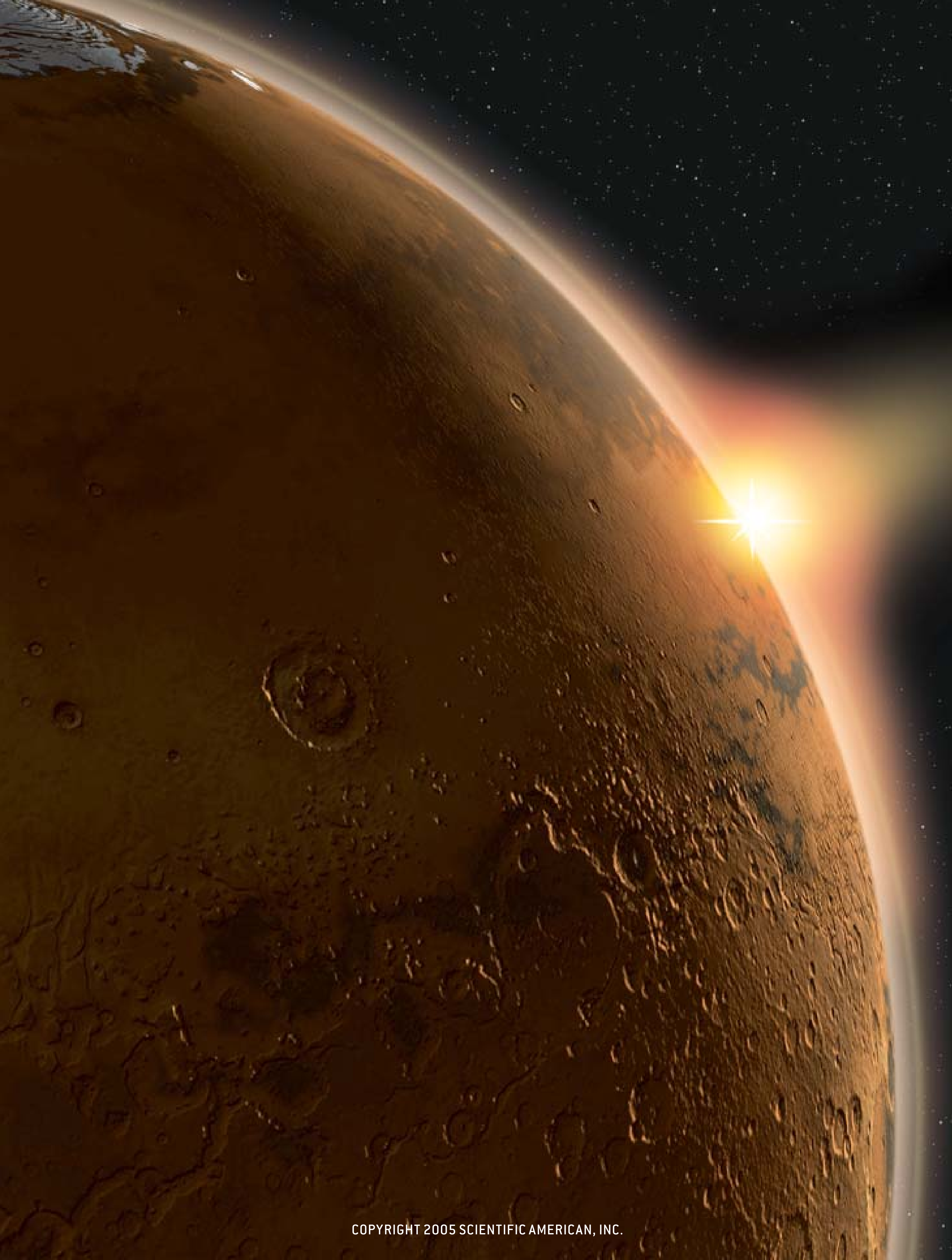
# The Many Faces of Mars

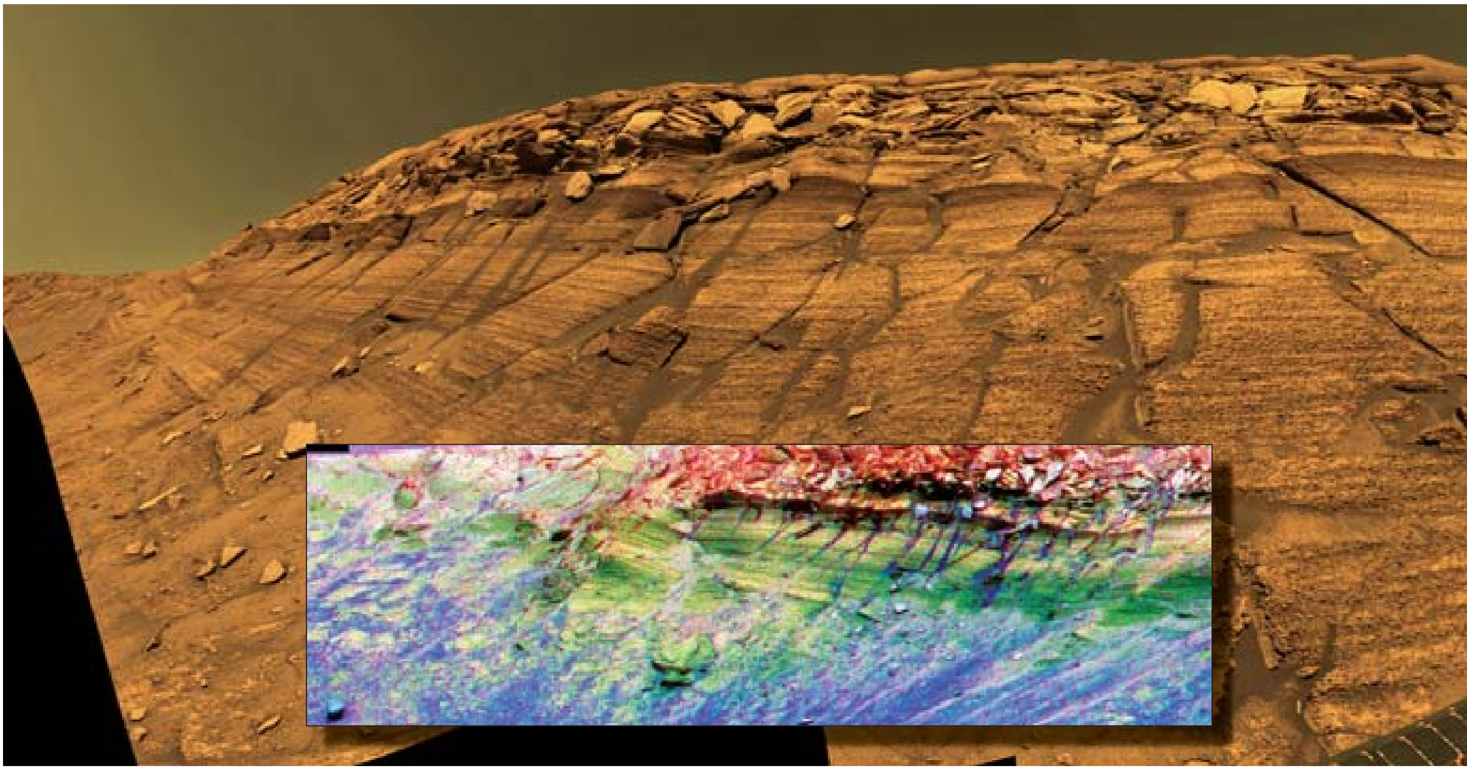
By Philip R. Christensen

**One rover found an ancient desert; the other, a once watery world. The Red Planet's diversity rivals Earth's**

Many people venture into the desert for its starkness and simplicity, but I go there for its complexity. The rocks of western Arizona, where I work, reveal one of the most tangled histories on Earth. Layers of carbonate limestones, silty mudstones, quartz sand and solidified lava show that within the past 600 million years, this area was a warm, shallow sea, then a muddy swamp, then a vast desert of shimmering hot dunes, then a glacial ice sheet, then a shallow sea once again. Erupting volcanoes formed islands like Japan, which in turn got shoved 100 miles onto the continent along massive faults, tilting the rock layers on edge and cooking them to create marble and quartzite. Uplift and erosion at last produced the desert landscape we see today.

SUNRISE OVER ARABIA TERRA, looking east toward Utopia Planitia: This artist's reconstruction of orbital images shows the margins of Vastitas Borealis, a vast, low plain where floodwaters from ancient channels may have ponded. Toward the center, the sun is casting its first rays on the western rim of the crater Lyot.





This kind of detailed historical reconstruction has long been impossible for Mars. Within my lifetime, the Red Planet has been transformed from a point in the night sky into a land of towering volcanoes, dried-up riverbeds, ancient lakes and windswept lava plains. Clearly, Mars has one of the most glorious histories in the solar system. Yet scientists have been able to piece together only the sketchiest outlines of that history. For years, we have debated such sweeping questions as whether Mars was once "warm and wet" and Earth-like or "cold and dry" and barren like the moon, as though the story of an entire world could be reduced to a sound bite.

## Overview/*Martian Oddities*

- The Spirit and Opportunity rovers have been rambling around Mars for one and a half years, while three orbiters have mapped the planet's topography and mineral composition with a precision once available only for Earth.
- Until these missions, the primary evidence for past water on Mars was morphological: landform shapes, which are suggestive but ambiguous. Now the main evidence is mineralogical (the presence of iron oxides and sulfate salts) and textural (spherules and ripples in bedrock), leaving no doubt that the Opportunity landing site, at least, is an ancient lake bed.
- Yet the geologic history of the planet varies tremendously, and bizarrely, with location and time. Much of the planet has seen scarcely a drop of water; even the Opportunity site went through long dry spells. Other geologic features, such as volcanoes, are also unexpectedly diverse.

Over the past decade, though, we have entered the third great era of Mars exploration, the first two being the telescopic observations of the 19th century and the initial spacecraft reconnaissance of the 1960s and 1970s. Recent orbiter and rover missions have mapped the planet's topography, determined its mineralogy, imaged its surface in sufficient detail to interpret geologic processes, and merged orbital data with ground truth. Mars has finally become a place that I can study as a geologist does, using its rocks, minerals and landforms to weave a narrative.

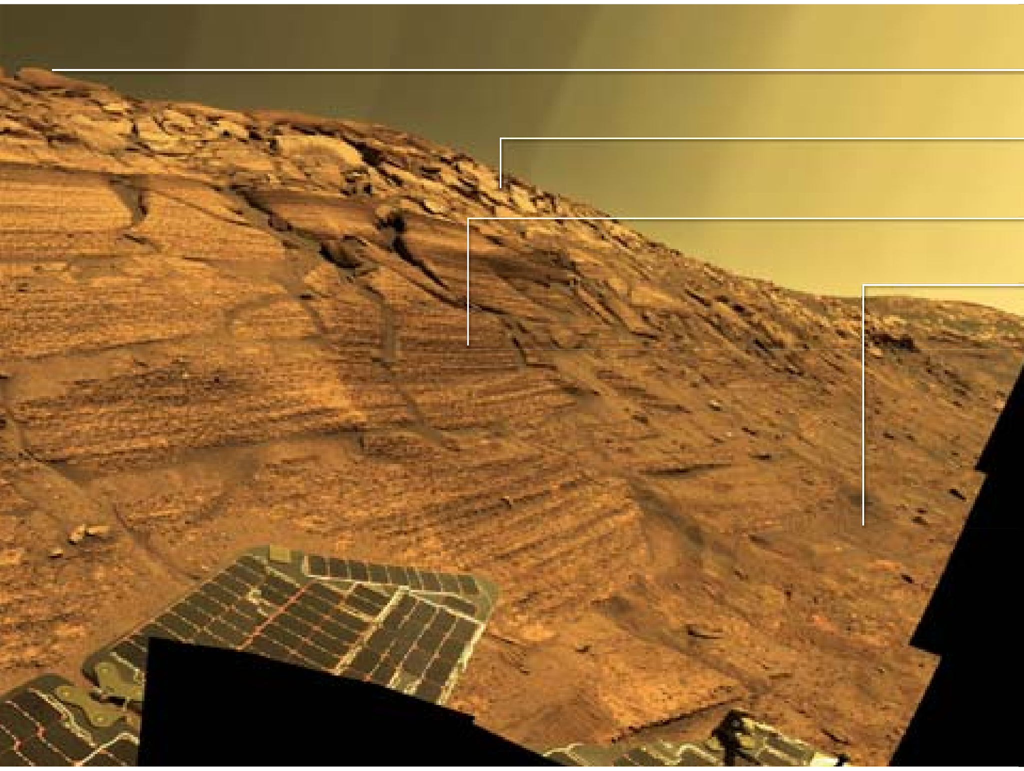
What we have discovered is that Mars has experienced a striking diversity of processes and conditions throughout its history. The Mars we are coming to know has embraced environments ranging from bone-dry to soaking wet to blanketed with snow and ice. Simple labels no longer fit. Rather than "warm" or "cold," we ask: How warm? How wet? For how long? Where? The emerging answers bear on what compels so many of us to study the Red Planet: its potential for harboring life, either now or in the past.

### Two Places, Two Views

IN JANUARY 2004 NASA landed two of the most complex machines ever built at two very different sites on Mars. Packed with cameras and spectrometers to determine soil and rock composition, the Spirit and Opportunity rovers set out to answer the central question of Martian geology: What has been the role of water? Spirit bounced down in Gusev Crater, which had been chosen for the shape of its landforms: images taken from orbit have long shown that a valley, Ma'adim, opens into the crater, as if Gusev was once a lake.

Initially the site proved to be somewhat of a letdown. Spir-

RON MILLER (*preceding pages*)




BURNS CLIFF is a spectacular rock outcrop explored intensively by the Opportunity rover. The cliff, three stories tall, forms part of the rim of Endurance Crater, about 700 meters from the rover's landing site. Its uppermost rocks, like those at the landing site, are rich in sulfate salts (*red, yellow in false-color inset*) and were probably deposited as the area repeatedly flooded and dried out. Underneath are fine and coarse layers—a mixture (*green*) of the water-related mineral hematite and water-phobic basaltic minerals. These appear to be ancient sand dunes that were generally dry but located near a large basin of water. The floor of the crater is covered with basaltic sand (*blue*).

NASA/JPL/CORNELL

it found no signs of past water. What it saw were volcanic rocks, which spectrometers indicated were composed of olivine and pyroxene, minerals broken down by even the barest amount of liquid water. The rocks could not have been exposed to any significant amount of water in the three billion years or so since erupting. As Spirit climbed into the Columbia Hills, which overlook the landing site, the situation got more interesting. There the rover discovered high abundances of sulfur salts. Evidently, volcanic rocks had been ground into small grains and then cemented together by salt, a process that may have involved liquid water percolating through the rocks or sulfuric acid reacting with minerals that were already in the rock. Despite this hint of water, however, these rocks still contained significant amounts of olivine and pyroxene. Thus, even on what may once have been a lake bed, water appears to have played a minor role over the past few billion years.

The Opportunity rover headed to the plains of Meridiani. The selection of this site marked a new phase in humanity's exploration of the solar system: never before had planetary scientists sent a probe to a location for its mineralogy. Early spacecraft missions to Mars ascertained the composition of the surface in terms of chemical elements, but identifying the minerals—the compounds and crystal structures that these elements formed—required the Thermal Emission Spectrometer (TES), an instrument I developed for NASA's Mars Global Surveyor orbiter, which reached the planet in 1997. In the mineral maps we prepared, Meridiani stood out for its high abundance of crystalline hematite.

This iron oxide, common on Earth, forms by several processes, most of which involve water. One is the precipitation from fluids circulating through sediments; another, the deposition and dehydration of water-bearing iron minerals such as goethite, a reddish-brown mineral found in many desert soils. The Meridiani hematite-rich rocks appeared to be finely layered and easily eroded; they sat on top of the older, heavily cratered surface, suggesting a sedimentary deposit; and they filled in preexisting channels and other low areas of topography, suggesting that these rocks were deposited in water rather than draped across the landscape as volcanic ash or windblown dust.

Within days of landing, Opportunity confirmed that Meridiani had once been underwater. It immediately spotted outcrops of layered sedimentary rocks, the first ever seen on Mars. The rocks were so full of sulfate—30 to 40 percent by weight—that only the evaporation of sulfur-rich water could account for them. The sulfates at Gusev were not nearly so extensive. The hematite took the form of spheres (dubbed "blueberries") one to five millimeters across that were embedded in the rock layers and scattered all over the ground.

THE AUTHOR

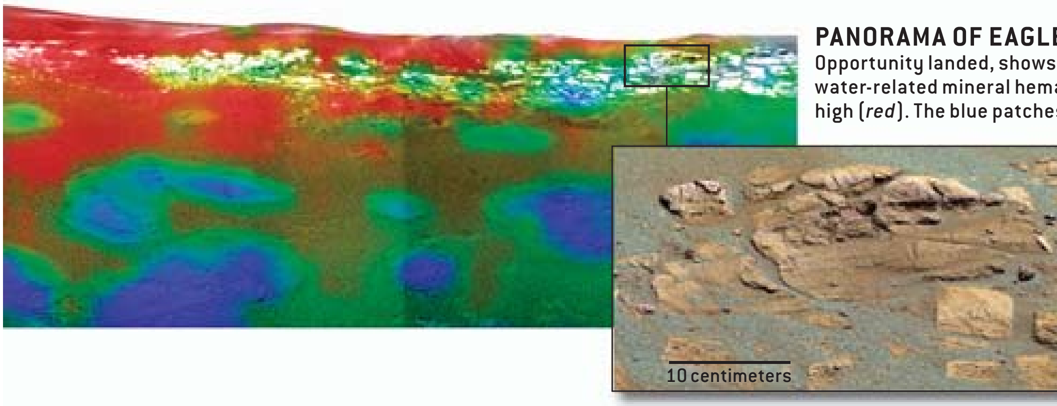
*PHILIP R. CHRISTENSEN* got interested in geology as a kid traveling throughout the American West. He first looked at Mars through a telescope his parents gave him when he was 12. Now a professor at Arizona State University at Tempe, he is the world's leading expert on the composition of the Martian surface. His research team developed the infrared instruments for the Mars Global Surveyor, Mars Odyssey and Mars Exploration Rover missions. In 2003 NASA awarded him its Exceptional Scientific Achievement Medal for his pioneering scientific observations of Mars in the infrared. Since the mid-1990s he has also used spacecraft observations to study environmental and urban development problems on Earth.

The largest outcrop that Opportunity explored, named Burns Cliff, appeared to be a series of preserved sand dunes that were wetted by surface and ground waters. Many of the grains in them were sulfates formed from the evaporation of standing water, perhaps in the level areas (known as playas) between the dunes. Judging from analogous features on Earth, the rocks of Burns Cliff took thousands to hundreds of thousands of years to form. The spherical hematite grains may have been created later from iron-rich fluids circulating through sediments. For the first time ever on Mars, scientists investigated an outcrop in the multifaceted way geologists on Earth do.

Even the morphology of the Meridiani plains, one of the flattest landscapes observed on any planet, looks like a lake bed. The extent of hematite mapped from orbit suggests it was an isolated large lake or small sea rather than part of a global ocean. Several craters to the south and west of the main hematite deposit also have hematite-rich layered rocks; perhaps they were separate lakes.

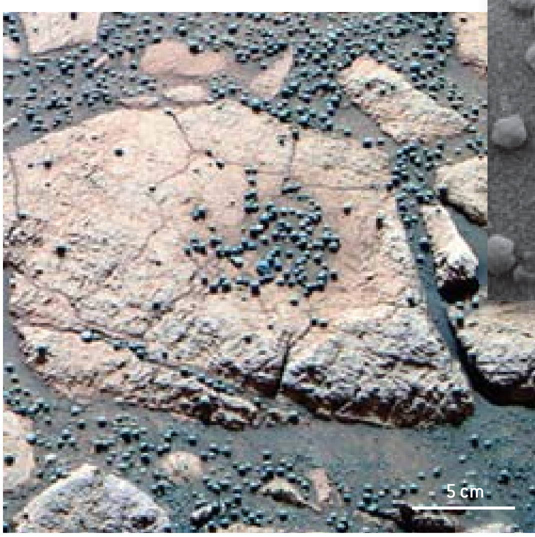
In short, it was as if the two rovers had landed on two completely different planets: one drier than any desert on

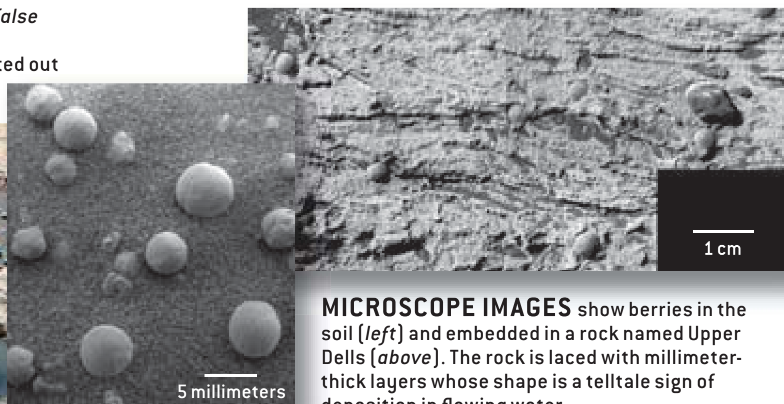
## WHERE MARS WAS WET



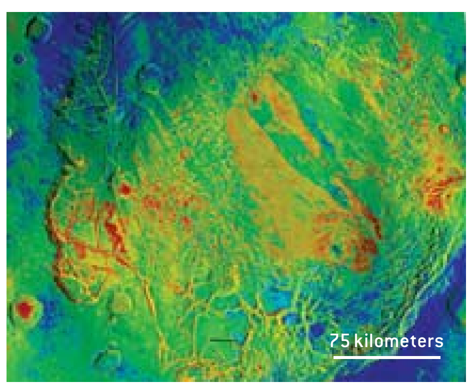

**PANORAMA OF EAGLE CRATER,** where Opportunity landed, shows varying amounts of the water-related mineral hematite, from low (*blue*) to high (*red*). The blue patches in the foreground are meter-size bounce marks created by the rover during landing. The white areas to the rear are rock outcrops such as El Capitan (*inset*); on detailed examination, they were found to consist of water-lain deposits of sulfate and hematite.

**"BLUEBERRIES"** are BB-sized spherules scattered all over the landing site. The high concentration of them on this rock, the so-called Berry Bowl (*shown here in false color*), allowed the rover to get a good reading of their composition: it is hematite, which probably precipitated out of water in the pore spaces of lake-bed sediments.



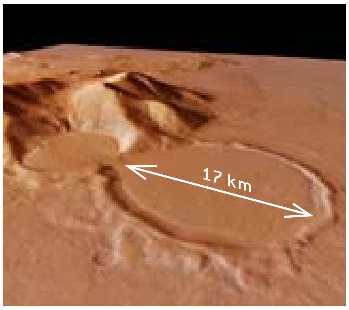



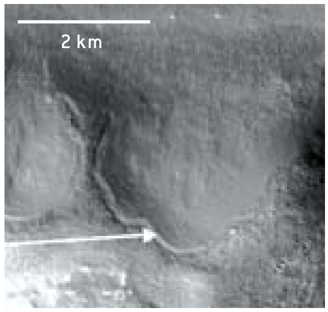

**MICROSCOPE IMAGES** show berries in the soil (*left*) and embedded in a rock named Upper Dells (*above*). The rock is laced with millimeter-thick layers whose shape is a telltale sign of deposition in flowing water.

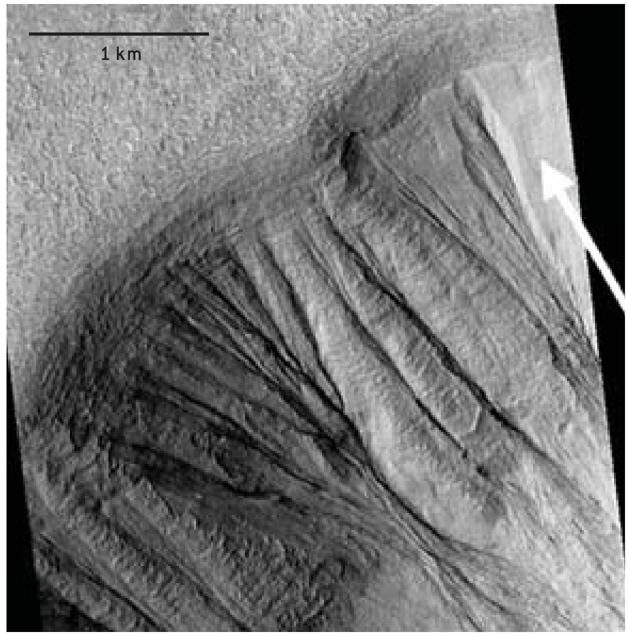



**ARAM CHAOS** is an impact crater that, like the Opportunity site, is flush with hematite. Nighttime temperatures, measured by the Mars Odyssey orbiter, indicate the consistency of material: warm (*red*) means rock, cold (*blue*) means dust and sand. The flat rocks in the center of the crater (*orange*) appear to be lake-bed sediments. The fractured terrain to the south indicates that the ground suddenly collapsed, perhaps when subsurface water rushed out.

NASA/JPL/CORNELL/ARIZONA STATE UNIVERSITY (*Eagle Crater panorama*); NASA/JPL/CORNELL (*El Capitan and Berry Bowl*); NASA/JPL/CORNELL/USGS (*microscope image of berries and embedded berries*); NASA/ARIZONA STATE UNIVERSITY/TIM GLOTCH (*Aram Chaos*)




LET IT SNOW: Mars may not be quite as dynamic as it used to be, but there is life in the planet yet. The Mars Express orbiter saw what appeared to be geologically recent glaciers flowing through mountain ranges and craters (*left*). The Mars Odyssey orbiter detected snow deposits (*arrows, center* and *right*) on pole-facing slopes. Snow may be the source of the water that produced fresh gullies (*right*). If microbes survive anywhere on present-day Mars, these snowpacks would be one obvious place.

ESA/DLR/FU BERLIN (G. NEUKUM) (*left*); NASA/JPL/MALIN SPACE SCIENCE SYSTEMS (*center*); NASA/JPL/MALIN SPACE SCIENCE SYSTEMS/PHILIP CHRISTENSEN (*right*)

Earth, the other a land of a thousand lakes. Are these the only possibilities, or is Martian geology even more varied? Do these two sites, thousands of kilometers apart, represent the total range of rock compositions and aqueous activity on Mars? To answer these broad questions, scientists have looked anew at data taken from orbit.

## Lava Land

OVER THE PAST eight years, the TES instrument has discovered that Martian rocks and sands are composed almost entirely of the volcanic minerals feldspar, pyroxene and olivine—the components of basalt. In the spring of 2004 the European Space Agency's Mars Express orbiter, carrying the OMEGA near-infrared spectrometer, joined the effort and verified the extensive presence of these minerals. Olivine is exposed more than 4.5 kilometers below the surface in the walls of the Valles Marineris canyon system; it appears all over the equatorial plains, including the floors of channels. The discovery of basalt did not come as a great surprise. Basalt also covers much of Earth and the moon; the lava that oozes across Hawaii is basalt. It is a pristine type of lava—formed from the first stage of melting of the planet's mantle—and on Earth it continuously erupts from mid-ocean ridges to create the seafloor.

Another discovery, though, was unexpected. Whereas the rocks in the ancient heavily cratered terrains were basaltic, the younger rocks of the northern lowlands resembled a more highly evolved type of lava called andesite: they contained more glass, more silica-rich minerals and fewer iron-bearing minerals. On Earth, andesites typically form when descending tectonic plates mix water into subterranean molten rock. The possible existence of andesites on Mars is intriguing. It may indicate that the Martian mantle is wetter than Earth's or that younger lavas melted at different temperatures or pressures than the older basalts. To be sure, some scientists propose that the supposed andesites are basalts masquerading as such; a fog of water or acid could react with the minerals to create an andesitelike veneer. Researchers may have to wait for detailed surface studies of these rocks to resolve this question.

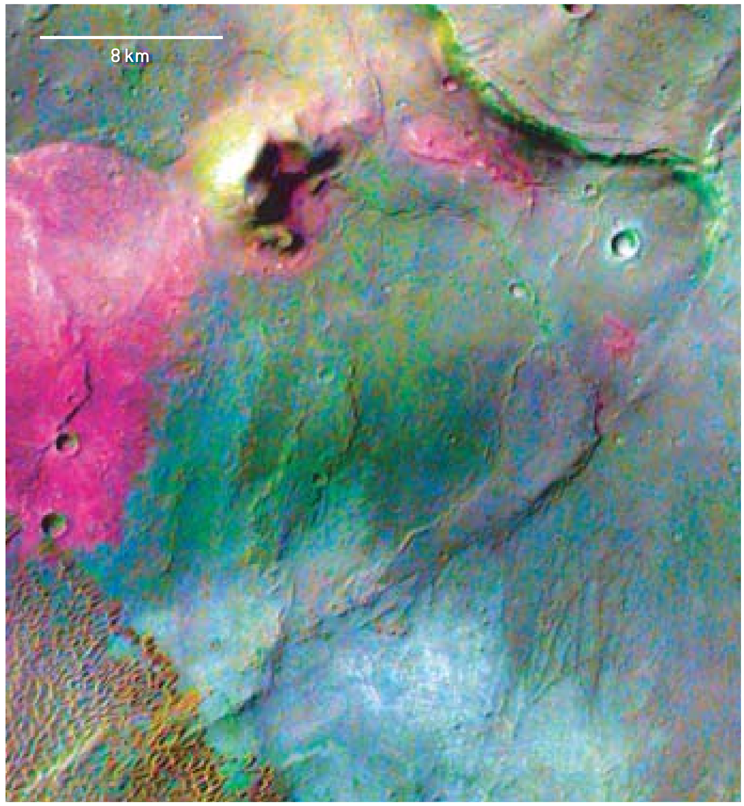
The TES instrument has fairly low spatial resolution: a pixel is several kilometers across. So the true variety of Martian mineralogy started to become apparent only in 2001, when THEMIS, an infrared camera that my group developed for another NASA orbiter, Mars Odyssey, began mapping the planet with 100-meter resolution. It and OMEGA have revealed a diversity of igneous rock compositions that rivals Earth's.

Near the Martian equator sits a volcano 1,100 kilometers in diameter named Syrtis Major. A series of collapse craters, or calderas, lie at its summit. The bulk of the volcano is basaltic, but the slopes are dotted with cones and lava flows consisting of glassy, silica-rich lavas called dacites. This rock type originates in the magma chambers that underlie volcanoes. As magma cools, the first minerals to crystallize are olivine and pyroxene, which are rich in iron and magnesium. They settle to the bottom of the chamber, leaving the remaining magma enriched in silica and aluminum—from which dacites emerge. The central peaks of several craters on the flanks of Syrtis Major are made up of an even more silica-rich rock, granite, that may have formed by extreme crystal separation or by large-scale remelting of earlier basalts.

Researchers conclude that this volcano went through many stages of development. Basaltic lava first erupted from the center and built up the volcano. As the magma evolved chemically, it withdrew from the chamber underneath the summit, causing the ground there to collapse and feeding eruptions on the flanks. Not only are Martian volcanoes huge, they are surprisingly complex.

## And There Will Come Soft Rains

JUST AS IMPORTANT as what Mars has is what it lacks. Quartz is common on Earth but exceedingly rare on Mars, indicating that granite, from which it forms, is scarce. Nor is




NILI PATERA, a region at the summit of the giant volcano Syrtis Major, contains both older basaltic lavas (*blue*) and younger dacite cones and flows (*red*). The sand dunes (*orange*) are a mixture of the two types. Martian volcanism is more chemically complex than scientists expected.

there evidence for metamorphic minerals such as slate or marble, produced when volcanic or sedimentary rocks are subjected to high pressure or temperature. The main implication is that Mars does not have tectonics capable of driving rocks to great depths (where they are heated and squeezed) and then bringing them back to the surface.

Earth has vast deposits of carbonate rocks such as limestone, which precipitated from warm, carbon dioxide–rich oceans. Planetary scientists, reasoning that Mars used to be warmer and wetter, thought it, too, would have thick layers of carbonates. But none have been found. That means any oceans were cold or short-lived or ice-covered or otherwise hostile to carbonates. The ubiquitous dust does contain small amounts of carbonate, but it probably formed by direct interaction with water vapor in the atmosphere rather than liquid water on the surface. Another class of water-related minerals, clays, is also rare on Mars—again suggesting that the planet has been mostly dry. That accords with the widespread presence of the water-shy minerals olivine and pyroxene.

In this sense, what Spirit saw at Gusev is more representative of Mars than what Opportunity found at Meridiani. And yet Meridiani is not the only place where lakes appear in the orbital images. Aram Chaos, a 280-kilometer-diameter crater, has an outflow channel and is filled with layered rocks that contain hematite. Gigantic blocks of rock litter the crater floor. It looks as though a torrent of subsurface water was catastrophically released, causing the overlying terrain to collapse. Some of the water ponded in the crater, forming the layers of hematite-bearing sediments.

Similarly, troughs in Valles Marineris contain hematite-bearing rocks in fine, easily eroded layers, matching what one expects from deposition in standing water. These rocks, and others throughout the equatorial region, are rich in sulfates, a telltale sign of water-lain sediments. The lakes may have undergone numerous episodes of inundation, evaporation (and possibly freezing), and desiccation. In addition to the ancient lake beds are regions carved with dense networks of channels, seemingly created by rainfall and surface runoff. Some researchers have argued that Mars had extensive oceans: images and topographic data hint at shorelines and smooth ocean floors.

Together these discoveries provide strong evidence that water was stable in isolated regions for brief periods. What factors caused water to accumulate and remain stable at these sites? A leading guess is a combination of geothermal heat, large doses of salt (which lowered the freezing temperature) and a protective covering of ice. Large meteor impacts may have occasionally thickened and warmed the atmosphere.

But the idea of a once Earth-like planet seems to be passé. The overwhelming impression from the global mineral mapping is of an ancient surface whose original volcanic minerals are still preserved, little altered by water. Even at Meridiani, basaltic sands lie atop the lake sediments, indicating that the site has been parched for two billion to three billion years. Lakes and riverlike networks do exist, but water may have flowed through them only briefly. It is possible that water remained frozen for most of the time, was occasionally released and quickly refroze. Still, planetary scientists puzzle over how a world that was so arid in general could have been so watery at certain places and times.

## Planet of the Long Seasons

MARS'S EPIC PAST tends to get the most attention, but two developments have reinvigorated study of its present-day activity. First is the growing consensus that Mars has been geologically active in the recent past. Most large volcanoes and lava plains are old, dating to the first half of the planet's history, but the lack of meteor impact craters on lava flows in regions such as Athabasca suggests they are young (by a geologist's standards), the result of eruptions within the past few million years. Researchers have looked for active volcanic or geothermal hot spots in nighttime infrared images but so far have seen none. Mars appears to have cooled to the point where volcanism is very rare, although lava does occasionally erupt onto the surface.

The second is the discovery that Mars has colossal reservoirs of frozen water that migrate around the planet as its climate changes. To begin with, both poles have deposits of ice or ice-rich sediments that are up to several kilometers thick over a combined area nearly twice the size of Arizona. Infrared

NASA/ASU/NOEL GORELICK


APOLLINARIS PATERA, a broad but low volcano, spewed lavas of varying composition. It may be the source of the ash found by the Spirit rover 350 kilometers to the south. The volcano's deposits have been deeply carved by water. Spacecraft have noticed active landslides in the area.

NASA/ASU/NOEL GORELICK

temperature readings in the 1970s demonstrated that the north polar cap is water ice but did not settle the composition of the south polar cap. Its surface temperature matches that of carbon dioxide ice, but might water ice lie underneath? Recent temperature readings by THEMIS have detected water ice poking through in certain places, so the answer seems to be yes.

Adding to the known inventory of water is the underground ice detected by the Gamma Ray Spectrometer and the High Energy Neutron Detector instruments on Mars Odyssey. These instruments measure gamma rays and neutrons, which are produced when cosmic rays collide with atoms in the soil. The energy distribution of gamma photons and neutrons reveals the elemental composition of the soil to a depth of several meters. For instance, hydrogen strongly absorbs neutrons, so a dearth of neutrons implies subsurface hydrogen—most probably the $H_2$ of $H_2O$. In the regions between 60 degrees latitude and each pole, water appears to make up more than 50 percent of the soil. Ice abundances this high could not have formed by the simple diffusion of water vapor from the atmosphere into the pores of the soil. Instead the ice must have been deposited as snow or frost.

Unusual landforms seen throughout the midlatitudes also hint at ice. A basketball-textured terrain occurs between 30 and 50 degrees latitude in both hemispheres; it may form as soil warms up and ice evaporates, causing the soil to crumble apart. A second type of deposit, found in hollows on cold, pole-facing slopes, is a layer of material up to 10 meters thick—a possible remnant of nearly pure water snow. One of the most remarkable discoveries has been the small, fresh gullies at midlatitudes, perhaps the result of spring water, melting of near-surface ice, or melting of snowpacks from the bottom up.

All these water-related features suggest that Mars, like Earth, goes through a cycle of ice ages. The tilt of the planet's spin axis oscillates by as much as 20 degrees over a period of 125,000 years. When the tilt is modest, the poles are the coldest places on the planet. More snow falls there than evaporates, leading to a net accumulation of ice. As the tilt increases, the poles receive more sunlight and warm up, at the expense of the midlatitudes. Water tends to move from the poles toward the equator. As snow builds up on the surface, running water can trickle out. Today the midlatitudes are warming up, and the snow cover has mostly disappeared. If the ice-age model is correct, they will return over the next 25,000 to 50,000 years.

The story of Mars science is like the tale of the blind men describing an elephant: the geology seems to change depending on where you look. The planet is a richly textured place with an amazingly dynamic present and an intricate, even paradoxical, past. Its volcanic rocks are as diverse as Earth's, and the manifestations of water vary tremendously. The planet experienced heavy flooding and perhaps even rainfall earlier in its history, yet its ancient rocks still contain minerals that quickly break down in a wet environment. The climate is dry and cold, yet the Opportunity rover found itself on the floor of an ancient sea, indicating that the climate used to be very different. Liquid water is unstable under present conditions, yet gullies formed recently and may continue to do so.

The diversity of surface environments from place to place and time to time is one of the most hopeful indicators for Martian biology: it provides a rich suite of environments where life may have taken hold. Water was abundant in lakes for long, if intermittent, periods. It may have been around long enough for inanimate matter to come alive. Organisms may still cling to life, hibernating during the cold spells and thawing out when climate conditions improve. The remnant snow patches, gullies and similar regions would be an excellent place to search for life on future robotic missions. SA

## MORE TO EXPLORE

**Global Mapping of Martian Hematite Mineral Deposits: Remnants of Water-Driven Processes on Early Mars.** P. R. Christensen, R. V. Morris, M. D. Lane, J. L. Bandfield and M. C. Malin in *Journal of Geophysical Research,* Vol. 106, Part 10, pages 23,873–23,885; 2001.

**Morphology and Composition of the Surface of Mars: Mars Odyssey THEMIS Results.** Philip R. Christensen et al. in *Science,* Vol. 300, No. 5628, pages 2056–2061; June 27, 2003.

**Spirit at Gusev Crater.** Special issue of *Science,* Vol. 305, No. 5685, pages 793–845; August 6, 2004.

**Opportunity at Meridiani Planum.** Special issue of *Science,* Vol. 306, No. 5702, pages 1697–1756; December 3, 2004.

**Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet.** Steve Squyres. Hyperion, 2005.