A MARTIAN CHRONICLE

Although the "fossils" in the Mars meteorite probably have a mineral origin, rock hounds now think they know where to look for life on the red planet

BY ANDREW H. KNOLL

Scanning electron micrograph of purported microfossils of bacteria in Martian meteorite ALH84001, magnified 70,000 diameters

ON A CLEAR night, confronted with the vast starry blackness of the sky, it is hard not to wonder about the possibility of life beyond our planet. But despite that primeval human curiosity, facts have been elusive. The planets and moons of our solar system have proved devilishly hard to fathom. The investigations that have been launched—the Pathfinder mission to Mars last year is the most prominent recent example—have yielded images and data, but no evidence of life.

Small wonder, then, that scientists and the public alike were exhilarated by the stunning announcement of August 7, 1996: members of a research team led by the geochemist David S. McKay of the NASA Johnson Space Center in Houston, Texas, had discovered what they called convincing evidence for an ancient, microscopic form of life in a small piece of igneous rock that had fallen to earth from Mars.

The rock had been part of the Martian crust, which formed by cooling 4.5 billion years ago. About 16 million years ago, the impact of a meteorite uprooted the rock from the Martian surface and launched it into space [see "Blast Off," by H. Jay Melosh, page 40]. The rock wended its way through space until it fell into the gravitational influence of the earth: from that moment it was only a matter of time before it spiraled ever closer to our planet and finally fell to the surface—as it happened, onto the Allan Hills region of Antarctica, directly south of New Zealand, some 13,000 years ago. There it remained until an international team of geologists that searches each year for Antarctic meteorites picked it up on December 27, 1984. The rock languished for a decade, however, before investigators ascertained that it was from Mars, and more time passed while the analyses suggesting life were done.

It has been nearly two years since ALH84001, as it is known to planetary scientists, burst into the public consciousness. President Clinton announced the story from the White House—that the meteorite might hold clues to life on Mars—and that event triggered a degree of interest in planetary exploration not seen since the glory days of NASA a quarter century ago. The interest, in my view, is entirely justified, and yet the four-pound-three-ounce potato-shaped rock that started all the excitement is probably not the "smoking gun" its proponents originally maintained it was.

The reported evidence for life within the rock is based primarily on cracks that developed early in its history, probably between 3.6 and four billion years ago. The cracks contain small patches, or blebs, of carbonate minerals deposited when warm water trickled through. The blebs are associated with chemical, mineralogical and microstructural features that on earth are often the products of biological activity. But continuing analyses, performed with an unprecedented degree of sophistication and precision, have failed to confirm (or definitively reject) the biological hypothesis. According to the most recent studies, particularly the ones conducted by a team led by the geochemist John P. Bradley of MVA Inc. in Norcross, Georgia, the Mars rock does not constitute compelling evidence of extraterrestrial life.

Those negative findings do not mean that the idea of life on Mars is a fantasy. On the contrary: reasonable inferences about the environment of Mars—liquid water likely once existed there, for instance, and water may persist below the surface as permafrost—combined with striking new discoveries of terrestrial organisms that thrive in habitats once thought inhospitable to life, lend credence to the idea that our celestial neighbor might now or in the past have supported a biosphere. Where, then, should the organizers of the next mission to Mars direct the spacecraft? And once there, how best to sample the planet for life?

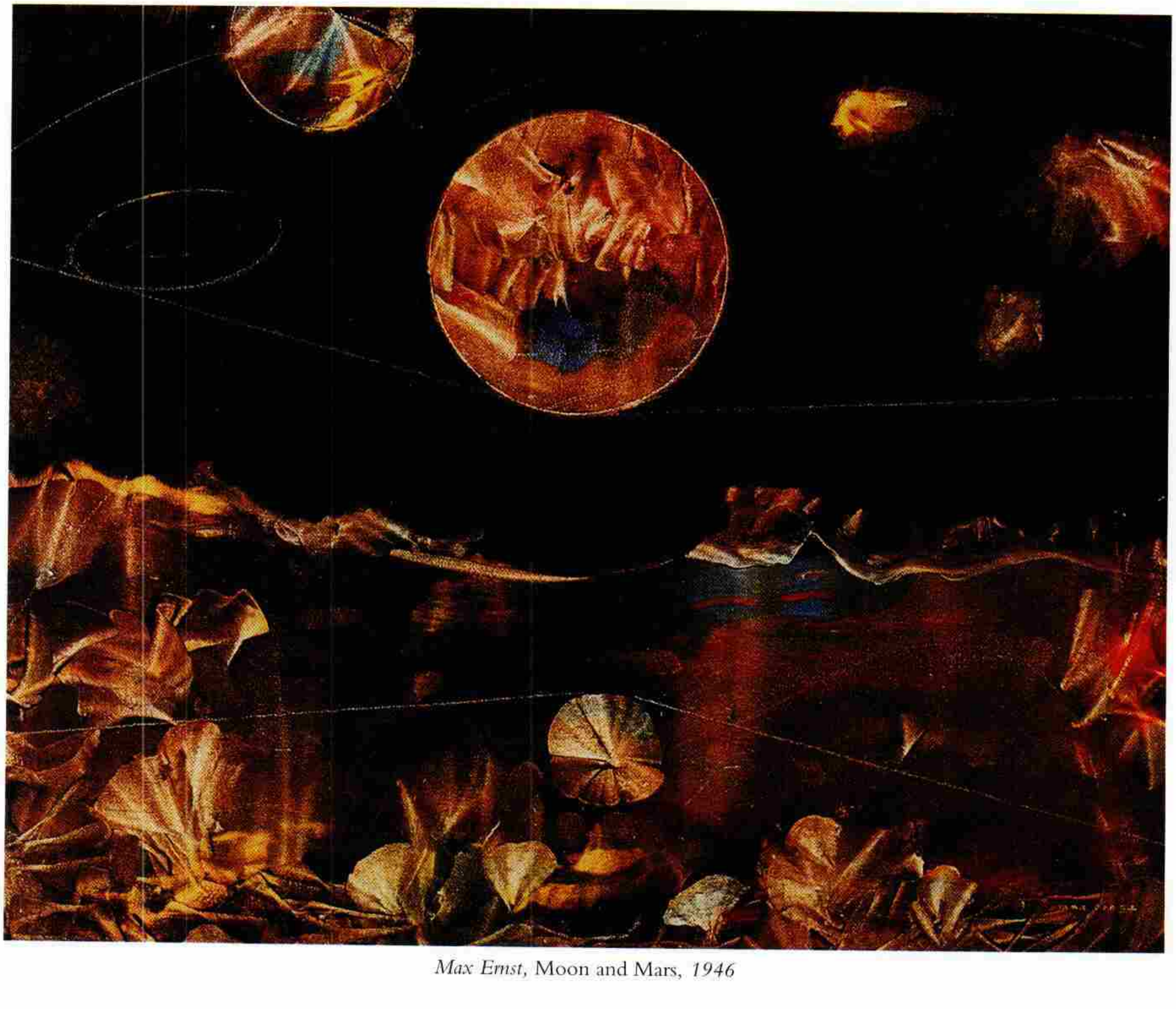
THE HUNT FOR LIFE ON MARS HAS A LONG, and some would say credulous, history [see "Mission Impractical," by Norman H. Horowitz, March/April 1990]. At the end of the nineteenth century the American astronomer Percival Lowell built a special Mars observatory near Flagstaff, Arizona. Training his telescope on the red planet, Lowell discerned what he took to be a system of artificial canals for channeling water from the polar ice caps to more temperate regions of the planet. The canals, he theorized, had been built by intelligent beings as part of an ingenious strategy for surviving in the inhospitable Martian climate. Lowell's ideas inspired everything from advertising campaigns to serious scientific proposals for communicating with the canal builders. The public imagination was aroused—enough so that a slightly-too-realistic 1938 radio dramatization of H. G. Wells's *War of the Worlds* caused a mass panic in which millions of people became convinced that hostile Martians had invaded the earth.

In the 1950s a theory arose that vegetation existed on Mars, based on a wave of darkness that had been observed to envelop the planet on a seasonal basis. In time, however, both Lowell's canals and the vegetation theory were relegated to the realm of science fiction; sharper images of the planet made from satellite-mounted instruments portrayed a bleak landscape formed over the ages by volcanism, asteroid impacts and erosion.

This much is certain: conspicuous, intelligent beings have never evolved on Mars. But it was only recently, geologically speaking, that modern human beings evolved from what began 3.5 billion years ago as a stirring in the primeval oceans. The history of life on earth is principally the history of microorganisms, and so, as McKay and his colleagues rightly recognized, if one is to find signs of life on Mars, one should look not for little green men but for bacteria.

THE CREATURES WHOSE TRACES MCKAY AND his colleagues asserted they had evidence for would have lived on Mars billions of years ago, when Mars is thought to have had a warm, wet climate quite different from the cold, desertlike one of today. McKay and his coworkers based their assertions on the presence of four mineral and organic substances detected, in close spatial association, in the Allan Hills meteorite:

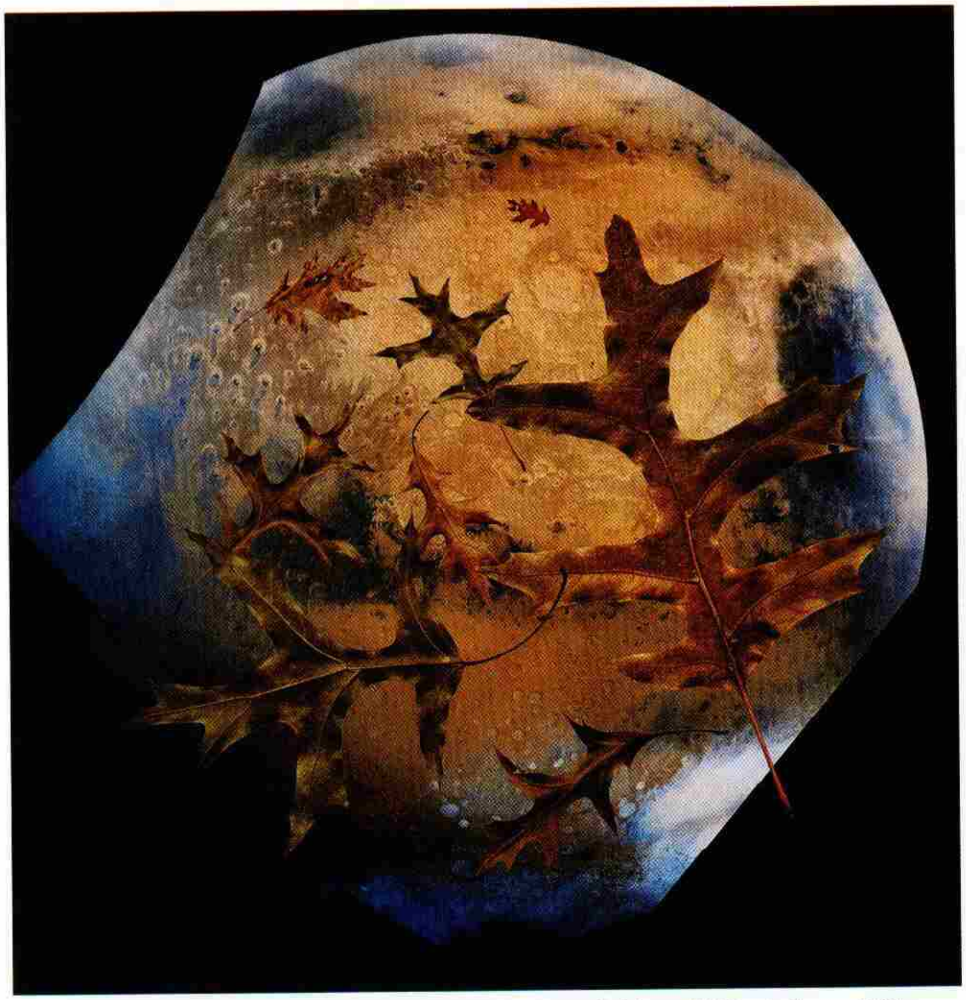
- The precipitated carbonate minerals, which, as I noted earlier, are much like carbonate deposits associated with biological activity on earth;



Max Ernst, Moon and Mars, *1946*

- Distinctive grains of the mineral magnetite, which resemble the crystals formed within some terrestrial bacterial cells;
- Complex organic molecules, interpreted as evidence of the breakdown of biomolecules; and perhaps most striking,
- Minuscule rodlike structures, interpreted as microfossils [*see the micrograph on page 20*].

Essentially, McKay has advanced a series of arguments that, by his own acknowledgment, are not conclusive individually. Taken together, however, they portray an environment that might well have harbored life. McKay's approach is like that of a prosecutor who argues a criminal case on the basis of strong circumstantial evidence: no one saw Jones kill his wife, but based on the fact that he had threatened her, taken out a large insurance policy in her name and lied about his whereabouts on the fatal evening, the jury might find him guilty. Then again, it might not.



Douglas Prince, Signs of Life: Oak Leaves over Mars, Schiaparelli Hemisphere, *1997*

The carbonate precipitates are a good example of the logic in question. By themselves, they imply only that the cracks in the Allan Hills meteorite once served as a conduit for fluids that were supersaturated with carbonate minerals. Carbonate minerals—a group that includes common limestone—often form as a result of bacterial metabolism. For example, it is widely accepted that in marine sediments sulfate-reducing bacteria can change the *p*H of the water, causing calcium carbonate to settle out and accumulate as limestone. But carbonate minerals can also form under circumstances in which no biological influence is possible—deep in the interior of the earth, for instance, at temperatures of hundreds of degrees Fahrenheit. The temperature at which the Allan Hills carbonate minerals accumulated is much debated, but at least some investigators echo McKay in asserting that they formed within a temperature range conducive to life. Even if that is so, however, the only valid conclusion is that the carbonate precipitates are consistent with the presence of life—not that they require it.

The magnetite crystals, McKay's second piece of evidence, have equally controversial origins. Magnetite, a mineral made of oxygen and iron, is found within the bodies of a variety of organisms, from homing pigeons to whales, and is thought to act as a kind of internal compass, helping them navigate by sensing the magnetic field of the earth. Among those species are certain kinds of bacteria, which harbor a chain of crystallographically uniform magnetite grains within their cytoplasm. When such bacteria die, the magnetite crystals can be preserved in sediments. McKay and his colleagues argue that the Allan Hills magnetite crystals accumulated in just that way.

One problem with that scenario is that the magnetite crystals in the meteorite come in different sizes and shapes. Hence, a biological origin would imply that the traces were left by many different species of magnetite-containing microorganisms: an ancient bacterial community of surprising complexity and diversity. But Bradley and his colleagues have recently reported a finding that is even more damaging to the Martian life hypothesis. At least some of the magnetite grains in the meteorite have defects in their crystal structures—defects that are known to form only at unlivable temperatures of several hundred degrees.

McKAY'S THIRD PIECE OF EVIDENCE FOR ancient life on Mars is the presence of complex organic molecules in the meteorite. Known as polycyclic aromatic hydrocarbons, or PAHs, the molecules are found in small concentrations almost everywhere on earth. They often form through the breakdown of biological molecules: the burning or decomposition of plant matter, for instance. PAHs occur naturally in coal and oil (which accrue from the altered remains of plants, animals and microorganisms) and are released by smokestacks and automobile engines. PAHs also occur, however, in carbonaceous meteorites formed in the outer solar system, so their association with biology is not obligatory.

Critics have suggested that the PAHs in the Allan Hills meteorite may actually have originated on earth. Antarctic ice contains small amounts of them, and so in the thousands of years the meteorite was lodged in the ice sheet, meltwater from freeze and thaw cycles could have percolated through cracks in the rock, leaving PAHs behind. Indeed, the presence in the meteorite of carbon 14 and minute amounts of terrestrially derived amino acids—reported this past January—have confirmed that groundwater did infiltrate the rock after it landed on earth.

That line of criticism, however, now seems relatively moot. Recent investigations by the cosmochemist Simon J. Clemett (a member of McKay's team) and his colleagues at Stanford University have argued convincingly that, regardless of any terrestrial contamination, most of the PAHs in the Allan Hills meteorite did come from Mars. Clemett's team found that PAHs were more abundant deeper inside the meteorite, where the terrestrial contamination would not have reached.

A Martian origin for the PAHs, however, does not necessarily prove they have any connection with life. A team that included the geochemist Luann Becker, then at the Scripps Institution of Oceanography in La Jolla, California, compared ALH84001 with other Antarctic meteorites, including a second meteorite thought to have originated on Mars. The second meteorite is much younger than the Allan Hills rock. It appears to have formed relatively late in Martian natural history, long after liquid water ceased to be a prevalent feature—and thus during a lifeless period on the planet's surface. Yet despite those differences, the second meteorite carried a suite of PAHs similar to that of the Allan Hills rock. Becker and her colleagues concluded that the PAHs in ALH84001 and its cousin came from some nonbiological source—either during the rocks' relatively recent sojourn in Antarctica or millions of years ago, when carbonaceous meteorites and interplanetary dust particles were bombarding Mars. Ultimately, the lesson must be that because PAHs make up less than 1 percent of the organic carbon in the meteorite, and because they are not always associated with life, they are probably not terribly useful as biological markers.

McKAY'S APPROACH TO HIS CASE
for life on Mars is like that of a criminal prosecutor who must make do with strong circumstantial evidence.

WHAT, THEN, ABOUT McKAY'S FOURTH piece of evidence: the elements interpreted as microfossils? The structures look like simple bacterial cells, except that they are exceedingly small: compared with them, *Escherichia coli* bacteria are as elephants to mice. In fact, the microbiologist Kenneth H. Nealson of the Jet Propulsion Laboratory in Pasadena, California, calculated that the cell-like structures in the Allan Hills meteorite are so small that they could be made up of only a handful of molecules—whereas a one-celled organism on earth is made up of millions.

But McKay and his team have a clever rejoinder. The images they generated with a scanning electron microscope exploited the cutting edge of technology, showing unusually small objects at remarkable resolution. No one really knows, they contend, what could lie in store when comparable methods are applied to earthbound niches. Perhaps living among us are terrestrial bacteria so small they have managed to elude detection. Indeed, recent images made by the geologist Robert L. Folk of the University of Texas at Austin show minute round structures in many terrestrial limestones—though the origin of those spheres remains obscure.

To bolster its argument, the McKay team calls attention to recent reports that Finnish biologists have isolated unprecedentedly small bacteria from the human bloodstream. Such reports are intriguing, but not directly relevant. Like viruses, bacteria living parasitically in a host that fulfills most of their biochemical needs can afford to be remarkably small; free-living microorganisms cannot, because of the number of molecules needed for metabolism and reproduction.

It could be, of course, that the rodlike Allan Hills microstructures record life in some early stage of evolution—before the rise of molecular complexity—and thus are unlike anything known today on earth. Or perhaps they are the remnants of more conventional cells that shriveled during postmortem decay. But further work by Bradley and his colleagues discourages those ideas. The Bradley team has concluded that the structures trumpeted by McKay as microfossils are probably mineral grains instead, unrelated to any biological process. With transmission electron microscopy—which shows the interior structure of objects, not just their surfaces—Bradley and his group found magnetite crystals that were remarkably similar in size and shape to McKay's alleged microfossils.

McKAY AND COLLEAGUES COUNTER THAT the history of the carbonate precipitates in the Allan Hills meteorite is complex and that Bradley and colleagues were not looking at the same structures. That possibility notwithstanding, Bradley and colleagues have still more recently noted that the alleged microfossils may actually be mineral ledges whose wormlike appearance has been accentuated by the treatment process that electron microscope samples undergo.

It is all too easy to become mired in an endless debate whose boundaries are constantly shifting. A Bradley says "Gotcha," and a McKay replies, "You're not looking at what I was looking at." In this case, though, the burden of proof ultimately rests with McKay and others who maintain that ALH84001 carries traces of life. It is hard, of course, to disprove such claims definitively. But to hold up under cross-examination, the circumstantial evidence must be much more tightly constructed.

However adaptable, however variable life might be, its essential ingredients are well established: water, nutrients

PERHAPS LIFE STILL THRIVES ON MARS *in subterranea*

and a source of energy. Furthermore, those ingredients tend to be useful only in certain forms. Most of the familiar creatures on land, for instance, from ferns to giraffes, survive only on freshwater at temperatures from just below freezing to about 120 degrees F., and their energy comes, either directly or indirectly, from sunlight.

But life on earth is turning out to be far more diverse and tenacious than anyone suspected. In the past two decades workers have shown that even apparently barren habitats support remarkable communities. Many microorganisms, it turns out, can live at extraordinarily high temperatures—up to 235 degrees F. (113 degrees Celsius). Furthermore, such microorganisms can extract the energy they need not from the sun but from chemical reactions in which hydrogen, sulfur or other simple substances are combined metabolically with carbon dioxide, oxygen or compounds of nitrogen and sulfur. Such compounds are readily available in hydrothermal environments such as the geysers and hot springs at Yellowstone National Park in Wyoming.

More recently, bacteria in abundance have been discovered in fluid-filled cracks in igneous rocks—sound familiar?—more than a kilometer below the earth's surface [see "Stone Soup," by Ricardo Guerrero and Lynn Margulis, page 34]. Some members of those unanticipated populations live by metabolizing the hydrogen gas given off in chemical reactions between minerals and water. Such populations are the first human contact with what may turn out to be a huge reservoir of biological activity within the outer crust of our planet. And diverse microorganisms also live at hydrothermal vents all along the oceanic ridge—a single system that sutures the planet along a continuous 46,000-mile-long path, like the stitching on an enormous baseball [see "Floor Show," by John R. Delaney, page 27].

DESCRIBED AS HYPERTHERMOPHILIC BECAUSE of their ability to survive and reproduce at high temperatures, many of those unfamiliar creatures cannot grow at the temperature used to pasteurize milk (162 degrees F.)—not because it is too hot but because it is too cold! The remarkable micromenagerie includes:

- *Sulfolobus acidocalderius,* a lobed ball between one and two microns in diameter that thrives in a hot acid environment and can extract or acquire the sulfur it needs by leaching it out of pyrite, or fool's gold;
- *Aquifex pyrophilus,* a similarly small organism that runs on the energy released when hydrogen is combined with trace amounts of oxygen to form water; and
- *Pyrodictium occultum,* a disk-shaped microorganism that sustains itself by converting sulfur and hydrogen to foul-smelling hydrogen sulfide—at temperatures as high as 234 degrees F. (112 degrees C.).

Had I described such physiologies on exams in the microbiology class I took in college, I would have failed the course. But it turns out that not only do such creatures live on earth, they occupy a privileged position. Hyperthermophilic organisms reside on the deepest known branches of the evolutionary tree, suggesting that the last common ancestor of all organisms alive today on earth may have lived in a hydrothermal environment.

The frontiers of life are expanding: the range of habitable environments now includes polar regions well below the freezing point, as well as scalding thermal springs. As biologists explore those frontiers, we often speak of such organisms, in our anthropocentric way, as "extreme" or "unusual." But in an evolutionary sense, it may be that we are the unusual ones. And those resilient hyperthermophilic lifeforms may provide the closest terrestrial analogy to any life that might have existed, and perhaps may persist, on Mars.

EVEN A CURSORY EXAMINATION OF THE IMAGES transmitted last year by the Mars *Pathfinder* landing craft and its slow-moving robot *Sojourner* suggests that the ingredients required for life are in short supply on the surface of Mars. The Pathfinder analyses confirm and extend those made twenty years ago by Pathfinder's intellectual and technological predecessor, the Viking missions of 1976. The two Viking spacecraft found a landscape that is inhospitable even by the highly tolerant standards of bacteria. The Martian surface is highly oxidizing (hence its red color), essentially devoid of organic matter, and apparently without persistent bodies of water. It is subject to strong ultraviolet radiation, and it is extremely cold—the mean annual temperature at the Martian equator is about sixty degrees below zero F.

The Viking missions convinced many biologists that there is no life on Mars—although a more careful and correct interpretation of the data would be that life is unlikely to exist currently on the Martian surface. Such an interpretation leaves open the possibility of subsurface life. Perhaps—just perhaps—life still thrives in subterranean oases where hydrothermal water circulates through volcanically heated crust—and if not now, then possibly in the past.

Although Viking failed to detect microorganisms, it did

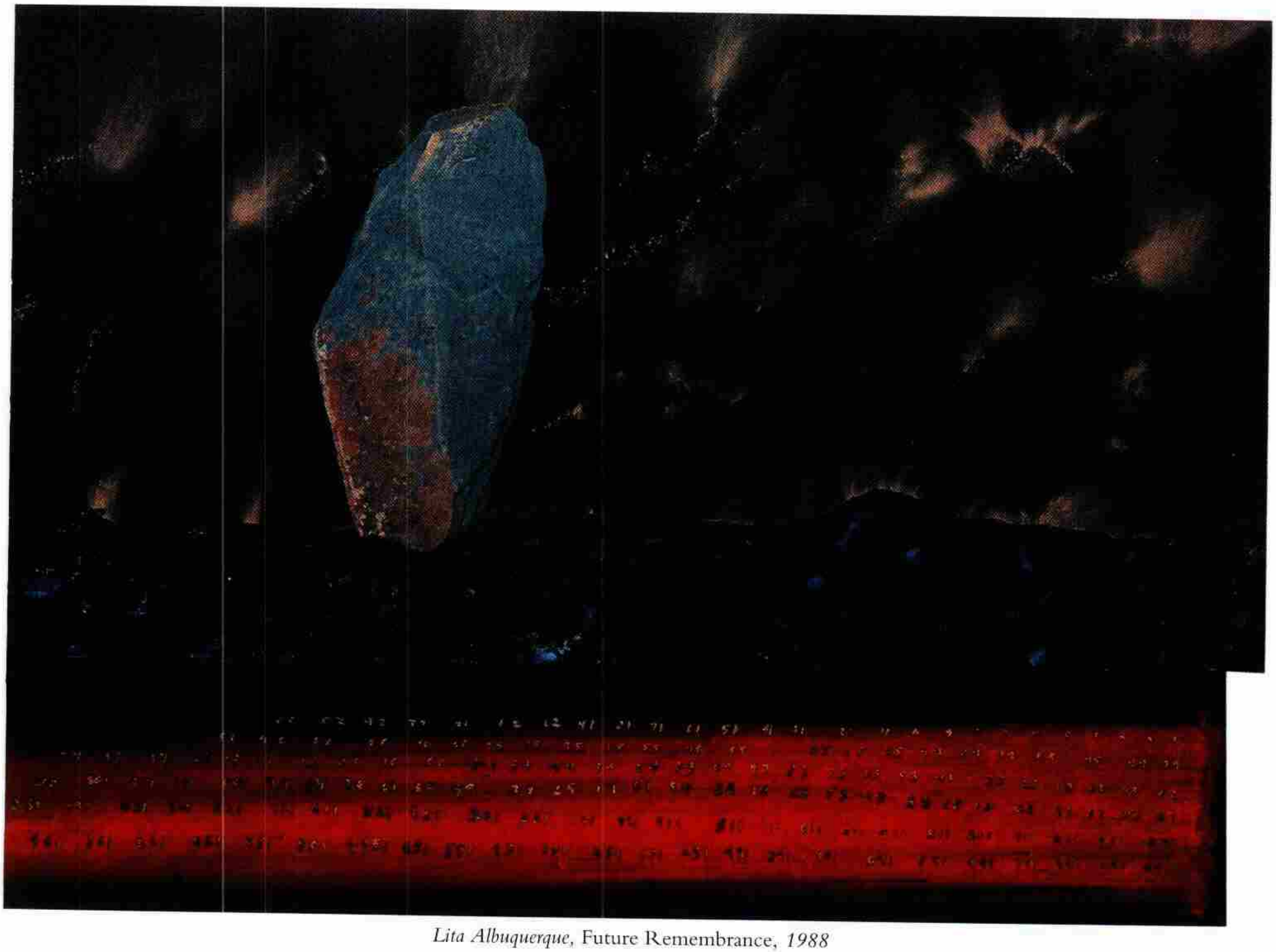
oases where water circulates through volcanically heated crust.

yield remarkable observations that have fueled continuing interest in Martian biology. Simply put, the Viking data suggest that whereas the surface of Mars today is very different from the surface of the earth, four billion years ago—when life was emerging on earth—the two planets had much more in common. Early in its history Mars had a thick atmosphere, abundant volcanism and, at least intermittently, liquid water. Under those conditions, the conclusion is inescapable that Mars harbored widespread hydrothermal activity both above and below ground. The Viking craft found what appear to be dry river channels on Mars, as well as evidence of flash flooding—large, striking geologic features that were almost certainly carved by running water.

SURPRISINGLY, THEN, THE SCIENTIFIC DISCIPLINE best suited for finding evidence of life on Mars may be not microbial ecology but paleontology. Frequent encounters with dinosaurs in museums and movie theaters have assured the public that large creatures can leave an interpretable fossil record in the form of bones. But fossils of . . . bacteria? It turns out that some microorganisms form extracellular walls that, like mineralized skeletons, resist decay. When buried in fine-grained sediments, or entombed in precipitated minerals, such remains provide a remarkable record of the deep evolutionary history of life.

Not only can microscopic bacteria become fossils, but recently investigators have discovered molecular fossils: complex organic molecules derived from living organisms. Patterns in the relative amounts of various carbon isotopes present in limestones and sedimentary organic matter can point to a biological origin. Less direct but equally important traces of life are the stromatolites, which are laminated trace fossils of microbial mat communities.

I have spent half a lifetime scouting for fossils—in cliffs and rocky canyons in Australia, China, Panama, Siberia, Sweden and elsewhere. In South Africa I dug up the remains of single-celled organisms that lived 3.5 billion years ago, when life on earth was nothing but a bold and rather tenuous innovation. I have focused not on trilobites or mastodons, but rather on the earliest traces of life, and on



Lita Albuquerque, Future Remembrance, *1988* the even deeper question such finds raise: How did life begin?

When, more than a decade ago, I joined NASA's research program in planetary biology, I realized that here lay the logical extension of my work. The idea of expanding the search for life not only back in time but to other planets is wildly exciting—but also quite reasonable. Mars, like the earth, has sedimentary rocks where the remains of organisms may have been buried. And that fossil record may actually be easier to read on Mars than on earth.

The reason is that Mars is smaller, and lacks the volatile internal heat sources that have given rise to the tectonic shifts of the continents of the earth. That constant shifting, the consequent smashup and erosion of the continents, and the continual upwellings of magma to form new terrestrial crust, have led to the destruction of much of the most ancient sedimentary record. On Mars, however, where the crust has remained more or less stationary, investigators can have access to a direct geological record of the earliest chemical and biological evolution.

TERRESTRIAL EXPERIENCE SUGGESTS WHERE and how to look for life on Mars. Both biology and paleontology indicate that investigators should seek evidence of water and hydrothermal mineral deposits. If life was ever present on Mars, it most likely left its calling card where muds dropped out of suspension in an ancient water body or where minerals such as calcium carbonate have accumulated at or near the surface of the planet.

But a landing site chosen according to the usual criteria—because it is flat or relatively easy to reach—probably will not lie within rover range of such prime targets for biological investigation. Like more conventional paleontologists, exopaleontologists who study Mars must begin by consulting maps that show the distribution of key features on the surface of the planet. Existing images show that biologically promising locations do exist—on Apollinaris Patera, for instance, an ancient volcano whose summit displays whitish patches that can be interpreted as precipitates formed from hot escaping gases; or at Dao Vallis, a large outflow channel on the flank of Hadriaca Patera, another ancient Martian volcano. Here water flowed out from the heated subsurface and could have sustained hydrothermal activity, leaving behind mineral deposits that could preserve microbial remains.

Randy Polumbo,
Rover, *1997*

Careful mapping must be followed by meticulous field exploration. Early in the next century NASA is scheduled to launch another in its series of Mars lander missions. The payload will include an advanced technological descendant of *Sojourner*—a mechanical geologist able to make a wide range of maneuvers, images and analyses on command from earth. *Sojourner* looked at pretty much whatever rocks it stumbled across. The new ambulatory robot will travel about 100 meters a day (compared with a few meters for *Sojourner*); come equipped with more sophisticated photographic and chemical equipment; and, unlike *Sojourner*, have the ability to take core samples of rock. The new rover will collect about 100 grams of such samples from Martian rocks and prepare them for retrieval by a later mission, scheduled for 2007.

When the new rover lands, I, along with a number of other scientists, will be stationed at the Jet Propulsion Laboratory with the once-in-a-lifetime chance to see what the rover sees and instruct it to do what we want it to do. Fossil hunting is a tactile activity, and doing it remotely—with a screen for eyes and remote-controlled robotic limbs for hands—will not be easy. But until people can land on Mars, that seems the best way to go about the painstaking work of extraterrestrial paleontology.

ONCE ROCKS FROM MARS REACH OUR earthbound laboratories, what will we look for in them? There can be no more basic question, but the answer is far from simple. Paleontological studies of the early earth rely on knowledge of terrestrial biology. Presumably then, morphological, sedimentary or chemical patterns that organisms are known to form, and that do not derive from any known nonbiological processes, all count as evidence of ancient life. That second criterion is critical. It explains why fossils of dinosaurs, trilobites and even cyanobacteria are readily identified as biological, whereas the simple structures and chemical compounds in the Allan Hills meteorite are not.

Understanding the limits of physical and chemical processes is also important, because it is hard to know which features of terrestrial life are likely to prove general and which are the specific products of our own peculiar natural history. Most biologists agree that life elsewhere, if it exists, is likely to be based on the chemistry of carbon, and it may even rely on amino acids, nucleotides and sugars similar to the ones in our bodies. But photosynthesis, multicellularity and jointed legs are far from givens. And extraterrestrial paleontologists composing essays on word processors? Such things may be rare in the universe.

Whatever the outcome of continuing studies of Mars, David McKay and his colleagues have taken a bold leap, which has given us all a precious opportunity to road test our philosophical and analytical approaches to extraterrestrial samples, years in advance of the day when intelligently chosen chunks of Mars are rocketed back to the earth. More than that, McKay's work has resonated deep within the human spirit. It has crystallized our resolve to address one of humankind's oldest and most basic questions: Are we alone in the universe? It is our remarkable good fortune to be part of the first generation in history that has a chance of finding the answer. •

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