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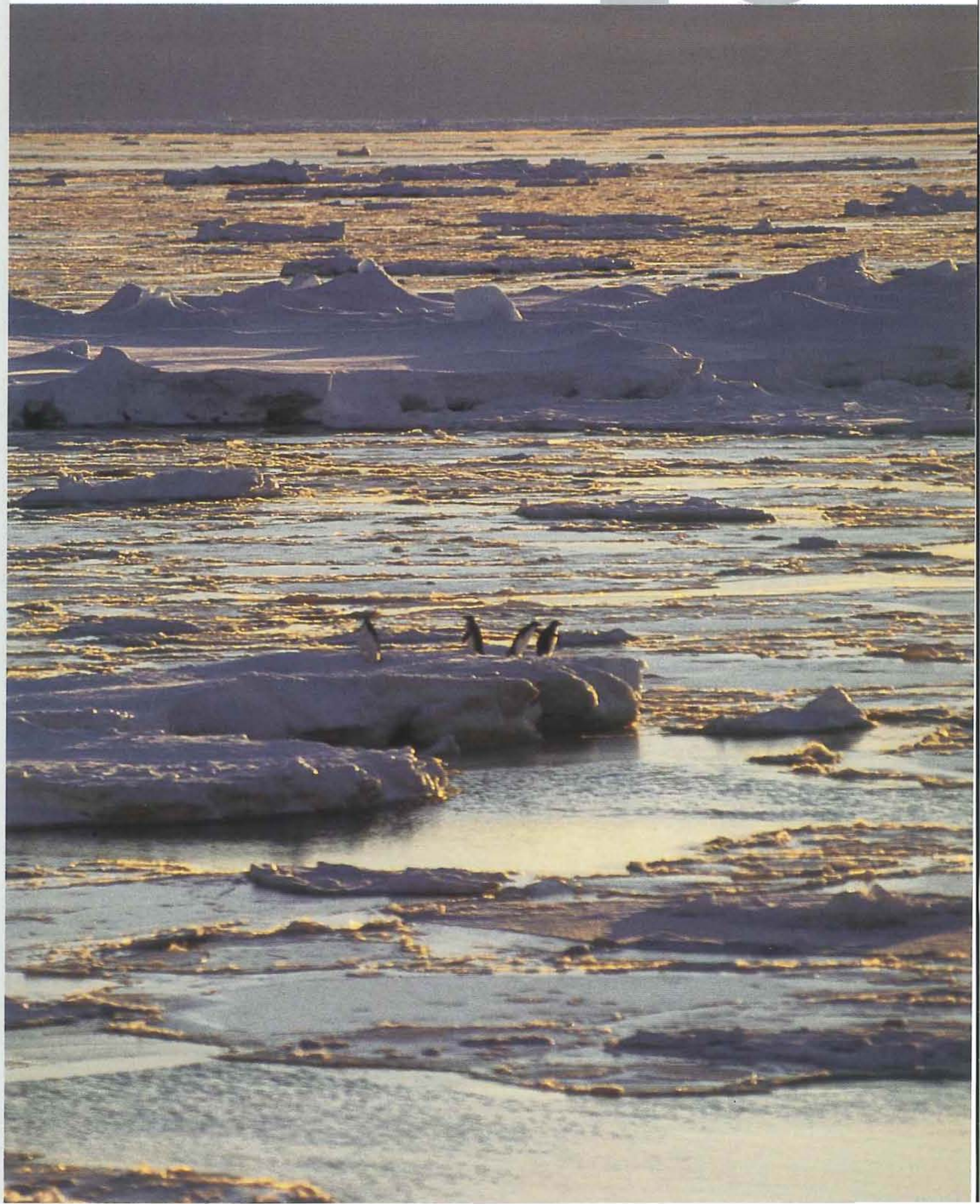
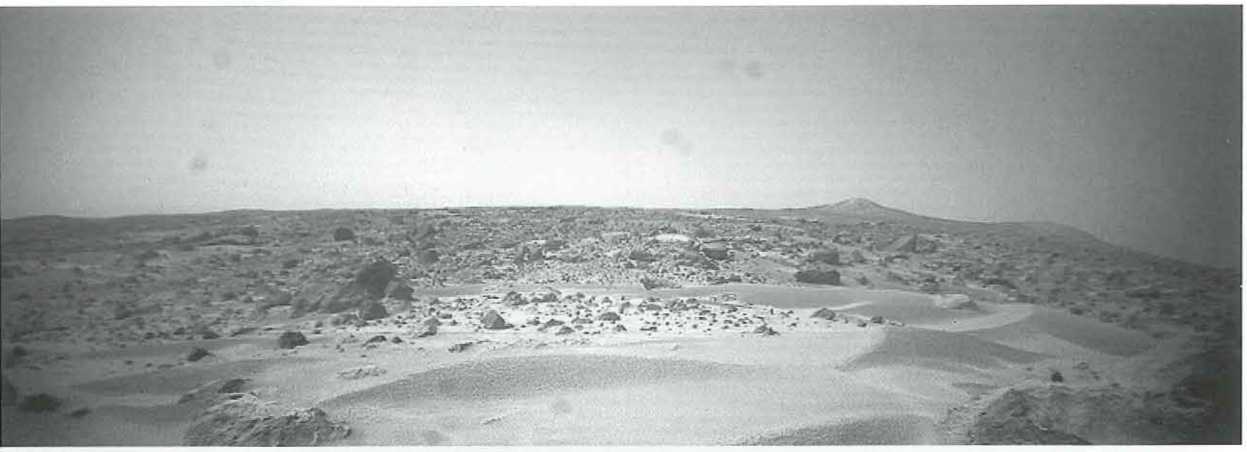
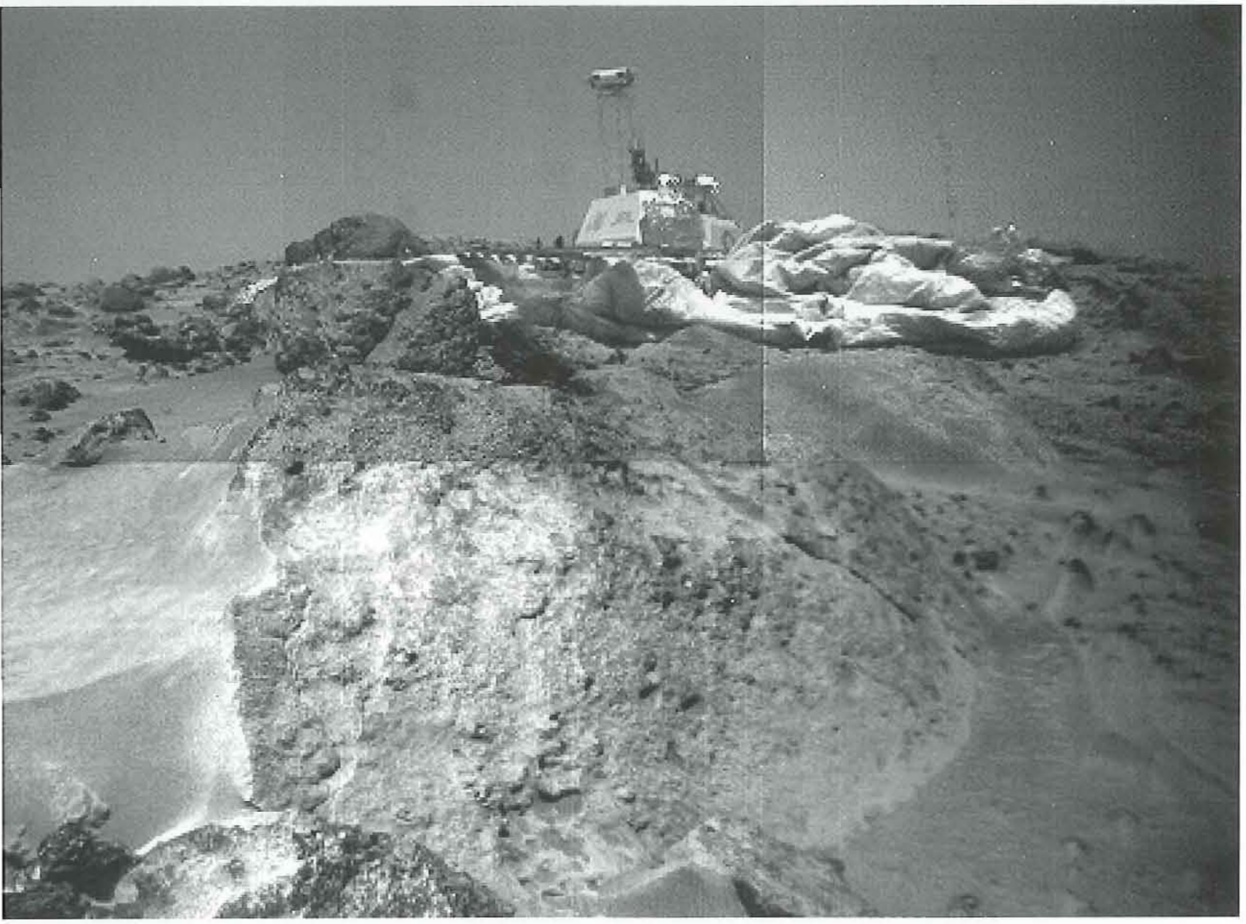
IN THIS ISSUE







Top: Every explorer wants to see what's on the other side of the next hill. When Sojourner, the Mars Pathfinder's rover, peered over a nearby crest on Sol (Martian day) 76, it saw what appear to be sand dunes. If the stuff really is sand (a question that is still being debated), it implies the likely long-term presence of liquid water—the most plausible agent for creating sand-sized grains. The Twin Peaks are on the horizon on the right; the "Big" Crater is on the left.

Bottom: The rover took this picture of the lander, nesting comfortably in its deflated air bags, on Sol 33. You can see the forward ramp, which sticks straight out like a diving board instead of bending down to touch the Martian surface (the rover drove off the rear ramp). And if you think you see E.T.'s face, you're not far wrong—Pathfinder's camera has two "eyes" spaced 15 centimeters apart for stereo vision. For a look at what else Pathfinder has seen, turn to page 8.

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On the cover: The early morning sun glints off the ice in Antarctica's Ross Sea. As the penguins frolic, a group of Caltech scientists is using shipboard geophysical techniques to examine the seafloor for clues to the tectonic plates' motions. How the Antarctic and Pacific plates have wandered with respect to each other has consequences elsewhere—where the Pacific plate rubs past North America, for example. The story of what these scientists found, and what life aboard a research ship is like, begins on page 18.

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Bill Johnson shows off a prototype putter whose head is one solid piece of metallic glass. The pizza paddle behind him is actually the biggest chunk of metallic glass ever cast, and is typical of the ingots from which the club-face inserts are cut.

FORE!

“When the liquid becomes complicated enough, it can’t figure out how to crystallize because there aren’t any nice, simple, orderly patterns it can settle into, and while it’s thinking about it, we can cool it enough to solidify it.”

Tiger Woods doesn’t really need them, and the average duffer probably can’t afford them, but a new set of golf clubs that can easily add ten yards or more to your drive is coming on the market. The reason you’re reading about them in *Engineering & Science* instead of *Golf Digest* (where they’ll appear next month) is that these clubs have a face, or striking surface, made of a metallic glass developed by Caltech researchers and trade named Liquidmetal. This stuff is perfectly elastic, says William Johnson (PhD ’75), the Mettler Professor of Engineering and Applied Science. To prove it, he drops a ball bearing on a titanium plate—the high-tech metal of choice for golf-club heads. The bearing bounces perhaps a dozen times. When the demonstration is repeated with a Liquidmetal plate, the bearing bounces like a Superball.

Ordinary metals are crystalline—as the melt cools, the atoms snuggle together in neat, orderly arrays. When you apply stress to the metal —by hitting a golf ball with it, for example—one plane of atoms slips partially out of alignment with the neighboring plane, creating the equivalent of a wrinkle in a rug. These dislocation defects, as they’re called, absorb energy that would otherwise be imparted to the ball. (Ultimately, of course, if you put enough stress on the metal the slippage leads to metal fatigue and fractures.) So if you could get rid of the crystalline structure, you’d get a much stronger, more flexible metal that can take high stresses without absorbing energy. (You’d get other interesting properties as well—see *E&S*, Winter 1990.)

Metallic glasses, however, are amorphous, not crystalline. Like a big paper bag stuffed full of golf balls, the atoms are loosely jumbled, with no regular pattern to their arrangement—no neat arrays. A glass is really just a very cold liquid in that respect, but an extremely viscous one—the atoms are packed so densely that they aren’t free to move or flow.

Amorphous metal ribbons less than a tenth of a millimeter thick have been on the market since 1973, but that’s all that has been available until now. Ordinary metals crystallize so incredibly rapidly that bypassing the process means cooling the melt by a million degrees per second or more, which can only be done with very thin layers of metal. And the cooling has to be rigorously uniform throughout the piece—a few scattered crystals in the interior of the material, and it becomes as brittle as a common ceramic. Try teeing off with a porcelain golf club!

In order to make chunks instead of ribbons, you’d have to figure out how to cool the melt at a more reasonable rate—a few degrees per second, say—while still forestalling crystallization. Atakan Peker (PhD ’94) did just that in his thesis, says Johnson. “He realized that we had to go to a very complicated material. We need to have four or more atoms with different chemical characteristics before the liquid gets sufficiently frustrated in its efforts to crystallize. When the liquid becomes complicated enough, it can’t figure out how to crystallize because there aren’t any nice, simple, orderly patterns it can settle into, and while it’s thinking about it, we can cool it enough to solidify it. We might call this the ‘confusion principle.’” Peker used a five-metal mixture of zirconium, titanium, nickel, copper, and beryllium, but even that only glassifies over a very narrow range of compositions.

But why take this marvelous material and make golf clubs? Well, you’ve got to start somewhere. And, says Johnson, “golf is a very demanding application. When a good golfer hits the ball, the club head is moving at 100–110 miles per hour, and you do this thousands of times over the life of the club." Casting a club head is no stroll down the fairway, either—drivers are hollow, irons are concave in back, and even the simple slab of the humble putter is problematical. The trouble is that the metallic-glass-forming melt is a hundred to a thousand times more viscous than an ordinary molten metal alloy. "It's more like a thermosetting polymer," says Johnson. "It doesn't flow very well. Bubbles don't float; debris doesn't sink." David Lee (PhD '94) and Michael Tenhover (MS '78, PhD '81) had to develop an entirely new set of manufacturing techniques to work with the stuff.

So the first clubs have a 2.5- to 3-millimeter-thick amorphous insert for the striking face, bonded to a steel or titanium club head. They recently went on sale in Japan, where golf is really big and folks are willing to pay top dollar for the latest technological wrinkle. (It made sense to start selling them there first, says Johnson, in order to cover the new technology's startup costs.) But now Amorphous Technologies International, the Laguna Niguel company where Peker et al. now work, is gearing up to start production of fully amorphous club heads here in the United States. If they meet their goal of having a set of irons on the market by April, 1998, says Johnson, it will set some sort of record for moving a material from a laboratory curiosity to a consumer product. And the lessons learned while making golf clubs can be applied not only to other sporting goods such as tennis rackets, baseball bats, and bicycle frames, but to such demanding applications as jet-engine compressor blades and medical prostheses. ☐—*DS*

GOOD NEWS AND BAD NEWS FOR MARTIAN MARINERS

The good news is that Mars Global Surveyor, which slid into orbit around the red planet on September 11, has discovered a Martian magnetic field. (Previous, more distant observations by several spacecraft had been inconclusive.) The bad news is, you can't navigate by it.

The existence of a planetary magnetic field is often seen as a prerequisite for the development and continued existence of life. A strong magnetic field would shield a planet from the fast-moving, electrically charged particles of the solar wind that would otherwise bombard the upper atmosphere, breaking water and other molecules down into ions that then escape into space. So a strong magnetic field helps a planet keep its atmosphere, and with a dense enough, warm enough atmosphere, Mars could have had liquid water on its surface. The field would also intercept cell-damaging cosmic rays that would otherwise penetrate to the surface.

Planets like Earth, Jupiter, and Saturn generate their magnetic fields by means of a dynamo made up of moving molten metal at the core. This metal is a very good conductor of electricity, and the rotation of the planet creates electrical currents deep within the planet that give rise to the magnetic field. (Mars presumably used to have a molten interior, too, since huge, dead volcanoes dot the planet's surface.)

But that dynamo is no longer turning fast enough to sustain a single, global field, because Mars Global Surveyor's magnetometer swung wildly as the spacecraft buzzed the planet. In some places the field is pointing straight up; in others, straight down; and in still other places the field lies parallel to the surface. This indicates that the field is a fossil frozen into the rocks of the crust, and that it has splintered and rotated with the rocks carrying it. If the patchwork could be reconstructed, it would tell scientists a lot about the planet's geological history. The strongest patches were 40 times the strength of comparable regions on Earth, so the Martian field must once have been quite substantial.

The spacecraft discovered the outermost boundary of the Martian magnetic field—known as the bow shock—during the inbound leg of its second orbit around the planet, and again on the outbound leg. The discovery came just before Mars Global Surveyor began its first aerobraking maneuver, in which the spacecraft dips into the upper fringes of the Martian atmosphere, allowing the drag on its solar panels to slow it down and eventually plop it into the circular orbit from which it will map the planet. It will continue aerobraking through the Martian atmosphere for the next four months, until it is flying about 378 kilometers above the Martian surface.

Additional information is available at several World Wide Web sites, including the JPL home page at http://www.jpl.nasa.gov/marsnews, the Mars Global Surveyor home page at http://marsweb.jpl.nasa.gov, and the Goddard Space Flight Center magnetometer site at http://mgs-mager.gsfc.nasa.gov.

The Mars Global Surveyor is managed by the Jet Propulsion Laboratory, which Caltech manages for NASA. JPL's industrial partner is Lockheed Martin Astronautics, in Denver, Colorado, which developed and operates the spacecraft. ☐

ACE IS HIGH

NASA's Advanced Composition Explorer (ACE), which lifted off on August 25, carries two Caltech instruments. ACE is headed for an orbit around the point between Earth and the sun where the gravitational and centrifugal pulls balance. Once there, it will sample the not-so-empty space of our solar system. The atoms and ions whizzing around out there come from three sources: the sun, the local interstellar medium, and the Great Beyond. Each particle has a tale to tell about when and where it was born, and where it's been since.

ACE's nine instruments will count the particles, measure their kinetic energies and ionization states, and even discriminate between different isotopes of every chemical element from helium to zinc. Between them, the instruments cover a millionfold range of particle energies with a sensitivity 10–1,000 times better than previous missions. The two Caltech instruments—the Cosmic Ray Isotope Spectrometer and the Solar Isotope Spectrometer—were built in the Space Radiation Lab by teams headed by Senior Research Associate in Physics Richard Mewaldt and Member of the Professional Staff Alan Cummings (PhD '73), in collaboration with researchers from JPL, NASA/Goddard, and Washington University. Caltech also had overall responsibility for the other instruments. (The spacecraft itself was built by Johns Hopkins University's Applied Physics Lab.)

Parked as it will be between us and the sun, it is probably not surprising that the sun looms large on ACE's agenda. The solar wind and other, higher-energy particles, both of which come from the sun's outer layers, are the only solar matter that humans can analyze directly, says Mewaldt. The relative abundances of various isotopes in those particles, which ACE can measure and cameras and spectrographs can't, will tell us more about what matter in the universe was like when the sun condensed, 4.6 billion years ago. And instruments that measure the charge on individual particles will take the temperature of the region of the sun that the particles came from—hotter layers strip off more electrons from the ions they emit. ACE will also study the sun's enormous magnetic field, and as a side benefit will provide about one hour's warning of the powerful magnetic storms that can black out power grids, disrupt communications, and even fry satellites.

Moving up the energy spectrum are the so-called "anomalous cosmic rays," which are atomic nuclei from the interstellar medium—the thin, thin gas that lies beyond the boundaries of our solar system. As stars age, they create elements heavier than helium in their bowels. When they die, some of this material is ejected into the interstellar medium for future stars to condense from. Thus the matter from which tomorrow's stars will be born is not what it was when the sun was conceived; ACE will tell us how it has changed.

And finally, the most energetic particles ACE can detect are the galactic cosmic rays, which come from within our galaxy but may have traversed it many times, trapped in its magnetic field, before blundering into our solar system. Their exact origin is still a mystery, which ACE should help resolve, but the relative abundances of radioactive isotopes in them (the same principle as carbon-14 dating) shows that, on average, they are 10–20 million years old, says Cummings. They thus constitute a sample of galactic matter of intermediate age.

ACE entered its design phase in 1991, just in time to be a guinea pig for NASA's "faster, better, cheaper" mandate. "We had a cost cap and a fixed launch date," Cummings recalls. "Miraculously, we hit our launch window, and even had some $30 million left to give back to the agency." He credits close cooperation with JPL, which provided technical support and experienced personnel to help keep track of the instruments that Caltech wasn't building. (It probably didn't hurt that Ed Stone, director of JPL and vice president of Caltech, is ACE's principal investigator.) "It's a model for how the Explorer program can run in the future." ☐—*DS*

SEE MARS IN 3-D; HEAR IT IN STEREO

Dramatic 3-D pictures from JPL's Mars Pathfinder mission will be shown during a performance of Gustav Holst's "Mars" at the season's first Caltech-Occidental Concert Band performance, conducted by William Bing, who has purchased 600 sets of 3-D glasses for the occasion. The pictures come courtesy of Robert Manning (BS '82), a trumpet player with the Caltech Jazz Band and Pathfinder's chief engineer. The concert begins at 8 p.m. Saturday, November 15, in Caltech's Beckman Auditorium. The concert is free and open to the public, with seating available on a "first come" basis.

In addition to the performance of "Mars" from Holst's suite *The Planets*, the program will include music by George Gershwin and excerpts from the musical *Ragtime*. Guest conductor Daniel Kessner will conduct one of his own compositions, which was recently commissioned by a consortium of colleges, including Caltech.

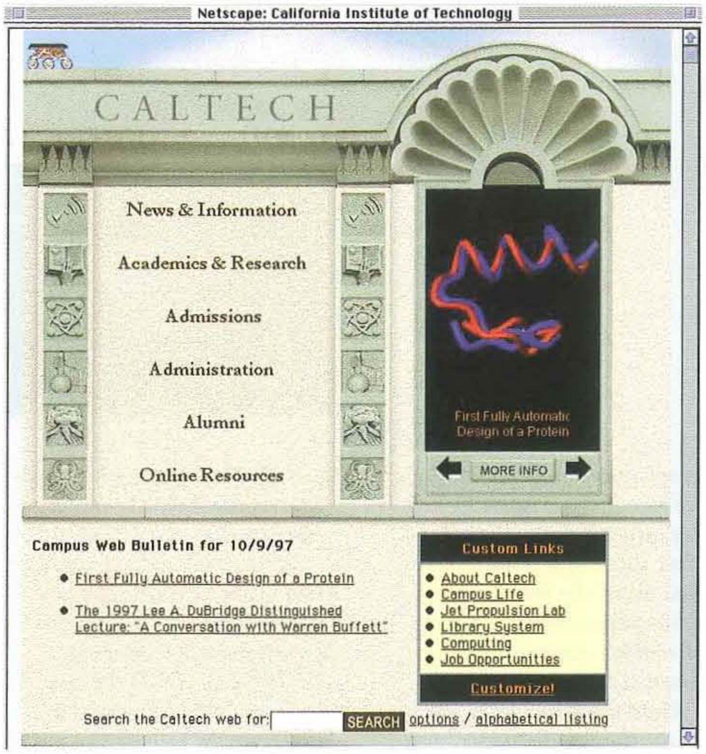
FALL WATSON LECTURES SET

This year marks the 75th anniversary of the Earnest C. Watson Lectures, a series that has not only grown up with the Institute, but literally shaped it: Beckman Auditorium was designed in part with these public lectures in mind. On October 29, David and Judith Goodstein will present "Earnest Watson and the Amazing Liquid Air Show" in homage to that first talk in 1919.

Then, on November 5, in "Gamma-Ray Bursts: Dying Cries from the Deep Universe," Professor of Astronomy and Planetary Science Shrinivas Kulkarni will describe astronomers' search for the source of these bursts, and present their surprising conclusions.

In "Touching Mars," on November 19, Donna Shirley, manager of JPL's Mars Exploration Program, will discuss the ambitious slate of one Mars mission every 26 months through about 2015 that began with the Pathfinder and Mars Global Surveyor.

And in "The World of Our Grandchildren: Visualizing Alternative Futures with the World Wide Web," on January 14, 1998, Professor of Planetary Science and Geology Bruce Murray will talk about the "Hyperforum," an experiment in discourse that uses the World Wide Web to analyze complex problems such as the long-term sustainability of global development.



Campus Web Bulletin for 10/9/97

- First Fully Automatic Design of a Protein
- The 1997 Lee A. DuBridge Distinguished Lecture: "A Conversation with Warren Buffett"

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Caltech's homepage, http://www.caltech.edu, has a new look. Designed by Aurelius Prochazka (PhD '97) and colleagues Jacob Mandelson, Danny Petrovich, and Athina Peiu Quake (wife of Assistant Professor of Applied Physics Stephen Quake), the Web site was commissioned by Provost Steve Koonin and the Web Executive Council. Members of the council would appreciate feedback on the new site. For a list of members and their e-mail addresses, visit http://caltech/subpages/credits.html; or e-mail the council directly at web@cco.caltech.edu.

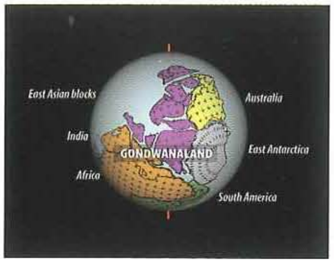
CASSINI LAUNCHED AT LAST

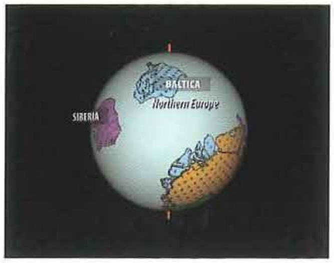
In other news from the Cape, JPL's Cassini mission to Saturn was finally launched at 4:43 a.m. Eastern Daylight Time on October 15, after numerous delays. The spacecraft will get gravity-assisted boosts from Venus (twice), Earth, and Jupiter en route, and is slated to arrive at the ringed planet in July 2004. Once there, it will spend four years studying the Saturnian system much as Galileo is doing at Jupiter. Cassini even has a probe of its own—the European Space Agency's Huygens, which will parachute into the nitrogen-rich atmosphere of Titan, Saturn's largest moon. If the probe survives the landing, it will study Titan's hydrocarbon-rich surface, which in some ways may resemble that of the prebiotic Earth.

ATLAS SHRUGGED

Caltech researchers think they have solved part of the mystery of the "evolutionary big bang" that occurred half a billion years ago. At that time, life on Earth underwent a profound diversification that saw the first appearance in the fossil record of virtually all animal phyla living today. With relative evolutionary rates of more than 20 times normal, nothing like it has occurred since. In a paper published in the July 25th issue of *Science*, the Caltech group reports that this evolutionary burst coincides with another apparently unique event in Earth history—a 90-degree change in the direction of Earth's spin axis relative to the continents. Professor of Geobiology Joseph Kirschvink (BS, MS '75), lead author of the study, speculates that a major reorganization of tectonic plates during the late Precambrian changed the balance of mass within the Earth, triggering the reorientation. Thus, the regions that were previously at the north and south poles were relocated to the equator, and two antipodal (or opposite) points near the equator became the new poles.

"Life diversified like crazy about half a billion years ago," says Kirschvink, "and nobody really knows why. It began about 530 million years ago, and was over about 15 million years later. It is one of the outstanding mysteries of the biosphere. The





Above are three views of how Earth's continents were arranged about 530 million years ago. The red posts are Earth's spin axis; the colors are keyed to today's continents. (India is under the "wana" in "Gondwanaland.") Most of the continental mass is concentrated around the south pole (which is projecting outward in the middle picture), a rotationally unstable situation. The planet compensates by shifting its axis until the excess mass is centered on the equator, as shown in the sequence of pictures above right. (Although the axis moves with respect to the continents, as shown here, it remains fixed with respect to the plane of the solar system.)

geophysical evidence that we've collected from rocks deposited before, during, and after this event demonstrate that all of the major continents experienced a burst of motion during the same interval of time."

Grad student David Evans, a coauthor of the paper, notes that it is very difficult to make large continents travel at speeds exceeding several feet per year; typical rates today are only a few inches per year.

"Earth has followed a 'plate-tectonic speed limit' for the past 200 million years or so, with nothing approaching the rates needed for this early Cambrian reorganization," Evans said. "Some other tectonic process must have been operating that would not require the continents to slide so rapidly over the upper part of Earth's mantle."

In fact, geophysicists have known for over half a century that the solid, elastic part of a planet can move rapidly with respect to its spin axis via a process known as "true polar wander." True polar wander, Kirschvink explains, is not the same as the more familiar plate motion that is responsible for earthquakes and volcanism. While the latter is driven by heat convection in Earth's mantle, true polar wander is caused by an imbalance in the mass distribution of the planet itself, which the laws of physics force to equalize in comparatively rapid time scales.

During this redistribution, the entire solid part of the planet moves as a unit, avoiding the internal shearing effects that impose the speed limit on conventional plate motions. (While this is happening, of course, Earth maintains its original spin axis in relation to the plane of the solar system.) Thus, true polar wander can result in land masses moving at rates hundreds of times faster than tectonic motion caused by convection.

An analogy of the effect can be seen by cementing lead weights at antipodal points on a basketball. If the ball is then set on a slick floor and spun with the weights along the equator, the ball will spin in the manner one would normally expect, with the weights remaining on the equator. If the ball is spun on one of the lead weights, however, the axis of rotation will tend to migrate until the weights are again on the ball's equator. This way, the spinning ball has aligned its maximum moment of inertia with the spin axis, as required by the laws of physics.

As for astronomical evidence that such a phenomenon can occur, the authors point to Mars. Along the equator of the red planet is a gigantic volcano called Tharsis, which is known to be the largest gravity anomaly in the solar system. Tharsis could have formed on the equator, but more likely formed elsewhere on the planet and then migrated to the equator via true polar wander because of rotational torques on its excess mass.

Something similar must have happened to Earth, says Kirschvink. At about 550 million years ago, 20 million years before the evolutionary burst, one or more of the chief subduction zones in the ancient oceans closed down during the final stages of assembly of the supercontinent of Gondwanaland, leading to a major reorganization of plate-tectonic boundaries.

Geophysicists have known for many years that this type of reorganization could, in theory, yield a sharp burst of true polar wander. In particular, if Earth were slightly "football shaped," with a major, stable mass anomaly on the equator and a more equal distribution of mass elsewhere, only slight changes of the smaller masses would be needed to produce large motions. A burst of motion up to 90 degrees in magnitude could even be generated if the maximum moment of inertia (about which the planet spins) became less than the intermediate moment (which is always on the equator). The massive plate motions observed by the Kirschvink group fit the predictions of

"A progressive shift of this magnitude could cause oceanic circulation patterns to become rather unpredictable, jumping from one semi-stable configuration to another on a million-year time scale. Imagine the havoc that would result in Europe if the Gulf Stream were to disappear suddenly."

this "inertial interchange" event rather closely.

Over the 15 million year duration of this true polar wander event, the existing life forms would be forced to cope with rapidly changing climatic conditions as tropical lands slid up to the cold polar regions, and cold lands became warm. "Ocean circulation patterns are sensitive to even slight changes in the location of the continents," says coauthor Robert Ripperdan (MS '85, PhD '90), a geochemist at the University of Puerto Rico. "A progressive shift of this magnitude could cause oceanic circulation patterns to become rather unpredictable, jumping from one semi-stable configuration to another on a million-year time scale. Imagine the havoc that would result in Europe if the Gulf Stream were to disappear suddenly."

These jumps offer an explanation for yet another unique mystery of the Cambrian explosion, which is a series of nearly a dozen large swings in the marine record of carbon isotopes. "Repeated changes in global oceanic circulation patterns should ventilate organic carbon buried in the deep oceans, producing these carbon wiggles," Ripperdan says. "We used to think that they were somehow due to repeated expansion and contraction of the entire biosphere, but no one could think of a mechanism to do that. All of the evidence suddenly makes sense with this true polar wander model."

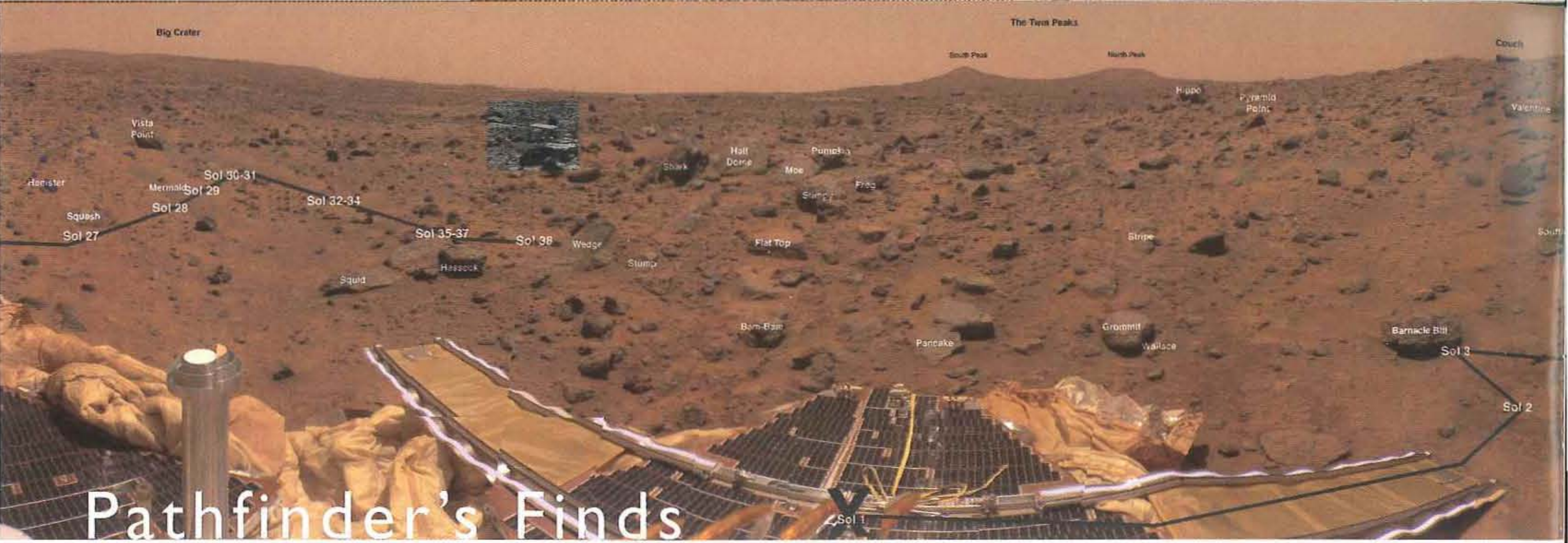
But what caused the evolutionary burst? Kirschvink notes that these global shifts in oceanic circulation will also act to disrupt regional ecosystems, breaking them down into smaller, more isolated communities. "Evolutionary innovations are much more likely to survive in a small, inbreeding population, rather than in large, freely interbreeding groups," he notes. "And the carbon cycles are telling us that major changes in ocean circulation happened about every million years or so. That is certainly enough time for natural selection to weed through the fragments left by the last disruption, and to form new, regional-scale ecosystems. Then, wham! They're hit again and the process repeats itself. That is a great script for increasing diversity, particularly as it seems to have happened shortly after the evolution of major gene systems that regulate animal development." The upshot was that evolution proceeded nearly 20 times faster than its normal rate, and the life of the planet diversified into many groups still living today.

Kirschvink and his collaborators base their conclusions on data collected from 20 years of work on numerous well-exposed sections of the Precambrian-Cambrian and Cambrian-Ordovician eras. By using ultrasensitive superconducting magnetometers to study the weak fossil magnetism (paleomagnetism) left in many rocks as they formed, the researchers can recover the direction of the ancient geomagnetic field. This points in the vicinity of ancient north, for the same reason that a magnetic compass can be used to find the approximate north direction today.

This remanent magnetism can also provide an estimate of the ancient latitude in which the sediments were deposited, as the inclination (or dip) of the magnetic field changes smoothly with latitude—it points vertically at the poles and is horizontal (tangent to Earth's surface) on the equator. Therefore, the fact that magnetic materials are found pointing in other directions is evidence that the ground itself has moved in relation to Earth's magnetic north, which is locked over time to the spin axis.

Geological samples collected by the Caltech group in Australia (which has some of the best-preserved sediments of this age from all of Gondwanaland) demonstrate that this entire continent rotated counterclockwise by nearly 90 degrees, starting at about 534 million years ago (coincident with the onset of the major radiation event in the Early Cambrian), and finishing sometime during the Middle Cambrian. North America, on the other hand, moved rapidly from its end-of-the-Precambrian position deep in the southern hemisphere, and achieved a position straddling the equator before the beginning of the Middle Cambrian, about 518 million years ago. Even the type of marine rocks deposited on the various continents —carbonates in the tropics, and clays and clastics in the high latitudes—agree with these paleomagnetically determined motions. The paleomagnetic directions are accurate within about 5 degrees, the authors write. Latitudes are quite reliable, but because the poles moved so rapidly, even the relative longitude between blocks can be determined. This true polar wander analysis predicts a unique "absolute" map of the major continental masses during this event, an animation of which can be viewed at http://www.gps.caltech.edu /~devans/iitpw/science.html.

"This hypothesis relating abrupt changes in polar wander to evolutionary innovations could be tested in many ways," notes Kirschvink, "as there are some interesting events in the paleontological record during the following 200 million years which might have been triggered by similar processes. There's lots of work to do." ☐—*RT*



Pathfinder's Finds

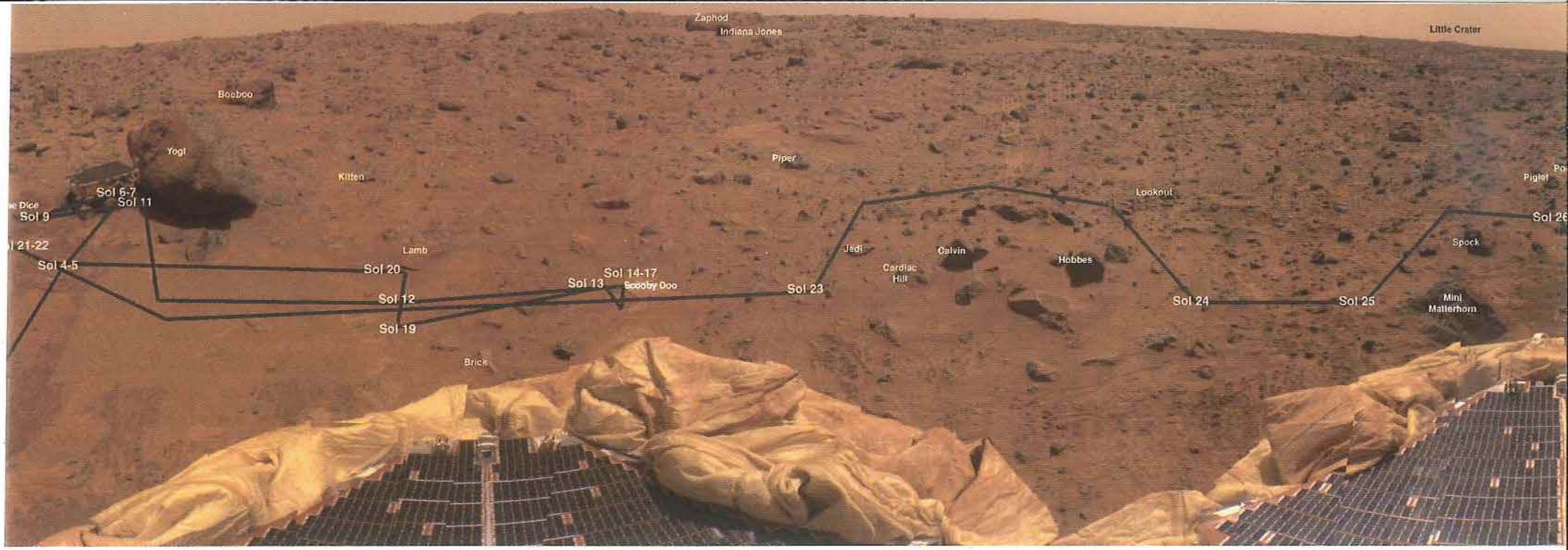
by Douglas L. Smith

Above: The spacecraft came to rest where the floodplain of Ares Vallis, a channel carved aeons ago by the sudden release of enough water to fill the Mediterranean Sea, spills into the vast flatnesses of Chryse Planitia. This panoramic view of the landing site shows some of the names that have been assigned to rocks and other features. (None of these names have any official standing.) The rover's movements over the mission's first 38 sols (Mars days) are shown by the dark line. The rover spent the next 33 sols in the area bounded by Wedge, Flat Top, Moe, and Shark, known as the Rock Garden. As of September 26, the rover, named Sojourner, had more than 100 meters on the odometer. When last seen, the rover was in the vicinity of a rock named Chimp (gray insert).

The Pathfinder landed on the Fourth of July, and now Labor Day has come and gone. The "plucky Mars rover" has dropped off the front page of the nation's newspapers. But the mission continues, and with some three months of data in hand, the mission's scientists are beginning to take stock of their results. What follows is an amalgam of hard data, preliminary interpretations, and informed speculations on everything from Mars's air to its core.

On the meteorological front, Pathfinder started taking atmospheric data on the way in. The spacecraft's Atmospheric Sciences Instrument (ASI)/meteorological package contains instruments similar to those of the Viking missions of 20 years ago, but considerably more sensitive, says JPL's Tim Schofield, leader of the ASI/met team. And while the temperature data taken on the way down are unreliable because of the unsteady airflow around the recessed instruments, Julio Magallhães of NASA's Ames Research Center, at Moffett Field, California, has constructed a temperature profile from the atmospheric drag recorded by the accelerometer. (See picture on page 10). The data resemble those from Viking 1, which landed more than 800 kilometers away at very nearly the same latitude and elevation, albeit somewhat earlier in the northern-hemisphere summer. Pathfinder's temperature readings were, on average, 20 kelvins (K) lower at altitudes above 60 kilometers—probably because Viking touched down at four in the afternoon, while Pathfinder bounced in at three in the morning, local Martian time. From about 60 kilometers on down, Pathfinder's data match Viking's to within five or ten degrees. This leaves unresolved the debate about whether Mars is getting colder—ongoing telescopic observations of the lowest 20 kilometers of atmosphere of the planet as a whole have been reading about 20 degrees cooler than in the days of the Vikings. Furthermore, the telescopes don't see that much dust in the air—important because

Above: Pathfinder landed within 20 kilometers of its aim point, a feat that one member of the navigation team has likened to playing a par-four hole with the tee in Los Angeles and the hole in Houston, with a regulation ball and cup. By triangulating from the Twin Peaks and other landmarks on Pathfinder's horizon that also show up in photos from the Viking orbiters, the spacecraft's position is now known to within 15 meters.



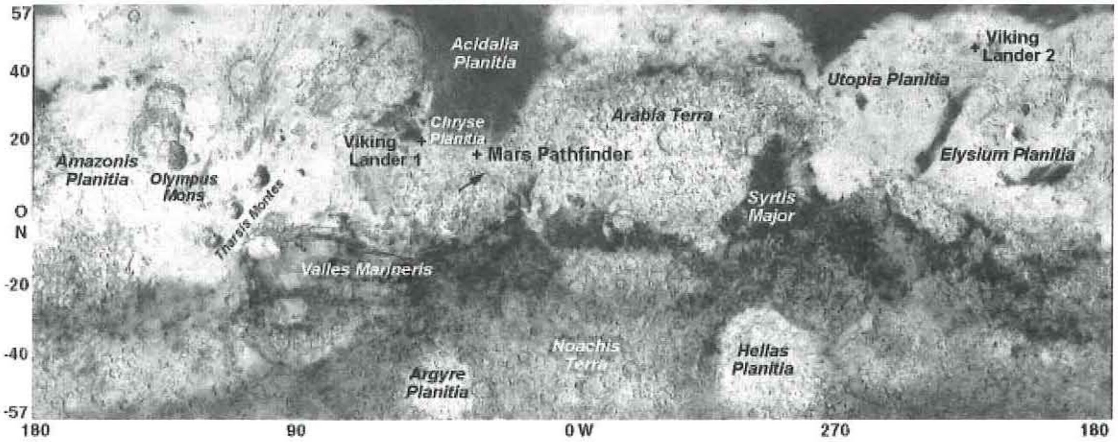
the dust is heated directly by sunlight—while Pathfinder's camera is seeing as much dust as the Vikings did.

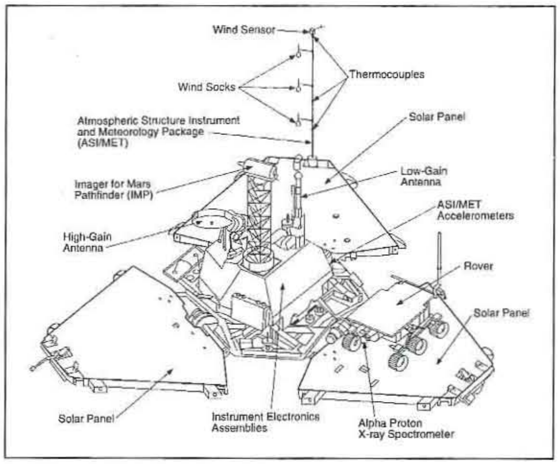
Pathfinder did find it as much as 50 K nippier at altitudes between 60 and 100 kilometers, however. This again is probably due to day-night differences, possibly accentuated by thermal tides in the atmosphere, a phenomenon seen on Earth that would be accentuated by Mars's thinner air. These tides begin at the planet's surface, where heated air expands by day. This creates a wave that travels upward, with the amplitude of the temperature variation increasing with height. At about 80 kilometers, the temperature bottomed out at 92 K—cold enough to freeze carbon dioxide, which makes up some 95 percent of the Martian atmosphere. There's speculation that this dry ice may form clouds, but if so, they haven't been seen.

Since the landing, Pathfinder's weather station has been recording barometric pressure, temperature, wind direction, and speed. For the 30 sols—as the Martian day of 24 hours, 37 minutes, and twenty-odd seconds is called—of the primary mission, it took data day and night. (On some days, in the meteorological equivalent of the panoramic views, the lander took data at four-second intervals for an entire sol.) During the extended mission, Pathfinder goes to sleep at night to conserve power, so weather data is taken during daylight hours. But once every couple of weeks or so, the scientists make the spacecraft stay up all night to see what they're missing. Pathfinder's weather reports average 10 degrees warmer than Viking 1's during the day, and 12 degrees warmer at night. Part of the reason may be that the Pathfinder site is darker and thus absorbs heat better; its rocks also retain heat longer than did the finer sand and dust at the Viking site.

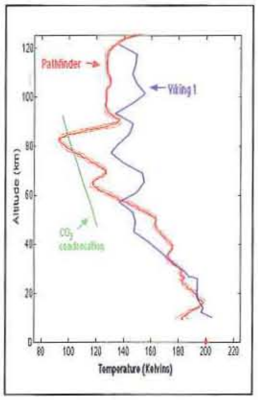
But the barometer watch is going to be the real gold. "Temperature and wind just tell you what's happening where you are," says Schofield. "But pressure readings tell you about the whole column of atmosphere from the surface all the way up." Pathfinder landed in the northern hemisphere during late winter in the southern hemisphere, when pressure wanes planetwide because some 20 percent of the atmosphere's carbon dioxide freezes out into the south polar ice cap. Pathfinder

Below: The green cross in this view from the Hubble Space Telescope marks the Pathfinder landing site. Right: The two Viking landers are also shown on this Mars map; the arrow points to Ares Vallis.





Above: Pathfinder's principal parts. On July 5, the lander portion was renamed the Carl Sagan Memorial Station. Below: During its descent, Pathfinder found the air cooler than Viking I did—cold enough to make dry-ice clouds at one point. These temperature measurements were actually derived from an accelerometer—the rate at which the spacecraft decelerates as it descends is a function of atmospheric drag, which in turn depends on the air's density. Air that's cooler than expected is denser, and thus generates more drag, than would be expected at a given altitude. The data is good down to about nine kilometers, when the parachute opens.



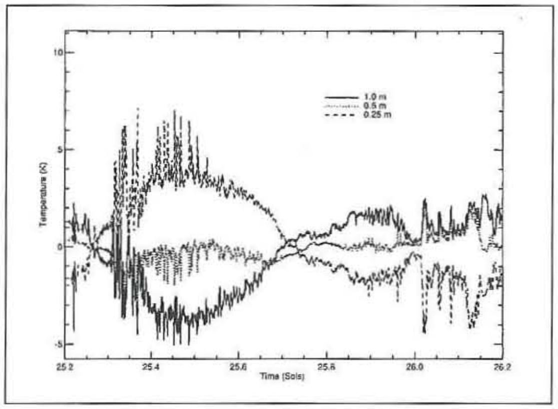
caught the depth of this cycle on Sol 20, when the pressure bottomed out at about 6.7 millibars (a millibar is a thousandth of the atmospheric pressure on Earth's surface). But the pressure is rising rapidly with the spring thaw, reaching 7.2 mb on Sol 83, and Schofield expects it to peak at about 9 mb within the next hundred sols.

Summer on Chryse Planitia is a lot like summer in Los Angeles, at least as far as consistency goes—one day is pretty much like the next. But as autumn draws on, Schofield expects to see more variety—weather fronts rolling down from the poles, just as they do on Earth. And the extra heat that Mars gets from being closer to the sun in the southern summer may bring on those famous planet-enveloping dust storms. But before these long-term patterns unfold, the day-to-day data are revealing short-term patterns of their own.

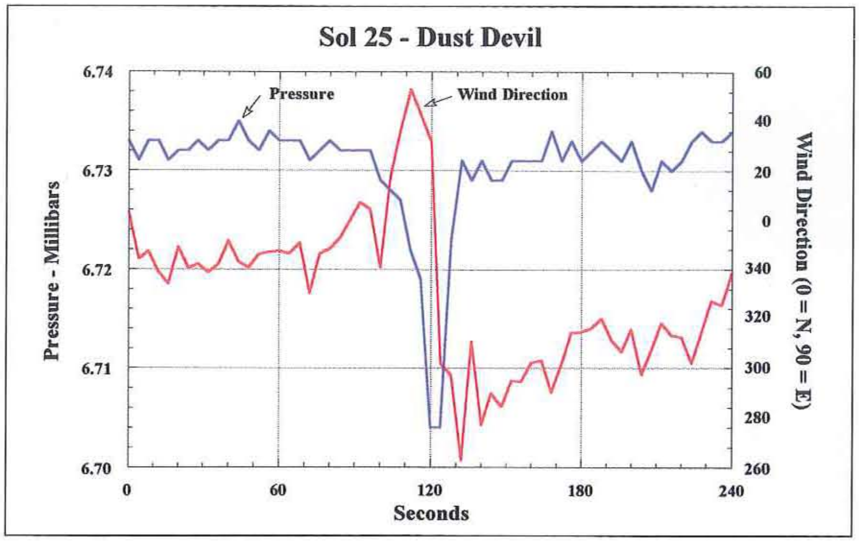
The winds in the lander's vicinity, for example, blow in a topographically driven cycle. They're called "slope winds," says Schofield, and on the simplest level they work like this: at night, cold air descends from the highlands hundreds of kilometers south of the landing site, sighing down through the canyons toward the lander. During the day, the sun heats the flatlands around the lander, and the warm air rises back up through the canyons. The upshot is that the wind makes a daily sweep clockwise through every point of the compass, lingering in the south overnight—a progression so regular during the first 30 sols that any resident Martians at the landing site could set their watches by it.

There's also cool stuff in the temperature data. The meteorology mast carries three thermometers at heights of one-quarter, one-half, and one meter. (The Vikings only had one temperature sensor each.) There's a dramatic temperature stratification—if you were standing next to the lander at midday, your shoes would be 10 degrees hotter than your belt buckle, because the sun-warmed ground heats the air in contact with it. (The pattern reverses after sundown, because the ground loses heat faster than the air, but the nighttime spread is only a few degrees.) All three sensors reach a daily peak in the early afternoon, and then cool overnight until dawn. Superimposed on this gentle swell are spiky features—15-degree variations over tens of seconds—caused by bubbles of heated, unsteady air convecting and mixing. Even after dark, when the warm air is on top and one might assume things would be calmer, the nighttime winds periodically overturn the layers.

When the bubbles of hot air coalesce into a vertical pipeline you get a dust devil, which is the weathermen's hottest quarry. The weather station



Above: A sol's worth of output from the three thermocouples (temperature sensors). In this decimal representation of time, .0 sols is midnight and .5 sols is noon. Sunrise and sunset are at roughly .25 and .75 sols respectively. The data are plotted as the difference from the mean value of all three sensors at that moment, accentuating the temperature spread between the top and bottom sensor. By day, the bottom sensor is the warmest (peaking this day at a balmy 270 K, or very nearly 0° C), but at night, the ground cools faster, and the bottom sensor is the coldest. The spikes are caused by winds mixing the air masses. The temperature resolution is 0.01 K.



Above: A dust devil's signature is written on the wind and pressure sensors. The wind suddenly changes from its prevailing direction, accompanied by a sudden, sharp pressure drop. As the dust devil passes overhead, the wind abruptly whips around to the opposite direction; the pressure and wind readings then rapidly return to normal as the dust devil moves on.

is recording an average of one devil every other day, and on a big day it will see three. These tiny tornadoes register as brief, sharp pressure drops—in the largest one to date, the pressure plummeted about .05 millibars, or 1 percent of the ambient pressure, in a few seconds. (For comparison, a terrestrial tornado causes about a 10 percent pressure drop.) If the dust devil passes directly overhead, the lander also records a sudden reversal of wind direction and a temperature drop. Dozens of dust devils had been inferred from Viking wind and temperature data, but the pressure data lacked fine enough resolution to see them. They could be an important dust-raising mechanism between local and global storms, says Schofield—a host of the little guys all over the planet could easily help keep the observed background levels of dust aloft.

They *could* be—we don't know yet whether they actually carry dust. They may not get enough oomph from the tenuous Martian atmosphere to pick up anything, in which case they'd be invisible, like the wind shear at airports. Pathfinder's camera hasn't caught one yet, but that's just a matter of time. (Schofield and his team plan to search all the images returned so far to see if they can spot one in the background.) But there are hints that the dust devils really are dusty—on Sol 62, a photocell that monitors the light striking the solar panels noted a dimming in the ambient light five minutes after a dust devil passed by. The phenomenon lasted for 10 minutes or so, and could be the receding dust devil's shadow. Schofield estimates this dust devil's diameter at about a quarter of a kilometer, based on the shoulder-to-shoulder width of the pressure minimum and his best guess at its rate of travel. This jibes with numerous transient blobs of roughly similar size seen by the Viking orbiters' cameras. Some of the blobs cast shadows indicating that they stood six to seven kilometers tall.

When the dust devils give way to a planetwide dust storm, it could endanger the Mars Global Surveyor, which slipped into orbit on September 11. MGS will spend the next several months "aerobraking"—raising its solar panels up into a V and dipping repeatedly into the very top of the Martian atmosphere, where the drag will slow the spacecraft and eventually drop it into the nice, circular orbit from which it will map the planet. But suspended dust sops up heat from the sun, warming and swelling the atmosphere. With the atmosphere extending farther out into space, MGS could be sailing through air that's three to four times thicker than expected, and the extra friction could overheat and perhaps even incinerate the spacecraft. Pathfinder's barometer should give enough advance notice, in the form of a sudden increase in the difference between the daytime and nighttime pressure, for JPL to raise MGS's orbit to a safe height, and the Hubble Space Telescope will be keeping a watchful eye as well.

The dust gives the air at the landing site an optical density of about 0.5—the visual equivalent of a smoggy day in L.A., says Mark Lemmon, a research associate at the Lunar and Planetary Laboratory of the University of Arizona, in Tucson. (The U. of A. led the team that developed the mission's camera, puckishly known as the IMP, or Imager for Mars Pathfinder.) Optical density is a measure of the number of dust particles in a given volume of air, but the math gets complicated by assumptions about particle size (believed to be a little less than a micron, or millionth of a meter, based on how they scatter light), and whatnot. An optical density of 1.0 means that if all the dust suddenly precipitated, it would cover the ground in a layer exactly one particle thick. The optical density has remained rock-steady so far, but that will change with the advent of dust-storm season. Five of the densest 10 days have been very recent, but the peak was only 0.6. "You wouldn't notice the difference visually if it was 0.5 one day and 0.6 the next," says Lemmon, "but you might if it happened suddenly." The group measures optical

"Red sky at morning, sailors take warning." Martian mariners would live in a constant state of terror, as this predawn IMP shot shows. The colors are real—the red sky is due to dust suspended in the air, but nobody knows what's in the blue clouds.

density by pointing the IMP at the sun, and comparing the apparent brightness to what it would be without the intervening dust. They also check the sun when it's low in the sky to look at layering in the atmosphere, and have determined that most of the dust hangs in the lowest 13 kilometers.

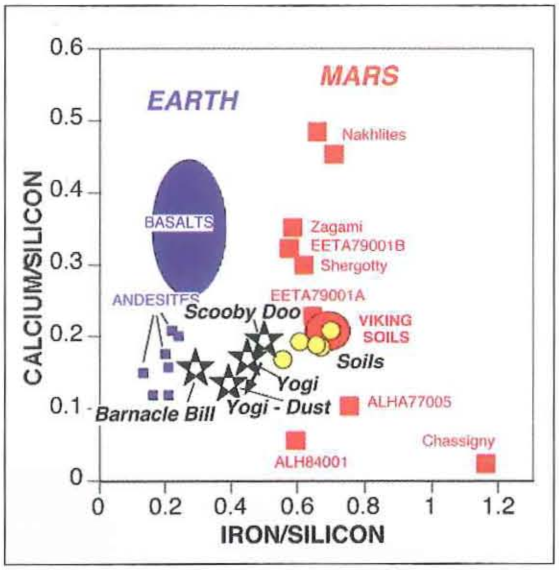
But the most remarkable atmospheric phenomenon that the IMP has captured to date is the blue clouds that are seen occasionally about an hour and a half before dawn. Illuminated by the sun from below the horizon, they burn off rapidly under direct sunlight. Nothing much is known about them, except for the inference that whatever makes them up must be about 0.1 microns in size because it scatters blue light. ("This is going to be one of the most complicated analyses we'll have to do," says Lemmon. "We'll have to model Mars's spherical form, and the sun angle, and all these other geometric effects." Lemmon plans to consult with a research group at the University of Alaska at Anchorage that, in a classic example of making lemonade when life gives you lemons, leads the field of terrestrial twilight studies.) The consensus is that the clouds probably lie at about 13–15 kilometers altitude, and that they're probably made of water. But this is based on several assumptions—for one thing, the clouds aren't reflective enough for the IMP to pick up the water's spectral signature. (The IMP *can* measure the total amount of water aloft by looking at the sun through a special filter—an exercise at the extreme limits of IMP's sensitivity.)

Sojourner does an APXS analysis of a rock named Moe. The APXS sensor head is the inverted demitasse cup pressed against the rock. It takes all sol to get a reading.

Designers of future Mars missions need to know whether the dust settles fast enough to pose a serious problem for solar-powered devices. Geoffrey Landis of NASA's Lewis Research Center in Cleveland, Ohio, principal investigator of the rover's Materials Adherence Experiment (MAE) and a photovoltaics expert, had predicted a coverage rate of 0.22 percent per day. The MAE is logging about a quarter of a percent per day, which Landis thinks is no problem for Pathfinder but could present difficulties for missions of a year or longer. The experiment consists of a glass plate covering a small solar cell on the rover. Once a day, the glass rotates out of the cell's line of sight, and the cell's output with and without the cover plate is compared. The plate is moved by a thin wire of an alloy called nitinol, which contracts when heated. Once the wire has cooled, the glass returns to its initial position. Meanwhile, an adjacent sensor weighs the dust deposited on a quartz crystal by recording its change in vibration frequency. The whole package draws an infinitesimal amount of power—the price for riding the rover—and is slightly larger than an Elvis stamp.

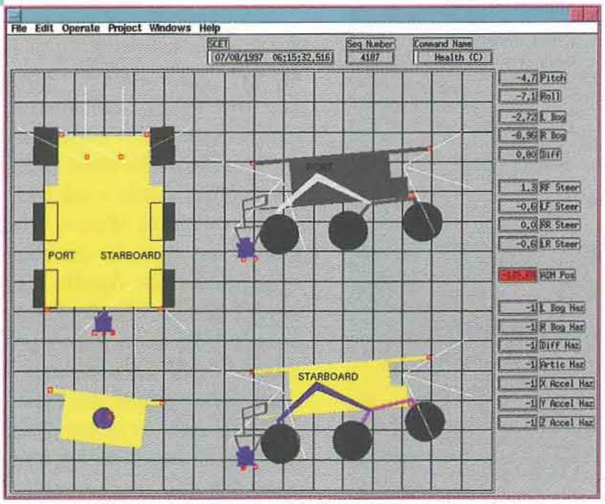
If the rover is a six-wheeled geologist, as it's frequently been called, then its rock hammer and loupe is the Alpha Proton X-ray Spectrometer (APXS). The APXS is three instruments in one, and is designed to give a complete elemental analysis of the soils and rocks the rover encounters. So far, all the results reported about the chemical composition of the landing area's soil and rocks have come from the X-ray mode because the alpha-scattering and proton-emission portions of the instrument, which analyze the light elements, are having calibration problems and will have to be recalibrated. Because nobody knows how long the rover will last, the team is focusing on collecting data rather than analysis, says Tom Economou, senior scientist at the Enrico Fermi Institute at the University of Chicago and coinvestigator for the APXS. As of September 26, the APXS has taken nine rock and seven soil samples.

The biggest surprise actually came from Barnacle Bill, the first rock to be sampled. The conventional wisdom said that Mars, being about half Earth's diameter, would have cooled fairly quickly as planets go. Therefore Mars rocks shouldn't have undergone much remelting, and were expected to be primordial basalts—like Earth's ocean floors, the rock samples brought back from the moon, and the so-called SNC



Left: The ratios of various elements to one another, rather than the elements' absolute abundances, can be more useful in comparative mineralogy. The APXS data from rocks at Pathfinder's landing site (stars) are more Earthlike than the soils (yellow circles), which resemble the Viking soil samples (red circle) and various Martian meteorites (red squares) in composition. The star labeled "Yogi – Dust" is an attempt to correct for the dust layer on Yogi's surface.

The wheel thing. The Wheel Abrasion Experiment (left) consists of 15 panels—three metals each in five films ranging from less than 100 to a few hundred atoms thick, deposited on black, anodized aluminum for contrast. The soil-mechanics experiments depend on knowing the position of the rover's suspension system (below). This tells you how much weight is resting on the wheel, and how deeply it has dug in (which gives the surface area in contact with the soil). Contact area times weight is "normal stress," which is plotted against "shear stress" (derived from the contact area and the torque needed to just begin turning the wheel) to give a straight line from whose slope the friction angle is derived.



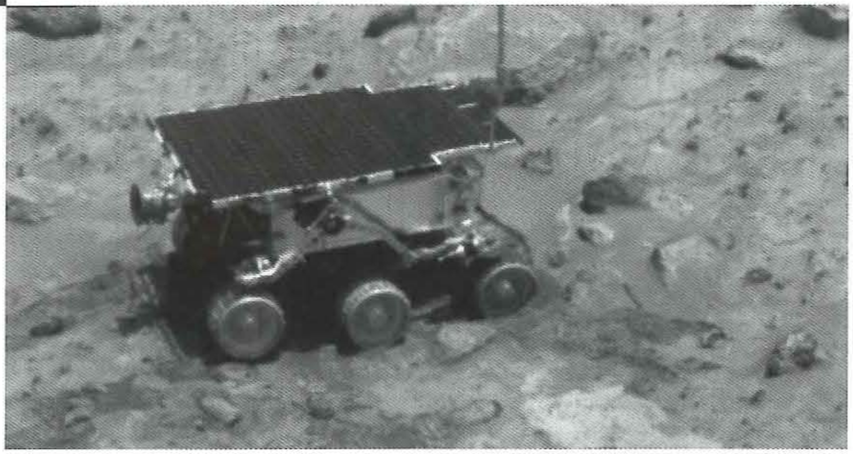
SCET 07/08/1997 06:15:32.516
Seq Number 4187
Command Name Health (C)
-4.7 Pitch
-7.1 Roll
-2.72 L Bog
-8.96 R Bog
0.80 Diff
1.3 RF Steer
-0.6 LF Steer
0.0 RR Steer
-0.6 LR Steer
[illegible] ROM Pos
-1 L Bog Haz
-1 R Bog Haz
-1 Diff Haz
-1 Artic Haz
-1 X Accel Haz
-1 Y Accel Haz
-1 Z Accel Haz

meteorites, which are believed to be Mars rocks blasted to Earth by a meteorite hit on the red planet. Instead, Barnacle Bill had way too much silica, indicating that at least part of Mars's interior had been through enough cycles of melting and cooling for some silicon to separate from the heavier elements and float like soap scum to the top of the mantle before condensing into rock. The exact mineralogy isn't known yet, partially because of the lack of good oxygen data from the alpha-scattering portion of the spectrometer, and partially because Economou would have to get a confirming set of readings from a terrestrial sample of the same mineral. "I get e-mails and samples every day from people who think they've found an Earth analog to what we're seeing," he says. "It'll take years to analyze all of them."

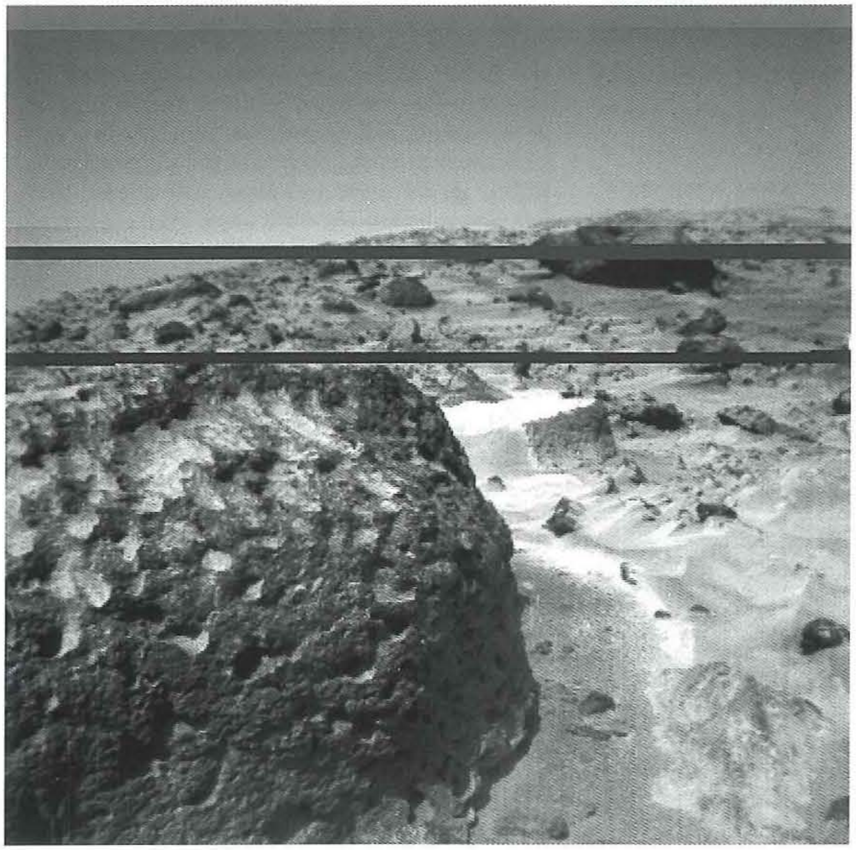
Subsequent rocks have either resembled Barnacle Bill or have been roughly basaltic. But even the basaltic rocks aren't entirely as expected, having more sulfur and chlorine than either their earthly counterparts or the SNCs. What this means is uncertain, but it shouldn't come as a total surprise, says Economou—nobody knows what part of Mars the SNCs came from, but it's not unreasonable to suppose that the rock mineralogy varies from place to place, as Earth's does. On the other hand, the soil APXS results have been identical not only with one another but with the soils at the two Viking lander sites, separated by nearly 180 degrees of longitude. This strongly indicates that the soil, presumably carried on the wings of the wind, is the same all over the globe.

As Sojourner plods from sampling point to sampling point, it takes note of what's underfoot. The Wheel Abrasion Experiment, also run by NASA Lewis, consists of a bunch of thin films of aluminum, nickel, and platinum that run in a ribbon around the middle of the right center wheel. As the rover goes about its business, the soil slowly grinds the films away. You can scratch an aluminum pan with a fingernail, and a nickel with your car keys, but platinum is pretty tough stuff, so the rate at which the various films get chewed up will give us some idea of how hard or sharp-edged the soil particles are. Twice each sol, the rover spins the test wheel to dig into the soil, and a photocell senses changes in the films' reflectivity. The wheels have accumulated a lot of dust, complicating the interpretation, but signs of wear are beginning to show, says Dale Ferguson, the experiment's principal investigator.

Locking five wheels and spinning the sixth one can tell you a lot of other things about the soil's mechanical properties, says Henry Moore, the Pathfinder Rover Scientist and scientist emeritus with the U.S. Geological Survey in Menlo Park, California. Perhaps the most important parameter that can be measured this way is the friction angle. When the soil is not cohesive—and this stuff isn't—the friction angle is nearly equal to the angle of repose, which is the angle at which the

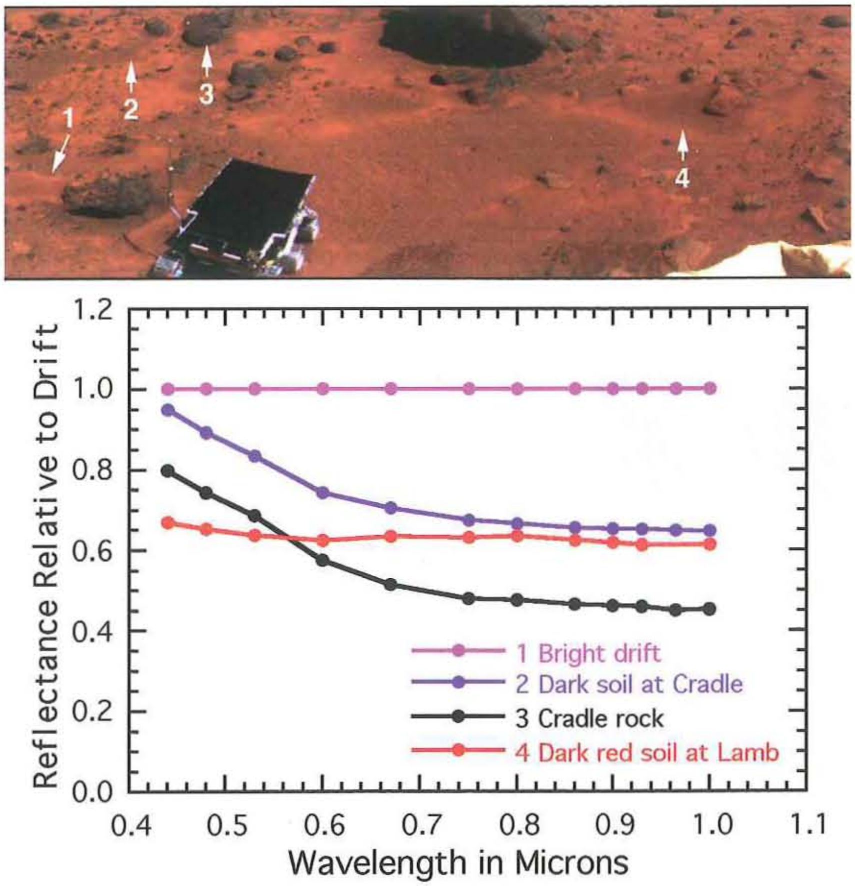


Sojourner as geologist. The rover drove over some compressible soil en route from Barnacle Bill to Yogi, as the above view from the rover's camera looking back toward the lander shows. At right, the rover digs in a wheel near a rock named Shaggy on Sol 23. And the rover's camera goes where the IMP can't, as in the rover's-eye view of Stimpy, below. Stimpy's fluted, pockmarked surface suggests sandblasting by the wind; windblown deposits of drift can be seen to the right. Flat Top is visible behind Stimpy; off in the distance, partially hidden by the top strip of missing data, is a profile of Yogi unseeable from the lander.

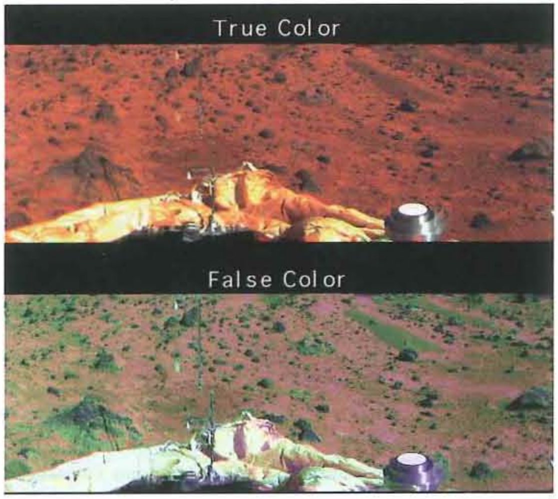


soil naturally "cones" in piles. The friction angle of a natural, dry material is related to its bulk density, which in turn underlies its radar and thermal properties as seen from afar. The rover's "ground truth" agrees quite well with the values derived from satellite and Earth-based measurements, says Moore, which is all the more remarkable in that these techniques look at average values from much larger swaths of terrain than Sojourner could ever possibly sample. But since the bulk density comes out the same either way, it inspires confidence in the accuracy of the remote methods.

Sojourner also learns about the soil by driving through it and looking at the tracks. Three basic types of soil have been classified this way. The first is a low-density, compressible soil, like the stuff near Casper. The rover leaves sharp, clear tracks there—the individual tines on the wheels' cleats are visible. Only a talclike powder will catch such fine detail, says Moore, who estimates the grain size as less than 40 microns—very like the dust returned by the Apollo missions. (The Viking 1 lander saw similar-looking soil, but of course couldn't drive on it.) A possibly identical material called "drift" accumulates in the lee of the boulders. The second soil type, which Moore calls "cloddy soil," is quite dense and is a mixture of dirt clods, small rocks, and sand- to silt-sized particles that mechanically resembles what



Left: Seen through the IMP's geology filters, the bright red drift (1), the dark gray rock named Cradle (3), and two kinds of soil (2 and 4) each have their own distinct spectral signature. (Spectra 2–4 have been plotted against the drift's spectrum in order to highlight their differences.) The strong upward kink in the two soils' spectra at visible wavelengths (less than 0.78 microns) indicates that they are more weathered and have more Fe^{+3}-containing minerals than does the rock. Soil 2, which is intermediate in color between the drift and the rock, has intermediate spectral characteristics as well, while the dark red soil (4) has a spectrum that suggests either a higher Fe^{+3} content or a larger particle size.



Left: The geology filters' output can also be converted into false-color images to summarize a region's spectral properties at a glance. In this view of the Mermaid Dune area, blue is the least weathered, green is intermediate weathering, and red is the most weathered.

Viking 2 found. Cloddy soil covers most of the area, and has been found to underlie the finer soils in places where the rover wheel has dug deeper than a centimeter or two. The rover leaves tracks in this stuff, but not crisp ones. And finally, there's the "indurated" soil, of which Scooby Doo is an example—a cohesive crust that's so tough that the rover's wheel just skitters across the surface instead of digging in.

And while the rover explores individual features of the landscape, the lander is getting the Big Picture. Literally. The IMP, as well as taking stereo pictures for the rover team to navigate by and the rest of us to ooh and ahh over, has a set of 12 "geology" filters that span the visible and near-infrared spectrum from 0.43 to 1.0 microns and are keyed to specific minerals that the scientists expected to find, allowing spectral data to be taken from anything the lander can see. According to the University of Arizona's Dan Britt, coinvestigator and project manager for IMP, the Super Panorama and the Super-Resolution Panorama now being completed are two "Cadillac data sets" that people will be studying for the next decade. The Super Pan covers the entire scene in all 12 geology filters *and* three color filters, in stereo—a compendium of the spectral characteristics of all 2,039 visible rocks (pity the poor soul who counted them!) and the intervening soil patches. And while previous images have been compressed by 6:1 or more, this color data is 1:1. (The geology data gets a very mild 2:1 compression.) The Super-Resolution Pan wrings extra detail from the camera by taking 25 lossless views of every vista, which are then combined in supercomputers at NASA Ames to sharpen the image by a factor of four to eight.

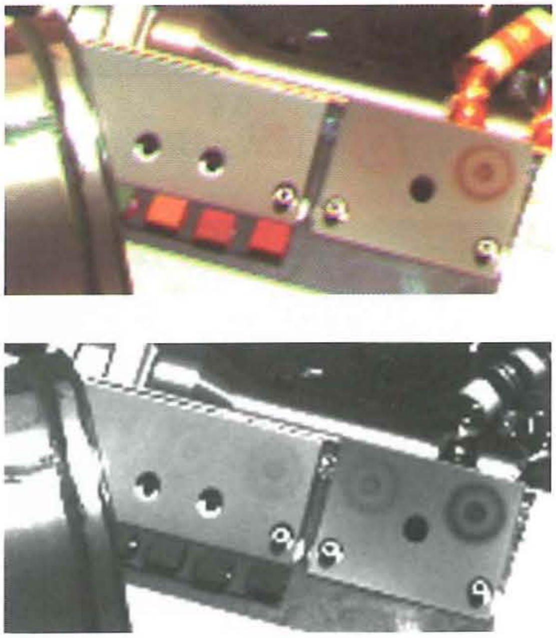
The IMP's view of the rocks dovetails with the APXS data, which means that elemental compositions can be assigned to a host of rocks that the lander can see but the rover can't reach. Yogi and the other big rocks are more weathered, says Britt,

The bright object off in the middle distance of this portion of the Super-Resolution Pan isn't a data-processing artifact or a sign of an alien civilization—it's Pathfinder's backshell, which was cut loose just two seconds before the spacecraft hit the ground. The spacecraft, swaddled in its airbags, bounced from there to its present location. This image fortuitously caught a glint of sunlight off the backshell, making it easier to spot.

which means they've been sitting in their present locations for quite a while. They also tend to be rounded, like boulders in a stream, implying that they were sculpted by water—presumably while being tumbled for hundreds of miles down Ares Vallis from parts unknown. The smaller, jagged rocks like Shark and Wedge are less weathered, and thus relative newcomers. They're also higher in silica, so they must have come from a different place. One popular conjecture has them being impact ejecta from the so-called Big Crater to the south.

Britt classifies Scooby Doo and its kin as a third kind of rock that he calls "caliche-like," after a cemented mineral common in the Tucson area. When it rains in the desert, calcium-rich salts leach out of the upper soil and begin to percolate downward. But before they've penetrated more than a foot or so, the water evaporates in the scorching heat, concentrating them into a layer—caliche—that has many of the properties of concrete. Says Britt, "There's a big debate about whether the caliche-like stuff should be classified as soil or rock. The people from moist climates who have never tried digging in it call it soil. Those of us from arid regions call it rock. And since I'm the chair of the mineralogy and geochemistry science group, it's rock."

The IMP is also a vital part of the Magnetic Properties Experiment being run by the Niels Bohr Institute for Astronomy, Physics, and Geophysics at the University of Copenhagen, Denmark. Iron and liquid water are chemically the best of friends, so the state of Mars's iron can tell us a lot about the history of Mars's water and the former potential for life therein. Iron is the third most abundant element in the Martian soil (after oxygen and silicon), and the magnets carried by the Viking landers rapidly became saturated with dust. So Pathfinder carries arrays of weaker magnets, whose rate of dust accumulation should tell us how strongly magnetic the dust is. Iron comes in two ionic forms: it dissolves out of its native rock as Fe^{+2}, but dissolved oxygen converts it to Fe^{+3}. Fe^{+3} is insoluble, and rapidly precipitates. On Earth, Fe^{+3} eventually becomes hematite (a popular gemstone) or goethite (the primary constituent of rust), neither of which is strongly magnetic. Fe^{+2} can linger in solution for years before eventually settling out as the terrestrially less common iron oxides maghemite (the magnetic coating on cassette tapes and floppy disks) or magnetite (humankind's first compass, also known as lodestone). So dust consisting of clays with a strong magnetic component will imply that liquid water played a long-term role in the dust's formation. The IMP looks at the array every few days to see if the accumulating dust matches any of the patterns these minerals made on an identical array on Earth, and once a week tries to identify the minerals spectroscopically through the geology filters. The dust appears to be a composite of mainly silicate particles containing maghemite, says Jens Martin Knudsen, IMP coinvestigator from the University of Copenhagen.



Pathfinder carries two arrays of five bull's-eye magnets of increasing strength from left to right. The upper array is for airborne dust; the lower array is near the lander's base, in hopes of collecting sand grains as well. These two images of the upper array are from Sol 64. The black-and-white image has been contrast-enhanced to reveal that dust is sticking to four of the five magnets. The dust's color is suggestive of maghemite, but the fact that little, if any, appears to be sticking to the weakest magnet so far implies that there's a lot of nonmagnetic silica mixed in.

But dust devils may strip off weakly magnetic dust, says Britt, so the results have to be interpreted with care. A further complication is that some or all of the dust may be of recent vintage, as the surface of Mars continues to rust to this day. Dust inherited from the underlying rocks will contain titanomagnetite, which has been found in many Mars rocks (including the SNC meteorites). If there's titanium in the dust adhering to the magnets, it would mean that water played a smaller part in the dust's formation. The dust's titanium level should be revealed when the rover returns to the ramp it disembarked from on July 5. A magnet at the ramp's foot, placed there to answer this very question, awaits the APXS.

And finally, there's the question of what lies underground. Mars Global Surveyor's discovery that Mars does, in fact, have a vestigial magnetic field (see Random Walk) implies that Mars used to have a liquid core of nickel-iron, as Earth does. Such a core's heat-driven churnings could have sustained a magnetic field strong enough to fend off cell-damaging cosmic rays—another prerequisite for ancient life. JPL's William Folkner, leader of the rotational and orbital dynamics team, is trying to determine whether the core is still a liquid, albeit one too cool and sluggish to convect, or whether it has long since solidified. Folkner's group tracks the Doppler shift in Pathfinder's radio signals. By combining this data with old results from the Viking landers, they have been able to calculate Mars's polar moment of inertia to within 1 percent. Extended-mission data should shave off an additional factor of three, enough to distinguish between the core sizes, densities, and temperatures predicted by various geophysical models. Some models posit that the core is colder than Earth's, for example, because Mars is smaller and cooled more rapidly; others argue that the core should actually be warmer, at a given pressure, than Earth's, because the outer core, which solidified first, would insulate the interior. Folkner's group has already ruled out the models that predict a core less than 1,300 kilometers in diameter, but otherwise can't yet declare a winner.

With a little luck, a liquid core might manifest itself directly. As every fourth-grader knows, a hard-boiled egg spins differently than a raw egg. If the core happens to have a rotational period that's some whole-number fraction of the Martian year—two-thirds, say—a resonance will show up in the planet's nutation rate. (Nutation is the "nodding" of the planet's rotational axis as the axis itself precesses; think of a pleated lampshade as seen from overhead—the circle of the lampshade is the precession, and the pleats are the nutation.)

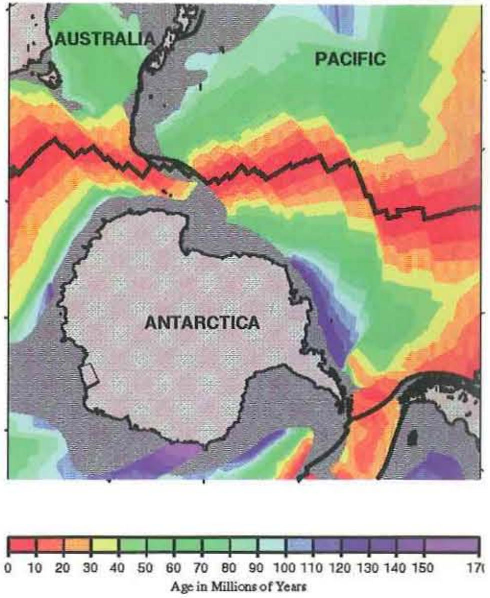
Meanwhile, as the south polar cap recedes, the gas it liberates thickens the air around the equator enough to detectably slow the planet's rotation, just as a figure skater spins more slowly with arms outstretched than with folded arms. (The same thing happens, to a lesser degree, during the northern summer.) The mass lost from the polar cap, and hence its change in thickness, can be calculated from the change in spin rate. This would double-check a calculation done using atmospheric pressure-change data from the Vikings, which indicated that the caps may be astonishingly thin: the loss of about 50 centimeters' worth of carbon dioxide "snow"—a knee-deep layer—is enough to make the cap retreat southward some 1,400 kilometers. (The northern cap gains and loses a thickness of about 15 centimeters.)

Another extended-mission gleam in the eye is to measure the masses, and hence the densities, of some nearby asteroids, from which something about their composition can be inferred. This was actually done for three asteroids in the Viking days, and involves watching how Mars's orbit is perturbed as an asteroid passes by. The ranging data is acquired by measuring the round-trip time of flight of a signal from Earth to Pathfinder and back. "This competes directly with telemetry, and so far telemetry wins," says Folkner. "But the only asteroids we know the masses of are those three and Mathilde, which the NEAR mission just visited, plus a couple more for which the data aren't very good. If we could learn three or four more densities from Pathfinder, that would double our data set." They've compiled a list of a dozen or so asteroids they'd like to try if they get the chance.

Let's hope they do. The spacecraft gave its handlers a very nasty scare by falling silent on September 28. Contact was briefly reestablished on October 7. It looks like the lander's batteries, which had lasted three times longer than their planned lifetime, have expired. This in itself is not a problem, as the lander, which also relays instructions and data to and from the rover, is designed to operate indefinitely on nothing but solar power. However, the unscheduled transition to solar-only mode appears to have caused the onboard clock to quit. If so—among other consequences—the spacecraft would have no idea when and where to aim the high-gain antenna to find Earth. Furthermore, the dead battery could be siphoning off power from the solar array. As of this writing, the flight team has successfully disconnected the battery from the rest of the power system. They think they've reset the clock as well, but Pathfinder has since gone silent again. With the spacecraft uncommunicative, nobody knows if the commands being uplinked to it are getting through, but the engineers are plugging away at the problem. Once they get Pathfinder back to its old convivial self, they'll use the IMP to hunt for the rover, which is programmed to head in the lander's general direction if contact is lost for more than five days—a precaution built into the software in case the rover inadvertently moved out of radio range. And then, with luck, Pathfinder will be back to business as usual. ☐

Right: This map of the age of the seafloor around Antarctica shows that, with the exception of some older floor around the Weddell Sea (the purple and dark blue at bottom), the continent is surrounded by young seafloor from spreading mid-ocean ridges (red). The gray parts are still a mystery.

Below: Mount Erebus, an active volcano near McMurdo Station, is thought to be the surface expression of a hot spot with its volcanic source deep in the Earth, below the tectonic plates. Relationships between this and other hot spots around the globe may give clues to how the plates have moved.



Geophysical Secrets Beneath Antarctic Waters

by Joann M. Stock

Cruising around Antarctica is a perk that a group of us from Caltech have enjoyed over the past few years. You might be curious about how we book one of these cruises. First of all, we write a proposal and send it to the National Science Foundation, which has an Office of Polar Programs and an Office of Marine Geology and Geophysics. If the proposal is approved, we're scheduled for time on board one of the NSF ships. We had proposed several projects to answer some nagging plate-tectonic questions about the history and evolution of the Antarctica plate, which may hold the key to understanding movement of some of the other plates and other global geophysical problems, such as relative motions among the hot spots.

The idea behind plate tectonics is that the surface of the Earth is composed of a number of relatively rigid plates that move with respect to one another at speeds of a few inches per year. The deformation—fault slip, earthquakes, mountain building, seafloor spreading—between the plates is concentrated along the plate boundaries, of which there are several different kinds. For instance, the Pacific plate is moving along the San Andreas fault system sideways relative to North America. In some places the plates are colliding, and in others the plates are moving apart. The latter describes the case we were interested in—where the Pacific and Australia plates are moving away from Antarctica. And the evidence of the movement lies at the bottom of the ocean, in the seafloor formed by the spreading ridges that mark these plate boundaries.

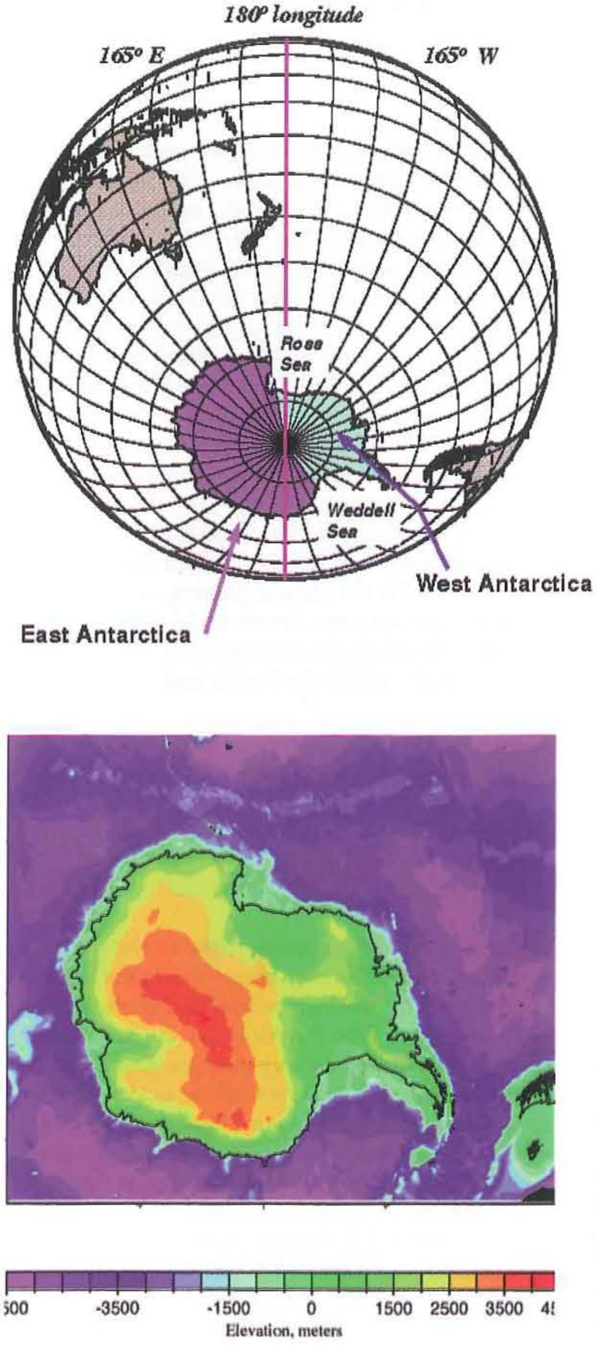
Few geophysical data have been collected around much of Antarctica because it's so out of the way. . . . So we went there ourselves.

The ocean floor is younger close to the spreading ridges and gets older as it spreads away. The map above shows the age of the ocean floor: red is very young, grading through yellow and green into blue and purple, which is very old ocean floor. You'll notice that much of the area around the Antarctica plate is surrounded by very young regions that formed at mid-ocean ridges. There's a little bit of older seafloor in the Weddell Sea and a lot of gray representing the gaps in our knowledge—no one knows exactly what the age of the seafloor is in those places. In fact, for much of the region surrounding Antarctica, there is very little detailed information. There haven't been very many scientific expeditions here compared to other parts of the oceans. There's good reason for this, as we discovered.

The particular knowledge gap that we were trying to close in our own surveys concerns the development of the Antarctic plate. It was part of a larger group of continental blocks called Gondwanaland, which, more than a hundred million years ago, included Africa, South America, Australia, India, Antarctica, and fragments of New Zealand. We can tell how fast the plates spread apart and in which direction by studying the seafloor, and what we find when we calculate the relative rates of motion along the plate boundaries, while these plates were separating, is that there had to be some other deformation somewhere. If these plates were rigid, you would expect that the motion across the spreading center, the convergence in one place and the extension in another, would add up to zero. But in fact, scientists who have reconstructed the positions of the plates over the last 70 million years have found that the motion doesn't add up correctly; there's some motion missing. This motion had to be either through Antarctica or through the Pacific plate, in the area of New Zealand. From what's known about New Zealand geology during that time, we don't think there was deformation going on there early in this period, between about 72 to 56 million years ago, so any extra deformation in that period had to be accounted for in what was thought of as a single, rigid Antarctica plate. And for the last 42 million years, the Pacific plate, Australia, and Antarctica have indeed behaved more or less as rigid plates.

Antarctica is surrounded by spreading ridges, and it's been growing in the sense of oceanic material being added to the edges of the continent as the ridges spread away from the center. This extra deformation might be accounted for within Antarctica or on the seafloor that is considered part of the Antarctica plate. New Zealand is the other possibility, before 42 million years ago. So our expeditions focused on surveying this region of the West Antarctica margin, between the Ross Sea and South America and between the Ross Sea and New Zealand, to try to figure out what really happened in the early history of plate formation.

What do we mean by "West" Antarctica if every direction from the South Pole is north? "West" is determined by longitude lines. The part of Antarctica that lies within longitudes that are within 180 degrees east of the Greenwich Meridian (south of the Indian Ocean, south of Africa, India, and Australia) is called East Antarctica. And West Antarctica is the part that lies in the western longitudes, or the western hemisphere, south of the Atlantic and Pacific Oceans and South America. What we actually consider the boundary between East and West Antarctica doesn't coincide exactly with the longitudes, but rather with a fundamental geological boundary that runs through the continent very roughly along the longitudinal divide. And we can tell from the topography that there is something very different going on in these two halves of the Antarctic continent. East Antarctica is fairly high above sea level, while West Antarctica is a lot lower in elevation. A fairly steep topographic gradient runs right along the boundary between the two parts of the continent, a boundary that also extends offshore into some of the region that we were surveying.



Antarctica divides into east and west fairly neatly along with the eastern and western hemispheres—but not exactly. The Transantarctic Mountains (the yellow-green band crossing through the center of Antarctica in the topographical map below) form the actual boundary between East Antarctica and West Antarctica for geologists. East Antarctica is much higher above sea level than the western half; the Transantarctic Rift System (the green basins to the right of the mountains) has undergone a lot of geological extension and has sunk below sea level.

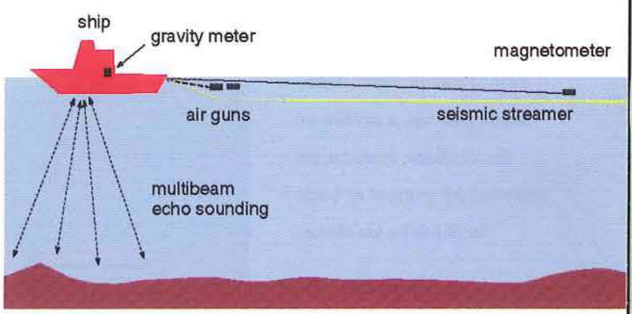
Members of the crew deploy the seismic streamer off the Nathaniel B. Palmer's rear deck, a precarious place to be in rougher weather than this. The ship also towed a magnetometer behind it, and mounted on the ship itself are a gravity meter and an array of instruments to map a three-dimensional swath of the seafloor beneath the ship (below).

Almost all of Antarctica is covered with glaciers, and it's hard to know what rocks are beneath them, although a few exposures of rock that poke up through the ice have given geologists some idea. We do know that East Antarctica is composed of much older rocks than most of West Antarctica. The major geological boundary between East and West Antarctica is a huge mountain range, the Transantarctic Mountains, next to a big basin—the large green areas on the right in the map on the opposite page. This adjacent area of West Antarctica, the zone called the Transantarctic Rift System, has suffered a lot of geological extension; it thinned out and sank below sea level. It may have suffered as much as a thousand kilometers of relative opening. Active volcanoes, including Mount Erebus near McMurdo Station, indicate that some tectonic activity is still going on here. Almost all of West Antarctica is below sea level and covered permanently with ice, and you can't get to the rocks at all. Even the surrounding seafloor is usually covered with sea ice, but if you can get close to it during the summer season, when the ice has retreated, you can study the seafloor using marine geophysical techniques.

The geophysical techniques sense what is on the seafloor, since we can't actually get down there and measure things directly. We're particularly interested in looking at features formed by a spreading center, or "ridge," between two tectonic plates, which leaves behind magnetic anomalies on the seafloor that we can measure with a magnetometer. It might also leave gravity anomalies that we could measure. If the ridge stops spreading and dies, it may leave a trace that we can see in the symmetry or the relief of the seafloor. And we also look for offsets in the spreading ridge system, called transform faults, whose extinct traces some distance away from the spreading center are called fracture zones. These track the direction of relative motion between the plates.

Few geophysical data have been collected around much of Antarctica because it's so out of the way. It's not on major shipping lanes, for example. So we went there ourselves. And we found out for ourselves *why* not many people go there. In addition to the problems of the sea ice, the weather can be very bad. We had 50-foot seas for a while, and some waves got up to 60 feet. I got very seasick, and spent much of the bad weather in my bunk. But the weather wasn't bad all the time.

The 308-ft.-long Nathaniel B. Palmer is the kind of ship you need for work in Antarctica. It can break ice three feet thick at a speed of three knots, and it can deal with the difficult weather conditions. (The other ship we cruised on—the Maurice Ewing, run by the Lamont-Doherty Earth Observatory—is not an icebreaker, but we didn't need this capability every time.) The Nathaniel B. Palmer doesn't just do geophysics; it's a multidisciplinary ship, run year-round by the National Science Foundation, and is also involved in marine biology, oceanography, aquatic chemistry—you name it. The NSF tries to coordinate investigations, so often different groups of investigators who want to go to the same place for different reasons find themselves together on the ship. One year we shared the ship with two ocean engineers from MIT, who were building a remote-controlled submersible device that could swim around by



Above: The Nathaniel B. Palmer at dock. The picture of a 60-foot wave about to crash over the bow of the ship was taken from the bridge; the mast at far right on the ship can be seen against the wave for scale.

itself and make measurements under the sea ice; and another year we shared space with researchers from the National Oceanic and Atmospheric Administration who were collecting gas and water samples. Although these projects had no impact on the work that we were doing, sometimes we can actually use data that others have collected on cruises. For example, another group might be towing a magnetometer on a cruise that's primarily for some other purpose, and we can analyze the data for our own work.

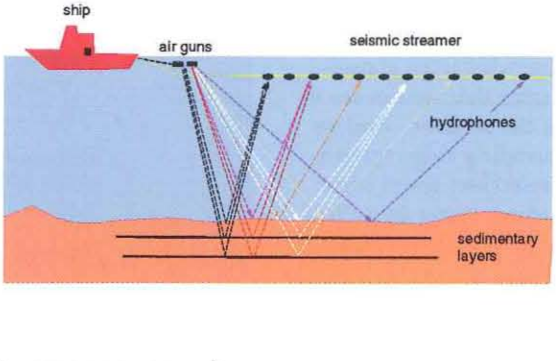
The standard geophysical equipment we use on these cruises includes some instruments mounted on board and some towed behind the ship. We usually do tow a magnetometer behind the ship, as well as a seismic streamer. There's a gravity meter mounted on the ship and an array of transmitters and receivers for multibeam echo-sounding built into the hull; this allows us to map out a three-dimensional image of a swath of the seafloor beneath us. With the magnetometer we're looking for variations in the magnetic field that are related to changes in magnetization of the seafloor caused by symmetric seafloor spreading. These occur because Earth's magnetic field reverses through time, every million years or so, and when the lavas cool at the mid-ocean ridge, they acquire the magnetization of the field at that time. Then, if the field reverses, the next batch of lavas gets magnetized in the opposite direction. This creates patterns of magnetic anomalies that we can identify and date. We can match up these characteristic patterns with what we observe from the ship; this will tell us how old the seafloor is and allow us to map out which way the plates were spreading. But we need *a lot* of magnetic data to cover as much of the seafloor as possible, which is why we often combine our observations with the magnetic anomalies observed by previous cruises.

Our seismic system consists of air guns that bounce pressure pulses off the seafloor and also off sedimentary layers beneath the seafloor, essentially making seismic waves that travel through water and rock. The pulses are received by a series of hydrophones along the streamer, which we tow more than 12 ship lengths (on 3,600 ft. of cable) behind the ship. The seismic data give us a profile of the seafloor. We can also see details of the sedimentary layering below the bottom, which is important for helping us understand the timing of deformation, how deep the basins are, and so on. Analysis of these seismic data is very time-consuming and computer-intensive, so we do what we can on board, but have to save most of it for later when we're back in our labs.

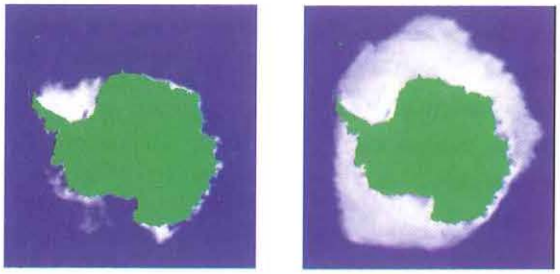
We also tried to dredge rocks off the seafloor. First we have to pull in all the rest of the gear we're towing so that it doesn't get tangled up. Then we tow a chain-link dredge bucket on enough cable for it to reach the bottom. We drag it along for a while and then bring it back up, just hoping to get some rocks.

When we're deploying our equipment—the dredger and various instruments—off the ship's rear deck, we have to wear float suits that are full of foam. So if you are unfortunate enough to fall overboard, you wouldn't live very long in the icy water, but at least your body would float and the crew could find you. And when the back gate is actually open you have to have a rope tied around your waist, so you can't go very far if you're washed overboard. Other than that, however,

The seismic system's air guns bounce pulses off the seafloor and the sedimentary layers beneath, back up to hydrophone receivers along the 3,600 feet of cable towed behind the ship. Most of these data, which provide a profile of the seafloor, have to be analyzed by computer back in the labs on shore.



Even in March (left), there's a lot of ice to navigate through around Antarctica, and by September, at winter's end, the continent is so completely surrounded by ice that no ship would be able to get through.



As the Palmer cuts through the ice (below right), its wake quickly fills in again behind the ship. Ice *on* board ship, as this stairway shows, can be almost as dangerous as the stuff in the sea.

shipboard life is pretty cushy compared to some other kinds of field work. In the Mexican desert, for example [see *E&S* Fall 1993], you have to do your own cooking. There's no water, so you can't take showers. It's hot; there are rattlesnakes; your truck breaks down; you get lots of flat tires. . . .

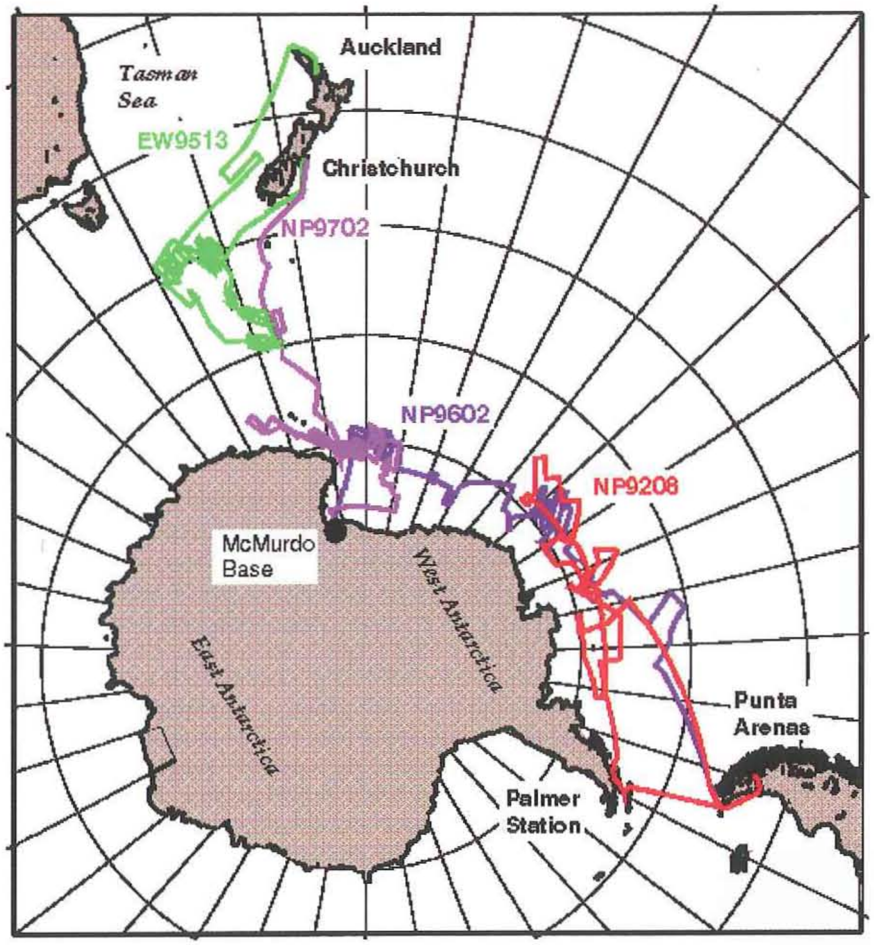
But on ship there's much more infrastructure supporting you—technical support people as well as the ship's crew. (The Nathaniel B. Palmer carries a crew of 25 and about 37 scientists.) The crew members make their own fresh water from the sea water and they have plenty of it; you can have a hot shower any time you want one. They have laundry machines. They have someone else doing the cooking. We even have recreational activities. When the weather is good, you can go out and build snowmen on the helicopter deck. If the weather is not so good, but you can still stand up, you can play Ping-Pong in the cargo hold. We had a couple of Ping-Pong tournaments with the crew and gave out prizes of Caltech hats and T-shirts.

There are also comprehensive computer facilities, as well as lab space where you can lay out maps, make big color plots, and hold meetings to discuss the latest scientific results. Team members stand watch 24 hours a day, in 6-hour shifts, monitoring the computer screens and making sure that all the equipment is functioning and that we are registering all the data that we need to be collecting. As the data come in, they're constantly being analyzed and processed to the extent that we can do that on board. So if a problem with an instrument occurs, we can try to get it working again and not lose too much data. Sometimes in the southern oceans you might not really notice that you're working such weird hours—like midnight to 6 a.m.—because it stays light so long. On one of our cruises in December and January, it didn't get dark at all for four weeks; the sun doesn't set when you're that far south at that time of year.

The time of year that we do this work is pretty important, because the sea ice surrounding Antarctica expands dramatically in the austral winter and then shrinks again in the austral summer. All the area we were surveying would have been chock-full of ice in September, and we wouldn't have been able to work there. In March it was a little better, but we still ended up plowing our way through ice, which was already building up again toward the end of the summer. Large icebergs aren't too much of a hazard because they can be seen on the radar and the ship can adjust course to avoid them. The problem situation is with ice three feet thick or more. As the prow of the ship physically breaks up the ice, big chunks of ice flow by the side of the ship and fill in the wake behind, often endangering our equipment. We tow most of the equipment below the surface, but the ice chunks also extend down some distance. So, whoever is in charge of each science watch spends a lot of time running up and down from the bridge, consulting with the captain and the mates about the ice, trying to decide if we need to pull the equipment out, if we should go a different way, or if we have to give up and turn around.

How do we decide on our course in the first

Wearing and carrying identical NSF-issued gear, Joann Stock (from bottom), Katrin Hafner, and Igor Sidorin, wait at the U.S. Navy station in the Christchurch, New Zealand, airport for the cargo plane to McMurdo Station. This was the February 1996 cruise, marked in blue on the map below.

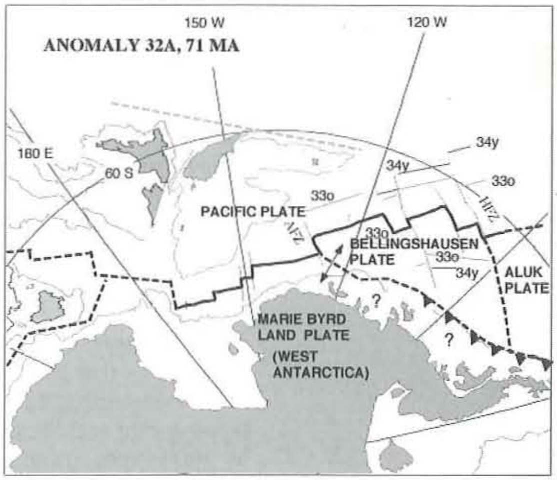


The Caltech group participated in four Antarctic cruises between 1992 and 1997, three on the Nathaniel B. Palmer (NP) and one, around New Zealand, on the Maurice Ewing (EW). Two of the trips (red and blue) concentrated on the area off Marie Byrd Land, and the other two on the Ross Sea and Tasman Sea between Antarctica and New Zealand.

place? We use satellite gravity data to guide us in picking the ship tracks. Satellites measure the height of the sea surface by bouncing a radar signal off it. Even though the sea surface is pretty rough and ragged, if you average a number of observations in the same place, you come up with a smooth version of the potential surface of the ocean (the geoid). This tells you something about the topography of the ocean floor, because variations there cause gravity anomalies that affect the shape of the sea surface. Knowing the general position and shape of features on the ocean floor, even if not the exact details, is an immense help to us in deciding where to go. For example, there's a gravity anomaly in the Tasman Sea that corresponds to a ridge that stopped spreading 56 million years ago between Australia and New Zealand. (Such an event might be related to plate tectonics elsewhere; for example, some subduction zone stopping or starting somewhere else on Earth affects the mantle flow patterns and causes repercussions in the spreading system.) We could plan our ship track—that cruise was in late 1995 and early 1996 on the Ewing—to look at that ridge, making sure that we got data in the places that we wanted.

Our various cruises are shown on the map at left. In 1992–93, we went from Punta Arenas near the tip of Chile along the West Antarctica margin over to the Marie Byrd seamounts and back. We went on two cruises in 1995–96: one out of New Zealand to survey the South Tasman Sea, and the other from McMurdo going along the edge of West Antarctica and ending up in southern Chile. In February and March of 1997, we went from McMurdo up to New Zealand. In each case we were planning our tracks to cover specific areas of the seafloor that would answer our questions about plate tectonics, to look at the spreading ridges between plates, and to see where the fracture zones come into the continental margin, which will help us reconstruct the plate-tectonic history of the region from East Antarctica to Australia. We also looked at some enigmatic features of the seafloor that had never been surveyed and found some new and interesting things.

If you look at the tracks in detail, they look very erratic. There are little kinks where the ship had to turn into the waves so that not so much water would come crashing onto the back deck while the equipment was being deployed; and some funny squiggles where the ship kept turning to avoid big chunks of ice, or even icebergs. And sometimes, if we needed satellite access for e-mail or essential communications, we would have to turn east or west for a while because the satellites, which are sparse in the southern oceans in any case, are low on the horizon and our antenna couldn't pick them up if we were heading south. The little boxes along the tracks mark places where we were trying to establish exactly where a particular feature lay



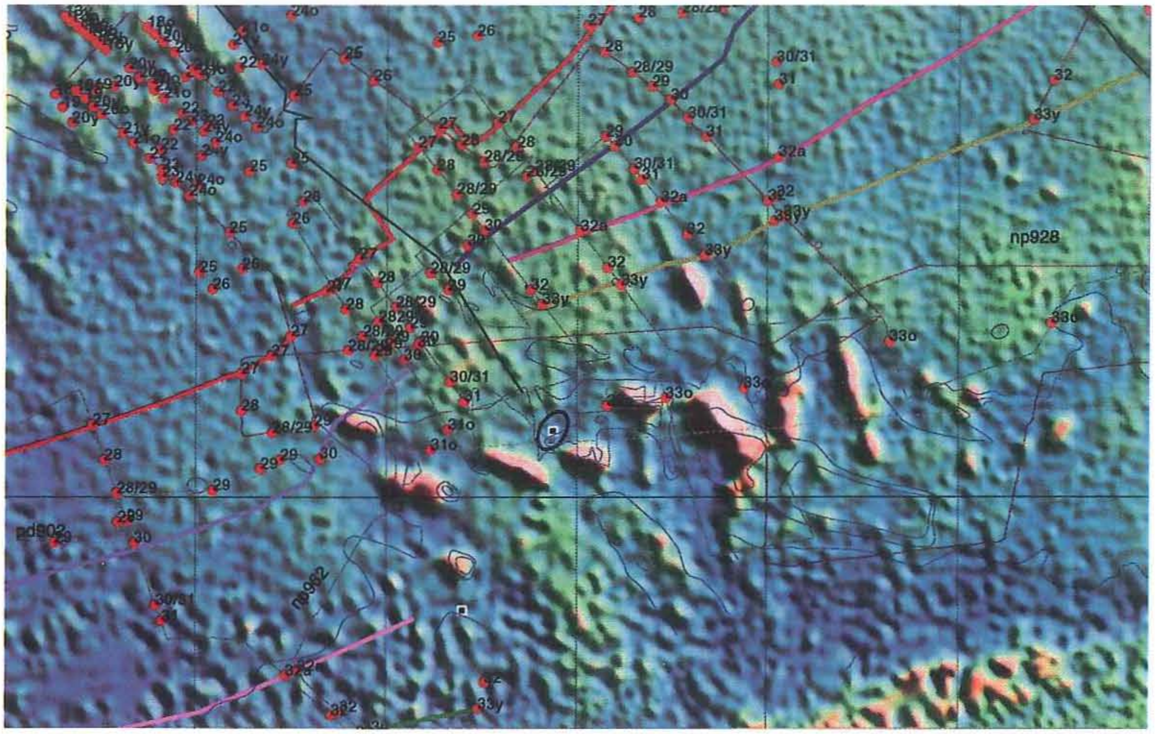
Right: Data collected off Marie Byrd Land in West Antarctica led the researchers to conclude that 71 million years ago three spreading ridges came together in a triple junction, where the Pacific and Antarctic plates came up against a third, the Bellingshausen plate.

on the seafloor; for example, trying to fix the position of a fracture zone with our magnetic, gravity, and seismic measurements. Locating the fracture zone will help us match it back to its counterpart fracture zone near New Zealand, to determine the positions of the plates when the first rifting occurred. We already know where these fracture zones lie on the New Zealand side, but we didn't know exactly where they were in Antarctica.

In 1996 we also surveyed in a region where we thought, from our previous studies, that there might have been an old plate boundary within West Antarctica. This region is all now just part of the Antarctica plate, but we thought it might once have been two plates, and we wanted to try to confirm this. That has turned out to be the case, although the boundary is somewhat obscured by sea mounts—volcanoes that had erupted on the seafloor after spreading had occurred. They poke up through the seafloor and remove the evidence of the magnetic anomalies that had been there. Based on the ages that we determined for the Antarctica seafloor (isochron lines, or lines of constant age), we can see that something happened near the Marie Byrd seamounts to split it open. Much of this region was actually formed by seafloor spreading at some ridge that is now dead. Comparing this with a map of the whole South Pacific area, we were forced to conclude that these magnetic isochrons were formed by two separate spreading ridges and that there had been a third spreading ridge trending south toward West Antarctica from the triple junction of the three ridges. We ended up with a model (above) for the positions of the plates 71 million years ago, in which the Pacific plate was moving relative to another plate called the Bellingshausen plate, which was moving relative to West Antarctica. This is a very important result, because it tells us that if we want to know the position of the Pacific plate relative to Antarctica, we have to use the data from the region between the Campbell Plateau, near New Zealand, and Marie Byrd Land. They give us a different answer from what was done before, using the data farther to the northeast.

We also found another place with evidence of relative motion within a plate that formerly had been thought to be a single plate. It's the Adare Trough, which connects up to the West Antarctica

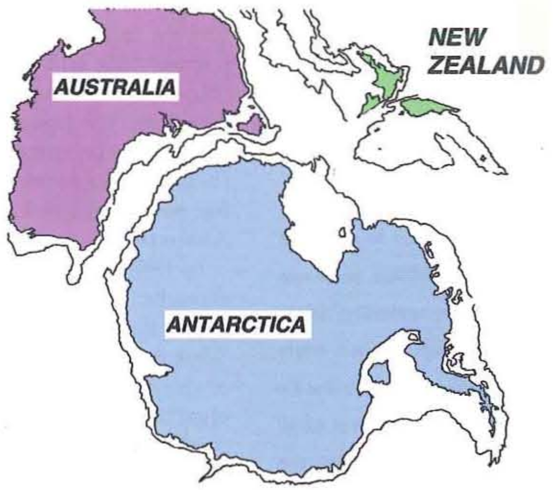
Above: One of the underwater volcanoes off Marie Byrd Land, imaged by the ship's multi-beam echo sounding system. The Caltech group tried to dredge rocks from this seamount with little luck.

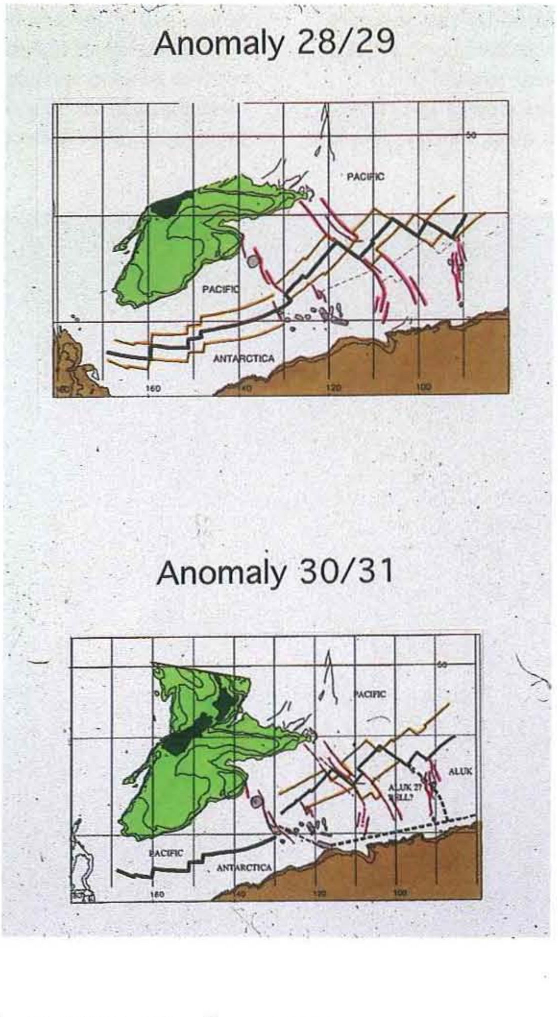


Right: Isochrons indicating seafloor age are superimposed on an image from gravity anomaly data around the Marie Byrd Land seamounts. The red line, marked 27, tracks seafloor that is 62 million years old; the blue line (30) is 67 million years old; purple (32) indicates 72 million years. These isochrons enable researchers to reconstruct spreading ridges on the seafloor.

ridge system and is part of a region that seems to have endured seafloor spreading between East and West Antarctica. It isn't very much motion, only about 150 or 200 kilometers, which probably all took place before roughly 35 million years ago. This is important to models of past plate motions because it allows us to place some constraints on how much relative motion there could have been between East and West Antarctica. Other models have proposed as much as a thousand kilometers of "missing" motion, but we don't see that—at least not in the last 70 million years. You can tell from the geology that there must have been some extension or stretching, and we try to close that out by lapping East and West Antarctica back together by 200 kilometers and then trying out various reconstructions of the plates. Our magnetic-anomaly data give us more constraints in fitting the different pieces of Antarctica back together, and we can tell which reconstructions will work and which will not.

70 MILLION YEARS AGO....





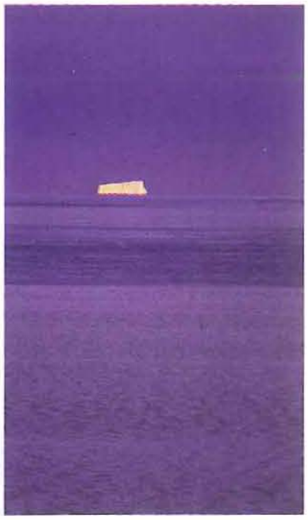
Right (above): About 70 million years ago, as Gondwandaland was continuing to break up, Australia and Antarctica were separating into continents opening up the Tasman Sea as they spread apart from the Pacific Plate and New Zealand. Right (below): A closer look at the isochrons around the Campbell Plateau region (light green) off New Zealand (dark green). Anomaly 28/29 indicates where the spreading was about 63–65 million years ago, while anomaly 30/31 shows its position 67–69 million years ago. The spreading ridge of the plate boundary (black line) can be reconstructed from these Campbell Plateau data, critical to determining the relative positions of the Pacific and Antarctic plates.

Hot spots, which have been used as an alternative method of reconstructing plate positions, offer another possible constraint (Mount Erebus, which I mentioned earlier, may be a hot spot). Hot spots are thought to have some source of volcanism from beneath the plates, possibly deep in the Earth, in the mantle or at the core-mantle boundary. As a plate moves over a hot spot, it leaves behind a trail of volcanoes.

One example of a hot spot track is the Hawaiian chain of islands, which is part of a longer group of seamounts (underwater volcanoes) called the Hawaiian and Emperor seamounts. Since the ages of these submarine features are known, we can map the progression of the Pacific plate over the hot spot that gave rise to them. We can tell that the Pacific plate has to be moving northwest relative to some fixed hot spot because of the direction in which it's dragging the volcanoes. A number of hot spots are thought to exist on the Earth, and it has also been postulated that they are all fixed relative to one another—that there is some fixed reference frame deep in the mantle or at the core-mantle boundary where these hot spots originate. If this were so, you could apply it to help reconstruct the past positions of the plates.

But if you assume that the African hot spots formed a fixed reference frame relative to the others, and then reconstruct the Pacific plate relative to Antarctica and Africa, you find that this doesn't work. Using the data that we collected to get plate motions for Pacific–Antarctica–Africa, if we try to hold the Hawaiian hot spot fixed to the African hot spots, it doesn't reproduce the geometry of the Hawaiian seamount chain. This forces us to conclude that the hot spots must be moving relative to one another.

Others have argued that perhaps the Antarctica plate was really more than one plate, with a thousand kilometers of opening along the Transantarctic rift system. If these plate reconstructions of the Pacific plate or the African plate are all wrong, then perhaps the hot spots could constitute a fixed reference frame. We can conclude, however, from our new data in the Ross Sea that West Antarctica and East Antarctica were separate during the last 70 million years, but the amount of relative motion was less than has been postulated—a few hundred but not a thousand kilome-



Right: An iceberg catches the late afternoon light. Below, right: Happy to be on land again, after the Nathaniel B. Palmer docked in Lyttelton, New Zealand, last winter are (from left): Jane Heinemann, Magali Billen, Joann Stock, and Katrin Hafner.

ters. We know there's no easy way to reconcile these different hot spot traces. This strengthens the case for the hot spots to be in relative motion with respect to one another.

Why, you might ask, do we care about the position of the Pacific plate with respect to Antarctica? It's actually very important for a number of reasons, but, in particular, it helps us form a clearer picture of what's going on closer to home. For example, if we want to determine the relative position of the Pacific plate with respect to North America for some time in the past, we would reconstruct, by means of the spreading ridges, the position of the Pacific plate relative to Antarctica, Antarctica to Africa, and Africa to North America. But this model assumes that the Antarctic plate was entirely rigid, with no internal deformation between the east and west parts. Whether this is a valid assumption depends on the time we're looking at. The motion between the Pacific and North America plates is of importance to geologists trying to understand the history of the geologic evolution of western North America, where we see evidence of volcanism and deformation, which we are trying to link to the plate motions. The details of what was going on in the Antarctica plate provide a key to the other plate motions and, ultimately, to a better understanding of western North America.

Because our results help us figure out the amount of deformation in Antarctica, we can then reconstruct the position of the Pacific plate with respect to all the other plates. Once we can do this, we can then build other observations into our models—for example, the wandering of the Earth's magnetic pole. The Earth's magnetic pole coincides with the planet's spin axis, which has wandered a certain amount with respect to the plates or to the hot spots. The various models that assume that the hot spots are fixed, or are not fixed, give different pictures of how the magnetic pole has actually wandered over the past several million years. We haven't yet incorporated the results from our cruises into these kinds of models, but we expect they're going to be important. Our new data from the Antarctica plate will probably also help solve a disagreement, arising from plate reconstructions, about the Pacific plate's latitude relative to the Hawaiian hot spot.

Now our task will be to analyze all of these data we've collected. But in the meantime we're planning another cruise in May to gather still more data to help us reconstruct the Pacific plate relative to other plates. We won't need an ice-breaker this time, and there won't be any snowmen on the helicopter deck. We'll be surveying the seafloor around the Manihiki Plateau—sailing from American Samoa to Honolulu. ☐

Joann Stock delivered the Watson Lecture on which this article is based last March, shortly after returning from her latest journey to Antarctica. She travels a lot—her article in the Fall 1993 issue of E&S *described her field work in Baja California, which has been rifted away from the North American plate as the Pacific plate slides past. Since then Stock has continued to work in Baja California as well as Antarctica; she has also been granted tenure and had a daughter, Gabriella Wernicke, now going on 3. (Stock's husband is Professor of Geology Brian Wernicke.) Stock received her BS and MS in geophysics (1981) and her PhD in geology (1988) from MIT and has been associate professor of geology and geophysics at Caltech since 1992.*

Also involved in the Antarctica research were Steven Cande of the Scripps Institution of Oceanography; Carol Raymond of JPL; Dietmar Müller of Sydney University in Australia; and Robert Clayton, professor of geophysics at Caltech. Several Caltech grad students have also participated in these cruises: Tim Melbourne, Magali Billen, Jane Heinemann, Nathan Niemi, Igor Sidorin, and Judy Zachariasen, as well as undergrad Katy Quinn. Katrin Hafner, member of the professional staff, was also part of the group and took many of the photographs in this article. The work was supported by the National Science Foundation.

Solar Fuel

by Harry B. Gray

Harry Gray and Mr. Sun enjoy each others' company.

In the next century, burning hydrocarbons—oil, gas, and coal—is going to be a no-no. And it won't be for the reason you think, which is greenhouse warming—it won't be because Cleveland will bake, and Pasadena will drown. We have to stop burning hydrocarbons as soon as possible because they're wonderful raw materials. We desperately need them to make dyes and drugs and T-shirts and chairs and automobiles—it's crazy to burn them. So sometime in the next century you'll see a massive conversion of this fossil-fuel-burning world of ours into a world that burns clean fuel. There are really only two clean fuels: hydrogen (H_2) and electrons. Hydrogen is clean, because when you burn it you get water back. (And, of course, the water can be split again to make more H_2.) Electrons are clean only if they're generated cleanly, and the best way to do that in the long term is by nuclear fusion. I'll be overjoyed the day that fusion power comes to pass, but I'm a chemist, so this article is about chemists and other scientists who have tried to convert sunlight and water into oxygen (O_2) and hydrogen.

First, I'm going to give you a short course in solar energy. (In fact, this article is a bunch of short courses. You can either buy thick textbooks and get hernias from carrying them around, or you can read this.) There are three fundamentals of solar-energy conversion. The first is light capture—absorbing the sunlight, basically. The second is electron transfer—pushing a sunlight-excited electron off its home atom in order to harvest it. The third is catalysis—the efficient making and breaking of chemical bonds using the harvested electrons and the oxidized atoms they've left behind. Each fundamental builds on the preceding ones, so if we can do all three, we're most efficient. If we only capture light, we turn sunlight to heat, which can then create steam to run turbines to make electricity. We've known how to do that for a long time, but it's very inefficient. A few years ago, we took the next step, and fig-

We have to stop burning hydrocarbons as soon as possible because they're wonderful raw materials. We desperately need them to make dyes and drugs and T-shirts and chairs and automobiles—it's crazy to burn them.

ured out how to do both light capture and electron transfer. This requires light-sensitive semiconductors—photovoltaics such as silicon that convert sunlight into electricity. We now have durable silicon devices with reasonable efficiencies—say, 10 to 15 percent of sunlight converted to electricity. In fact, we could convert Los Angeles into a solar city right now, and we probably should. But if we make electrons, we've got to use them on the spot or lose them. We can store them on a small scale in batteries, of course, but my point is more general: we've got to be able to store the energy on a larger scale for use later. So the goal is to do all three steps, so that we can store the electrical energy in chemical bonds—the hydrogen-hydrogen bond, in this case.

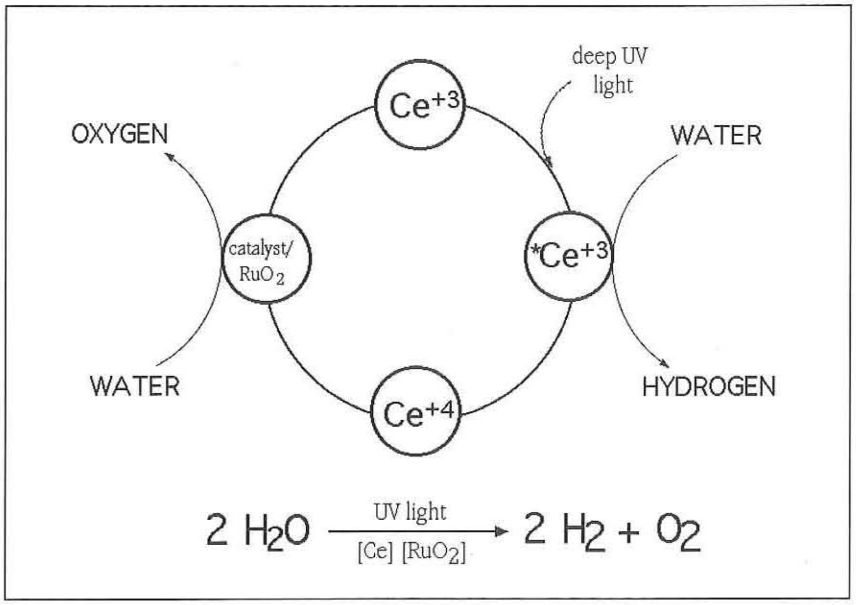
Now for the short course in photosynthesis: photosynthesis is extremely simple. A good book on photosynthesis runs about 1,600 pages. You can't read 1,600 pages without falling asleep, so you may as well take my word that photosynthesis is easy to understand. You start with sunlight, CO_2, and water, run them through a green leaf, and you get O_2 and carbohydrates. God took the three-step solar-energy scheme, and optimized each component. Chlorophyll is pretty good at capturing the sunlight that reaches the Earth's surface. The electron acceptors—the organic molecules that siphon off the electrons after the light's been captured—are nearly 100 percent efficient. And God made something I'm still marveling at—a beautiful manganese cluster that catalyzes the evolution of oxygen. Photosynthesis is 6 percent efficient overall in converting sunlight to stored chemical energy. You may not think that's much, but it's been enough to run this planet for a very long time.

We know that we can turn a leaf that makes carbohydrates and O_2 into a water-splitting system that makes H_2 and O_2, because Eli Greenbaum at the Oak Ridge National Laboratory in Oak Ridge, Tennessee, has done it. (Greenbaum—what a wonderful name for a guy who's doing artificial photosynthesis!) Eli's no fool—while the rest of us were trying to work up these incredible catalysts from scratch, he figured he could take God's invention, and just add one component—a catalyst that couples protons and electrons to make hydrogen. That catalyst is platinum, so Eli got some leaves, took the chloroplasts—the photosynthetic organs—out of them, filled a little Baggie full of chloroplasts, put in a platinum solution, dried off the chloroplasts, added some fresh water, shone sunlight on them, and boom! hydrogen and oxygen. It's beautiful. So we know this can be done, because Eli's done it. God plus Eli—God did all the hard parts, and Eli added a platinizing solution to a Baggie. And guess what? Eli picked up a percentage point of efficiency! (How'd he do that? There must be an error somewhere in the paper.) Eli's water splitting is 7 percent efficient, which corresponds to a semiconductor making electrons at 10 percent or higher efficiency because the hydrogen is stored chemical energy. This is incredible. What's the catch? Why don't we all quit and go home?

The reason we can't quit—and if you don't remember anything else, I want you to remember this—is that efficiency by itself is not enough. If you read about a process that's 7 percent efficient, you should then ask the following question: how long does it last? Will it keep going? The answer here is, no! God made chloroplasts full of wimpy organic molecules that break apart. After being exposed to light for several hours, Eli's platinized leaf poops out and it's history. God doesn't mind, because if any part of the photosynthetic system breaks down, the leaf just makes more. (The leaf is a wonderful synthetic chemist!) But in artificial photosynthesis, we can't do that. We've got to make something that lasts forever. Not only does it have to be efficient, it's got to be durable. Rugged. No wimpy organic molecules.

I'm proud to be an inorganic chemist. Inorganic

Inorganic chemists are the Marines of chemistry. We knew we could make a simple, inorganic, artificial photosynthetic system that would last forever.



Above: How to turn sunlight into hydrogen without wimpy organic molecules. At the top of the cycle, ultraviolet light kicks a cerium atom (Ce^{+3}) into an excited state ($^*Ce^{+3}$), which promptly sheds the extra energy and an electron by jolting a hydrogen atom off a water molecule, becoming Ce^{+4}. A ruthenium-oxide catalyst scrounges replacement electrons from other water molecules, liberating oxygen. (The complete set of reactions is too complex to show.)

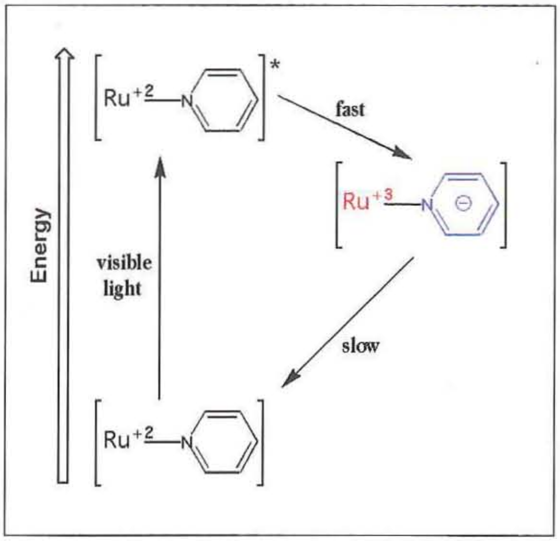
chemists are the Marines of chemistry. We knew we could make a simple, inorganic, artificial photosynthetic system that would last forever. We didn't need CO_2 inputs, because we didn't want to make carbohydrates—they're too complicated. All we wanted to do was run water in, and run hydrogen and oxygen out. We made our system out of cerium, which is a tough, macho metal. We hit Ce^{+3} with deep ultraviolet light, and it split water to hydrogen. This left us with Ce^{+4}, which with a ruthenium-oxide catalyst converted water to oxygen and gave Ce^{+3} back. Our system was all rugged metals, with no organic components—it would never run down. Unfortunately, it was not very efficient—less than 10^{-10} percent efficient in practice! The problem is that we don't get deep UV light down here on the Earth's surface, because the ozone layer in the stratosphere acts as a filter. Out beyond the ozone layer, this system will be very useful for space travelers and space colonists, but here on Earth, it's back to the drawing board. We hit the beach, all right—we made the system so rugged that if it covered the entire surface of the Pacific Ocean, and we irradiated it for a billion years, we'd only make enough hydrogen to drive your car a couple of blocks! So you've got to have both durability and efficiency.

We know, in principle, how to do this. We have to build a molecule that will absorb light efficiently (step one of the grand photosynthetic plan). The absorbed energy pushes the molecule into an activated state, denoted with a star, in which all the light energy has been imparted to one electron, kicking it into a more energetic orbit. While the electron is running around frenetically, it's more loosely attached to its home atom, which gives us a window of opportunity to do step two of the grand plan—electron transfer. A properly designed molecule will encourage the excited electron to forsake its home atom and visit some other part of the molecule, creating a positive charge—a "hole"—on the jilted atom, and a negative charge wherever the electron winds up. This negative charge, this electron, can then be diverted to a catalytic center to make hydrogen, and the hole can find another catalyst to make oxygen—step three.

But time is working against us. If we don't separate the active state into positive and negative charges in a few picoseconds (trillionths of a second), the electron sheds its excess energy and returns to the ground state. And once we separate the charges, we have to hold them apart for at least a thousandth of a second—a millisecond—or possibly a second, long enough to interface with the catalysts. If the electron falls back into the hole, we just get a little heat and we're toast. So we have to make the recombination rate slower than the rate at which we can siphon off the electrons. How in the world are we going to do this?

Rudy Marcus, who's here at Caltech, won the Nobel Prize in 1992 for telling us how to start this process. [See *E&S*, Fall 1992.] About 40 years ago Rudy predicted what's now called the inverted effect: that you could build molecules where the recombination rate would go up for a while as you increased the energy of the reaction, and then come back down. Everybody knows that if you put more energy into something, it should go faster and faster, but very few people thought that at very high reaction energies the rates would start going back down again. But in the mid-'80s, a group at the University of Chicago and the Argonne National Laboratory was finally able to verify the inverted effect. After that, we figured out how to build inverted-effect molecules, and now we've got tons of them.

On the opposite page is an example that uses ruthenium and pyridine. (You'll notice that we've gone back to wimpy organic molecules. We figured, why not—let's throw a bone to the organic chemists. So I apologized to all the organic chemists and said we're gonna need your wimpy molecules back again. But this time we put them on some nice, firm metals.) The ruthenium-pyridine



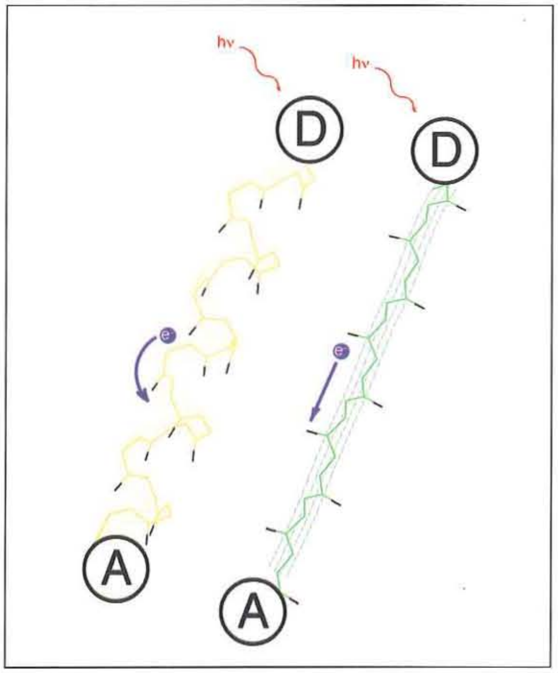
Above: This ruthenium (Ru^{+2})-pyridine (the hexagon) complex obeys the Marcus inverted effect. When it absorbs light, an electron immediately jumps from the ruthenium to the pyridine. And there the system pauses for a moment—the charge-separated state (negative in blue, positive in red) is slightly less energetic than the initial excited state, but the electron has too much energy to fall back into the hole very fast.

> So I apologized to all the organic chemists and said we're gonna need your wimpy molecules back again. But this time we put them on some nice, firm metals.

complex absorbs visible light, which helps with the light-capture part of the problem. The electron transfer from the excited state to the charge-separated state (with the electron on the pyridine, and the hole on the ruthenium atom) is very, very fast—about 50-60 femtoseconds (a femtosecond is a thousandth of a picosecond!). And the charge-separated state lingers for about a microsecond—a millionth of a second. So Rudy got us part way, but we need to buy another factor of a thousand to a million in time—to reach a millisecond or a second in separation time—to give the energized molecule enough time to make hydrogen and oxygen.

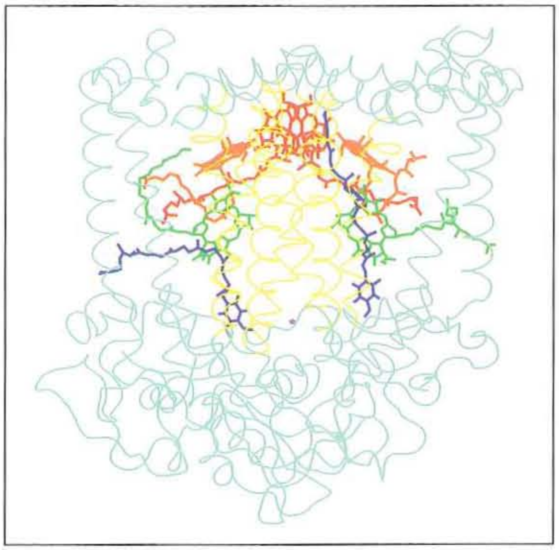
To figure out how to buy this extra time, Jay Winkler [PhD '84], who's a Member of the Beckman Institute, I, and several other researchers in the Beckman Institute Laser Resource Center here at Caltech have been studying electron tunneling over long distances. [See *E&S*, Fall 1991.] In general, these experiments involve putting an electron donor and an electron acceptor on opposite ends of various kinds of molecules—for example, a protein structure called an alpha helix (shown in yellow in the figure at right), or another protein structure called a beta strand (shown in green). Then we zap the electron donor with a laser beam, kicking an electron loose, and we measure how long it takes the electron to arrive at the acceptor. We've also varied the molecular geology, as it were, within a given structural class, and we've shown that electrons tunnel through some features faster than others. This means that electrons can't go through empty space—they have to tunnel through chemical bonds. And you can see for yourself that if electron tunneling goes through bonds, it's going to take forever to go through the twisty α helix, while the β strand is a straight shot. So, in relative terms, a β strand is a conductor, and an α helix is an insulator.

And, of course, God figured this out before we did. The structure of the natural photosynthetic reaction center is known, and guess what? There are α helices everywhere you look! Light hits a pair of chlorophyll molecules, creating an excited state that does electron transfer to a charge-separated state. Then the electron hops around from molecule to molecule and finally ends up on a quinone. And between the quinone and the first chlorophyll pair is a long stretch of α helix, so the



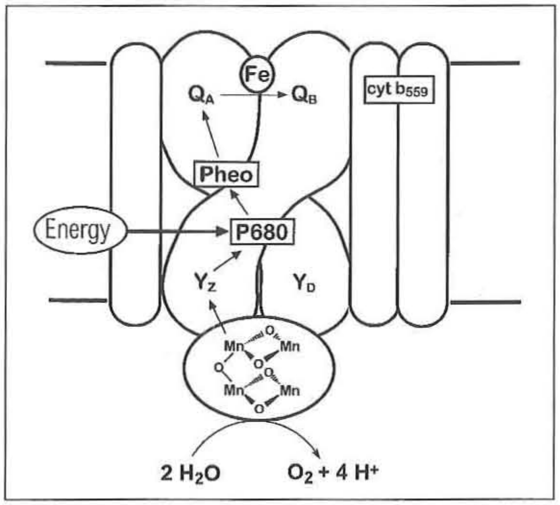
A molecular drag race. Each electron donor (D) is separated from its acceptor (A) by some 20 carbon-atom diameters as the photon flies. The electrons, however, have to tunnel along the chemical bonds shown in color. It takes an electron 1–10 seconds to travel the corkscrew α helix (yellow, at left), but a mere thousandth of a second to zigzag down the much straighter β strand (green, at right).

Right: Nature's photosynthetic center, as embodied in *Rhodobacter Sphaeroides* and elucidated by Ermler et al. Light hits the pair of chlorophyll molecules (red), sending electrons leapfrogging along the accessory chlorophylls (orange) and pheophytins (green) to the quinones (blue). The yellow curls between the quinones and the chlorophyll pair are α helices; the long tail from one quinone that appears to reach back up to the chlorophyll sticks out of the plane of the page and is not an electron-transfer route. The purple blob is an iron atom.



electron and the hole don't crash back together and make heat. The initial hops from the chlorophyll pair onward only go forward, never backward, because of the inverted effect. But by the time the electron arrives at the quinone, the inverted effect has played out, so you need an insulator—an α helix. It's beautiful.

The one remaining problem is the catalytic step—how do we split water after we've manipulated all these electrons and holes? Nature does it with the manganese system below, which no chemist has ever been able to make. And the manganese system evolves O_2 very efficiently, but we don't want to do that. Plants make O_2 and carbohydrates, but we want to make H_2 for fuel without liberating O_2. It turns out that O_2 causes the poop-out problem. Whenever we make O_2, we run the risk of also producing an energetic form of oxygen called singlet oxygen—a very reactive molecule that oxidizes everything, including the organic molecules that make up our photosynthetic system. That's why we all eventually die—oxygen is good for us, but it's also bad for us. In the long term, we all get oxidized—some of us faster than others.

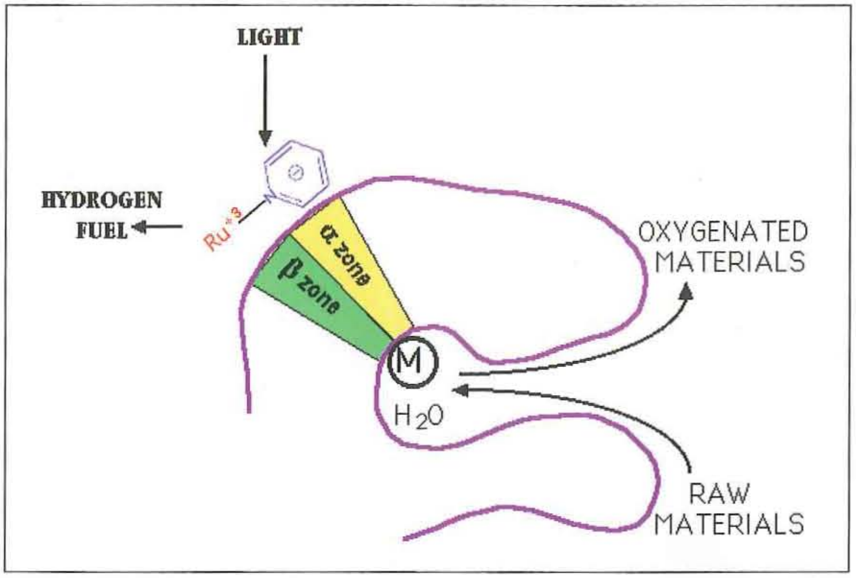


Above: The molecular scaffolding surrounding the oxygen-generating manganese system (the cluster of Mn's and O's at the bottom) is almost an inverted version of the photosynthetic center. Electrons follow the arrows from the P680 (a kind of chlorophyll) to the Pheo (a pheophytin) to the quinones Q_A and Q_B.

So we're now trying to figure out how to make catalysts that will take electrons and holes and make new materials as well as fuel. In a new and improved water-splitting scheme, oxygen won't be allowed to escape, but instead will be incorporated into molecules that can serve useful purposes. One possible system for doing this is shown at right. It's purely a conceptual drawing—nobody has made such a thing yet, but a lot of people are working in this area. In addition, we're going to have to learn how to get materials from carbon dioxide, water, and solar energy, because we're going to run out of hydrocarbons before long. People say we have enough coal for a few hundred years, but a few hundred years is nothing in the life of our planet.

I'm encouraged by our prospects, because we've made enormous progress in related fields—for example, the methanol fuel cell is here right now. I believe you'll see one in your car, and possibly in your house, in the next few years. It uses a ruthenium-platinum anode to oxidize methanol to carbon dioxide. This generates electrons that flow through a wire to run your car motor or your computer or whatever, and eventually return to the cathode and reduce oxygen to water. So you put methanol in and get electricity out.

In about 10 or 15 years your car will run on electricity. General Motors' EV-1, which uses a big lead-acid battery that goes only 50-60 miles on one charge, is already on the road. But the car of the future will have an advanced, lightweight battery, not a lead-acid battery; a methanol fuel cell; and, eventually, a solar-paneled roof, so that the battery can charge during the day while the car is sitting in the parking lot. The fuel cell will be for long-range driving—to San Francisco, say; if you're just driving around town, you'll run on sunlight. GM has a methanol-fuel-cell car on the drawing board now that will come out in 2004, and they aren't the only company that's getting into the game. Mercedes-Benz has plans to mass-produce 100,000 such cars a year by 2005, according to the *Los Angeles Times*, and Toyota, Chrysler, and Ford have all announced fuel-cell projects. These cars will not only be environmentally better, they'll be better in absolute terms. People are going to *want* these cars! Who wouldn't want something that looks like a Porsche, burns rubber, and gets (in the more advanced models that have solar roofs) over a thousand miles per gallon? So when they become available, people are going to



Above: The "T. rex" scheme for splitting water. (This just sounds more dignified than the "sock puppet" scheme!) The dinosaur's head is a shorthand representation of the sort of molecular scaffolding that surrounded the chlorophylls and quinones on the previous page.

Sunlight hits the ruthenium-pyridine complex as before, briefly separating an electron (blue) and a hole (red) under the Marcus inverted effect. Meanwhile, in T. rex's mouth, the metal atom (M) strips an electron from a water molecule while catalyzing the conversion of oxygen to oxygenated materials. The liberated electron tunnels up the green β strand to the surface and falls into the hole on the ruthenium, leaving the electron on the pyridine free to make hydrogen fuel. The electron doesn't tunnel backward because of the insulating α helix (yellow) between the pyridine and the metal.

Designed for suburban commutes and urban drives, the EV-1 is already on the road.

be knocking each other down to get them. There's going to be a big rush, and then people will say, gee, while we're at it, let's convert Los Angeles into a solar city.

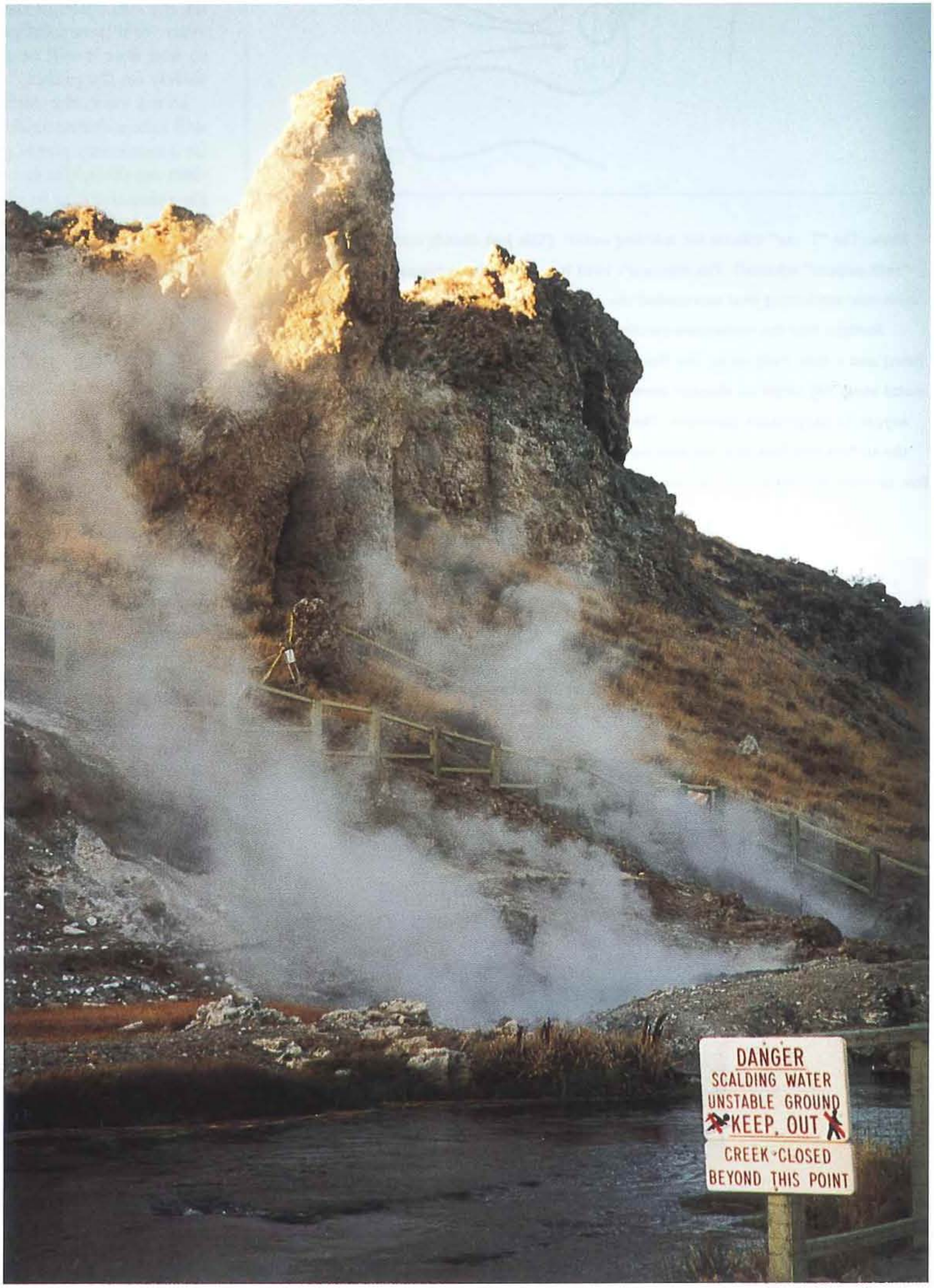
And I'm not just talking about places like L.A. and Tucson—everybody's got sunlight. Every year since the mid-'70s, physicists, chemists, and engineers have improved solar efficiencies as well as the durabilities of solar materials, and we're almost to the point where we can get good solar conversion, using layered semiconductors, even when we can't see the sun through the clouds. In the next 10 years we'll have solar power generation working so well that it will be a shame if we don't use it widely on the planet.

In my view, the overall change to solar fuel will take a dramatic demonstration of a vehicle (or a stationary power plant) that runs much better than anything else has ever run, because changing the infrastructure in this country is going to be very, very difficult. There's great resistance to change, and it's going to cost a lot of money. Right now, we could put silicon on the roof of your house. You'd sell electrons to the power plant during the day and buy them back at night, and at the end of the month you'd get a check instead of a bill. But if we put a solar roof on every house in Los Angeles, there'd be a huge capital cost, so there'd have to be tax credits to help out. All sorts of people would have to clamor for change, in order to get the appropriate tax legislation passed. On top of all this, Southern California Edison would have to agree to buy electrons from some of its customers.

I hope we will phase out fossil fuels in a rational way, but I'm afraid the change won't be orderly. We won't say, "Gee, we need these hydrocarbons for materials. We're burning the most valuable resources we have. This is really stupid." We should be using clean fuels wherever we can right now, and we should be learning how to convert the rest of our fossil-fuel-guzzling technologies before we're forced into a corner by some war or other disaster. It's going to cost a lot of money to make this conversion, but after we do it, we'll have a planet that runs on clean fuel—an ecologically sounder, infinitely more sustainable place to live. ☐

Harry B. Gray, Beckman Professor of Chemistry and director of Caltech's Beckman Institute, came to Caltech from Columbia University as a visiting professor in 1965, and returned for good in 1966. For his research in bioinorganic chemistry and inorganic photochemistry, he received the National Medal of Science from President Reagan in 1986 and the Priestley Medal from the American Chemical Society in 1991. His work on electron tunneling in proteins is supported by the National Science Foundation and the National Institutes of Health. This article was adapted from a SURF (Summer Undergraduate Research Fellowship) seminar.

To find the source of the arsenic in this water supply, we have to go back up to the Owens Valley. . . . The focus of our studies has been the geothermal inputs of arsenic at Hot Creek Gorge.



Chinatown Revisited: Arsenic and the Los Angeles Water Supply

by Janet G. Hering

Above: L. A. Aqueduct workers set a record for hard-rock drilling at the Elizabeth Tunnel, just north of the San Fernando Valley. Left: Steam rises off the bubbling hot springs of Hot Creek Gorge; geothermal activity loads relatively high concentrations of arsenic into the creek, which flows into the Owens River and eventually to Los Angeles.

In his 1974 film *Chinatown*, Roman Polanski created an enduring modern myth based loosely on the fascinating history of the Los Angeles Aqueduct. Although separating all the details of historical fact from fiction is beyond the scope of this presentation, it is worth examining some of this history, particularly from an engineering perspective. We will also see how this development of water resources set the stage for environmental problems that persist to the present day.

Even though massive hydraulic works characterize water supply throughout the western United States, it's still hard to realize just how dramatically the patterns of development in Los Angeles have been shaped by water resource management. Los Angeles originally obtained its water from three sources—rainfall, groundwater, and the Los Angeles River—all of which supported a population of about 100,000 people in 1900. This number had almost doubled by 1904, and there was widespread concern at the time that development would soon be limited by insufficient water. Indeed, at the dedication of the Los Angeles Aqueduct in November 1913, William Mulholland, chief engineer of the Los Angeles Department of Water and Power (DWP) and architect of the Big Ditch, declared of the city: "We have the fertile lands and the climate. Only water was needed to make this region a rich and productive empire, and now we have it."

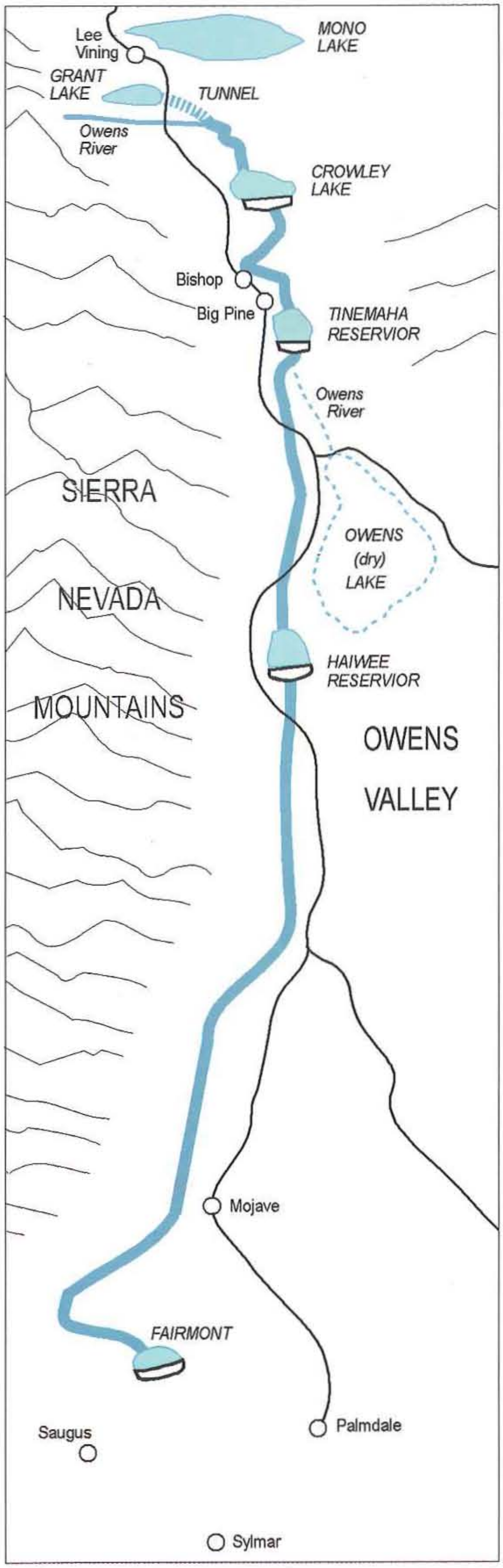
Certainly, the existing level of growth in Los Angeles would have been impossible without many water projects, of which the Los Angeles Aqueduct was only the first. A number of other aqueducts, including the California Aqueduct (from the Sacramento Delta down through the Central Valley) and the Colorado River Aqueduct, followed, making possible the population of 9 million that Los Angeles supports today, as well as extensive agriculture throughout Central and Southern California.

The development made possible by the L.A. Aqueduct, however, came at the price of the prosperity of Owens Valley, a thriving agricultural area at the turn of the century. The problem was exacerbated when, beginning in 1919, Owens Valley groundwater was pumped into the Los Angeles Aqueduct to supplement the drought-depleted surface waters of the Owens River. Within a decade the Owens Valley was transformed, in the words of Will Rogers, into a "valley of desolation."

Despite the political machinations surrounding the L.A. Aqueduct and its economic impacts on the Owens Valley, its engineering accomplishments still must provoke admiration. Although the entire aqueduct is gravity-fed, some impressive mountain ranges stand between the Owens Valley and Los Angeles. The drilling of the tunnels through these mountains was one of the most technically challenging aspects of the entire project. Recognizing this, Chief Mulholland ordered the tunneling begun before the rest of the aqueduct construction. The Elizabeth Tunnel through the Sierra Madre Mountains was drilled from both the north and south ends simultaneously to meet in the center, an engineering feat that would be considered challenging even today. A world's record for hard-rock drilling was set there—567 feet in a single 24-hour period with crews working around the clock. In the entire drilling period of 1,239 days, they drilled 26,860 feet.

Another remarkable engineering task was the construction of the giant siphons that were built as an alternative to tunnels in some areas. When this project was started, there was no motorized transport powerful enough to move the huge siphon pieces (8 to 12 feet in diameter), so they were transported by mule trains. The siphons were the most vulnerable links in the aqueduct; the Jawbone Siphon, one of the longest, failed the first time the aqueduct was opened, delaying the actual opening for repairs. The siphons were also

The Los Angeles Aqueduct carries water about 250 miles—from Lake Crowley to the Fairmont Reservoir in the San Fernando Valley. Over part of its length, giant siphons, such as the Jawbone Siphon below, pipe the water over mountains. The enormous siphon sections had to be lugged to their positions by mule train (above, right).

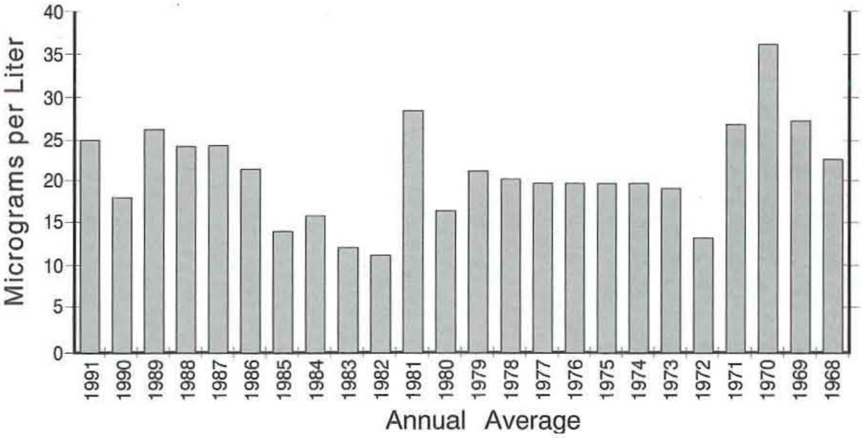


vulnerable to sabotage. After exhausting all other possibilities to forestall the export of Owens Valley water through the aqueduct, Valley residents resorted to dynamiting the siphons.

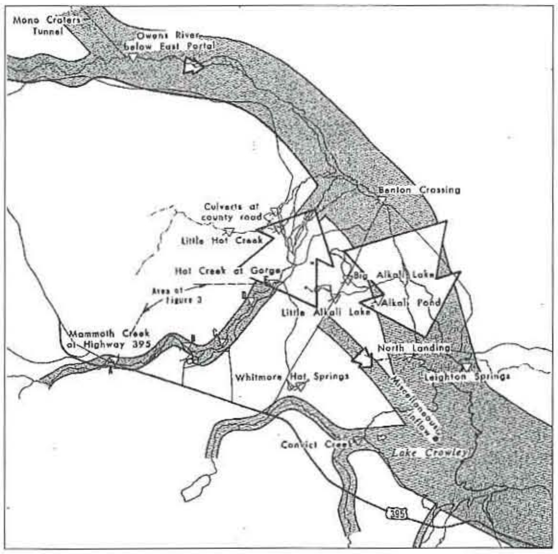
Nonetheless, the aqueduct, begun in 1907, was opened on schedule and within budget on November 5, 1913. About one in five Los Angeles inhabitants, who were obviously much happier about the project than the people of Owens Valley, joined the party for the San Fernando opening. In the view of the people of Los Angeles, the aqueduct would enable the city to achieve its true potential as a world-class city. They were right.

As we will see, it may be that present-day Owens Valley residents may recover through the courts at least some of what their ancestors could not, even with dynamite, retain. But for the meantime, the L.A. Aqueduct system provides a sizeable percentage of the city's water supply by transporting water from the Owens Valley. Snowmelt runoff from the Sierra Nevada drains into the Owens River, a tributary of Lake Crowley, the terminal reservoir in the aqueduct system. From Lake Crowley, the water is transported approximately 250 miles through the aqueduct to the Fairmont Reservoir in the San Fernando Valley and treated at the filtration plant in Sylmar.

In general, the quality of this water is excellent. The DWP has done a very good job in protecting the watershed and preventing any contamination of the water. But one of the water's natural constituents—arsenic—does pose a potential problem. The plot at the top of the next page shows data from 1968 to 1991 collected by the DWP at their Sylmar filtration plant. As the bars show, the concentration of arsenic over this roughly 25-year period averages approximately 20 micrograms (millionths of a gram) per liter. Since the current drinking-water standard, or maximum contaminant level (MCL), is 50 micrograms per liter, the DWP values are well below it. The U. S. Environmental Protection Agency is, however, reevaluat-



Above: Concentrations of arsenic at the DWP's Sylmar filtration plant from 1968 to 1991 lie well below the current drinking-water standard of 50 micrograms per liter. If that standard drops to 2–20 μg/l, however, there will be trouble meeting it.



The schematic view of the region north of Lake Crowley (above) shows that most of the water flowing into the aqueduct system, indicated by the width of the gray bands, comes from the Owens River. The flux of arsenic, however, shown by the size of the white arrows, comes predominantly from Hot Creek Gorge (above right), which is contributing relatively little water. (Diagram from Eccles, USGS Water Resources Investigations, 1976.)

ing the standard, and the range under consideration is between 20 and 2 micrograms per liter. It's clear that the DWP is going to have a problem meeting a standard in that range. In 1993, the World Health Organization recommended a value of 10 micrograms per liter, based both on health effects and other considerations. Epidemiological studies in Taiwan and in the West Bengal region of India have shown that chronic exposure to arsenic in drinking water causes health effects that range from skin diseases to cancer.

To find the source of the arsenic in this water supply, we have to go back up to the Owens Valley. Studies conducted by the U.S. Geological Survey in the 1970s quantified the fluxes of water and arsenic to Lake Crowley. In the illustration above, the width of the shaded lines shows that the water flux to Lake Crowley comes predominantly from the Owens River; very little flow, in comparison, comes from Hot Creek Gorge. The size of the arrows indicates the flux of arsenic, and here you can see the opposite: the arsenic comes mostly from Hot Creek Gorge, with very little of it coming down from the Owens River.

As its name indicates, Hot Creek is a geothermal area. It's in an active volcanic region, where a massive volcanic explosion occurred about 750,000 years ago, with lesser eruptions more recently. The area, which is at an altitude of 7,000 feet, is characterized by geothermally altered rocks and by the hot springs that provide most of the local place names. Arsenic occurs at extremely elevated concentrations in the geothermal waters and is derived from degassing of arsenic (a volatile element) from the magma. The focus of our studies has been the geothermal inputs of arsenic at Hot Creek Gorge.

The gorge itself is about half a mile long with very steep sides. Geothermal pools lie along both sides of the creek, and a large number of springs occur within the streambed itself. This gives the water a comfortable constant temperature in the low- to mid-70s (22-24 degrees C) year-round, making it a popular place for swimmers. Many of the pools along the bank, however, are close to boiling.

We studied the arsenic concentrations in these pools and in the creek as well as the oxidation state of the arsenic. In natural waters, arsenic commonly occurs in two oxidation states, the more oxidized +V state and the less oxidized (or more reduced) +III state. As(V), or arsenate, is the thermodynamically stable form in water exposed to the atmosphere; As(III), or arsenite, is stable under more reducing conditions.

The oxidation state in which arsenic occurs in water is important because it affects the toxicity of arsenic, its mobility in aquatic systems, and the efficiency with which it can be removed in treatment processes. As(III) has been shown to be more acutely toxic than As(V). This distinction may be less consequential for chronic exposure and carcinogenesis since As(III) and As(V) can be interconverted within the body. The mobility of arsenic in natural waters is often governed by the sorption of arsenic onto mineral surfaces—these interactions are generally stronger with As(V) than with As(III). Many treatment processes similarly rely on sorption and are thus more effective for As(V).

At Hot Creek, we found that, in the hot bubbling pools, As(III) was roughly 60 to 70 percent of the total arsenic concentration. At depth, the contribution of As(III) might be even higher, but we were unable to sample geothermal water that had not already been exposed to the atmosphere. In the gorge area of the creek, we found less of the arsenic as As(III)—only 40 to 50 percent, the remainder being As(V). Interpreting this information, however, is complicated by the variable total arsenic concentrations in the creek water, which result from the numerous and scattered sources of arsenic within the gorge.

This finding led us to the boundary of the hydrothermal area and to look downstream from it. We found that the concentration of total arsenic was quite constant, indicating that we were, in fact, downstream of the source of any significant arsenic inputs to the creek water. The percentage of As(III) dropped from about 30 percent at that boundary down to nearly 0 about a mile downstream. What's interesting here is the contrast between total arsenic, which is conserved, and As(III), which is being lost; the total arsenic concentration is not changing, but As(III) is being oxidized to As(V).

We could estimate the rate of oxidation based on the time of travel for this one-mile stretch of the river by assuming that the water is simply traveling in a plug-flow manner and by measuring its velocity, which is about 0.4 meters per second. This gives a half-life for this oxidation process of about a third of an hour, which is very fast. As(III) is thermodynamically unstable with respect to As(V) in the presence of oxygen, but that reaction is very slow, with a half-life on the order of 100 days. So we cannot account for this fast reaction simply by the reaction of As(III) with oxygen. What, then, is the oxidizing agent?

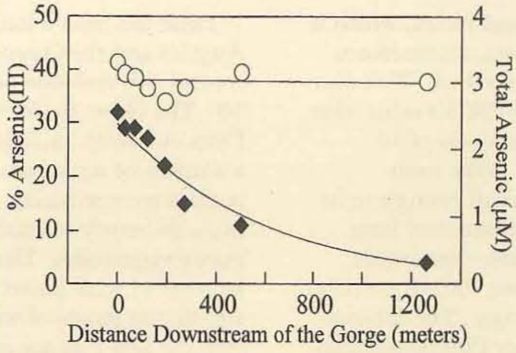
In trying to discover this agent we looked at a number of possibilities, including indirect photochemical reactions and reactions with constituents from sediments (manganese oxide, for example). But both of these were too slow to provide the explanation. The last possibility that we looked at was a biologically mediated reaction. Right around the boundary of Hot Creek's hydrothermal area, particularly just downstream of the hydrothermal inputs, we observed very lush vegetation of various species of aquatic plants (or macrophytes). One of these has slender stems and grass-like leaves and another a thick foliage of small leaves that form dense mats on the water. Since the water temperature in this stream remains constant throughout the year, this plant life is also present year-round. These macrophytes haven't yet been positively identified, but the predominant species resemble plants growing in the geothermally influenced Waikato River system in New Zealand.

Various species of aquatic plants, such as the grass-like one at right, grow just downstream of the hydrothermal area, where they provide a home for a multitude of bacteria (below), which appear to oxidize arsenic.

A scanning electron micrograph of the Hot Creek Gorge plant material shows the striations of the plant leaf itself, covered by an abundant microbial community.

We then designed an experiment to compare our field observations of rapid As(III) oxidation with a number of different controlled cases. In the first case, we took a sample of the macrophytes along with anything that happened to be attached to their surface, and simply enclosed the sample in a container of some of the surrounding water. In the second case, we shook off anything attached to the plants' surface and, removing the plants, left only the surface material, which has a large component of bacteria, in the container of stream water. We also had two abiotic controls. In the first of these, we took the sample with the surface material from the macrophytes and put it through a sterile filtration system—a 0.2 micrometer filter that removes most bacteria fairly effectively. And in the second case, we added antibiotics to the subsample containing surface material from the plants to eliminate any bacterial activity. To make a long story short, in the first two cases, with the plants plus surface material and the surface bacteria alone, we saw rapid arsenic oxidation. When we eliminated the biological activity, either by the sterile filtration or the antibiotic treatment, the arsenic oxidation did not occur.

Some of our data appear opposite. The top graph shows the loss of As(III) with distance from the geothermal inputs; total arsenic is conservative. The lower three graphs show the results of the incubation studies. In the upper panel, As(III) is seen to be rapidly oxidized in the presence of surface material from the macrophytes. This same data (marked "unfiltered") is shown in logarithmic form in the middle panel. In contrast, the abiotic, sterile-filtered sample shows no As(III) oxidation—the As(III) concentration remains constant over the course of the incubation. The antibiotic treatment in the bottom plot looks a little more complicated, because antibiotic activity is not instantaneous. Antibiotics are not a poison. They don't kill the organism immediately, but rather they interfere with its metabolic processes, and it



The plot at right shows As(III) as a percentage of the total concentration of arsenic, measured downstream of Hot Creek Gorge. Total arsenic remains constant, but As(III) decreases dramatically.

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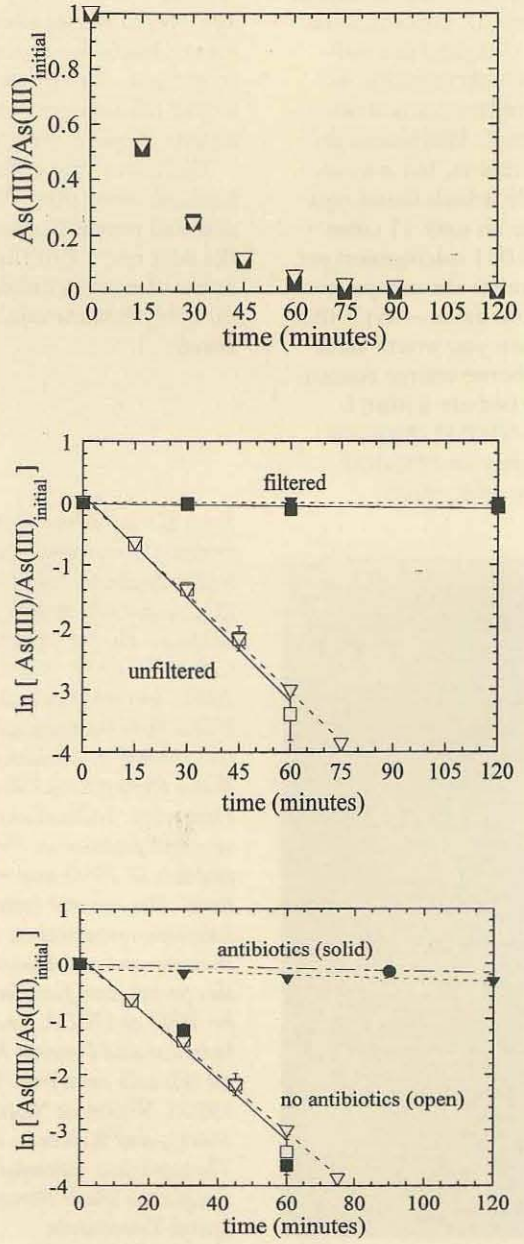
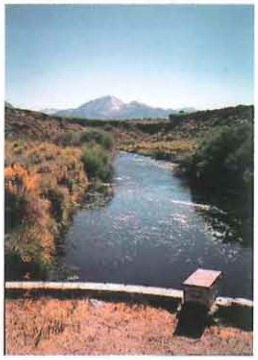


All of the lower three plots show the ratio of As(III) concentrations to their initial value over time. The top one represents two experiments done with water containing the surface material from the macrophytes (the squares are ambient As(III) and the triangles represent an additional spike of As(III)). The concentration under both conditions drops to zero in just under an hour. In the next plot, this data is shown in logarithmic form. First-order loss of As(III) is observed in the unfiltered system, but when the water is run through a sterile filter to remove the bacteria, the As(III) concentration does not decline. The bottom plot shows what happens to As(III) in the presence of antibiotics added at the beginning of the experiment (solid squares), after three hours (solid triangles), and after 72 hours (solid circles).

takes a certain incubation time for that to happen. These observations indicate that the As(III) oxidation that we observed is due to the activity of microorganisms. When we compare all of our batch studies with the rates we measured in Hot Creek, we get a very good correspondence, indicating that the microbial oxidation of As(III) can indeed account for the oxidation that we see in the creek.

This is important, because the treatability of arsenic depends on its oxidation state. One of the possibilities that the DWP is considering, if they do need to meet a more stringent drinking-water standard for arsenic, is to site a treatment facility near the source of the arsenic, rather than waiting till the water arrives at the Sylmar filtration plant where they would have to deal with a much larger volume. The gauging station that already exists on Hot Creek is one of the possible sites that the DWP might consider for a treatment facility. Our studies show that such a facility could rely on the indigenous microorganisms in the stream to do the work of oxidizing As(III) to As(V). Then As(V) could be efficiently removed from the water by any one of a number of treatment technologies, such as sorption onto alumina or iron-coated sand.

Arsenic and the L.A. Aqueduct have also had environmental consequences for the Owens Valley. These are not part of my current research, but since they are the focus of intense current interest and some litigation, I'd like to mention them here. One of these problems is the airborne arsenic blowing off the Owens lake bed. Before the aqueduct was constructed, Owens Lake, at approximately 73,000 acres, was the third largest lake in California. It was a terminal alkaline lake, with very high salinity and most probably very high arsenic concentrations as well—similar to those in Mono Lake. With the construction of the aqueduct diverting water from the lower Owens River, Owens Lake just dried up. Thousands of acres of land that had formerly been covered with water



Above: The gauging station on Hot Creek might be a convenient site for a treatment facility for removing the arsenic close to its source, employing the local microorganisms for oxidation. Below: A large crowd celebrates the release of Owens River water at the Owensmouth Cascades near Sylmar, on November 5, 1913. Los Angeles has thrived on this water in the intervening decades, but old and new problems persist.

are now dry. And when the wind blows, which it does quite frequently in that area, an enormous amount of dust swirls off the lake bed. This dust poses two problems: one is the PM-10 value, that is, particulate matter with a diameter of 10 microns. This size of particles is the most troublesome, because they're small enough to be transported relatively long distances and large enough to cause health problems. You inhale them but you don't exhale them; PM-10 particles settle or are captured in the lungs. The national ambient air-quality standard for PM-10 particles is 150 micrograms per cubic meter in 24 hours. When the wind is blowing hard on Owens Lake, the PM-10 value has been measured at 3,000 micrograms per cubic meter, 20 times the national standard.

The other problem with the dust is its arsenic content. There is no national air-quality standard for arsenic concentration, but there's still reason to be concerned about it. The arsenic concentration in the dust is approximately 100 parts per million, so the particulate arsenic concentration in the air during one of these windstorms is about 0.3 micrograms per cubic meter. Unfortunately, there's not much to compare this to, but we can look at a 1994 Canadian study, which found that the mean concentration in the air over 11 cities and one rural area was only 0.001 micrograms per cubic meter. We could also make the comparison with occupational exposure standards—levels that are generally much higher than you would want in ambient air. The peak airborne arsenic concentrations near the Owens lake bed are within a factor of 10 of the suggested NIOSH (National Institute for Occupational Safety and Health) standard of 2 micrograms per cubic meter.

There has been a long-raging battle between Los Angeles and the Owens Valley over the need to control this airborne pollution, specifically PM-10. The Great Basin Air Quality Management District, which includes Owens Valley, has issued a number of recent administrative rulings that require reconstituting part of the lake by irrigating sufficiently to establish a salt-marsh kind of grassy vegetation. The rest of the lake bed would be covered with gravel. Even this would involve a significant return of water to the Owens Valley, a step the DWP is not eager to take.

The second issue is the loss of the riparian ecosystem on the lower Owens River, which, like Owens Lake, dried up when the water was diverted to Los Angeles. After a long court battle over the environmental impact of groundwater pumping in the valley, the DWP and various representatives of the Owens Valley signed a "memorandum of understanding" a few months ago, which would allow for the rehydration of the lower Owens River and re-establishment of its ecosystem. The measures agreed upon, however, would not solve the problem of the particulate arsenic blowing off the dry lake bed.

The historical conflicts involving water quantity have persisted from the turn of the last century and will probably continue through the turn of the next one. But the issues of water *quality*, in terms of ecosystem health and human health, will probably become equally important in the years ahead. ☐

Janet Hering joined the Caltech faculty as associate professor of environmental engineering science in 1996, and no time was lost in recruiting her for a Seminar Day session last spring, from which this article is adapted. Hering received her AB in chemistry from Cornell in 1979, AM in chemistry from Harvard in 1981, and PhD in oceanography from MIT and the Woods Hole Oceanographic Institution in 1988. She then worked as a research fellow for the Institute for Water Resources and Water Pollution Control in Dübendorf, Switzerland, before coming to UCLA as an assistant professor in 1991. She was named associate professor in 1995 and remains an adjunct professor there. Her research centers on the chemistry of trace inorganic contaminants in natural waters and soils and in water and wastewater treatment. Also involved in this project were Jennifer Wilkie, who recently finished her PhD at UCLA, and Caltech grad students Tina Salmassi and Penelope Kneebone. Historical information for this talk came from The Great Thirst *(Hundley, 1992),* Vision or Villainy *(Abraham and Hoffman, 1981), and* Rivers in the Desert *(Davis, 1993). The work was supported by funds from the University of California Water Resources Center and the National Science Foundation.*

EUGENE M. SHOEMAKER
1928–1997

Carolyn and Gene Shoemaker in front of the Alumni House during Commencement weekend in June 1997.

Eugene M. Shoemaker, one of the world's foremost planetary scientists, was killed in an automobile accident in Australia on Thursday, July 17. His wife, Carolyn, was also injured in the accident.

Shoemaker first came to Caltech as an undergraduate, and earned his bachelor's degree in 1947 and his master's in 1948. He received a second master's degree and his doctorate from Princeton University, and returned to Caltech in 1962 as a visiting professor. He served as a research associate in astrogeology here from 1964 to 1968, as professor of geology 1969–1980, and professor of geology and planetary science 1980–85. Shoemaker served as chairman of the Division of Geological and Planetary Sciences from 1969 to 1972.

He also worked for many years with the U.S. Geological Survey, and was affiliated with the Lowell Observatory at the time of his death. He was a principal investigator for geological field investigations for the Apollo lunar programs from 1965 to 1970, and was also involved in the Ranger and Surveyor missions.

After leaving Caltech for Flagstaff, Arizona, in 1985, Shoemaker focused his studies on impact craters, asteroids, and comets. His observing team, which included his wife, Carolyn, discovered several thousand asteroids and 33 comets, including Comet Schoemaker-Levy 9, which crashed into Jupiter in 1994.

Shoemaker's many other scientific accomplishments included setting up the Interplanetary Geological Time Scale, based on crater densities on planetary surfaces. This allows age estimates to be made for terrains from other planets based on space photographs.

His other research included exploration for uranium deposits and salt structures in Colorado and Utah, research on the geology and geochemistry of the Colorado plateau country, studies of the structure and mechanics of meteor craters, the search for planet-crossing asteroids, and studies of the magnetostratigraphy of sedimentary rocks.

He codiscovered the mineral stishovite, which is a high-pressure form of quartz produced only during large impact events. This discovery established the extraterrestrial origin of many cryptoexplosion structures.

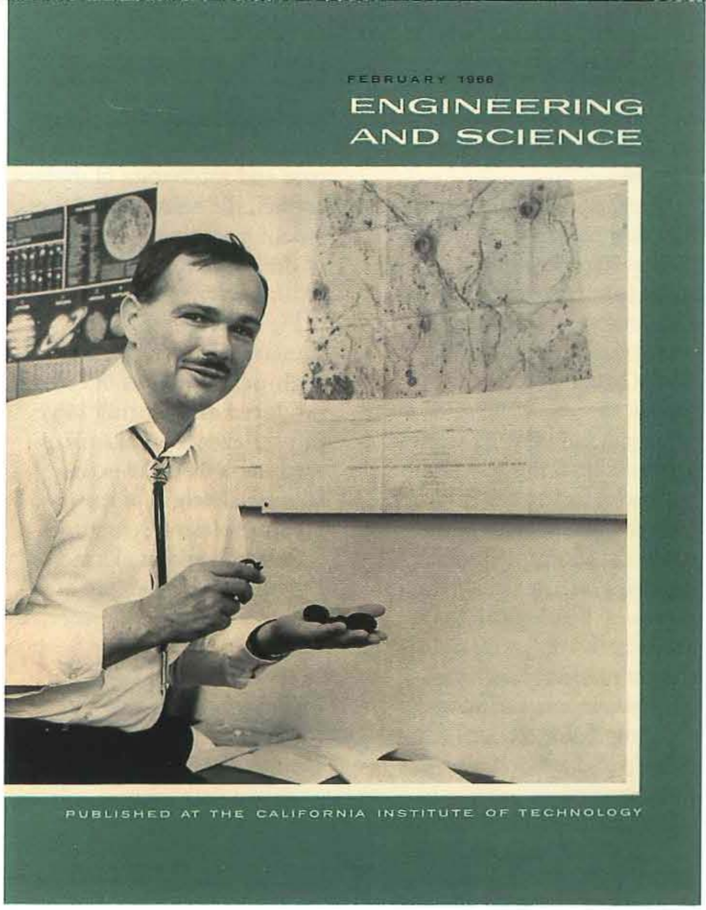
Shoemaker was elected to the National Academy of Sciences in 1980; he received the National Medal of Science in 1992, and the Bowie Medal (the highest award of the American Geophysical Union) in 1996.

A Celebration of Life for Eugene Shoemaker was held in Flagstaff October 11. Harrison "Jack" Schmitt (BS '57, Apollo 17 astronaut, and former senator from New Mexico) delivered the main address, from which the following is adapted.

When I received the phone call about this celebration of life for Gene, I was reading *Undaunted Courage*, Stephen Ambrose's remarkable narrative about Meriwether Lewis, Thomas Jefferson, and the opening of the American West. I could not absorb Ambrose's words without relating those events, people, and consequences to our own experiences in the 1960s.

As I reached the end of the book, I was reminded particularly of Gene's most unique quality during those heady days. I could not help but compare Gene as leader, as well as a scientific explorer, to Captain Lewis and an earlier Corps of Discovery. Paraphrasing just a little, as Ambrose said of Lewis: "How he led is no mystery. His techniques were time-honored. He knew his [people]. He saw to it that they had [regular inspiration, neces-sary resources, sufficient tools]. He pushed them to but never beyond the breaking point. He got out of them more than they knew they had to give. His concern for them was that of a father for his son. He was head of a family."

Many of us saw our lives moved forward professionally because of Gene's knack for inspiring people to go far beyond what any of us believed we could do. We knew then as we know now that we worked with one of the truly great scientists and visionaries of this latest age of exploration. Like Lewis, "[h]is intense curiosity about everything new he saw around him was infectious.



On the February 1966 cover of *E&S*, Gene Shoemaker holds a handful of tektites, which he thought were remnants of lunar material ejected from the Moon's surface during impact from a high-speed object. Such objects (meteorites, asteroids, comets) Shoemaker believed, also created the craters visible on the Moon, Mars and Earth, a theory now universally accepted.

Certainly he would be anyone's first choice for a companion on an extended camping trip."

Before I arrived on the Shoemakers' doorstep in Flagstaff in 1964, Gene and I wrote two letters that had literally crossed in the mail. He was contacting people on the Geological Survey's list of those who had passed its 1963 employment exam, and I was looking for a job.

Interesting and adventurous jobs in geology seemed nonexistent to this new PhD in 1964—none in academia, and the ongoing slump in metal prices didn't help in other areas where "hard-rock" and field experience might be applied. Fortunately, I remembered that in 1960, after helping line up a trip to look for West Coast eclogites, Bob Coleman had taken me down a dark hallway in the Survey's Menlo Park facility and introduced "Gene Shoemaker, who is doing weird things like mapping the Moon. Danny Milton is even working for him," he added. Well, I had no idea who Gene Shoemaker might be, but Danny and I had overlapped at both Caltech and Harvard. If Danny thought what Gene was doing was interesting, it almost certainly was!

Not having any idea what I was getting into, I headed out of Cambridge in my '55 Chevy Business Coupe for Route 66, Flagstaff, and the old Astrogeology Branch Headquarters. I became a little suspicious only when Danny and others in Menlo decided not to relocate in Flag. What did they know that I didn't know? Exciting things, however, were about to happen.

After arrival at the old museum offices in the pines at the north edge of town, and JoD Swann's enthusiastic welcome, Gene provided me with a tough choice between joining Don Elston, Ray Batson, and others on the ongoing Surveyor television project, or heading up work on a new NASA contract to develop lunar field geological methods. Surveyor was very real and had exciting science potential. Lunar field work was in the misty, undefined future, but there was really no choice: as important as Surveyor was and would turn out to be, in Apollo lay the emotion, the excitement, and, we believed, the science of the future. A few days later, Gordon Swann and others arrived and, with Gene's daily inspiration, an eclectic group went to work.

We began learning our new lessons by trial and error, mostly error—lessons that ultimately were to become part of the foundations of Gene's Apollo field geology experiment, underpinning almost everything Apollo accomplished scientifically on the Moon. With Arizona freshmen, Spence Titley, long hours, and Jim Beam, we set about answering questions never asked before.

How do you communicate detailed geologic notes by radio across the 240,000 miles of space, when Swann keeps stepping on your lines? How should the lunar surface debris, later to be defined by Gene as the now famous lunar regolith, be sampled, when the old International Travel-Alls can't get us to Tom McGetchin's Mexican Hat kimberlite location? How do you photographically document a sample location and orientation without using more than an absolute minimum of extraordinarily valuable time, when Schmitt can't keep the Polaroid film out of the Hopi Buttes' dust? What

Gene, "more than any other individual, was responsible for the incorporation of geology into the American space program." We might add that, more than any other individual, he was responsible for our present consideration of the Moon and Mars as places for future settlements of our children and grandchildren.

training vocabulary do you use when your field men are not geologists but rather are headstrong test pilots? Ultimately, all our questions had answers, but none was obvious when Gene started geology down this path of lunar exploration and stardom.

Also during this period, November 1964 to be more exact, NASA and the National Academy of Sciences jointly asked for applicants for the first selection of scientist-astronauts. The geological horizon Gene had seen so clearly for so long had suddenly brightened for others. Even though, as graduate students in 1963, some of us had joked about the possibility of going to the Moon, when an Academy report stated that "the first person on the Moon should be a hard-rock geologist," no significant thought or relevant action had followed.

After one and only one conversation with Gene on a fall afternoon in 1964, and after a few more seconds of consideration, I decided to volunteer to be an astronaut. Gene clearly knew what he would have done, having decided this point many years before anyone else. I was concerned about my commitment to Gene and the Survey. The question I asked myself, however, was, "If someone actually does land on the Moon, and if I passed up a chance to try to be that person, would I regret it?" The answer being obvious, the rest is history—helped along, I strongly suspect, by Gene's position as chair of the Academy's scientist-astronaut selection committee.

Some time coincident with this astronaut selection process, Al Chidester assigned me, along with Newell Trask, to do the final work for publication of Gene's Copernicus lunar quadrangle map. No single study affected the course of lunar science more than Gene's early telescopic and photographic examination of the crater Copernicus. Building on his skillful field and theoretical work on Meteor Crater, and his pioneering definition of a stratigraphic system for the Moon, Gene created the scientific base for mapping the Moon and now, by extension, mapping humankind's third home, Mars. As Don Wilhelms has written, Gene, "more than any other individual, was responsible for the incorporation of geology into the American space program." We might add that, more than any other individual, he was responsible for our present consideration of the Moon and Mars as places for future settlements of our children and grandchildren.

Gene's influence within the space agency in the 1960s was far greater than even he imagined. He become a looming spirit behind the most critical managers of the Apollo program—George Low, Bob Gilruth, Gene Krantz, and Sam Phillips. They knew that Apollo could do more than meet John Kennedy's challenge "to put men on the Moon and return them safely to Earth." Gene's continuing enthusiastic presence and his pressure for NASA to take advantage of this extended capability, led to the inclusion of the Field Geology Team as part of the Apollo Mission Team, from equipment selection to crew training to mission control activities. It wasn't everything we wanted or could have done, but it was there, and it was of critical importance.

Thinking back on this pervasive and unprecedented experiment in lunar field geology, and on Gene's pivotal influence on the plans for lunar sample analysis, brings Meriwether Lewis and Thomas Jefferson to mind again. Gene provided the intellectual foundation for this history of science to record that for the first time we had gained a first-order understanding of another planet.

In 1992, Gene joined a University of Wisconsin team as chief scientist on a proposal to operate two scientific rovers simultaneously and cooperatively on the surface of the Moon. Our objectives were to unravel the three-dimensional nature of the regolith and to define the basis for bringing its energy resources back to Earth. Who would have thought when we first gathered in Flagstaff in the '60s that Gene's legacy would include the potential for providing for the long-term energy and environmental needs of humankind? Gene would have. Yes, indeed! With the usual unbounded enthusiasm, he joined in our preparations, saying to the group during a luncheon pep talk, "I've waited 30 years to do this!"

With a vigor, joy, and wisdom beyond that ever expected of anyone, Gene celebrated his own life and the lives of those around him. ☐

Harrison H. Schmitt

Honors and Awards

For her work at the interface of chemistry and biology, Jacqueline Barton, the Arthur and Marian Hanisch Memorial Professor and professor of chemistry, has been awarded the 1997 Nichols Medal by the New York Section of the American Chemical Society. She is the first woman to receive the award in its 95-year history.

Erick Carreira, associate professor of chemistry, has received the National Fresenius Award from the Virginia Polytechnic Institute.

Samuel Epstein, the William E. Leonhard Professor of Geology, Emeritus, has been elected a Foreign Fellow of the Royal Society of Canada by the members of the Society's Academy of Science.

Peter Dervan, the Bren Professor of Chemistry and chair of the Division of Chemistry and Chemical Engineering, has been elected to the Institute of Medicine of the National Academy of Sciences. Membership is based on professional achievement and on involvement with issues that affect public health.

Morteza Gharib, PhD '83, professor of aeronautics, and Paul Sternberg, professor of biology and investigator, Howard Hughes Medical Institute, have each received $100,000 one-year grants from the Seaver Institute. Gharib's grant will support his "Implantable Heart Pump" project; Sternberg's grant is for a one-year extension of his research project in molecular genetics, "Genetics of Genes in Cancer Cells." Established in 1955 by Frank R. Seaver, the Seaver Institute focuses its giving program on four essential areas: scientific and medical research, education, public affairs, and the cultural arts.

Kevin Gilmartin, associate professor of literature, has received the 1996–97 Arnold L. and Lois P. Graves Award in the Humanities from the American Council of Learned Societies.

Emlyn Hughes, associate professor of physics, has received a Sloan Fellowship from the Alfred P. Sloan Foundation of New York City. The fellowships, awarded for studies in science, technology, economics, and public policy, include $35,000 in unrestricted research funds.

John Ledyard, professor of economics and social sciences and chair of the Division of the Humanities and Social Sciences, and David Porter, visiting associate in economics, have been selected by Koc University of Istanbul as joint winners for 1996 of the Koc University Annual Prize for Best Paper in Economic Design. Entitled "The Allocation of a Shared Resource Within an Organization," the paper was written with Charles Noussair.

David Middlebrook, professor of electrical engineering, has been selected to receive the 1997 Richard P. Feynman Prize for Excellence in Teaching. The prize, made possible by an endowment from Caltech Associates Ione and Robert Paradise, is awarded annually for "unusual ability, creativity, and innovation in undergraduate and graduate classroom and laboratory teaching." The Feynman Prize selection commitee cited Middlebrook's 40-year history of teaching not just a body of knowledge, but a way of thinking—"how to simplify complex subjects, and how to marry theory and experiment."

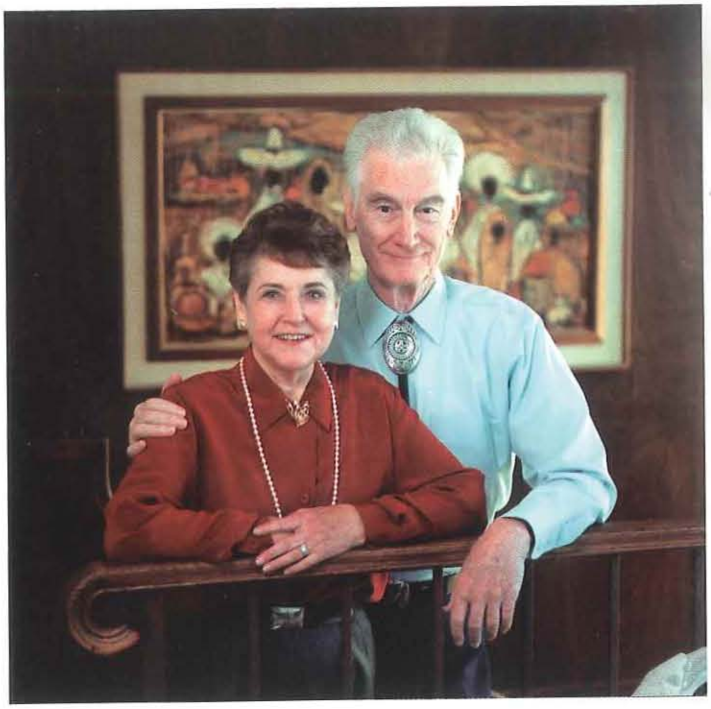
Edward Stone, Caltech vice president, director of JPL, and the David Morrisroe Professor of Physics, has been inducted into the Aviation Week and Space Technology Hall of Fame.

Four Caltech faculty were recently elected fellows of the American Academy of Arts and Sciences: Pamela Bjorkman, associate professor of biology and associate investigator, Howard Hughes Medical Institute; Andrew Ingersoll, professor of planetary science; Jerrold Marsden, professor of control and dynamical systems; and Douglas Rees, professor of chemistry. The Academy is an honorary society that recognizes achievement in the natural sciences, social sciences, arts, and humanities, and conducts a varied program of projects and studies responsive to the needs and problems of society.

Recipients of the 21st annual ASCIT teaching awards from the Associated Students of Caltech were Glen George, BS '81 and '82, lecturer in computer science and electrical engineering; Kevin Gilmartin, associate professor of literature; Emlyn Hughes, associate professor of physics; Charles Steidel, PhD '90, associate professor of astronomy; and Richard Wilson, professor of mathematics. In addition, ASCIT recognized two outstanding graduate teaching assistants: Sean Mauch, applied math, and Brian McKeever, mathematics.

The Graduate Student Council (GSC) bestowed its 1997 teaching awards on James Beck, PhD '78, professor of applied math and civil engineering, and Kenneth Farley, associate professor of geochemistry. Kerry Vahala, BS '80, PhD '85, professor of applied physics, and Simon Wilkie, assistant professor of economics, received GSC's mentor awards, which recognize "those professors who display a commitment to the personal side of their students' education and who offer steadfast guidance at the beginning of the student's career." Awards for outstanding graduate student teaching assistant went to Amit Manwani, Sam Roweis, and Erik Winfree, all of computation and neural systems; and Dave Polidori and Mike Vanik, both of applied mechanics. □

A CAPITAL IDEA


Duane and Betty McRuer

When Duane McRuer retired as president and technical director of Systems Technology, Inc. (STI), the internationally recognized research company that he cofounded 40 years ago, he had acquired a significant amount of stock as a result of leaving his company's Employee Stock Option Plan. McRuer had several choices to deal with the stock: he could hold onto it and collect the dividends, sell it and face a whopping tax bill, or use it to help Caltech, his alma mater. He chose the latter.

McRuer, who received both his bachelor's degree in mechanical engineering in 1945 and his master's degree in electrical engineering in 1948 from Caltech, has been a longtime supporter of the Institute. He has also set a goal to leave a substantial part of his estate to the Institute. Retiring from his company gave him the chance to help Caltech by using the stock to establish a charitable remainder unitrust with the Institute last December. It provides him and his wife, Betty, who worked at STI for 35 years as treasurer and contract administrator, with income for the rest of their lives and helped him avoid capital gains taxes. When they die, the remaining funds in the trust go to Caltech.

"We have a long-term commitment to Caltech that's grown through the years," says McRuer, who was elected to the board of directors of the Caltech Associates last year. "We could have established a charitable remainder trust to support other institutions, but Caltech is our main interest and will continue to be. This was an attractive way to help Caltech."

McRuer, who received Caltech's highest honor, the Distinguished Alumni Award, in 1983, helped build STI into one of the world's leading research firms, which focuses on guidance and control problems for a wide range of vehicles, from cars to rotor crafts to hypersonic aircraft. Since he and his cofounder, Irving Ashkenas (also a Caltech graduate—BS '37, MS '38, '39) believed that people in their company were its primary assets, they set up an Employees Stock Ownership Plan (ESOP) that allowed the employees to buy the company. After selling his STI stock back to the ESOP, he bought a broad spectrum of securities. In considering the long term, the McRuers found that if they sold the securities they would pay a 40 percent capital gains tax, while if they passed the stock on to their two children, estate taxes would take all but 15 percent of its value.

"Both of our children are successful and will be taken care of," says McRuer. "If you put these things in a charitable remainder trust, you pay no capital gains taxes." Plus, McRuer says that establishing the trust provided them with a tax deduction for a charitable donation to Caltech and has at least doubled the income that they were getting from the stocks' dividends.

"But the key factor in all this was helping Caltech," says McRuer, who plans to designate that the trust eventually support student aid or endow a professorship. "Almost everything I learned at Caltech helped my career. It gave me the broad knowledge in science that enabled me to expand from one thing to another. The charitable remainder trust was a convenient estate-planning tool and a neat way of helping Caltech, which I believe is the finest educational institution in the world."

Contact us for more information, or ask for our brochure.

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