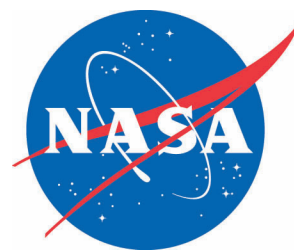


NASA Facts

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109



Mars Exploration Rover

In April 2004, two mobile robots named Spirit and Opportunity successfully completed their primary three-month missions on opposite sides of Mars and went into bonus overtime work. These twin vehicles of NASA's Mars Exploration Rover project continued their pursuit of geological clues about whether parts of Mars formerly had environments wet enough to be hospitable to life.

Opportunity hit the jackpot early. It landed close to a thin outcrop of rocks. Within two months, its versatile science instruments found evidence in those rocks that a body of salty water deep enough to splash in once flowed gently over the area. Preliminary interpretations point to a past environment that could have been hospitable to life and also could have preserved fossil evidence of it, though these rovers are not equipped to detect life or to be fossil hunters.

As Opportunity's primary mission ran out and an extended mission began, the rover was headed for thicker layers of exposed bedrock that might bear evidence about how long or how often water covered the region.



Shadow of rover Opportunity in "Endurance Crater," July 26, 2004.

Spirit, during its primary mission, explored a plain strewn with volcanic rocks and pocked with impact craters. It found indications that small amounts of water may have gotten into cracks in the rocks and may also have affected some of the rocks' surfaces. This did not indicate a particularly favorable past environment for life.

Spirit's extended mission began with the rover starting a long trek toward a range of hills on the horizon whose rocks might have come from an earlier and wetter era of the region's past.

Second Extension as Adventure Continues

In late September 2004, NASA approved a second extension of the rovers' missions. The solar-powered machines were still in good health, though beginning to show signs of aging. They had come through the worst days of the martian year from a solar-energy standpoint. Also, they had resumed full operations after about two weeks of not driving in mid-September while communications were unreliable because Mars was passing nearly behind the Sun.

Spirit had driven 3.6 kilometers (2.25 miles), six times the goal set in advance as a criterion for a successful mission. It was climbing hills where its examinations of exposed bedrock found more extensive alteration by water than what the rover had seen in rocks on the younger plain. During the long trek, Spirit's right front wheel developed excessive friction. Controllers found a way to press on with the exploration by sometimes driving the rover in reverse with the balky wheel dragging.

Opportunity had driven about 1.6 kilometers (1 mile). It was studying rocks and soils inside a crater about 130 meters (142 yards) wide and 22 meters (24

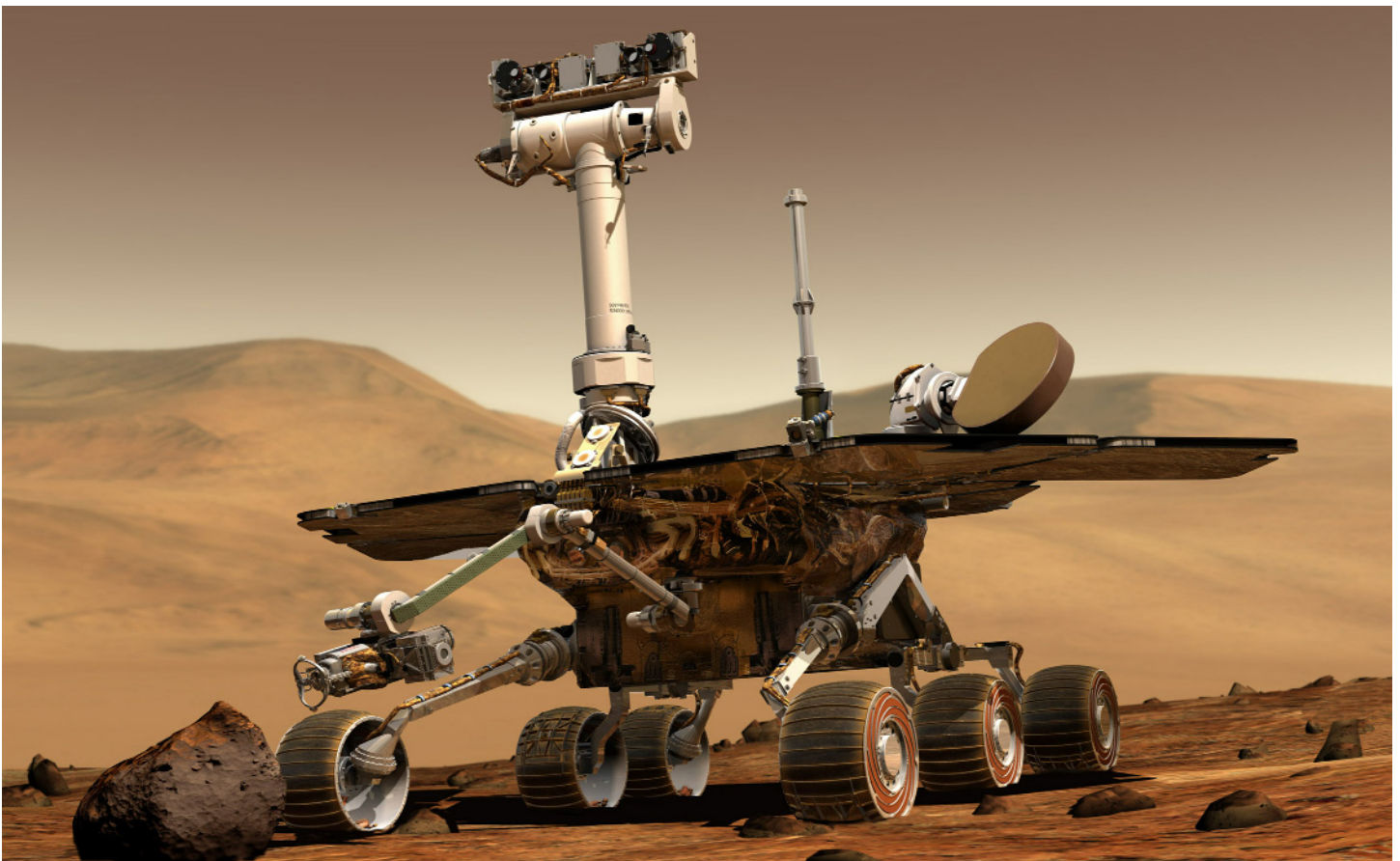
yards) deep. The rover entered this crater in June after careful analysis of its ability to climb back out. Inside, Opportunity examined layer upon layer of bedrock with characteristics similar to those of the outcrop inside the smaller crater where it landed. This indicated a much longer duration for the watery portion of the region's ancient past. The rover also found some features unlike any it had seen before, evidence of changes in the environment over time.

Whether the rovers' unpredictable life spans would extend only a few more days or several more months, they had already racked up successes beyond the high expectations set for them when the Mars Exploration Rover project began.

Favorable Time to Build on Experience

Mars came closer to Earth in August 2003 than it had in thousands of years. NASA decided in the summer of 2000 to take advantage of this favorable planetary geometry to send two rovers to Mars.

The design began with some basics from Sojourner, the rover on NASA's 1997 Mars Pathfinder mission. Some of the carried-over design elements are



Artist's simulation of a Mars Exploration Rover at work on Mars.

six wheels and a rocker-bogie suspension for driving over rough terrain, a shell of airbags for cushioning the landing, solar panels and rechargeable batteries for power, and radioisotope heater units for protecting batteries through extremely cold martian nights. However, at 174 kilograms (384 pounds), each Mars Exploration Rover is more than 17 times as heavy as Pathfinder. It is also more than twice as long (at 1.6 meters or 5.2 feet) and tall (1.5 meters or 4.9 feet). Pathfinder's lander, not the Sojourner rover, housed that mission's main communications, camera and computer functions. The Mars Exploration Rovers carry equipment for those functions onboard. Their landers enfolded them in flight and performed crucial roles on arrival, but after Spirit and Opportunity rolled off their unfolded landers onto martian soil, the landers' jobs was finished.

NASA's Jet Propulsion Laboratory, Pasadena, Calif., designed and built the two new rovers plus the lander and the cruise stage for each. The cruise stage provided capabilities needed during the journey from Earth to Mars. In early 2003, the hardware arrived at NASA's Kennedy Space Station in Florida for final assembly, testing and integration with Boeing Delta II launch vehicles.

While the twin spacecraft were being built, scientists and engineers winnowed a list of 155 candidate landing sites to a final pair best suited to the missions' goals and safety. More than 100 Mars experts participated in evaluating the sites. They made heavy use of images and other data from NASA's Mars Global Surveyor and Mars Odyssey orbiters.

The rover project's science goal has been to assess the history of environmental conditions at sites that may once have been wet and favorable to life. Each of the two selected landing sites showed evidence detectable from orbit that it may have once been wet. For Spirit, NASA chose Gusev Crater, a Connecticut-size basin that appears to have once held a lake, judging from the shapes of the landscape. A wide channel, now dry, runs downhill for hundreds of kilometers or miles to the crater and appears to have been carved by water flowing into the crater. For Opportunity, NASA chose part of a broad plain named Meridiani Planum based on a different type of evidence for a possibly watery past. A mineral-mapping instrument on Mars Global Surveyor had identified there an Oklahoma-

size exposure of gray hematite, a mineral that usually forms in the presence of liquid water.

Getting to Mars

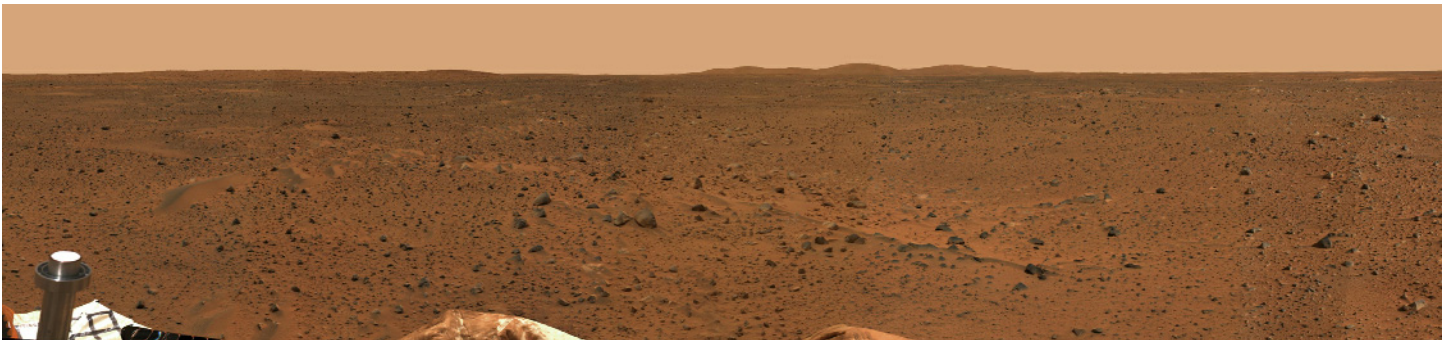
Both rovers were launched from Cape Canaveral Air Force Station on central Florida's Space Coast. Spirit ascended in daylight on June 10, 2003. Opportunity followed with a nighttime launch on July 7 after several days of delays for repairing cork insulation.

During the cruise to Mars, Spirit made four trajectory correction maneuvers. Opportunity performed three. The two spacecraft survived blasts of high-energy particles from some of the most intense solar flares on record. To prevent possible problems from the flares' effects on computer memory, mission controllers commanded rebooting of the rovers' computers, a capability originally planned for use on Mars but not during the cruise.

Each rover made the trip tightly tucked inside its folded-up lander, which was encased in a protective aeroshell and attached to a disc-shaped cruise stage about 2.6 meters (8.5 feet) in diameter. The cruise stage was jettisoned about 15 minutes before the spacecraft reached the top of Mars' atmosphere.

With the heat-shield portion of the aeroshell pointed forward, the spacecraft slammed into the atmosphere at about 5.4 kilometers per second (12,000 miles per hour). Atmospheric friction in the next four minutes cut that speed by 90 percent, then a parachute fastened to the backshell portion of the aeroshell opened about two minutes before landing. About 20 seconds later, the spacecraft jettisoned the heat shield. The lander descended on a bridle that unspooled from the backshell. A downward-pointing camera on the lander took three pictures during the final half-minute of the flight. An onboard computer instantly analyzed the pictures to estimate horizontal motion. In the final eight seconds before impact, gas generators inflated the lander's airbags, retro rockets on the backshell fired to halt descent speed, and transverse rockets fired (on Spirit's lander) to reduce horizontal speed. The bridle was cut to release the lander from the backshell and parachute. Then the airbag-encased lander dropped in free fall.

Spirit landed on Jan. 4, Universal Time (at 8:35 p.m. Jan. 3, Pacific Standard Time). It bounced



Spirit's landing site on a plain inside Gusev Crater, viewed with the rover's panoramic camera before leaving the lander.

about 8.4 meters (27.6 feet) high. After 27 more bounces and then rolling, it came to a stop about 250 to 300 meters (270 to 330 yards) from its first impact. Spirit had journeyed 487 million kilometers (303 million miles). JPL navigators and engineers successfully put it only about 10 kilometers (6 miles) from the center of its target area. Coordinates of Spirit's landing site are 14.57 degrees south latitude and 175.47 degrees east longitude.

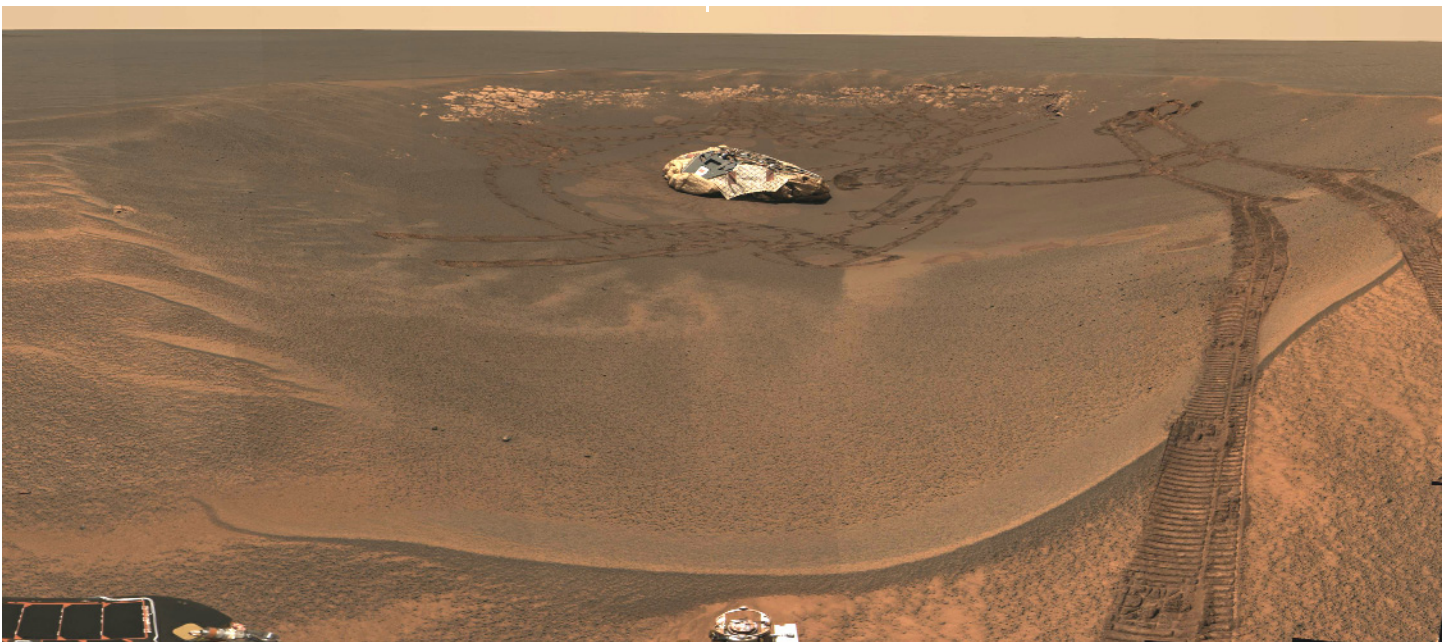
Opportunity landed on Jan. 25, Universal Time (at 9:05 p.m. Jan. 24, Pacific Standard Time). It traveled about 200 meters (220 yards) while bouncing 26 times and rolling after the impact, with a 90-degree turn northward during that period. It came to rest inside a small crater. One scientist called the landing an "interplanetary hole in one." Opportunity had flown 456 million kilometers (283 million miles) from Earth and landed only about 25 kilometers (16 miles) from the center of the target area. The landing-

site crater, later informally named "Eagle Crater," is about 22 meters (72 feet) in diameter, 3 meters (10 feet) deep. Its coordinates are 1.95 degrees south, 354.47 degrees east.

Science Instruments: A Geology Toolkit

Like a human field geologist, each Mars Exploration Rover has the capabilities to scout its surroundings for interesting rocks and soils, to move to those targets and to examine their composition and structure.

Spirit and Opportunity have identical suites of five scientific instruments: a panoramic camera provided by JPL; a miniature thermal emission spectrometer from Arizona State University, Tempe; a Moessbauer spectrometer from the Johannes Gutenberg University, Mainz, Germany; an alpha particle X-ray spectrometer from Max Planck Institute for Chemistry, also in Mainz, Germany; and a micro-



Opportunity's landing site inside "Eagle Crater," looking back at the empty lander after leaving the crater.

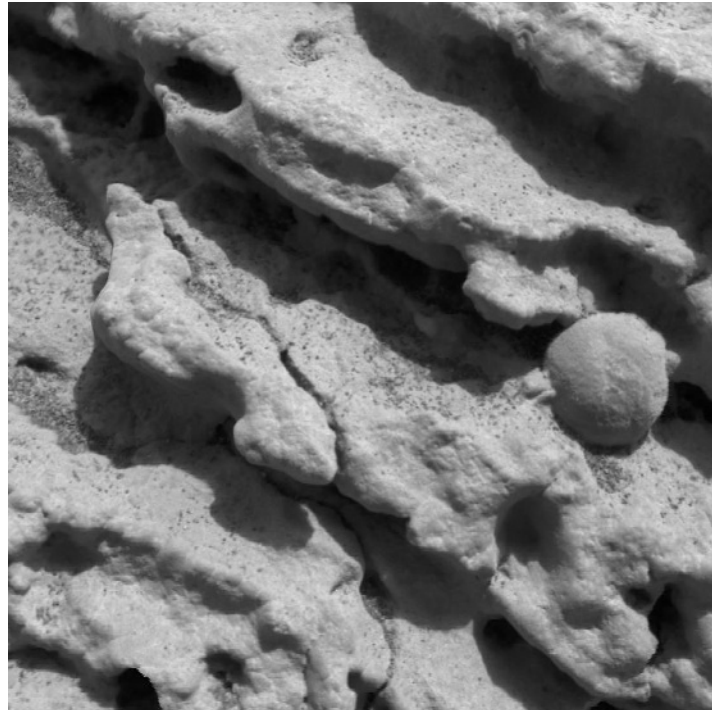
scopic imager from JPL. These are augmented by a rock abrasion tool from Honeybee Robotics, New York, N.Y., for removing the weathered surfaces of rocks to expose fresh interiors for examination. The payload also includes magnetic targets provided by Niels Bohr Institute in Copenhagen, Denmark, to catch samples of martian dust for examination. The spectrometers, microscopic imager and abrasion tool share a turret at the end of a robotic arm provided by Alliance Spacesystems Inc., Pasadena, Calif.

❑ **Panoramic Camera — Providing the geologic context:** This high-resolution stereo camera reveals the surrounding terrain at each new location that the rover reaches. Its two eyes sit 30 centimeters (12 inches) apart, atop a mast about 1.5 meters (5 feet) above the ground. The instrument carries 14 different types of filters, allowing not only full-color images but also spectral analysis of minerals and the atmosphere. Its images are used to help select rock and soil targets for more intensive study and to pick new regions for the rover to explore.

❑ **Miniature Thermal Emission Spectrometer — Identifying minerals at the site:** This instrument views the surrounding scene in infrared wavelengths, determining types and amounts of many different kinds of minerals. A particular goal is to search for distinctive minerals that are formed by the action of water. The spectrometer scans to build up an image. Data from it and from the panoramic camera are used in choosing science targets and new areas to explore. Scientists also use it in studies of Mars' atmosphere.

❑ **Moessbauer Spectrometer — Identifying iron-bearing minerals:** Mounted on the rover arm, this instrument is placed against rock and soil targets. It identifies minerals that contain iron, which helps scientists evaluate what role water played in the formation of the targets and discern the extent to which rocks have been weathered. The instrument uses two cobalt-57 sources, each about the size of a pencil eraser, in calibrating its measurements. It is a miniaturized version of spectrometers used by geologists to study rocks and soils on Earth.

❑ **Alpha Particle X-Ray Spectrometer — Determining the composition of rocks:** An improved version of an instrument used by the Sojourner rover, this spectrometer is also similar to instruments used in geology labs on Earth. It uses



Picture from Opportunity's microscopic imager showing an iron-rich spherule embedded in layered rock. The area covered in this image is 3 centimeters (1.2 inch) wide.

small amounts of curium-244 in measuring the concentrations of most major elements in rocks and soil. Learning the elemental ingredients in rocks and soils helps scientists understand the samples' origins and how they have been altered over time.

❑ **Microscopic Imager — Looking at fine-scale features:** The fine-scale appearance of rocks and soils can provide essential clues to how those rocks and soils were formed. For instance, the size and angularity of grains in water-lain sediments can reveal how they were transported and deposited. This imager provides the close-up data needed for such studies.

❑ **Supplemental Instruments — Engineering tools aid science:** Each rover also has other tools that, while primarily designed for engineering use in the operation of the rover, can also provide geological information. The navigation camera is a wider-angle stereo instrument on the same mast as the panoramic camera. Hazard-avoidance cameras ride low on the front and rear of the rover in stereo pairs to produce three-dimensional information about the nearby terrain. The front pair provides information to aid positioning of the tools mounted on the rover's arm. Rover wheels, in addition to allowing mobility, are used to dig shallow trenches to evaluate soil properties.



Spirit's robotic arm reaching to a rock informally named "Adirondack" for examining the rock with tools on the arm.

Names of Rovers and Features

The names of the rovers, Spirit and Opportunity, were selected in a student essay contest that drew nearly 10,000 entries.

After the spacecraft reached Mars, NASA dedicated the landers as memorials to astronauts who perished in space shuttle accidents. Spirit's lander became Columbia Memorial Station. Opportunity's became Challenger Memorial Station.

A committee of the International Astronomical Union designates official place names on Mars, such as the names Gusev Crater and Meridiani Planum. NASA and members of the rover science team have put unofficial names on many natural features seen by the rovers.

A range of hills that Spirit saw on the eastern horizon from the rover's landing site is unofficially called the "Columbia Hills," with seven individual hilltops named for members of the Space Shuttle Columbia's last crew: Anderson, Brown, Chawla, Clark, Husband, McCool and Ramon. Spirit drove more than three kilometers (about two miles) to reach those hills and begin climbing them.

As in earlier Mars surface missions — Viking and Pathfinder — scientists assign informal names to smaller features, such as rocks and patches of soil in

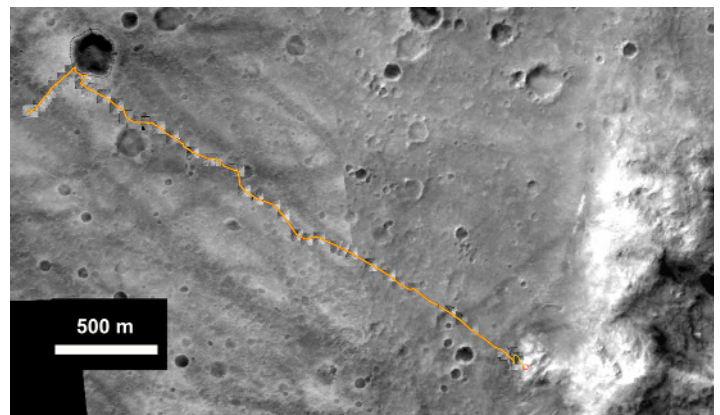
order to avoid confusion when talking about plans and results related to those features. The named features range from stadium-size craters to coin-size spectrometer targets on rocks.

Persistent Spirit

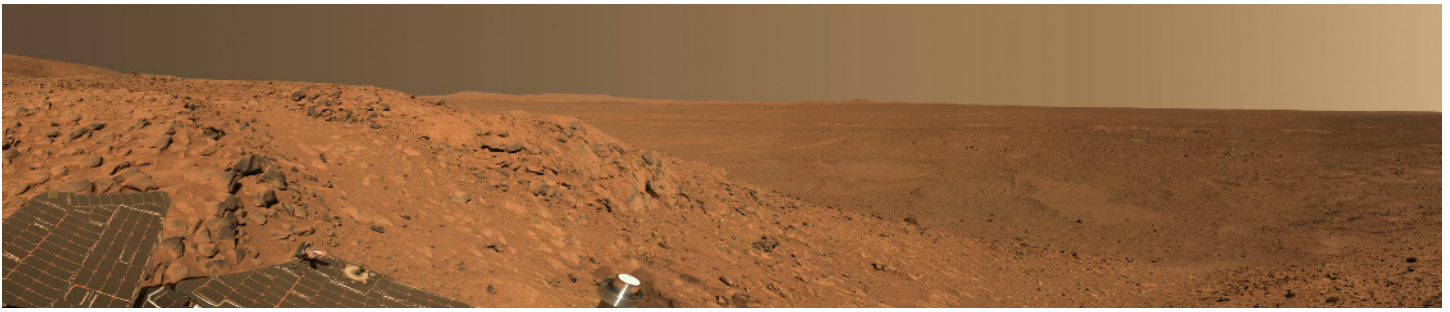
Spirit's first photos looking around its landing site revealed a rock-strewn plain. A few shallow, dusty hollows lay nearby and a few hills and crater rims interrupted the flat horizon. Even before the rover had rolled off its lander platform, scientists chose "Bonneville Crater," about 300 meters (328 yards) to the northeast, as a destination that might offer access to underlying rock layers. They eyed the Columbia Hills, about 2.6 kilometers (1.6 miles) to the southeast, as a tempting but probably unreachable goal for later.

An airbag that was not fully retracted under the lander presented an obstacle to simply driving Spirit forward off the lander. Engineers had practiced many scenarios for getting the rover off. They chose to tell Spirit to turn in place about 120 degrees before driving down a side ramp. The rover rolled onto martian soil on Jan. 15. The next day, it extended its robotic arm to a patch of soil and took humankind's first microscopic image of the surface of another planet. Scientists chose a nearby, football-size stone dubbed "Adirondack" as the first rock to get full research treatment with all four tools on the arm. Spirit reached out to the rock on Jan. 20, but the examination was interrupted by a computer and communication crisis.

Spirit stopped communicating on Jan. 21. For two



Map of Spirit's travels through Sept. 3, 2004, from landing site at left northeastward to rim of "Bonneville Crater" then southeastward into the "Columbia Hills." Scale bar is 500 meters (1,640 feet).



Spirit's view after climbing into "Columbia Hills," part of a full-circle panorama taken between Aug. 9 and Aug. 19, 2004.

worry-filled days, it sometimes failed to send signals at all and other times sent signals without meaningful data. Engineers began to coax some helpful data from Spirit on Jan. 23. They learned the onboard computer had rebooted itself more than 60 times in three days. They developed a strategy to stabilize the rover while continuing to diagnose and remedy the problem over the next several days. The diagnosis was a flight-software glitch that obstructs proper management of the onboard computer's flash memory when the memory is too full. The main remedy was to clear Spirit's flash memory and, from that point on, to avoid getting the memory too full on either rover.

Spirit finished with "Adirondack," where the rock abrasion tool provided the first-ever look inside a rock on Mars. Then the rover set out toward "Bonneville Crater," examining "Humphrey" and other rocks on the way. It reached the crater rim on March 11 and looked inside. No bedrock layers were visible to tempt the team into sending Spirit down into the bowl. On March 31, the rover completed an eight-day inspection of a wind-scalloped boulder called "Mazatzal" just outside the crater. That rock, like all others examined on the plain Spirit was crossing, came from a volcanic eruption. However, thin coatings on the rock and veins inside it suggest that it might have been affected by water at some point.

The rover spent 10 weeks driving from near "Bonneville" to the edge of "Columbia Hills" while surveying soils, rocks and smaller craters along the route. Its longest single-day advance was 123.7 meters (135 yards) on May 10, about 20 percent farther than Sojourner drove during its entire three months of operations on Mars in 1997. As became typical for long-drive days, the feat combined a blind-drive portion, in which Spirit followed a route that rover planners at JPL had determined in advance using stereo images, and an autonomous navigation

portion, during which the rover watched ahead for hazards and chose its own path to avoid them.

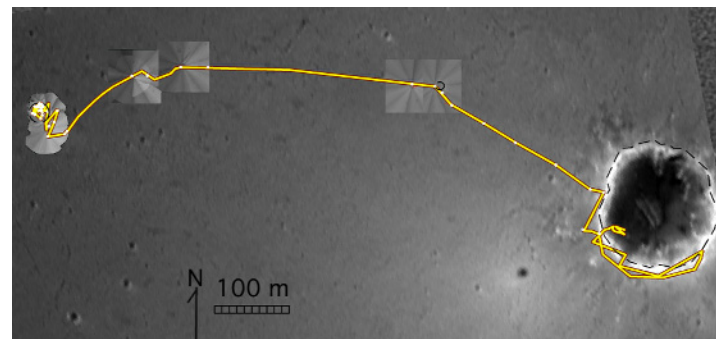
Spirit reached the base of the hills on June 11. There, it examined an oddly knobby rock dubbed "Pot of Gold" and other eroded features before ascending a ridge called "West Spur." Climbing that ridge in early August, Spirit reached exposed bedrock for the first time, seven months after landing.

Well-Placed Opportunity

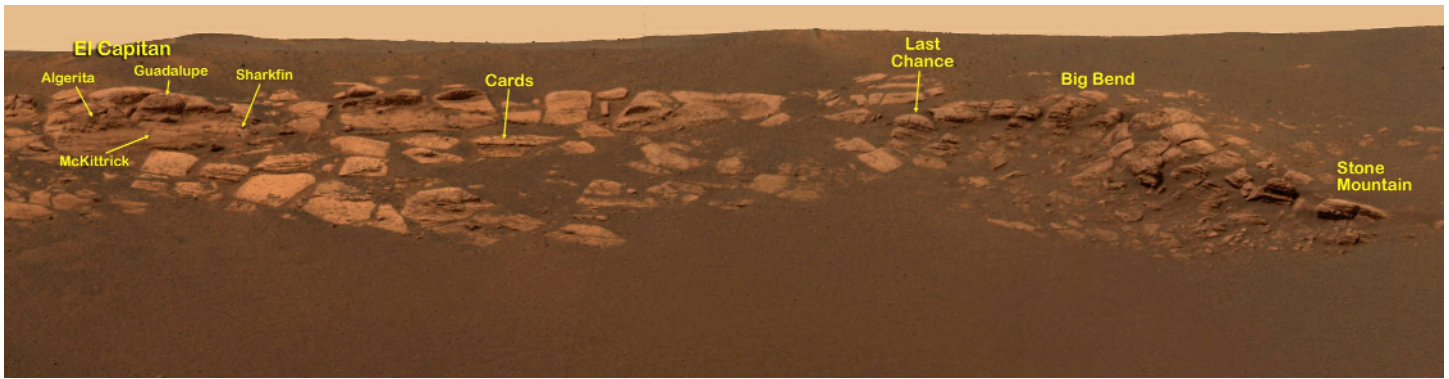
Opportunity drove up to exposed, layered bedrock in "Eagle Crater" on Feb. 7, just two weeks after landing. It spent most of the next six weeks examining this outcrop, which arcs about halfway around the inner slope of the crater but stands only about as high as a street curb.

The rover discovered BB-size gray spheres embedded in the rock like blueberries in a muffin. These spherules are also plentiful in the soil of the area, apparently set loose when erosion wore away softer rock material around them. They contain hematite, the mineral whose detection from orbit had made Meridiani a compelling landing site.

Spectrometers on the rovers found that the outcrop is rich in sulfate-salt minerals, evidence that the



Map of Opportunity's travels through Aug. 21, 2004, from landing site on left eastward to "Endurance Crater," then into that crater. Scale bar is 100 meters (328 feet).



Portion of the outcrop in “Eagle Crater,” where Opportunity landed. The rocks are about 10 centimeters (4 inches) tall.



Opportunity’s view northeastward into “Endurance Crater,” combining frames taken with the panoramic camera between May 23 and May 29, 2004. The crater is about 130 meters (about 425 feet) in diameter.

rock had been drenched with salty water. The spherules are distributed throughout the rocks, rather than only in particular layers. This observation contributed to a conclusion that they are concretions, another sign of mineral-rich water soaking through the rocks. The microscopic imager revealed rippled bedding patterns in some of the finely layered rocks, indicating that the rocks not only were exposed to water after they formed, but actually formed from sediment particles laid down in flowing water.

Opportunity climbed out of Eagle Crater on March 22. It examined some rocks and soil on the dark surrounding plain, then headed east toward a stadium-size crater called “Endurance.” It set a one-day martian driving record of 140.9 meters (462 feet) on April 17 and reached the rim of the crater on April 30.

The rover’s panoramic camera and miniature thermal emission spectrometer surveyed the interior of “Endurance” from two overlook points about a third of the way around the rim from each other. That information helped the rover team plot the safest route to the most interesting targets accessible. The rover drove into “Endurance Crater” on June 8. It found that as far down as outcrops extended, they bore evidence of extensive exposure to water.

Project/Program Management

The Mars Exploration Rover program is managed for NASA by JPL, a division of the California Institute of Technology, Pasadena, Calif.

At NASA Headquarters, David Lavery is the program executive and Dr. Curt Niebur is the program scientist. Dr. Catherine Weitz was the program scientist through August 2004. At JPL, Peter Theisinger was project manager until February 2004, followed by Richard Cook and, currently, Jim Erickson. JPL’s Dr. Joy Crisp is the project scientist. The principal investigator for the science payload is Dr. Steve Squyres from Cornell University, Ithaca, N.Y. Deputy principal investigator is Dr. Ray Arvidson from Washington University, St. Louis.

On the Internet

Additional information and images are available on Web sites for the Mars Exploration Rover Mission at <http://marsrovers.jpl.nasa.gov> and for the suite of science instruments at <http://athena.cornell.edu> .