INTELLIGENT ROBOTIC AIDS HELP MARS EXPLORATION

Dr. Antal Bejczy
Senior Research Scientist
JPL/CALTECH
Pasadena, California
(antbej@earthlink.net)

Abstract – *The first Mars rover mission Pathfinder in 1997 with the small Sojourner rover, and the Mars Exploration Rover **(MER)** mission in 2004 with the twin rovers – Spirit and Opportunity – have been designed and operated as intelligent robotic aids for scientists, suited to "reading the rocks" littered across Martian surface, in order to understand the mysterious history of water, and even of possible life-friendly ancient environments there. This presentation outlines the MER mission's science objectives, describes the engineering features and science instruments of the twin rovers, and quotes a few interesting and illustrative findings obtained by scientists through the twin rovers. The presentation concludes with brief discussion of future intelligent robotic capability needs and NASA mission plans for continued Mars exploration.*

INTRODUCTION

An important part of the NASA "Origin" program is the investigation of *possibilities of life in the Universe,* and specifically is looking for life and its possibilities in other places of our solar system, beyond our "garden planet" Earth. For this purpose, scientists have chosen to *"follow the water trail"* because water – along with carbon – is the basis of all known life on Earth. Both water and carbon have unique molecular properties that make them perfect biological building blocks. (Of course, this "water trail" approach to search for life possibilities does not exclude other life "building block" alternatives that are beyond our experience on Earth.) Following the water trail lead NASA to support robotic surface exploration of Mars. Why Mars?

The Mars Global Surveyor (MGS) and Mars Odyssey (MO) spacecrafts that currently orbiting Mars have in the past few years revealed many surface features that strongly appear to have been shaped by *running water* that has since disappeared, and some of it is possibly buried as layers of ice just under the planet's surface. Scientists are also intrigued by the possibility that life in some form, possibly very simple microbes, may gained existence in ancient times when Mars may have been warmer and wetter. It is not unthinkable that life in some form could persist even today in underground springs warmed by heat vents around smoldering volcanoes, or even beneath tick ice caps. To investigate those possibilities, scientists must learn more about the history of water on Mars. This simple water trail scientific search strategy motivates the robotic rover missions on Mars. Water-carved landforms are visible from orbiting spacecrafts, but the details of the water's story on Mars are locked up in the rocks scattered across the planet's surface.

Rocks are made up of building blocks known as minerals, each of which tells a story how it became a part of a given rock. Some types of minerals, for example, are known to form on Earth only submerged underwater, while others profoundly altered when hot water runs through them, leaving behind residues. By understanding the Martian rocks in a more complete manner, scientists can gain a better view into the history of liquid water on the Red Planet, Mars.

The first Mars rover mission Pathfinder, landed in 1997 with the small Sojourner rover, and the **M**ars Exploration **R**over (**MER**) mission in 2003, landed in 2004 with the twin robotic rovers called **Spirit** and **Opportunity**, have been designed to support mobile platforms as *robotic geologists* directed from Earth and suited to *reading rocks* littered across the Martian surface, in order to help scientists understand the mysterious history of water, and even of possible life-friendly ancient environments there.

LANDING SITES FOR ROBOT ROVERS

Accurate laser altimeter measurements from the MGS orbiter provided a topographic map of the Mars surface that revealed a significant asymmetry between the northern and southern hemisphere of Mars. The southern hemisphere is several kilometers higher than the average, while the northern hemisphere is several kilometers lower than the average. (The difference from the highest to the lowest point on Mars is more than 30 kilometers!) Ancient streambeds are visible on the southern hemisphere, carved by ancient water flowed into the huge low-lying northern basin.

Landing sites selection for the 2003 MER mission twin robots involved more than two years of intensive studies by more than 100 scientists and engineers. Their task was to find sites that offered both excellent chances for safe landings and outstanding science investigation possibilities after landings are achieved. It should be noted, that – for economic reasons – the twin MER robots, like the 1997 Pathfinder spacecraft, were designed for *airbag-cushioned bouncing landing* which implies that the location of the final stop is not controllable and predictable. This fact had to be incorporated into the consideration of selecting qualified candidate landing sites. Other selection criteria required that the candidate sites be near the Mars equator, low enough in elevation (so the spacecraft would pass through enough atmosphere to slow down), not too rugged, not too rocky, and not too dusty. Out of the some 150 potential acceptable landing sites two made the final cut: *Gusev Crater* and *Meridiani Planum*. Both satisfied all safety criteria, and also offered significant evidence of past liquid water, but in two very different ways.

The Gusev Crater, where the Spirit robot rover landed on January 3, 2004, is an impact crater about 150 kilometers in diameter and about 15 degrees south of the Mars' equator. It lies near the transition between the planet's ancient highlands to the south and smoother plains to the north. There is a 900-kilometer-long zigzag valley that enters the crater from the southeast. It is believed that this valley has been eroded long ago by flowing water, and the water likely cut through the crater's rim and filled much of the crater, creating a large lake not unlike crater lakes on Earth. The lake is gone now, but the floor of Gusev Crater may contain water-laid sediments that still preserve a record of what conditions were like in the lake when the sediments were deposited.

The Meridiani Planum area, where Opportunity robot rover landed on January 24, 2004, is near the Martian equator and halfway (about 180 degrees) around the planet from Gusev Crater. It is one of the smoothest, flattest places on Mars. The scientific appeal of this area comes from its strange mineral composition sensed by the thermal emission spectrometer on the MGS orbiter. It has shown that Meridiani Planum is rich in an iron oxide mineral called *gray hematite* which is found on Earth, where it is usually – though not always – forms in association with liquid water.

The relative location of the twin robot rovers landing sites is shown in a rectangular frame of Figure 1, including the landing sites of the 1997 Pathfinder and the two Viking (non-roving) spacecrafts that landed there in 1976 and 1978, respectively. (The Figures are at the end of the text.)

SCIENCE OBJECTIVES AND INSTRUMENTS OF ROBOT ROVERS

NASA summarized the MER mission's science objectives in eight points:

- Search for and characterize a diversity of rocks and solids that hold clues to past water activity (water-bearing minerals and minerals deposited by precipitation, evaporation, sedimentary cementation, or hydrothermal activity.)
- Investigate landing sites, selected on the basis of orbital remote sensing, that have high probability of containing physical and/or chemical evidence of the action of liquid water.
- Determine the spatial distribution and composition of minerals, rocks and soils surrounding the landing sites.
- Determine the nature of local surface geologic processes from surface morphology and chemistry.
- Calibrate and validate orbital remote sensing data and assess the amount of scale of heterogeneity at each landing site.
- For iron-containing mineral, identify and quantify relative amounts of specific mineral types that contain water or hydroxyls, or are indicators of formation by an aqueous process, such as iron-bearing carbonates.
- Characterize the mineral assemblages and textures of different types of rocks and soils and put them in geologic context.
- Extract clues from the geologic investigation, related to the environmental conditions when liquid water was present, and assess whether those environments were conducive for life.

Each of the twin robots of the MER mission, working as "robotic field geologists," is equipped with a package science instruments relevant for geological investigations along the above-quoted science objectives. The sketch of the MER robot with its instruments is shown in Figure 2. The twin robots, Spirit and Opportunity, have identical structure, instruments, and functional capabilities. Some details of the robot rovers' science instruments are summarized below.

The Panoramic Camera System uses two high-resolution color stereo cameras, complementing the rover's *navigation cameras.*
The Mini Thermal Emission Spectrometer sees infrared radiation emitted by objects. It helps determine from afar the mineral composition of Martian surface features and allow scientists to select specific rocks and soils for detailed investigation.
The Microscopic Imager is a combination of a microscope and a camera. It produces extreme close-up views (at a scale of hundreds of microns) of rocks and soils examined by other instruments on the robot rover's arm, providing context for the interpretation of data about minerals and elements.
The Moessbauer Spectrometer is designed to determine with high accuracy the composition and abundance of iron-bearing minerals that are difficult to determine by other means. (The most important minerals on Mars contain iron.)
The Alpha Particle X-Ray Spectrometer accurately determines the elements that make up rocks and soils. This information is used to complement and constrain the analysis of minerals and soils provided by the other instruments.
The Rock Abrasion Tool, when positioned against a rock by the rover's instrument arm, uses a grinding wheel to remove dust and weathered rock, exposing fresh rock underneath. It exposes an area with 4.5 centimeters in diameter, with a depth to as much as 5 millimeters.
Magnet Arrays collect airborne dust (Mars is a dusty place!) for analysis by science instruments. Some of the dust can be highly magnetic.
Calibration Targets on the rover are serving imagers and other science instruments.

It is noted that some of the instruments listed above are not carried by a field geologist on Earth, but used in a laboratory investigating collected rocks and soils. The MER robot geologists, therefore, also perform some typical laboratory analysis functions on the Martian field sites, and send *analytic data* back to scientists on Earth.

ENGINEERING FEATURES OF ROBOT ROVERS

Each MER robot is 1.6 meters long and weighs 174 kilograms. Each carries all equipments needed for telecommunication, camera and computer functions. The robot rovers do not interact with their landers any further once they rolled off. The landers only played the role of holding platforms for the robot rovers, and they remain as passive structures on Mars after the rovers departed from them.

The core structure of each MER robot is made of composite honeycomb material, insulated with a high-tech material called aerogel. This core body, called the warm electronics box, is topped with a triangular surface called the equipment deck. The deck is populated with three antennas, a camera mast and a panel of solar cells. Extra solar panels are connected by hinges to the edges of the triangle surface deck. See again Fig.2. The extra panels fold up to fit inside the lander during the trip to Mars from Earth, and deploy after landing to form a total area of 1.3 square meters of three-layer photovoltaic cells. Each layer is of different materials: gallium indium phosphorus, gallium arsenide, and germanium. The area can produce 900 watt-hours of energy per Martian day (or sol). By the end of the prime mission time (that is, after the first three months), the energy generating capability is reduced to 600 watt-hours per sol because of accumulating dust and the change in seasons. The solar array repeatedly recharges two lithium-ion batteries inside the warm electronics box.

Each MER robot is equipped with six-wheel drive. A rocker-bogie suspension system, which bends at its joints rather than using any springs, allows rolling over rocks bigger that the wheel diameter of 26 centimeters. The distribution of mass on the vehicle is so that the center of mass is near the pivot point of the rocker-bogie system. That enables the MER robot to tolerate a tilt up to 45 degrees in any direction without overturning, although onboard computers are programmed to prevent tilts of more than 30 degrees. Independent steering of the front and rear wheels allows the rover to turn in place or drive in gradual arcs.

The MER robots have navigation software and hazard-avoiding capabilities they can use to make their own way toward destinations identified to them in a daily sets of commands. They can move up to 5 centimeters per second on flat hard ground, but under automated control with hazard avoidance, they normally travel at an average speed about one fifth of that.

Two stereo pairs of hazard-identification cameras are mounted below the deck: one pair at the front and the other at the rear of the rover. Besides supporting automated navigation, the one on the front also provides imaging of what the rover's arm is doing. Two other stereo camera pairs sit high on a mast rising from the deck: the panoramic camera system is included as one of the science instruments, and a wider-angle, lower-resolution navigation stereo camera pair. The mast also serves as a periscope for the miniature thermal emission spectrometer (see again Fig.2).

Four science instruments (two spectrometers, microscopic imager, and rock-abrasion tool) are mounted at the end of an arm, called "the instrument deployment device." It sits under the front of the rover while the vehicle is traveling, and extends forward when the rover is in position to examine a particular rock or a patch of soil.

The computer in each MER robot runs with a 32-bit Rad 6000 microprocessor, a radiation-hardened version of the PowerPC chip used in some models of Macintosh computers, operating at a speed of 20 million instructions per second. Onboard memory includes 128 megabytes of random access memory, augmented by 256 megabytes of flash memory, and smaller amounts pf other non-volatile memory, which allows the system to retain data even without power.

Batteries and other components that are not designed to survive cold Martian nights are located in the warm electronics box. (Nighttime temperatures on Mars may fall as low as minus 105 C!) The batteries need to be kept above minus 20 C when they are supplying power, and above 0 C when they are being recharged. Heat inside the warm electronics box comes from a combination of electrical heaters, eight radioisotope heater units, and heat given off by electronic components. – Each radioisotope heater unit produces about one watt of heat and contains about 2.7 grams of plutonium dioxide as a pellet about the size and shape of the eraser on the end of a standard pencil. Each pellet is encapsulated into a specifically designed safety box rendering the complete unit about the size and shape of a C-cell battery. This radioisotope heater technology has been used on other spacecraft, Including Sojourner rover in 1997, and its safety has been tested extensively.

Throughout each MER robot's surface mission, a rover-mounted antenna enables communication with the MGS and MO orbiters once or twice per Martian day (per sol) while each of the two orbiters pass overhead, via a UHF link at 128,000 bits per second rate. It is possible to use direct-to-Earth communications with the MER robots that are critical to mission success. But most of the date from the MER robots could be relayed via the two quoted orbiters.

ACHIVEMENTS AND SOME EXPLORATION RESULTS

Both MER robots have completed their originally planned 90-day mission, and started working on extra-credit assignments. As of the end of April, Spirit traveled more than 1.2 kilometers, and Opportunity drove more than 800 meters and sent home 15.2 gigabits of data about Mars, including more than 12-thousand images. Similar amount of data and images were received from Spirit. Since both MER robots are healthy, NASA approved necessary funding for extending their operation on Mars through September, 2004. When they reach that far in time, each will have operated and explored the Martian surface for about eight months.

Figure 3 shows the image resulted from history's first grinding of a rock on Mars.. The rock abrasion tool on the Spirit rover robot ground off the surface of a patch 45.5 millimeters in diameter on a rock called "Adirondack" during Spirit's 34th day (or sol) on Mars. The hole is 2.65 millimeters deep, exposing fresh interior material of the rock for close inspection with microscopic imager and two spectrometers on Spirit's robotic arm. This image was taken by Spirit's panoramic camera, providing a quick visual check of the success of the grinding. – Figure 4 is an image from Spirit's front hazard avoidance camera showing a trench excavated by Spirit's left front wheel on Spirit's 47th day (or sol) on Mars. The trench, dubbed "Road Cut," is 7 centimeters deep. It is notable that the soil at this location is more cohesive than the material where Spirit's twin, Opportunity, dug its first trench at Meridiani. Spirit made 11 back-and-forth passes to dig this trench, and still did not produce as deep a hole as Opportunity dug in 6 passes.

Figure 5 is an image taken by Opportunity's front hazard avoidance camera on the rover's 35th day (or sol) of Opportunity's Mars journey. It shows the two holes (see the dotted encircling in the Figure), made by the robot rover's rock abrasion too, that allowed scientists to peer into Meridiani Planum's wet past. By analyzing the freshly exposed rock with the rover's science instruments package, scientists gathered evidence that this part of Mars may have once been drenched in water. The lower hole, located on a target called "McKittrick," was made on the 30th "sol" and the upper hole located on a target called "Guadalupe" was made on the 34th "sol" of Opportunity's journey on Mars. Figure 6 is a microscopic image of a target called "Flatrock" taken on Opportunity's 43rd "sol" on Mars. This image is representative of the science team's goal at the rock outcrop under investigation at Meridiani Planum.

Opportunity found rock exposures in late April similar to the ones near its landing side that yielded evidence for a body of salty water covering the area ling ago. In mid-April, Opportunity paused beside a small crater called "Fram" (about 15 meters in diameter) and examined a rock studded with small, iron-reach spherules that are one part of the evidence for past water in the region. The robot rover used its rock abrasion tool to grind a hole, allowing the interior examination of the rock, called "Pilbara."

When preparing this article in May, 2004, Opportunity is performing investigations around and about 50 centimeters close to the edge of an impact crater informally called "Endurance" which is roughly 130 meters across and about 20 meters deep. Scientists are eager to explore the crater's exposed fascinating walls that provide a window to what lies beneath the surface of Mars and thus what geologic processes occurred there in the past. At the same time, Spirit rover robot is on its way to an area informally called "Columbia Hills," which still lies about 1.2 kilometers away, where nighttime surface temperatures indicate that some areas within the hills are rockier than others. Scientists are interested to investigate the processes that formed the intriguing features in the hills, and especially interested if water played any role there. The autonomous navigation software of the twin rovers has been upgraded recently, based on the positive autonomous navigation performance experience during the first three months of the rovers' activities on Mars. This will expand the rovers' options to extended planning of routing onboard, yielding faster progress toward a designated area. The engineers, therefore, hope that Spirit will reach the "Columbia Hills" by end of June, though stopping here and there to take images
and examine rocks, if requested.

An all-important aspect of the twin robot rovers' exploration activities on the Martian surface is the meaningful coordination of the desired scientific investigations. and the available technical capabilities onboard, taking account of local environmental constraints that only partly may be known ahead of time. A very elaborate software system, called Science Activity Planner (SAP), was developed to analyze the data received from Mars and help plan the next rover actions, taking account of science interests, rover capabilities, and local constraints. The SAP software package also has powerful visualization features aiding situation perception and activity conceptualization of operating scientists and engineers. – In a pioneering public outreach effort, a release of this software (called "Maestro") was made available on-line. It offers the experience to the interested general public to use an actual space mission operation tool that will help understand the many sophisticated aspects of exploratory operations on a distant planetary surface. - Many more information about achievements and results can be found on the Mars Exploration homepage at www.jpl.nasa.gov - including information about downloading "Maestro."

FUTURE MARS SURFACE EXPLORATION

NASA plans for the coming years include: (1) Mars Reconnaissance Orbiter in 2005, with advanced surface mapping capabilities, aiding selection of future landing sites. (2) Mars Scouts, with a variety of new functional capabilities in 2007, like a surface laboratory on Mars' northern planes to investigate water ice, organic molecules, and climate. (3) Mars Science Laboratory in 2009. It will be a mobile robotic geologist with new measurement capabilities, paving way for new mission definitions in subsequent years, like sample return to Earth, searching for the "missing carbon" needed for life, etc.

In order to accomplish future Mars mission goals, improved technical capabilities are needed. Among the needs are: (1) Permanent local power source, like a Radioisotope Thermic Generator (RTG), independent of the photovoltaic generator capability of Sun, already used in many space missions. (2) Well-controlled soft landing for affordable cost. (3) More autonomy capability in navigation and local task performance to increase productivity by decreasing R/T telecommunication with ground controllers. (4) Safe mobility capabilities for challenging terrains. – Some work is already in progress on these items.

REFERENCES - In preparing this article, the following references were used freely:

(1) Edward C. Stone, "Sampling the Solar System," *Engineering and Science,* a CALTECH Publication, Volume LXIII, No 1, 2000.
(2) Mars Exploration Rover Launches, a *NASA Press Kit,* June, 2003.
(3) Relevant JPL web-sites about Mars Exploration: www.jpl.nasa.gov

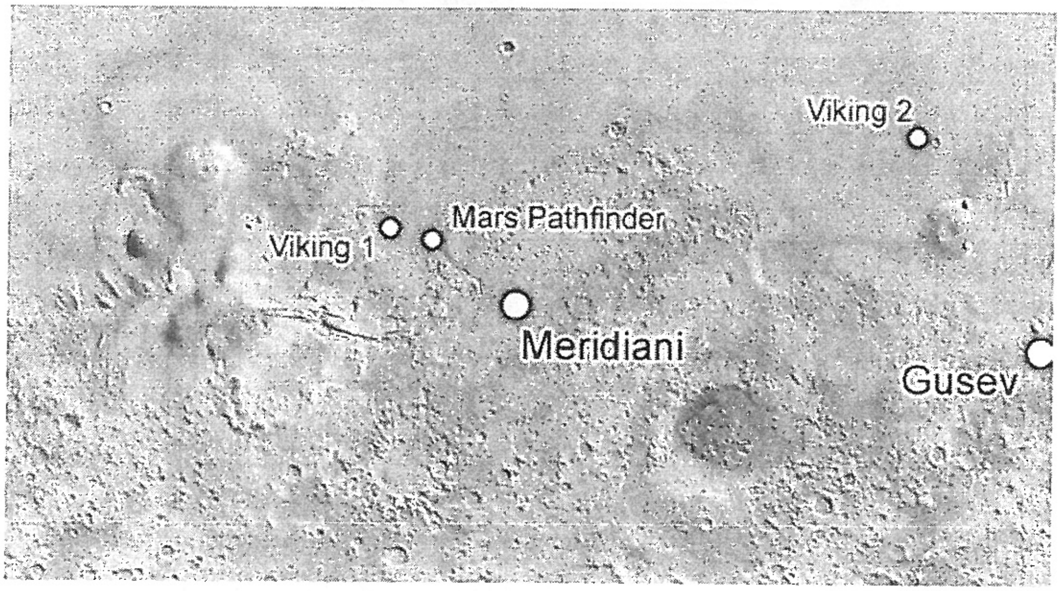

Figure 1. Landing sites on Mars

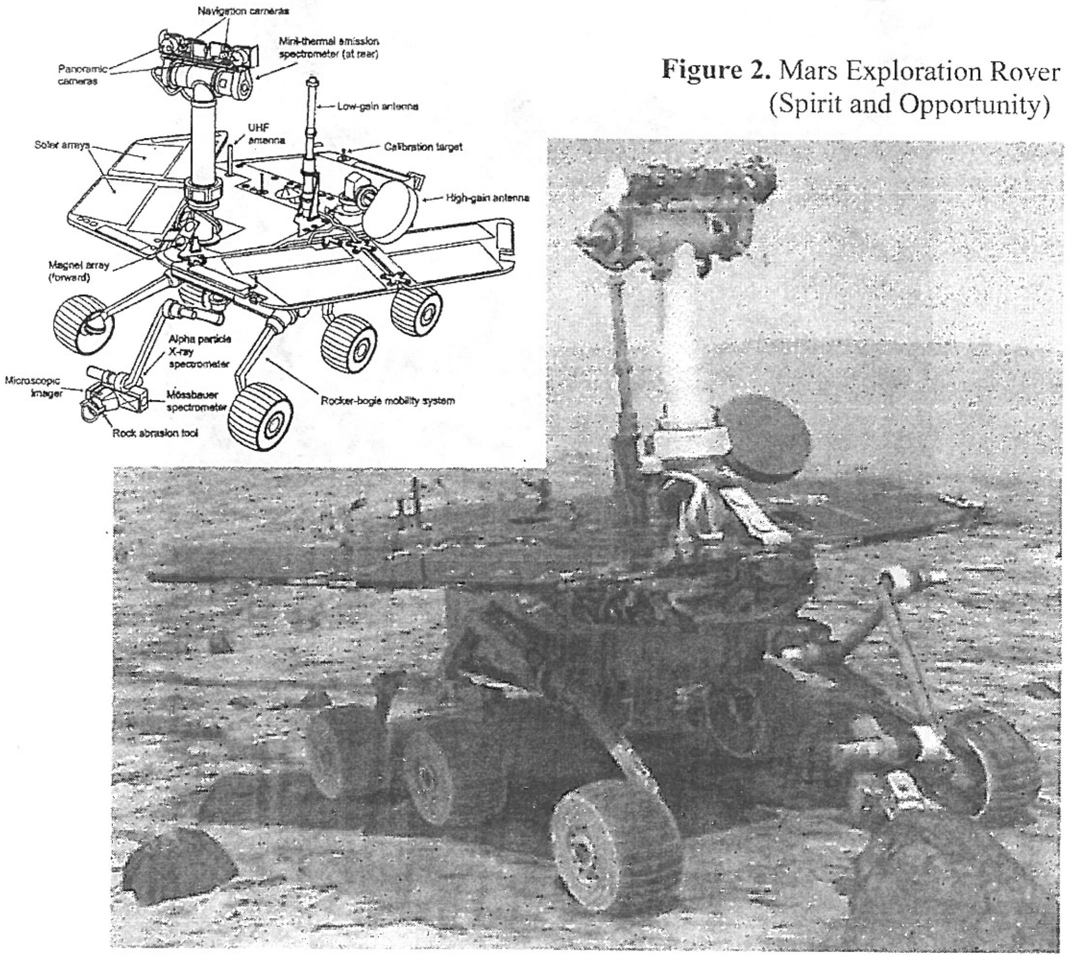

Figure 2. Mars Exploration Rover (Spirit and Opportunity)

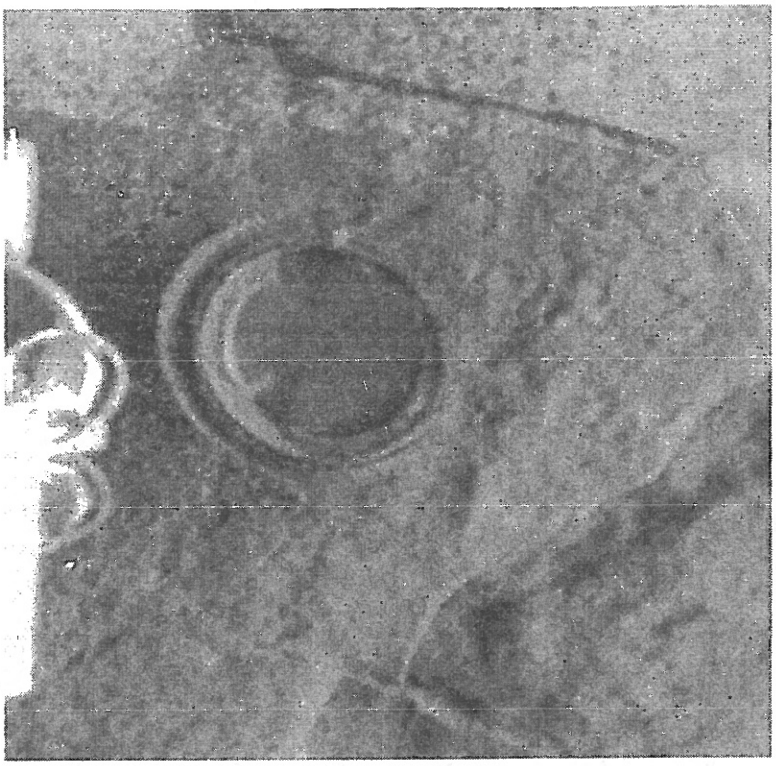

Figure 3. First Grinding of a Rock on Mars
Image from Spirit Feb. 7, 2004

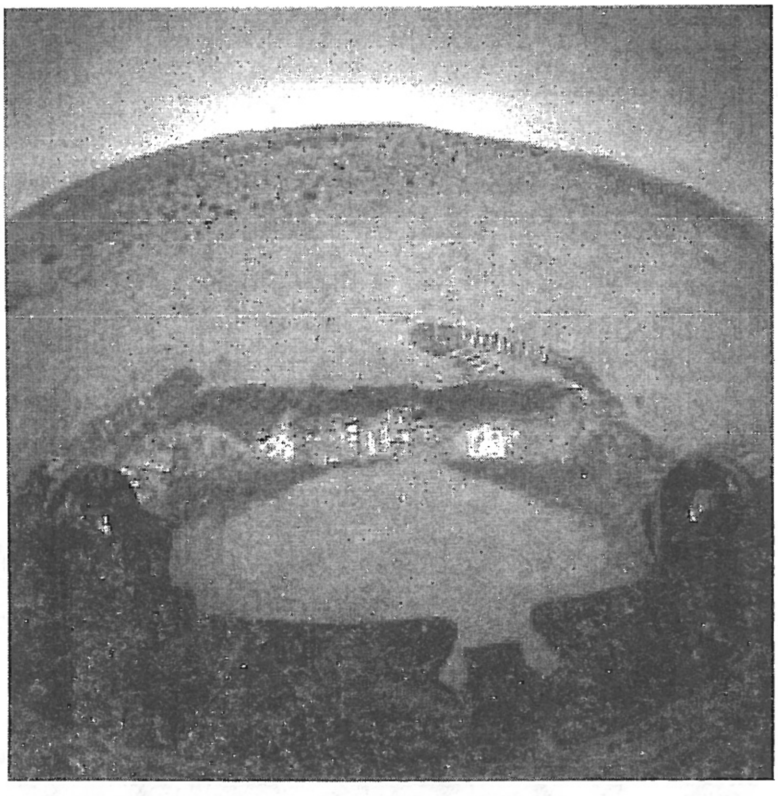

Figure 4. Spirit Digs a Trench
Image from Spirit Feb. 20, 2004

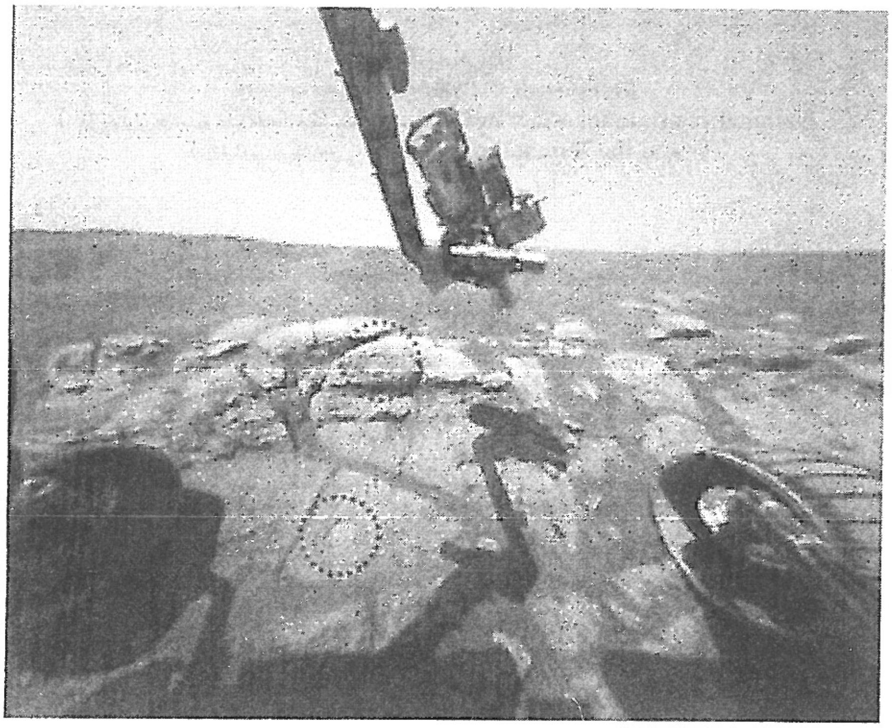

Figure 5. Windows to Meridiani's Water-Soaked Past
Image from Opportunity Mar. 5, 2004

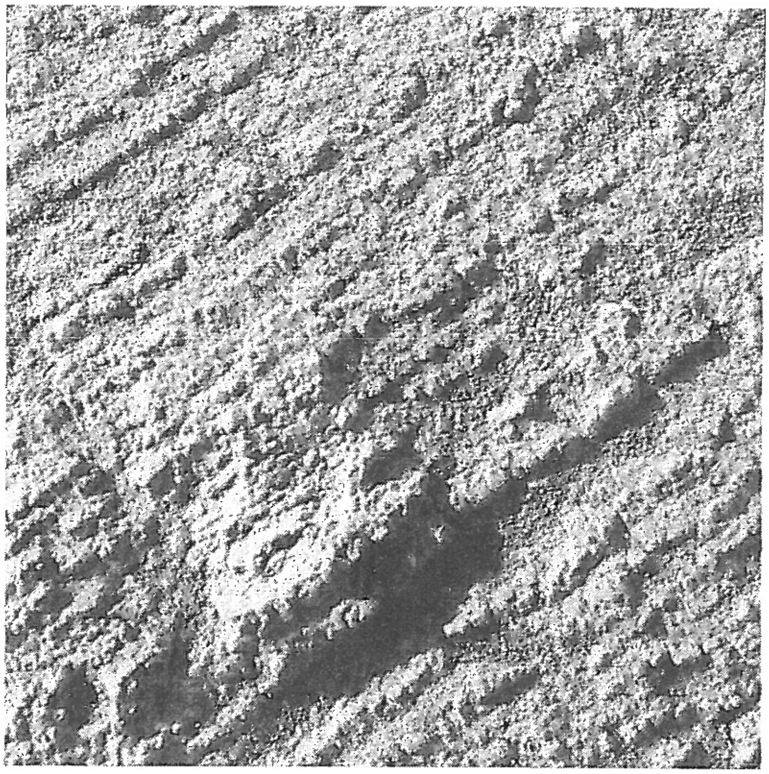

Figure 6. Fleshing out "Flatrock"
Microscopic Image from Opportunity Mar. 8, 2004