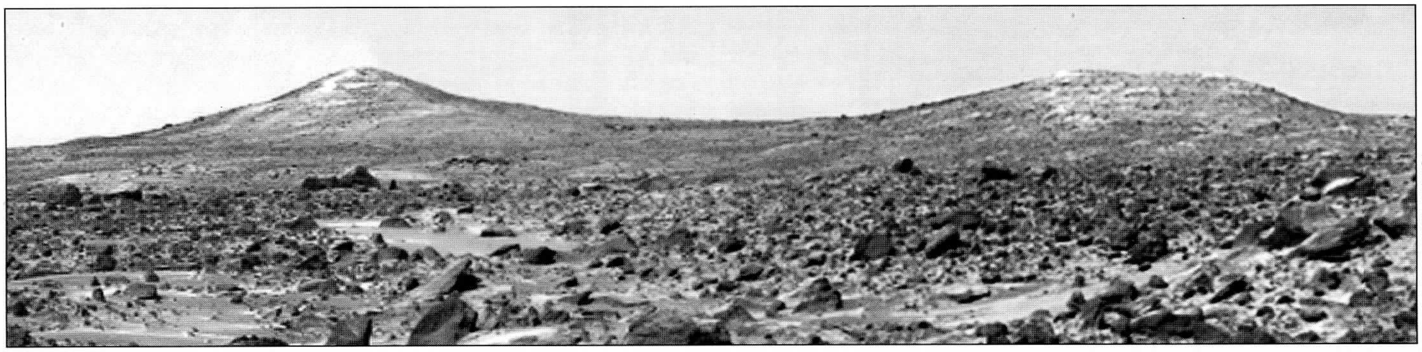
VOLUME 4, NUMBER 3

SETIQuest®

The Magazine of SETI and Bioastronomy



Ancient Mars: Latest Evidence for a Habitable Past

by Andrew J. LePage

Figure 1: *Some of the most compelling evidence for running water on ancient Mars has come from the Mars Pathfinder landing site. Pictured here are a pair of hills, one kilometer from the lander, dubbed "Twin Peaks." Erosion from the floods that carved this landscape is evident in the form of terraces that can be seen on the flanks of these 50-meter-tall outcrops.*

During the first half of this century, our meager knowledge about Mars was based on interpretations of telescopic observations that were influenced by the writings of the American astronomer Percival Lowell. As a result, in the decades before the first automated spacecraft reached Mars it was generally believed that the planet was a smaller, colder, and drier version of the Earth.

Reflecting the prevailing view of the time, an article appearing in the September 1955 issue of *National Geographic* stated as a matter of fact that primitive forms of life such as lichen thrived on the Martian surface and were responsible for some of the observed seasonal changes (1).

While the Lowellian view continued to color the perception of Mars in the opening years of the Space Age, the probes that began to fly by Mars in the middle to late 1960s gave us our first look at what the planet is really like. Initial close-up observations by the Mariner probes clearly demonstrated that Mars was much more hostile to life than previously believed.

The small fraction of Mars's surface imaged at moderate resolution during these brief encounters revealed a heavily cratered, Moon-like landscape that showed no clear signs of geologic activity nor indications for the presence of liquid water. A low atmospheric surface pressure of six millibars precluded the existence of liquid water and allowed deadly solar radiation to bathe the Martian landscape (2).

Based on these earliest close-up observations, planetary scientists began to think of Mars not as a smaller version of the Earth but as a larger version of the Moon with a much diminished possibility of supporting life.

A History of Its Own: Epochs on Mars

After an armada of American and Soviet spacecraft performed the first comprehensive global survey of the Red Planet during the 1970s, planetary scientists were once again forced to drastically revise their views (2). While these probes confirmed that the Martian surface is extremely arid and shows few signs of geologic activity today, they also supplied ample evidence that Mars had been very different in its distant past. Vast regions were found to be dominated by the largest volcanoes and rift valleys in our Solar System. And virtually everywhere that orbiting spacecraft looked, evidence that liquid water once flowed across the Martian surface was found (3). Obviously the Martian atmosphere was much denser and the environment much wetter during some long past era. Mars was no longer considered a scaled version of the Earth or Moon, but was found to be a planet with its own unique history and characteristics.

Based largely on the images returned by the Viking orbiters, the first meaningful geologic maps of the Martian surface were constructed (3). Geologic features were assigned to lithostratigraphic units based on distinct differences in crater density. Planetary scientists frequently use crater densities to gauge the relative ages of surface features on planets and moons throughout the Solar System. No matter what the details of a planet's cratering record, old terrains are exposed to the influx of crater-producing meteorites asteroids, and comets longer than young terrains. As a result, older landscapes have more craters than younger landscapes.

The relative ages of features can be determined by measuring the density of craters that pepper various geologic units in combination with the analysis of regional stratigraphy. A rough geologic history of Mars has been constructed using this geologic chronology along with information from better studied planetary bodies such as the Earth and Moon. As with the study of the Earth's geology, planetary geologists have divided Martian history into epochs (4). On Mars, the oldest and most heavily cratered regions date to the Noachian. Hesperian landscapes are younger and have only a fraction of the crater density of Noachian regions. The youngest and least cratered areas date from the Amazonian. The Noachian and Amazonian are currently subdivided further into Early, Middle, and Late epochs and the Hesperian is subdivided in Early and Late epochs.

While the relative ages of geologic features are largely known, a determination of the absolute ages is a different matter altogether. In theory, if the details of a planet's cratering rate through the ages were known, the absolute ages of its surface features can be determined from the observed crater densities (5). Scientists have already been able to deduce a reasonably accurate cratering history

SETIQuest®

The Magazine of SETI and Bioastronomy

TABLE OF CONTENTS

VOLUME 4, NUMBER 3

— Editorial and Business Offices —

SETIQuest
Helmers Publishing, Inc.
174 Concord Street
Peterborough, NH 03458-0874
USA
(603) 924-9631 • Fax (603) 924-7408
www.setiquest.com

SETIQuest Magazine (ISSN 1077-6605) is published quarterly by Helmers Publishing, Inc. The U.S. subscription rate is $39.00 (includes surface mail delivery). For air-mail shipping to Canada & Mexico, add $9; all other countries, add $17. Back issues are $12 each: Canada/Mexico, add $1.25 per issue shipping; all other countries, add $3 per issue shipping. Checks must be drawn on a U.S. bank. MasterCard, VISA, & American Express accepted.

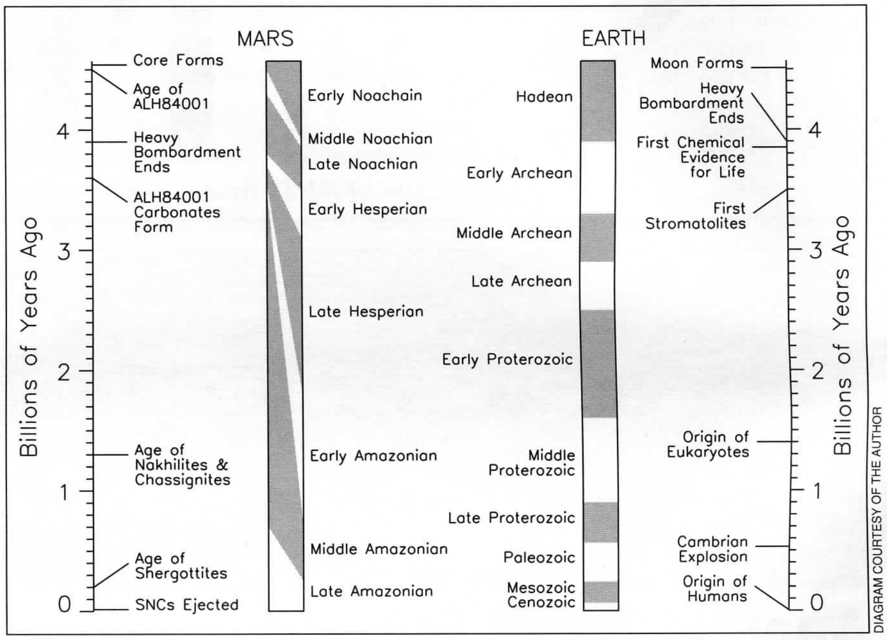


Figure 2: *The major epochs in the geologic history of the Earth and Mars are compared above using key events as time markers. Uncertainties in the Martian cratering record have led to the disparate estimates for the ages of the boundaries between various geologic epochs.*

of the Moon based on dates derived from lunar samples collected at documented sites. Such a history can only be worked out for the Red Planet with dated samples whose origins and geologic context are known.

Nonetheless, inferences from the Moon's better studied geologic history have allowed rough determinations of absolute ages to be made. Estimates for the absolute chronology of Mars's geologic epochs (6,7) and a comparison of Earth's geologic history is shown in Figure 2. As can be seen, estimates for the ages of boundaries between Mars's geologic epochs are still quite uncertain and can vary by as much as a factor of two.

New Data from MPF and MGS

While a more accurate determination of the absolute ages of Martian surface features will have to wait until the first documented surface samples are returned to Earth in the opening decades of the next century, refinements are still being made to the relative chronology of Martian geologic events. Studies of SNC (Shergotty-Nakhla-Chassigny) meteorites which are widely believed to have come from Mars (8), data returned by earlier spacecraft analyzed using new techniques, and a better understanding of planetary evolution in general have all helped considerably.

But even more substantial improvements in our understanding of Martian geologic history are promised by a flood of data from the two latest spacecraft to reach Mars: Mars Pathfinder (MPF), which landed on Mars on July 4, 1997, and continued to operate for three months, and the Mars Global Surveyor, which entered orbit around Mars on September 12, 1997, and is currently aerobraking into a smaller mapping orbit around Mars.

While the analysis of Mars Pathfinder data has just begun and the Mars Global Surveyor (MGS) has yet to begin full-time science observations, a wealth of new information about conditions on ancient Mars has already come to light. Most exciting of all is an ever-growing body of evidence that Mars possessed biocompatible—or even habitable—conditions during the same period of history that life became widespread on Earth.

When taken in combination with evidence from SNC meteorites, there is reason to believe that Mars may have supported life in a long past epoch and that life might have survived in protected environments to this day.

The Noachian: The First Evidence of Water

One of the first phases of planetary evolution is differentiation and the formation of a crust. The silicate-rich composition of the 4.5 billion year old SNC designated ALH84001 indicates that this process was well under way by the time Mars was less than 100 million years old (9). The formation of the Martian crust took place in the Early Noachian epoch and marks the beginning of Mars's geologic record. During this epoch, Mars experienced the worse of the heavy bombardment and witnessed the formation of large impact structures like the ancient and heavily eroded Hellas and Argyre basins (5). Much of Mars's southern hemisphere preserves a record of this ancient bombardment as do the lunar highlands. It was images of these regions returned by the first Mars probes that misled scientists in their early efforts to characterize Martian geologic history.

From the Middle to Late Noachian epochs the cratering rate began to slacken significantly and Mars shows the first preserved signs of volcanism and other tectonic processes (3,5). During these epochs some as yet unknown series of geologic events produced the scarp that separates the old highland terrains of the southern hemisphere from the younger lowland plains of the northern hemisphere (10). Also seen all over Mars is the formation of network channels and other signs of running water during this time (11). Analysis of these various features to date indicates that ground water—and not precipitation—was primarily responsible for the formation of these features. Still, the fact that liquid water was apparently stable on the surface indicates that the Martian atmosphere was significantly denser during the Noachian than it is today.

While evidence for running water is common on the Martian surface, unambiguous indications of standing water are harder to come by (11). High resolution images returned by the Mars Global Surveyor of an unnamed southern polar crater offers a close-up view of one possible site (12). As can be seen in Figure 3, the walls of this crater show signs of channeling and the floor is covered by a dark material that seems to be confined below a certain topographic contour. One possible explanation for these features involves water: Running water cut the channels in the crater wall and subsequently ponded in the crater floor, allowing dark sediments carried by the flowing water to settle out. The ripples in the sediments were either caused by wave action in this lake or are dunes produced from the material after the lake disappeared (12).

This potential ancient crater lake lies on the cratered plains of southern Noachis Terra (which is the archetype of Noachian terrains (3)). Adjacent to this area is a stretch of etched landscape that probably formed when subsurface volcanic heating melted underground ice, causing parts of the surface to subside (13). To the south is a region of pitted terrain associated with a possible volcanic fissure at Sisyphi Cavi. All these features are believed to have formed during the Middle Noachian and hint that subsurface water was abundant during this time in the region of the unnamed crater examined by the Mars Global Surveyor. The age of the features in this crater have yet to be determined, but there is no evidence of small craters on the deposits hinting that the lake could postdate the Noachian. It is also possible that this surface does not preserve craters well or that they have been covered by windblown material (12), making it impossible to establish an age for the putative lake bed without surface samples. The identification and study of other sites like this elsewhere on Mars will be of great interest to exopaleobiologists.

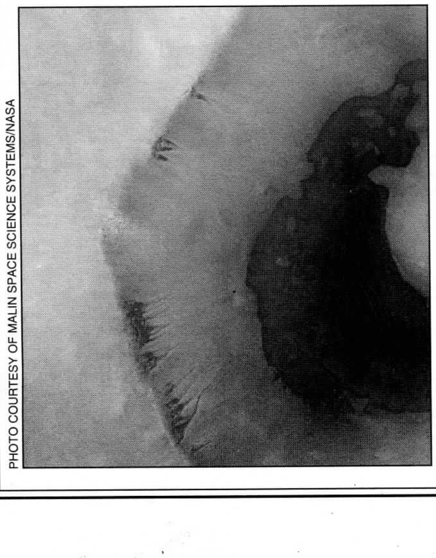


Figure 3: *This is a high-resolution view of a southern crater on Mars located at 65 degrees south, 15 degrees west. It was taken by the Mars Global Surveyor on December 29, 1997. This 25 by 31 kilometer frame shows channels in the crater wall and a bottom filled with dark material. The evidence suggests that this might be the site of an ancient crater lake.*

With the presence of water and volcanism, there exists the possibility of hydrothermal activity. Terrestrial hydrothermal systems frequently support a wide array of life forms and their presence on Mars would provide a possible environment for life to thrive there (14). Images of Mars have revealed possible sites of Martian hydrothermal activity (11) but, as with bodies of standing water, unambiguous evidence has been difficult to find.

Recent measurements made by the Thermal Emission Spectrometer (TES) carried on the Mars Global Surveyor may have finally provided the needed evidence (15). TES has identified a 500-kilometer-wide region in Terra Meridiani straddling the Martian equator that is rich in coarse-grained hematite. This iron-oxide mineral was already believed to exist on Mars as dust and is probably one of the minerals responsible for Mars's red color. While the ubiquitous hematite dust could have formed from the slow weathering of iron-rich surface materials under contemporary conditions, these recently discovered deposits of sand-sized hematite are interesting because such crystals are known to form in large amounts from hydrothermal activity in iron-rich rocks (15). Volcanically heated water dissolves the iron from the rocks and carries it toward the surface. As the water cools, the iron precipitates out of solution to form large crystals of hematite.

The region of Terra Meridiani where these deposits were found contains small volcanoes of indeterminate age resting on cratered plains that formed in the Late Noachian epoch (16). While the age or a connection between these volcanic features and the hematite deposits has yet to be established, it seems likely that hydrothermal activity was present at some time from the Late Noachian onward. Identification of similar deposits elsewhere on the planet will serve as a useful indicator of an ancient hydrothermal environment where life could thrive.

A Noachian Magnetic Field

In addition to the crust, planetary differentiation also results in the formation of a mantle rich in heavy silicates and a dense core of iron or iron sulfide. Using the recently developed technique of tungsten-hafnium chronometry on SNCs, the Martian core is believed to have formed approximately 4.54 billion years ago when the planet was only about 30 million years old (17). The isotopic heterogeneity of the SNCs examined to date also hints that Mars did not suffer a catastrophic impact late in its formation as the Earth did. Such an impact on the proto-Earth 4.52 to 4.54 billion years ago not only thoroughly mixed Earth's upper layers—yielding a more homogeneous isotopic fingerprint—but it is also believed to have resulted in the formation of the Moon (18).

Accurate radio tracking of the Mars Pathfinder lander while it was active on the Martian surface during the summer of 1997, in combination with earlier tracking data of the Viking landers, have indirectly allowed planetary scientists to better constrain the size of the planet's core (19). Measurements of the rate at which the rotational axis of Mars precesses allows the planet's moment of inertia to be determined. When combined with models of the interior structure, the size of the core can be estimated. Depending on the assumptions made about the interior conditions of Mars, the core radius can be as small as 1200 kilometers or as large as 2400 kilometers (19). Wherever the true size of the core is ultimately found to be in this range, the Martian core accounts for a smaller fraction of planetary mass than does Earth's core. Despite its size, the Martian core would still be expected to produce a magnetic field that would shield its atmosphere and surface from solar radiation. Exactly how long Mars could maintain a dynamo depends critically on the size, composition, and thermal history of the Martian core.

Past attempts to measure the strength of the present Martian magnetic field have failed, hinting that any Martian dynamo was at best only weakly active in the present epoch (20). Sensitive measurements, made by the magnetometer and electron reflectometer carried by the Mars Global Surveyor during periapsis passes, which were as

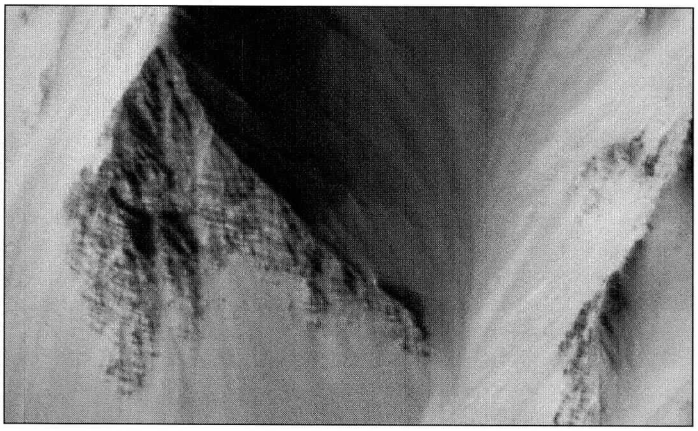


PHOTO COURTESY OF MALIN SPACE SCIENCE SYSTEMS/NASA

Figure 4: *This high-resolution view of western Tithonium and the Ius Chasmata portion of Valles Marineris, obtained on October 3, 1997, clearly shows layers of volcanic bedrock ranging from 5 to 50 meters in thickness. The presence of these strata indicates that Martian volcanic activity in the Late Noachian to Early Hesperian epochs could have been an order of magnitude greater than previously estimated.*

close as 100 kilometers to the Martian surface during the last quarter of 1997, showed that Mars's dipole strength is less than 4×10^{-4} times that of Earth (21). These measurements have definitively eliminated the possibility of a global Martian magnetic field today.

While no global magnetic field has been found, localized magnetic anomalies a couple of hundred kilometers in extent were detected (21). The strength of these anomalies is consistent with the presence of remnant magnetic fields in distinct blocks of Martian crust. These remnant fields are most likely fossils of the global Martian magnetic field that existed when the rocks of these regions formed. The data that have been published to date are limited to 32 and 35 degrees north latitude and are scattered in longitude. These initial observations show that magnetic anomalies in this latitude belt are confined to a region between 270 and 30 degrees west longitude (21). Two clusters of anomalies have been identified: one near the eastern edge of Chryse Planitia and the other near the northern boundary of Arabia Terra between 30 and 40 degrees north latitude and 270 to 356 west longitude.

While the results are hardly definitive, all these anomalies are associated with regions of ancient Noachian crust, hinting that Mars possessed an active dynamo comparable to Earth's during this time. A more thorough mapping of Mars's magnetic anomalies in the months and years to come should allow scientists to construct a history of Mars's magnetic field and determine when its dynamo ceased to function. This should help to further constrain the composition of the Martian core (21) and improve our understanding of planetary magnetic fields.

The Intense Volcanism of the Hesperian

The second major era in the geologic history of Mars is the Hesperian. While the cratering rate continued to decline, there is evidence of major changes to the ancient Martian landscape. During the Early Hesperian epoch, lava flows began to lay down the first of Mars's vast ridged plains (3). At the same time tectonic activity resulted in the initial rifting that opened the enormous Valles Marineris canyon system that straddles the Martian equator.

Just as terrestrial canyons allow geologists to study a deep cross section of the Earth's strata, close-up views of Valles Marineris obtained by the Viking orbiters gave planetary geologists their first good glimpses of a cross section of Hesperian strata in the canyon walls. The best views showed some indications of stratification in the upper kilometer or so but none farther down among older layers. The prevailing interpretation of these observations was that the layered portions represented the lava flows of the Hesperian (22). The lower parts of the canyon walls where no stratification was observed probably dated from the Noachian where heavy cratering disrupted the bedrock layers and formed irregular fused masses of rock fragments or megabreccia. Similar formations have also been seen on the better studied Moon, thus adding weight to this particular explanation.

Much higher resolution views of sections of Valles Marineris returned by the Mars Global Surveyor indicate that this explanation is in need of revision. Images like that in Figure 4 with a resolution of a few meters have, for the first time, clearly shown rock layers from 5 to 50 meters thick everywhere the bedrock is exposed in the rift system to more than 5 kilometers below the surrounding plateau (23). While some of these strata might be sedimentary, the large volume implied by the estimated 5 to 10 kilometer total thickness of these layers strongly suggests that they are the result of repeated volcanic flows. Since these layers lie below the Early Hesperian ridged plains (which formed after the disruptive heavy bombardment had ended), investigators believe that they date from the Late Noachian to the beginning of the Early Hesperian epoch (23,24).

Earlier work had suggested that the volcanic deposits of these epochs should be on average about 200 meters thick (25). But if the 5 to 10 kilometer thickness implied by the recent observations of Valles Marineris is typical, the total volume of Martian volcanic deposits produced during this time is more than an order of magnitude larger than previously estimated (24). Such intense volcanic activity over a period of less than 600 to 750 million years and the accompanying release of volatiles like carbon dioxide and water vapor has major implications for the Martian climate three or four billion years ago and the planet's potential to support life during that time (24).

Based in part on an analysis of SNC meteorites, it has been assumed that these Hesperian volcanic deposits were composed of basalt just like the lunar mare. On July 4, 1997, Mars Pathfinder landed in Chryse Planitia which is generally believed to be Early Hesperian ridged plains covered with a veneer of later deposits. While it was originally hoped that the landing site would be a "grab bag" of rocks from various areas, it now seems that the rocks were primarily derived from the volcanic flows that form the bedrock of

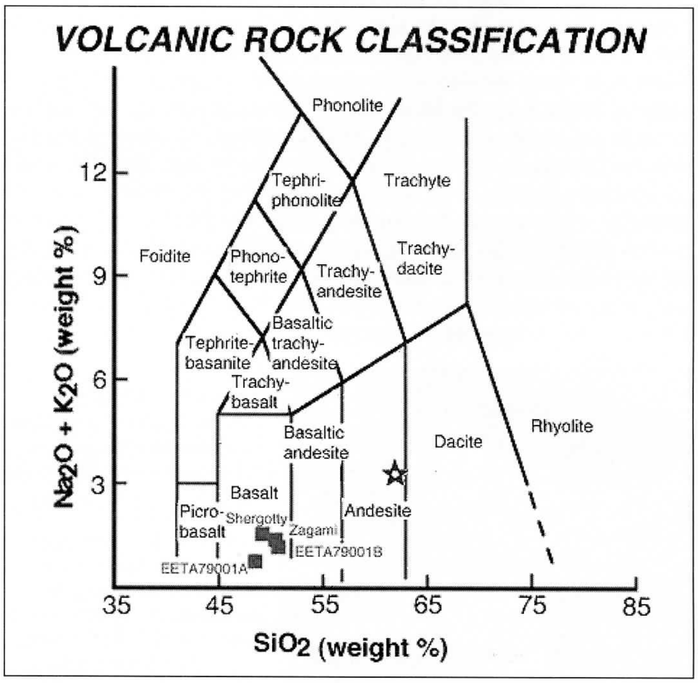


DIAGRAM ADAPTED FROM ONE COURTESY OF JPL/NASA

Figure 5: *The classification of volcanic rocks based on their silica content and the combined weight of sodium and potassium oxides is shown in this diagram. The position of selected SNC (Shergotty-Nakhla-Chassigny) meteorites shows that they are basalts. The typical rock from the Mars Pathfinder landing site, indicated by a star, establishes it as a silica-rich andesite.*

the region (26). The Sojourner rover carried by the Mars Pathfinder lander was equipped with an alpha proton X-ray spectrometer (APXS) to determine the elemental composition of these rocks. Combined with a precise spectral signature derived from photometrically calibrated images obtained by the lander and rover through various colored filters, scientists have been able to determine the composition and mineralogy of some of these Hesperian volcanic rocks for the first time (27).

Much to the surprise of the Mars Pathfinder science team, initial analysis of the rocks in the landing area indicated that they had more silica than basalts. After the effects of sulfur-rich dust clinging to the rocks is taken into account, APXS and spectral analyses indicate that they contain about 62 percent silica by weight (27). When combined with the quantities of other elements present, as shown in Figure 5, rocks at the Mars Pathfinder site are classified as andesites instead of the relatively silicate-poor basalts like SNCs. The composition of the rocks at the landing site is also quite close to the mean composition of the Earth's crust.

This finding initially produced a flurry of excitement about the potential complexity of ancient Martian geology. On Earth, andesites are formed out of water-rich, oceanic rocks that have been subducted and recycled in mountain building (or orogenic) regions that line convergent tectonic-plate margins like those in the Andes Mountains (after which "andesites" are named). A similar origin for the Chryse andesites would imply that ancient Mars possessed more complex geologic processes, such as plate tectonics, than originally supposed (28).

But a more detailed analysis of the composition of the rocks at the Mars Pathfinder landing site indicates that this might not be the case after all. The rocks examined by Pathfinder have less alumina and more iron for a given silica content than is typical for terrestrial orogenic andesites (29). Instead these rocks appear to be more closely related to the terrestrial anorogenic andesites known as icelandites which are found at hot-spot volcanic centers like Iceland and the Galapagos Islands. Icelandites form from the fractional crystallization of a ferrobasalt magma (29). In other words, before the iron-rich magma reaches the surface, it pools underground long enough for it to cool, allowing certain minerals like silica to crystallize and separate from the melt. While the presence of these icelandites does not imply Martian plate tectonics, they do hint that Martian volcanic processes were more complex than has been seen on the Moon, for example.

Water Shapes the Hesperian

While the dendritic valley networks seen during the Noachian become increasingly uncommon during the Hesperian, there are numerous signs of regionally intense releases of water dating from this time (11). The presence of beds of sediments and possible paleoshores in the eastern portions of Valles Marineris indicate that they held deep bodies of standing water during much of the Hesperian. There appear to be several occasions when water from these chasms was suddenly released, causing floods in the regions to the north. The first was during the Early Hesperian epoch when a large release of water from Capri and Eos Chasmata washed northward over a vast region of Xanthe Terra (30). The flood heavily eroded this cratered Noachian landscape and set the stage for what was to come.

As Mars entered the Late Hesperian epoch, we see signs of escalating activity in the volcanic regions of Tharsis, Alba Patera, Elysium, and Syrtis Major (3). The continued uplift of the Tharsis region in particular resulted in further rifting and broadening of the Valles Marineris system to the southeast. Volcanic heating of subsurface ice deposits near these active regions led to the collapse of vast areas and the formation of chaotic terrains as water was catastrophically released in several distinct episodes during the Hesperian (11). The water released from these chaotic terrains as well as from the canyons of the rift system created enormous outflow channels in several areas of Mars. The bulk of these channels are concentrated around Chryse and Acidalia Planitiae and cut through Xanthe Terra and to the northwest through the Early Hesperian epoch volcanic plains of Lunae Planum (11).

Figure 6: *This is a high-resolution view of the Mars Pathfinder landing site obtained by the Mars Global Surveyor on April 22, 1998. While the high angle of the Sun washes out many of the details, the location of several landmarks was determined as well as the presence of bedrock layers along the walls of "Big Crater."*

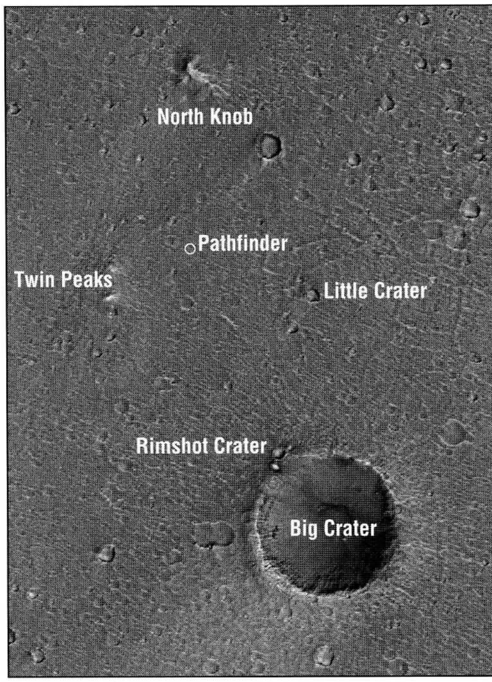


PHOTO COURTESY OF MALIN SPACE SCIENCE SYSTEMS/NASA

Recently an accurate topographic profile near the mouth of one of these channels, Ares Vallis, was obtained by the Mars Orbiter Laser Altimeter (MOLA) carried on the Mars Global Surveyor (31). Ares Vallis first formed in eastern Xanthe Terra during the Early Hesperian when water being released from Iani Chaos was eventually diverted away from Arabia Terra further to the north and east (30). This channel experienced two more episodes of flooding through to the Late Hesperian when it carried water away from Hydaspis Chaos and later Aram and Iani Chaos.

The part of Ares Valles measured by the Mars Orbiter Laser Altimeter is about 35 kilometers wide at the uppermost terrace which is taken to be the level of this channel's largest flood (31). The maximum depth from this point to the bottom of the debris-filled channel was found to be 1,300 meters—more than three times deeper than previously estimated. Combined with new measurements of the slope of the channel, investigators estimate that this one channel carried as much as 10 cubic kilometers of water per *second* when filled (31). This is an order of magnitude larger than previous estimates (32). If subsequent topographic measurements of other outflow channels indicate that they also experienced much higher discharge rates than currently estimated, Mars was much wetter during the Hesperian than previously imagined.

About 500 kilometers downstream from where the Mars Orbiter Laser Altimeter sounded Ares Vallis lies Chryse Planitia and the Mars Pathfinder landing site. Ground-level observations made by the lander and the Sojourner rover have provided additional evidence for catastrophic flooding in this region. Mars Pathfinder came to rest on Late Hesperian debris carried by Ares and Tiu Valles (26,30). Layers of bedrock beneath the flood sediments are seen in the walls of "Big Crater" to the southeast of the Mars Pathfinder landing site in Figure 6. They are either volcanic ridged plains or flood-derived sedimentary deposits from the Early Hesperian epoch.

Evidence for multiple flooding events can be seen in the close-up view of the Twin Peaks in Figure 1. These 50-meter tall hills, about a kilometer west of the Mars Pathfinder landing site, show what seem to be several terraces formed by running water of various depths (26). The landing site itself is dominated by debris from the Twin Peaks with a peppering of rocks from more recently formed

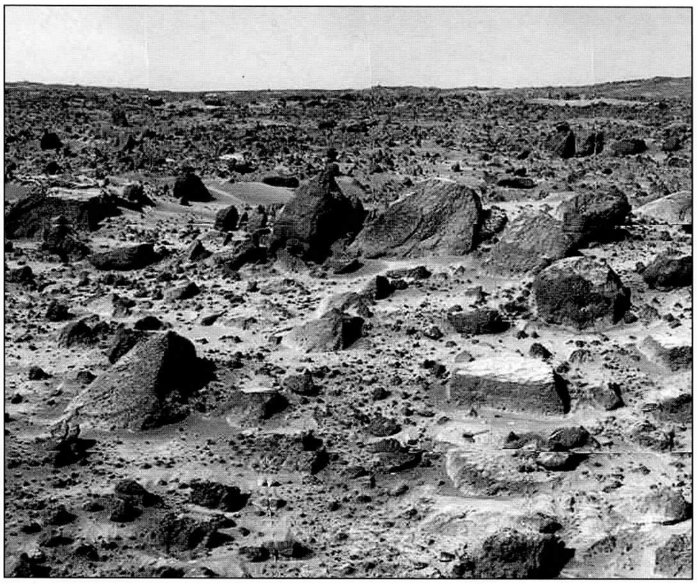


PHOTO COURTESY OF JPL/NASA

Figure 7: *This is a close-up view of the "Rock Garden" obtained by the Mars Pathfinder lander. Analysis of these images along with close-up observations by the Sojourner rover indicate that these rocks were modified and deposited by massive floods that once covered the landing site about two billion years ago.*

craters in the vicinity. Most of the large rocks in the area are tabular and semirounded with fluting and pits (33). One group of nearby rocks in what was called the "Rock Garden" shown in Figure 7 rest against each other and display a preferred orientation. Stereoscopic analysis of images returned by Mars Pathfinder indicates that the landing site has a ridge and trough structure with an amplitude of about five meters and a crest spacing of 15 to 25 meters (26). There were also signs of gullies that have long since filled with wind-blown dust. All this, as well as the distribution of rock sizes and the presence of sand (which was seen on Mars for the first time by Mars Pathfinder), supports the theory that this region was once inundated by enormous floods of fast-moving water (33).

Most of the rocks in the landing site are thought to be igneous in origin. But a close inspection of a handful of them by the Sojourner rover revealed some surprises. Some of the rocks seem to show layering that could be the result of sedimentation in a large body of water (34). Others show pits and sockets, which apparently held smaller stones that have since become dislodged. This is typically seen in sedimentary rocks called conglomerates, which are cemented collections of various size stones, pebbles, and sand. Conglomerates are typically composed of debris from fast-moving water. Additional study of the data in hand will be required to determine if these rocks are sedimentary, igneous, or even metamorphic in origin.

A recent re-analysis of the stratigraphy of the Mars Pathfinder landing site and the surrounding region suggests another possible explanation for the observations. A water-rich mass flow from Simund and Tiu Valles in the Late Hesperian could be responsible for the uppermost deposits observed instead of the floods of water that originally scoured the region (35). The scale of ridge and trough structure of the landing area and other evidence for fluvial deposits would be consistent with such an explanation. In either case, copious quantities of water played an important role in the geology of this region during the Hesperian and must have significantly modified the Martian environment during this time.

In addition to these catastrophic floods, the Hesperian has shown signs that it also supported continuous, albeit more modest, flows of water (11). To the west of the large outflow channels just discussed is a more modest valley system called Nanedi Vallis. This and similar network valleys are thought to form from sapping as groundwater flowed away and caused the surface to collapse (11). A recent close-up view of this valley obtained by the Mars Global Surveyor also shows terraces and other evidence of downcutting (36). While much of the valley floor is covered by debris that collapsed from its walls and was subsequently modified by the action of the Martian winds, it does show signs of oxbows and, in one portion shown in Figure 8, a 200-meter-wide channel.

While the formation of this valley may have been started by sapping, it appears that subsequent downcutting from a continuous flow of water derived from an ancient aquifer in the upland regions of Xanthe Terra also occurred for a time during the Late Hesperian epoch (16). While an argument could be made that a thin Martian atmosphere during the Late Hesperian might not stop a catastrophic flood like those that formed Ares Vallis, a modest flow of water like that which cut Nanedi Vallis once again requires that the Martian atmosphere was much denser than it is today.

The Amazonian: A Slow Slide to a Global Deep Freeze

The most recent period of Martian geologic history is the Amazonian. From the Late Hesperian into the Early Amazonian epoch, Martian geologic activity began to noticeably wane (3). The character of what volcanic activity existed also began to change. Instead of the lava flows that tended to produce vast ridged plains during the Noachian and Hesperian, Amazonian volcanic activity produced the enormous shield volcanoes of Olympus Mons, Tharis Montes, and the smaller edifices in Elysium Planitia to the west. Most of the SNC meteorites, whose ages cluster around 1.3 billion and 200 million years old, are likely derived from these Early to Middle Amazonian epoch volcanic structures and their surroundings (8).

While the total volume of these volcanic deposits are thought to be much smaller than those from earlier epochs, they nonetheless may have contributed to Mars's inventory of volatiles and episodically produced more habitable conditions during the Early and Late Amazonian. But as Mars entered the present geologic epoch, the Late Amazonian, the planet slowly evolved into the frozen desert we see today (3). In today's Late Amazonian epoch, when volcanic and tectonic activity has virtually ceased, the surface is dominated by eolian processes and the formation of today's polar deposits.

While the catastrophic flooding Mars experienced during the Hesperian disappeared during the Amazonian, the incredible volumes of water carried by the flood channels had to go somewhere. Some of this water could have formed small lakes in craters downstream from the channels (11). Much of the water may have eventually been soaked up by the porous surface to form permafrost. But some believe that all this water had a much more spectacular and biologically interesting destination.

PHOTO COURTESY OF MALIN SPACE SCIENCE SYSTEMS/NASA

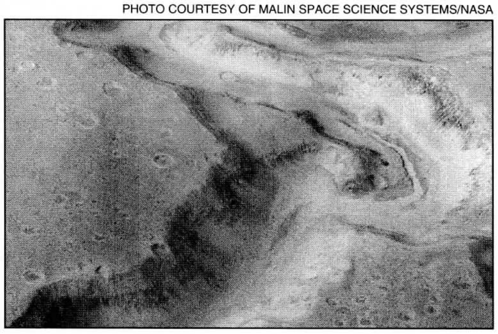


Figure 8: *This ten-by-six-kilometer image shows a portion of Nanedi Vallis in Xanthe Terra observed by the Mars Global Surveyor on January 8, 1998. The presence of oxbows, terraces, and the 200-meter-wide channel indicate that this valley was cut by a sustained flow of water as recently as the Late Hesperian epoch.*

Among the relatively young Amazonian landscapes of the northern hemisphere, scientists have found evidence of what could be vast stretches of paleoshores (37,38). When combined with the low elevations that dominate the topography of the northern hemisphere, some scientists now believe that Mars's northern hemisphere was the home of a bona fide ocean (39).

Provisionally dubbed Oceanus Borealis, this ocean more than likely would have first formed during the Hesperian due to the catastrophic floods. It is possible that only a short-lived "ocean" episodically

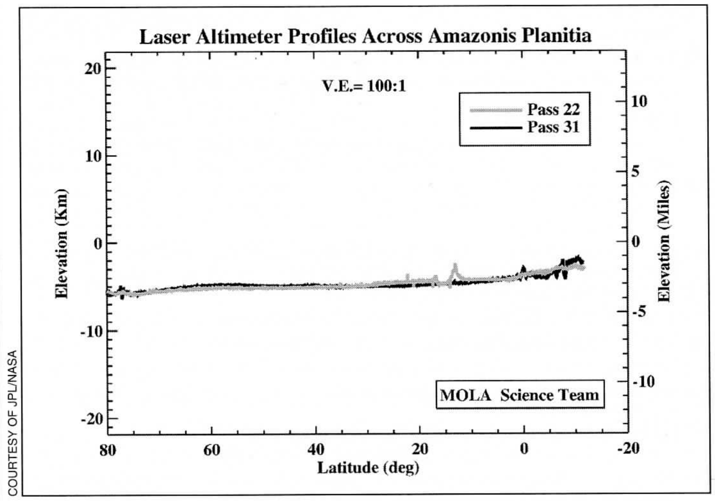


Figure 9: *This plot shows the topographic profile across a portion of Amazonis Planitia obtained by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor during Revolutions 22 and 31. Centered roughly on 182 and 164 degrees west longitude, respectively, these profiles show Mars's northern plains to be incredibly flat. The only other landscapes in the Solar System to show this degree of flatness on such a scale are the sediment-covered abyssal plains of Earth's oceans.*

formed and disappeared, but others argue that Oceanus Borealis was a more permanent Martian feature whose size was constantly in flux as a result of changes in the flow of water from the channels and into geologic and atmospheric sinks (11). Assuming that it had a more permanent nature, an ice-covered but ever-shrinking Oceanus Borealis could have remained on Mars into the Early to Middle Amazonian epoch where it would have provided an environment comparable to those in the ice-covered lakes of the Antarctic dry valleys on Earth today.

More to Gain

While the existence of Oceanus Borealis is hotly debated, it is hoped that the Mars Global Surveyor will obtain high-resolution images that can help determine its reality and map its boundaries (40,41). In the meantime, the Mars Orbiter Laser Altimeter may have already provided some evidence to support the existence of an ancient Martian ocean. The Mars Orbiter Laser Altimeter surface elevation measurements, like those in Figure 9, have shown the northern hemisphere outside of the volcanic Tharsis region to be extremely flat over thousands of kilometers (31). Except for some locally rough areas surrounding recent impact craters, the topography of the northern plains is dominated by a gentle slope upward toward the south at an angle of only 0.056°. This slope is primarily caused by Mars's center of mass being displaced toward the north pole away from the geometric center as well as the one-kilometer increase in the mean equatorial diameter caused by the bulge in the Tharsis region (31). It is only when the scarp separating this flat region from the cratered highlands to the south is reached that the topography becomes rougher.

The only other place where such a smooth landscape has been observed on such a large scale is in the volcanic abyssal plains of Earth's oceans where the contours have been softened by eons of sedimentary deposition (31). While hardly proof, this does hint that the same processes that produced the abyssal plains of terrestrial oceans may have been at work at one time in Mars's northern hemisphere. If Oceanus Borealis actually existed, the Mars Orbiter Laser Altimeter topographic measurements indicate that it had a total volume of about 15 million cubic kilometers if it were just a kilometer deep (31). With a volume of about twice that of Earth's Arctic Ocean, Oceanus Borealis could have been filled in about a month or two by a single flood from a channel comparable in size to Ares Vallis, also measured by the Mars Orbiter Laser Altimeter.

While the recent findings of Mars Pathfinder and the Mars Global Surveyor offer compelling evidence that water existed on the ancient Martian surface, much more work remains to be done to determine if large standing bodies of water dotted the landscape and what effects they had on Mars's climatic history. Some of the expected remnants of ancient lakes or an ocean have yet to be found.

One of the more notable "fossils" expected from this warmer and wetter past is carbonates. Analysis of the Sojourner's alpha proton X-ray spectrometer data has yet to reveal any evidence for carbonates at the Mars Pathfinder landing site (42). The Mars Global Surveyor's Thermal Emission Spectrometer measurements have placed a qualitative upper limit of 10 percent on the concentration of carbonates in the areas it has observed to date (43).

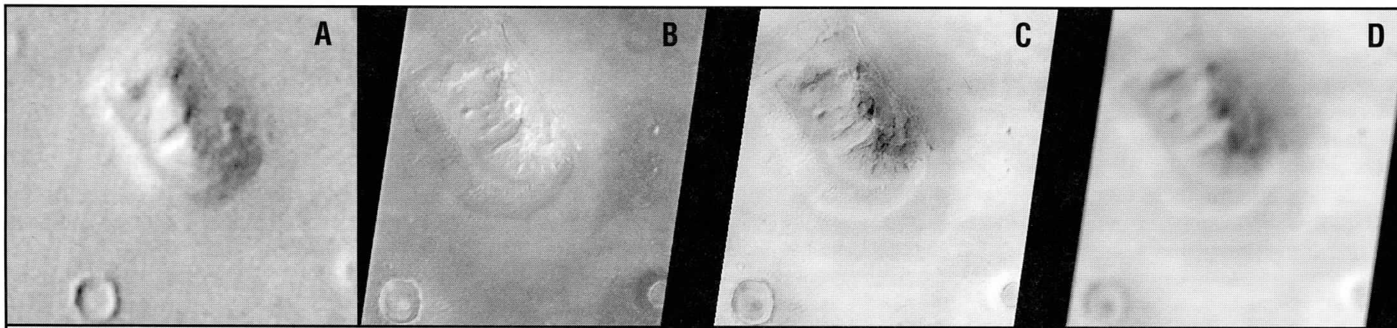
Answers to these questions will have a significant influence on our assessment of Mars's biological potential, past and present. Once the Mars Global Surveyor enters its final observation orbit around Mars, combined with the upcoming launches of additional probes to Mars as well as an eventual sample return mission, we may finally be able to make more definitive deductions of importance to exobiology.

REFERENCES

1) E.C. Slipher, "New Light on the Changing Face of Mars," ***National Geographic***, Vol. 108, No. 3, pp. 426-436, September 1955
2) Edward Clinton Ezell and Linda Neuman Ezell, *On Mars: The Exploration of the Red Planet 1958-1978*, NASA SP-4212, Washington, DC, 1984
3) Kenneth L. Tanaka, David H. Scott, and Ronald Greeley, "Global Stratigraphy," in *Mars*, Hugh H. Kieffer, Bruce M. Kakosky, Conway W. Snyder, and Mildred S. Matthews, eds., University of Arizona Press, pp. 345-382,1992
4) D.E. Wilhelms, "Geologic Mapping," in *Planetary Mapping*, Ronald Greeley and Raymond M. Batson, eds., Cambridge University Press, pp. 208-260,1990
5) Robert G. Strom, Steven K. Croft, and Nadine G. Barlow, "The Martian Impact Cratering Record," in *Mars*, Hugh H. Kieffer, Bruce M. Kakosky, Conway W. Snyder, and Mildred S. Matthews, eds., University of Arizona Press, pp. 383-423, 1992
6) Kenneth L. Tanaka, "The Stratigraphy of Mars," Proceedings of the 17th Lunar and Planetary Science Conference, ***Journal of Geophysical Research Supplement,*** Vol. 91, pp. E139-E158, November 30, 1986
7) Kenneth L. Tanaka and Phillip A. Davis, "Tectonic History of the Syria Planum Province of Mars," ***Journal of Geophysical Research***, Vol. 93, pp. 14893-14917, December 10, 1988
8) Harry Y. McSween Jr., "SNC Meteorites: Clue to Martian Petrological Evolution?" ***Reviews of Geophysical Research,*** Vol. 23, No. 4, pp. 391-416, November 1985
9) G. Dreibus et al., "Chemical and Mineral Composition of ALH84001: A Martian Orthopyroxenite," ***Meteoritics***, Vol. 29, No. 4, p. 461, 1994
10) H. Frey, S.E.H. Sakimoto, and J.H. Roark, "MOLA Topographic Constraints on the Nature and Origin of the Crustal Dichotomy Boundary Zone, Mars," Spring Meeting of the American Geophysical Union (AGU) (Boston, MA), Paper P31A-11, May 26-29, 1998
11) Michael H. Carr, *Water on Mars*, Oxford University Press, 1996
12) "Seepage and Ponding within a Southern Hemisphere Crater," Mars Global Surveyor MOC2-49 American Geophysical Union Press Conference Release, May 27, 1998
13) Kenneth L. Tanaka and David H. Scott, "Geologic Map of the Polar Regions of Mars," I-1802-C, USGS, 1987
14) Everett L. Shock, "High Temperature Life Without Photosynthesis as a Model for Mars," ***Journal of Geophysical Research—Planets***, Vol. 102, No. E10, pp. 23687-23694, October 25, 1997
15) "Mars Global Surveyor TES Instrument Identification of Hematite on Mars," NASA MGS TES (Thermal Emission Spectrometer) Press Release, May 27, 1998
16) David H. Scott and Kenneth L. Tanaka, "Geologic Map of the Western Equatorial Region of Mars," I-1802-A, USGS, 1986
17) Der-Chuen Lee and Alex N. Halliday, "Core Formation on Mars and the Differentiated Asteroids," ***Nature***, Vol. 388, pp. 854-857, August 28, 1997
18) Der-Chuen Lee et al., "Age and Origin of the Moon," ***Science***, Vol. 278, No. 5340, pp. 1098-1103, November 7, 1997
19) W.M. Folkner et al., "Interior Structure and Seasonal Mass Redistribution of Mars from Radio Tracking of Mars Pathfinder," ***Science***, Vol. 278, No. 5344, pp. 1749-1752, December 5, 1997
20) J.G. Luhmann et al., "The Intrinsic Magnetic Field and Solar-Wind Interaction of Mars," in *Mars*, Hugh H. Kieffer, Bruce M. Kakosky, Conway W. Snyder, and Mildred S. Matthews, eds., University of Arizona Press, pp. 1090-1134, 1992
21) M.H. Acuna et al., "Magnetic Field and Plasma Observations at Mars: Initial Results of the Mars Global Surveyor Mission," ***Science***, Vol. 279, No. 5357, pp. 1676-1680, March 13, 1998
22) B.K. Lucchitta et al., "The Canyon System on Mars," in *Mars*, Hugh H. Kieffer, Bruce M. Kakosky, Conway W. Snyder, and Mildred S. Matthews, eds., University of Arizona Press, pp. 453-492, 1992
23) M.C. Malin et al., "Early Views of the Martian Surface from the Mars Orbiter Camera of Mars Global Surveyor," ***Science***, Vol. 279, No. 5357, pp. 1681-1685, March 13, 1998
24) A.S. McEwen and M.C. Malin, "Layering in the Upper Crust of Mars Seen in Valles Marineris by the Mars Orbital Camera," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1908, March 16-20, 1998

25) Ronald Greeley and Byron D. Schneid, "Magma Generation on Mars–Amounts, Rates, and Comparisons with Earth, Moon, and Venus," ***Science***, Vol. 254, pp. 996-998, November 15, 1991
26) P.H. Smith et al., "Results from the Mars Pathfinder Camera," ***Science***, Vol. 278, No. 5344, pp. 1758-1765, December 5, 1997
27) R. Rieder et al., "The Chemical Composition of the Martian Soil and Rocks Returned by the Mobile Alpha X-ray Spectrometer: Preliminary Results from the X-ray Mode," ***Science***, Vol. 278, No. 5344, pp. 1771-1774, December 5, 1997
28) R. Cowen, "Postcards from the Red Planet," ***Science News***, Vol. 152, No. 2, pp. 20-21, July 12, 1997
29) H.Y. McSween Jr., J.P. Greenwood, and A. Ghosh, "Rocks of Andesitic Composition at the Mars Pathfinder Site: What Do They Mean?" 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1054, March 16-20, 1998
30) D.M. Nelson and R. Greeley, "Xanthe Terra Outflow Channel Geology at the Mars Pathfinder Landing Site," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1158, March 16-20, 1998
31) D.E. Smith et al., "Topography of the Northern Hemisphere of Mars from the Mars Orbiter Laser Altimeter," ***Science***, Vol. 279, No. 5357, pp. 1686-1692, March 13, 1998
32) G. Komatsu and V.R. Baker, "Paleohydrology and Flood Geomorphology of Ares Vallis," ***Journal of Geophysical Research—Planets***, Vol. 102, pp. 4151-4160, 1997
33) T. Basilevsky, W.J. Markiewicz, and H.U. Keller, "Morphology of Rocks within and Nearby Rock Garden: Mars Pathfinder Landing Site," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1378, March 16-20, 1998
34) Rover Team, "Characterization of the Martian Surface Deposits by the Mars Pathfinder Rover, Sojourner," ***Science***, Vol. 278, No. 5344, pp. 1765-1768, December 5, 1997
35) K.L. Tanaka, "Mars Pathfinder Landing Site: Regional Geology and Mass-Flow Interpretation," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1800, March 16-20, 1998
36) "Nanedi Vallis: Sustained Water Flow?" Mars Global Surveyor Press Release, February 2, 1998
37) T.J. Parker et al., "Transitional Morphology in the West Deuteronilus Mensae Region of Mars: Implications for Modification of the Lowland/Upland Boundary," ***Icarus***, Vol. 82, pp. 111-145, November 1989
38) T.J. Parker et al., "Coastal Geomorphology of the Martian Northern Plains," ***Journal of Geophysical Research—Planets***, Vol. 98, No. E6, pp. 11061-11078, June 15, 1993
39) V.R. Baker et al., "Ancient Oceans, Ice Sheets and the Hydrological Cycle on Mars," ***Nature***, Vol. 352, pp. 589-594, August 15, 1991
40) T.J. Parker, "Mapping of Possible 'Oceanus Borealis' Shorelines on Mars: A Status Report," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1965, March 16-20, 1998
41) W.B. Banerdt and T.J. Parker, "Elevations of the Ancient Shorelines on Mars Derived from the Mars Orbiter Laser Altimeter," Spring Meeting of the American Geophysical Union (AGU) (Boston, MA), Paper P31A-07, May 26-29, 1998
42) T.E. Economou et al., "The Chemical Composition of Martian Rocks and Soil: Preliminary Analysis," 29th Lunar and Planetary Science Conference (Houston, TX), Abstract No. 1711, March 16-20, 1998
43) P.R. Christensen et al., "Results from the Mars Global Surveyor Thermal Emission Spectrometer," ***Science***, Vol. 279, No. 5357, pp. 1692-1698, March 13, 1998
44) JPL Viking Press Release P-17384, July 31, 1976
45) V. DiPietro and G. Molenaar, *Unusual Martian Surface Features*, Mars Research, 1982
46) Randolfo Rafael Pozos, *The Face of Mars*, Chicago Review Press, 1986
47) Richard Grossinger, *Planetary Mysteries*, North Atlantic Books, 1986
48) Richard C. Hoagland, *The Monuments of Mars: A City on the Edge of Forever*, North Atlantic Books, 1987
49) Mark J. Carlotto, "Digital Imagery Analysis of Unusual Martian Surface Features," ***Applied Optics***, Vol. 27, No. 10, pp. 1926-1933, May 15, 1988
50) Brian O'Leary, "Analysis of Images of the 'Face' on Mars and Possible Intelligent Origin," ***Journal of the British Interplanetary Society***, Vol. 43, No. 5, pp. 203-208, May 1990
51) Mark J. Carlotto and Michael C. Stein, "A Method for Searching for Artificial Objects on Planetary Surfaces," ***Journal of the British Interplanetary Society***, Vol. 43, No. 5, pp. 209-216, May 1990
52) "Mars Orbiter Camera Views 'Face on Mars'," Mars Global Surveyor Press Release, April 6, 1998

ANDREW J. LEPAGE *is a scientist at Visidyne, Inc., where he specializes in the processing and analysis of satellite imagery. He is a freelance writer and regular contributor to* SETIQuest, *where he serves as a member of the Editorial Board. He can be contacted via e-mail at* ***lepage@bur.visidyne.com***



IMAGES COURTESY OF MALIN SPACE SCIENCE SYSTEMS/NASA

Resolving the 'Face on Mars' Controversy

Probably one of the best known features on the Red Planet that has been widely discussed in the popular press has been the "Face on Mars" shown in Panel **A** of the figure above. Located at 40.8 degrees north, 9.6 degrees west among a group of isolated hills and mesas called Cydonia Mensae, this two-kilometer-wide hill resembled a human face in Viking orbiter images (44). As with New Hampshire's famous "Old Man of the Mountain," this feature is generally thought to be a hill that by chance has eroded into a shape that looks like a face under certain lighting and viewing conditions. Geologically, the hills and mesas of the area are thought to be outcrops of erosion-resistant Noachian and Hesperian highland on the border between the old highlands of Arabia Terra and the young lowlands of Acidalia Planitia surrounded by deposits laid down as recently as the Amazonian epoch (16).

But in the 1980s, a vocal minority began to make claims for a much different theory of the origin of these features. An examination of Viking images indicated that the face was not an artifact of noise; the rectilinear placement of this and other nearby hills suggested to the proponents of the ideas that they were part of a complex of artificial structures constructed by some alien race (45,46,47,48). Subsequent detailed analysis of the images of the face showed that its appearance was not merely an illusion but that, at least to the limits of the images' resolution, it actually had the three-dimensional structure of a human face (49,50). "Fractal analysis" of the face and the hills in the putative city were also said to strongly suggest an artificial origin (51).

To help settle the issue of the origin of these features, the Mars Global Surveyor obtained an image of the face on April 5, 1998. With a resolution of about four meters, the new image has more than ten times the resolution of the best Viking orbiter images obtained two decades ago. The new image, shown in Panel **B** of the figure above, clearly resolves the face into a badly eroded ridge of hills surrounded by an apron of debris (52).

To better simulate the different lighting conditions of the original Viking images, a reverse contrast version of the Mars Global Surveyor image shown in Panel **C** was prepared by mission scientists. Despite this adjustment some still find it difficult to see the face, so in Panel **D** I have further degraded the resolution of the digital image to enhance the appearance of the face.

While there are still those who believe that these features are constructed by aliens and charge that NASA is conspiring to hide the real images, in scientific circles the question of the origin of the face seems to be settled, as the late Carl Sagan predicted. **—AJL**