Roving on Mars

Having spent almost six years on the red planet, the Mars Exploration Rovers are proving to be one of the most successful missions of all time, revealing a wet and complex world.

On May 6, 2009, Spirit got stuck. The Mars rover, about the size of a go-kart, was traveling south on the red planet when it found itself hubcap-deep in loose, flourlike sand. To make matters worse, the rover's right front wheel had locked up three years earlier, leaving it with only five working ones. Fearful of its digging in deeper with every turn of the wheels, Spirit's controllers at JPL called a halt until they could find a way to get it out. Since then, the engineers have been testing maneuvers here on Earth in a big sandbox with two rovers—an exact replica and a lighter one that's closer to what Spirit weighs on Mars. The team is still at it as of this writing, and so far this Spirit is anything but free.

Such setbacks aren't new, however. Less than three weeks after Spirit landed on January 4, 2004, it fell silent. Engineers scrambled to solve the problem, hoping there wouldn't be a repeat of the previous two American missions to Mars. On December 3, 1999, the Mars Polar Lander had been lost, apparently due to a software error that shut off its descent engine too soon. Accompanying the lander was the Mars Climate Orbiter, which was incinerated when a mix-up between metric and imperial units caused it to enter the Martian atmosphere too low. Mars is an unforgiving destination—in fact, more than a third of all spacecraft sent there have never made it. The memory of past failures was still fresh and, with Spirit, the future of the entire Mars program might well have been hanging in the balance. Meanwhile, Spirit's twin was

The Mars Reconnaissance Orbiter snapped this shot of Victoria Crater on October 3, 2006. The ripples at the bottom of the 750-meter-wide crater are sand dunes, created by wind-blown dust. If you squint, you can see the Opportunity rover at the crater's edge on the left, just above the widest lobe.

An artist's rendition of the lander enclosed in airbags as it bounces along the Martian surface. After it stops rolling, the airbags deflate and the lander unfolds to reveal the rover. For an animation of the trip to Mars, click here (RealVideo).

By Marcus Y. Woo

scheduled to land on the other side of the planet. With Spirit's life in doubt, everything now depended on the rover named Opportunity.

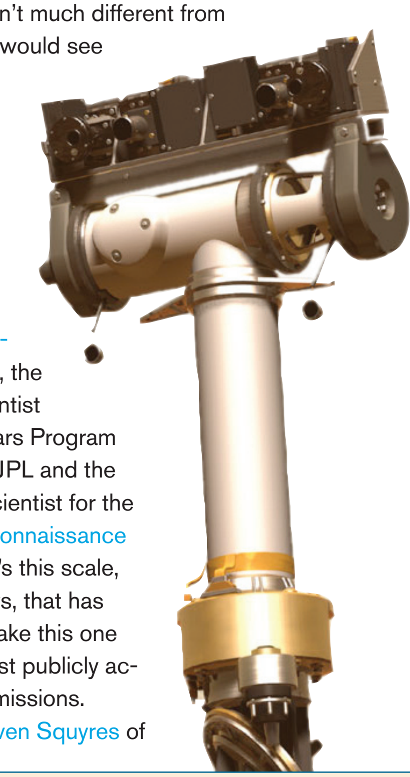
Fortunately, Opportunity landed without a hitch, and the team soon diagnosed Spirit's problem as a software glitch. By February, Spirit was back on track. The two machines, together known as the Mars Exploration Rovers (MERs), then began one of the most successful planetary missions ever. Designed to last only 90 Martian days, or sols, the MERs have now been roving for more than 2,000 sols—nearly six Earth years. These proxy geologists have poked and drilled their way into history, having explored an unprecedented amount of real estate on an alien planet. They have revealed conclusively a watery world with shallow lakes and seas, and with water underground, suggesting that at one time Mars could have been suitable for life.

Spirit and Opportunity wouldn't have been possible had it not been for their predecessor, the 1997 Pathfinder mission (see *E&S* 1997, No. 3)—NASA's first return to Mars since the Viking landers in the 1970s. The Pathfinder lander, which carried most of the instruments, brought along the original Mars rover, a lawn-mower-sized vehicle named Sojourner. This six-wheeled robot spent nearly three months exploring the Martian surface, taking thousands of pictures and analyzing the soil and rocks. Because the rover depended on Pathfinder to relay information back to Earth, Sojourner couldn't venture far and was restricted to covering 250 square meters—an area less than the size of a tennis court. Still, it was proof of principle that you could land a mobile robot on another planet, paving the way for future, more sophisticated vehicles.

And Spirit and Opportunity are sophisticated indeed. Although they share the same basic six-wheeled design, if Sojourner were a push mower, the MERs would be John Deere yard tractors. They can talk to Earth directly via their own antennas or through orbiting spacecraft and have solar panels that generate about 140 watts of power; Sojourner could only produce a maximum of 16 watts. Instead of venturing just tens of meters from their landing sites, the rovers have together already traveled tens of *kilo*meters—far beyond what their designers were hoping. Sojourner's simple instruments—including three cameras and a spectrometer—were attached to its body. To identify minerals with its spectrometer, it had to drive right up to the rock. In contrast, each MER has *two* spectrometers at the end of a robotic arm that, with a shoulder, elbow, and wrist, has the same dimensions and maneuverability as a human one. Also attached at the end are a microscopic imager and a rock abrasion tool that drills into rock to expose the unweathered interior for analysis—the robot geologist's loupe and rock hammer, respectively.

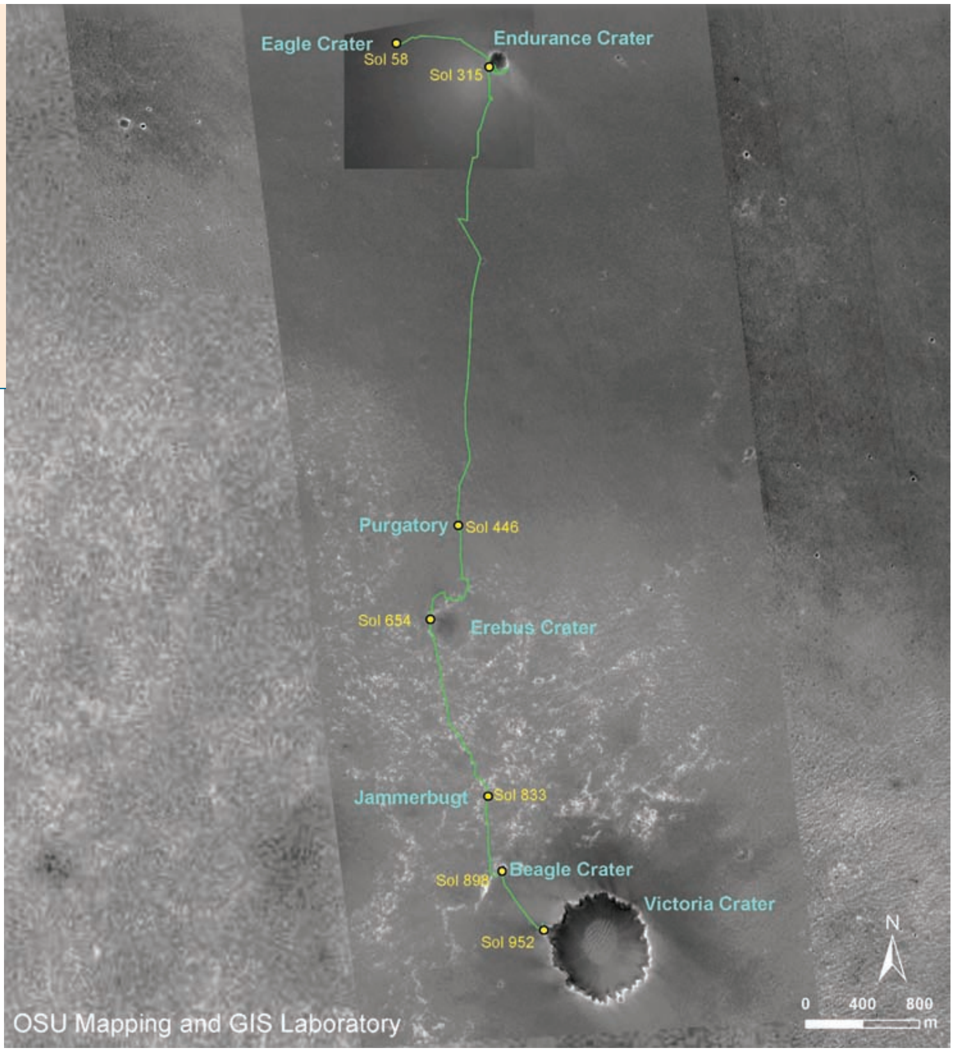
Finally, each rover's high-resolution panoramic stereo camera, perched above the ground at a human's eye level, has perhaps been most responsible for capturing the public's imagination. Not only has it taken thousands of stunning images, bringing the Martian landscape to the living room, but this set of eyes has given the rovers an identifiable and humanized familiarity. The vehicles bear a remarkable resemblance to robots in pop culture, such as Number Five in the film *Short Circuit* and, most recently, the title character of *WALL-E*. (In fact, Pixar animators had used the rovers for inspiration when developing the film.) The anthropomorphizing of the rovers is made even easier by the fact that while space is an incomprehensibly large place, Spirit and Opportunity operate at the human scale. "What the rovers see isn't much different from what you would see wearing a space suit standing on the surface of the planet," says Richard Zurek, the chief scientist for the Mars Program Office at JPL and the project scientist for the Mars Reconnaissance Orbiter. It's this scale, Zurek says, that has helped make this one of the most publicly accessible missions.

As Steven Squyres of



The rover's eyes—a stereo panoramic camera that stands at roughly eye-level above the ground. The "eyes" are spaced 30 centimeters apart, providing full-color, 3-D panoramas of the Martian landscape.

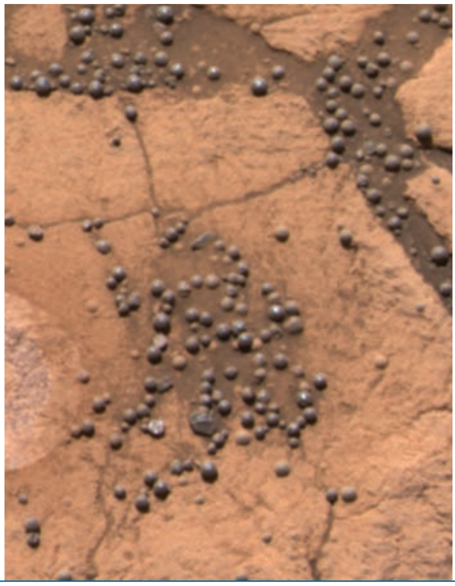
A map of Opportunity's path through its first 952 sols. After spending two years exploring the outer rim of Victoria, Opportunity headed south toward Endeavour Crater 17 kilometers away. Now, the rover is about three kilometers south of Victoria.



Cornell—MER's principal investigator—told Caltech alumni during last May's Seminar Day, it has been the adventure of a lifetime. "The goal of our mission," Squyres said to the crowd at Beckman Auditorium, "is to go to two places on Mars and try to read the story in the rocks and to learn what the conditions were like in the early days of Martian history. Was it warm? Was it wet? Would the conditions there be suitable for life?"

The two rovers were sent to two different sites on opposite sides of the planet. Spirit went to Gusev Crater (14.6° S, 175.3° E), which was chosen based on physical features—a dry river bed flows into it, suggesting the 150-kilometer-wide crater was once a lake. Opportunity's landing site on Meridiani Planum, near the equator (2.0° S, 6.0° W), was chosen based on surface chemistry. The Mars Global Surveyor, an orbiter launched in 1996, had observed patches of hematite, a type of iron oxide that often requires water to form, on Meridiani—the only place on Mars where large deposits of it were found.

Each spacecraft carrying a rover arrived at Mars careening at 5,400 meters per second—6,000 times the cruising speed of a 747. The atmosphere then slowed down the rover, packed in its aeroshell, to 430 meters per second—about seven times as fast as a Cessna—as the heat shield reached a scalding 1,400 degrees Celsius. Parachutes slowed it further, but because of the thin atmosphere, chutes weren't enough. Airbags covering the lander inflated and retro-rockets briefly fired. Looking a little like a big popcorn kernel, the lander was cut loose from the chutes at about 15 meters above the surface. After the lander finished bouncing around, the airbags deflated, and like mechanical origami, the lander's petals opened and the rover unfolded.



WHAT AN OPPORTUNITY

Opportunity settled into a 20-meter-wide crater—a 90-million-kilometer hole in one. As Squyres remarked, "Tiger Woods on his best day could not have pulled off this landing." Before the rover touched down, Squyres was worried that the surface of Meridiani would be too smooth, lacking enough

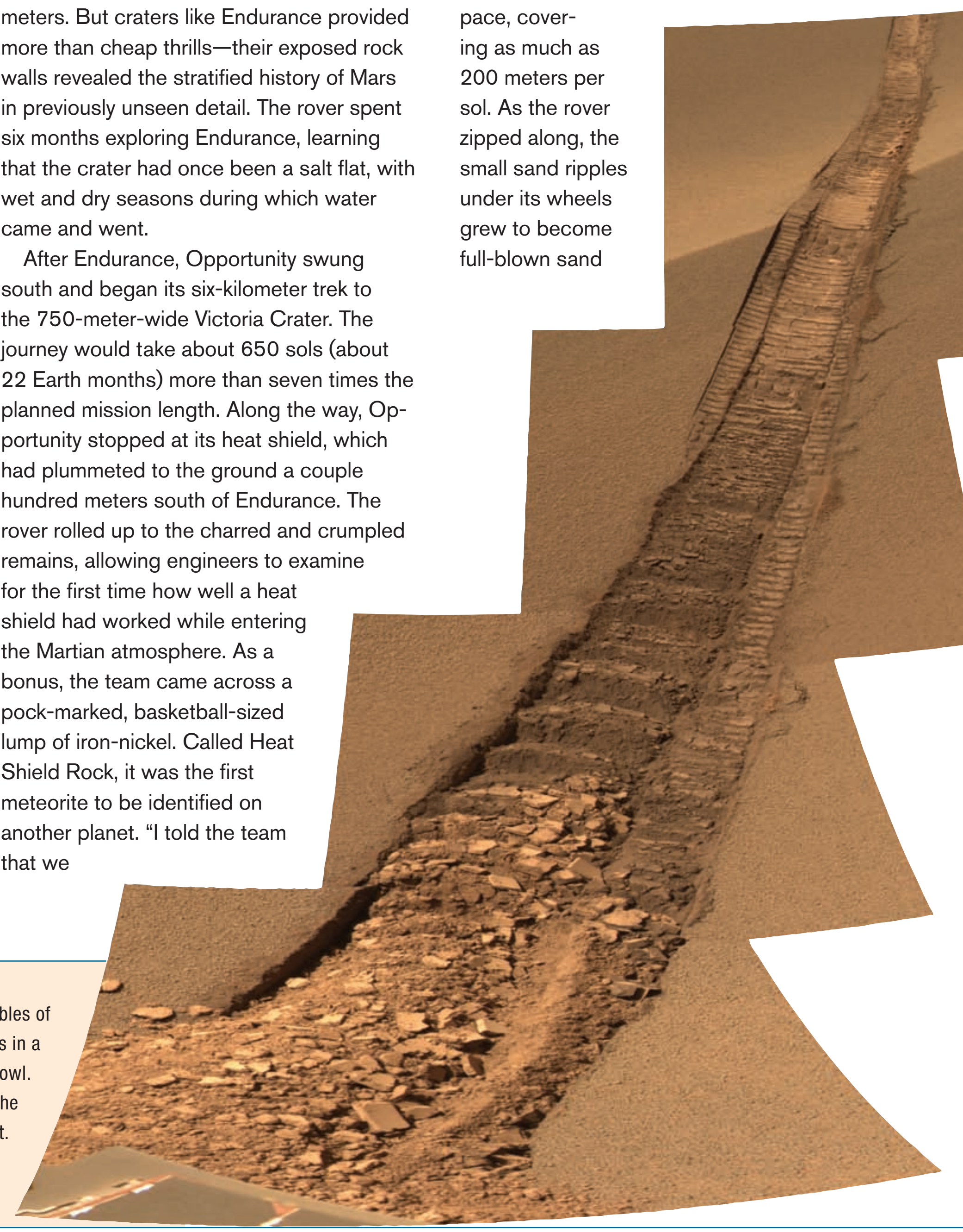
geological variation and rock to study. When Opportunity opened its eyes for the first time, however, it saw exposed bedrock, ripe for digging and analyzing. The team couldn't tell how high the outcrop was, and for all they knew it could've been quite tall, so they dubbed it the Great Wall. But after surveying it with the stereo camera and doing some math, they found out it was just 10 to 20 centimeters tall—barely ankle-high. Still, the entire landing site was full of exposed rock—crucial because it's relatively young and accessible.

Then, as Opportunity looked around, it made what is likely the mission's signature discovery. It saw small pebblelike objects scattered across the surface, and when it went over to take a closer look, it identified the five-millimeter spheres—dubbed blueberries—as hematite. The blueberries hadn't rolled in from somewhere else, but were embedded in the rock. They proved to be geological features called concretions, which require water to form. When water saturates porous sedimentary rock, minerals precipitate out and fill the voids inside the rock. Over time, the precipitates accumulate, layer by layer like an oyster's pearls, eventually forming the blueberries. Wind then erodes the surrounding rock to expose the hematite. The rock and soil surrounding the blueberries were rich in sulfates, another chemical signature of water. The researchers also saw petrified ripples in the sand, possibly created by slow-moving waves on an ancient shoreline.

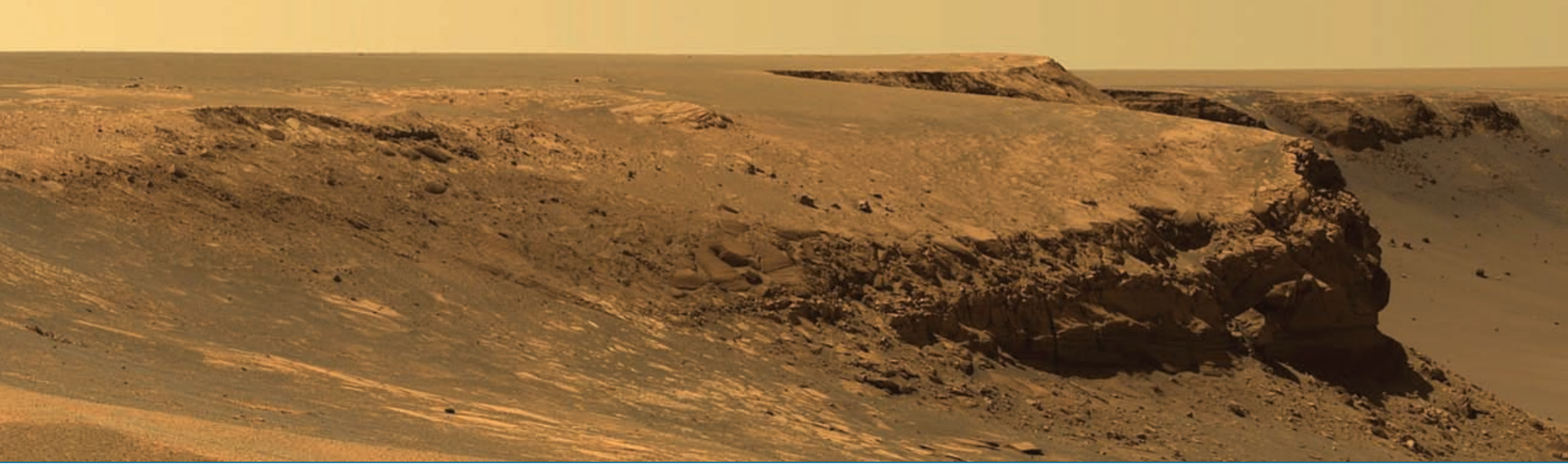
Opportunity explored this crater, called Eagle, for two months before starting the 800-meter trip eastward to Endurance Crater, which, with a diameter of 130 meters, was the size of a small stadium. Once there, Opportunity inched its way down the western ridge, an 18-degree slope, for about 17 meters. But craters like Endurance provided more than cheap thrills—their exposed rock walls revealed the stratified history of Mars in previously unseen detail. The rover spent six months exploring Endurance, learning that the crater had once been a salt flat, with wet and dry seasons during which water came and went.

After Endurance, Opportunity swung south and began its six-kilometer trek to the 750-meter-wide Victoria Crater. The journey would take about 650 sols (about 22 Earth months) more than seven times the planned mission length. Along the way, Opportunity stopped at its heat shield, which had plummeted to the ground a couple hundred meters south of Endurance. The rover rolled up to the charred and crumpled remains, allowing engineers to examine for the first time how well a heat shield had worked while entering the Martian atmosphere. As a bonus, the team came across a pock-marked, basketball-sized lump of iron-nickel. Called Heat Shield Rock, it was the first meteorite to be identified on another planet. "I told the team that we shouldn't stay here," Squyres said. "This is obviously a place where big metal objects fall from the sky."

There were a few brief stops along the way at smaller craters, but Opportunity maintained a brisk pace, covering as much as 200 meters per sol. As the rover zipped along, the small sand ripples under its wheels grew to become full-blown sand



Left: Soon after landing, Opportunity discovered pebbles of hematite embedded in sedimentary rock, like blueberries in a muffin. The team called this site the berry bowl.
Top: Smash! Opportunity explores its fallen heat shield. The main part is on the left; the impact site is on the right.
Right: Opportunity's tracks during its effort to free itself from Purgatory Dune.



dunes, and halfway between Endurance and Victoria, Opportunity got stuck. The wheels racked up 50 more meters on the odometer before anyone realized the rover hadn't actually gone anywhere. (The team aptly named this unplanned stop Purgatory Dune.) To figure out how to get the rover out, they had to recreate its situation, so they fanned out to hardware stores across the Los Angeles area to buy the ingredients for mock Martian soil: sand, clay, and diatomaceous earth—a material made of ground-up fossilized algae that is used in swimming-pool filters. After six weeks with the rover in Purgatory, according to Squyres, the team discovered that the best way to spring the vehicle free was "to put it in reverse and gun it." With its renewed freedom, Opportunity continued to Victoria Crater, where it would spend the next 682 sols.

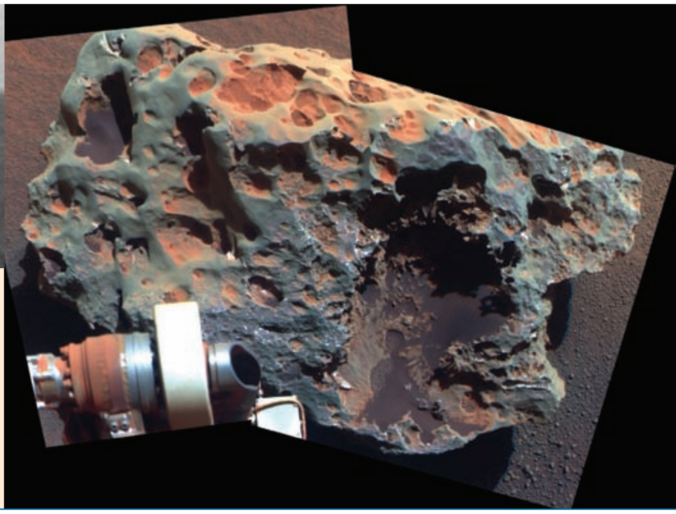
"When Spirit ended up on the lava plains, the team didn't give up on it," Zurek says. "It headed for the hills—literally."

Victoria is 75 meters deep, and although Opportunity didn't go all the way to the bottom, where the rover would have become mired in a dune field, this expedition was the deepest yet. The rover spent nearly two years exploring the edge and outer regions of the crater, venturing in when the slope was shallow and safe, finding more evidence of water and of wind erosion. Blueberries were all over the place, and they got bigger as the rover went deeper—a sign of more groundwater deeper underground, which meant more hematite-producing chemistry.

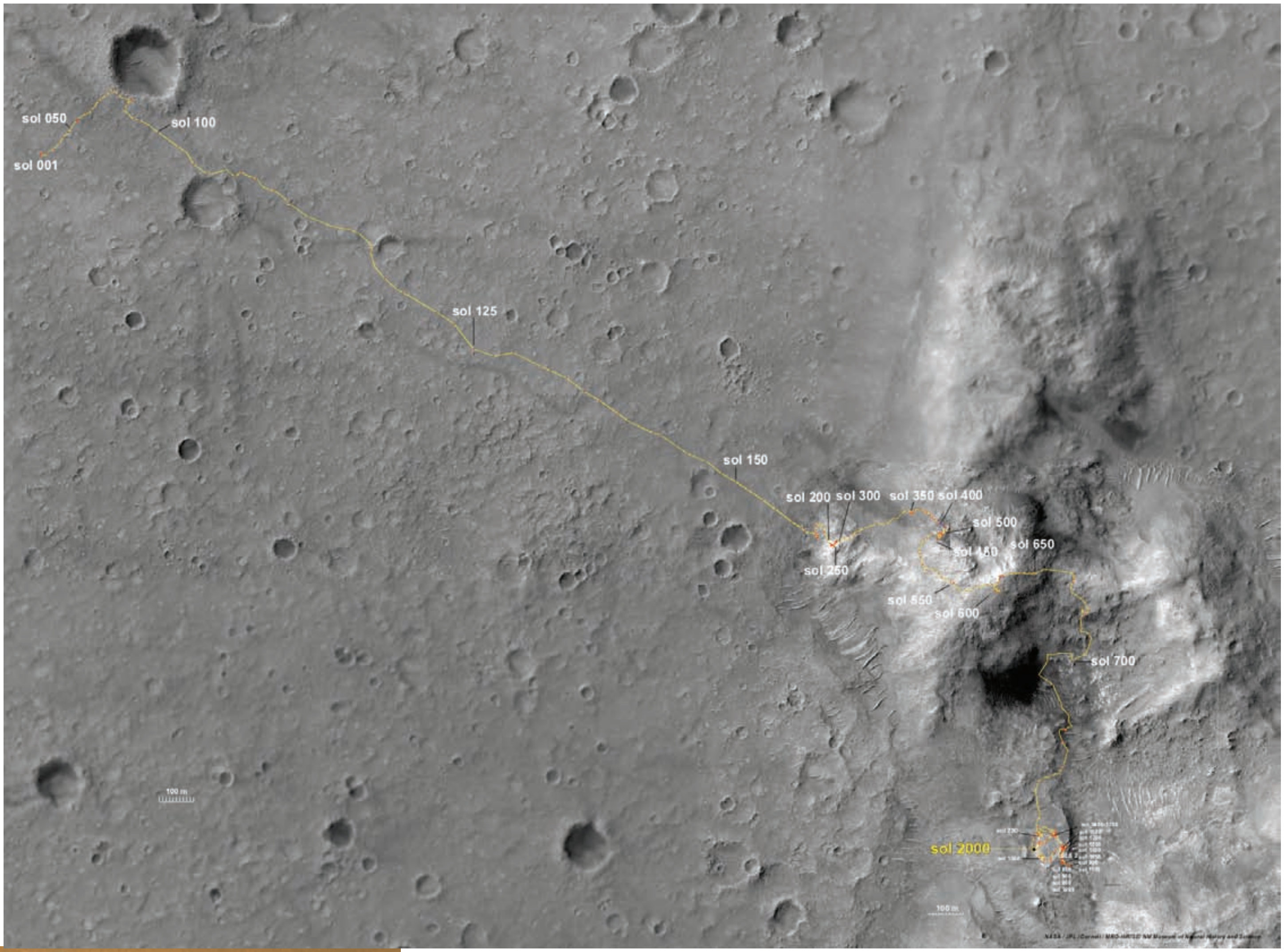
From the bits of meteorite and ejected rocks strewn about from the original impact, the researchers deduced that the initial crater had been 600 meters wide and 125 meters deep. Over time, wind had widened the crater and blown sand into the bottom. The layering in the rock also suggested a windy past, and the variations in rock composition were similar to those found in Eagle and Endurance Craters, implying that the whole region underwent similar geological processes.

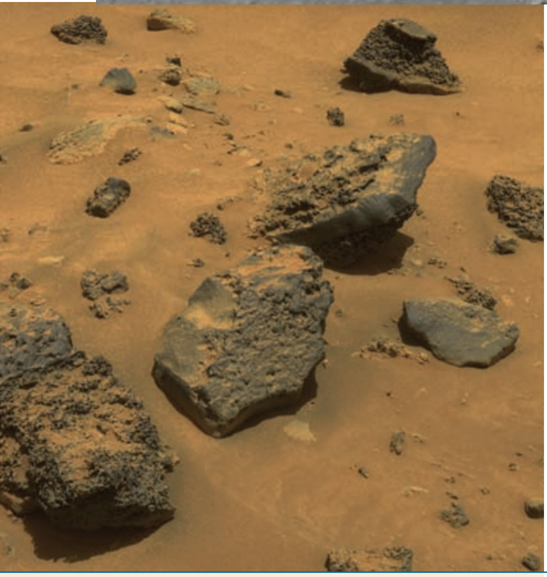
Then, some 1,500 days past the planned mission duration, Opportunity was still chugging along, so scientists set their sights on Endeavour Crater, a 22-kilometer-wide, 300-meter-deep behemoth roughly 17 kilometers away. As of this fall, the rover has been en route for about a year. There's still a long way to go, because engineers are rerouting the rover to avoid road hazards, such as other sand dunes similar to Purgatory (the team calls them "purgatoids"). These detours will add another 30 percent to the distance Opportunity will travel. On March 7, 2008, Opportunity caught its first glimpse of Endeavour's edge from 12 kilometers away.

Throughout its journey to Endeavour, Opportunity has been looking at the soil and rock, mapping the changes in composition and chemistry. In late July, it took a picture of a dark, bluish rock the size of a big pumpkin that didn't quite match the other rocks in the area. Opportunity had already driven about 180 meters past the rock by the time the image, which was stored onboard for a few days, arrived on Earth. When the researchers saw the odd object, they turned the rover around and returned to take a closer look. Called Block Island, the rock turned



Top: A promontory called Cape Verde at Victoria Crater. The wall is about 6 meters high.
Above: On March 7, 2009, Opportunity took a snapshot of the northern ridge of Endeavour Crater. This part of the crater is about 20 kilometers away.
Right: Block Island is the largest nickel-iron meteorite found on Mars.





out to be an iron-nickel meteorite with a mass of about 500 kilograms—roughly ten times as massive as Heat Shield Rock.

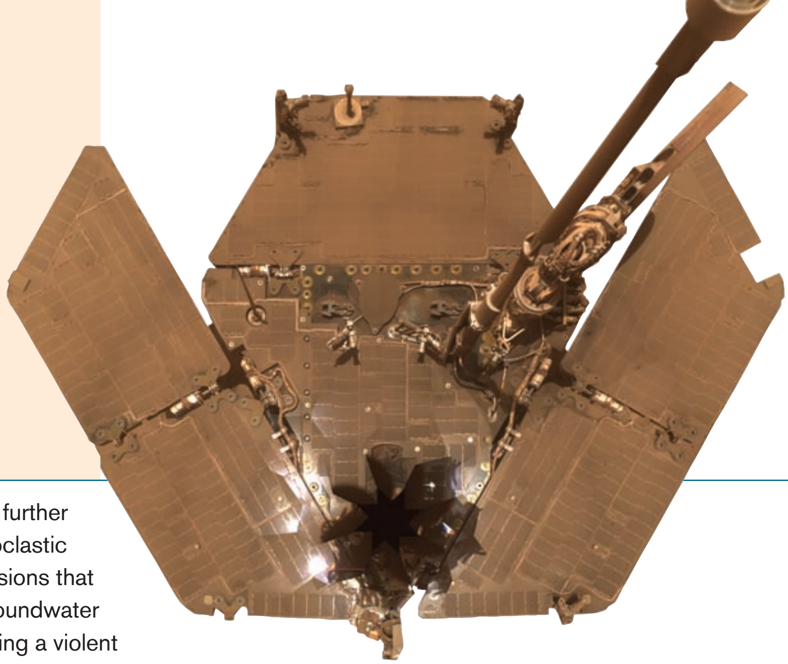
THAT'S THE SPIRIT

On the other side of the planet, Spirit quickly overcame its initial software hiccup and has since made plenty of its own discoveries—although its path hasn't been nearly as smooth. The team had sent Spirit to what appeared to be a dried-up lake, but it proved to be a volcanic plain surrounded by lava rocks. "It was a bitter disappointment," Squyres says. The mission's goal was to look for signs of water, not magma. Most likely there were sedimentary deposits—just underneath the lava layer, beyond Spirit's reach. But then Spirit saw a potentially more interesting spot in the Columbia Hills, three kilometers away. "When Spirit ended up on the lava plains, the team didn't give up on it," Zurek says. "It headed for the hills—literally." Had Spirit been a lander, it would've been stuck with boring basalts. Had Spirit only lasted its planned lifespan, it would not have made it to the Columbia Hills, 156 sols into the mission.

The hills are named after the ill-fated space shuttle *Columbia*, and each of the

Top: Spirit's route from Gusev Crater to the Columbia Hills and Home Plate, near its current location.
Bottom: Scientists were hoping to find sedimentary rocks, which would harbor evidence of past water, at Spirit's landing site in Gusev Crater. Instead, the rover found a volcanic plain strewn with lava rocks.

Exploring Mars can be a dirty job. The dust on Spirit's solar panels once caused power levels to dip dangerously low. Luckily, the rover was saved when some wind cleaned off the dust.

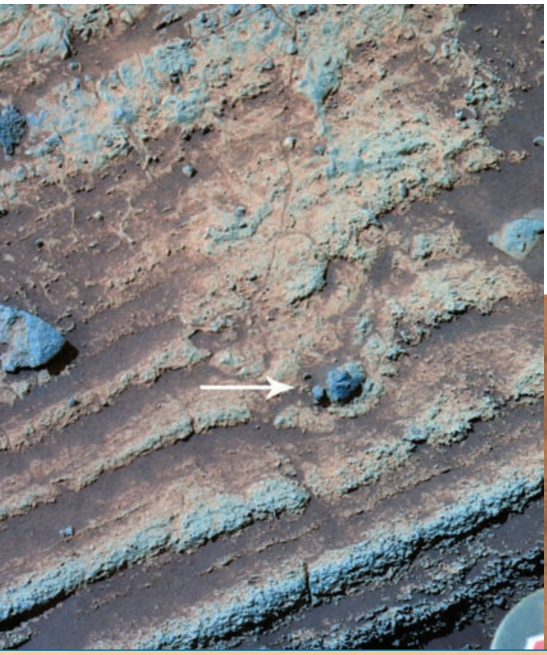


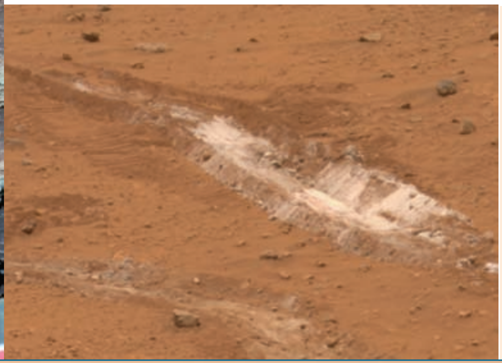
seven peaks bears the name of a crew member. Spirit arrived on June 16, 2004, and approached the region from the northwest, starting from the base and winding its way up and around the gentle slopes. The rover identified iron sulfate salts, a sign of groundwater. The team then drove it over to a 90-meter-wide plateau dubbed Home Plate, where Spirit has since spent the majority of its time. There, it has discovered a piece of volcanic rock embedded in the sedimentary layers. This kind of rock, called a bomb sag, becomes implanted after volcanic explosions have blasted it into the air and it lands in soft material—deformable dirt or maybe even mud. High concentrations of elements like chlorine, bromine, zinc, and germanium were further evidence for pyroclastic eruptions—explosions that happen when groundwater meets lava, creating a violent outburst of steam and flying rock.

In the spring of 2006, after about 800 sols on Mars, Spirit had descended from the top of Home Plate and started toward McCool Hill when its right front wheel jammed. Engineers spent weeks trying to fix it, to no avail. Spirit was now hobbled, but it could make do if it drove backward, dragging the lame wheel along behind it. It turned out, though, that the wheel would become a scientific tool. It carved a trench as Spirit rambled on, and in the summer of 2007, it uncovered a surprise—white soil that lay beneath the red surface.

The white stuff was amorphous silica, which precipitates from hydrothermal activity. These deposits don't form in days or weeks, but in anywhere from a few years to a few thousand years, says Diana Blaney, the MER deputy project scientist. Evidently, Mars may once have been home to hot springs, and if they're anything like the ones on Earth (in Yellowstone National Park, for example), they can be abodes for all sorts of life. There has been other evidence for such mineral spas. In 2008, the Mars Reconnaissance Orbiter's high-resolution camera took snapshots of Vernal Crater in Arabia Terra, and found mounds and channels that looked like those made by hot springs in Yellowstone.

Finding silica was serendipitous, but Spirit also needed luck just to survive. Earlier, less than 400 sols into the mission, the rover had run dangerously low on power when dust blanketed the solar panels. At peak performance, Spirit could generate 900 watt-hours of energy per day, but now it was down to 300 watt-hours. If production dropped to 200 watt-hours, the rover would die. Luckily, Mars appears to have a natural





Far left: A bomb sag. When lava meets steam, an explosion blasts volcanic rock into the air, and it falls and becomes embedded in the ground.
Left: Spirit's defunct wheel dug up amorphous silica from under the surface—evidence for hydrothermal vents.
Below: The Columbia Hills from a couple kilometers away.

vacuum cleaner—not a Dirt Devil but maybe a dust devil, or simply a gust of wind—that blew off the dust, returning energy production to 850 watt-hours. Spirit was up and moving again—that is, until May of this year, when it got stuck in a place called Troy, west of Home Plate.

According to John Callas, MER project manager, Troy is a fascinating site, with layered terrain chock full of sulfates and amorphous silica. Researchers still don't know how old these minerals are, Callas says, and there's a possibility they could have a relatively recent origin. Now, while the engineers work to get Spirit out, the rover is still busy doing science, analyzing the soil and silica deposits around it, trying to glean as much information as it can. As Zurek says, "We're literally just scratching the surface of understanding the history of the planet."

ROVING INTO THE FUTURE

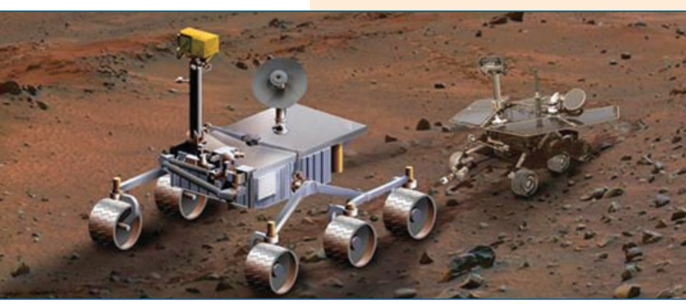
In 2011, NASA will launch the Mars Science Laboratory (MSL). Now also known as Curiosity, MSL is the next-generation rover, a bigger vehicle that will be better equipped to analyze Martian chemistry and further gauge the planet's habitability for life. MSL will have instruments that can identify organic compounds, and instead of relying on solar panels and the occasional Martian wind to keep them clean, MSL will use a chunk of plutonium to power its year-long mission. After MSL comes Maven, an orbiter that will study Mars's upper atmosphere. Planned for launch in 2013, Maven got the go-ahead from NASA last fall.

Eventually, researchers hope for a sample-return mission. Even with improving technology, a rover can't replace a laboratory on Earth. Some experiments—such as accurate radiometric dating to establish a chronology of Mars, which is still a major source of uncertainty—require elaborate sample preparation or instruments too heavy to put on a rocket. With Martian rocks on hand, scientists can get immediate results on follow-up experiments without having to send another spacecraft to find out more, Zurek explains. "In a way, sample return replaces multiple missions."

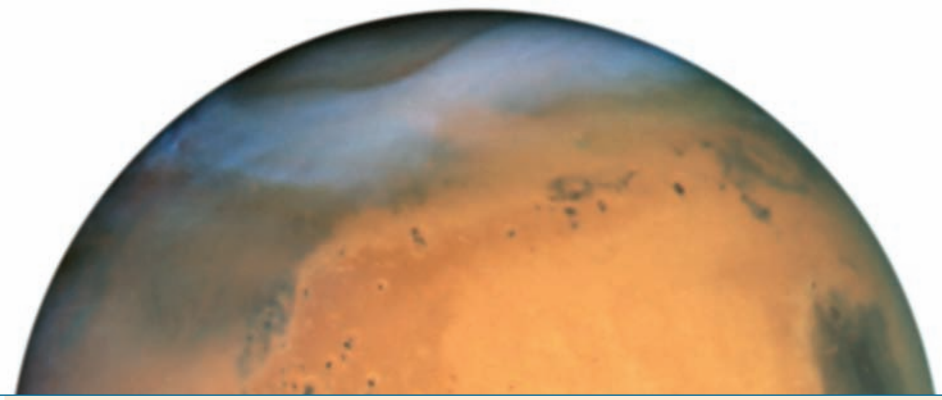
Spirit's and Opportunity's wheels just keep spinning. "The ability to go several kilometers is what has set them apart," notes Zurek. They have also proven that you can't fully understand Mars unless you're on the ground, digging in the dirt. Otherwise, researchers would never have been able to identify the blueberries, discover silica deposits, explore the Columbia Hills and the Meridiani craters, or find meteorites. Other NASA spacecraft have also lasted far beyond their design lifetimes—Voyagers 1 and 2, for example, have been zipping through space for more than three decades and are now beyond the orbit of Pluto. But vehicles roaming the surface of other planets are another matter. Daily temperature swings of over 100 degrees torture electronics, because the cycles of hot and cold can snap delicate connectors, and dust and grit can jam joints and wheels.

Despite their durability, the rovers are showing signs of age. Spirit once ignored its morning wake-up call last spring, and has occasionally rebooted its computer

Right: An engineering prototype of the Mars Science Laboratory tests its wheels on a mock Martian surface at JPL.



Below: A rendering of MSL and Spirit showing their relative sizes.



for no known reason. Periodic dust storms have covered both rovers' solar panels with dirt, requiring more wind cleanings. In April, Spirit's power production once again dipped to 240 watt-hours per sol before the winds came. Eventually, the mission will end—either mechanical parts or software will break down, or the Martian wind won't come to the rescue in time. "We're way past the warranty on these things," Blaney says. But "they'll keep going until stuff breaks."

As of now, Opportunity is continuing its journey to Endeavour Crater, and engineers are hopeful that they will free Spirit soon. But whatever their fates, the twin rovers have already made their mark. "We'll always have a special place in our exploration hearts for those two vehicles," Zurek says. "Even as we come up with more sophisticated and bigger ones in the future, these are the ones that showed us we could get around and find things—and that's pretty powerful." e&s

WHY MARS?

In recent years, other planetary bodies have grabbed headlines. Enceladus, one of Saturn's moons, has towering, water-rich geysers. Saturn's biggest satellite, Titan, hides liquid-ethane seas under its thick methane atmosphere. Jupiter's moon Europa is thought to harbor an ocean below its icy surface. These discoveries point to a newfound potential for life on the moons of the outer planets, and with such diverse environments, these places would seem to be the next frontier in solar-system exploration. If that's the case, why are we still going to Mars?

One simple reason is that it's close, Blaney says. While it takes 6 to 10 years to go to the outer solar system, we can get to Mars in six months every couple of years when it aligns with Earth. Being a rocky planet, it's also easier to explore. To get to Europa's subsurface ocean, for example, you would have to drill through kilometers of thick ice. And unlike on Venus with its thick, heat-trapping clouds, spacecraft don't melt on Mars.

Furthermore, much of Mars's history mirrors that of Earth, and because it's now much less geologically active than Earth, its surface hasn't been erased by earthquakes, volcanoes, and drifting tectonic plates, Zurek explains. Studying Mars, then, is like looking at Earth's past. Mars could hold insights into our history that are not found elsewhere in the solar system.

Beyond the science, Mars has always had a certain allure. "It has a psychological accessibility that makes the public see it differently from the rest of the solar system," Zurek says. With canyons, mountains, wind, ice, clouds, and even snow, Mars is similar enough to Earth that we can envision walking there. "It's hard to think of astronauts being on Io, Europa, or Venus," he says. At the same time, Mars still has an alien appeal. In 2004, President Bush outlined a plan to send humans to Mars. Whether or not the American space program will indeed go in that direction remains to be seen. In September, the U.S. Human Space Flight Plans Committee, a congressionally appointed panel of experts charged with assessing the program, issued a summary report that says there isn't enough money allocated to send humans to the moon and Mars. "The U.S. human spaceflight program," the summary reads, "appears to be on an unsustainable trajectory." But regardless of whether we explore it in person or by proxy, Mars is still capable of stirring anyone's adventurous spirit. e&s

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