SPECIAL ISSUE The search for new life

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Life in the SOLAR SYSTEM

Is there life on MARS?

Earth's neighbor once had a climate conducive to life. Now scientists are trying to learn if the Red Planet turned those chances into reality.

BY JIM BELL

THE MODERN ERA OF MARS EXPLORATION provides abundant evidence that at least some of Mars' surface may once have been a habitable environment for life as we know it — and that parts of the planet's subsurface could still be habitable today. This parade of evidence dates back to the early 1970s with the Mariner 9 orbiter, which returned spectacular photos of water-carved landforms. These and higher-resolution images from more recent spacecraft have revealed a wealth of geologic features indicating water's presence: landscapes carved by catastrophic floods; streams, rivers, and deltas created by the persistent flow of water; and enigmatic gullies on hillsides and other channel-like landforms that hint at water running underground.

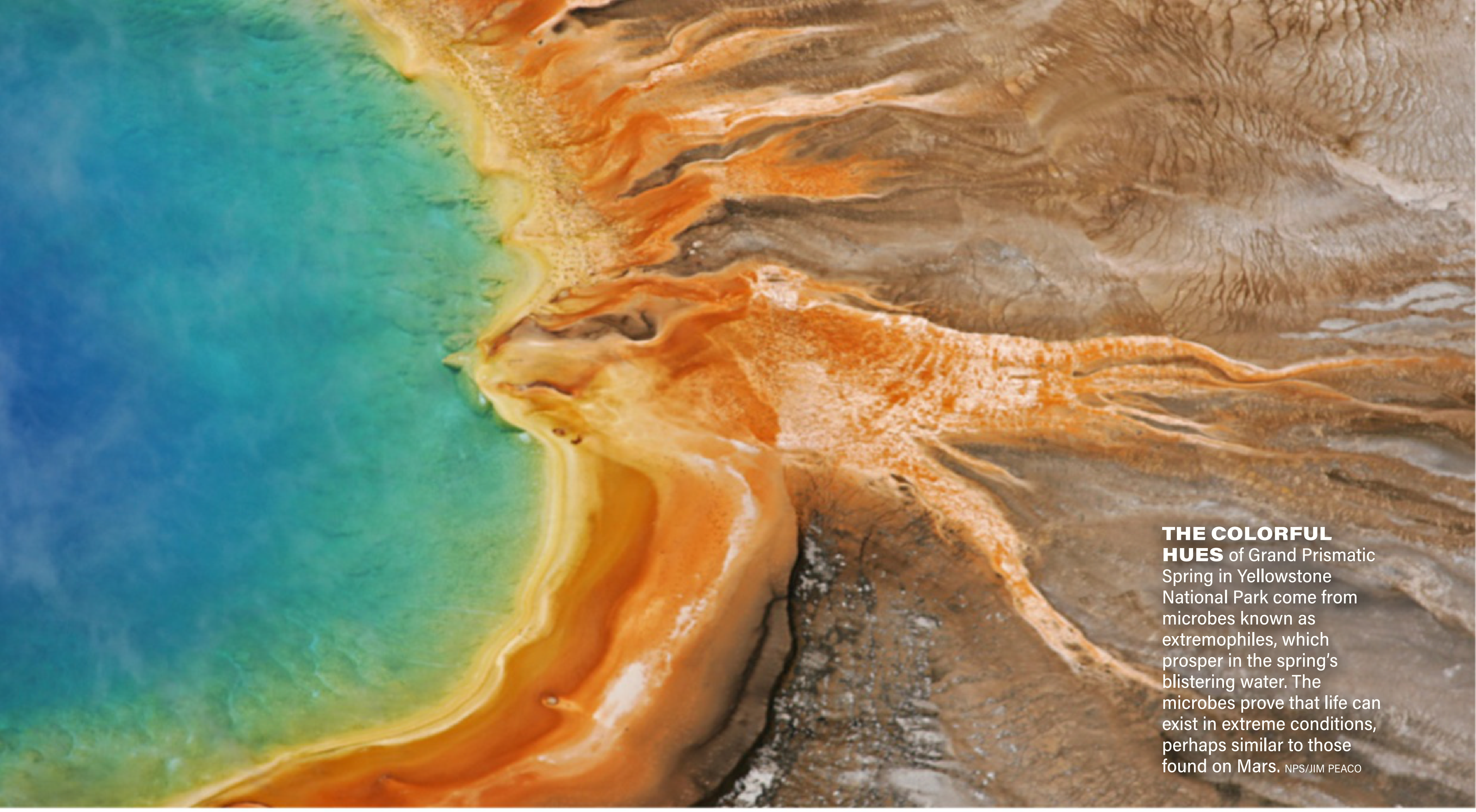
All these features support the hypothesis of Mars' habitability because they invoke the presence of liquid water. Along with the existence of energy sources and organic molecules, water is one of the three key ingredients necessary for life as we know it.

Perhaps there was a period in the first billion years or so of the planet's history when the environment was significantly warmer and the atmospheric pressure at the surface was much higher than it is now. Today, Mars' average temperatures fall well below freezing and the atmospheric pressure is nearly 100 times lower than Earth's. The melting of subsurface ice and glaciers, or even rainfall, might have allowed significant amounts of liquid water to interact with the landscape over potentially lengthy spans of geologic time during such periods.

Or perhaps the martian climate warmed during shorter and more sporadic episodes, maybe as a result of rare large impacts or occasional intervals of increased volcanic activity. During such times, ground ice might have melted and formed groundwater

THE VAST VALLES MARINERIS canyon system on Mars dominates this mosaic of images from the Viking 1 orbiter. The Red Planet has captured the human imagination since time immemorial; now, some scientists think it is the solar system's most likely abode for life beyond Earth. NASA/USGS

INSET: **THE DELTA IN JEZERO CRATER** is the target for NASA's 2020 rover. This mineral map shows clay minerals (green) that ancient rivers brought into a long-departed shallow sea. The delta's well-preserved sediments should be a great place to search for signs of past or present martian life. NASA/JPL-CALTECH/MSSS/JHUAPL



THE COLORFUL HUES of Grand Prismatic Spring in Yellowstone National Park come from microbes known as extremophiles, which prosper in the spring's blistering water. The microbes prove that life can exist in extreme conditions, perhaps similar to those found on Mars. NPS/JIM PEACO

systems that could have nurtured subterranean habitable environments. The presence of relatively fresh-looking gullies and seasonally changing dark slope streaks on some crater rims and other ridges provides evidence — though controversial — that groundwater might still be on the move in some places. This would be possible thanks to interior geothermal heat or some other energy source, which is another key ingredient to establish habitable environments.

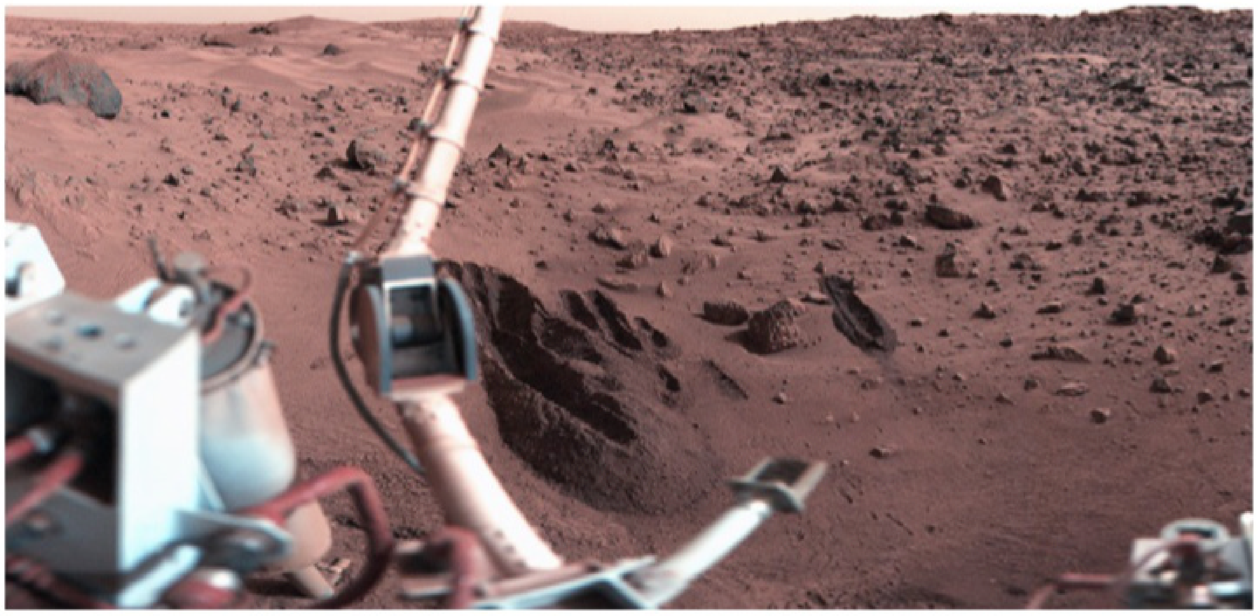
Learning whether Mars was, or still is, habitable has been a major focus of the astrobiological exploration of the Red Planet for the past few decades. Since the answer appears to be yes, the focus for future Mars exploration is turning toward asking the obvious follow-up question: Was there ever life on Mars, and is there anything alive there today?

Viking's tentative first steps

The twin Viking landers of the 1970s took a direct and somewhat risky approach to testing the hypothesis that life exists on Mars. The Vikings scooped up fine dust and soil from sites that were safe to land in but somewhat geologically unknown, and then performed organic chemistry and mass spectroscopy experiments on those materials. Given what was known at the time, the science team was taking a reasonable chance that the martian environment harbored no processes that would destroy organic molecules at the surface, and that the landing sites represented places that might have been or still were habitable.

The Viking biology results came out either negative or ambiguous. This soured many researchers on the prospects for life on Mars for several decades. However, the discoveries made by later missions have shown that neither assumption made in the Viking-era search for life was valid. Specifically, neither landing site shows any particularly strong geologic or compositional evidence that it might have been a promising place for either the existence or preservation of past (or present) life-forms.

In addition, the discoveries made by the Vikings and subsequent missions revealed not only that high-energy ultraviolet radiation from the Sun continuously bathes the surface and breaks down organic molecules, but also that the soils and dust are laced with a strongly

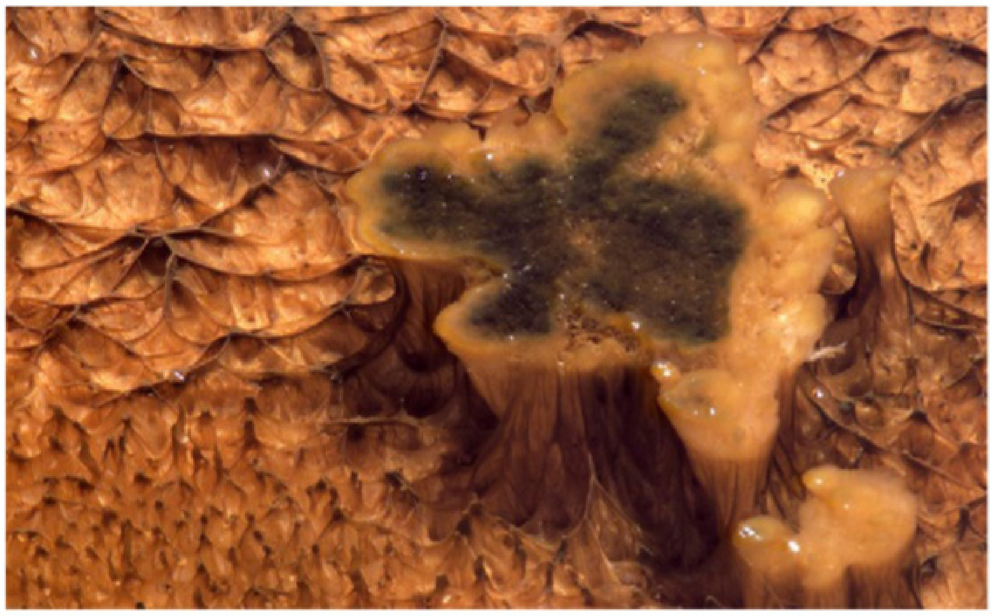


THE VIKING 1 LANDER made the first attempts to find life on Mars. The craft's robotic arm dug these trenches and delivered samples to three biology experiments, though the results proved ambiguous at best. NASA/JPL oxidizing compound — identified as perchlorate by the 2008 Phoenix Mars lander team — that *also* breaks down organic molecules. In retrospect, it shouldn't have been a surprise that the Vikings' search for organic compounds came up blank.

These findings opened up a new, two-pronged pathway in the search for martian life. First, scientists would need to find places whose geology or composition suggests that they are or once were habitable. Second, researchers would have to devise search strategies that could focus on sampling materials from beneath the surface that have had little or no exposure to the current harsh-for-organics surface environment. Sifting through data from more than a dozen successful orbiter, lander, and rover missions since the Vikings, geologists, geochemists, and mineralogists have helped resurrect the search for life on Mars using this approach.

Those missions have identified a diverse range of potentially habitable environments well beyond what scientists knew about based on Viking and earlier results. In particular, researchers have been able to interpret past and present environmental conditions through detailed spectroscopic measurements of the composition of the surface.

Just like on Earth, the kinds of minerals detected and even the specific ratios of different chemical elements in those minerals can sometimes provide unique information on the temperature, pressure, salinity, and acidity of the water prevalent at the time the minerals formed. The spectroscopy results nicely complement the geologic interpretations of the landscape that come from imaging at ever-finer scales. Detailed photos reveal that martian sedimentary rocks have experienced a rich and surprising history of buildup and erosion. Indeed, it is the fusion of both high-resolution imaging and spectroscopy that has allowed scientists to gain a deeper understanding of Mars' habitability.



THE HEAT-LOVING ALGAE in this close-up image thrive in the scorching waters of Yellowstone National Park. Scientists think that similar hydrothermal areas on the Red Planet could be good places to search for life on Mars. NPS/J. SCHMIDT

DARK, NARROW STREAKS arise from the boulder-strewn terrain at left, just one of many examples of such features seen across Mars. Some scientists think the streaks, which appear to flow down steep slopes and grow, fade, and reappear every martian year, could be seasonal flows of briny water. NASA/JPL/UNIVERSITY OF ARIZONA

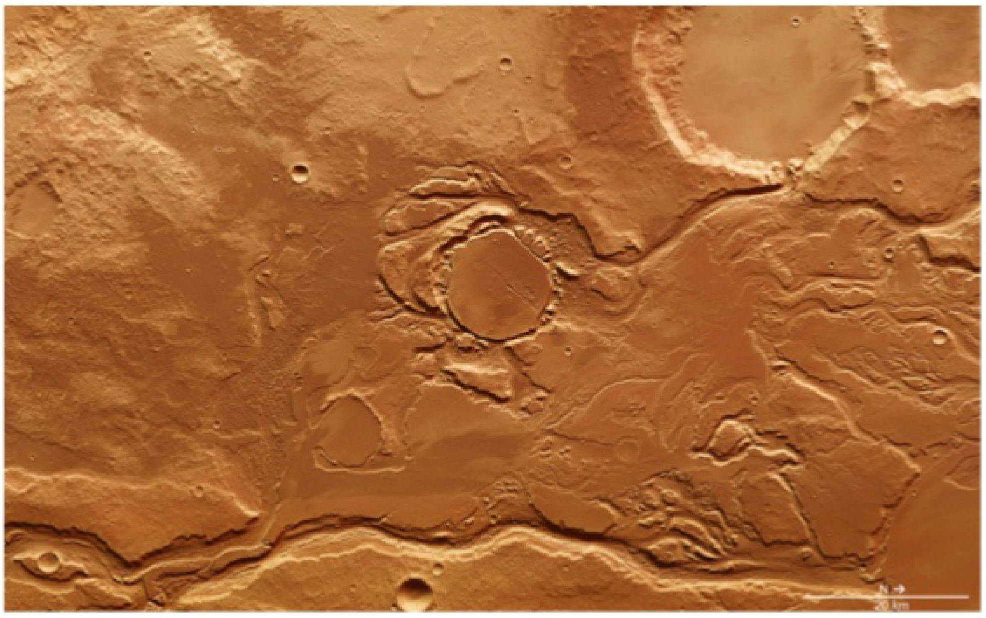
ENIGMATIC GULLIES occur on the steep slopes of many martian craters, particularly those at middle and high latitudes. Many planetary scientists believe liquid water carved the gullies, which typically show a branching pattern at their head and a fan-shaped debris apron at their base. NASA/JPL/UNIVERSITY OF ARIZONA

Mars as a living world?

The 1989 Russian Phobos 2 mission, the first successful Mars orbiter after Viking, acquired a number of high-resolution infrared spectra of the surface that revealed evidence for water or hydroxyl within specific kinds of clay minerals. This suggested that water interacted with rock in specific places early in Mars' history. Images from NASA's Mars Global Surveyor spacecraft (1999–2006), at 10 to 100 times better resolution than the Viking orbiters achieved, provided a detailed geologic context on those specific places, showing that they often associate with water-carved landforms, sedimentary layers, or both.

The ongoing Mars Reconnaissance Orbiter (MRO) mission has expanded on those earlier discoveries. Using even higher-resolution imaging and spectroscopy, this NASA spacecraft has uncovered the most diverse set of potentially habitable environments on Mars. In particular, MRO has found sedimentary layers all over the planet that contain hydrated minerals (those chemically united with water) like iron-bearing sulfates and silica materials like opal, as well as clays rich in iron, magnesium, and aluminum.

The detection and mapping of clay minerals, in particular, continues to yield



FLOWING WATER in huge volumes carved the intricate channels seen in the Mangala Valles region. Scientists suspect heat from the nearby volcanoes of the Tharsis bulge melted subsurface ice and triggered the formation of this outflow network. ESA/DLR/FU BERLIN

CURIOSITY ROVER has been exploring Gale Crater since 2012. Winds removed overlying layers from the formation and exposed the rocks some 70 million years ago. These ancient lake and stream deposits testify to a past environment that would have been favorable to microbial life. NASA/JPL-CALTECH/MSSS

exciting discoveries about the history of specific watery environments on Mars. In fact, some of that water is still there today, trapped inside these minerals. And a number of surface regions — including deltas, ancient lake beds, and hot springs environments — appear to have been persistently wet for significant periods of geologic time. This excites astrobiologists thinking about the implications of these long-lasting habitable environments on the origin and evolution of life on the Red Planet.

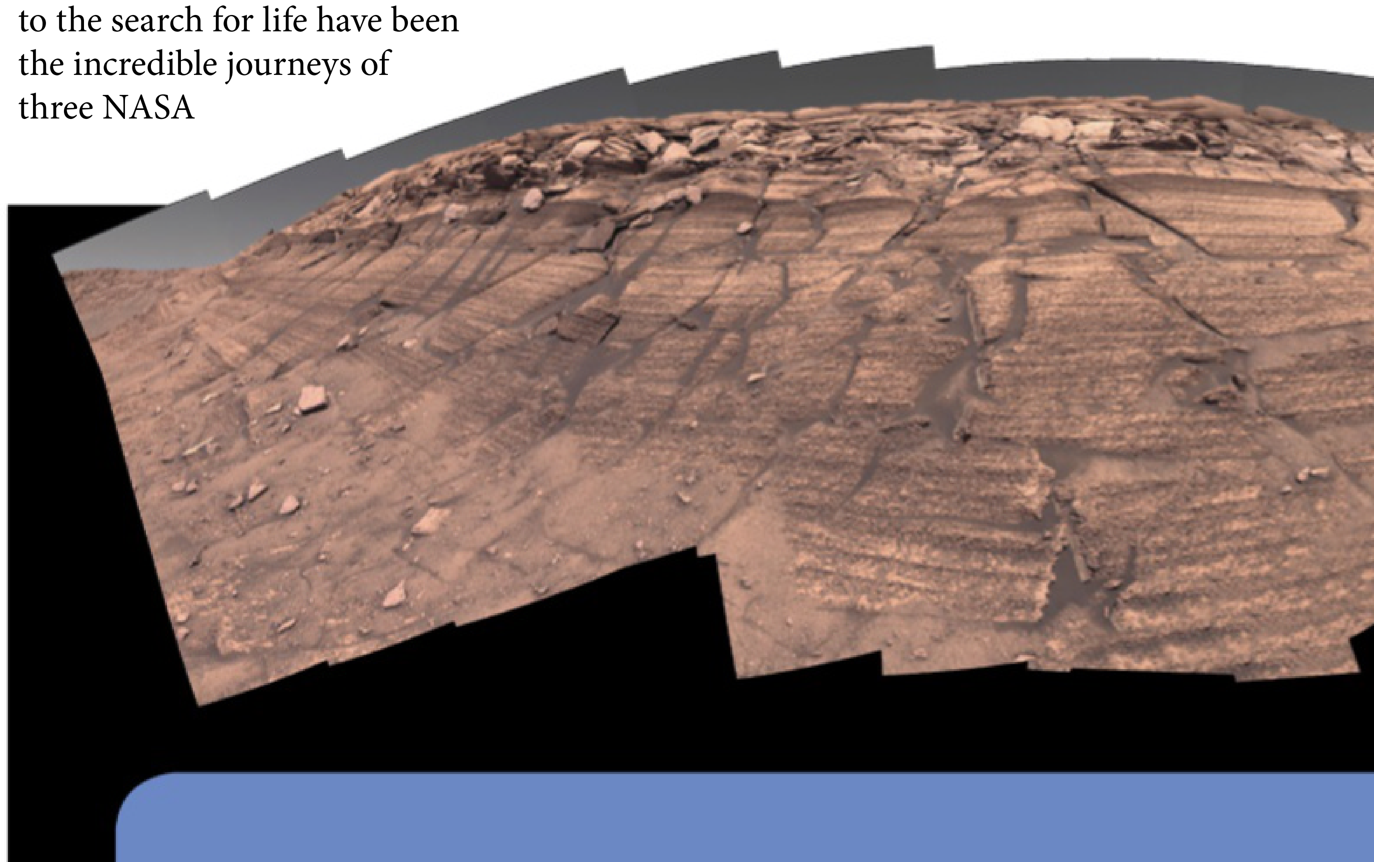
Indeed, astrobiologists studying our own planet have also played an important role in resuscitating the search for life on Mars. Over the past few decades, they have helped revolutionize our understanding of the limits of both simple and complex life on Earth. In particular, the study of extremophiles — organisms that can thrive in extreme temperatures, pressures, salinity, acidity, and/or radiation — has made the idea of ancient or even existing life in an extreme environment like the subsurface of Mars more mainstream than ever.

Roving Mars

Those discoveries have amplified the importance of the close-up lander and rover studies conducted at six additional landing sites since the two Vikings set down in 1976. Of particular relevance to the search for life have been the incredible journeys of three NASA rovers — Spirit, Opportunity, and Curiosity — each of which found minerals occurring as layers of sandstones or other fine-grained sedimentary rocks that point to the intimate interactions between these rocks and surface water and/or groundwater.

For example, after several years of exploring the primarily bone-dry volcanic plains of Gusev Crater, the Spirit rover spent more than four additional years discovering evidence of water-altered iron oxides, carbonates, and hydrated sulfates and silica in places associated with a probable hydrothermal environment. Scientists think these places are similar in some ways to the hot springs around Yellowstone National Park in Wyoming. With liquid water, ample heat and energy sources, and possibly organic molecules (at least from the constant rain of cometary and asteroidal organics that pummel all the planets), Gusev Crater certainly qualifies as having been a potentially habitable environment. Still, no direct evidence exists that the surface or subsurface is inhabited today.

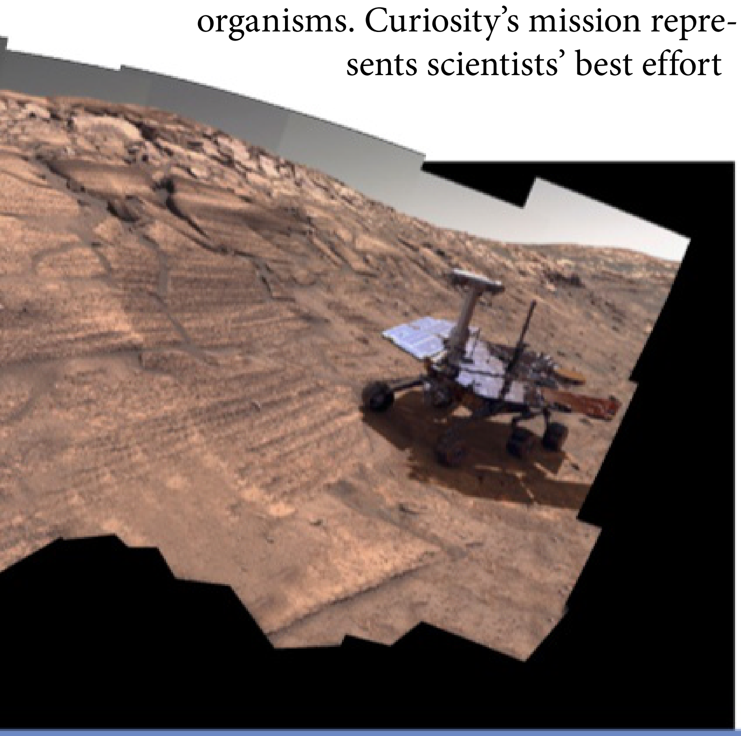
The Opportunity rover made related discoveries during its more than 14-year traverse across the flat, cratered plains of Meridiani Planum. Scientists found evidence that abundant surface water and groundwater altered the pre-existing volcanic rocks, and the specific minerals identified showed that the water varied from somewhat acidic to more typical freshwater along the rover's path. Using crater walls as probes into the subsurface, the rover team found the record of Meridiani's watery past extends many tens to hundreds of meters underground,

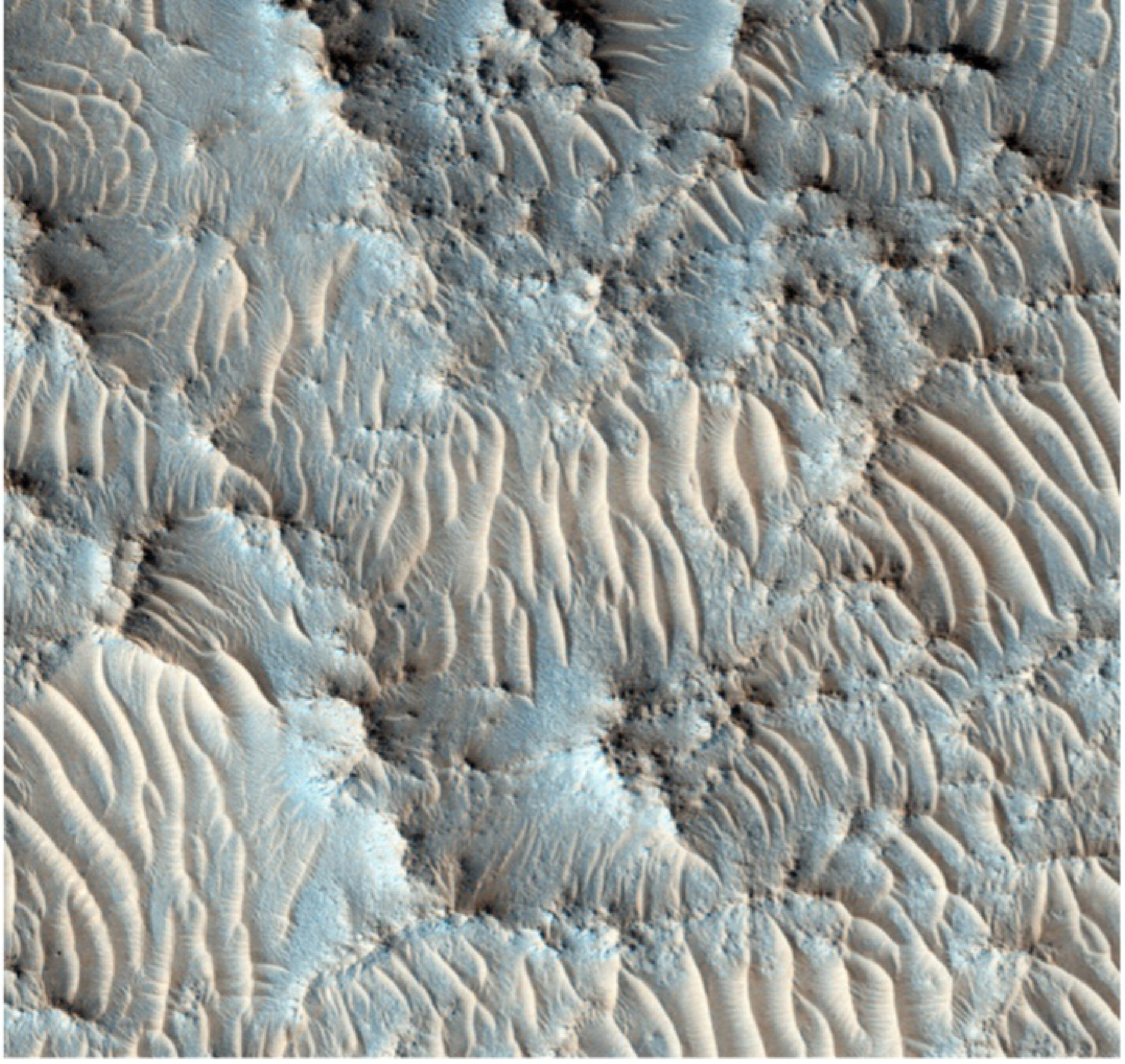


NASA'S OPPORTUNITY ROVER captured this view of Burns Cliff, which forms the southeastern wall of Endurance Crater. Most of the layered bedrock here formed in liquid water — one of three key ingredients for life as we know it. This wide-angle mosaic includes a photorealistic model of the rover for scale. NASA/JPL-CALTECH/CORNELL suggesting the environment would have been habitable over significant amounts of geologic time. Again, however, Opportunity uncovered no specific evidence of extinct or existing life. Like Spirit, it did not carry any instruments capable of making a detailed analysis of organic molecules.

The Curiosity mission is in the middle of perhaps the most ambitious effort yet to search for evidence of life on the surface and shallow subsurface of Mars. Since 2012, this rover has been exploring an enormous mound of sedimentary deposits containing clays, sulfates, and iron oxides in Gale Crater. Curiosity carries sophisticated chemical, mineralogic, and organic detection instruments as well as a drill that can penetrate the uppermost 2 inches (5 centimeters) of the subsurface. The rover is exploring an eroding landscape in which some of the sedimentary layers have been buried for perhaps billions of years before being exposed relatively recently. As such, drilling and sampling these layers provides a way to study materials that have been protected from much of the harmful ultraviolet radiation and oxidizing perchlorates for much longer than many other places on Mars.

Indeed, Curiosity's instruments have discovered relatively simple indigenous organic molecules — though they could be related to organics delivered by meteorite falls or atmospheric processes that can create small amounts of organic molecules from ultraviolet radiation. Still, every time Curiosity drills a hole, the science team could discover stunning evidence of preserved *complex* organic molecules from living or once-living organisms. Curiosity's mission represents scientists' best effort yet to systematically search for evidence of life on Mars.





SAND DUNES PACK this tiny section of Jezero Crater, the landing site for NASA's next rover, which is set to launch in summer 2020 and land in February 2021. Scientists will use high-resolution images like this one from the Mars Reconnaissance Orbiter to choose a safe, but scientifically interesting, landing site. NASA/JPL/UNIVERSITY OF ARIZONA

The future of life on Mars

The next best effort will begin in 2020, when NASA will launch a still-unnamed rover toward Jezero Crater, an ancient basin where a beautifully preserved river delta once flowed its sediments into a shallow sea. On Earth, such deltas are excellent environments for preserving organic materials and even fossils transported by gentle downstream currents. By exploring such an environment and drilling into the delta's layers, scientists will maximize their chances of finding evidence of past or present life on Mars.

Even better, NASA intends to store the Jezero drill samples in a few dozen core tubes that will be cached on the surface. Then, later in the 2020s, a future rover will collect and launch them in a capsule to Mars orbit, where another orbiter will capture the capsule and deliver it to Earth. Back here, in laboratories much more sophisticated than any we could currently deploy on Mars, those samples will be interrogated for the subtlest signs of complex organic molecules or other potential chemical or isotopic biosignatures. Such a Mars sample return mission would be the next step in searching for life on the Red Planet.

Beyond the 2020s, NASA and SpaceX are contemplating human missions to Mars. Such ventures would likely target mid-latitude regions where there's enough sunlight to provide adequate power and where ground ice could be mined most easily to help sustain a small initial settlement. The presence of ground ice, and the potential for past or present associated groundwater, means such places also could be habitable. Bringing human explorers — with their associated expertise, intuition, and expanded capabilities for accessing the subsurface — into those kinds of environments could represent the next giant leap in the search for life on Mars.

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