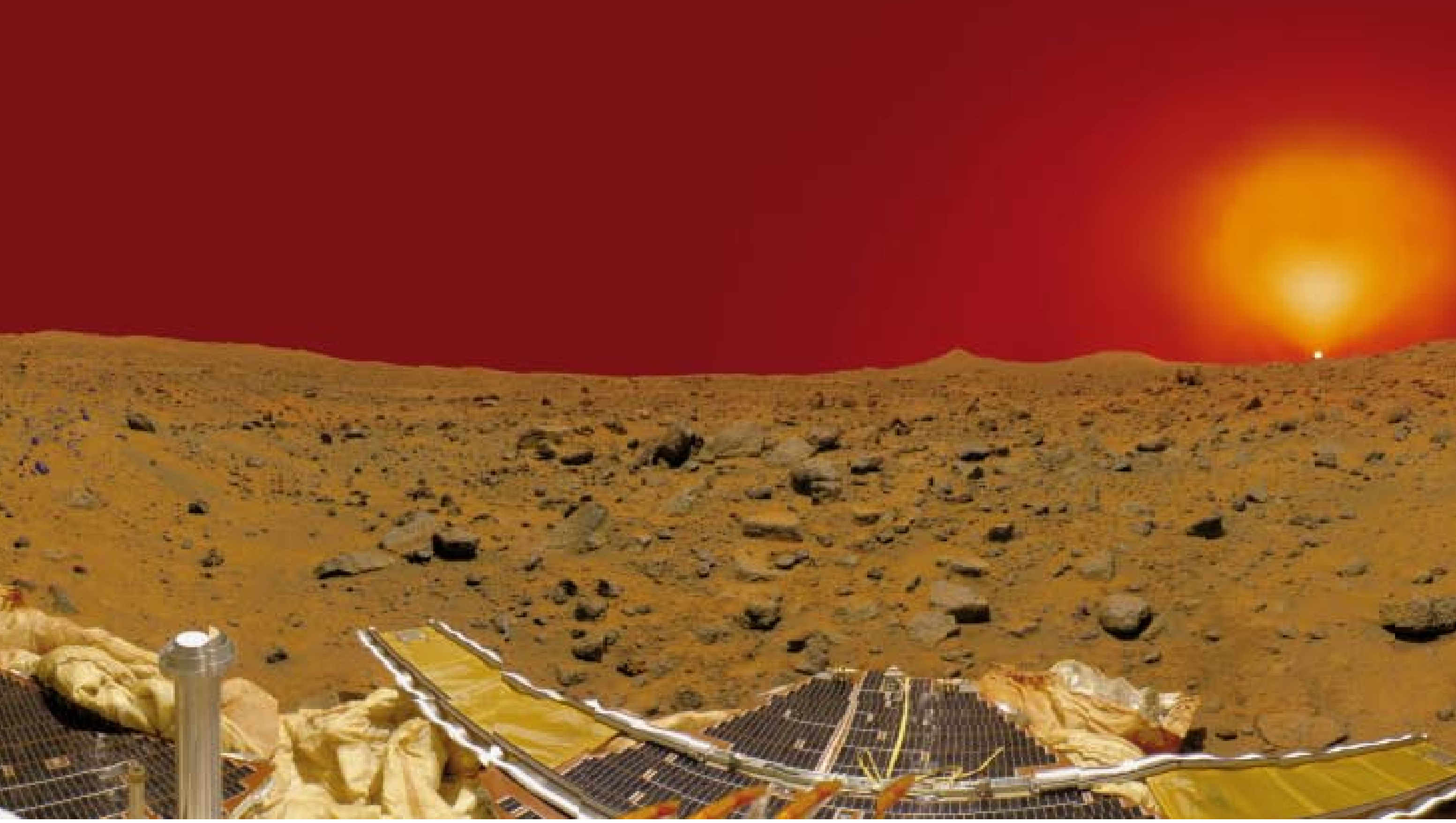
The Mars Pathfinder



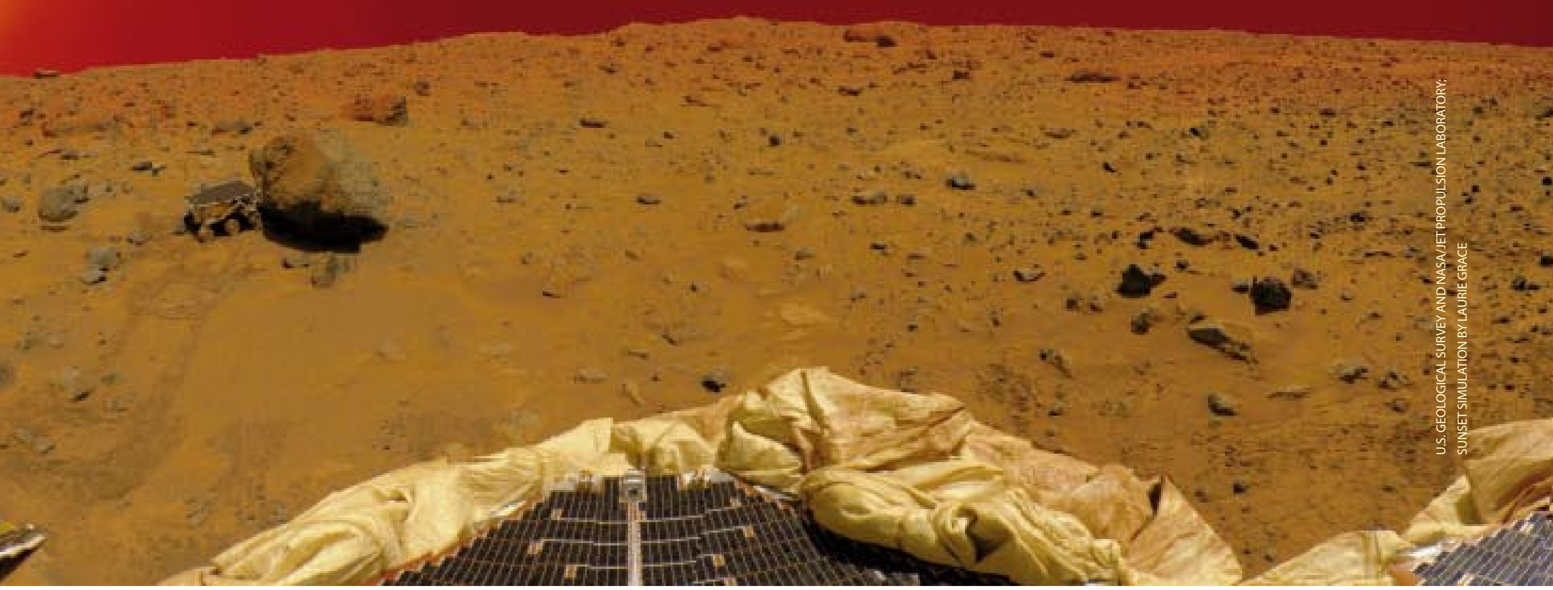
Rocks, rocks, look at those rocks," I exclaimed to everyone in the Mars Pathfinder control room at about 4:30 P.M. on July 4, 1997. The Pathfinder lander was sending back its first images of the surface of Mars, and everyone was focused on the television screens. We had gone to Mars to look at rocks, but no one knew for sure whether we would find any, because the landing site had been selected using orbital images with a resolution of roughly a kilometer. Pathfinder could have landed on a flat, rock-free plain. The first radio downlink indicated that the lander was nearly horizontal, which was worrisome for those of us interested in rocks, as most expected that a rocky surface would result in a tilted lander. The very first images were of the lander so that we could ascertain its condition, and it was not until a few tense minutes later that the first pictures of the surface showed a rocky plain—exactly as we had hoped and planned for.

Why did we want rocks? Every rock carries the history of its formation locked in its minerals, so we hoped the rocks would tell us about the early Martian environment. The two-part Pathfinder payload, consisting of a main lander with a multispectral camera and a mobile rover with a chemical analyzer, was suited to looking at rocks. Although it could not identify the minerals directly—its analyzer could measure only their constituent chemical elements—our plan was to identify them indirectly based on the elemental composition and the shapes, textures and colors of the rocks. By landing Pathfinder at the mouth of a giant channel where a huge vol-

Mission

The first rover to explore Mars found in situ evidence that the Red Planet may once have been hospitable to life

by Matthew P. Golombek



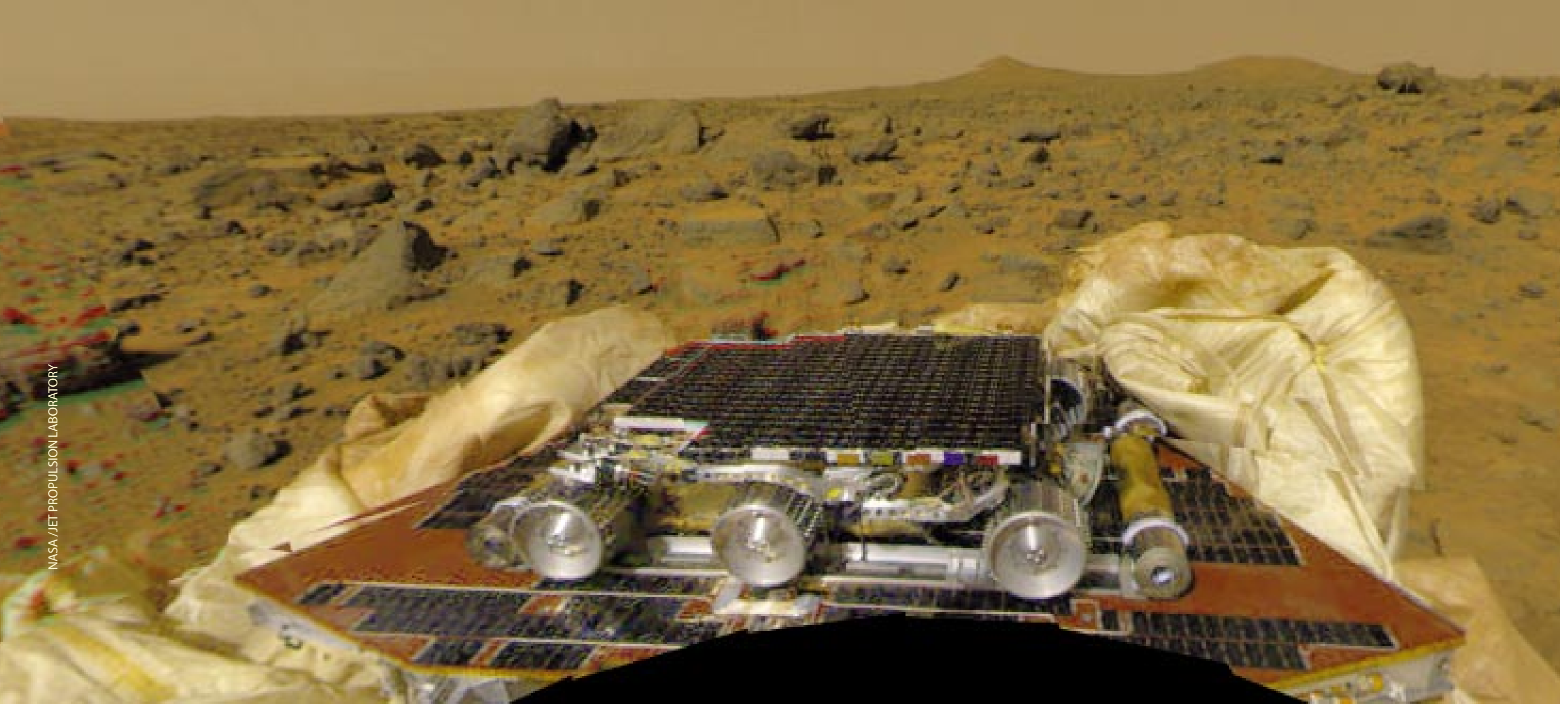
U.S. GEOLOGICAL SURVEY AND NASA/JET PROPULSION LABORATORY; SUNSET SIMULATION BY LAURIE GRACE

TWILIGHT AT ARES VALLIS, Pathfinder's landing site, is evoked in this 360-degree panorama, a composite of a true sunset (*inset at left*) and other images. The rover is analyzing the rock Yogi to the right of the lander's rear ramp. Farther right are whitish-pink patches on the ground known as Scooby Doo (*closer to lander*) and Baker's Bench. The rover tried to scratch the surface of Scooby Doo but could not, indicating that the soil in these patches is cemented together. The much studied Rock Garden appears left of center. Flat Top, the flat rock in front of the garden, is covered with dust, but steep faces on other large rocks are clean; the rover analyzed all of them. (In this simulation, parts of the sky and terrain were computer-adjusted to complete the scene. During a real sunset, shadows would of course be longer and the ground would appear darker.) —*The Editors*

ume of water once flowed briefly, we sought rocks that had washed down from the ancient, heavily cratered highlands. Such rocks could offer clues to the early climate of Mars and to whether conditions were once conducive to the development of life [*see top illustration on page 36*].

The most important requirement for life on Earth (the only kind we know) is liquid water. Under present conditions on Mars, liquid water is unstable: because the temperature and pressure are so low, water is stable only as ice or vapor; liquid would survive for just a brief time before freezing or evaporating. Yet Viking images taken two decades ago show drainage channels and evidence for lakes in the highlands. These features hint at a warmer and wetter past on Mars in which water could persist on the surface [see "Global Climatic Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; Scientific American, November 1996]. To be sure, other explanations have also been suggested, such as sapping processes driven by geothermal heating in an otherwise frigid and dry environment. One of Pathfinder's scientific goals was to look for evidence of a formerly warm, wet Mars.

The possible lake beds are found in terrain that, judging from its density of impact craters, is roughly the same age as the oldest rocks on Earth, which show clear evidence for life 3.9 billion to 3.6 billion



FIRST IMAGES
from Mars Pathfinder were assembled into this panorama of dark rocks, yellowish-brown dust and a butterscotch sky. Many rocks, particularly in the Rock Garden (*center*), are inclined and stacked—a sign that they were deposited by fast-moving water. About a kilometer behind the garden on the west-southwest horizon are the Twin Peaks, whose prominence identified the landing site on Viking orbiter images. After touching down, the lander pulled back the air bag and unfurled two ramps; the rover trundled down the rear ramp onto the surface the next day. (The small green and red streaks are artifacts of data compression.)

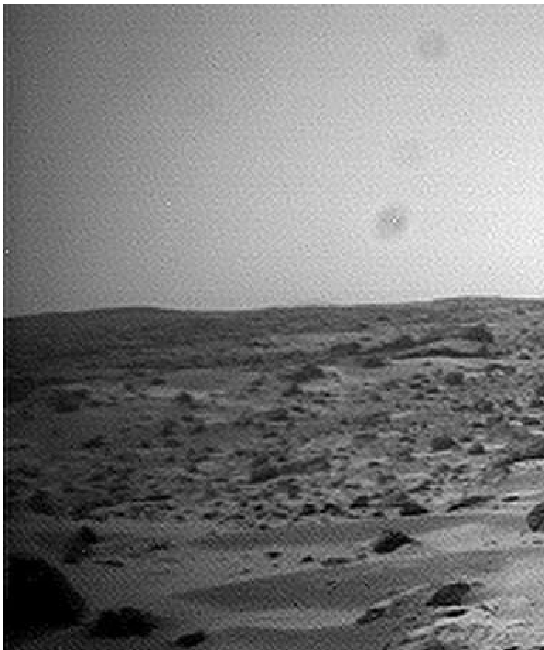
years ago. If life was able to develop on Earth at this time, why not on Mars, too, if the conditions were similar? This is what makes studying Mars so compelling. By exploring our neighboring planet, we can seek answers to some of the most important questions in science: Are we alone in the universe? Will life arise anywhere that liquid water is stable, or does the formation of life require something else as well? And if life did develop on Mars, what happened to it? If life did not develop, why not?

Pathfinding

Pathfinder was a Discovery-class mission—one of the National Aeronautics and Space Administration's "faster, cheaper, better" spacecraft—to demonstrate a low-cost means of landing a small payload and mobile vehicle on Mars. It was developed, launched and operated under a fixed budget comparable to that of a major motion picture (between $200 million and $300 million), which is a mere fraction of the budget typically allocated for space missions. Built and launched in a short time (three and a half years), Pathfinder included three science instruments: the Imager for Mars Pathfinder, the Alpha Proton X-ray Spectrometer and the Atmospheric Structure Instrument/Meteorology Package. The rover itself also acted as an instrument; it was used to conduct 10 technology experiments, which studied the abrasion of metal films on a wheel of the rover and the adherence of dust to a solar cell as well as other ways the equipment on Pathfinder reacted to its surroundings.

In comparison, the Viking mission, which included two orbiter-lander pairs, was carried out more than 20 years ago at roughly 20 times the cost. Viking was very successful, returning more than 57,000 images that scientists have been studying ever since. The landers carried sophisticated experiments that tested for organisms at two locations; they found none.

The hardest part of Pathfinder's mission was the five minutes during which the spacecraft went from the relative security of interplanetary cruising to the stress of atmospheric entry, descent and landing [*see illustration on page 37*]. In that short time, more than 50 critical events had to be triggered at exactly the right times for the spacecraft to land safely. About 30 minutes before entry, the backpack-style cruise stage separated



SAND DUNES
provide circumstantial evidence for a watery past. These dunes, which lay in the trough behind the Rock Garden, are thought to have formed when windblown sand hopped up the gentle slope to the dune crest and cascaded down the steep side (which faces away from the rover in this image). Larger dunes have been observed from orbit, but none in the Pathfinder site. The discovery of these smaller dunes suggests that sand is more common on Mars than scientists had thought. The formation of sand on Earth is principally accomplished by moving water.

from the rest of the lander. At 130 kilometers above the surface, the spacecraft entered the atmosphere behind a protective aeroshell. A parachute unfurled 134 seconds before landing, and then the aeroshell was jettisoned. During descent, the lander was lowered beneath its back cover on a 20-meter-long bridle, or tether.

As Pathfinder approached the surface, its radar altimeter triggered the firing of three small solid-fuel rockets to slow it down further. Giant air bags inflated around each face of the tetrahedral lander, the bridle was cut, and the lander bounced onto the Martian surface at 50 kilometers per hour. Accelerometer measurements indicate that the air-bag-enshrouded lander bounced at least 15 times without losing air-bag pressure. After rolling at last to a stop, the lander deflated the air bags and opened to begin surface operations.

Although demonstrating this novel landing sequence was actually Pathfinder's primary goal, the rest of the mission also met or exceeded expectations. The lander lasted three times longer than its minimum design criteria, the rover 12 times longer. The mission returned 2.3 billion bits of new data from Mars, including more than 16,500 lander and 550 rover images and roughly 8.5 million individual temperature, pressure and wind measurements. The rover traversed a total of 100 meters in 230 commanded movements, thereby exploring more than 200 square meters of the surface. It obtained 16 measurements of rock and soil chemistry, performed soil-mechanics experiments and successfully completed the numerous technology experiments. The mission also captured the imagination of the public, garnering front-page headlines for a week, and became the largest Internet event in history at the time, with a total of about 566 million hits for the first month of the mission—47 million on July 8 alone.

Flood Stage

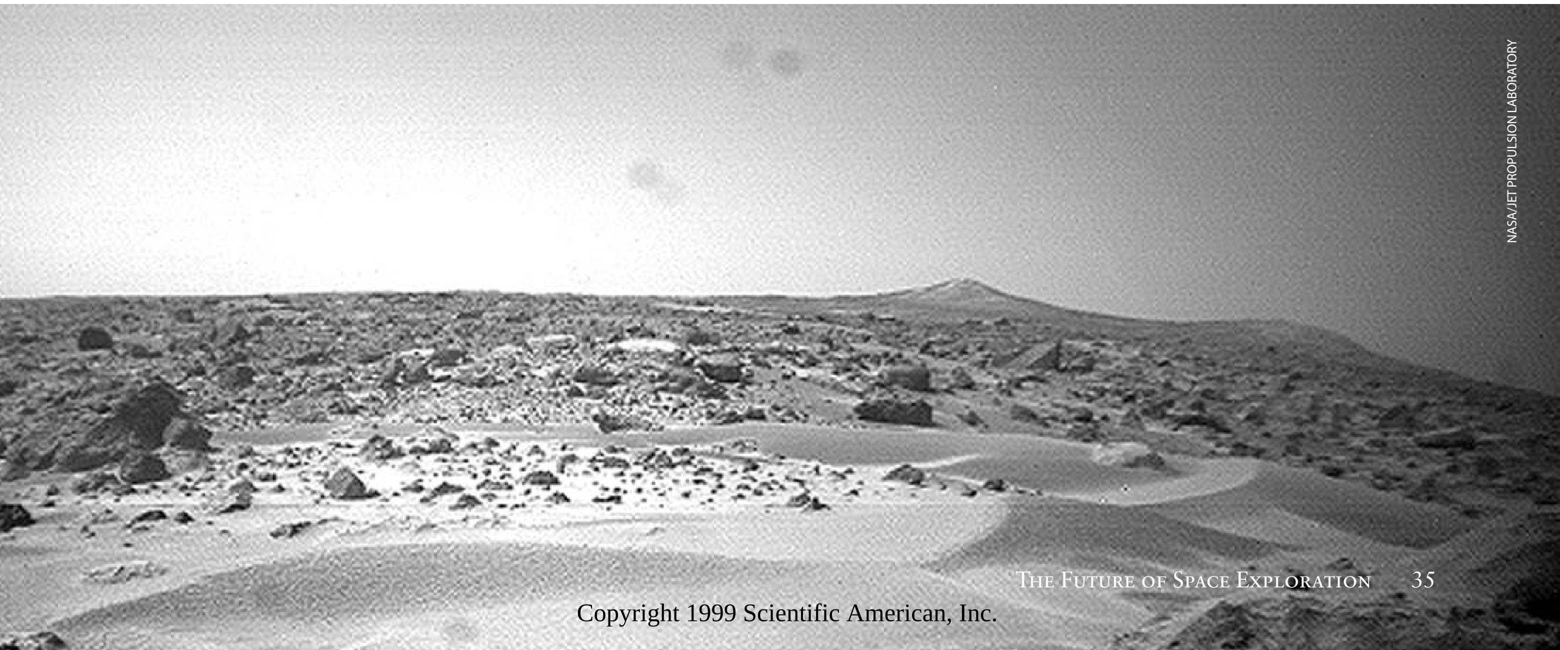
The mosaic of the landscape constructed from the first images revealed a rocky plain (about 20 percent of which was covered by rocks) that appears to have been deposited and shaped by catastrophic floods [*see top illustration on opposite page*]. This was what we had predicted based on remote-sensing data and the location of the landing site (19.13 degrees north, 33.22 degrees west), which is downstream from the mouth of Ares Vallis in the low area known as Chryse Planitia. In Viking orbiter images, the area appears analogous to the Channeled Scabland in eastern and central Washington State. This analogy suggests that Ares Vallis formed when roughly the same volume of water as in the Great Lakes (hundreds of cubic kilometers) was catastrophically released, carving the observed channel in a few weeks. The density of impact craters in the region indicates it formed at an intermediate time in Mars's history, somewhere between 1.8 billion and 3.5 billion years ago.

The Pathfinder images support this interpretation. They show semirounded pebbles, cobbles and boulders similar to those deposited by terrestrial catastrophic floods. Rocks in what we dubbed the Rock Garden, a collection of rocks to the southwest of the lander, with the names Shark, Half Dome and Moe, are inclined and stacked, as if deposited by rapidly flowing water. Large rocks in the images (0.5 meter or larger) are flat-topped and often perched, also consistent with deposition by a flood. Twin Peaks, a pair of hills on the southwest horizon, are streamlined. Viking images suggest that the lander is on the flank of a broad, gentle ridge trending northeast from Twin Peaks; this ridge may be a debris tail deposited in the wake of the peaks. Small channels throughout the scene resemble those in the Channeled Scabland, where drainage in the last stage of the flood preferentially removed fine-grained materials.

By exploring our neighboring planet, we can seek answers to some of the most important questions in science.

The rocks in the scene are dark gray and covered with various amounts of yellowish-brown dust. This dust appears to be the same as that seen in the atmosphere, which, as imaging in different filters and locations in the sky suggests, is very fine grained (a few microns in diameter). The dust also collected in wind streaks behind rocks.

Some of the rocks have been fluted and grooved, presumably by sand-size particles (less than one millimeter) that hopped along the surface in the wind. The rover's camera also saw sand dunes in the trough behind the Rock Garden [*see illustration below*]. Dirt covers the lower few centimeters of some rocks, suggesting that they have been exhumed by wind. Despite these signs of slow erosion by the wind, the rocks and surface appear to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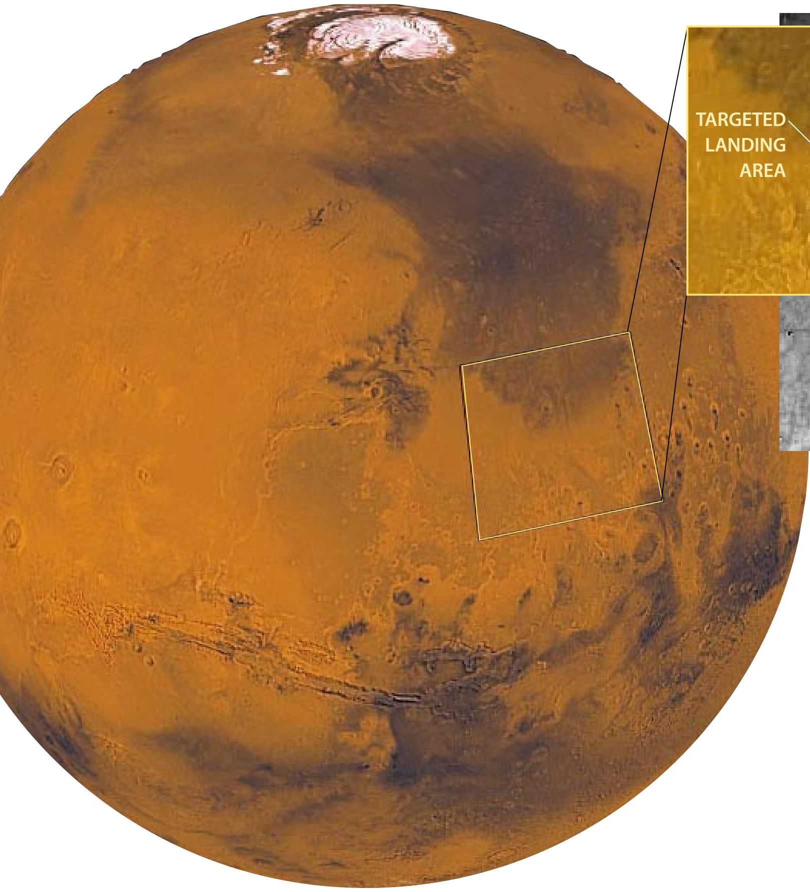
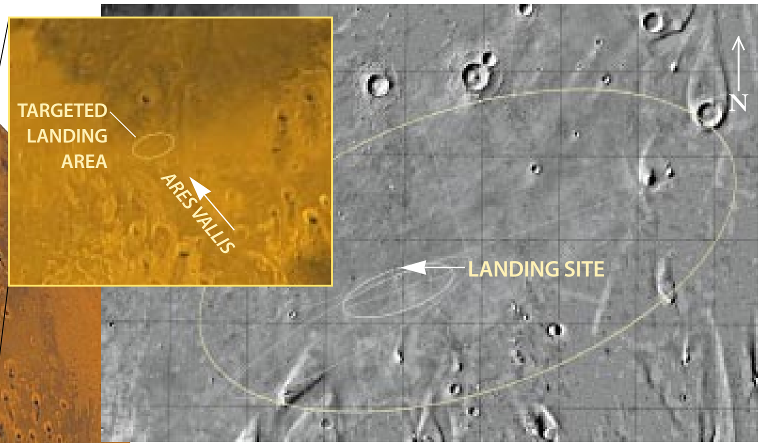




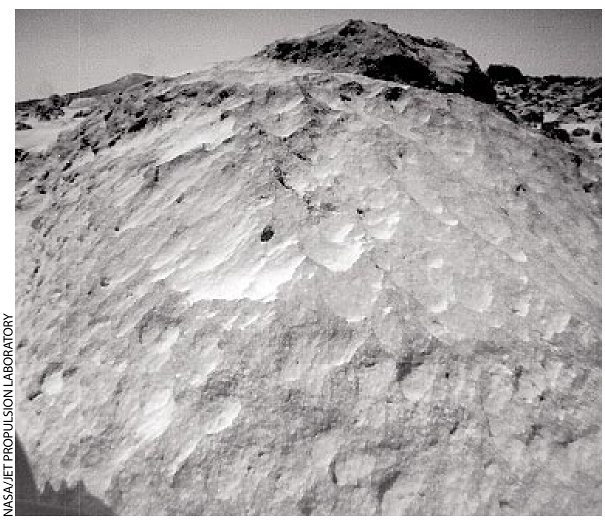
U.S. GEOLOGICAL SURVEY

LANDING SITE
is an outflow channel carved by mammoth floods billions of years ago. It was chosen as the Pathfinder landing site for three reasons: it seemed safe, with no steep slopes or rough surfaces detected by the Viking orbiters or Earth-based radars; it had a low elevation, which provided enough air density for parachutes; and it appeared to offer a variety of rock types deposited by the floods. The cratered region to the south is among the oldest terrain on Mars. The ellipses mark the area targeted for landing, as refined several times during the final approach to Mars; the arrow in the larger inset identifies the actual landing site; the arrow in the smaller inset indicates the presumed direction of water flow.

have changed little since they were deposited by the flood.

The Alpha Proton X-ray Spectrometer on the rover measured the compositions of eight rocks. The silicon content of some of the rocks is much higher than that of the Martian meteorites, our only other samples of Mars. The Martian meteorites are all mafic igneous rocks, volcanic rocks that are relatively low in silicon and high in iron and magnesium. Such rocks form when the upper mantle of a planet melts. The melt rises up through the crust and solidifies at or near the surface. These types of rocks, referred to as basalts, are the most common rock on Earth and have also been found on the moon. Based on the composition of the Martian meteorites and the presence of plains and mountains that look like features produced by basaltic volcanism on Earth, geologists expected to find basalts on Mars.

The rocks analyzed by Pathfinder, however, are not basalts. If they are volcanic, as suggested by their vesicular surface texture, presumably formed when gases trapped during cooling left small holes in the rock, their silicon content classifies them as andesites. Andesites form when the basaltic melt from the mantle intrudes deep within the crust. Crystals rich in iron and magnesium form and sink back down, leaving a more silicon-rich melt that erupts onto the surface. The andesites were a great surprise, but because we do not know where these rocks came from on the Martian surface, we do not know the full implications of this discovery. If the andesites are representative of the highlands, they suggest that ancient crust on Mars is similar in composition to continental crust on Earth. This similarity would be difficult to reconcile with the very different geologic histories of the two planets. Alternatively, the rocks could represent a minor proportion of high-silicon rocks from a predominately basaltic plain.



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SANDBLASTED ROCK
named Moe resembles terrestrial rocks known as ventifacts. Their fluted texture develops when sand-size particles hop along the surface in the wind and erode rocks in their path. On Earth, such particles are typically produced when water breaks down rocks. Moe's grooves all point to the northwest, which is roughly the same orientation as the grooves seen on other rocks at the site.

Sedimentary Rocks?

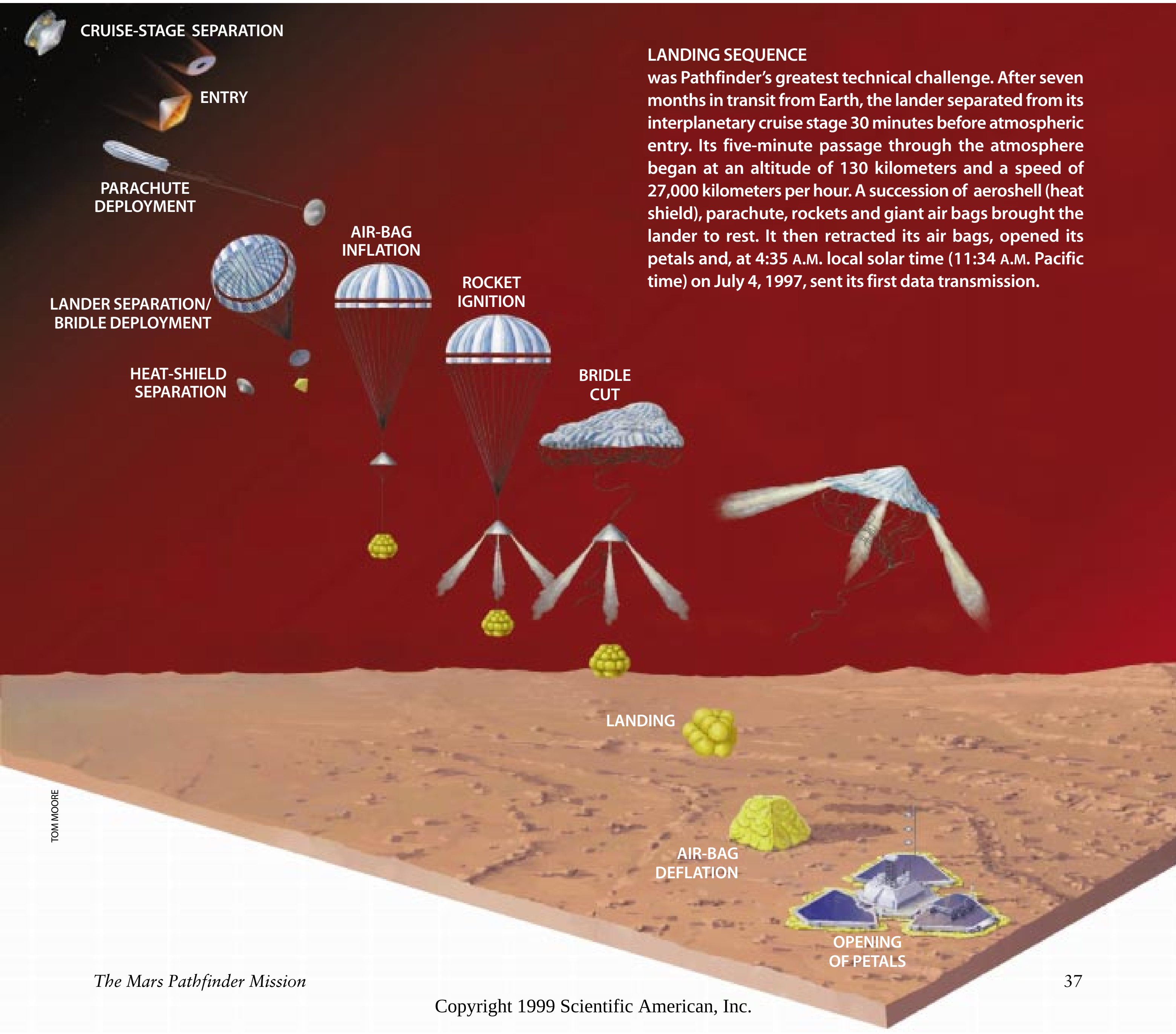
Intriguingly, not all the rocks appear to be volcanic, judging by the diversity of morphologies, textures and fabrics observed in high-resolution images. Some rocks appear similar to impact breccias, which are composed of angular fragments of different materials. Others have layers like those in terrestrial sedimentary rocks, which form by deposition of smaller fragments of rocks in water. Indeed, rover images show many rounded pebbles and cobbles on the ground. In addition, some larger rocks have what look like embedded pebbles and shiny indentations, where it looks as though rounded pebbles that were pressed into the rock during its formation have fallen out, leaving holes. These rocks may be conglomerates formed by flowing liquid water. The water would have rounded the pebbles and deposited them in a sand, silt and clay matrix; the matrix was subsequently compressed, forming a rock, and carried to its present location by the flood. Because conglomerates require a long time to form, if these Martian rocks are conglomerates (other interpretations are also possible) they strongly suggest that liquid water was once stable on the planet and that the climate was therefore warmer and wetter than at present.

Soils at the landing site vary from bright reddish dust to darker-red and darker-gray material, generally consistent with fine-grained iron oxides. Overall, the soils are lower in silicon than the rocks and richer in sulfur, iron and magnesium. Soil compositions are generally similar to those measured at the Viking sites, which are on opposite hemispheres (Viking 1 is 800 kilometers west of Pathfinder; Viking 2 is thousands of kilometers away on the opposite, eastern side of the northern hemisphere). Thus, the soil appears to include materials distributed globally on Mars, such as the airborne dust. The similarity in compositions among the soils implies that the variations in color at each site may be the result of slight differences in iron mineralogy or in particle size and shape [*see top right illustration on next page*].

A bright reddish or pink material also covered part of the site. Similar to the soils in composition, it seems to be indurated or cemented because it was not damaged by scraping with the rover wheels.

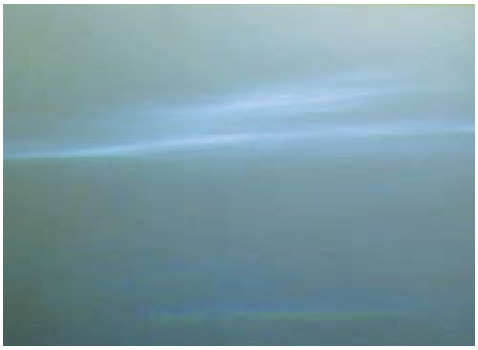
Pathfinder also investigated the dust in the atmosphere of Mars by observing its deposition on a series of magnetic targets on the spacecraft. The dust, it turned out, is highly magnetic. It may consist of small silicate (perhaps clay) particles, with some stain or cement of a highly magnetic mineral known as maghemite. This finding, too, is consistent with a watery past. The iron may have dissolved out of crustal materials in water, and the maghemite may be a freeze-dried precipitate.

The sky on Mars had the same butter-



LANDING SEQUENCE was Pathfinder's greatest technical challenge. After seven months in transit from Earth, the lander separated from its interplanetary cruise stage 30 minutes before atmospheric entry. Its five-minute passage through the atmosphere began at an altitude of 130 kilometers and a speed of 27,000 kilometers per hour. A succession of aeroshell (heat shield), parachute, rockets and giant air bags brought the lander to rest. It then retracted its air bags, opened its petals and, at 4:35 A.M. local solar time (11:34 A.M. Pacific time) on July 4, 1997, sent its first data transmission.

WISPY, BLUE CLOUDS in the dawn sky, shown in this color-enhanced image taken on sol 39 (the 39th Martian day after landing), probably consist of water ice. During the night, water vapor froze around fine-grained dust particles; after sunrise, the ice evaporated. The total amount of water vapor in the present-day Martian atmosphere is paltry; if it all rained out, it would cover the surface to a depth of a hundredth of a millimeter. The basic appearance of the atmosphere is similar to what the Viking landers saw more than 20 years ago.



MULTICOLORED SOILS were exposed by the rover's wheels. The rover straddles Mermaid Dune, a pile of material covered by dark, sand-size granules. Its wheel tracks also reveal dark-red soil (*bottom left*) beneath the bright-reddish dust. Scientists were able to deduce the properties of surface materials by studying the effect that the wheels had on them.

PHOTOGRAPHS BY NASA/JET PROPULSION LABORATORY

scotch color as it did when imaged by the Viking landers. Fine-grained dust in the atmosphere would explain this color. Hubble Space Telescope images had suggested a very clear atmosphere; scientists thought it might even appear blue from the surface. But Pathfinder found otherwise, suggesting either that the atmosphere always has some dust in it from local dust storms or dust devils, or that the atmospheric opacity varies appreciably over a short time. The inferred dust-particle shape and size (a few microns in diameter) and the amount of water vapor in the atmosphere (equivalent to a pitiful hundredth of a millimeter of rainfall) are also consistent with measurements made by Viking. Even if Mars was once lush, it is now drier and dustier than any desert on Earth.

Freezing Air

The meteorological sensors gave further information about the atmosphere. They found patterns of diurnal and longer-term pressure and temperature fluctuations. The temperature reached its maximum of 263 kelvins (–10 degrees Celsius) every day at 2:00 P.M. local solar time and its minimum of 197 kelvins (–76 degrees C) just before sunrise. The pressure minimum of just under 6.7 millibars (roughly 0.67 percent of pressure at sea level on Earth) was reached on sol 21, the 21st Martian day after landing. On Mars the air pressure varies with the seasons. During winter, it is so cold that 20 to 30 percent of the entire atmosphere freezes out at the pole, forming a huge pile of solid carbon dioxide. The pressure

Summary of Evidence for a Warmer, Wetter Mars

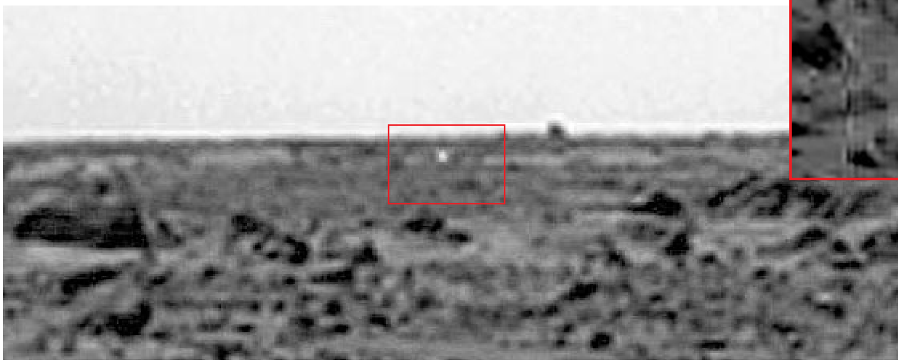
Over the past three decades, scientists have built the case that Mars once looked much like Earth, with rainfall, rivers, lakes, maybe even an ocean. Pathfinder has added evidence that strengthens this case (*red*).

GEOLOGIC FEATURE	PROBABLE ORIGIN	IMPLICATION
Riverlike valley networks	Water flow out of ground or from rain	Either atmosphere was thicker (allowing rain) or geothermal heating was stronger (causing groundwater sapping)
Central channel ("thalweg") in broader valleys	Fluid flow down valley center	Valleys were formed by water flow, not by landslides or sapping
Lakelike depressions with drainage networks; layered deposits in canyons	Flow through channels into lake	Water existed at the surface, but for unknown time
Possible strand lines and erosional beaches and terraces	Possible shoreline	Northern hemisphere might have had an ocean
Rimless craters and highly eroded ancient terrain	High erosion rates	Water, including rain, eroded surface
Rounded pebbles and possible conglomerate rock	Rock formation in flowing water	Liquid water was stable, so atmosphere was thicker and warmer
Abundant sand	Action of water on rocks	Water was widespread
Highly magnetic dust	Maghemite stain or cement on small (micron-size) silicate grains	Active hydrologic cycle leached iron from crustal materials to form maghemite

LISA BURNETT

PIECES OF PATHFINDER

spacecraft show up as bright spots in these highly magnified images. The heat shield (*below*) fell about two kilometers southwest of the lander. The backshell (*right*) landed just over a kilometer to the southeast. These resting places and the location of the lander indicate that a breeze was blowing from the southwest.



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minimum seen by Pathfinder indicates that the atmosphere was at its thinnest, and the south polar cap its largest, on sol 21.

Morning temperatures fluctuated abruptly with time and height; the sensors positioned 0.25, 0.5 and one meter above the spacecraft took different readings. If you were standing on Mars, your nose would be at least 20 degrees C colder than your feet. This suggests that cold morning air is warmed by the surface and rises in small eddies, or whirlpools, which is very different from what happens on Earth, where such large temperature disparities do not occur. Afternoon temperatures, after the air has warmed, do not show these variations.

In the early afternoon, dust devils repeatedly swept across the lander. They showed up as sharp, short-lived pressure changes with rapid shifts in wind direction; they also appear in images as dusty funnel-shaped vortices tens of meters across and hundreds of meters high. They were probably similar to events detected by the Viking landers and orbiters and may be an important mechanism for raising dust into the Martian atmosphere. Otherwise, the prevailing winds were light (clocked at less than 36 kilometers per hour) and variable.

Pathfinder measured atmospheric conditions at higher altitudes during its descent. The upper atmosphere (altitude above 60 kilometers) was colder than Viking had measured. This finding may simply reflect seasonal variations and the time of entry: Pathfinder came in at 3:00 A.M. local solar time, whereas Viking arrived at 4:00 P.M., when the atmosphere is naturally warmer. The lower atmosphere was similar to that measured by Viking, and its conditions can be attributed to dust mixed uniformly in comparatively warm air.

As a bonus, mission scientists were able to use radio communications signals from Pathfinder to measure the rotation of Mars. Daily Doppler tracking and less frequent two-way ranging during communication sessions determined the position of the lander with a precision of 100 meters. The last such positional measurement was done by Viking more than 20 years ago. In the interim, the pole of rotation has precessed—that is, the direction of the tilt of the planet has changed, just as a spinning top slowly wobbles. The difference between the two positional measurements yields the precession rate. The rate is governed by the moment of inertia of the planet, a function of the distribution of mass within the planet. The moment of inertia had been the single most important number about Mars that we did not yet know.

From Pathfinder's determination of the moment of inertia we now know that Mars must have a central metallic core that is between 1,300 and 2,400 kilometers in radius. With assumptions about the mantle composition, derived from the compositions of the Martian meteorites and the rocks measured by the rover, scientists can now start to put constraints on interior temperatures. Before Pathfinder, the composition of the Martian meteorites argued for a core, but the size of this core was completely unknown. The new information about the interior will help geophysicists understand how Mars has evolved over time. In addition to the long-term precession, Pathfinder detected an annual variation in the planet's rotation rate, which is just what would be expected from the seasonal exchange of carbon dioxide between the atmosphere and the ice caps.

Taking all the results together suggests that Mars was once more Earth-like than previously appreciated. Some crustal materials on Mars resemble, in silicon content, continental crust on Earth. Moreover, the rounded pebbles and the possible conglomerate, as well as the abundant sand- and dust-size particles, argue for a formerly water-rich planet. The earlier environment may have been warmer and wetter, perhaps similar to that of the early Earth. In contrast, since floods produced the landing site 1.8 billion to 3.5 billion years ago, Mars has been a very un-Earth-like place. The site appears almost unaltered since it was deposited, indicating very low erosion rates and thus no water in relatively recent times.

Although we are not certain that early Mars was more like Earth, the data returned from Pathfinder are very suggestive. Information from the Mars Global Surveyor, now orbiting the Red Planet, should help answer this crucial question about our neighboring world. SA

Matthew P. Golombek is project scientist of Mars Pathfinder, with responsibility for the overall scientific content of the mission. He conducts his work at the Jet Propulsion Laboratory in Pasadena, Calif. He is chair of the Pathfinder Project Science Group, deputy of the Experiment Operations Team and a member of the project management group. He has written numerous papers on the spacecraft and its results and has organized press conferences and scientific meetings. Golombek's research focuses on the structural geology and tectonics of Earth and the other planets, particularly Mars. This article updates a version that appeared in the July 1998 issue of *Scientific American*.