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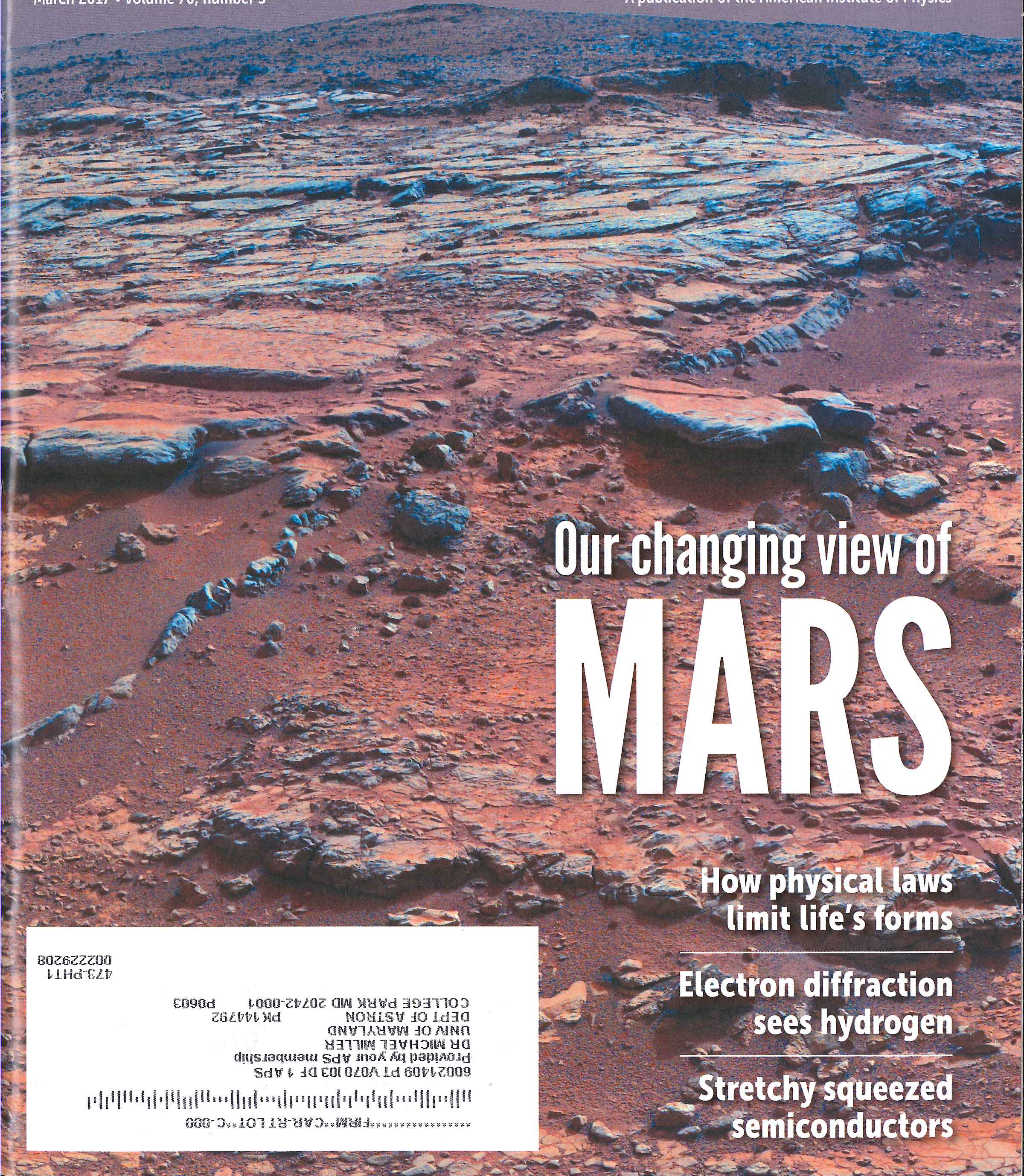


Our changing view of MARS

How physical laws limit life's forms

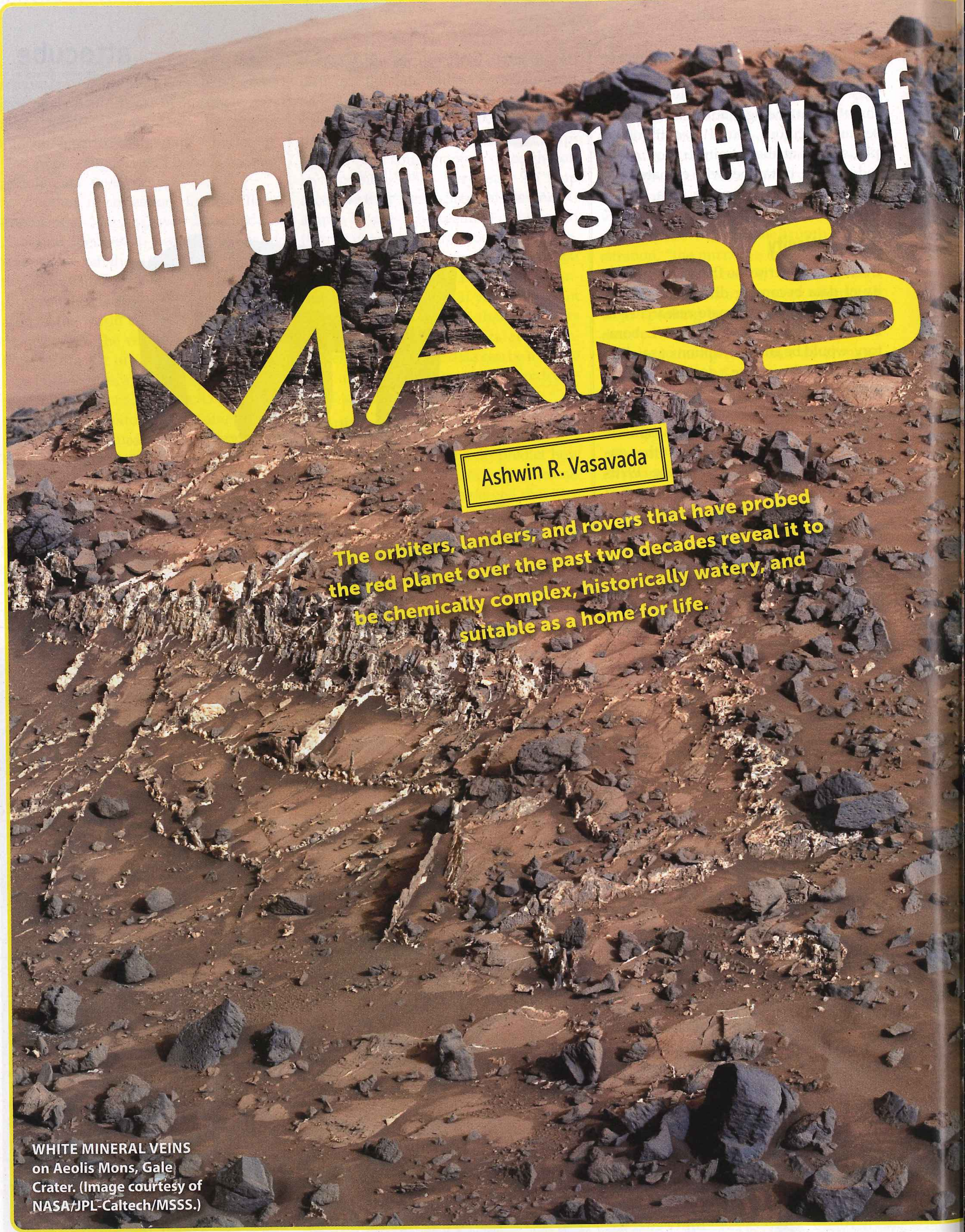
Electron diffraction sees hydrogen

Stretchy squeezed semiconductors

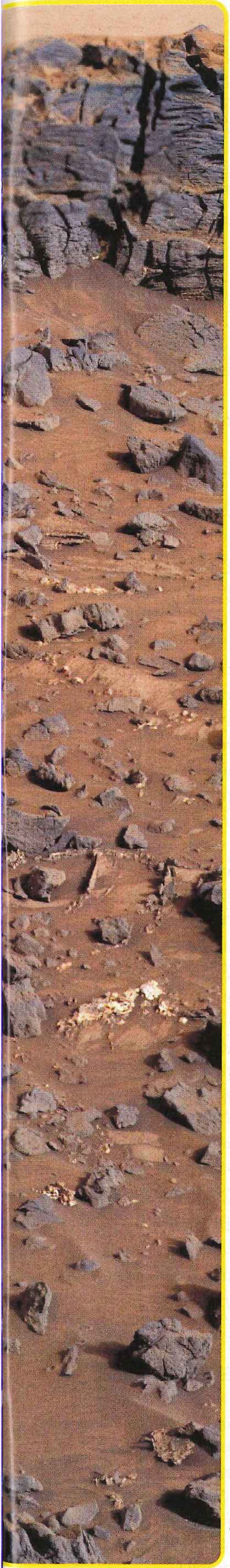
Our changing view of MARS

Ashwin R. Vasavada

The orbiters, landers, and rovers that have probed the red planet over the past two decades reveal it to be chemically complex, historically watery, and suitable as a home for life.



WHITE MINERAL VEINS on Aeolis Mons, Gale Crater. (Image courtesy of NASA/JPL-Caltech/MSSS.)



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Mars has always captivated us. Its fiery color and erratic apparent motion got the attention of sky watchers across the ancient world. Nineteenth-century astronomers interpreted its complex surface markings as evidence for river channels or, more imaginatively, an engineered network of canals. Changes in Mars's appearance throughout its annual cycle—later understood to be caused by seasonal ice and dust—prompted talk of an active biosphere until the dawn of the space age.

Today hundreds of scientists around the world study the planet through the virtual eyes of an international fleet of robotic surrogates. Robots in the form of orbiters, landers, and rovers have operated continuously on or around Mars since 1997; currently eight sent by NASA, the European Space Agency, Russia, and India are active. Surely, future historians will look back on the past couple of decades as a time when space-faring nations became focused on, if not obsessed with, exploring Mars.

Several motivations came together at the end of the 20th century to spark that focus. The long gap in exploration after the foundational 1976 Viking mission continued to grow after the loss of the *Mars Observer*, which went incommunicado just prior to its arrival at Mars in 1993. Rapid advances in the understanding of life in Earth's extreme environments suggested that the outlook for life on Mars might not be as bleak as scientists had previously thought—especially beneath the planet's cold, arid, oxidizing, and irradiated surface. Both scientific and public interest were renewed in 1996 when a group of scientists claimed to have found evidence of microscopic Martian bacteria in a fragment of Martian rock collected in Antarctica as meteorite ALH84001.

With foresight and political savvy, NASA leadership channeled those developments into an ambitious new Mars Exploration Program (MEP). Formed in 2000, the program envisioned that robotic spacecraft would be sent to Mars every time planetary alignment would allow and that each new orbiter, lander, and rover would build on the scientific achievements and technologies of its predecessors.[1]

Strategy and synergies

At its core, NASA's MEP seeks to understand whether life ever took hold on Mars. Answering that question—and making sense of whatever the answer turns out to be—requires a systematic understanding of Mars across the disciplines of geology, climatology, and biology. The exploration strategy began with orbiters capable of systematically mapping the planet's surface using altimetry, imagery, and spectroscopy. Those orbiters also captured the modern climate by observing weather patterns and the cycles of carbon dioxide, water, and dust over multiple Mars years. With mapping under way, rovers were sent to sites on Mars that seemed especially promising for potential biology. Their tasks were first to look for past evidence of sustained liquid water (see the article by Bruce Jakosky and Michael Mellon, PHYSICS TODAY, April 2004, page 71) and then to make comprehensive inventories of the chemical and environmental conditions that might support or hinder microbial life.

Research consisting of theoretical, laboratory, and field work on Earth—some of it organized by competitively selected teams known as virtual astrobiology institutes—supplemented direct observations on Mars. The research also provided an important link to studies of the origin and evolution of life on Earth.

BOX 1. A BRIEF NATURAL HISTORY OF MARS

Mars formed in the solar nebula and differentiated into a crust, mantle, and core. During the subsequent Noachian period, which began about 4 billion years ago, impact cratering, volcanism, and erosion were extensive. River valleys cut into surfaces already eroded and altered by water, some pervasively. The Hesperian period, starting about 3.7 billion years ago, saw continued extensive volcanism. Erosion and the formation of river valleys slowed dramatically, but catastrophic floods occurred; some of those floods emanated from subsurface reservoirs and produced temporary lakes and seas. Tectonic activity opened large canyons. Aqueous alteration of surface materials was more localized and reflected a growing scarcity of water.

The Amazonian period, starting about 3 billion years ago and continuing today, is icy and dusty. Water remains in the climate system, but predominantly as ice that is redistributed across Mars's surface in climate cycles induced by the planet's orbit and orientation to the Sun. Erosion rates are extremely slow, with wind in the thin atmosphere being the dominant agent. The decreasing abundance and stability of liquid water over time are tied to the gradual loss to space of much of the early Noachian atmosphere and the planet's water inventory via thermal escape and ionization processes. The ionization processes were enhanced as the planet's interior cooled and the magnetic field that deflects charged particles from the solar wind diminished. Declining global temperatures and the thinning atmosphere makes any liquid water on the planet's surface vulnerable to freezing or evaporation.

Technology development initiatives enabled new spacecraft capabilities and fostered the creation of advanced payload instruments. Those investigations and initiatives were envisioned as culminating in a new attempt to directly detect evidence of past or present life on Mars. The attempt would be guided by a much better understanding of where and how to look than was possible at the time of the inconclusive Viking biology experiments. The bulk of the analyses would take place in Earth laboratories on samples returned from Mars.

The capabilities of robotic spacecraft and their scientific payloads have progressed greatly under the MEP, as have our understanding of Mars and the sophistication of our questions. Indeed, many of the questions planetary scientists currently ask about Mars were answered not so long ago about Earth; others are still being investigated on Earth today. Earth scientists are also increasingly drawn into Mars exploration as connections are made with terrestrial research. The cross-fertilization of complementary expertise has had a leveraging effect in advancing Mars science.

Science fiction often presents a view of alien worlds as exotic and wholly different from Earth. But the reality of Mars exploration is one of familiarity—in the raw materials found there and the processes at work—even though the two planets have evolved quite differently. Nonetheless, a fascinating aspect of studying Mars is the constant reminder that processes familiar on Earth are expressed completely differently on Mars—with its absence of plate tectonics, extremely thin atmosphere, and a surface that has been without rain and shaped primarily by wind for more than a billion years (see box 1).

Transformational discoveries

A key early MEP discovery came from the 1996 *Mars Global Surveyor*, the first of three orbiters sent to recapture and expand on the original goals of the *Mars Observer*. From pictures of stacked layers of rock on the planet's surface, imaging-team leaders

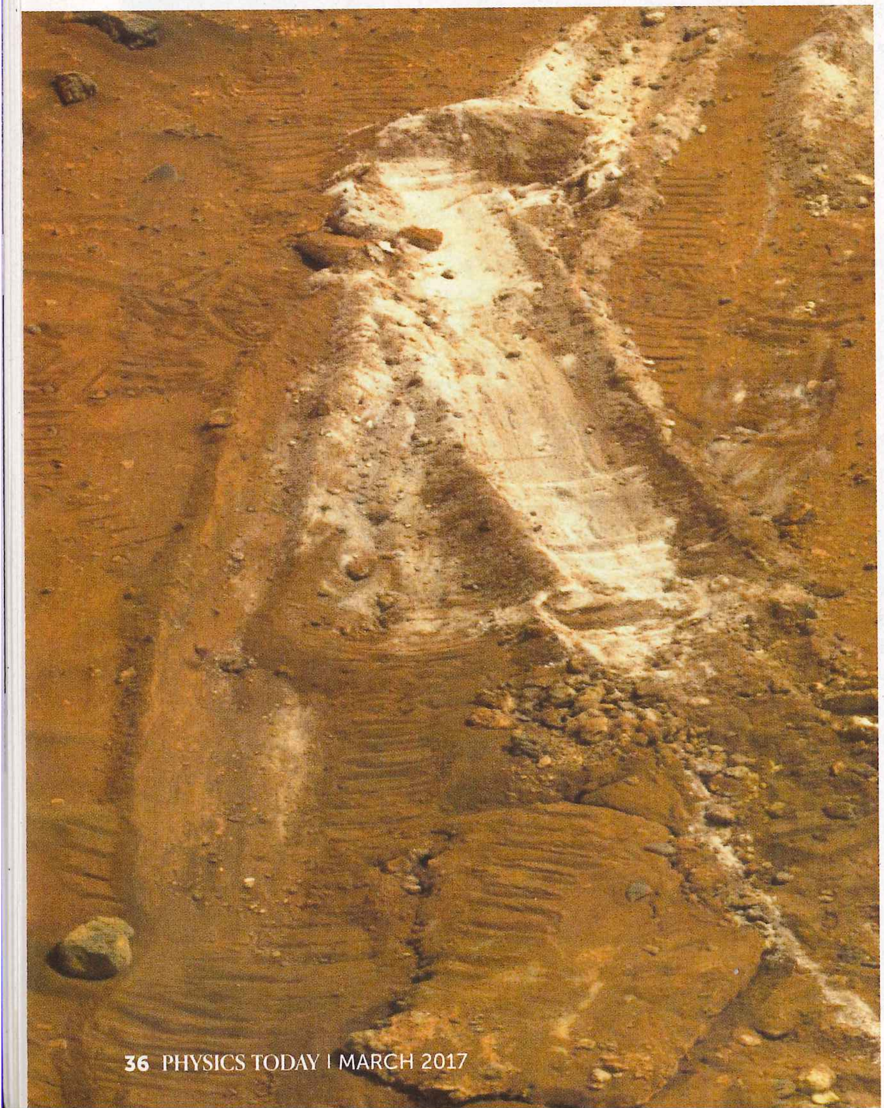


FIGURE 1. SKID MARKS. This trench, made in May 2007 as the *Spirit* rover was driving backward dragging its impaired front right wheel, reveals nearly pure silica in the soil. The opaline silica mineralogy (amorphous $SiO_2{\cdot}nH_2O$) fortuitously discovered by *Spirit* is evidence for ancient hydrothermal activity in that location. (Image courtesy of NASA/JPL-Caltech/Cornell.)

Michael Malin and Kenneth Edgett argued that Mars's ancient surface had been extensively eroded and redistributed by wind and water, which left behind vast deposits of sediment.[2] Well before then, it had been clear that impacts, volcanism, water, and wind had scarred the surface, both gradually and catastrophically, but little could be learned about the environmental changes that accompanied those processes. Malin and Edgett's discovery of sedimentary rocks started a new ball game; the textural, mineralogical, geochemical, and isotopic characteristics of the sedimentary strata provide an interpretable record of surface processes that were active when the layers were deposited. Just as a hike out of Earth's Grand Canyon allows geologists to time travel through ancient seas, swamps, and deserts, the analysis of a sequence of sedimentary rock layers on Mars tells a detailed story of the planet's own environmental evolution.

The NASA MEP rovers *Spirit* and *Opportunity* landed on opposite sides of the planet in 2004. The two missions benefited from the earlier discoveries of the *Mars Global Surveyor*, the 1996 *Mars Pathfinder* lander with its pioneering *Sojourner* rover, and the *2001 Mars Odyssey* orbiter. Having twin rovers allowed scientists to pursue two approaches in the search for evidence of water: *Spirit* would access the site of an ancient lake that dates back to the Noachian era around 4 billion years ago (see box 1) in Gusev Crater, while *Opportunity* would follow up on the detection from space of crystalline hematite,[3] an iron oxide mineral formed by the interaction of water and rock.

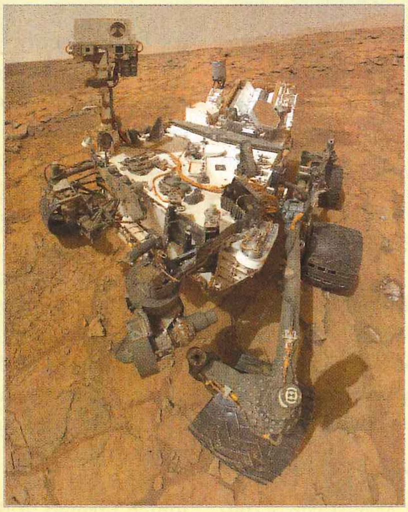
Each rover found evidence of sustained liquid water in the past, but not quite in the ways envisioned prior to landing. Although *Spirit* found rubble from ancient lava flows rather than a lake bed, it eventually discovered water precipitates in the form of iron hydroxide and carbonates in Noachian rocks,[4] soils rich in sulfates, and opaline silica rocks and soils that had been produced by volcanic hydrothermal activity.[5] Figure 1 shows one example. Meanwhile, *Opportunity* unexpectedly landed next to outcrops of sedimentary rocks. Investigation of those rocks and the surrounding area revealed an ancient, ephemeral lake environment where mud became enriched in sulfate salts that had precipitated from evaporating water, eroded into particulates, and subsequently accumulated as sulfate-rich sandstones,[6] as shown in figure 2. The percolation of groundwater through those rocks generated hematite concretions within them.

The European Space Agency's *Mars Express* orbiter and NASA's *Mars Reconnaissance Orbiter* arrived at Mars in 2004 and 2006, respectively. *Mars Express* brought for the first time a near-IR (NIR) solar reflectance spectrometer to survey the planet's surface. Prior thermal-emission spectroscopy had successfully found signatures of minerals such as hematite, but the new access to the NIR part of the reflectance spectrum led to a key breakthrough: The many additional spectral features allowed scientists to identify hydrous minerals such as phyllosilicates, or clay minerals,[7] and sulfates.[8]

The *Mars Reconnaissance Orbiter* carried its own NIR spectrometer and also a high-resolution camera capable of distinguishing topographic surface features just tens of centimeters in size. Hydrous minerals were soon discovered in many areas of the planet, including in particular sedimentary strata found in ancient Noachian crust. Because of the combination of the two instruments, it is now possible to identify landscapes

BOX 2. *CURIOSITY'S* EXPERIMENTAL METHODS

The suite of physical and chemical techniques available on modern spacecraft such as the *Curiosity* rover is truly remarkable. An assessment of the habitability of a location on Mars comes from taking into account several contributing factors, such as the environmental setting; the presence, longevity, pH, and salinity of liquid water; the availability of chemical elements and energy sources relevant to life; and the presence of any hazards to life. *Curiosity's* exploration of each new location begins with imaging and spectrometry of the landscape on spatial scales from millimeters to kilometers. The instruments capture visible and near-IR light.


NASA/JPL-CALTECH/MSSS

To survey the chemical makeup of its surroundings, the rover uses laser-induced breakdown spectroscopy. A pulsed laser deposits 10 MW/mm^2 into a 0.5 mm spot on a rock or soil to produce a 10^4 K plasma. As the plasma relaxes, a spectrometer records its UV, visible, and near-IR emission spectra to quantify the abundances of several chemical elements. The rover's arm can manipulate a "hand lens" camera with 14-μm spatial resolution to observe grain-scale rock textures and soils. The arm also carries a curium-244 source that irradiates targets with alpha particles and x rays. A cooled detector measures the particle-induced x-ray emission and x-ray fluorescence and thereby allows researchers to identify the rock-forming elements in the upper few hundred micrometers of the surface.

The most ambitious and novel aspect of the mission is the capability to acquire and analyze samples of rock, soil, and air in two onboard laboratories. One of the laboratories uses a cobalt source to generate a collimated x-ray beam that is sent through powdered rock samples. The resulting diffraction patterns can be tied to the unique crystalline structures of specific minerals. The other laboratory analyzes air and gases emitted during the pyrolysis of rock or soil samples. The suite of instruments used for that purpose includes a quadrupole mass spectrometer that can measure molecules up to 535 atomic mass units; an assembly of six gas chromatography columns that separate various inorganic and organic molecules; and a tunable laser spectrometer that precisely measures carbon dioxide, water vapor, methane, and their isotopic variants.

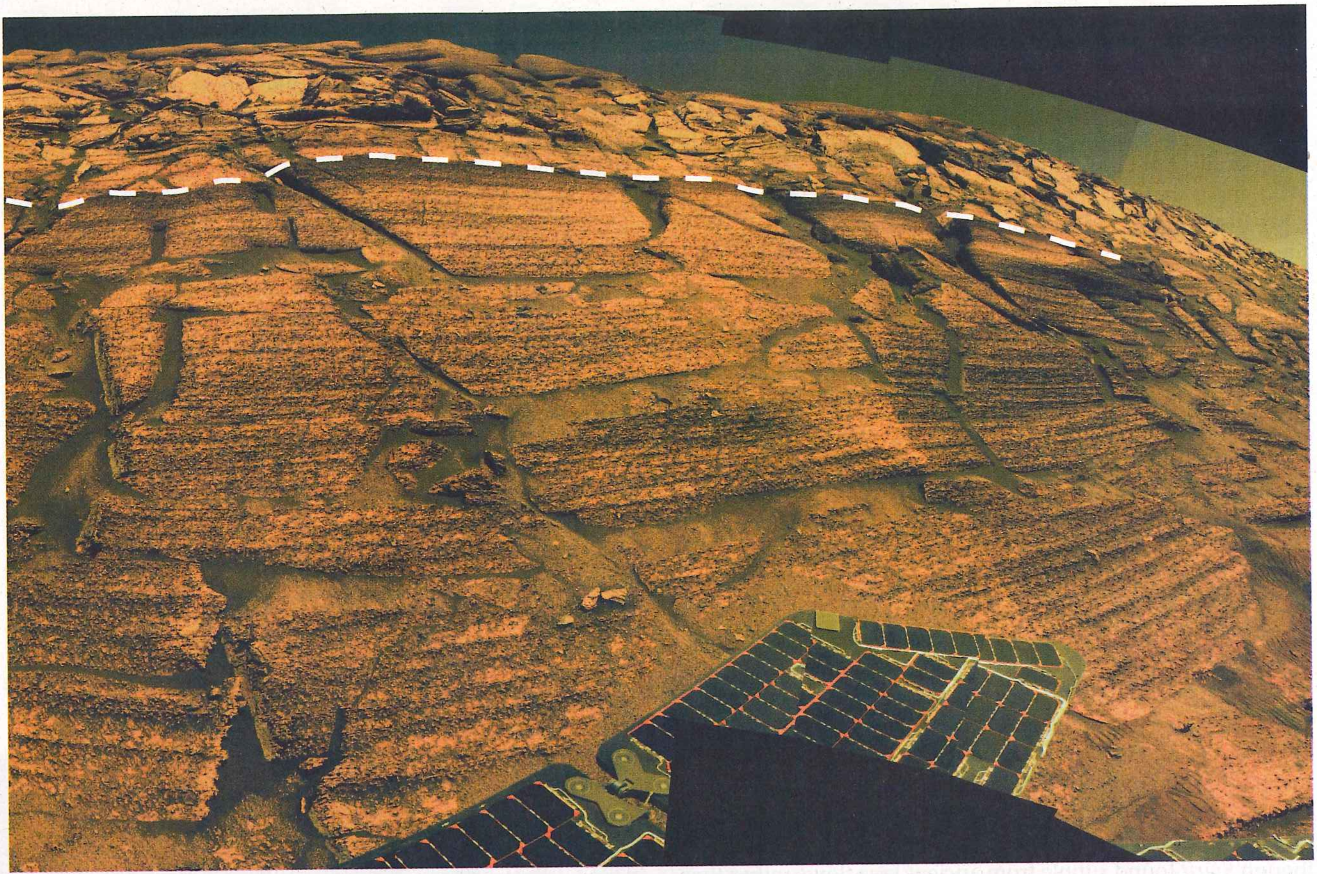


FIGURE 2. THE SOUTHEASTERN INNER RIM of Endurance Crater as photographed by the *Opportunity* rover in November 2004. Three layers of sandstone lie along the rim from bottom to top: a cross-bedded, or tilted, layer (not shown) indicative of wind-driven sand in large dunes; a transitional planar-bedded, or flat-lying, layer that is visible in most of the image; and (above the white dashed line) an upper layer that accumulated in ancient flowing water. Variations in the groundwater table were ongoing during the accumulation of the sands and led to their chemical alteration. The section shown spans about 7 vertical meters. Part of the rover's solar panel appears at the bottom of the picture. (Image courtesy of NASA/JPL-Caltech/Cornell.)

indicative of past aqueous activity not just by the landscapes' morphology but also by the water-driven alteration of Mars's crust into phyllosilicates and the presence of chemical precipitates like carbonates and sulfates. Figure 3 shows an example of an ancient delta where such minerals have been identified.

Curiosity's habitability investigation

With confidence from a decade of MEP and *Mars Express* discoveries, NASA conceived of a flagship mission that would attempt to quantitatively assess Mars's suitability for past or present life: the Mars Science Laboratory mission, with its rover, *Curiosity*, which carries the most advanced suite of instruments ever sent to the Martian surface (see box 2). But how does one measure the habitability of an environment?

The astrobiology community determined that an environment of a planet or moon is habitable if it can sustain life as we currently understand it, regardless of whether life originated there or was ever present. Furthermore, a habitable environment must provide liquid water as a solvent capable of supporting complex biochemistry, the energy sources needed to sustain metabolism, and environmental conditions that allow for the assembly, persistence, and function of complex structures and biomolecules.[9,10] Extremes of temperature, pH, radiation, and salinity can preclude habitability, even if liquid water is present.

The wealth of orbiter data ironically presented a challenge: Could the scientific community identify a landing site that would allow *Curiosity* the best chance of encountering evidence of an ancient habitable environment? The evidence for aqueous activity at *Spirit*'s landing site came from the morphology; at *Opportunity*'s site it came from the mineralogy. Some candidate sites date back to the Noachian era, a time when surface water is thought to have been widespread, whereas others preserve evidence from the planet's Hesperian era, about 3.7 billion years ago, when water was becoming sparser and more acidic.

NASA chose a site that seemed to offer it all: Gale Crater, which formed at the Noachian–Hesperian boundary and contains a 5-km-high, stratified mound. The texture and mineralogy of the mound's strata change with elevation in an intriguing way that is suggestive of a drying climate, with clay minerals near the base and sulfate salts slightly higher. Also at the site are morphological indicators of surface water and groundwater.

An important goal for *Curiosity* is to identify indigenous organic molecules that are the raw material for life or evidence

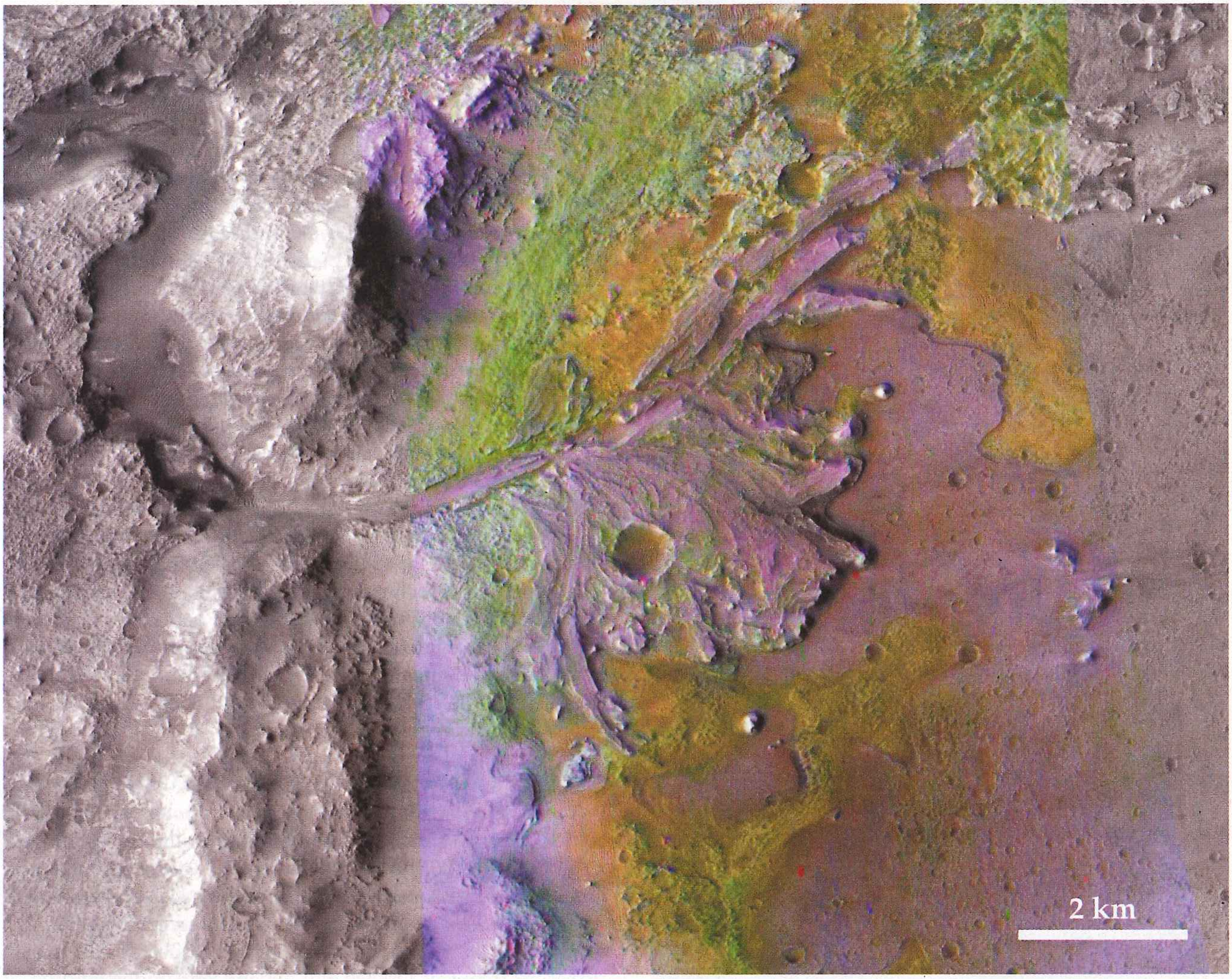


FIGURE 3. AN ANCIENT DELTA within the 45-km-diameter Jezero Crater, as photographed by the *Mars Reconnaissance Orbiter* in January 2007. (The outside rim of the crater appears white.) Layers of sedimentary rock on the crater floor contain spectral evidence of hydrous clay minerals and carbonates (green) among igneous minerals (yellow and blue). The sediments are thought to have come from nearby highlands, transported by water billions of years ago when the crater was a lake basin. The presence of clay minerals in such a deltaic setting is favorable for the accumulation and preservation of organic material.[17] (Image courtesy of NASA/JPL/JHUAPL/MSSS/Brown University.)

of past life. Today such material is easily destroyed by oxidizing chemistry at Mars's surface and by cosmogenic high-energy radiation. Insights from the study of early life on Earth and from the oil industry's search for hydrocarbon accumulations suggest that particular environments favor the initial concentration and long-term preservation of such organic compounds in sediments. Sites where sediments can quickly accumulate in a low-energy environment—that is, one lacking strong currents that would carry away fine particles, such as a river delta—are one promising target. Sites with accumulations of clay minerals are another, because the clays' sheet-like mineral structure can trap organic molecules and shield them from destructive chemistry. A deltaic site was the runner-up for *Curiosity*, but the longer history recorded in the rock at Gale Crater won the day.

Since landing at Gale Crater in 2012, *Curiosity* has conducted a detailed assessment (see box 2) of what is now known to be an ancient habitable environment, and its ongoing discoveries continue to expand the time period that Mars was habitable (see PHYSICS TODAY, May 2015, page 12). The rover first drove to a location the science team hypothesized was once an ancient lake. The team interpreted the fine-grained sedimentary rock at the site as having been deposited in the lake's silty waters. The elemental makeup of that sediment is similar to the basaltic composition of much of the planet's surface, but onboard analyses of rock samples there indicate that near-neutral pH water has altered some of the minerals into phyllosilicates.[11]

The discovery of organic molecules,[12] nitrates, and sulfur minerals in mixed redox states completed a picture of a site with water, the raw materials of biology, and the energy sources required for microbial metabolism. As *Curiosity* drove across the crater floor toward the base of the stratified mound, science team members documented a succession of river, delta, and lake deposits. Remarkably, they also found that the base of the mound itself was built by sediments from a series of lakes

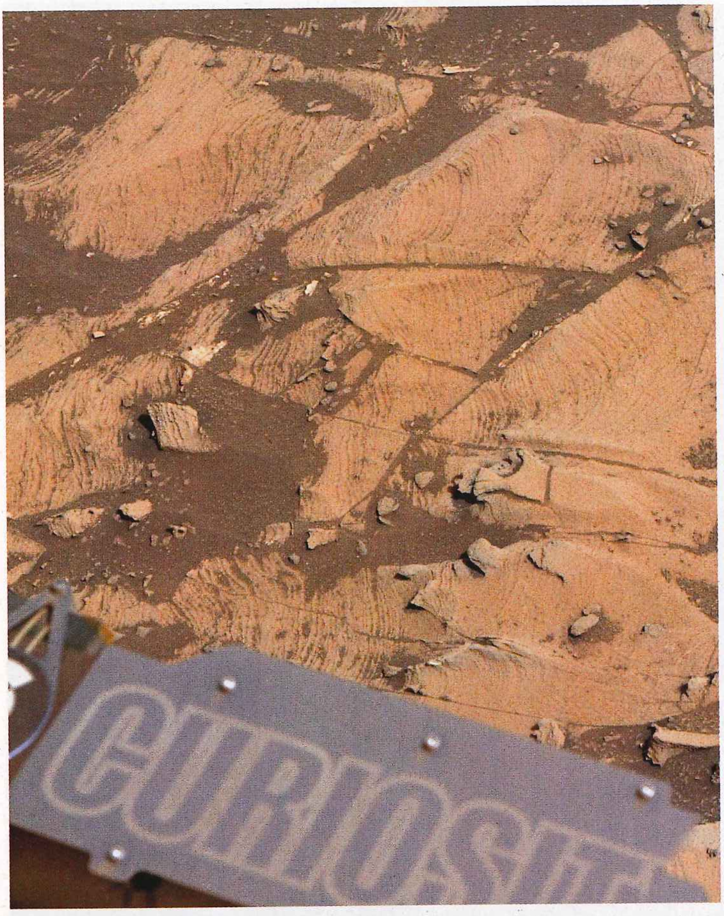


FIGURE 4. LAMINATED, SEDIMENTARY ROCK in Gale Crater, as imaged by the *Curiosity* rover in October 2014. The light-toned bedrock visible between drifts of darker sand consists of flat, millimeter-thick layers of sediment that settled at the bottom of an ancient lake. The layered deposits were subsequently cemented, buried, fractured, and eroded. A nameplate on the rover's stowed arm is visible in the lower part of the image. (Image courtesy of NASA/JPL-Caltech/MSSS.)

that once spanned the floor of the crater. The light-toned, flat-lying bedrock shown in the foreground of the opening figure on page 34 formed as mud in one of those ancient lakes. Calcium sulfate minerals precipitated from groundwater that flowed through the fractures. The whitish mineral veins now stand as ridges while the softer mudstone erodes around them.

Curiosity, which took that picture in March 2015, has now driven through more than 100 vertical meters of finely laminated sediment, interpreted primarily as lacustrine and shown in figure 4. Another 100 meters of potentially similar material lies above the rover. Although the time scales of sediment deposition within such dried-up Martian lake beds are uncertain, their terrestrial analogues suggest that the lakes themselves may have existed for millions to tens of millions of years.[13]

The lake beds in Gale Crater are exciting for their biological prospects. But the presence and longevity of lakes in the early Hesperian era present challenges to current conceptions of Mars's paleoclimate. There is little doubt that water carved extensive valleys and occasionally pooled in lakes in the Noachian period.[14] And great outflows of water coursed across the landscape in the early Hesperian, potentially forming transient seas. But was Mars's climate ever amenable to perennially stable open bodies of water that had evaporative losses moderated by atmospheric humidity or balanced by precipitation? Or was liquid water always out of equilibrium over climatic time scales, appearing only transiently as rivers and lakes that were charged by melting ice during seasonal, cyclic, or episodic events such as volcanic eruptions or asteroid impacts?

Generating a scenario in which Mars warms sufficiently to produce stable liquid water billions of years ago at low latitudes is conceptually difficult due to the faintness of the young Sun and the low pressure (less than 1 bar) of the planet's early atmosphere. Modelers have tried to simulate warm enough climatic conditions by taking into account the heat-trapping effects of clouds and the presence of such greenhouse gases as hydrogen, carbon dioxide, water vapor, methane, and sulfur—so far without success. The failure to produce the needed climate forcing with sophisticated climate models now stands in stark contrast to the strong geological evidence for persistent lakes in Gale Crater, where there also is no evidence of ice cover and where vigorous surface runoff and a supply of abundant sediment were likely.

Next steps for exploration

NASA's MEP has focused on the potential for life on Mars. But discoveries continue in other areas as well. The *MAVEN* (*Mars Atmosphere and Volatile Evolution*) orbiter is currently quantifying atmospheric loss processes, and the 2018 *InSight* lander will use a seismometer to study the interior of Mars. The newly arrived European and Russian *ExoMars Trace Gas Orbiter* will expand our understanding of atmospheric methane[15] and other gases. Ongoing studies of surface features created by Amazonian-era, cyclic climate change (see box 1) have been especially rich. Those features include high-latitude ground ice studied *in situ* by the *Phoenix* lander, remnants of low-latitude glaciers, landforms that still harbor relict ice, extensive latitudinal redistribution of surface ice, and complex stratigraphic and geometric patterns in the polar ice caps.

The most intriguing activity in Mars's recent history has occurred on slopes. One type of feature, collectively referred to as gullies, may be evidence of springs, melt-driven flows, or avalanches spurred by seasonal CO_2 frost. Another type, called recurring slope lineae (RSL), manifest as dark streaks that lengthen downslope, fade, and regrow with apparent seasonality (reference 16; see also PHYSICS TODAY, December 2015, page 24). Liquid water has been hypothesized for both gullies and RSL, potentially with its freezing point depressed by dissolved salts. Although the idea of liquid water on modern Mars is fascinating, considering the planet's cold, dry climate and thin atmosphere, its relevance to extant biology is less apparent given the ephemeral nature of any liquid water. It is also unclear whether the water, if it is briny, would be chemically suitable for biology.

With ancient habitable environments now firmly established, the next major step in NASA's MEP will be to search for signs of past life. A rover scheduled for launch in 2020 will carry a payload capable of identifying potential biosignatures—substances, patterns, or objects whose origin specifically requires a biological agent.[9] Those signatures might be chemical (organic or inorganic) or morphological (rock or mineral structures) in form. The rover's instruments will inspect rock interiors and measure the textures, chemistry, and mineralogy at the micrometer scale using imagers, laser spectroscopy, x-ray fluorescence, and UV Raman spectroscopy.

The 2020 mission also aims to acquire promising samples that may be returned to Earth and subsequently analyzed in laboratories worldwide—both immediately and well into the future as analytical techniques continue to improve. Evidence of past life likely would be faint and degraded; recognizing the evidence and distinguishing it from nonbiological samples would thus require state-of-the-art analytical techniques. In parallel, NASA and commercial space enterprises are gearing up to send humans to Mars. Those efforts have made more urgent the need to detect signs of extinct or extant life before a human presence may contaminate the surface.

As NASA's MEP enters its third decade, it builds on the discoveries of sustained liquid water and habitable environments. Whether or not evidence of life is found, the results will inform our understanding of life's origins and evolution on Earth and the potential for life in the oceans of the outer-planet moons, on the surface of Saturn's moon Titan, and on the untold number of potentially habitable worlds around other stars.

If life ever took hold on Mars, what environmental niches did it occupy? And what limited it? Did it ever become pervasive enough to modify its environment on the scale of Earth's oxygenation, for example? Was it resilient to the loss of Mars's atmosphere and hydrosphere? If life never took hold, what is that telling us, given Mars's likely similarity to early Earth and the availability of habitable environments?

The poet T. S. Eliot tells us that the end of exploration is to arrive where we started and to know the place for the first time. The end of Mars exploration is not in sight, but it is safe to say that we are learning more each day about where we started.

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