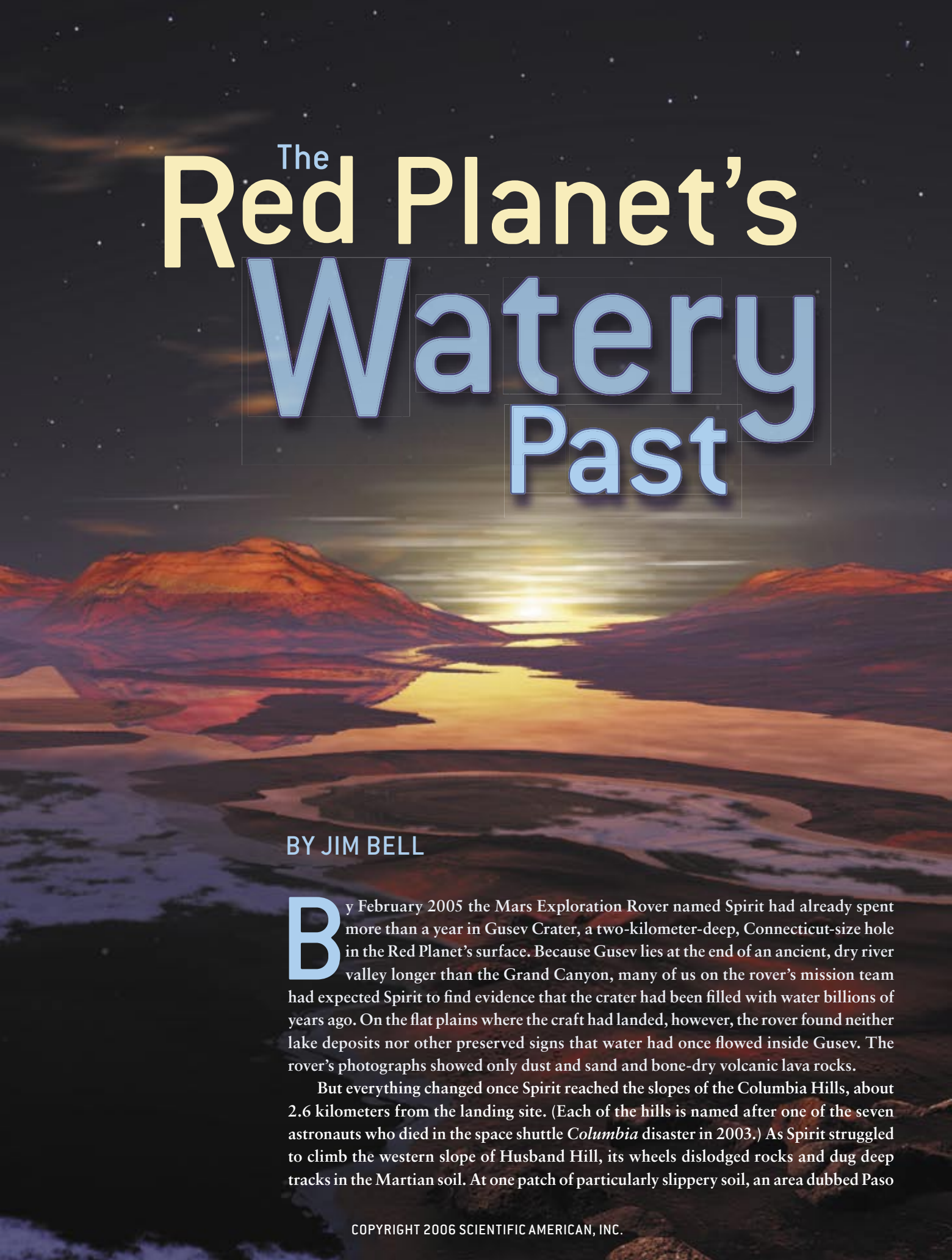
An artist's rendering of a Martian landscape. In the foreground, there are dark, rocky terrain and a large, dark body of water. The water reflects the sky and the surrounding landscape. In the middle ground, there are large, reddish-brown mountains with some darker patches. The sky is dark with many stars and a few crescent moons. The overall scene is a twilight view of a wet Mars.

New observations by rovers and orbiters
indicate that liquid water not only
existed on Mars, it once covered large
parts of the planet's surface, perhaps
for more than a billion years

WATER FLOWS ACROSS the Martian surface in an artist's rendering of how the Red Planet may have looked 2.5 billion to four billion years ago. Salt deposits along the water's edge appear purple in this twilight view.



The Red Planet's Watery Past

BY JIM BELL

By February 2005 the Mars Exploration Rover named Spirit had already spent more than a year in Gusev Crater, a two-kilometer-deep, Connecticut-size hole in the Red Planet's surface. Because Gusev lies at the end of an ancient, dry river valley longer than the Grand Canyon, many of us on the rover's mission team had expected Spirit to find evidence that the crater had been filled with water billions of years ago. On the flat plains where the craft had landed, however, the rover found neither lake deposits nor other preserved signs that water had once flowed inside Gusev. The rover's photographs showed only dust and sand and bone-dry volcanic lava rocks.

But everything changed once Spirit reached the slopes of the Columbia Hills, about 2.6 kilometers from the landing site. (Each of the hills is named after one of the seven astronauts who died in the space shuttle *Columbia* disaster in 2003.) As Spirit struggled to climb the western slope of Husband Hill, its wheels dislodged rocks and dug deep tracks in the Martian soil. At one patch of particularly slippery soil, an area dubbed Paso

Based on new evidence from recent missions to Mars, scientists have proposed a timeline positing an extensive watery past (dates are approximate).

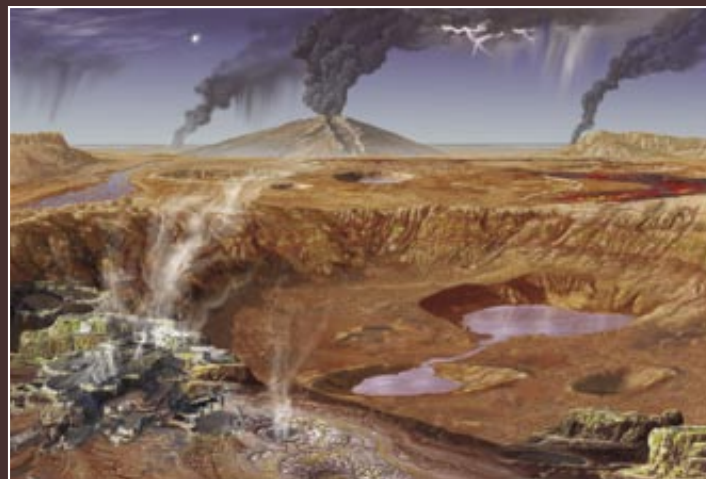
4.6 billion to 4.2 billion years ago



ERA OF GIANT IMPACTS

After Mars's formation, asteroids and comets bombard the planet, forming huge impact basins and triggering intense volcanism. Oceans of magma (liquid rock) flow across the surface.

4.2 billion to 3.5 billion years ago



EPISODES OF EARTH-LIKE CONDITIONS

As the impacts lessen, liquid water fills some of the basins and carves enormous river valleys. The water weathers the underlying rock, producing clays and other hydrated silicates.

Robles, the wheels accidentally uncovered some exotic, whitish deposits that were unlike anything we had seen before in Gusev. Actually, Spirit had driven well past the Paso Robles soils before the mission team noticed them; when we saw what we had uncovered, though, we did the rover equivalent of slamming on the brakes and pulling a U-turn.

On further inspection, we determined that the deposits were hydrated sulfate minerals, rich in iron and magnesium, concentrated just below the dusty surface. On Earth these kinds of deposits are found in places where salty water has evaporated or where groundwater interacts with volcanic gases or fluids. Either process could have also taken place on Mars. (Although scientists have found no active volcanoes in Gusev or anywhere else on Mars, eruptions certainly occurred earlier in the planet's history.) Regardless of which hypothesis was right, we realized that these buried sulfate salts could be remnants of a past watery environment in Gusev.

Spirit's serendipitous find was consistent with discoveries made by Opportunity, the rover investigating the other side of Mars, and the small armada of satellites photographing the planet's surface from orbit. For decades, scientists had be-

lieved that Mars had always been a cold, dry, inhospitable world; the signs of occasional floods and certain water-altered minerals were thought to be anomalies, representing brief deviations occurring in the very distant past, soon after the formation of the Red Planet 4.6 billion years ago. But the new rover and orbital and meteorite studies paint a picture that is quite different from the one many had imagined even just a few years ago. Water apparently covered large parts of the Martian surface for long periods, certainly very early in the planet's history and perhaps also more recently. The implications are profound: if the eras of Earth-like conditions were frequent and long-lasting, the possibility that life evolved on Mars appears much more likely.

Flowing Landscapes

FLUVIAL LANDFORMS—geologic features putatively formed by water—were identified in images of Mars taken by the Mariner and Viking spacecraft in the 1970s. These landforms included enormous channels carved by catastrophic floods and large-scale valley networks somewhat reminiscent of river drainage systems on Earth. Over the past decade, images from the Mars Global Surveyor, which has been orbiting Mars since 1997, have revealed spectacular examples of extremely small and seemingly young gullies formed in the walls of some craters and canyons. These observations indicate the past presence of liquid water on the Martian surface or just below it but not necessarily for long periods. The water from the catastrophic floods, for example, may have lasted only a few days or weeks on the surface before freezing, seeping back into the ground or evaporating.

Furthermore, the networks of riverlike valleys shown in the Viking orbiter images do not have the same characteristics as

Overview/Moist Mars

- Recent results from Mars rovers and orbiters show that warm, wet conditions may have prevailed on the planet for long periods during its early history.
- If the eras of Earth-like conditions were frequent and long, life would have had a better chance of evolving.
- Future missions to Mars may test this hypothesis by measuring the ages of ancient landforms.

RON MILLER (preceding pages); MICHAEL CARROLL (above and opposite page)

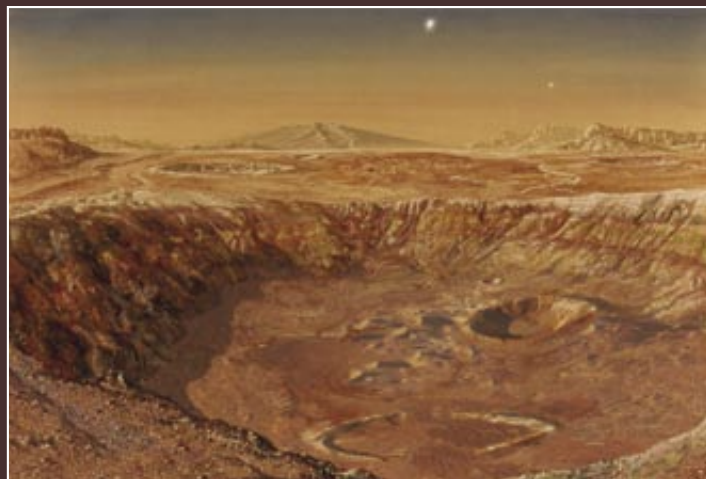
3.5 billion to 2.5 billion years ago



DRYING OUT AND COOLING DOWN

Sulfur from Mars's volcanoes dissolves in the pools of water, turning them acidic and destroying the clays. Surface water begins to freeze, but sporadic floods create large outflow channels.

2.5 billion years ago to present



ARID AND INHOSPITABLE

Volcanic activity wanes, and dust covers much of the planet. But liquid water may persist underground and occasionally burst to the surface, forming gullies in the walls of canyons and craters.

terrestrial river valleys when seen at higher resolution. The Martian valleys could have formed entirely from subsurface water flow and ground erosion—a process known as sapping—rather than from water moving over the surface. The gullies observed in the Mars Global Surveyor's images may also be the result of water seeping underground below ice or from buried snow deposits. Although these features are stunning and dramatic indicators of water on Mars, they do not firmly prove that the Red Planet once had a warmer, wetter, more Earth-like environment with long-lasting lakes and rivers.

In the past few years, however, new satellite images have provided much more compelling evidence that stable, Earth-like conditions prevailed on Mars for long periods. One of the most exciting discoveries is a class of features that look like river deltas. The best and largest example, photographed by the Mars Global Surveyor, is at the end of a valley network that drains into Eberswalde Crater in a region southeast of the Valles Marineris canyon system [see illustration on page 68]. This drainage system terminates in a 10-kilometer-wide, layered, fan-shaped landform characterized by meandering ridges that crosscut one another and show varying degrees of erosion. To many geologists, this feature has all the characteristics of a delta that formed at the end of a sediment-bearing river flowing into a shallow lake.

Like the Mississippi River delta, the structure of the Eberswalde fan suggests that it grew and altered its shape many times, most likely responding to changes in the flow of its ancient source river. If the Eberswalde fan actually is an ancient river-delta deposit, buried by later sediments and exhumed by more recent erosion, the implication is that liquid water persistently flowed across the Martian surface, eroding large volumes of sedimentary materials and transporting them down-

stream. Orbital images have revealed a handful of similar fans in other regions of Mars, but only 5 percent of the planet's surface has been photographed at the resolution needed to identify these features. Further orbital studies may allow researchers to test the river-delta hypothesis, but to determine how long the water flowed to create the fans, scientists will need to measure accurately the absolute or relative ages of different parts of the landforms. Determining absolute ages cannot be done from orbit; instead rock samples from these areas must be sent to Earth for detailed analysis or examined by future rovers that can perform radioisotope dating.

Additional evidence of an Earth-like climate in Mars's past comes from high-resolution images, taken by the Mars Odyssey and Global Surveyor orbiters, of the small-scale valley networks on the plateaus and walls of the Valles Marineris canyon system. Unlike previously identified valley networks that seem to have formed largely from subsurface flow, these newly found networks have characteristics that are consistent with their formation by rainfall or snowmelt and surface runoff. For example, the networks are arranged in dense, branching patterns, and the lengths and widths of the valleys increase from their sources to their mouths. Moreover, the sources are located along the ridge crests, suggesting that the landscape was molded by precipitation and runoff. Indeed, these landforms provide the best evidence to date that it may have rained on Mars.

A more speculative possibility is that these runoff features arose relatively recently, perhaps one billion to 1.5 billion years after Mars formed. To estimate the ages of Martian landforms, researchers count the number of impact craters on the feature—the more impacts the region has endured, the older it is. This dating method, however, has many uncertainties; it can be difficult to distinguish between primary and

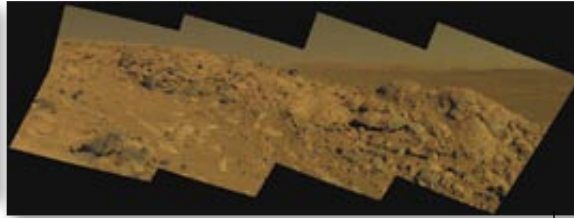
SNAPSHOTS FROM THE HUNT FOR WATER

Spirit and Opportunity, the Mars Exploration Rovers that have been operating on the Red Planet since January 2004, have revealed some of the best evidence of a warm, wet past.



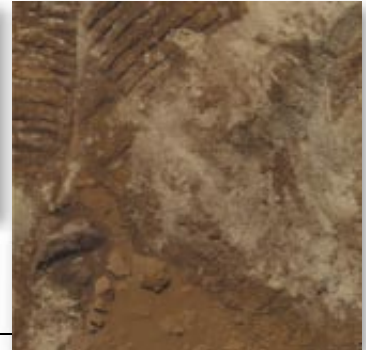
VIEW FROM LANDING SITE

Spirit found nothing but dust, sand and volcanic rocks at its landing site, but the Columbia Hills loomed in the distance.



LONGHORN AT WEST SPUR

Seven months into its mission, the rover reached the Longhorn outcrop in the West Spur region of the Columbia Hills.

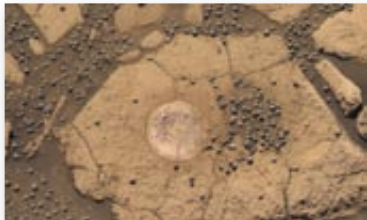


PASO ROBLES SOIL

On Husband Hill, the rover's wheels turned up whitish deposits of sulfate salts—possible remnants of a watery environment in Gusev.

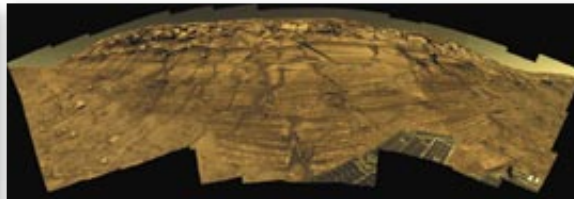


SPiRiT landed in the 165-kilometer-wide Gusev Crater (white dot at left), which lies at the end of an ancient, dry river valley. The rover discovered no preserved evidence of water, however, until it left the flat plain where it landed and entered the Columbia Hills 2.6 kilometers to the east.



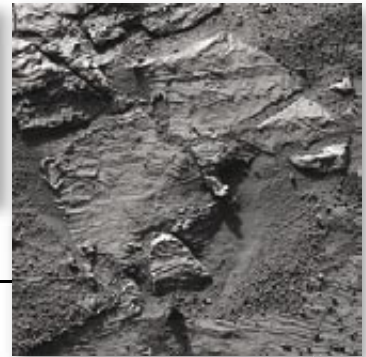
BERRY BOWL

In Eagle Crater's outcrops, Opportunity found millimeter-size spherical grains (nicknamed blueberries) that may have precipitated out of iron- or salt-bearing water as it evaporated.



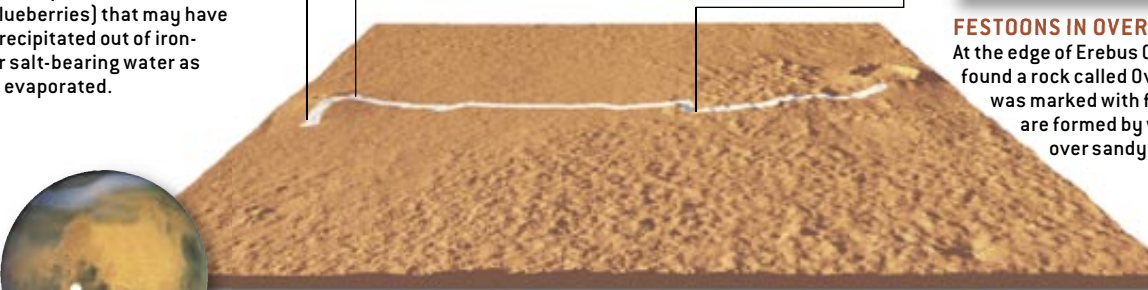
BURNS CLIFF

In nearby Endurance Crater the rover studied Burns Cliff, a massive layered outcrop that bolstered the hypothesis that water periodically covered the landscape.



FESTOONS IN OVERGAARD

At the edge of Erebus Crater the rover found a rock called Overgaard that was marked with festoons, which are formed by waves washing over sandy sediments.



OPPORTUNITY touched down inside Eagle Crater in the Meridiani Planum region and soon found extensively layered outcrops of sedimentary rocks, indicating that water was once aboveground for long periods. Since then, the rover has traveled south and begun exploring the 800-meter-wide Victoria Crater.

NASA/STScI/JIM BELL (global images); RON MILLER (traverse maps); NASA/JPL/CORNELL (landing site, Longhorn, Paso Robles); NASA/JPL/CORNELL (Berry Bowl, Burns Cliff); NASA/JPL-CALTECH/CORNELL (festoons)

secondary impact craters and volcanic calderas, and erosion has destroyed the evidence of craters in some regions. Still, if these surface runoff valleys do turn out to be relatively young, Mars may have had an Earth-like climate for as much as a third of the planet's history and perhaps longer if even younger valleys are eventually identified.

Yet another piece of evidence supporting persistent liquid water on Mars is the observation of truly enormous amounts of erosion and sedimentation in many parts of the planet. Making calculations based on new orbital imaging data, researchers have determined that the rate at which sediments were deposited and eroded in the first billion years of the plan-

id transport of millions of cubic kilometers of material across large fractions of the planet's surface, which apparently occurred repeatedly during Mars's early history. Flowing water, though, has routinely moved gargantuan amounts of sediment on Earth and could have done so on the Red Planet as well.

Clays, Berries and Waves

IN ADDITION TO scrutinizing the shape of Martian landforms, scientists have searched for hints of liquid water in the composition of the planet's minerals. One of the reasons why researchers had long believed that Mars never enjoyed an extensive period of warm and wet climate is that much of the surface

Mars may have had an EARTH-LIKE CLIMATE for as much as a third of the planet's history.

et's history may have been about a million times as high as the present-day rate. (Wind erosion rates have been estimated at the landing sites of the Spirit, Opportunity and Mars Pathfinder rovers.) For instance, the extensively gouged and pockmarked appearance of the region known as Meridiani Planum—the one-million-square-kilometer area in which Opportunity is operating—indicates that much of the terrain has been stripped by erosion and transported elsewhere. No one knows where all this eroded sediment ended up—that is one of the major unsolved mysteries in Mars research—but what does seem clear is that wind alone could not have excavated so much material.

In other places, such as the floors of some craters and the floors and walls of some canyons and chasms in Valles Marineris, cycles of deposition and erosion have apparently created tremendous stacks consisting of hundreds of layers of rock, each between 10 and 100 meters thick. One of the most remarkable examples sits inside the 170-kilometer-wide Gale Crater, which has a gigantic central mound of layered, eroded sedimentary rocks on its floor. The layers, channels and partially buried impact craters in the mound indicate a long and complex history of erosion and deposition. The most incredible characteristic of the mound, though, is that it rises to a height of nearly a kilometer above the rim of Gale Crater. It seems as if the crater and surrounding regions were completely buried by an enormous quantity of sediment, then partially exhumed and buried again, perhaps many times over a long period. The sediments have been eroding since the last burial event, exposing the crater's floor, but the central mound may be wearing down at a slower pace, explaining why it now stands higher than the crater's rim.

But what process could have transported the massive amount of sediment needed to bury almost everything in the Gale Crater region? Scientists believe flowing water offers the best explanation. Studies of erosion and sedimentation rates on Earth suggest that wind could have moved some of the Martian sediment in the past (just as it is doing today, albeit at a very slow pace). No viable wind-based scenario, however, can explain the rap-

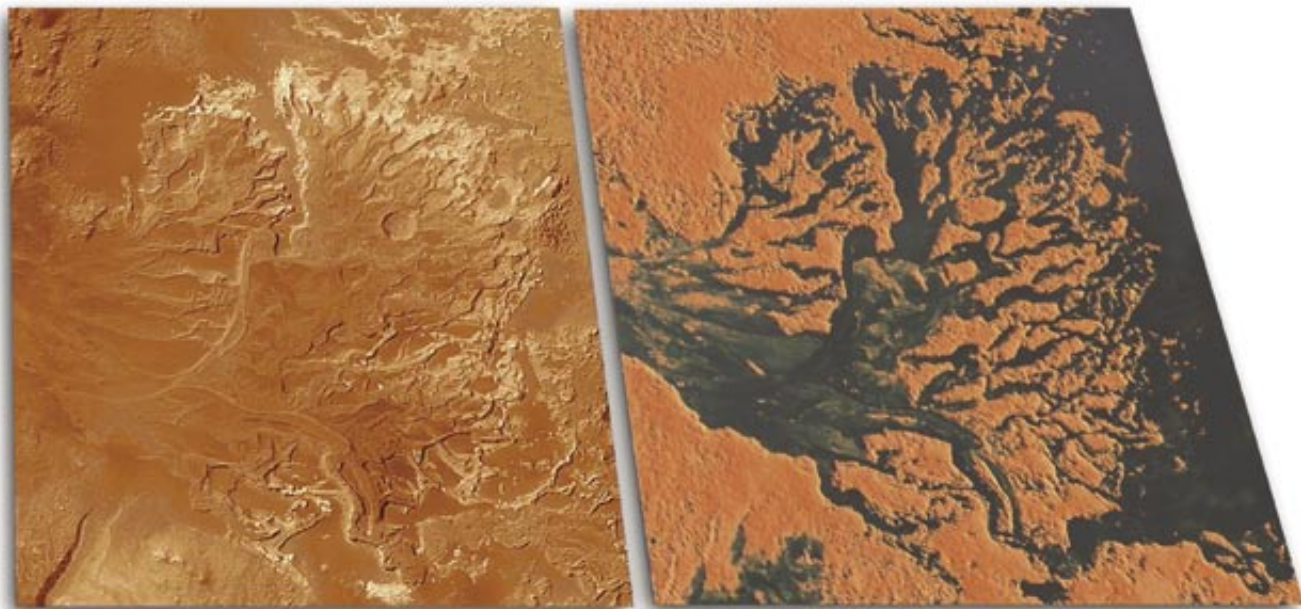
id transport of millions of cubic kilometers of material across large fractions of the planet's surface, which apparently occurred repeatedly during Mars's early history. Flowing water, though, has routinely moved gargantuan amounts of sediment on Earth and could have done so on the Red Planet as well.

not covered by wind-borne dust appears to be composed of material that is largely unweathered—pristine volcanic minerals such as olivine and pyroxene. If water had flowed over the surface for a long time, the argument went, it would have chemically altered and weathered the volcanic minerals, creating clays or other oxidized, hydrated phases (minerals that incorporate water molecules or hydroxide ions in their crystal structure). It turns out, though, that the scientists were not looking closely enough. New high-resolution orbital mapping data and close-up surface studies from the Mars rovers have revealed abundant deposits of clays and other hydrated minerals in many regions. For example, the OMEGA instrument on the European Space Agency's Mars Express orbiter—which is particularly good at detecting the kinds of minerals that form from the weathering of volcanic rocks—has found clays in the dust-free parts of what appear to be the oldest terrains on the surface. Based on the high number of impact craters in these areas, their ages span much or all of the first billion years of Martian history. The clay deposits are scattered all over the planet, in ancient volcanic surfaces and heavily cratered highland regions, some of which have apparently been exposed by erosion only recently.

The newly discovered clays are phyllosilicates—minerals composed of sheets of silica with water molecules and hydroxide ions trapped between the sheets. The clays have the diverse range of compositions that one would expect from the water-

THE AUTHOR

JIM BELL is an astronomer and planetary scientist who now spends most of his time designing and operating instruments for robotic spacecraft and analyzing the results. An associate professor at Cornell University, Bell is a member of the science teams for the Mars Pathfinder, NEAR, Mars Odyssey, Mars Exploration Rover, Mars Reconnaissance Orbiter and Mars Science Laboratory missions. He is the lead scientist for the Pancam color cameras on the Spirit and Opportunity rovers. His book of rover photographs, *Postcards from Mars*, has just been published by Dutton/Penguin.



EBERSWALDE FAN (*left*), photographed from orbit by the Mars Global Surveyor, lies at the end of a valley network leading into Eberswalde Crater. The meandering, overlapping channels in the 10-kilometer-wide

fan suggest that it was once a river delta draining into a shallow lake that may have filled much of the crater. The artist's rendering (*right*) portrays this delta as it might have looked billions of years ago.

related weathering of the various kinds of volcanic rocks that have been found on Mars. Although OMEGA has surveyed only a small fraction of the planet at high resolution so far, the discovery of these minerals is strong evidence of a long epoch of Earth-like conditions on early Mars.

Furthermore, researchers have detected minerals altered by water (clays, hydrated iron oxides and carbonates) in some Martian meteorites—rocks that were ejected from the Red Planet by comet or asteroid collisions and eventually landed on Earth. Scientists have hypothesized that the water-related weathering may have taken place underground, because most of the meteorites were part of the Martian crust, but not the uppermost surface, before they were blasted into space. And because some of the meteorites are thought to come from relatively younger parts of the Martian crust, investigators suspect that the subsurface weathering may be continuing today. Scientists may be able to test this important hypothesis in ongoing and future missions to Mars, perhaps by searching for evidence of active springs or hydrothermal activity. What is more, new landers, rovers or human missions could be equipped with drills for exploring deep underground.

The exploits of the Mars rovers have added the newest pieces to the Red Planet's climate puzzle. Eight months before the Paso Robles discovery, as Spirit was just beginning its climb into the Columbia Hills, the rover examined a knobby rock with its mineral-identifying instruments and detected hematite, a highly oxidized iron mineral that is common in soils on Earth that have been altered by water. Several months afterward, Spirit found evidence of phyllosilicates and goethite, an oxidized iron mineral that cannot form without water and that preserves water-derived hydroxide ions in its crystal structure. The Columbia Hills appear to record an ancient history of water-

rock interactions on Mars that was not apparent in the younger volcanic plains that Spirit investigated earlier in its mission.

As the rover crested the summit of Husband Hill and eventually made its way down the other side and into the basin to the south, it encountered even more Paso Robles-like subsurface salt deposits. Unfortunately, we could not adequately study the most extensive deposits, because as the seasons advanced into the rover's second Martian winter, we were forced to move Spirit onto north-facing slopes so that there would be enough sunlight on the rover's solar panels to keep the machine operating. If all goes well, we will send the rover back to the salt deposits once the Martian spring returns.

Meanwhile Opportunity has made equally amazing finds in Meridiani Planum. Within weeks of landing, the rover had discovered ancient deposits of extensively layered, sedimentary outcrop rocks that were porous, hydrated and salty. From complementary orbital observations, researchers knew that these deposits spanned the entire region. The layered outcrops studied by Opportunity showed that these kinds of sedimentary rocks extend tens of meters deep (or more) into the subsurface, indicating that liquid water was once aboveground for long periods. Opportunity's results, however, portray a different part of the history of water on Mars. The hydrated rocks found by the rover contain predominantly sulfur-rich minerals such as jarosite, and the sedimentary outcrop rocks are rich in chlorine and bromine as well as sulfur. All these elements are highly mobile in watery solutions, implying that the deposits formed after the evaporation of salty liquid water. Thus, the outcrops may bear witness to a time when the pools and streams of Meridiani Planum gradually shrank and dried up.

The rover's discovery of millimeter-size, hematite-bearing spherical grains—nicknamed blueberries—in the outcrops

NASA/JPL/MALIN SPACE SYSTEMS, INC. (orbital image); RON MILLER (rendering)

also bolstered the hypothesis of long-term standing water on Mars. We believe that the blueberries are what geologists call concretions, grains that precipitate out of iron- or salt-bearing water as it evaporates. If the process is slow and homogeneous enough, the resulting mineral grains grow spherically. On Earth, some concretions grow to the size of marbles or ping-pong balls; the ones seen on Mars are the size of ball bearings, two to three millimeters across on average. As Opportunity moved south from its landing site, the blueberries it found were smaller, suggesting possible variations in the duration of the watery environment or the rate of the water's evaporation.

The Martian environment began to change as the WATERS BECAME ACIDIC and geologic activity waned.

Opportunity has even photographed some outcrop rocks that appear to preserve the tracks of waves in shallow water. The best examples of these “festooned cross-bed sets,” which are formed by waves interacting with sandy sediments, were found earlier this year as the rover traveled south across the plains.

The Emerging Paradigm

THE RESULTS FROM the rovers underline the importance of sulfur, which presumably built up in the Martian environment because of the planet's early and active volcanic history. Sulfur and sulfur-bearing minerals can dissolve in water, and the resulting solutions can be quite acidic. Acidic water destroys many kinds of minerals, particularly carbonates, and it also inhibits the formation of other minerals such as clays. Thus, the buildup of sulfur on Mars may explain why scientists have not yet found any carbonates on the surface and why clays appear to be preserved in only the oldest terrains. The OMEGA instrument has detected sulfate deposits at other locations on Mars besides Meridiani Planum, but in general these regions appear to be younger than the areas with clays. So far sulfates and clays have not been found together.

The emerging paradigm is that Mars had an extensive watery past: puddles or ponds or lakes or seas (or all of them) existing for long periods and exposed to what must have been a thicker, warmer atmosphere. During the first billion or so years of Martian history, the Red Planet was a much more Earth-like place, probably hospitable to the formation and evolution of life as we know it. The Martian environment began to change, however, as sulfur built up, the waters became acidic and the planet's geologic activity waned. Clays gave way to sulfates as the acid rain (of sorts) continued to alter the volcanic rocks and break down any carbonates that may have formed earlier. Over time, the atmosphere thinned out; perhaps it was lost to space when the planet's magnetic field shut off, or maybe it was blown off by catastrophic impacts or sequestered somehow in the crust. Mars eventually became the cold, arid planet we recognize today. This sequence of events would explain why any volcanic rocks that have erupted onto

the surface in the past few billion years should still be unweathered and pristine. It is the older stuff underneath, serendipitously exposed by impacts or erosion or slip-sliding rovers, that holds the key to the planet's past.

This new view of Mars is not yet universally accepted, however. Key questions remain unanswered: How long did the waters flow in the Eberswalde delta—for decades or millennia? Where are all the sediments that appear to have been eroded from Meridiani Planum and places such as Gale Crater? And were they eroded by water or wind or something else? What is the global abundance of clay minerals on Mars, and were they

ever major components of the planet's crust? And, most vexing, where are the carbonates that should have formed in the warm, wet, carbon dioxide-rich environment but have not yet been observed anywhere on Mars, not even in the older terrains where clays have been detected? Acidic water could have destroyed the bulk of the carbonates but surely not all of them!

Perhaps the most important question of all is, Did life ever form on early Mars, and if so, was it able to evolve as the environment changed so dramatically to the present-day climate? The answer depends in large part on how long the Earth-like conditions lasted. None of the images or other data that we have in hand, as impressive as they are, can provide us with very good constraints on the duration of the warm, wet era. We simply do not understand the ages of Martian surfaces well enough. In fact, it may ultimately prove impossible to use the density of impact craters to establish absolute or even relative ages on a surface that has seen so many episodes of massive burial and erosion. A better method would be bringing Martian samples back to Earth for accurate radioisotope dating or sending miniature age-dating instruments on missions to the surface. Until then, orbital spacecraft will continue to hunt for key mineral deposits and identify the best sites for future landers and rovers, which may someday reveal indisputable estimates of the duration of the Red Planet's watery era. The past decade of discoveries on Mars may be only a small taste of an even more exciting century of robotic and eventually human exploration. SA

MORE TO EXPLORE

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