibly photolyzed to N_2 and H_2, and would therefore require some kind of shielding to be effective (Sagan and Chyba, 1997). For methane to work as a greenhouse gas, high concentrations of it would have been required. Global mean surface temperatures above freezing could have been maintained by an atmosphere containing several bars of CO_2 and ~1% CH_4 (Kasting, 2002). While there are abiotic sources of methane (serpentinization of ultramafic rocks), concentrations this high are most easily achieved by methane-producing bacteria. High concentrations of SO_2 ($>10^{-3}$ ppmv) are also required to produce significant greenhouse warming (Postawko and Kuhn, 1986). Here, the problem is not the source because volcanic emissions could easily supply this much SO_2. Instead, SO_2 is a highly soluble gas and is rapidly converted to sulfates if oxygen is available.

The alternative to having a sustained continuous greenhouse effect is episodic climate change brought about by impacts and/or brief periods of intense volcanism. Both processes were particularly active early in Mars' history. The climatic consequences of brief periods of intense volcanism on early Mars have not yet been quantitatively explored. One could imagine that the climate could easily have been altered following a violent outgassing event, but in what direction that change would have taken the planet's climate conditions is uncertain. On Earth, for example, volcanically emitted SO_2 is converted to sulfate aerosols in the stratosphere, which has a cooling effect. Impact-generated climate change, on the other hand, has received some attention.

Large impacts are capable of delivering enormous amounts of energy to the planet's surface, ranging from ~10^{24} J to produce a crater 250 km in diameter up to almost 10^{27} J for a 2,000-km-diameter impact basin. The effects of such a large and sudden energy input have been investigated by Segura *et al.* (2002), who found that the vaporization of impactor and target material, combined with the atmospheric and surface heating associated with the fallout of the resulting debris, could melt and vaporize polar and near-surface ice on a global basis. The water vapor introduced into the atmosphere following an impact will contribute to greenhouse warming. As the atmosphere cools, this vapor will condense and precipitate out, creating a hydrological cycle of continuing evaporation and precipitation for as long as the energy supplied by the impact keeps the planet warm. In this way, early one-dimensional simulations indicated that large impacts are capable of producing global-scale precipitation that lasts from weeks to decades (Segura *et al.*, 2002). Average precipitation rates during this period may exceed 1–2 m/year, depending on impactor size (Segura *et al.*, 2002). More recent results from a three-dimensional model that includes a hydrological cycle, the radiative effects of clouds, and atmospheric circulation (Colaprete *et al.*, 2004) have shown that the effects can be more complicated and result in significant variability in local precipitation and seasonally reoccurring episodes of "warm and wet" conditions for as long as the impact-induced thermal perturbation lasts. This study indicates that decades of warmth and precipitation may result from the impact of objects only 8 km in diameter.

An attractive aspect of the episodic hypothesis is that it is consistent with the presence of the primary igneous materials olivine and pyroxene, and the lack of widespread weathering products such as clays (Bibring *et al.*, 2005; Mustard *et al.*, 2005a). Olivine, for example, can survive in a short-lived watery environment. On the other hand, it is not clear whether the erosion power of impact-induced rainfall is sufficient to explain all of the fluvial features. Nanedi Vallis, for example, may have experienced thousands, if not millions, of years of steady flow to produce its meandering morphology.

Based on this discussion, a key question is: How do we distinguish between rainfall generated by a continuously warm/wet climate and that generated episodically by impacts and/or volcanism? Our ability to answer this question hinges on the answers to three others: What were the sources and sinks of candidate greenhouse gases, how much was initially present, and how long did it survive in the atmosphere? How much rainfall was required to produce the observed fluvial features, and what was its timing and duration? And, finally, how much rainfall could have been produced by impacts during the late heavy bombardment versus that from a sustained climate?

B5. What conditions and processes gave rise to the valley networks, and what were their discharge rates, durations, and continuity of flow? Valley networks are frequently cited as the best evidence that liquid water was present on the surface of early Mars (*e.g.*, Carr, 1996). Baker *et al.* (1992) even suggested that valley networks are indicative of a past hydrologic cycle, which makes Mars the only planet besides the Earth, where such processes have occurred. Because of the profound implications valley networks have with regard to understanding the history of water on Mars, past climatic conditions, and, potentially, the development of life, they continue to be the focus of intense study by numerous investigators. As our knowledge of valley networks has increased over the last few decades, our thinking about their origin and the associated climatic conditions under which they formed has almost come full circle. More importantly, new topographic data and a rich variety of imagery data from Mars Global Surveyor, Mars Odyssey, and Mars Express have positioned us to make a number of breakthrough discoveries about the nature and origin of these important and enigmatic features (Fig. 1B and C). Potentially, these discoveries will not only increase our understanding of valley networks, but terrestrial drainage systems as well.

Valley networks were first recognized in Mariner spacecraft images (Driscoll, 1972; Schultz and Ingerson, 1973), and they immediately posed a paradox that in many respects still faces us today: How can fluvial features form on a planet where liquid water is unstable? To resolve this paradox, early investigators suggested that faulting (Schumm, 1974), liquid hydrocarbons (Yung and Pinto, 1978), lava (Carr, 1974), and even wind (Cutts and Blasius, 1981) may have been responsible for eroding the valley networks. However, many valley networks contain numerous tributaries that form integrated systems and exhibit a complex, anastomosing behavior that makes their origin by processes other than fluvial erosion difficult to reconcile (*e.g.*, Carr, 1981). Because a vast majority of valley networks occur in the older, cratered highlands, Sagan *et al.* (1973) and Sharp and Malin (1975) suggested that the ancient atmosphere was warmer and denser. Using Viking data, Masursky *et al.* (1977) built upon this concept and argued that because valley networks are so widespread in the highlands and they often erode up to rim crests of craters, early climatic conditions on Mars must have been capable of supporting rainfall. The climatic implications posed by the newly discovered valley networks quickly established the model where the martian atmosphere evolved from early warmer, wetter conditions to the colder, drier conditions seen today (Walker, 1978; Pollack, 1979; Cess *et al.*, 1980).

There are a couple of key interpretations that influenced much of the thinking about valley networks during the Viking era. The first was that of Pieri (1976, 1980), who noted that many of the valley networks visible in Viking data had low drainage densities, were flat-floored, and terminate in amphitheater-shaped heads, all of which are evidence that they were formed by groundwater sapping. This hypothesis implies that much of the water on early Mars was contained below the surface. An additional observation was presented by Carr and Clow (1981), who suggested that because valley networks are located on both the older, cratered highlands and the younger Tharsis volcanoes, there may have been two distinct episodes of valley network formation. The latter observation, in particular, presented scientists with a problem because, without the benefit of an early warm and wet climate, some other explanation was needed to explain the younger valley networks. Presumably, any water in the martian regolith would have frozen as the climate

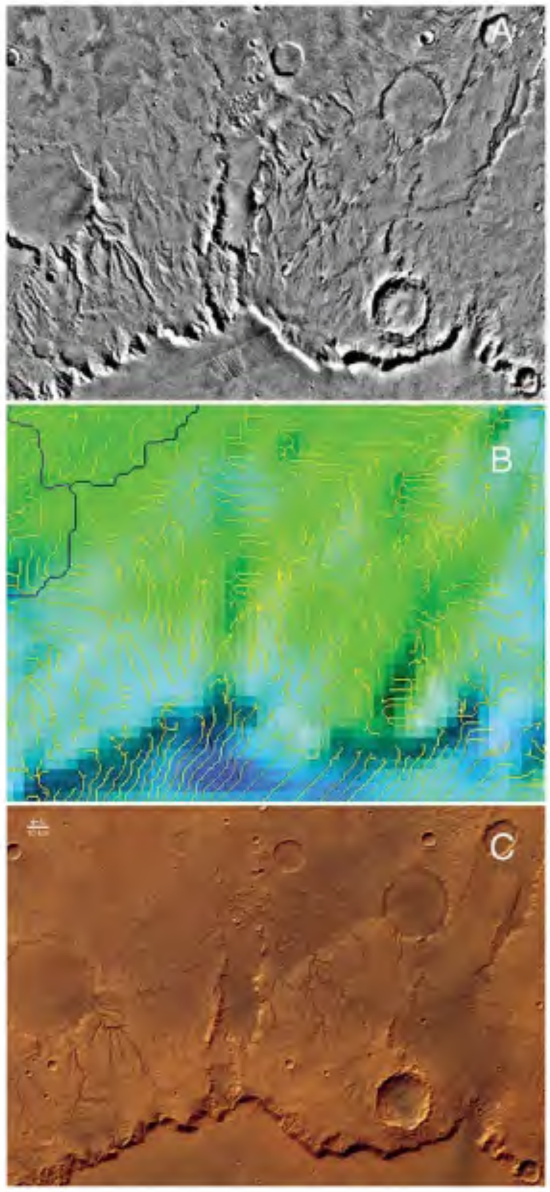

FIG. 1. Our understanding of valley networks has evolved as new and better spacecraft data have become available. A: An area west of the Huygens impact basin as seen by the Viking orbiter. Note that many valley networks are difficult to recognize, but seem to occur as small, isolated segments. The drainage density also appears to be extremely low. However, there is a clear temporal relationship between the valley networks and modified impact craters. **B**: A 1-km-gridded Digital Elevation Model of the same area made possible from MOLA data. Superposed on the Digital Elevation Model are all fourth-order and higher streams extracted from conventional geospatial analyses techniques. **C**: A color mosaic from the High Resolution Stereo Camera. Note that it is now apparent that there are many smaller order tributaries associated with valley network systems. Compare the location of these tributaries with the position of fourth-order streams shown above in B. Essentially, the tributaries are space filling, which is expected from stream systems fed from precipitation and surface runoff.

became colder, so Gulick and Baker (1990) proposed that the geothermal heating of ground ice in the flanks of the Tharsis volcanoes was the source of the water. In their model, a portion of this meltwater discharged to the surface and carved the valley networks through sapping. This provided an elegant solution to the origin of the younger valley networks, and it is also consistent with the isotopic evidence that the water in the SNC meteorites had circulated in an environment similar to terrestrial magmatic hydrothermal systems (Leshin-Watson *et al.*, 1994).

While a hydrothermal origin of the valley networks on the flanks of young volcanoes gained wide acceptance, the case for a precipitation-related origin of the oldest valley networks began to falter because climate modelers had difficulty in creating the warmer, wetter conditions necessary to sustain above-freezing temperatures. For example, Kasting (1991) noted that any CO_2 ice clouds that formed in the primordial atmosphere would have reduced the convective lapse rate of the troposphere, thus reducing surface heating. His model indicated that the martian climate had always been cold and dry, which created a significant problem for explaining the origin of the oldest valleys.

In response, Squyres and Kasting (1994) proposed that the earliest valley networks were also formed by the geothermal discharge of groundwater, which arose from a combination of a higher primordial heat flow and intense impact cratering during the period of heavy bombardment. Their model built on earlier work of Newsom (1980), Brakenridge *et al.* (1985), and Newsom *et al.* (1986), who had suggested that the interaction of impact melt, associated with a newly formed crater, with the water- or ice-rich early crust could have generated hydrothermal systems capable of eroding the valley networks that frequently emanate from crater rims. This explanation received additional support from Gulick (1998, 2001), who adapted the original hydrothermal model of Gulick and Baker (1990) and found that, given the proper conditions—such as high permeability and large igneous intrusions—geothermal heating could potentially explain the older valley networks. These models suggest that it is physically possible for valley networks to form in a cold, dry climate.

Although a possible hydrothermal origin for the valley networks is widely acknowledged, it does not appear to satisfy all of the observational evidence. The case for and against a cold, dry early Mars has been discussed by Craddock and Howard (2002), who presented several arguments that they believed refute a hydrothermal origin. The most persuasive of these is the observation that valley networks frequently incise the rim crests of impact craters. If the water that carved these features was hydrothermally circulated from the crater interior, why would it discharge at the very peak of the crater rim? In contrast, atmospheric precipitation could readily explain this observation.

A more subtle argument notes that the valley networks were forming at the same time as other widespread modifications were taking place across the Noachian landscape, particularly with regard to other morphological characteristics of impact craters (Fig. 1). Craddock and Howard (2002) maintained that any mechanism for creating one set of features should be capable of explaining the other. While comparatively small amounts of material were eroded to form the valley networks, massive amounts were eroded to give modified impact craters their characteristic flat-floored, rimless morphology (Craddock and Maxwell, 1990, 1993; Craddock *et al.*, 1997; Craddock and Howard, 2002; Forsberg-Taylor *et al.*, 2004). Analyses of these characteristics, coupled with computer simulations of the effect of various geologic processes on crater morphology, indicate that the Noachian craters were modified by a combination of rain-splash and surface runoff (Craddock *et al.*, 1997; Craddock and Howard, 2002; Forsberg-Taylor *et al.*, 2004), which suggests that valley networks were as well.

Following the Kasting (1991) model, there were a series of other efforts to model the early Mars climate, all of which contradicted one another (Forget and Pierrehumbert, 1997; Mischna *et al.*, 2000; Colaprete and Toon, 2003). Climate models are important for determining how sensitive certain variables may have been in creating the early climate on Mars, but they are largely based on parameters that are unknown. The onus is on the geologic record to provide the clues for the nature of the early martian climate. Was Mars always cold and dry, or was early Mars warmer and wetter?

Perhaps the greatest advancement to our understanding of valley networks has come from the MOLA data. Coupled with high-resolution imagery data, it finally became possible to compare the density and location of valley networks with topography (Fig. 1B), thus enabling tests of previous assertions that the drainage densities of valley networks were low (Pieri, 1976; Carr and Chuang, 1997) and the networks occurred as isolated features or in clusters (Gulick, 1998). Both observations are frequently cited in support of the assertion that the valley networks resulted from hydrothermally induced groundwater sapping.

With the aid of the gridded MOLA elevation data and new computational algorithms (*e.g.*, Tarboton, 1997), investigators were quick to extract drainage basin information pertaining to the networks (Hynek and Phillips, 2003; Mest and Crown, 2004, Stepinski and Collier, 2004). Drainages of different magnitude can also be identified following several conventions (Horton, 1945; Strahler, 1952; Shreve, 1967). This information can then be used to characterize a number of parameters useful for describing a valley network system (*e.g.*, contributing area, relief, stream order, etc.). Although the techniques used in each study are slightly different, the general assessment is that the drainage densities of martian valley networks are several orders higher than previously deduced from Viking imagery data (Carr and Chuang, 1997). Despite this fact, it is not immediately clear whether these drainage densities are more comparable to terrestrial systems carved by surface runoff or groundwater sapping (R.A. Craddock and R.P. Irwin, 2005, personal communication).

Finally, a number of fan-like deposits have recently been found in some large impact craters that lie at the terminus of major valley networks (Malin and Edgett, 2000; Williams *et al.*, 2004; Moore and Howard, 2005). Typically, these deposits contain branching, downslope ridges that are suggestive of a distributary system, as well as sinuous, meandering ridge forms that are suggestive of migrating and cutoff meanders. These features imply that surface flow was persistent on early Mars. Currently, it is not clear how widespread these fan-like features are, but they may imply that early martian climatic conditions did not simply decline monotonically with time. Rather, there is growing evidence from the study of valley networks to suggest that there was at least one or two "climatic optimums" during the early history of Mars (*e.g.*, Irwin *et al.*, 2005). Perhaps these climatic optimums were fed by geologic events, such as the outbursts associated with the formation of the large outflow channels, degassing associated with Hesperian volcanism, or the formation of large impact basins (Segura *et al.*, 2002). The acquisition of higher-resolution topographic and imagery data from existing and future spacecraft may resolve a number of these issues.

B6. How was the chemistry and mineralogy of the early martian crust influenced by atmospheric, surface, and subsurface processes? As argued in the discussions of the previous questions, there is considerable evidence that surface water was abundant on early Mars. Potential sources that may have contributed to aqueous alteration include the early atmosphere; drainage systems, lakes, and other large standing bodies of water (Baker *et al.*, 1991; Newsom *et al.*, 1996; Cabrol *et al.*, 2001; Clifford and Parker, 2001); and the likely presence of shallow and deep aquifers (Clifford, 1993; Forsberg-Taylor *et al.*, 2004).

Given the active igneous processes that were also occurring at this time, to what degree did water/rock interactions affect the martian crust? Such aqueous geochemical processes are important, not only with regard to their implications for the mineralogy of the early crust, but also because of their relevance to the habitability of Mars—including the existence of aqueous and hydrothermal environments connected with volcanism, impact crater formation, and with the origin of the surface "soil" deposits on Mars.

Evidence for aqueous alteration on Mars comes from the martian meteorites, orbital remote sensing, and surface missions. The martian meteorites represent actual samples of the upper crust, and their mineral composition (summarized by Bridges *et al.*, 2001) indicates conditions of formation that are somewhat different from those that are presently found at the surface. Although chemical and radiogenic evidence for a surface-derived chemical contribution to the alteration minerals surface component exists in some of the meteorites (*e.g.*, Rao *et al.*, 1999), their composition is most consistent with alteration in an alkaline and reduced environment controlled by water–rock interactions, and not the oxidized acidic environment found at the surface (Zolotov *et al.*, 2004). Precipitation of the carbonates in the ALH 84001 meteorite is consistent with fluids rich in CO_2 (Golden *et al.*, 2001), but carbonates are scarce on the surface, especially compared with sulfates. Orbital thermal infrared studies have revealed controversial spectral evidence in some areas that can be interpreted as widespread basalt alteration (*e.g.*, Wyatt and McSween, 2003). Evidence for the presence of clay minerals on the surface of the ancient highlands has recently been revealed in near-infrared data from Mars Express (Fig. 2) (Bibring *et al.*, 2005; Mustard *et al.*, 2005b).

The MERs have found dramatic evidence for aqueous geochemical processes in the form of chemical sediments (sulfates) and precipitates (hematite) in Meridiani Planum (Squyres *et al.*, 2004). Evidence for basalt alteration and chemical precipitates in rocks on the floor of Gusev crater and the nearby Columbia Hills has also been discovered (Fig. 3) (Haskin *et al.*, 2005). The identification of aqueous minerals by the MERs is based

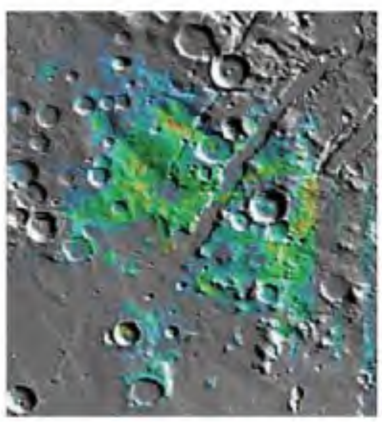

FIG. 2. Clay mineral occurrences in the martian highlands from the Omega instrument on Mars Express (Bibring *et al.*, 2005; Mustard *et al.*, 2005b).

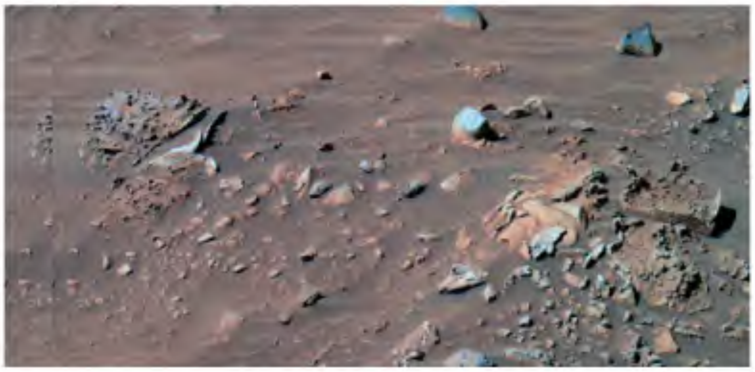

FIG. 3. MER rover Spirit PANCAM image of the breadbox (thick arrow) and pot of gold (thin arrow) outcrops. This outcrop exhibits morphological and chemical evidence for aqueous alteration processes.

on the bulk chemistry determined by the Alpha Particle X-ray Spectrometer and characteristic thermal infrared spectra from the Mini-Thermal Emission Spectrometer experiment, whereas iron-bearing minerals are identified by the Mössbauer spectrometer. In some cases, very high concentrations of sulfate salts (~30% SO_3) have been found in the soil, such as at the Paso Robles site.

The role of volcanism in hydrothermal processes has long been discussed, and theoretical studies suggest that hydrothermal systems should be common on Mars (Gulick, 1998). Volcanic aerosols are the canonical explanation for the high sulfur and chlorine in the martian soil (Clark and Baird, 1979) and the abundant sulfate at the MER landing sites, and volcanic hydrothermal fluids could have also transported mobile elements to the soil (Newsom *et al.*, 1999). However, there is no evidence to date of a martian "Yellowstone" hydrothermal deposit. The formation of large outflow channels and chaos regions are potentially indicative of magmatic interactions with ground ice (Carr, 1996; McKenzie and Nimmo, 1999), but evidence for the type of alteration in these areas that could be connected to such a process has not been discovered. As with large volcanoes, the formation of large craters on Mars should have resulted in massive hydrothermal systems that lasted for tens to hundreds of thousands of years (Newsom, 1980; Rathbun and Squyres, 2002). Impact crater hydrothermal processes may have also contributed to the formation of the martian soil (Newsom *et al.*, 1999; Nelson *et al.*, 2005).

The origin of the martian soil has received the most attention as far as the role of aqueous and hydrothermal processes on Mars. Models for the origin of the soil include palagonite formation, hydrothermal alteration, and acid-fog weathering. McSween and Keil (2000) showed that acid-fog weathering (Banin *et al.*, 1997) cannot satisfy the chemical constraints, though palagonitization (the alteration of basaltic glass) can satisfy them with the addition of volcanic aerosols.

Recent work on terrestrial analogues (Hagerty and Newsom, 2003) has shown that hydrothermal alteration can produce FeO-rich clay minerals, including saponite, that also have low CaO abundances and high FeO when compared with their basaltic protolith, which makes them ideal candidate components of the martian soil (Nelson *et al.*, 2005). The presence of a hydrothermal alteration component is consistent with an origin for the soil in which aeolian erosion of hydrothermally altered FeO-rich basaltic rock preferentially removed the altered minerals, and the basaltic rock then became a geochemical sink for mobile elements, such as S and Cl, which would have been contributed by fluids, volcanic aerosols, or a combination of both processes. An important aspect of this model is that the formation of the altered basalt component of the soil could have occurred at any time in the past, such as during wetter periods early in Mars history, which would explain the absence of soil components that require the presence of water. The identification of minerals such as jarosite and kieserite in the soils suggests that weathering on the surface, at least in the recent past, occurred in a very water-limited environment (Madden *et al.*, 2004). In addition, the soils contain unaltered olivine, possibly from aeolian erosion, which suggests that the present soil has not experienced much alteration (Morris *et al.*, 2004). Was the weathering environment drastically different early in Mars' history? As yet, we do not know for certain.

Group C. Did life arise on early Mars?

C1. Did life develop on early Mars, either through seeding by meteorite transport from Earth, or by an *independent genesis?* The question of martian life embodies essentially three basic aspects. The first involves the possibility that Mars may have sustained an independent origin of life. The second involves the potential for life to have developed on one planet and be subsequently transferred to another by impact ejection and gravitational capture (*i.e.*, panspermia). The third focuses on the potential for Mars to have sustained and evolved life, following its initial appearance. Questions of an independent origin of martian life or, alternatively, of an origin by panspermia are discussed here, while the question of habitability—a concept that bears most directly on the opportunity for Mars to sustain life after it appeared—is addressed in the next section.

How life begins anywhere remains a fundamental unsolved mystery. Clearly the origin (or origins) of life involves sequences of chemical processes that have been shaped by their environment. But life also embodies an inherent complexity (high information content) that consists of molecules and structures. Such complexity has emerged from an evolutionary process of survival against environmental challenges and changes. Like planets, biospheres embody the paths and outcomes of local history. Accordingly, the origin of life on Earth probably represents only one pathway among many along which life can emerge. Understanding the universal principles that underlie the origins of life therefore requires observations of inhabited planets in addition to Earth. These universal principles should be sought by determining what raw materials of life can be produced by prebiotic chemical evolution in space and on planets (Des Marais *et al.*, 2003). How organic compounds are assembled into more complex molecular systems and the processes by which complex systems evolve those basic properties that are critical to life's origin are key concerns that need to be addressed. Basic properties critical to life include, among others, capturing energy and nutrients from the environment, metabolism, and manufacturing copies of key biomolecules.

Mars is the most accessible and easily explored of all of the other planets that might have hosted another biosphere. Recent missions have shown that Mars may have been habitable, at least during certain epochs in its distant past (*e.g.*, Squyres *et al.*, 2004). The martian crust has probably retained an excellent record of its earliest history, an epoch when our own biosphere probably began but whose mark on the geologic record has been destroyed by tectonic activity. The early environments of Mars and Earth may have been more similar than those environments that emerged later in their histories (McKay and Stoker, 1989). Similarities include active volcanism (producing similar volcanic gases), meteoritic impacts, bodies of liquid water, and mildly reducing atmospheres. These shared traits imply that conditions for the origins of life on Earth and Mars also were similar.

We might expect, therefore, that prebiotic chemical evolution on Mars was similar to the sequence that occurred on Earth, though the inevitable divergence of environmental conditions on the two planets ultimately would have caused the trajectories of biological evolution to diverge. This hypothesis predicts that characteristics of any ancient martian life can be defined, at least in part, from studies of early life on Earth. In our biosphere, hydrogen and reduced sulfur compounds are near-universal substrates for bacteria and archaea; therefore early life probably utilized them. Microorganisms utilize redox reactions for energy. Most carbon compounds that serve as cellular constituents and core metabolism are the same. Reactions that lie at the core of intermediary metabolism might be similar for all carbon-based life (Morowitz, 1992).

But even if the early biospheres of Earth and Mars were indeed quite similar, our search for life on Mars clearly might reveal much more. Are the conditions that favor the origin(s) of life different from those that sustain it? Which environments were truly habitable on early Earth, and on early Mars? The presence of liquid water was probably not solely sufficient; sources of chemical energy (Hoehler, 2004) and some threshold of environmental stability were also required. How was any evidence of these environments preserved in rocks, and which particular features should be sought? If life emerged on Mars, did it adapt to changing conditions and persist for millions to billions of years? Did various key traits of life (*e.g.*, photosynthesis, methanogenesis, iron and sulfur oxidation, elaborate cellular shapes) develop, and, if so, when? And how is their evidence recorded in ancient geologic records? What limits the complexity of organisms?

One fruitful approach to address these and other questions for early Earth has been to define the crustal reservoirs of biologically important elements such as carbon (Des Marais, 2001), nitrogen, sulfur (Canfield, 2001), phosphorus, and key metals, and also to understand the processes that link those reservoirs. On Earth, these networks of processes and reservoirs are called biogeochemical cycles. Many of the key processes—namely, erosion, sedimentation, tectonics, volcanism, atmospheric exchange, and aqueous processes—have probably also been important on Mars. Studies of such cycles provide a valuable context for understanding the habitability and habitation of Mars, both today and in the distant past. They also help to define the geochemical "noise" against which any biological "signals" must be discerned. What has been the relationship between geochemical processes and near-surface environments? Have hydrothermal processes played major roles? What key minerals have affected the availability of nutrients for life? Which minerals have preserved records in ancient rocks of habitable environments and, potentially, life? What processes control the distribution of trace gases such as methane in the martian atmosphere? What are the key physicochemical parameters (pH, E_h, ionic strength, etc.) of potentially habitable environments, both in the deep subsurface and near the surface? How have these parameters changed over the history of Mars?

The proximity of Mars and Earth creates an ambiguity as to whether Earth and Mars hosted truly independent origins of life. Meteoritic impacts like those that delivered martian meteorites to Earth might also have exchanged microorganisms between the two planets. Impact events were even more frequent and substantial in the distant geologic past, including a period of time after which life began on Earth. Thus we cannot be sure whether the discovery of life on Mars would necessarily constitute the discovery of a truly independent origin of life. Successful interplanetary delivery of life would require a protective vehicle (*e.g.*, a large rock) that could transport life forms, unharmed, and host environments within which those life forms could colonize, thrive, and ultimately evolve. What traits of living organisms would enhance their survivability during such an interplanetary journey? If evidence of life were found, it would be crucial to determine its ultimate origin(s). Evidence of earthly origins might indicate remarkable survival skills, but evidence of a truly independent origin would indicate that life is indeed pervasive and diverse in the universe.

C2. Were habitable environments present on early Mars? Habitability may be defined as the potential for an environment to support life. This is independent of whether life is actually present. In posing the question of past or present habitable environments on Mars, our views are shaped by our understanding of the basic requirements for terrestrial life, played against what we perceive to be the environmental limits of living systems. As presently understood, the basic requirements for life include liquid water, local concentrations of the biogenic elements (C, H, N, O, and P, plus a variety of transition metals), and energy sources for sustaining metabolic functions.

On Earth, these basic requirements are met over a broad range of environmental extremes, most of which sustain life (Rothschild and Mancinelli, 2001). Studies of terrestrial extremophiles suggest that, within certain limits, wherever the basic requirements for life are met, it has expanded to take advantage of essentially every energy source available. The upper temperature limit for microbial growth has been reported as ~121°C (Chapelle *et al.*, 2002), with thermophiles persisting to temperatures perhaps as high as 130°C. At these high temperatures, specialized heat shock proteins act to stabilize complex biomolecules that would otherwise begin to denature. A practical upper temperature limit for life is probably ~150°C, where complex biomolecules degrade to their basic components (Stetter, 1996). Organisms have also been shown to use similar heat shock proteins to adapt to lower extremes of temperature (Trent, 1996). Psychrophiles have been found living at temperatures of -15°C (Mazur, 1980), where they exist within thin brine films surrounding grains of rock and soil in Siberian permafrost, or entrapped within brine inclusions or brine-filled microfractures in glacial ice.

Life has also been shown to occupy the full range of pH, with the fungus *Ferroplasma acidarmanus* growing at pH 0 in an acid mine drainage (Bond *et al.*, 2000), and other microbial groups preferring extreme basic values >10, common in alkaline lakes. Similarly, life also occupies the full range of salinity from fresh water to hypersaline brines formed by freezing or evaporation. Adaptations for extremes in radiation are also seen in terrestrial microbes that have evolved extremely rapid DNA repair systems, such as *Deinococcus radiodurans* (Battista, 1997), an organism that lives in association with natural radioactive mineral deposits and on fuel rods of nuclear power plants (*e.g.*, Rothschild and Mancinelli, 2001). Organisms have also developed strategies for maintaining viability during extreme, inclement conditions through the development of various types of encystment and resting stages. In certain environments, bacterial endospores can survive combined extremes of temperature, pH, radiation, and desiccation (including freezing). A desiccation (water activity) limit for life was recently reported for the Atacama Desert, where values fell below ~0.6. Below this value, life was absent, even as endospores (Navarro-González *et al.*, 2003). These observations support the following conclusions: Terrestrial life is extremely robust and has evolved to occupy a broad range of (as yet unknown) environmental limits, seemingly constrained only by the presence of liquid water, sources of biogenic elements, and energy. This perspective has had a profound effect on our perception of habitability, which has greatly expanded the scope of environmental possibilities for Mars.

While an Earth-centric view of life and its limits is both practical and logically defensible, there are associated risks that should be clearly understood (Benner, 2002). Specifically, our general ignorance of the processes and pathways that lead to the emergence of life on Earth, and of the factors that guided early biosphere evolution, suggests the need for caution when applying concepts of terrestrial habitability to other planets. In essence, while we choose to proceed with exploration based on what we know of terrestrial life, we must also leave the door open for alternative life forms that may have originated on a different basis, perhaps following prebiotic pathways and early evolutionary divergences very different from those seen on Earth. Active areas of research that have expanded our understanding of the potential for extraterrestrial life include extremophile research that seeks to expand the known environmental limits and metabolic (energy utilization) strategies for terrestrial life, genetic engineering of microbes to push the evolutionary and environmental limits of functional genomes, theoretical studies of hypothetical non-Earth life that might utilize replication systems that are not DNA- or RNA-based, and alternative biochemistries that have the potential to operate with solvents other than liquid water (Benner, 2003). It is indeed sobering to realize how little we actually know of biodiversity on planet Earth. It has been estimated that <2% of extant life forms have been sampled using modern methods of molecular biology (Pace, 1997), and an even smaller percentage of species have been cultured to understand their metabolic capabilities. Given this fact, our concepts of planetary habitability and the possibilities for life elsewhere could change dramatically as new discoveries are made here on Earth.

Liquid water is universally regarded as the most fundamental requirement for terrestrial life. This is reflected in a basic strategy that continues to guide Mars exploration—namely, "Follow the water." Indeed, all active biological processes require liquid water, and its universal importance as the primary medium for biochemistry is widely accepted. In part, the importance of liquid water may be explained by the extraordinary polar solvent properties of the water molecule and the broad temperature range over which it remains liquid. As outlined in previous sections, we now have compelling evidence that liquid water was widespread on the surface of Mars early in the planet's history (at least until the middle Noachian). Early atmospheric conditions on Mars appear to have sustained a hydrological cycle that included surface precipitation, run-off, and accumulation as streams, lakes (Squyres *et al.*, 2004), and perhaps oceans (Baker *et al.*, 1991). In addition, local habitable environments of liquid water were also present during younger periods of martian history as hydrothermally sourced surface springs, fluvial channels, and lakes sustained by magma–cryosphere interactions (Farmer, 1996) and impacts (Newsom *et al.*, 1996). In addition, large episodic volcanic eruptions and obliquity-influenced climate cycles may have provided additional opportunities for a surface hydrology through transient melting of the shallow cryosphere, with attendant increases in atmospheric density that could have placed surface pressures within the range for liquid water.

Under present martian atmospheric and climate conditions, the most widespread and stable source of liquid water is likely to be found in the deep subsurface (Clifford, 1993). On Earth, the subsurface is populated by a diverse microbiota that is sustained by a variety of chemotropic metabolic strategies. Such environments comprise a vast habitable zone that may support more than half of the Earth's total biomass (Gold, 1992). Of particular relevance for Mars are chemolithoautotrophic forms of life that utilize hydrogen, methane, and sulfur (Boston *et al.*, 1992; Max and Clifford, 2000). On Earth, such strategies have been observed over a broad range of environmental extremes of temperature, pH, and salinity (*e.g.*, Rothschild and Mancinelli, 2001). Models and empirical observations both argue convincingly for the existence of a past and present subsurface hydrosphere on Mars. Indeed, the martian subsurface may have been the most stable and continuously habitable environment over the history of the planet, with the evolutionary potential for having developed complex, highly integrated ecosystems and high levels of biodiversity.

The key to understanding the potential for subsurface habitats on Mars resides with future missions that will be able to penetrate the shallow crust, first from orbit using radar-based remote sensing, and then by drilling to depths of hundreds and, eventually, thousands of meters. An important step along the way could be surface missions with shallow drilling capabilities that have been targeted to sites where the deep groundwater has been brought to the surface/shallow subsurface by natural geological processes (*e.g.*, deep hydrothermal circulation) and subsequently incorporated as ground ice (Payne and Farmer, 2001). Good candidates include sites of recent volcano–ice interactions in polar regions where deeply convecting hydrothermal systems may have developed.

Liquid water provides a necessary, though insufficient, requirement for life. Living systems also require concentrations of the basic chemical building blocks for life, as well as a variety of micronutrients (mostly transition metals; see below) to support the full diversity of metabolic functions observed. In addition, organisms require sources of available energy. On Earth, organisms capture, store, and transfer energy through redox-coupled electron transfer reactions. Common strategies utilize organic compounds in the environment derived from the breakdown of preexisting biological materials (heterotrophs), inorganic carbon compounds produced by chemical weathering processes in the environment (chemolithotrophs), and, at the surface, sunlight for photosynthesis (phototrophs).

Elements that are known to be essential for terrestrial life include C, H, N, O, P, S, Na, Mg, K, Ca, and Cl. In addition, a variety of organisms require one or more of the following transition metals: V, Cr, Mo, Mn, Fe, Co, Ni, Cu, Zn, and Se. Previous lander missions and studies of martian meteorites have substantially advanced our understanding of the elemental chemistry of martian soils and rocks. Indeed, many of the required elements listed above have already been identified during previous surface missions. However, our knowledge of the light elements (particularly C and H, the most fundamental constituents of life) is still very limited. The Viking lander experiments looked for carbon in soils, but found nothing at the 1 ppb sensitivity level provided by those instruments (Klein, 1998). This was the case, despite the expectation that carbon-bearing compounds should be present from the constant rain of interplanetary dust particles and organic-rich meteorites being delivered to the martian surface. To account for the absence of organic compounds in Viking analyses, subsequent studies have emphasized the destructiveness of oxidation reactions in martian soils (Klein, 1999). That said, recent studies still predict the presence of recalcitrant carbon compounds that could have been missed by the Viking gas chromatography-mass spectrometry experiments (Benner *et al.*, 2000).

Most importantly, many of the important building blocks, particularly major elements heavier than nitrogen, that are required for living systems have been shown to be present in martian rocks and soils. These include many of the transition metals that are important as micronutrients and for redox-based energy reactions. However, we have yet to explore the light element chemistry of martian surface soils in any detail. Also, beyond the limited information provided by studies of martian meteorites, we have essentially no experience with subsurface environments on Mars, particularly for depths below the presumed zone of surface oxidation. Therefore, nested within the "Follow the water" strategy, is an important secondary objective—namely, "Follow the carbon and light elements." This objective will be pursued in a preliminary way during the Phoenix and Mars Science Laboratory missions, which will be launched in 2007 and 2009, respectively. However, the need to learn much more about basic building blocks and energy sources will certainly shape future missions.

C3. If life appeared on Mars, and has subsequently gone extinct, is its record preserved? Preservation is one of the key factors in the pursuit of Mars Exploration Program Analysis Group's Goal I (Mars Exploration Program Analysis Group, 2004), to determine whether life ever arose on Mars. What kinds of environments existed during Early Mars time that contained reduced carbon (either prebiotic chemistry or biology itself), and what has been the fate of those environments since? Our most fundamental questions about martian life can only be answered if we look in places where life may have existed *and* where the evidence has survived until the present.

Without liquid water life can remain viable in a dehydrated or frozen state. We do not know what limits the long-term survivability of dormant life forms on Mars. Organisms at the surface may be destroyed by the intense ultraviolet on very short time scales (minutes) and by the surface oxidant on much longer time scales ($\sim 10^5$ years). Dormant organisms shielded from the surface environment deep underground or frozen in the permafrost would be destroyed by crustal radiation (U, Th, K) on time scales that may be 100 Ma or longer. When the recurrence interval of liquid water habitats became longer than the time scale over which dormant life forms can remain viable, then life on Mars would have perished.

Evidence of past life on Mars could take the form of trace fossils. However, the ongoing debates related to the biogenicity of both fossils from the early Earth and features within the martian meteorite ALH84001 show the difficulty of assigning a uniquely biological origin to morphological microfossil-like objects. Preserved organic material (biomarkers) can provide a more convincing case for biological origin, but the oxidizing conditions on Mars may have destroyed any such organic traces. Important inorganic biomarker minerals produced by microorganisms are the small crystals of magnetite, certain apatites, and framboidal pyrite. Their occurrence in distinct sizes and in oriented chains would be compelling fossil evidence of life (Friedmann *et al.*, 2001). While such fossils would show that there had been life on Mars they would not be enough to determine the phylogenetic relationship between life on Mars and Earth. For that, intact organisms are needed: alive or dead.

Finding even a dead martian microorganism would be of exceptional interest. It has been suggested (McKay, 2004) that genetic studies of organisms preserved in the ancient permafrost on Mars would allow for a direct determination of the relationship between Earth life and Mars life even if the organisms are long dead by radiation. The ancient heavily cratered southern highlands of Mars, in particular those regions with preserved evidence of a former magnetic field, may contain ancient deep ice (the presence of ice is suggested by crater morphology). If the study of dead microorganisms preserved in this ancient ice reveals a distinctly alien biochemistry and/or genetic system, we would have for the first time evidence that life was not a singular event in our Solar System.

SUMMARY

Even though the questions addressed here relate to early Mars, the answers will have relevance to understanding Mars in a much broader context. Among the most important of the Pre-Noachian and Noachian developments was the differentiation and thermal evolution of the planet. These processes resulted in the degassing of much of the martian volatile inventory; led to the formation of a core and early magnetic field; and dictated the magnitude, spatial variability, and temporal decay of global heat flow. Indeed, it was the evolution of the planet's heat flow that likely exerted the greatest influence on the subsequent evolution of Mars, driving the tectonic and volcanic forces that led to the development of the crustal dichotomy: Tharsis and Valles Marineris. The formation of the crustal dichotomy was particularly significant, affecting the early distribution of surface water, the drainage of surface and groundwater from the southern highlands, and the resurfacing of the northern plains.

External processes, active during the planet's first billion years, exerted a lasting influence as well. Atmospheric erosion from large impacts, hydrodynamic escape, and a variety of other loss processes are believed to have contributed to substantial changes in the nature of the early atmosphere and surface environment. These changes affected the evolution and vigor of the martian hydrologic cycle and influenced the distribution and state of water on, and within, the planet's crust. While the very oldest geologic evidence suggests that sizable quantities of liquid water once resided on the surface, the decline in valley network formation and abrupt change in crater preservation state at the end of the Noachian indicate that, as time advanced, the early hydrosphere underwent dramatic change. By the Hesperian, the outflow channels provide persuasive evidence that much of the planetary inventory of water was now stored in the subsurface, divided between a thickening reservoir of ice-rich frozen ground and a progressively shrinking reservoir of subpermafrost groundwater, an evolution dictated by the thermal redistribution of subsurface water in response to the long-term decline in the planet's internal heat flow.

If life succeeded in establishing itself on early Mars, it may have done so first at the surface, where abundant water, plentiful sources of energy, and an early protective magnetic field may have supported the development of a diverse spectrum of microorganisms. But between ~3.8 to 3.7 Ga, the surface environment underwent profound changes that affected its habitability. For surface life to have survived this transition, it needed to adapt to a thinner atmosphere, colder temperatures, intermittent water, atmospheric oxidants, and increased solar radiation—changes that, while possible, represent a formidable evolutionary task.

But if life successfully adapted to a subpermafrost existence, then the combination of warmer temperatures, the potential long-term survival of a ready supply of groundwater, and the isolation of the environment from the external hazards posed by atmospheric oxidants and solar ultraviolet may have enabled life to persist throughout much of the planet's history—perhaps surviving even to the present day. Such life might well resemble the anaerobic bacterial communities found in the deep biosphere of the Earth (Stevens and McKinley, 1995). This possibility has been highlighted by the recent proposed detection of methane in the martian atmosphere (Formisano *et al.*, 2004; Krasnopolsky *et al.*, 2004; Muma *et al.*, 2004)—a constituent that may be derived from abiotic processes, such as volcanism and the serpentization of basalt, or potentially be emitted from subsurface methanogenic microorganisms (Farmer, 1996; Fisk and Giovannoni, 1999; Wallendahl and Treiman, 1999; Max and Clifford, 2000; Krasnopolsky *et al.*, 2004). Whether life did, in fact, originate and persist is of course one of the central questions of martian science.

Finding answers to the many questions we still have about early Mars (Table 2) will require the interdisciplinary efforts of terrestrial and planetary scientists working in many specialized fields. Insights may come from ongoing studies of the early Earth and Moon, the origin and diversity of terrestrial life, and from the data returned from past and present spacecraft missions. But definitive answers to some of the most intriguing questions—such as the nature of the early climate, the existence of former oceans and seas, or whether Mars ever gave rise to native life—may require more ambitious approaches, including robotic investigations of the planet utilizing new techniques and platforms or by returning samples to Earth for more intensive study. Ultimately, it may require the presence of humans, working out of long-term settlements and applying the methods and adaptable approaches of traditional field geologists. Either way, the near future of Mars exploration will undoubtedly yield a wealth of new information about the early development of our nearest planetary neighbor.

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ABBREVIATIONS

MER, Mars Exploration Rover; MOLA, Mars Orbiter Laser Altimeter; SNC, Shergotty-Nakhlite-Chassigny.

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