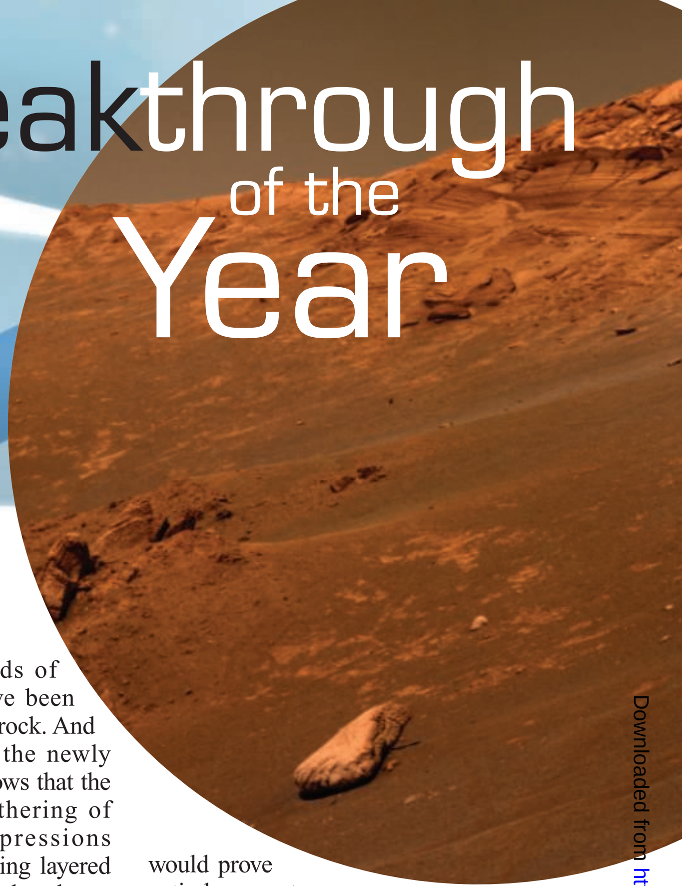
Breakthrough of the Year



THE WINNER

The Mars rovers, with the help of remote-sensing spacecraft, have sniffed out water and found the remains of one or more ancient environments where life could have survived. Indeed, early Mars is looking wetter and wetter

On Mars, a Second Chance for Life

Inanimate, wheeled, one-armed boxes roaming another planet have done something no human has ever managed: They have discovered another place in the universe where life could once have existed. Aided by other robots in orbit and a modicum of luck, the two Mars rovers earlier this year homed in on locales once rich with water.

BREAKTHROUGH ONLINE

For an expanded version of this section, with references and links, see www.sciencemag.org/sciext/btoy2004

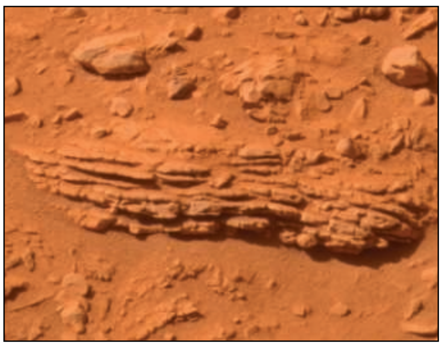
The Opportunity rover found the salty, rippled sediments of a huge shallow sea; the Spirit rover discovered rock once so drenched that it had rotted. Their finds mark a milestone in humankind's search for life elsewhere in the universe.

The two Mars rovers confirmed what many scientists have long suspected: Billions of years ago, enough water pooled on the surface of Earth's neighbor long enough to allow the possibility of life. Despite tantalizing hints starting with the Viking missions almost 30 years ago, Mars scientists could never be sure whether the water-carved valleys, channels, and gullies that they saw through orbiting cameras implied the prolonged presence of surface waters.

The Mars rovers have now put a bound on the water debate. Thanks to the hardy little robots, we know that Mars of several billion years ago was warm enough and wet enough to have a shallow, salty sea. This sea probably came and went, turning into wind-blown salt flats from time to time, but the puddles spanned an area the size of Oklahoma. Enough water passed through it to leave behind perhaps 300 meters of salt. And the dirty salt buried beneath its floor remained wet long enough to grow marble-size iron minerals.

On the opposite side of the planet, shallow groundwater also lingered long enough to transform hundreds of meters of what appears to have been volcanic ash into soft, iron-rich rock. And the latest spectroscopy from the newly arrived Mars Express orbiter shows that the salt from all this water-weathering of martian rock lingers in depressions elsewhere, sometimes in intriguing layered deposits that fill craters around the planet. For a time, it seems, early Mars was a watery, habitable place.

The Mars rovers didn't make their breakthroughs on their own. They had help from above. Opportunity needed guidance from the Thermal Emission Spectrometer (TES) on board the Mars Global Surveyor. TES



Rotted rock. The Spirit rover found this once-waterlogged rock that may have begun as volcanic ash.

was the first Mars-orbiting instrument to provide global coverage at infrared wavelengths where minerals leave distinctive signatures. The planet proved rather bland at TES wavelengths, but one area on the equator at the prime meridian was a glaring exception. The flat, dark Meridiani Planum jumped out as rich in gray hematite, an iron oxide. Researchers quickly came up with a half-dozen explanations for how gray hematite might have formed on Mars, most but not all of which involved water. None would prove entirely correct.

On arriving encased in protective balloons, Opportunity needed a couple of lucky breaks. First off, it stumbled—bounced and rolled, actually—into a geologist's perfect field site. As hoped, a small impact had exposed light-toned bedrock around the rim of its crater. This proved to be the long-sought evidence for prolonged surface waters. The booming hematite signal that drew the rover to Meridiani, on the other hand, actually came from marble-size "blueberries" of solid hematite that had weathered out of the sediment and now littered the ground as far as the rover could see. If the blueberries hadn't formed and been blasted out of the softer salt by windblown sand, TES never would have recognized the water signal.

Once on the scene, Opportunity could play field geologist to the hilt. Like Spirit, its identical twin on the opposite side of Mars, it came equipped with color-registering "eyes," a magnifying glass, a grinding wheel for exposing fresh rock, an elemental analyzer, and two mineral-identifying instruments: a remote-sensing "mini-TES" and a "hands-on" iron mineral identifier. With these tools, it set about unraveling the geologic story recorded in the curb-size outcrop of little Eagle crater.

Contrary to prelanding theorizing, Opportunity's story turned out to be about salt, an end product of the water weathering of rock, rather than the expected water-altered minerals. The Eagle outcrop is up to 40% salts, mostly magnesium and calcium sulfates. Much of the rest is "dirt," rock

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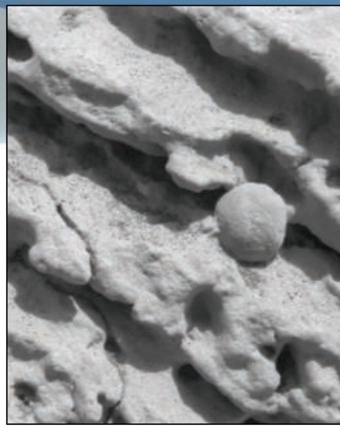
Burns Cliff. The late Roger Burns predicted that volcanic acid would make Mars salty, like his namesake.

altered beyond recognition by water. The presence of the mineral jarosite suggests that the water was quite acidic, presumably from the sulfur dioxide of early martian volcanoes. Acid waters leached salts from martian rock and flowed across the floor of a shallow sea, or perhaps a vast puddle, permanently rippling the surface of the ancient sediment.

Then the water evaporated away, leaving the salt and dirt behind. The wind blowing across the salt flats sometimes blew the dirty salt into dunes. But beneath the surface, water persisted long enough to grow the hematite blueberries. The water came back time and time again, laying down centimeter-thick layers until 300 meters accumulated, judging by the light-toned outcrops in Mars Global Surveyor images. The salty sea or puddles appear to have spanned more than 300,000 square kilometers of Meridiani Planum. Only the orbiters' big-picture perspective could broaden Opportunity's findings this way, but only the rover could make sense of the orbiters' remote sensing.

Salty signs of long-past water were not confined to Meridiani. In Gusev crater, Spirit never did find any trace of the ancient lakebed inferred from orbital imaging. Instead, it roved across an ancient sheet of lava pulverized by impacts. But it did find volcanic rocks coated by weathering rinds and riddled with mineral-filled veins. Presumably, these rocks had once been buried in wet soil. By luck, Spirit overshot its intended landing site a bit, putting it within driving range of the 100-meter-high Columbia Hills. Orbital imaging had given no clue as to the origin of the hills, but Spirit found them to be one big pile of finely layered, water-altered rock.



Salt of Mars. Layered dirty salt (with hematite spherule) speaks of surface waters evaporating in ancient times.

While the rovers have provided the closest look yet at evidence of water on Mars, other instruments are rounding out the picture on a broader scale than two rovers can manage. Salty remains of water weathering have turned up in early surveys by the OMEGA spectrometer on the European Space Agency's Mars Express that went into orbit last 25 December. Largely because it has greater resolution than TES does, OMEGA found sulfates in ancient depressions such as the canyon network of Valles Marineris and in Meridiani. In Juventae Chasma, a branch of Valles Marineris, a 50-kilometer-wide, 2.5-kilometer-high, light-toned mesa sandwiches calcium sulfate between layers of magnesium sulfate.

So Mars was wet in its earliest years, when life on Earth was getting its start. But even then, Mars was taking a different environmental path, one too stressful for any life that might have managed to take hold. Even at Meridiani, the most habitable site found so far, the water was acidic, briny, and, at least at the surface, intermittent—not a promising place for life to originate. Still, life on Earth has evolved many forms that would survive and even thrive under such extreme conditions. The rover science team has called Meridiani Planum "an attractive candidate" for future landings. And given that both sulfates and iron oxides like

Doing Science Remotely

Most scientists start their careers with an urge to do hands-on science: to mix the chemicals, hammer off a chunk of rock, or feel the fevered brow. But scientists increasingly want to go where no one has gone before, or at least where no one can afford to go or would risk going: the surface of Mars, kilometers beneath storm-tossed seas, or the inside of your small intestine. Now, remotely operated or even autonomous machines are letting scientists keep their hands on things from inner to outer space.

The Mars rovers are the most visible in a long line of instrumented robots that have given planetary scientists a presence from innermost Mercury to beyond the edge of the solar system. No single component of a rover is a breakthrough technology like the ion propulsion that just delivered Europe's Smart-1 spacecraft to lunar orbit. Even when combined into a complex 174-kilogram package, the rovers' technology isn't very flashy. Their speed tops out at a nearly imperceptible one-tenth of a kilometer per hour, they can take a whole day to analyze one spot on one rock, and a pebble lodged in the wrong crevice can stop the show for days. But slow and steady wins the race in space. Although rover engineers predicted that both rovers would likely freeze to death in the depths of the martian winter last September, Spirit is still hobbling along with a couple of bad wheels, while Opportunity shows no serious signs of age.

On a far smaller scale, advanced technologies are making their way into inner space. Over the past 5 years, bioengineers have made considerable strides using telemetry, miniaturized sensors, and even self-adjusting instruments to keep track of the inner workings of the human body. The efforts enable doctors to follow their patients' progress more precisely, in real time, and sometimes from kilometers away. The innovations are affecting many medical disciplines.

Take one and watch. "PillCam" includes a transmitter chip for beaming back views of the gut.

For more than 20 years, doctors have been able to monitor pacemaker function remotely, but now these devices, which keep the heart beating regularly, can also detect whether their host is, say, running or sleeping and adjust the heart rate to its natural rhythm. Wireless pressure sensors implanted into repaired spines inform surgeons about the healing process, sensing the spine's increasing ability to bear weight. Other pressure-sensitive monitors fit inside the aorta to keep track of how well this artery is working. Still others fit into the eye to give feedback about pressure inside the eyeball, helping the physician know when to adjust medication. Bite-sized stand-alone cameras pass through the digestive system, sending images along the way. In particular, the camera captures what's going on in the small bowel, which otherwise requires invasive surgery.

More imaginatively, there's talk of "smart clothes": wearable electronics that track vital signs. Other devices may one day make sure patients take their medicines, sending a message via the Internet to warn physicians of noncompliance. Now that's hands-on.

—ELIZABETH PENNISI AND R.A.K.

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hematite can preserve minute details of organisms, it could even be a good spot to find samples to send home to Earth.

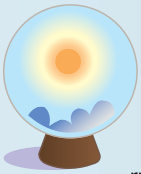
Much remains to be done, however, before anyone picks a site for sample return. The leading geologic problem on Mars—the nature of light-toned, layered deposits such as those beneath Meridiani Planum and in Juventae Chasma—could be addressed by NASA's powerful Mars Reconnaissance Orbiter, to be launched in August 2005. The Phoenix lander will arrive in 2008 to study the role of present-day water ice on Mars. Because the planet's poles warm up dramatically every few tens of thousands of years, ice-rich soils there could host dormant life. And in 2009 NASA may launch Mars Science Laboratory, a hulking, far-traveling analytical lab on wheels that could pave the way for future sample return. With humans on Mars a distant prospect, the robots alone will be striving for the next Breakthrough of the Year on the Red Planet.

–RICHARD A. KERR

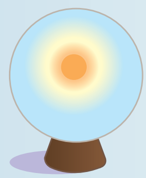
Scorecard 2003

Last year's forecasts of hot fields came close to the mark, on the whole.

Three on Mars. Two out of three isn't bad. The feisty Beagle 2 lander separated from the Mars Express mother ship handily but was never heard from again. But the two NASA rovers performed splendidly, and Mars Express itself is returning spectacular images. Opportunity easily found its prize, water-related mineralization, although the rock turned out to be a former salt flat rather than the expected hydrothermal deposits. As predicted, Spirit had trouble finding evidence of an ancient lakebed, which seems to have been covered by lava flows. In nearby hills, though, the hardy rover discovered something almost as good: volcanic ash once soaked and rotted by water.



Microbe militia. Biodefense flourished this year, as an estimated $7.5 billion flowed to efforts to develop everything from new drugs and vaccines to better sensors and new high-security laboratories. Gene libraries are filling up with data on potential bioweapons: Researchers completely sequenced the genomes of high-risk bacteria, such as anthrax, and have documented at least one strain of every virus and protozoan that might be weaponized. They've identified a cabinet full of promising treatments and started human trials on several new vaccines, including one for smallpox. But the government's new BioShield program, created to lure companies into the field, is off to a slow start, and critics say rules designed to keep bioweapons out of terrorists' hands continue to complicate research.



Genome data deluge. As predicted, the Internet is awash in genomic information. Chicken, rat, puffer fish, chimp, a red alga, and dozens of other genome sequences are now online, and dozens of researchers are comparing them in hopes of tracking evolution and pinpointing the causes of disease. Other researchers are busy building transcriptomes (broad looks at gene expression), interactomes (catalogs of protein interactions), regulomes (DNA elements that control gene function), epigenomes that explore nongenetic controls of gene function, and many other databases designed to illuminate how our genome works.

Open sesame. Efforts to make scientific information freely available over the Internet continue to grow—and so does controversy over who should pay the bill. In a major victory for open-access advocates, the National Institutes of Health is close to adopting rules that would require NIH grantees to make their papers freely available 6 months after they are published. Some publishers warn that the policy will sow confusion and financial chaos and may even bankrupt some journals. Meanwhile, open-access backers suffered a setback in the United Kingdom when the government declined to earmark funds to support free journals, concluding that it's still not clear the business model will prove viable.

Bottoms up. In 2003, physicists at the BELLE experiment in Japan announced a tantalizing hint of new physics in one particular decay of B particles. In 2004, however, new data have reduced the statistical significance of that result substantially. At the same time, lesser anomalies in other types of B decay keep the hope of new physics alive, so the issue has neither disappeared nor stood out in stark relief as predicted.

Digging deeper. More diverse and abundant than in any other ecosystem, the bacteria, viruses, and fungi under our feet have come to the fore in several fields: ecology, biodiversity, phylogeny, and environmental science. There's increased emphasis on the interactions between life below and above ground—for example, the effects of fungi on forest structure and the role of subterranean biodiversity on ecosystem health. These studies have driven home that the soil-microbe system is self-organized. The quest to understand this system has stimulated integrative studies that incorporate biochemical and biophysical, as well as biological, tools.

Science and security. Tightened U.S. security continues to give both American and foreign scientists fits, although some kinks in the new systems appear to be getting worked out. Surveys showed that enrollment of foreign graduate students at U.S. universities continues to slump, but fewer students are reporting visa-related delays. Foreign scientists are still having trouble making it to meetings in the United States, particularly on short notice, but many say border controls are improving. Several scientific societies, meanwhile, are suing the government over export-control rules that could make it illegal to edit papers submitted by researchers in a handful of "sensitive" nations. And some researchers are informally challenging agency decisions that put information once in the public domain—such as certain satellite photos and geological data—out of reach.

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Richard A. Kerr

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