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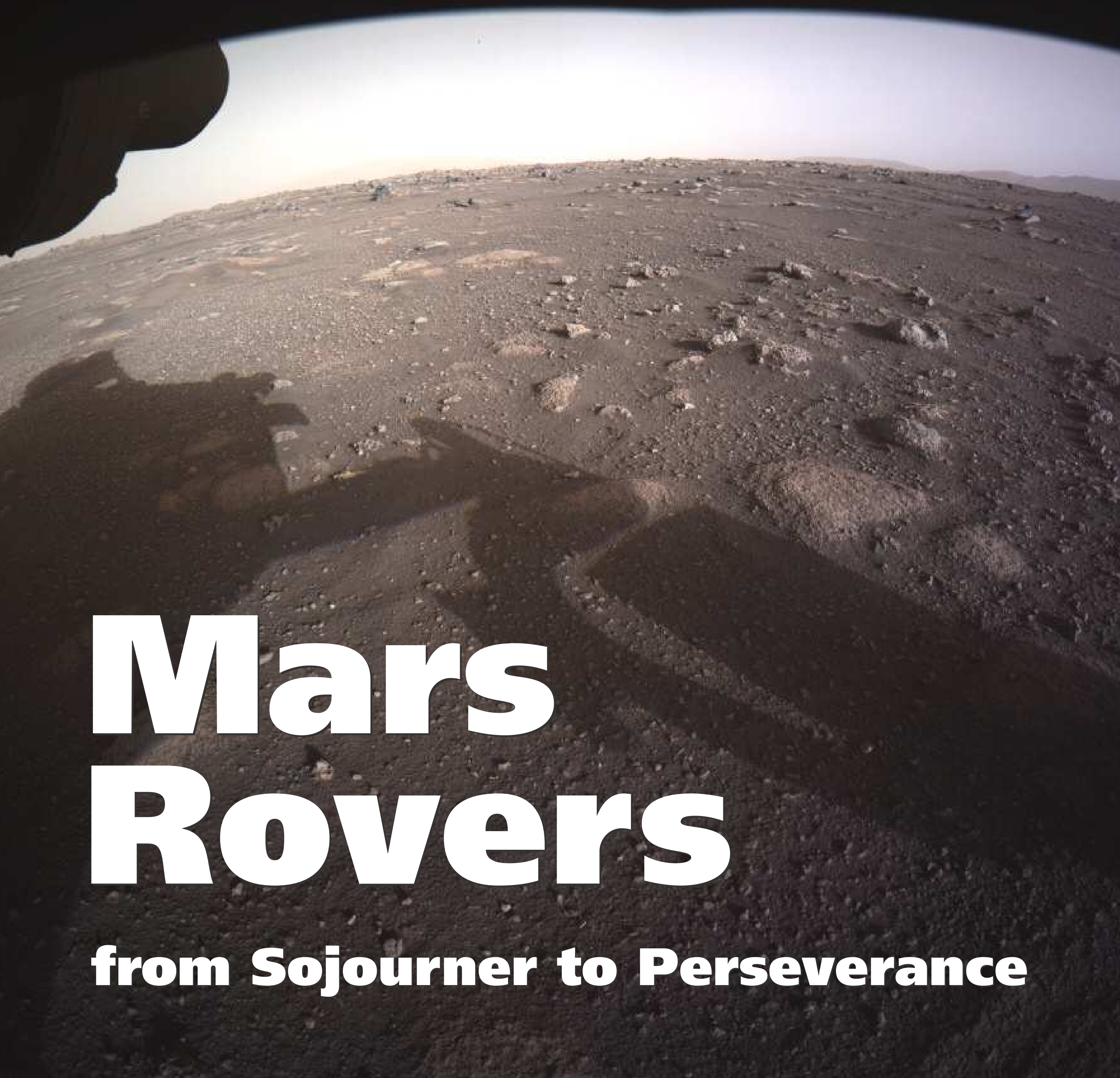
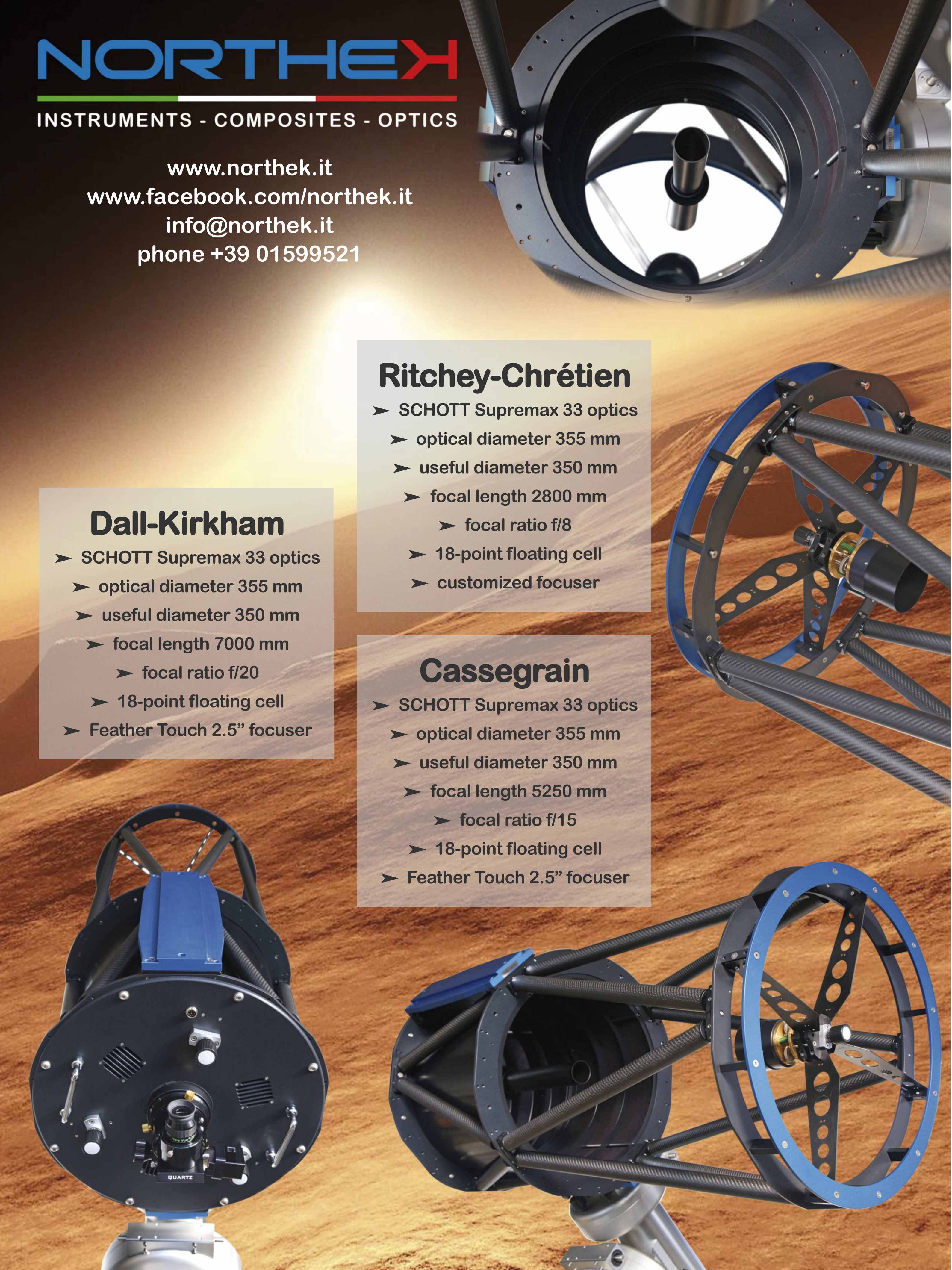
SPECIAL ISSUE



Mars Rovers

from Sojourner to Perseverance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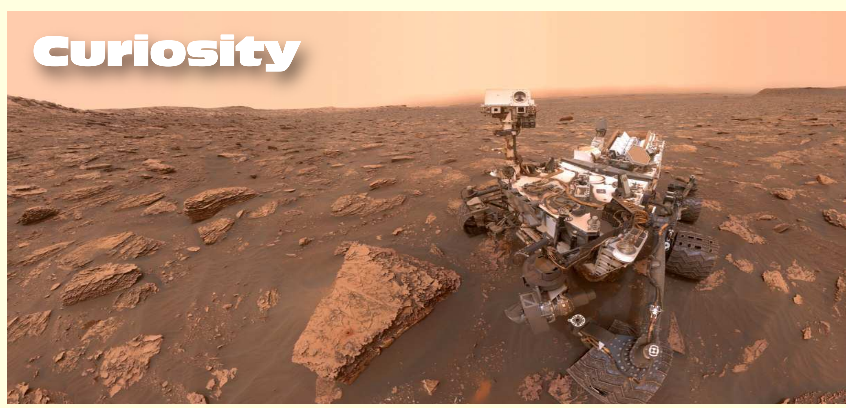
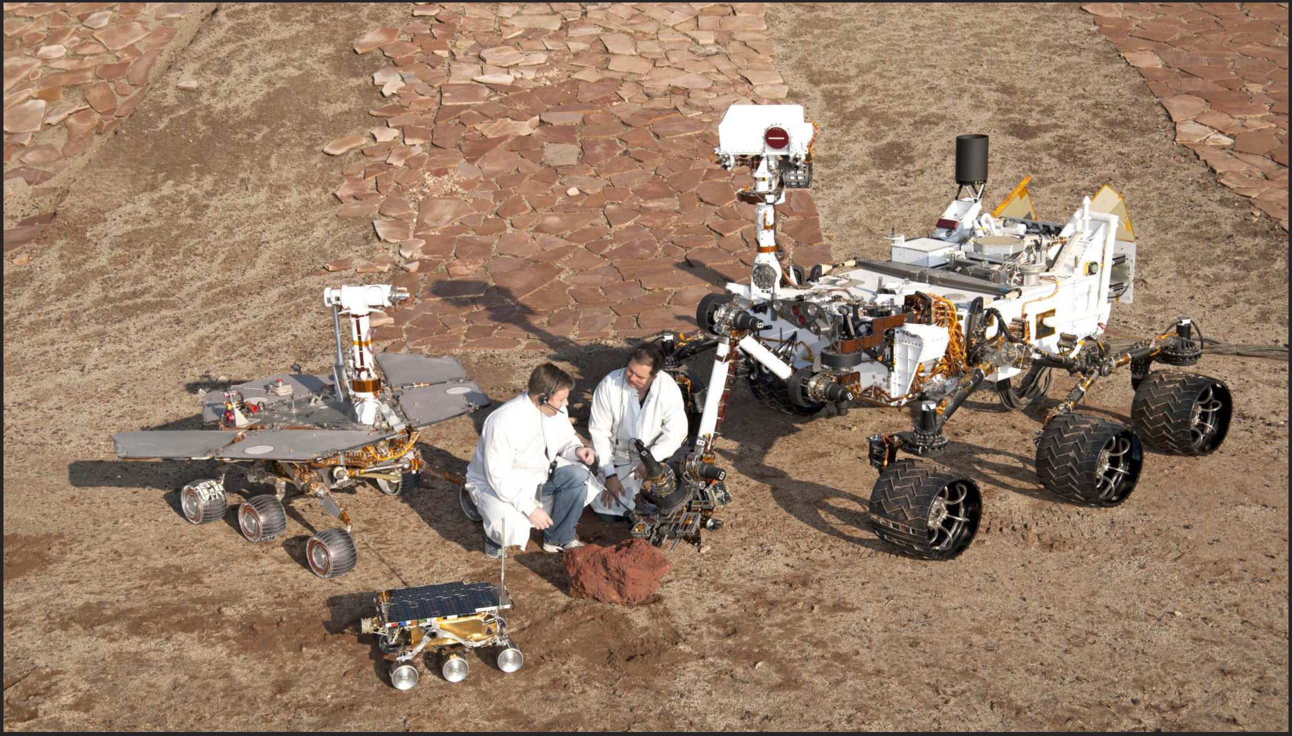


Mars Rovers

from Sojourner to Perseverance

by Michele Ferrara ❖ Based upon NASA sources ❖ Revised by Damian G. Allis, NASA Solar System Ambassador

In the mid-1970s, NASA accomplished the extraordinary feat of landing two science laboratories on Mars as part of the Viking 1 and Viking 2 missions. For the first time, two landers managed to land softly on the surface of the red planet, studying soil samples and transmitting data over an extended period. Five years earlier, a Soviet Union probe named Mars 3 had already managed to reach the surface un-



Two spacecraft engineers stand with a group of vehicles providing a comparison of three generations of Mars rovers developed at NASA's Jet Propulsion Laboratory, Pasadena, CA. The setting is JPL's Mars Yard testing area. Front and center is the flight spare for the first Mars rover, Sojourner, which landed on Mars in 1997 as part of the Mars Pathfinder Project. On the left is a Mars Exploration Rover Project test rover that is a working sibling to Spirit and Opportunity, which landed on Mars in 2004. On the right is a Mars Science Laboratory test rover the size of that project's Mars rover, Curiosity, which landed on Mars in August 2012. Sojourner and its flight spare, named Marie Curie, are 2 feet (65 centimeters) long. The Mars Exploration Rover Project's rover, including the "Surface System Test Bed" rover in this photo, are 5.2 feet (1.6 meters) long. The Mars Science Laboratory Project's Curiosity rover and "Vehicle System Test Bed" rover, on the right, are 10 feet (3 meters) long. [NASA/JPL]

The Perseverance rover in a clean room in Pasadena, California, before it was transported to Florida for its launch. Perseverance looks virtually the same as Curiosity, but there are a number of differences. The most remarkable is that this rover can sample and cache minerals. To do so, Perseverance has a new coring drill to collect samples. [NASA/JPL-Caltech]

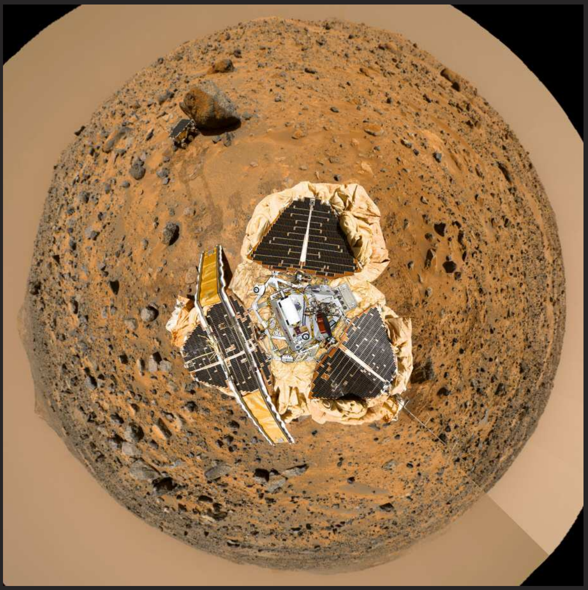
scathed but had sent data back to Earth for just 14.5 seconds. The controversial results provided by the Viking landers on the possible existence of traces of life on Mars highlighted the need for vehicles capable of moving to multiple locations on the Martian surface. This solution would have made it possible to carry out experiments at different geological sites and to choose the targets to be examined from time to time on the basis of the morphological and mineralogical characteristics of the soil.

The surface of Mars is made up of many types of rocks, each made up of a mixture of diagnostic minerals and chemicals.

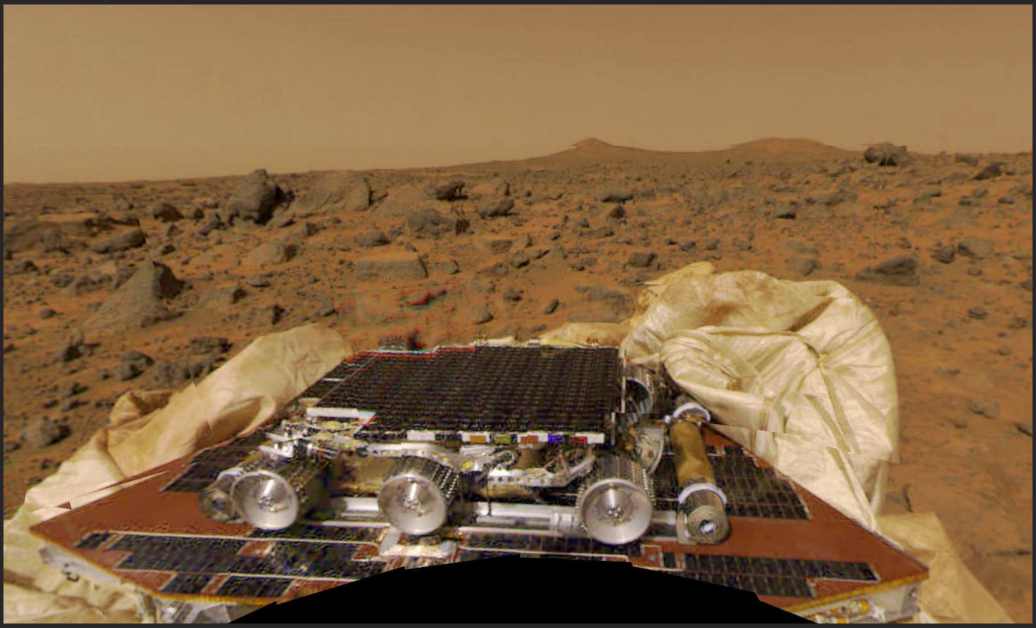
Unlike a simple lander, a rover can travel to different areas, studying different rocks and the different chemicals in each rock. These chemicals can tell scientists something about the environments that changed that rock over time and, in the search for ancient life, reveal clues of past water activity. Based on the many benefits of rovers, yet in a phase of considerable budget cuts for the American space agency, NASA and the Jet Propulsion Laboratory set up a mission known as Mars Pathfinder (MPF) in the early 1990s. The mission's goal was to demonstrate the technological feasibility of sending a stationary lander and a robotic rover to Mars to explore the surface.

Sojourner

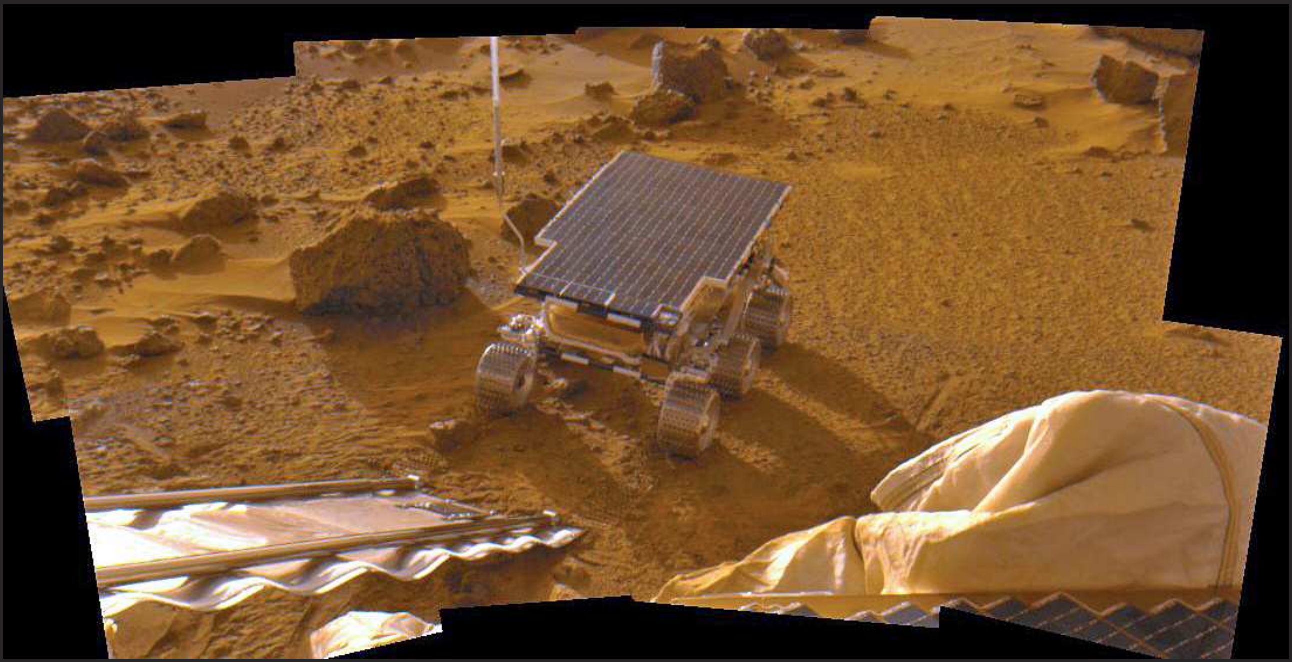
The mission launch took place on December 4, 1996, landing on Mars on July 4, 1997. Mars Pathfinder not only achieved its goal, but also returned an unprecedented amount of data while far exceeded the primary mission's uptime. Both the lander and the rover, named Sojourner, carried instruments for both scientific observations and to provide engineering data on the new technologies being demonstrated during the mission. Mars Pathfinder used an innovative method to directly enter the Martian atmosphere, assisted by a parachute to slow the early descent through the thin atmosphere and then a giant airbag system to cushion the impact. The landing site, an ancient floodplain in the northern hemisphere of Mars known as *Ares Vallis*, is among the rockiest regions of Mars. It was chosen because scientists believed it was a relatively safe surface to land on and because it contained a wide variety of rocks possibly deposited during an ancient catastrophic flood.



Mars Pathfinder "Filled Donut" mosaic, made of 3 data sets: (1) a color mosaic image of the "Gallery Panorama," (2) an image which indicates the distance to the nearest object at each pixel location, referred to as a range image, and (3) a digital image of a full-scale museum model of the MPF Lander. [NASA/JPL]



The Sojourner rover and undeployed ramps onboard the Mars Pathfinder spacecraft can be seen in this image, by the Imager for Mars Pathfinder (IMP) on July 4, 1997, (sol 1). [NASA/JPL]

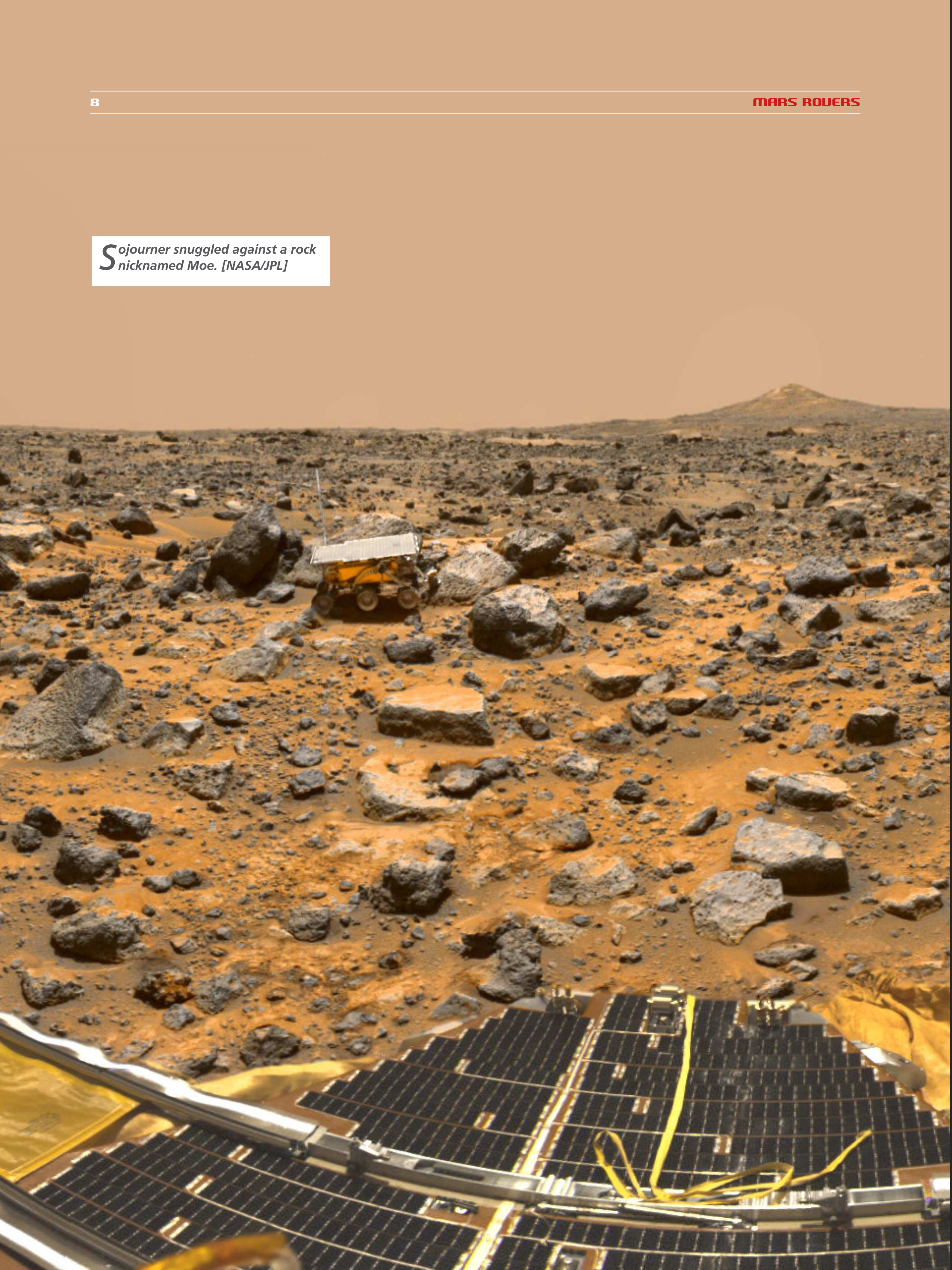


This 8-image mosaic is of Sojourner, NASA's first rover on Mars, and was acquired during the late afternoon on Sol 2, the second Martian day on the planet, as part of an "insurance panorama." This color image was designed as "insurance" against camera failure upon deployment. However, the camera deployment was successful, leaving the insurance panorama to be downlinked to Earth several weeks later. Ironically enough, the insurance panorama contains some of the best quality image data because of the lossless data compression and relatively dust-free state of the camera and associated lander/rover hardware on Sol 2. [NASA/JPL]

From landing to final data transmission, Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images taken by the lander and 550 images taken by the rover, more than 15 chemical analyses of rocks and soil, and data on winds and other meteorological features.

The results of investigations conducted by scientific instruments on both the lander and the rover have suggested that Mars may have been hot and humid in the distant past, with water present in a liquid state and the surface blanketed by a denser atmosphere. Sojourner was the first vehicle with wheels to roam another planet – 65 cm long, 48 cm wide, 30 cm high,

Sojourner view of Mars Pathfinder base station (Sagan Memorial Station) after driving off the ramps onto Mars. [NASA/JPL]

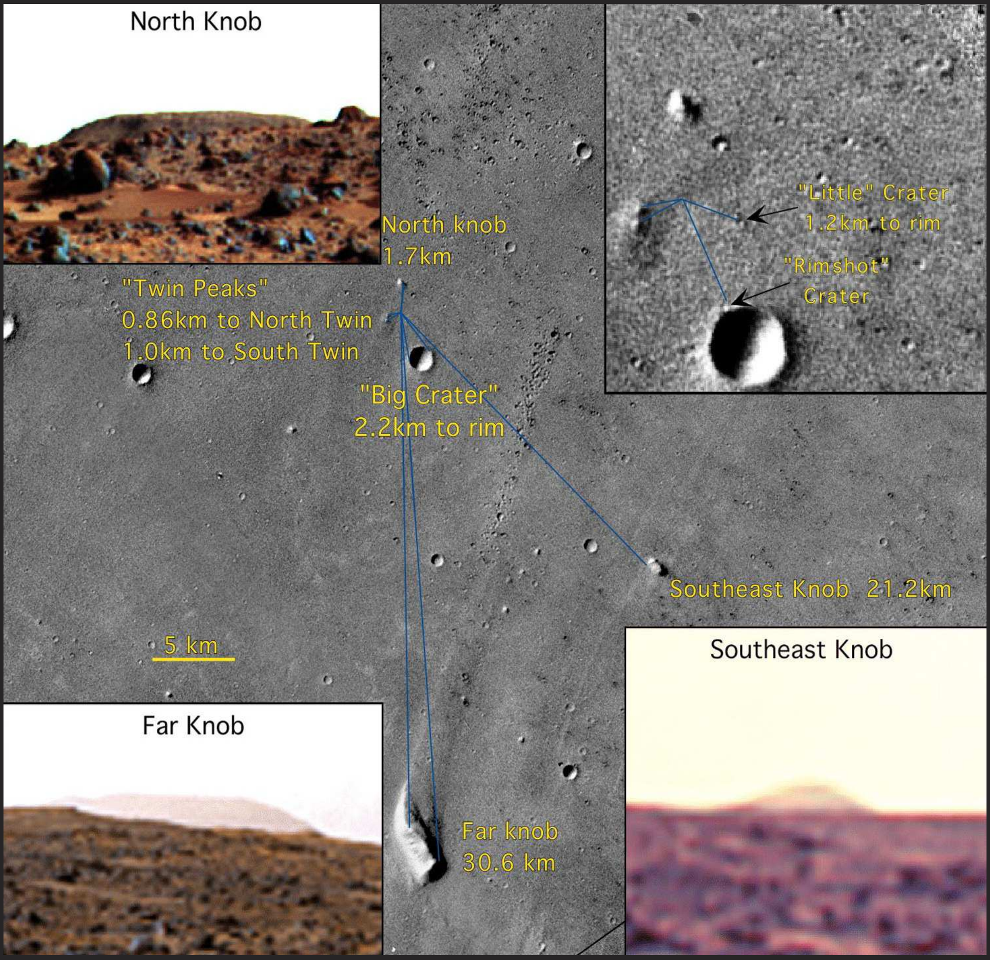


Sojourner snuggled against a rock nicknamed Moe. [NASA/JPL]

MARS PATHFINDER

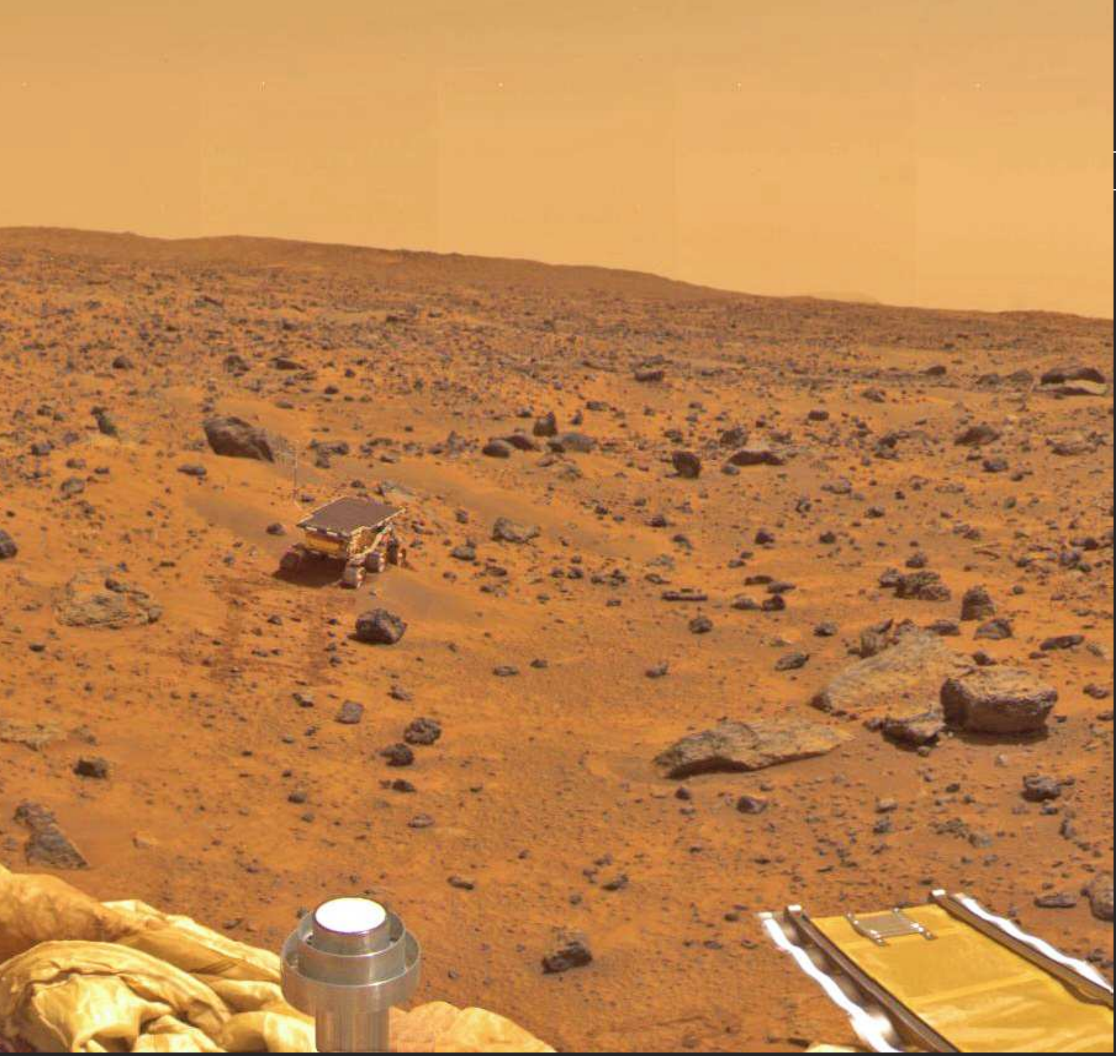
SCIENCE INSTRUMENTS

- **Alpha/Proton/X-ray Spectrometer (APXS): Determined the elemental composition of rocks and soils.**
- **Three Cameras: provided images of the surrounding terrain for geological studies, and documented the performance and operating environment for Pathfinder mission technologies.**
- **Atmospheric Structure Instrument/Meteorology Package (ASI/MET): Measured the Martian atmosphere during Pathfinder's descent to the surface, and provided meteorological measurements at the lander.**



Mars Pathfinder Landing Site. Mosaic of Viking orbiter images illustrating the location of the lander (19.17 degrees N, 33.21 degrees W in the USGS reference frame) with respect to surface features. Left, an animated overview of the Mars Pathfinder mission. [NASA/JPL]

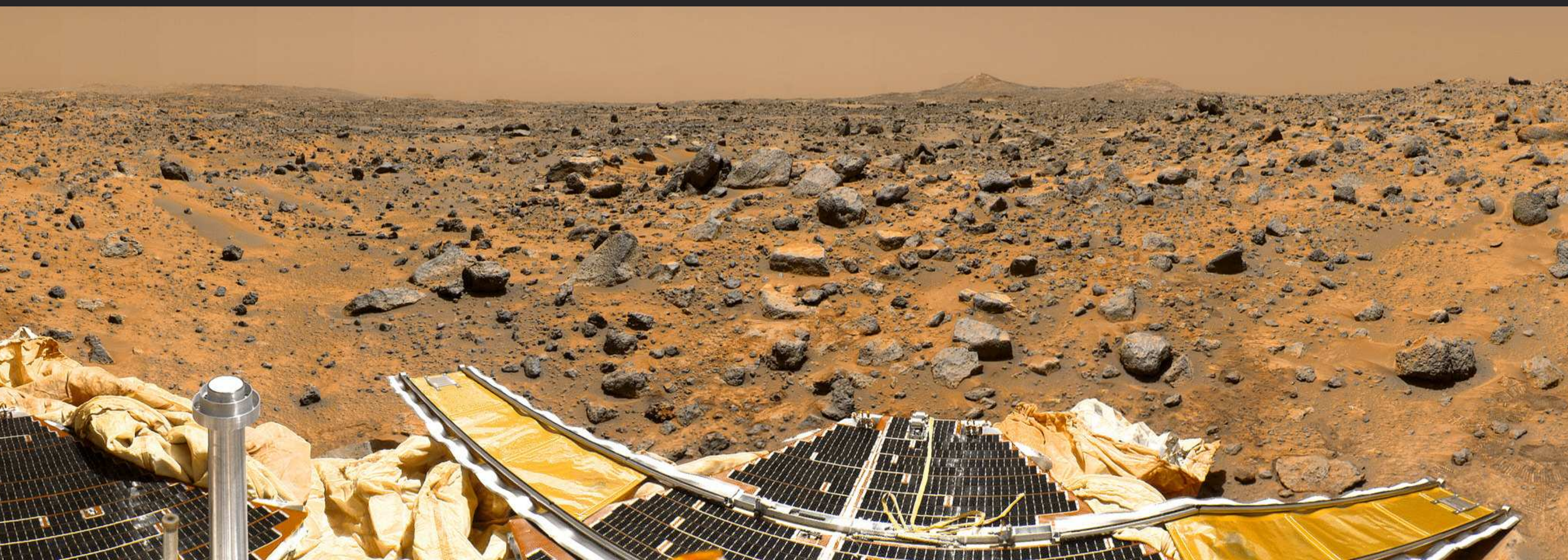
weighing in at 10.5 kg and with six wheels, it had front and rear cameras and hardware to conduct various scientific experiments. Designed for a mission lasting just seven sols (1 sol ≃ 1.0275 Earth days), with a possible extension to 30 sols, it was actually active for 83 sols (85 Earth days). The rover communicated with Earth via the Pathfinder base sta-

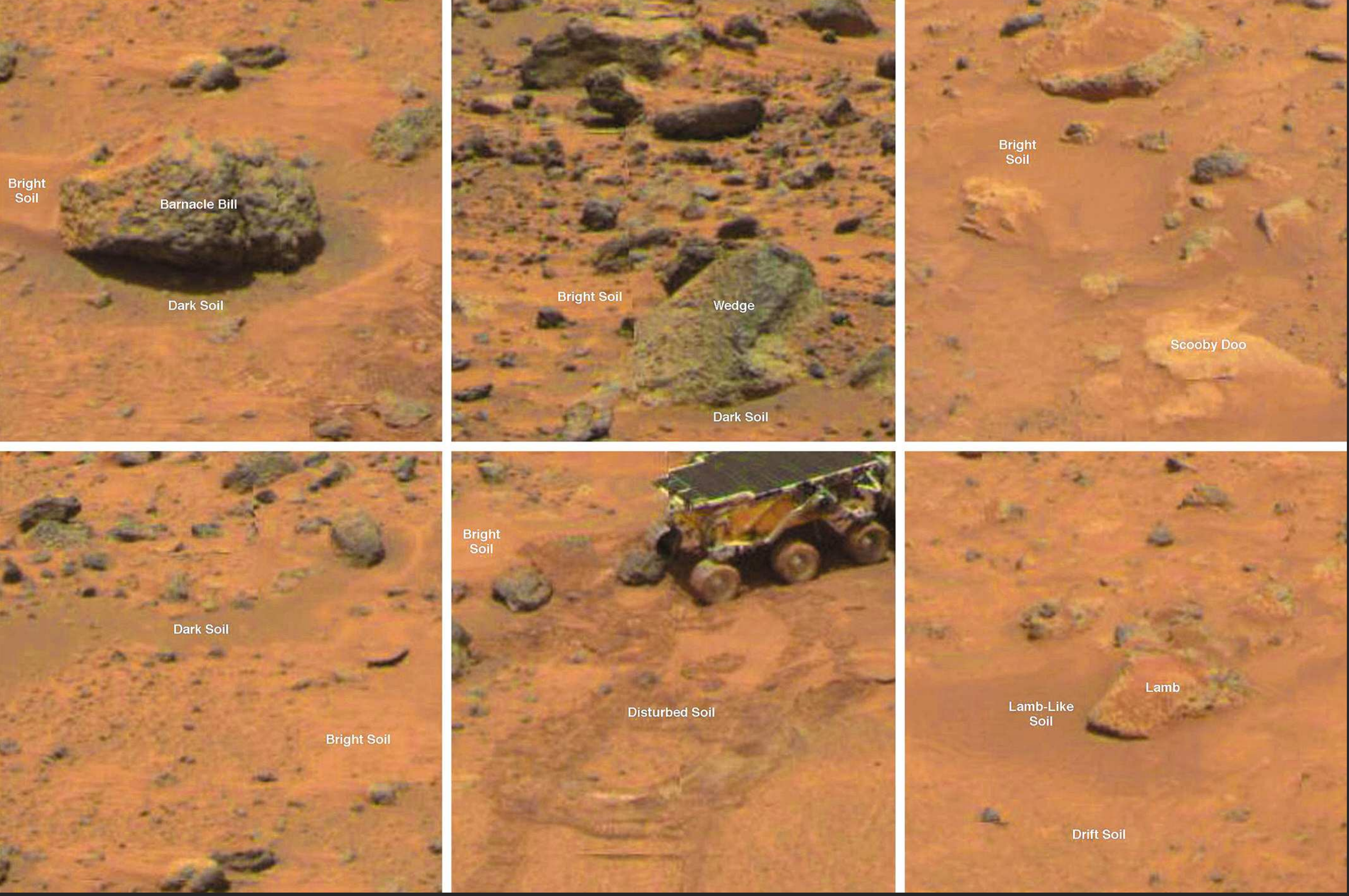


tion, which had its last communication session on September 27, 1997. That final communication also marked the end of Sojourner's mission, which up to that point had covered a distance of just over 100 meters. During that journey, the rover had made a series of analyses, the first of which was on a rock called "Barnacle Bill." The Alpha Proton X-ray Spectrometer (APXS) was used to determine its composition. The instrument took about ten hours to perform a full scan of the sample, finding many elements but only a small amount of hydrogen, which made up only 0.1 percent of the

TOP MARS PATHFINDER SCIENCE FINDINGS

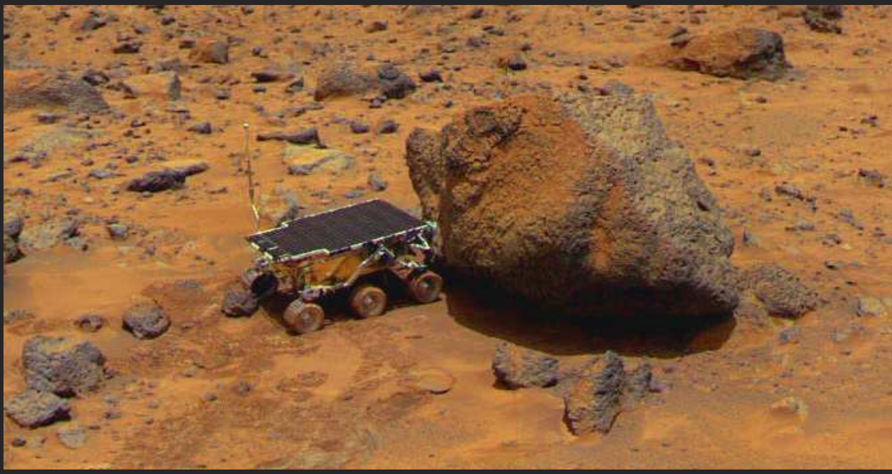
- **Rounded pebbles and cobbles at the landing site, and other observations, suggested conglomerates that formed in running water during a warmer past in which liquid water was stable.**
- **Radio tracking of Mars Pathfinder provided a precise measure of the lander's location and Mars' pole of rotation. The measurements suggested that the radius of the planet's central metallic core is greater than 800 miles (1,300 kilometers) but less than roughly 1,250 miles (2,000 kilometers).**
- **Airborne dust is magnetic, and its characteristics suggest the magnetic mineral is maghemite, a very magnetic form of iron oxide, which may have been freeze-dried on the particles as a stain or cement. An active water cycle in the past may have leached out the iron from materials in the crust.**
- **Dust devils were seen and frequently measured by temperature, wind and pressure sensors. Observations suggested that these gusts are a mechanism for mixing dust into the atmosphere.**
- **Early morning water ice clouds were seen in the lower atmosphere.**
- **Abrupt temperature fluctuations were recorded in the morning, suggesting that the atmosphere is warmed by the planet's surface, with heat convected upward in small eddies.**

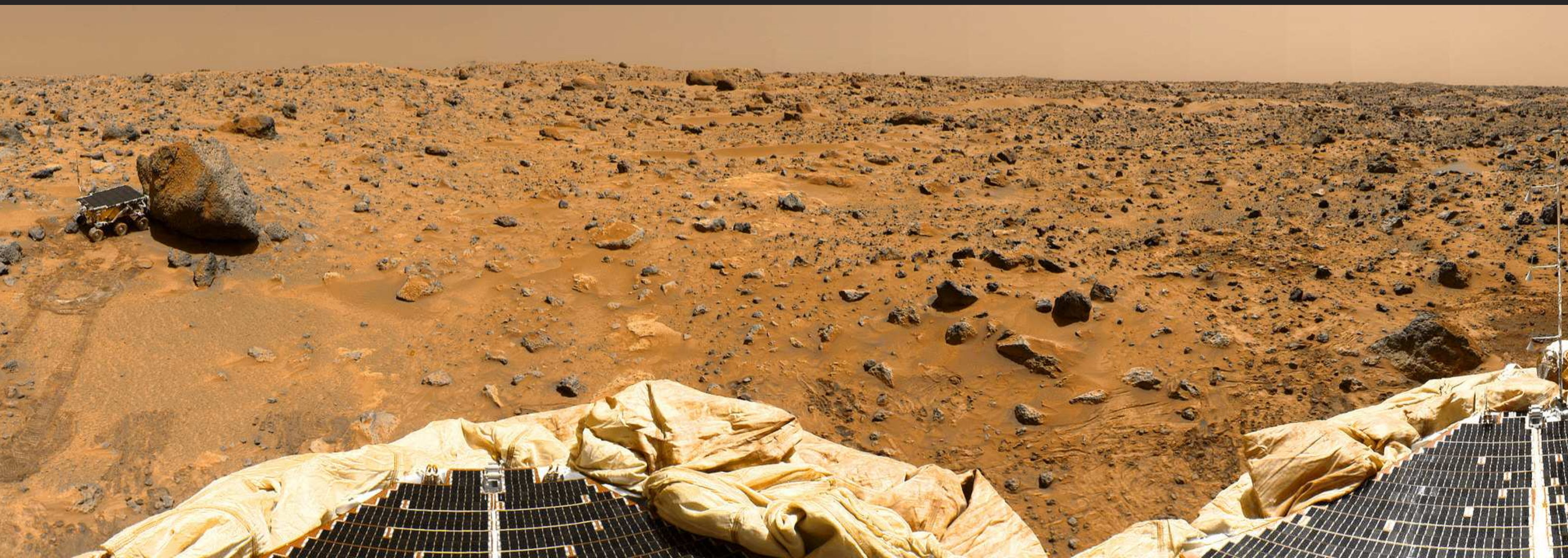




Previous page. Up, Sojourner atop the "Mermaid Dune" on Sol 30. Below, 360° view of the Mars Pathfinder landing site. This page, above, type areas of rocks and soils. (A) Dark rock type, e.g. "Barnacle Bill". Reflectance spectra typical of fresh basalt. (B) Bright rock type, e.g. "Wedge". Reflectance spectra typical of weathered basalt. (C) Pink rock type, e.g. "Scooby Doo". (D) Dark soil type, typically found on the windward sides of rocks or in rock-free areas. (E) Disturbed soil type: the result of changes in soil texture and compaction caused by movement of the rover and retraction of the lander airbag. (F) Lamb-like soil type, with characteristics intermediate between the bright and dark soils.

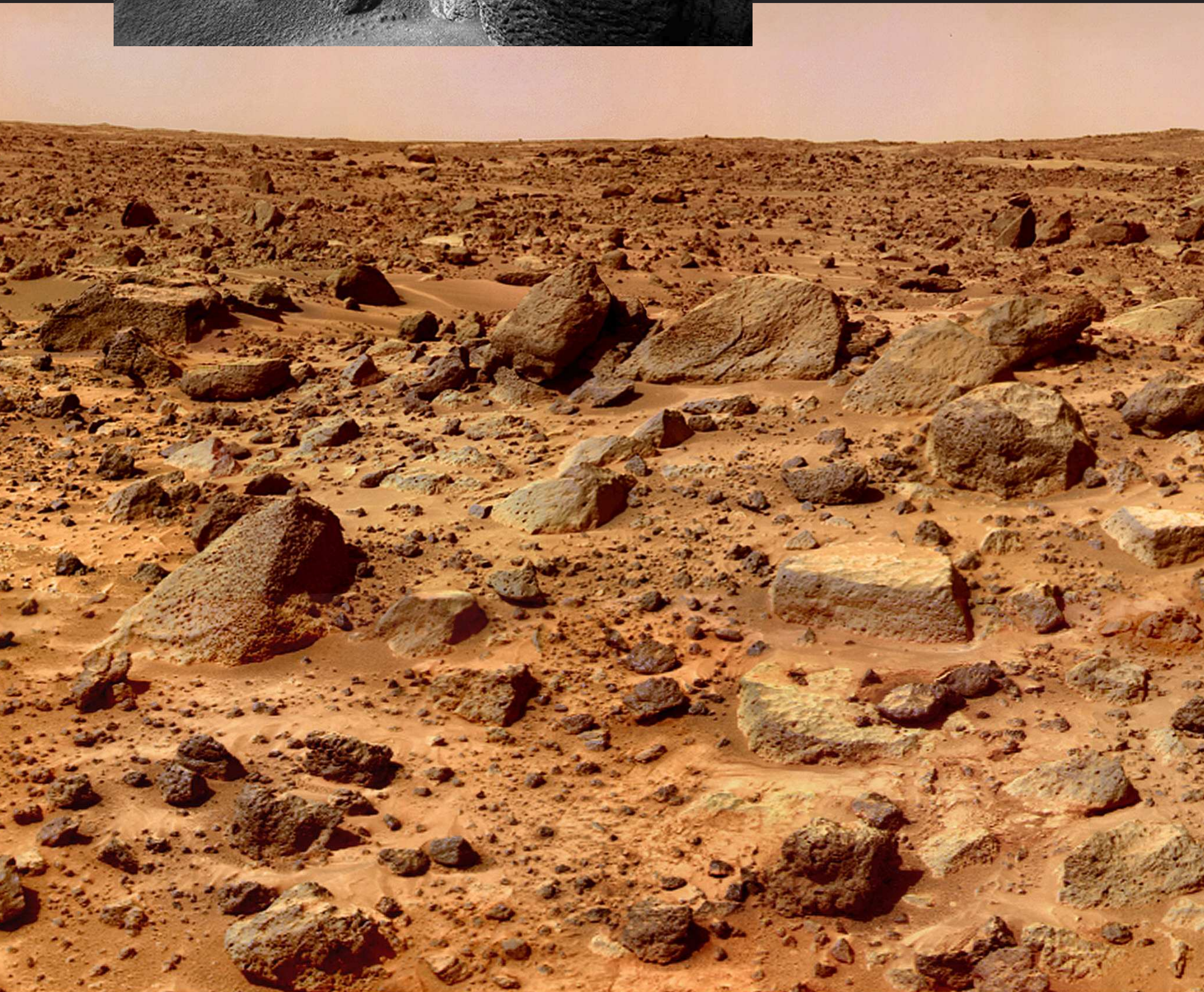
To the right, Sojourner analyzes "Yogi Rock" with the Alpha Proton X-ray Spectrometer (APXS). This rock was the first on Mars found to be made of basalt, which suggests previous volcanic activity in the region as basalt is an igneous rock. [NASA/JPL]





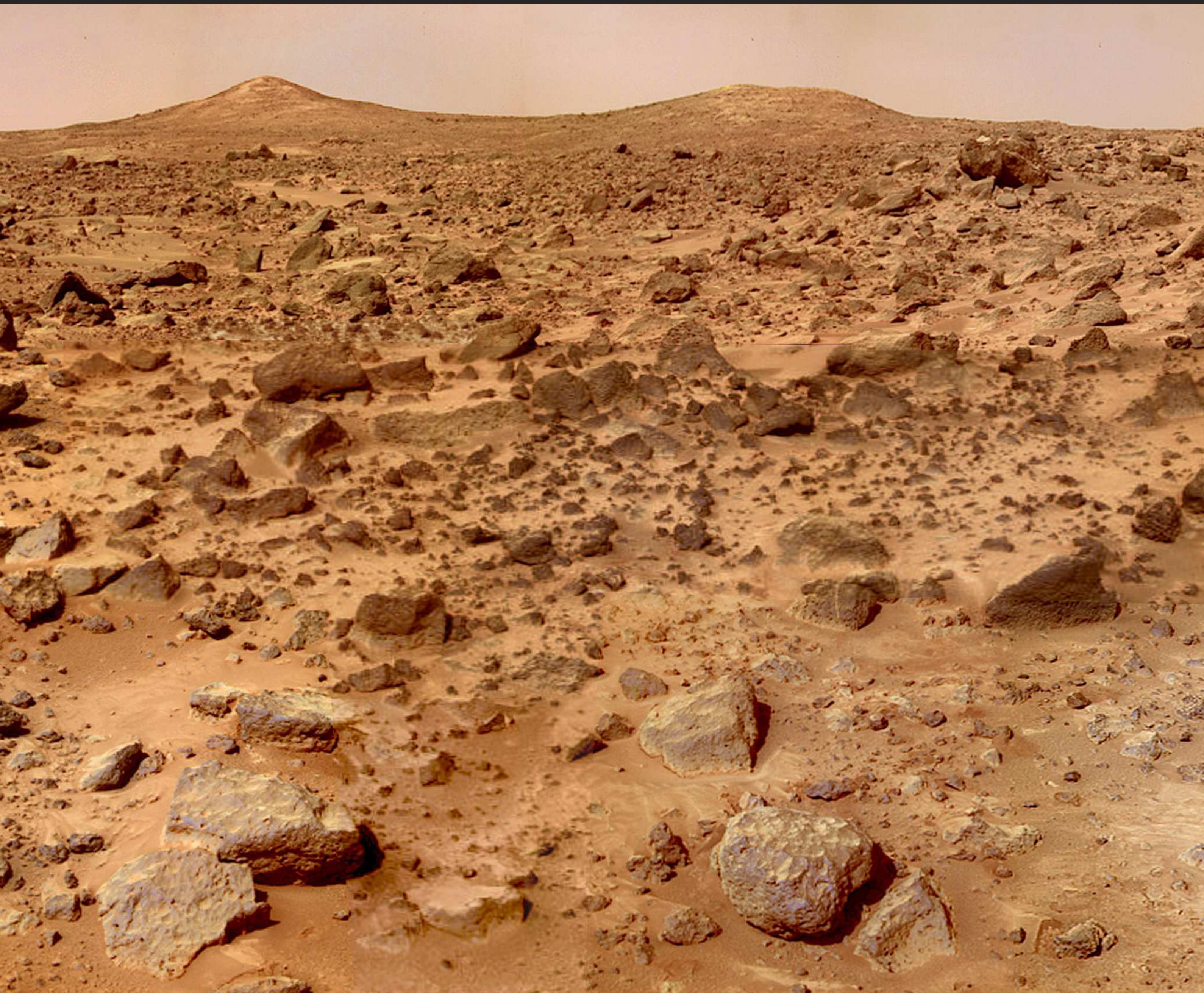
This view of the rock "Chimp" was acquired by the Sojourner rover's right front camera on Sol 74. Below, the "Twin Peaks", modest-size hills to the southwest of the Mars Pathfinder landing site. [NASA/JPL]

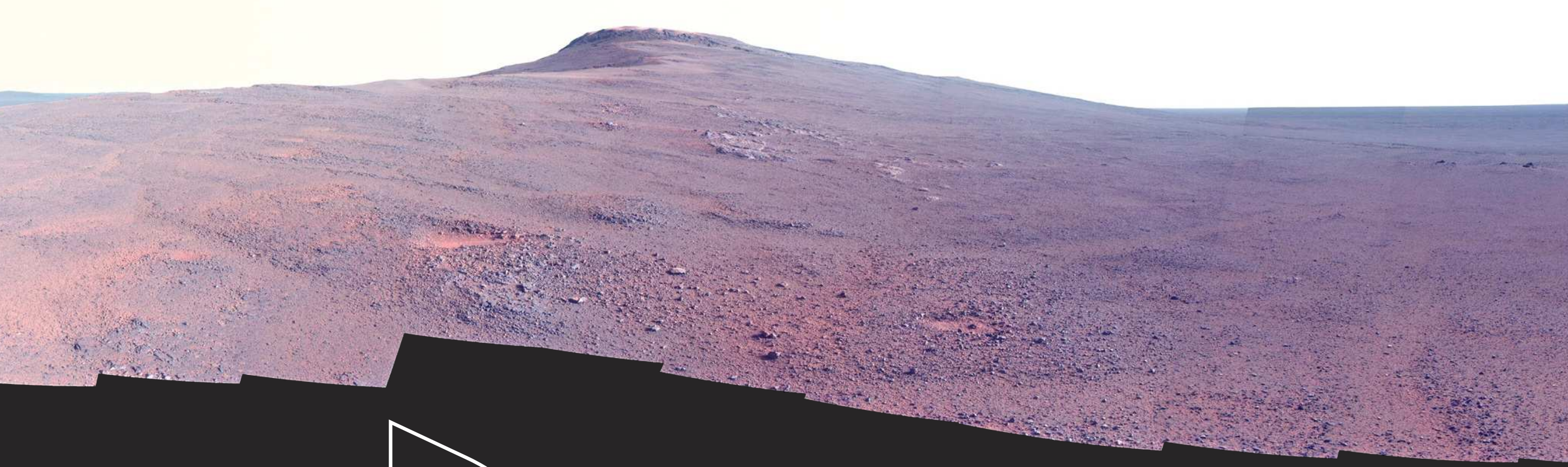
rock's mass – indicating very little water content. The APXS worked by irradiating rocks and soil samples with alpha particles (helium nuclei, i.e. two protons and two neutrons bound together). The results indi-



Martian clouds photographed by the Mars Pathfinder (IMP) Imager on Sol 16, about forty minutes before dawn. [NASA/JPL]

cated that Barnacle Bill was very similar to terrestrial andesites, confirming volcanic activity in the past. After Barnacle Bill, Sojourner analyzed a rock called "Yogi" with the APXS, which turned out to be of basaltic origin, therefore more primitive than Barnacle Bill. The shape and texture of Yogi show that it was probably deposited there by a flood. Another rock, called "Moe," instead showed signs of erosion caused by wind. Most of the rocks analyzed showed a high silicon content. Sojourner also visited an area known as "Rock Garden," where the rover encountered crescent-shaped dunes, similar to the crescent-shaped dunes on Earth, which are typically formed by winds blowing in one direction only.

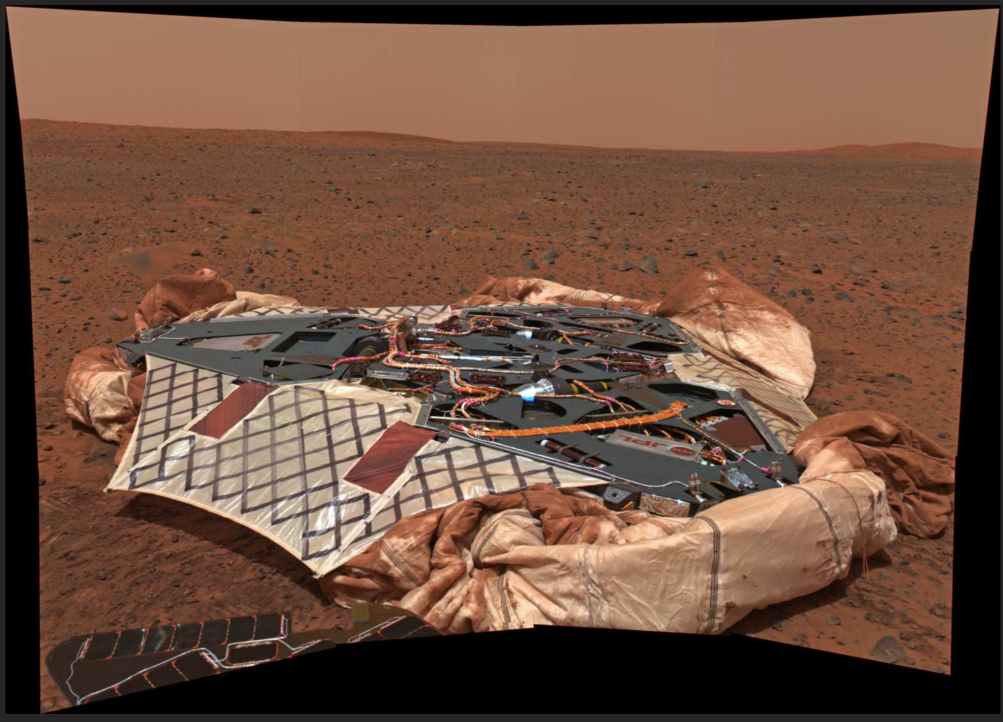


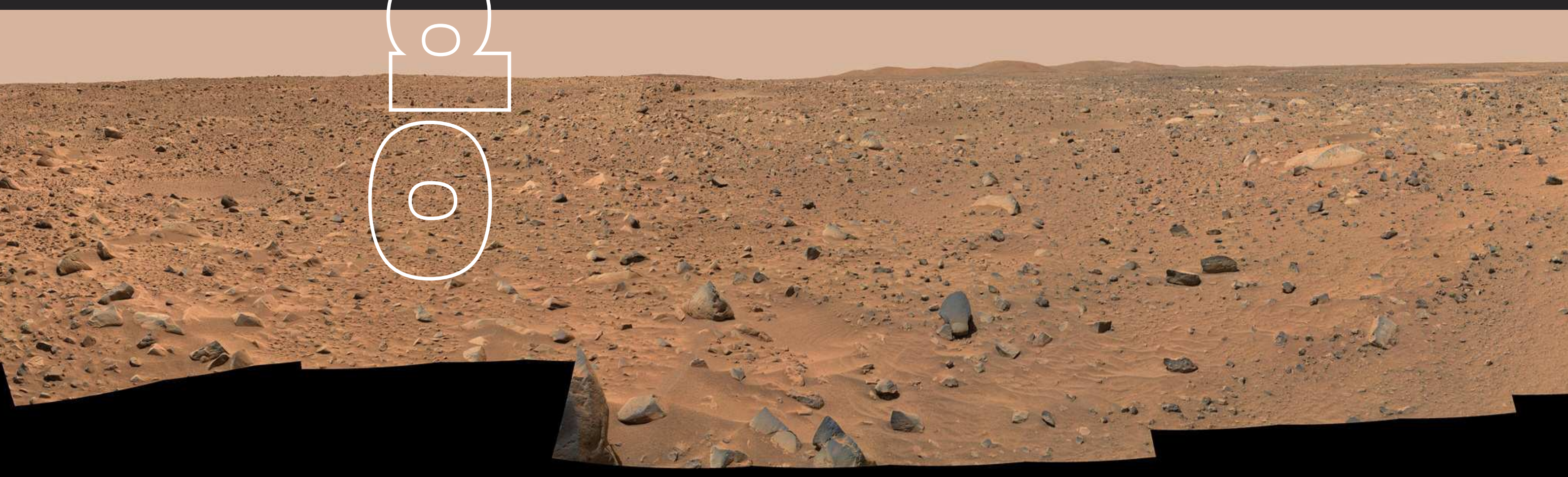


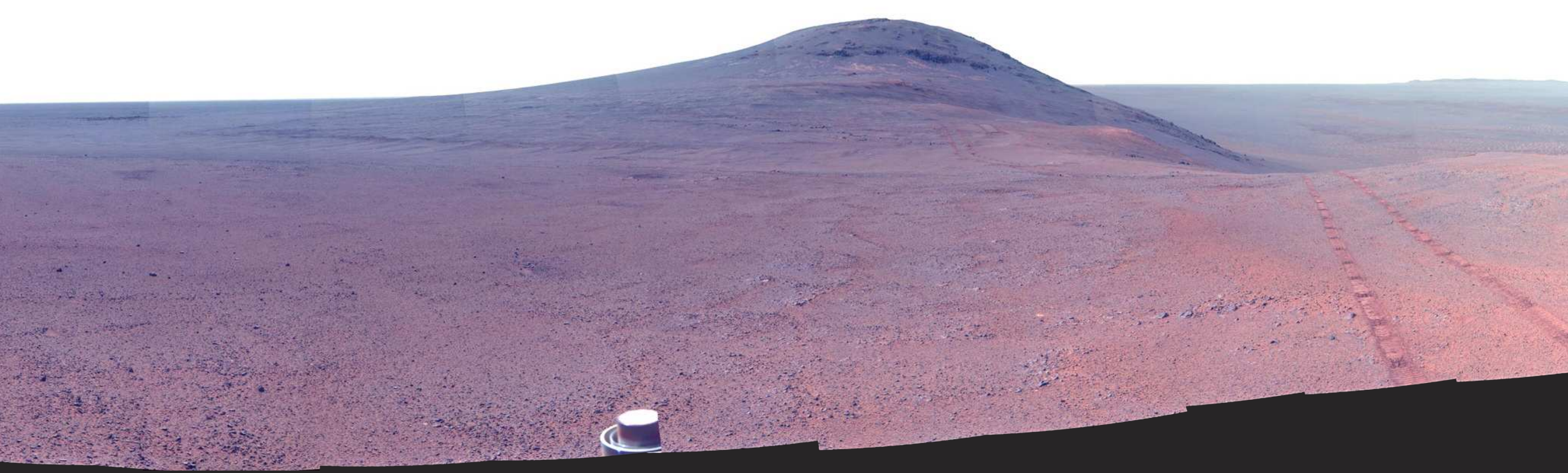
Spirit & Opportunity

Following the success of the Sojourner rover, NASA wanted to send two new rovers to learn much more about Mars. The rovers, named Spirit and Opportunity, were part of the Mars Exploration Rover mission, a long-term robotic exploration effort of the red planet. In 2003, Spirit and Opportunity were launched towards the Red Planet on June 10 and July 7, respectively. The landings on Mars took place on Jan-

Above, an enhanced-color panorama of Perseverance Valley taken by Opportunity. The panorama spans about three-fourths of a full-circle view, from southeastward on the left, through westward in the middle, to northeastward on the right. High points visible on the rim of Endeavour Crater include "Winnemucca" on the left and "Cape Tribulation" on the right. Below, an image mosaic taken by the panoramic camera onboard the Mars Exploration Rover Spirit, shows the rover's landing site, the Columbia Memorial Station, at Gusev Crater. [NASA/JPL-Caltech/Cornell/Arizona State Univ.]

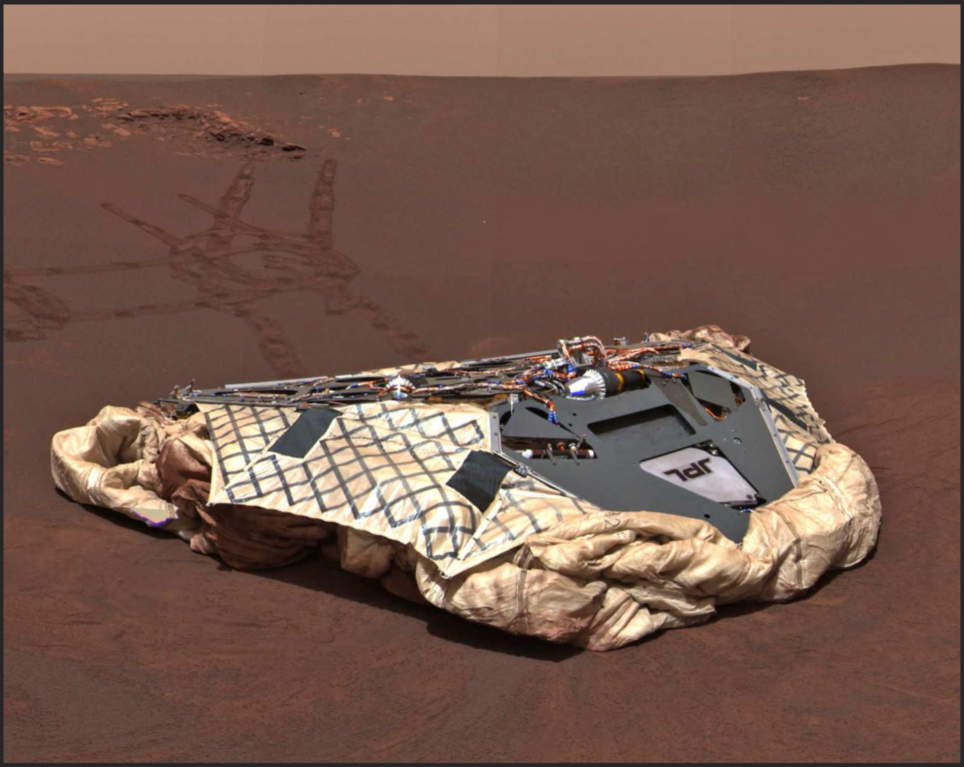




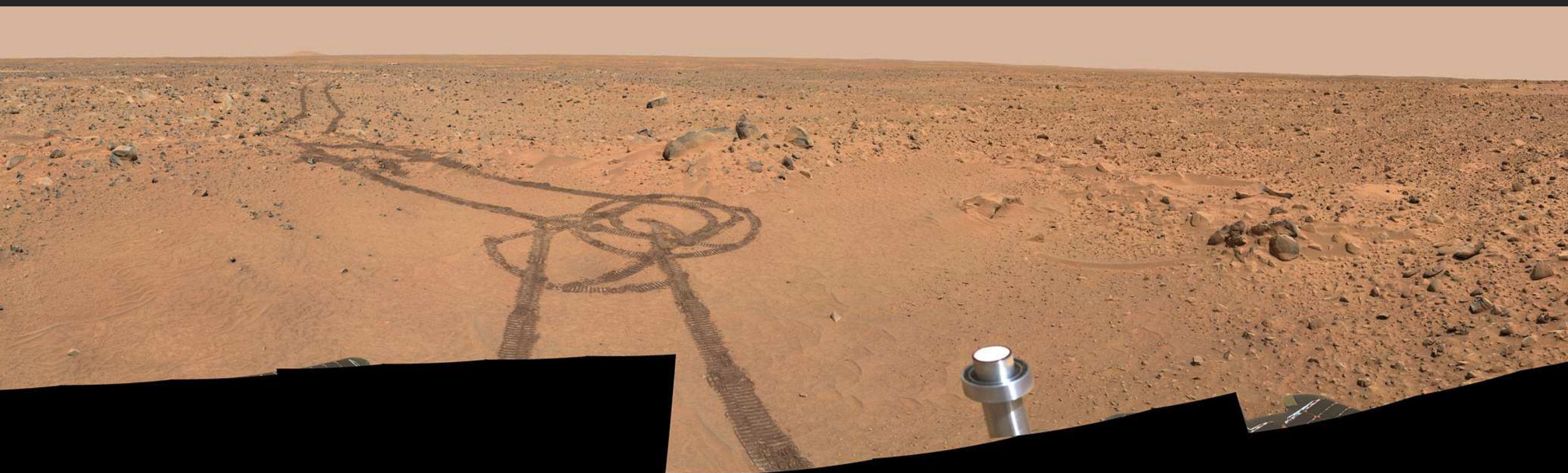


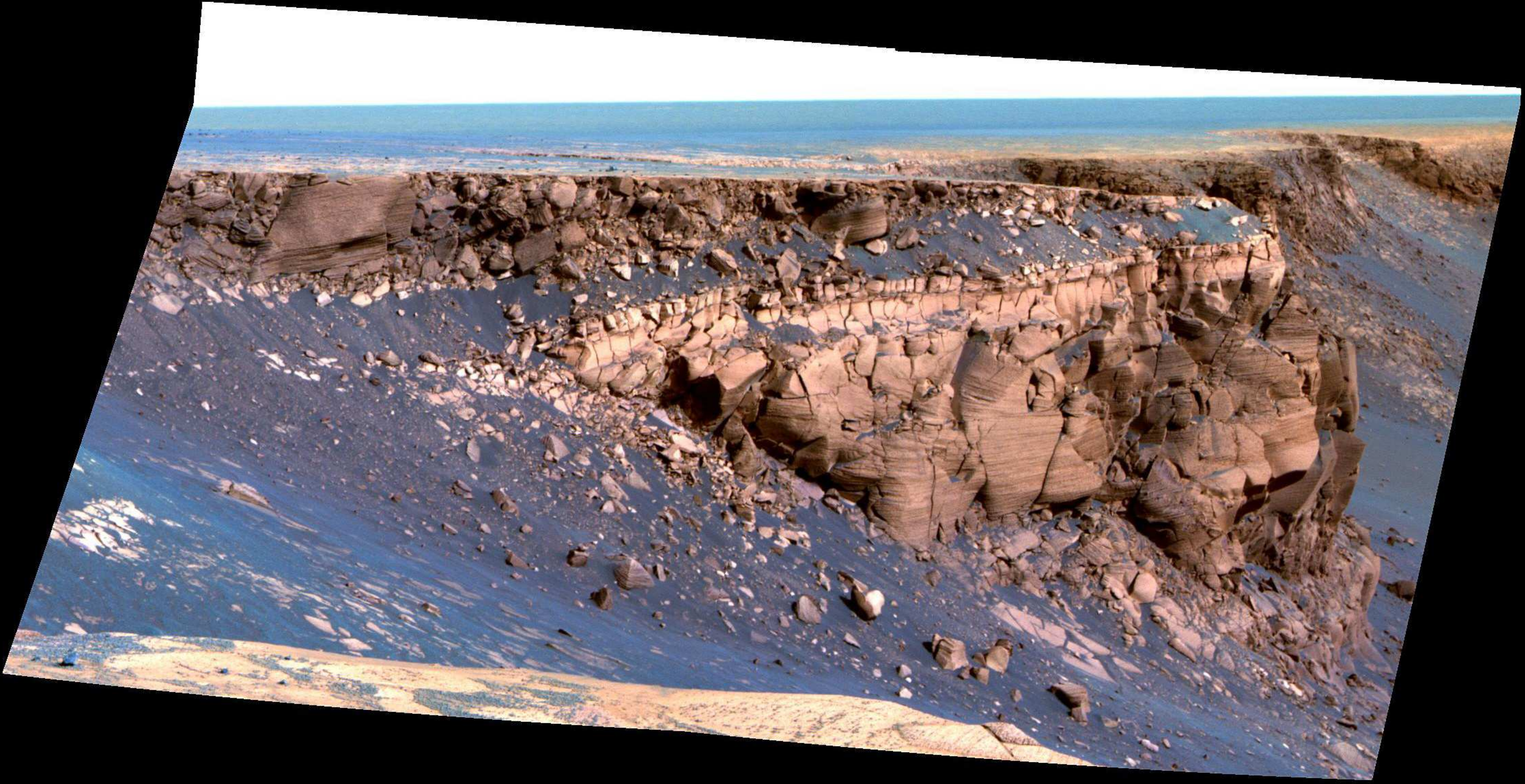
uary 4 and January 25, 2004. The two rovers, each the size of a golf cart, were twins equipped with identical scientific instruments.

On Earth, where there is water, there is life. Spirit and Opportunity were sent to Mars to find more clues to that planet's water history and to understand if it could have ever sustained life. To do this, the scientists sent the two rovers to two different landing sites on opposite sides of the planet, both of which appeared to have been affected by liquid water in the distant past. Spirit landed in a location named Gusev Crater, where a lake possibly once existed within the giant impact site. Opportunity landed in a region called *Meridiani Planum*, where mineral deposits, particularly hematite, suggested that the planet must have had a humid past. The two rovers bounced and rolled on the surface inside of airbag-protected landers. When they stopped, the airbags deflated and the landers opened. The rovers positioned themselves to take panoramic images that provided scientists with the information they needed to select promising geological targets, useful for telling part of the history of water on Mars. The rovers then began the exploration of those targets and even went far beyond to perform up-close scientific investigations.



This image taken by the panoramic camera aboard Opportunity shows the rover's empty lander, the Challenger Memorial Station, at Meridiani Planum. Below, a view captured by the panoramic camera aboard Spirit from a position about halfway between the landing site and the rim of Bonneville Crater. The location is within the transition from the relatively smooth plains to the more rocky and rugged blanket of material ejected from Bonneville by the force of the impact that dug the crater. The panorama spans 360 degrees and consists of images obtained in 78 individual pointings. The Columbia Memorial Station lander can be seen about 200 meters (about 650 feet) in the distance by following the rover tracks back toward right of center in the mosaic and zooming in. [NASA/JPL-Caltech/Cornell/Arizona State Univ.]





During its wandering, Spirit took many photos of the surface with its camera, the first true-color images taken by a rover on another planet. Spirit also found evidence of a humid past and evidence of geothermal or volcanic activity. The rover ended up exploring sites that may have been hot springs millions of years ago. Not to be outdone by its twin, Opportunity also took many real-color photos of the Martian landscape and found evidence for a distant past where water existed on the surface. Moreover, Opportunity studied mineral layers in the rocks near its landing site. The gathered evidence indicated that the site could have been, billions

This false-color image captured by Opportunity shows Cape St. Vincent, one of the many promontories that jut out from the walls of Victoria Crater. The material at the top of the promontory consists of loose, jumbled rock, then a bit further down into the crater, abruptly transitions to solid bedrock. This transition point is marked by a bright band of rock. [NASA/JPL/Cornell]

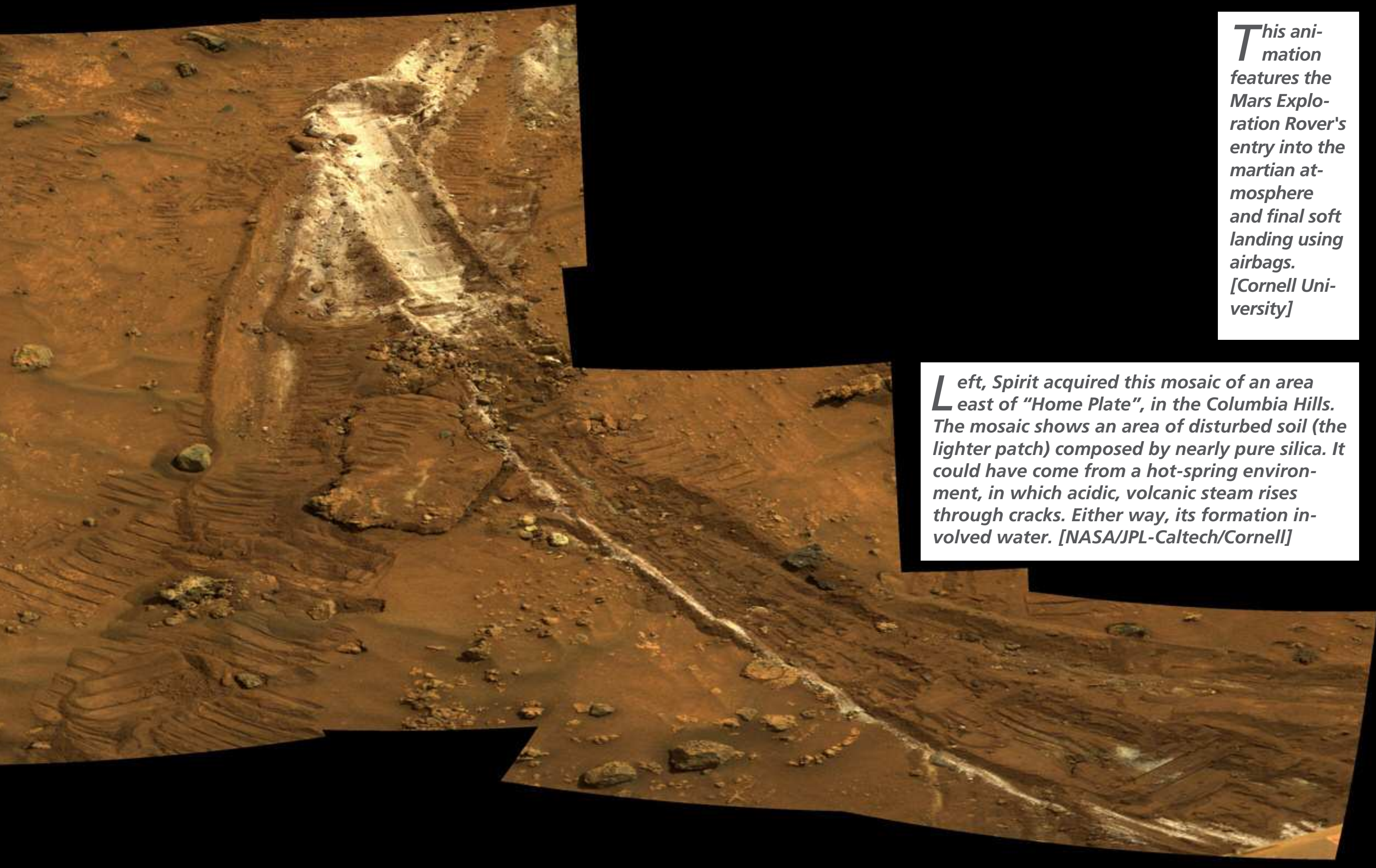
MARS EXPLORATION ROVERS SCIENCE INSTRUMENTS

- **Panoramic Camera (Pancam): for determining the mineralogy, texture, and structure of the local terrain.**
- **Miniature Thermal Emission Spectrometer (Mini-TES): for identifying promising rocks and soils for closer examination and for determining the processes that formed Martian rocks. The instrument is designed to look skyward to provide temperature profiles of the Martian atmosphere.**
- **Mössbauer Spectrometer (MB): for close-up investigations of the mineralogy of iron-bearing rocks and soils.**
- **Alpha Particle X-Ray Spectrometer (APXS): for close-up analysis of the abundances of elements that make up rocks and soils.**
- **Magnets: for collecting magnetic dust particles. The Mössbauer Spectrometer and the Alpha Particle X-ray Spectrometer are designed to analyze the particles collected and help determine the ratio of magnetic particles to non-magnetic particles. They can also analyze the composition of magnetic minerals in airborne dust and rocks that have been ground by the Rock Abrasion Tool.**
- **Microscopic Imager (MI): for obtaining close-up, high-resolution images of rocks and soils.**
- **Rock Abrasion Tool (RAT): for removing dusty and weathered rock surfaces and exposing fresh material for examination by instruments onboard.**

In this image, Opportunity used its navigation camera for this northward view of tracks the rover left on a drive from one energy-favorable position on a sand ripple to another. [NASA/JPL]

of years ago, the coast of a salty sea. The rocks that Spirit and Opportunity studied showed scientists that the types of water features on Mars could have been very similar to features on Earth. Once upon a time, Mars also had lakes and rivers on its surface. Additionally, it also had aquifers and water underground, as well as water vapor in the atmosphere.

Before landing, the goal for each rover was to travel up to 40 meters in a single day, for

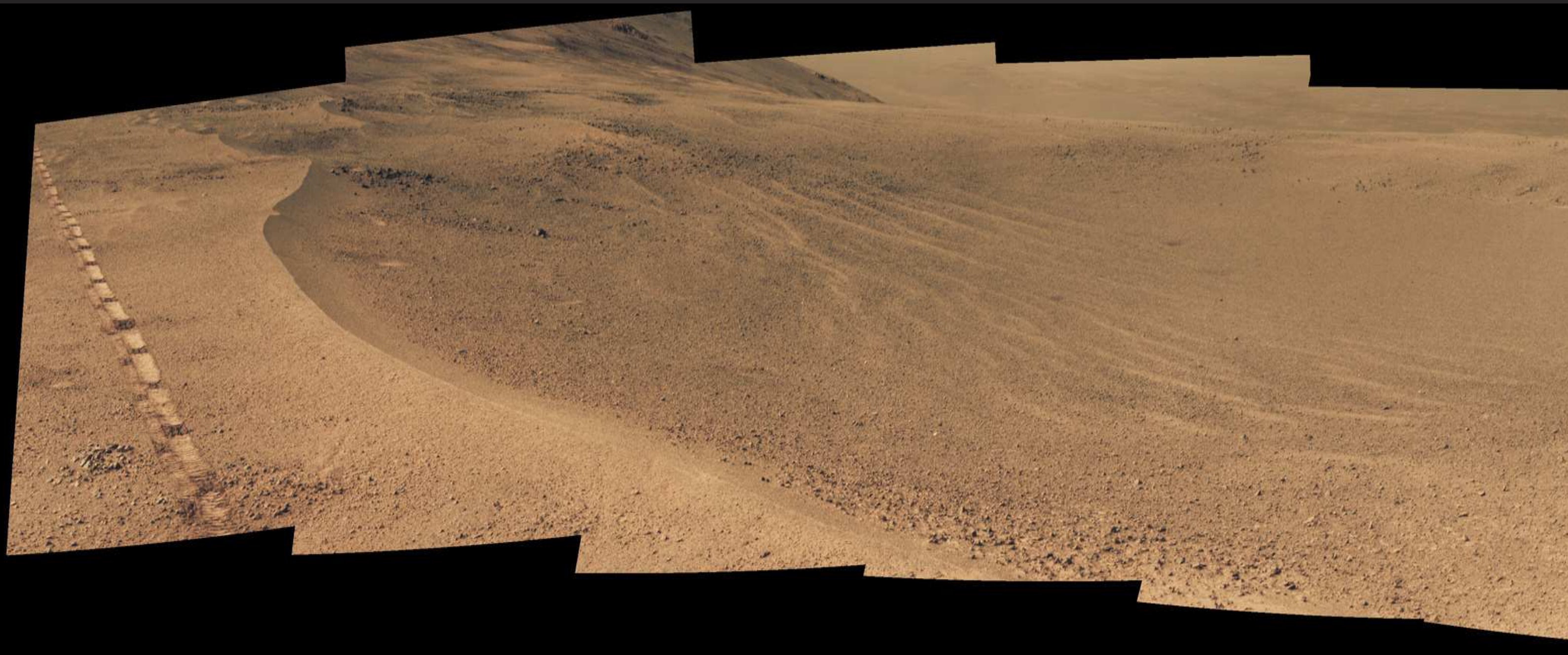


This animation features the Mars Exploration Rover's entry into the martian atmosphere and final soft landing using airbags. [Cornell University]

Left, Spirit acquired this mosaic of an area east of "Home Plate", in the Columbia Hills. The mosaic shows an area of disturbed soil (the lighter patch) composed by nearly pure silica. It could have come from a hot-spring environment, in which acidic, volcanic steam rises through cracks. Either way, its formation involved water. [NASA/JPL-Caltech/Cornell]

a total of one kilometer. Both rovers exceeded by many years the mission's expected duration, which was estimated at just 90 days. Spirit lasted over 20 times longer than the nominal mission, traveling 7.7 km instead of the expected 600 meters. Opportunity worked on Mars longer than any other human artifact: nearly 15 years. It communicated for the last time with the Earth on June 10, 2018. Three years earlier, Opportunity had broken the record for "extraterrestrial driving" by exceeding the distance of a marathon, at a total journey of over 45 kilometers.
Moving from place to place, the two rovers carried out geological surveys on various sites. Each rover was a kind of robot geologist that traversed the surface of Mars.
The cameras mounted at a height of 1.5 meters provided a 360-degree stereoscopic view of the area. A ro-

Above left, the rock called "Wishstone", abraded by Spirit with the Rock Abrasion Tool (RAT), to examine the internal composition, found to be rich in phosphorus. Next, a terrain strewn with dark volcanic rocks. Further to the right, a rocky outcrop called "Gasconade", studied by Opportunity, near the western end of the Endeavor Crater. [NASA/JPL-Caltech/ Cornell/ NMMN/USGS/ASU]



botic arm, able to move in much the same way as a human arm with an elbow and wrist, could position instruments directly against rocks and other targets to study. The first of the mission's scientific objectives was to search for and characterize a wide range of rocks and soils related to past water activity on Mars. Both Spirit and Opportunity found evidence that, long ago, Mars offered an environment that could have sustained any existing microbial life. Using the data from the rovers, the mission scientists reconstructed an era in which Mars appeared to be flooded with water.

After more than five years of exploration, during which Spirit visited craters, hills, valleys and analyzed many rocks and different terrains, the rover got stuck in a soft sandbar on May 1, 2009. For the next eight months, NASA carefully analyzed

Opportunity passed near this small, relatively fresh crater in April 2017, during the 45th anniversary of the Apollo 16 mission to the moon. The rover team chose to call it Orion Crater, after the Apollo 16 lunar module. The rover's Pancam recorded this view. The crater's diameter is about 90 feet (27 meters). Its age is estimated at no more than 10 million years. [NASA/JPL-Caltech/Cornell Univ./Arizona State Univ.]

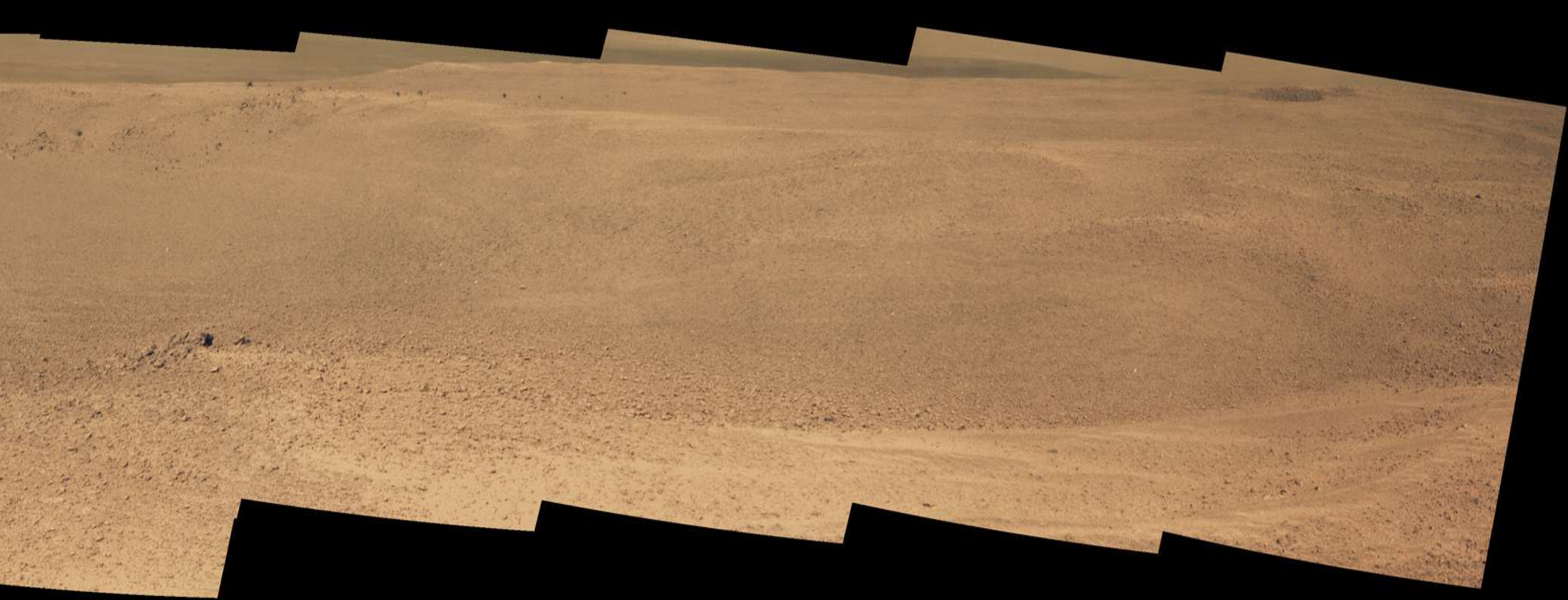


Image of a target called "Private Joseph Field", from Opportunity's microscopic imager, with enhanced color information added from the rover's panoramic camera. Geochemical data indicate the presence of magnesium and iron sulfates. [NASA/JPL-Caltech/Cornell/USGS/ASU]

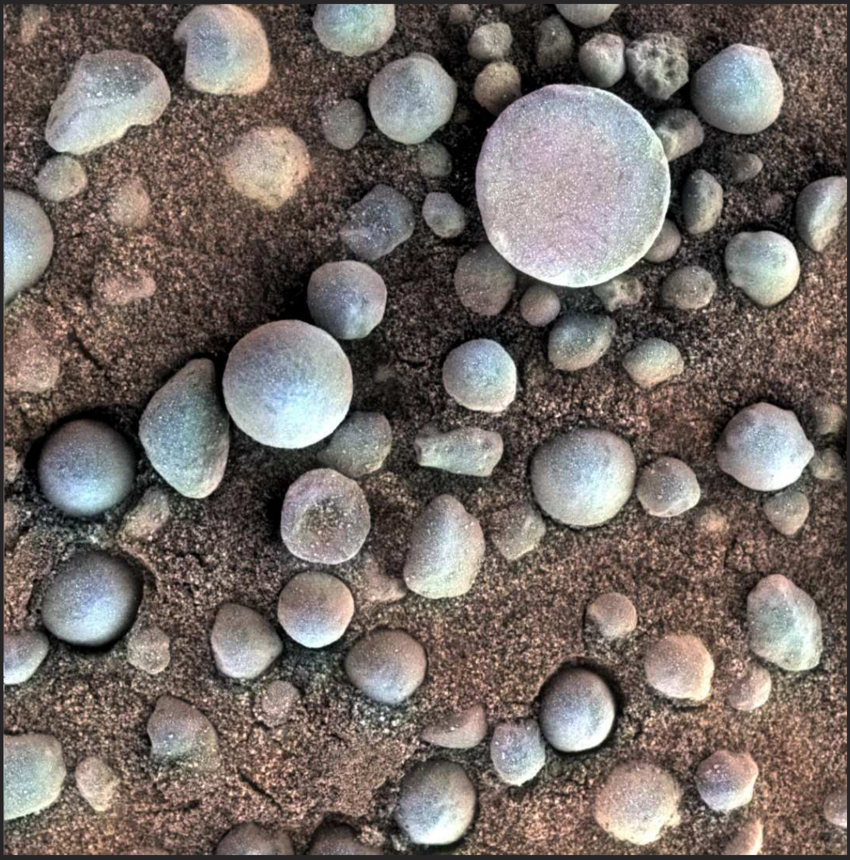
the situation, running various simulations on Earth in an attempt to solve the problem. The technicians then programmed the rover to perform a series of maneuvers in an attempt to free it. These efforts continued until January 26, 2010, when NASA announced that the rover was hopelessly stuck in the sand, although it was able to continue researching from its location. Spirit then transformed into a fixed scientific platform until communications were lost on March 22, 2010. The Jet Propulsion Laboratory attempted to restore contact until May 24, 2011, when NASA announced that efforts to communicate with the rover were

TOP DISCOVERIES BY SPIRIT

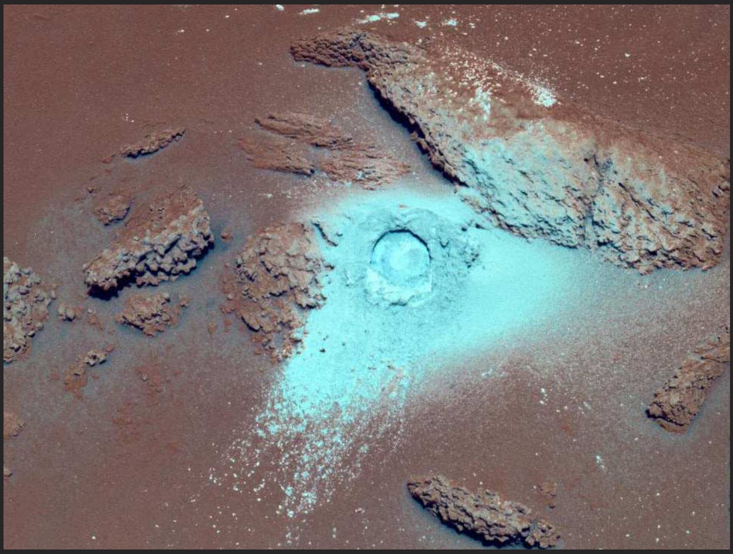
• At a place called Comanche, Spirit found rocks ten times richer in key chemicals (magnesium and iron carbonates) than any other Martian rocks studied before. These rocks formed when Mars was warm and wet (had a thicker carbon dioxide atmosphere and near-neutral-pH water). This warmer, watery environment could have supported life much better than the harshly acidic conditions the rover found elsewhere.
• While dragging a wheel, Spirit churned up soil and found 90 percent pure silica at "Home Plate." On Earth, this kind of silica usually exists in hot springs or hot steam vents, where life as we know it often finds a hot, happy home. Perhaps ancient microbes on Mars did as well.
• Spirit discovered that an ancient volcano erupted at "Home Plate," the rover's final resting place. Together, powerful steam eruptions from heated underground water produced some explosive volcanism. While violent, these extreme conditions can support microbial life on Earth. Once upon a time, maybe they did on Mars.

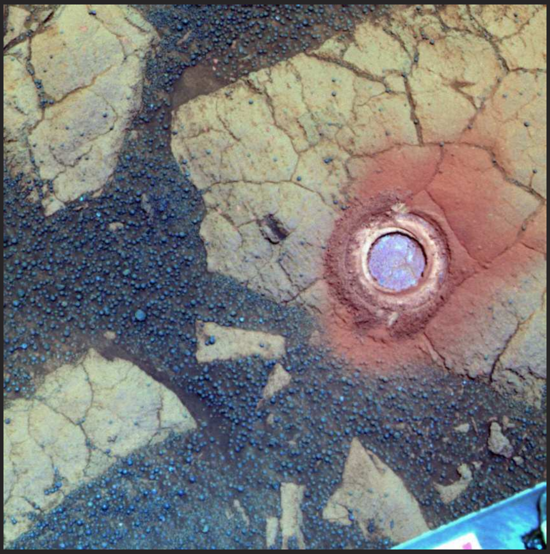
TOP DISCOVERIES BY OPPORTUNITY

• Landing in a crater, Opportunity scored a "hole in one" by finding the mineral hematite, which typically forms in water. Water is key to life as we know it. Yet, acidic water soaked this area in Mars' ancient past, making conditions harder for life to thrive.
• Score! Near the rim of Endeavor Crater, Opportunity found bright-colored veins of gypsum in the rocks. These rocks likely formed when water flowed through underground fractures in the rocks, leaving calcium behind. A slam-dunk sign that Mars was once more hospitable to life than it is today!
• Opportunity found compelling signs of a watery past on Mars: clay minerals formed in neutral-pH water. Of all the places studied by Opportunity, this environment at Endeavor Crater once had the friendliest conditions for ancient microbial life.



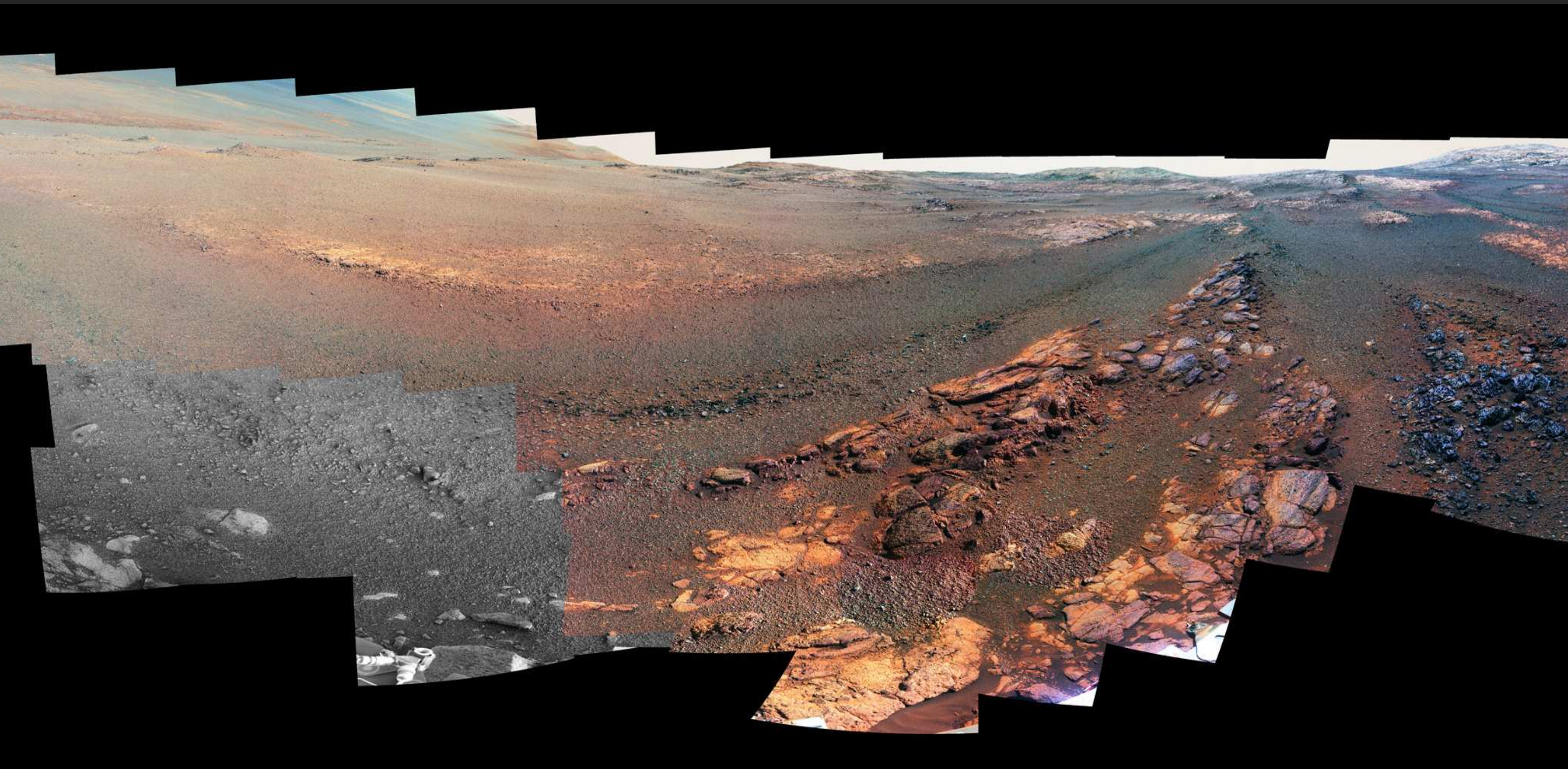
The small spherules on the Martian surface in this close-up image are near Fram Crater, visited by Opportunity. The area shown is 1.2 inches (3 centimeters) across. These are examples of the mineral concretions nicknamed "blueberries." Opportunity's investigation of the hematite-rich concretions during the rover's three-month prime mission in early 2004 provided evidence of a watery ancient environment. [NASA/JPL-Caltech/Cornell/USGS]





Left, sulfur-rich rocks in the Columbia Hills stand out in bright blue in this false-color image from the Spirit rover. Spirit used its Rock Abrasion Tool (RAT) to grind a hole in the rock, nicknamed "Peace." The rock's high sulfur content and softness are probably evidence of past alteration by water.
Right, Opportunity used its RAT on a rock informally named "Gagarin" at a target called "Yuri". The circle is about 1.8 inches (4.5 centimeters) in diameter. The view is presented in false color to emphasize differences among materials in the rocks and the soils. [NASA/JPL-Caltech/Cornell Univ./ASU]

finished, defining the completion of the mission.
Even Opportunity, after having explored targets similar to those assigned to Spirit and after having overcome difficulties of various kinds, ultimately surrendered to the adverse Martian conditions.
Due to a massive 2018 planetary sandstorm on Mars, the rover cut off communications and went into hibernation on June 10. It was expected to restart once the atmosphere cleared, but it did not, perhaps due to a technical fault or the deposition of a thick layer of dust on the solar panels that prevented the batteries from recharging. NASA hoped to reestablish contact with the rover thanks to a windy period that could have potentially cleaned



up the solar panels, but NASA could not. On February 13, 2019, the agency said the Opportunity mission had ended, after the rover had not responded to over 1,000 signals sent since August 2018.

Among the most notable discoveries made by the twin rovers during their long mission are: water interacting with hot rocks, whirlpools of Martian dust, an ancient hydrothermal system, sand ripples formed by wind, and a potentially habitable Martian environment long ago.

Opportunity has found an iron meteorite on Mars, the first meteorite of any type ever identified on another planet. The pitted, basketball-size object (left) is mostly made of iron and nickel. Readings from spectrometers on the rover determined that composition. Opportunity used its panoramic camera to take the images used in this approximately true-color composite on January 6, 2005. On the right, an image of a similar meteorite that Opportunity found and examined in September 2010. [NASA/JPL-Caltech/Cornell University]

This 360-degree panorama is composed of 354 images taken by the Opportunity rover's Panoramic Camera (Pancam) from May 13 through June 10, 2018, or sols (Martian days) 5,084 through 5,111. This is the last panorama Opportunity acquired before the solar-powered rover succumbed to a global Martian dust storm on the same June 10. The view is presented in false color to make some differences between materials easier to see. [NASA/JPL-Caltech/Cornell/ASU]

NORT

RAPIDO 450

ALTAZIMUTH NEWTONIAN TELESCOPE

- **SCHOTT Supremax 33 optics**
- **optical diameter: 460 mm**
- **useful diameter: 450 mm**
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The NortheK Rapido 450 is designed to be disassembled into essential parts for transport in a small car. Each component is equipped with its own case, facilitating transport and assembly. The main element weighs 27 kg. Incorporated mechanical devices and the precise execution of each component allows for the collimation of the optics with extreme ease, maintaining collimation throughout an observation session while eliminating twisting and bending, regardless of the weight of the accessories used. The very thin primary optic allows for rapid acclimatization and ensures thermal stability throughout the night. Two bars equipped with sliding weights allow for the perfect balance of the telescope and accessories. On demand, it is also possible to modify the support to mount the telescope on an equatorial platform. This instrument is composed of aluminum, carbon and steel, each perfectly selected according to strict mechanical standards. It is undoubtedly the best altazimuth Newtonian on the market.

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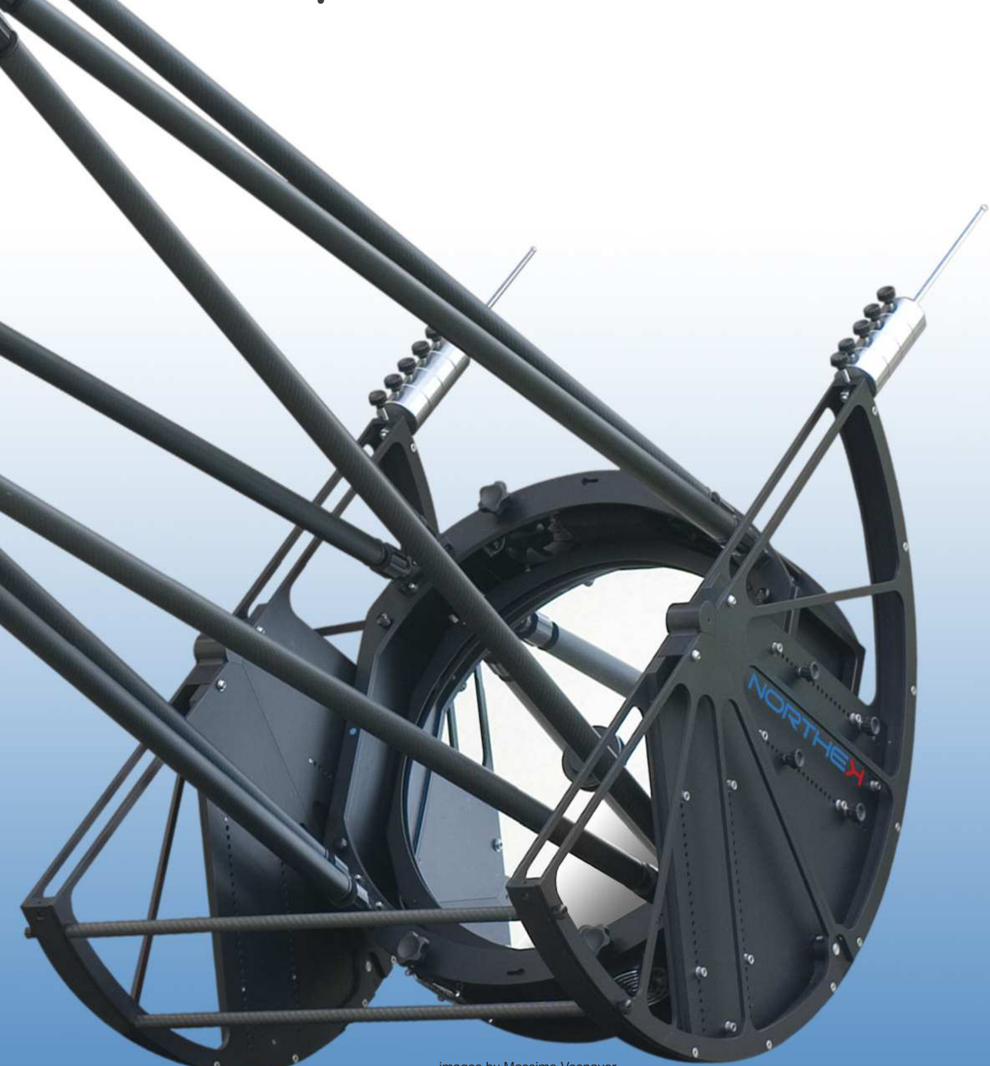
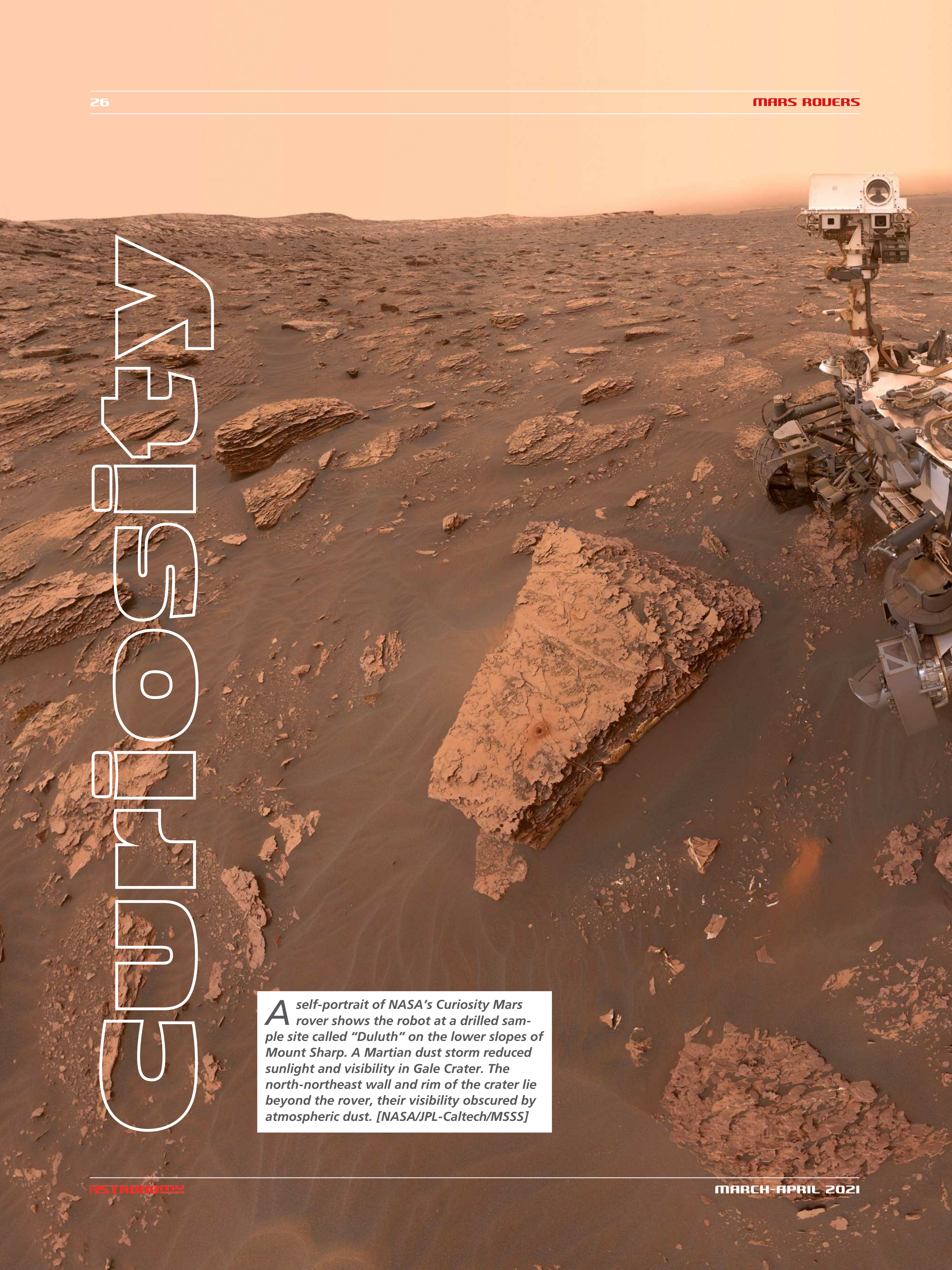


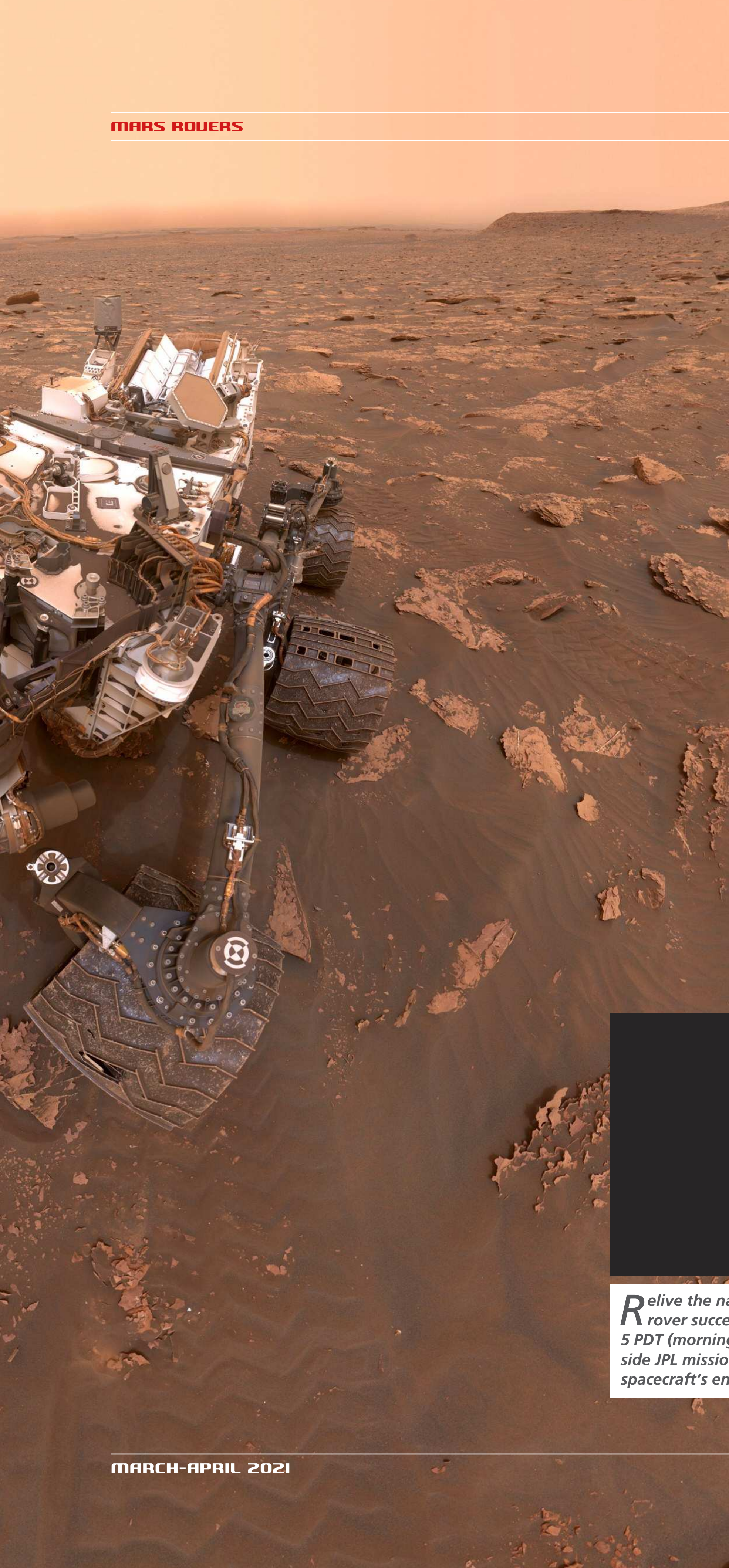
images by Massimo Vesnaver

MPOSITES - OPTICS



Curiosity

A self-portrait of NASA's Curiosity Mars rover shows the robot at a drilled sample site called "Duluth" on the lower slopes of Mount Sharp. A Martian dust storm reduced sunlight and visibility in Gale Crater. The north-northeast wall and rim of the crater lie beyond the rover, their visibility obscured by atmospheric dust. [NASA/JPL-Caltech/MSSS]



While Spirit and Opportunity were still operational, NASA had already set up their successor – the Mars Science Laboratory mission Curiosity, an SUV-sized rover equipped with far more scientific instruments than its predecessors. Launched on November 26, 2011, Curiosity landed on Mars on August 5, 2012 (1:32 EDT on August 6, 2012) and remains operational. In this mission, technological innovations were introduced that tested a completely new landing method. After atmospheric braking, the spacecraft dropped by hanging from a parachute. Shortly before landing, a rear rocket system further slowed the descent, allowing for a soft landing on the surface. The rover landed on its wheels and quickly got rid of the landing system, which fell at a safe distance away from the rover. Compared to the architecture of previous missions, that of the Mars Science Laboratory represents a significant step forward in the exploration of Mars, achieving three important milestones: landing a very large and heavy rover on the surface of Mars; demonstrating the ability to land within a pre-determined area of

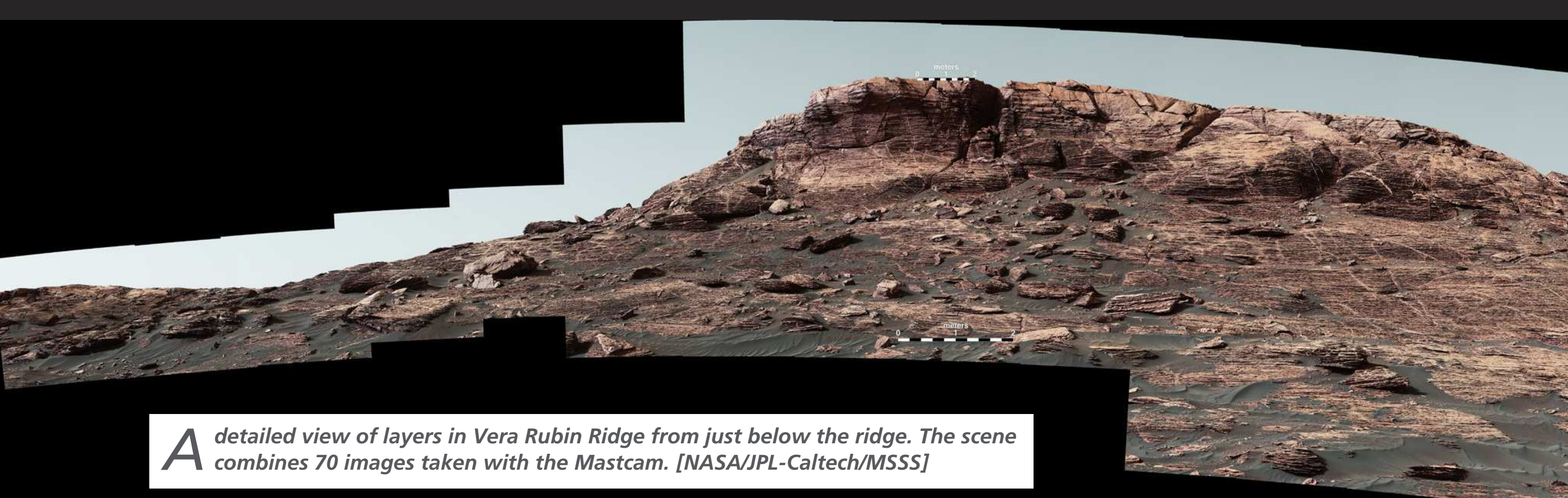
Relive the nail-biting terror and joy as NASA's Curiosity rover successfully landed on Mars the evening of Aug. 5 PDT (morning of Aug. 6 EDT). See and hear the team inside JPL mission control along with a visualization of the spacecraft's entry, descent and landing. [NASA/JPL]

This view from the Mast Camera (Mastcam) on NASA's Curiosity Mars rover shows finely layered rocks within the Murray Buttes region on lower Mount Sharp. [NASA/JPL-Caltech/MSSS]

just 20 kilometers; ensuring long-range mobility on Mars for the study of different environments and the analysis of samples found in different environments.

Curiosity carries larger and more advanced scientific instruments than those previously sent to the Martian surface. The history of Martian climate and geology is written in the chemistry and structure of rocks and soil. Curiosity is able to read the pages of that story, analyzing dust samples obtained from rock drilling and measuring the chemical footprints present in different rocks and soils to determine their composition and past interactions with water. All the rock, soil and air samples collected by Curiosity during the exploration of Gale Crater have been analyzed in its internal laboratory. This allows the rover to assess with increasing accuracy whether Mars ever had an environment capable of supporting microbial life. The Mars Science Laboratory mission and its Curiosity rover mark a transition between the "follow the water" and "seek signs of life" strategies. In addition to landing in a place with traces of the presence of water in the distant past, Curiosity is looking for evidence of organic substances, the chemical building blocks of life. Places with water and the chemistry necessary for life potentially provide habitable conditions. Thanks to this rover, NASA is close to achieving the four main scientific goals of the entire Mars Exploration Program.

The first goal is to determine if life ever appeared on Mars. To under-

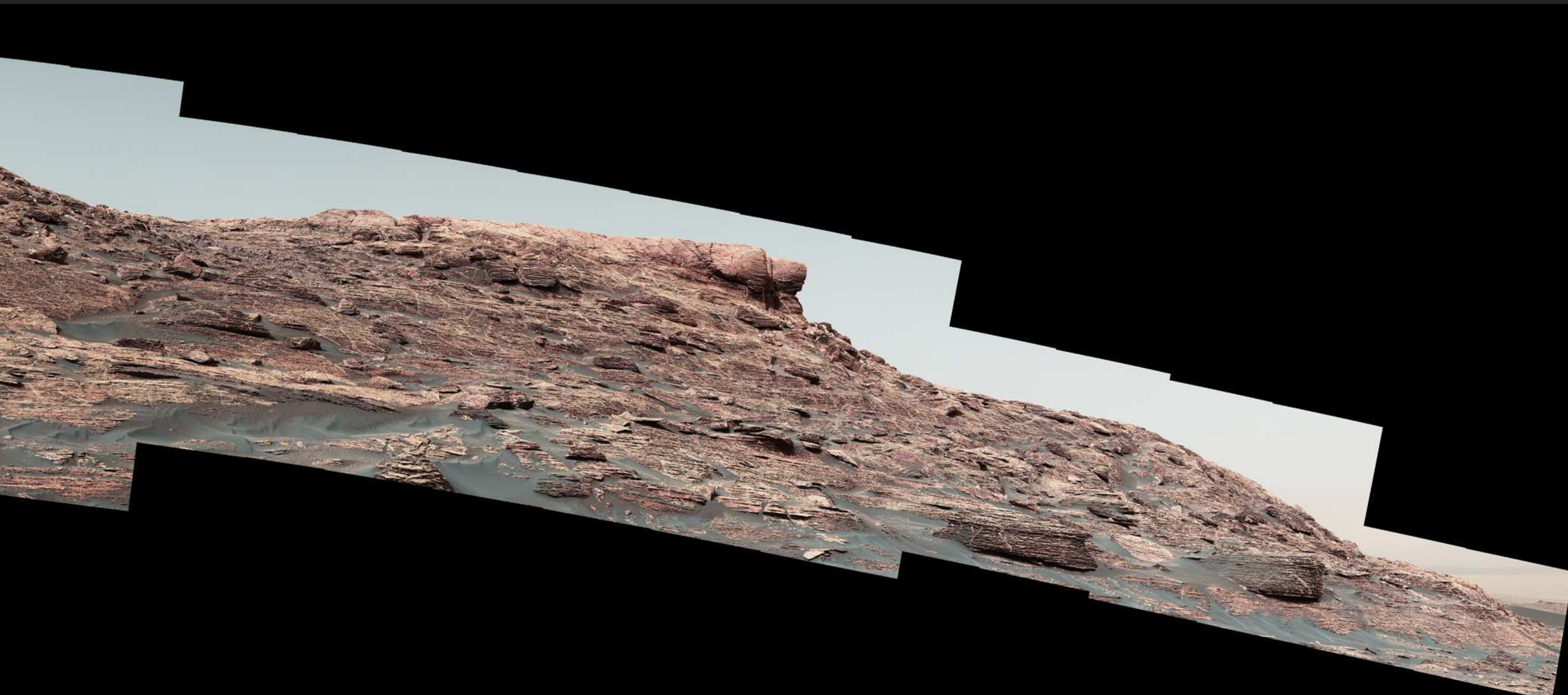


A detailed view of layers in Vera Rubin Ridge from just below the ridge. The scene combines 70 images taken with the Mastcam. [NASA/JPL-Caltech/MSSS]

Left and below, views from the Mastcam that show outcrops with finely layered rocks within the Murray Buttes region. The buttes and mesas rising above the surface in this area are eroded remnants of ancient sandstone that originated when winds deposited sand after lower Mount Sharp had formed. [NASA/JPL-Caltech/MSSS]

stand this, it is necessary to find out if the red planet has ever had environmental conditions capable of supporting life.

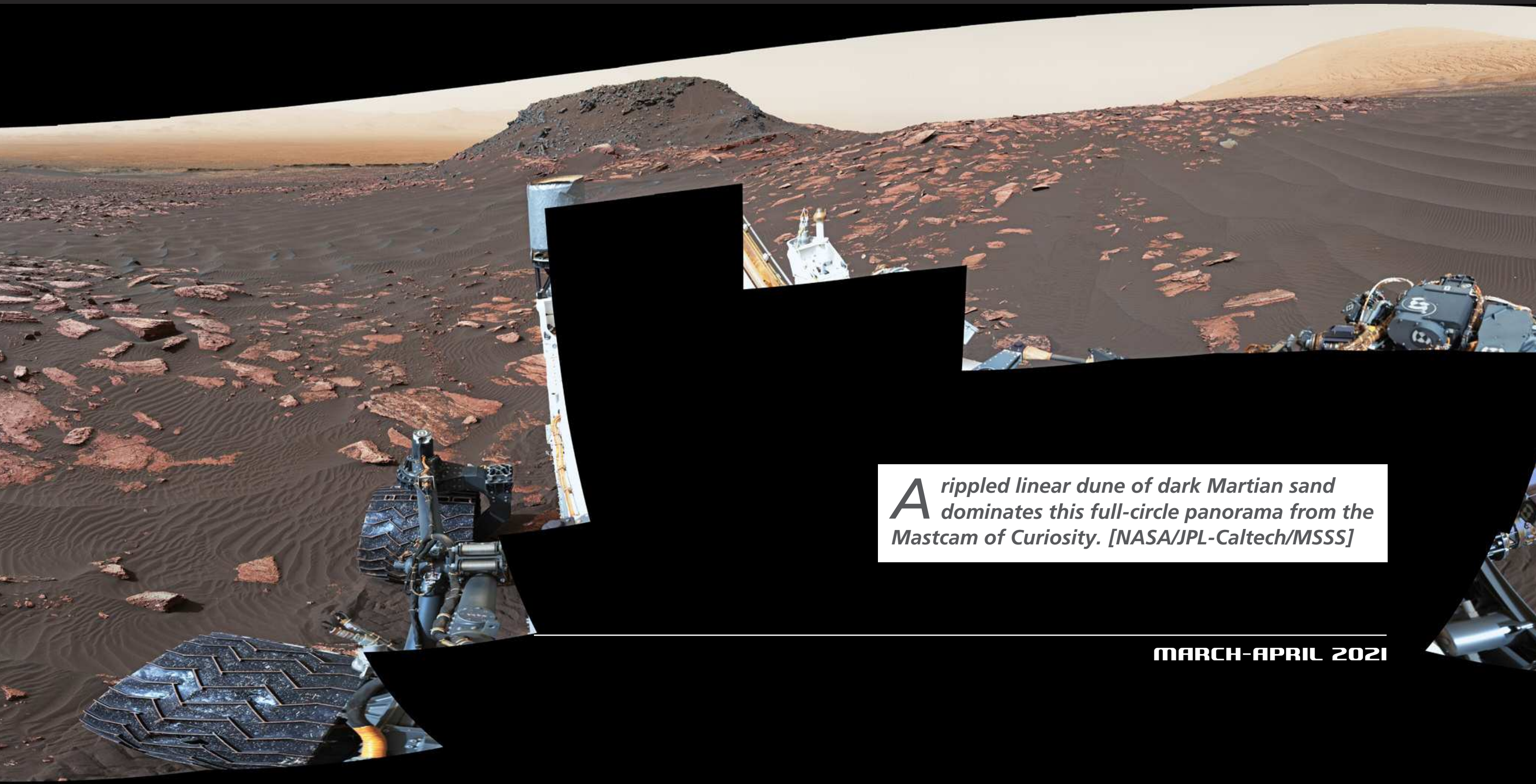
After Spirit and Opportunity strengthened the hypothesis that liquid water persisted on the surface of Mars in ancient times, scientists hoped to identify other ingredients necessary for life, such as nitrogen, carbon, phosphorus, hydrogen, oxygen and sulfur. Life al-



This animation shows the position of NASA's Curiosity rover as it journeyed 1,106 feet (337 meters) through an area of Mount Sharp called "the clay-bearing unit" between May 31 and July 20, 2019. Each of these two images were taken by the HiRISE camera on NASA's Mars Reconnaissance Orbiter. [NASA/JPL-Caltech/University of Arizona]

so requires small amounts of other elements, such as iron, along with sources of energy. On Earth, this energy comes from sunlight or electrons moving back and forth between elements and compounds in nature. Life also requires a sufficiently stable and protective environment to take hold to avoid being destroyed by excessive radiation from space or terrestrial natural phenomena, such as volcanism. Curiosity is studying the carbon and water cycles of Mars throughout its history. In particular, it seeks to determine in what form and quantity the most interesting elements and compounds are stored on the planet or in its atmosphere and how these values have varied over time.

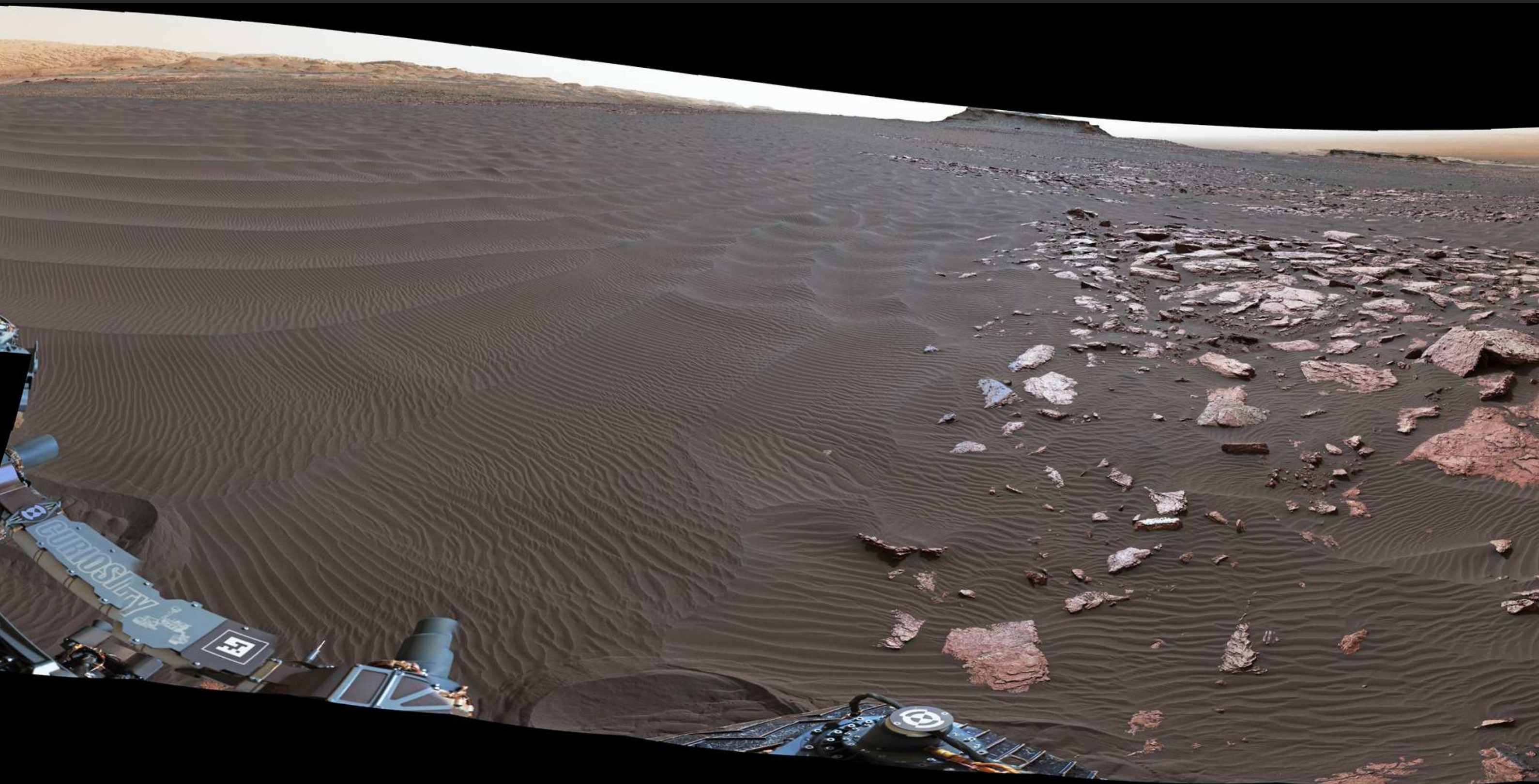
The second objective is the characterization of the ancient climatic processes of Mars. In the past, the planet was warmer and could have supported a denser and wetter atmosphere capable of supporting microbial life. But now, with a thinner and colder atmosphere, much of the Martian water has left the surface and the atmosphere. Most



A rippled linear dune of dark Martian sand dominates this full-circle panorama from the Mastcam of Curiosity. [NASA/JPL-Caltech/MSSS]

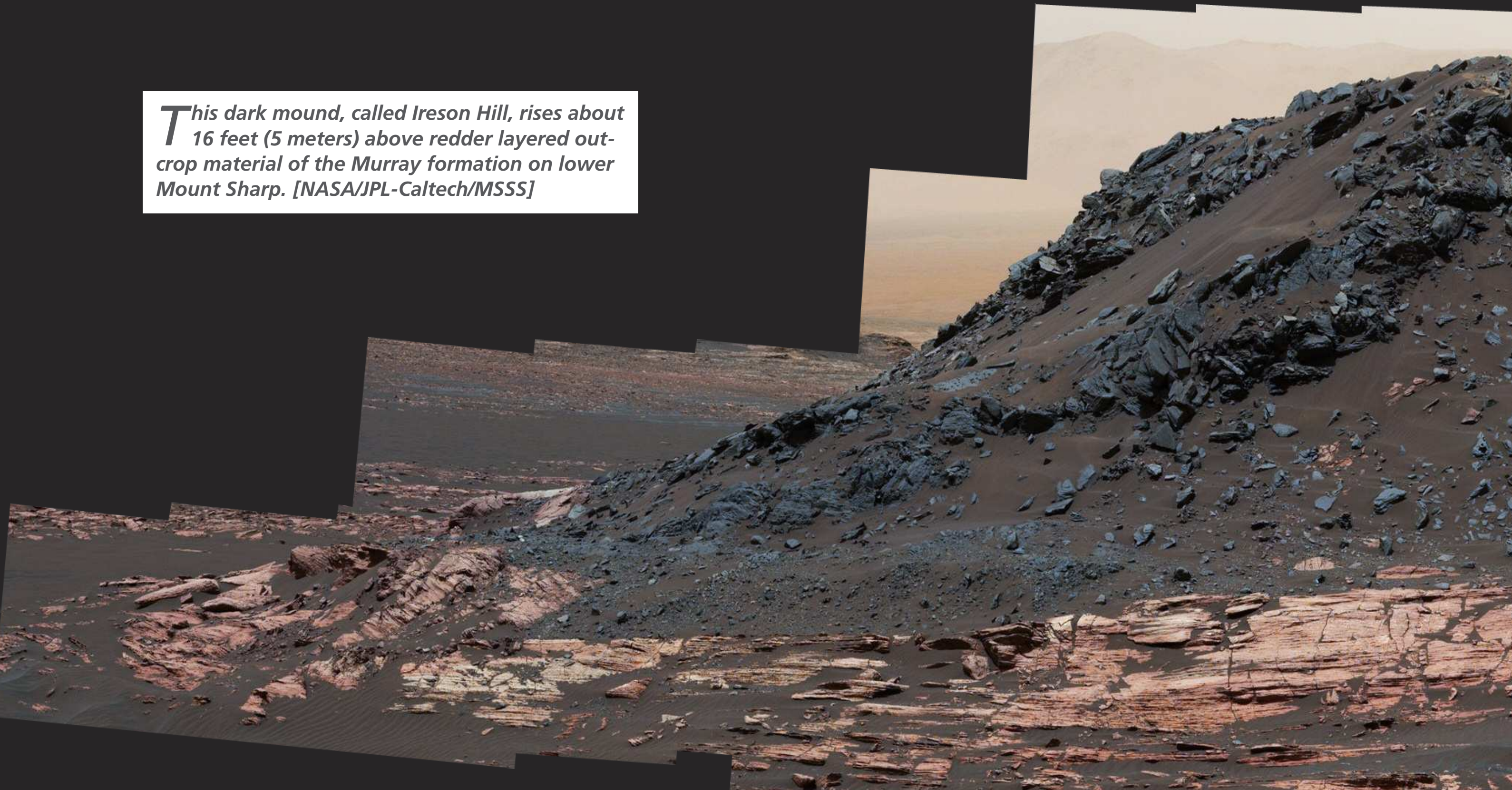
Left, the dark, stick-shaped features clustered on this Martian rock are about the size of grains of rice. This is a focus-merged view from the Mars Hand Lens Imager (MAHLI) camera on NASA's Curiosity Mars rover. It covers an area about 2 inches (5 centimeters) across. Above, an exposure of finely laminated bedrock that includes tiny crystal-shaped bumps, plus mineral veins with both bright and dark material. [NASA/JPL-Caltech/MSSS]

of it is likely trapped beneath the surface, frozen as ice or perhaps in liquid form if close enough to a heat source on the planet, such as a volcanic hot spring. Curiosity allows scientists to more accurately determine the composition of the Martian atmosphere, for example by measuring the stable isotopes of elements such as carbon. Most elements of biological interest have two or more stable isotopes. Organisms often selectively use particular isotopes based on their availability and mass, with



The dark, smooth-surfaced object at the center of this image from the Mastcam was examined by Curiosity with laser pulses and confirmed to be an iron-nickel meteorite. [NASA/JPL-Caltech/MSSS]

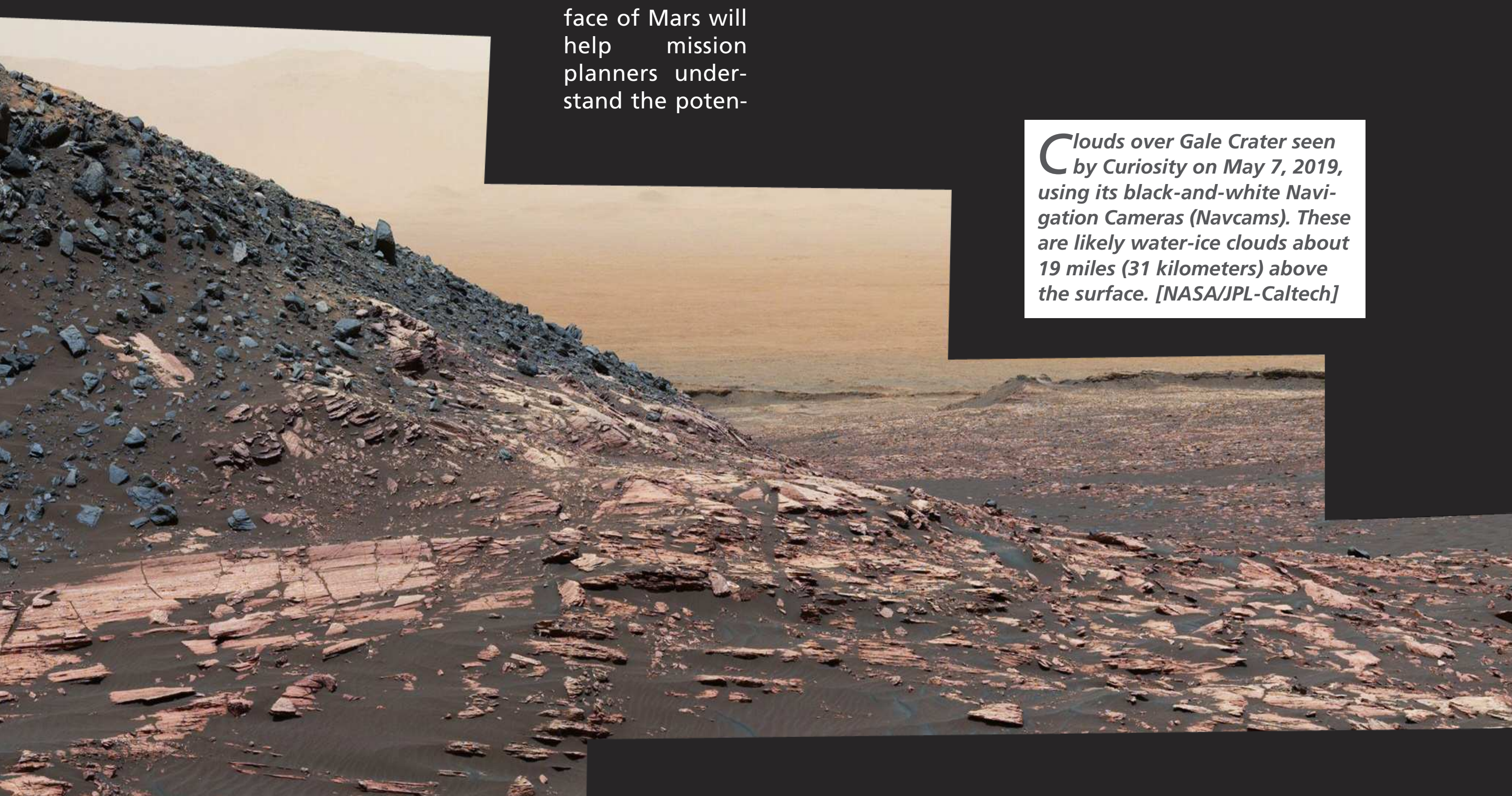
environmental conditions also affecting the availability of those various isotopes. Curiosity looks for possible traces left by elementary forms of past life, such as abrupt changes in isotopic abundance that could be associated with metabolic processes, and investigates the composition of rocks, soils and conformations that could be linked to changes in the planet's atmosphere over time. Curiosity is also characterizing the distribution of water, carbon dioxide and hydrogen in the atmosphere and near the surface. It also measures sur-



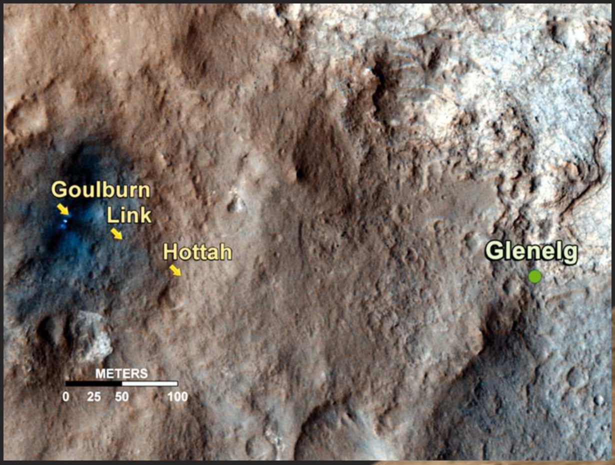
This dark mound, called Ireson Hill, rises about 16 feet (5 meters) above redder layered outcrop material of the Murray formation on lower Mount Sharp. [NASA/JPL-Caltech/MSSS]

Curiosity spotted this dust devil with one of its Navigation Cameras on Aug. 9, 2020. The frames in this GIF were shot over 4 minutes and 15 seconds. [NASA/JPL-Caltech/SSI]

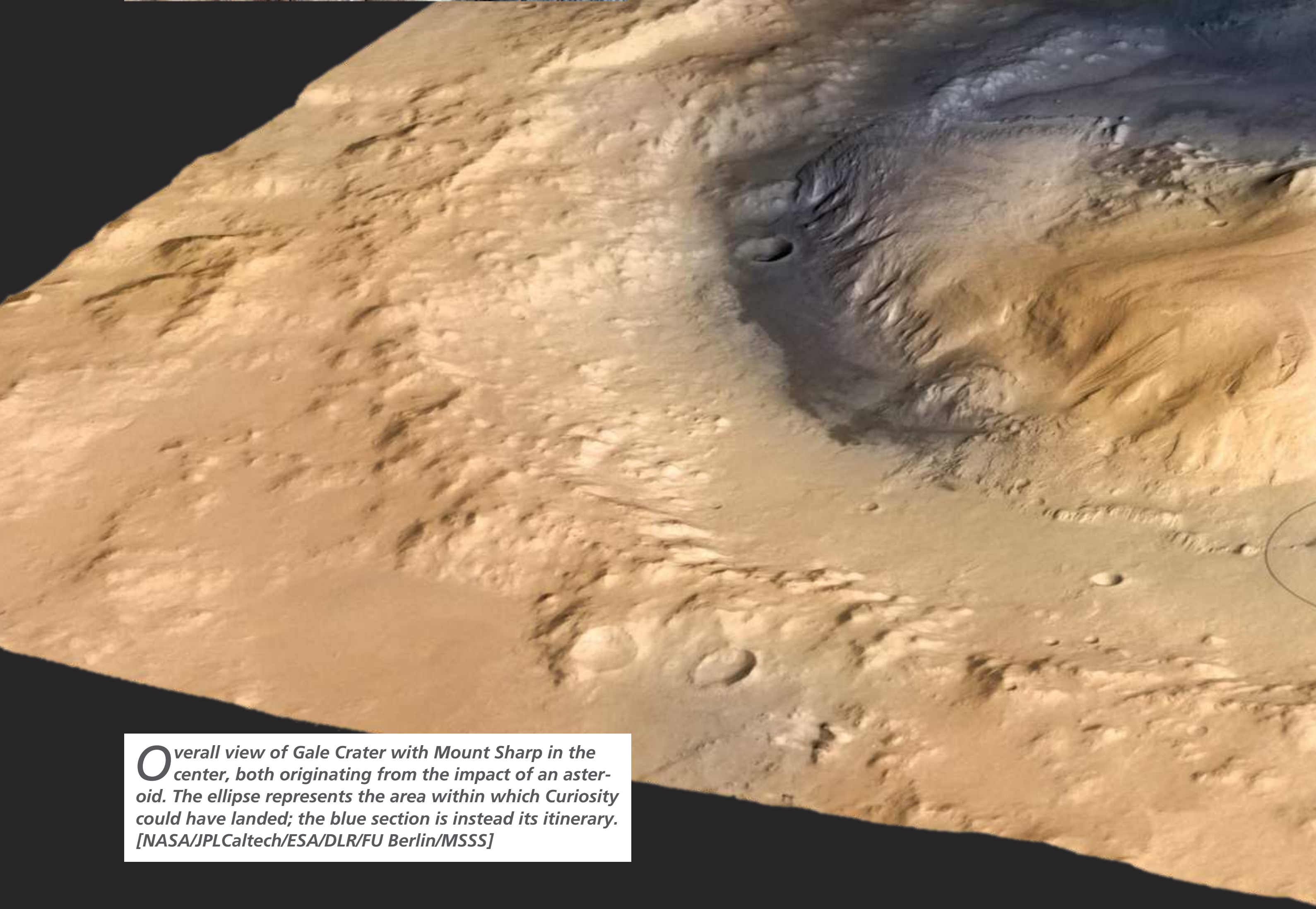
face radiation, including cosmic rays, solar protons and neutrons that bombard the planet from space.
The third objective is the characterization of the geology of Mars, whose history is recorded in the surface layers. Curiosity studies the chemical-physical characteristics of rocks and soil to understand the geological processes that have created and modified the crust and surface over time. In particular, it looks for traces of rocks that have formed in the presence of water.
The fourth objective was to demonstrate the ability to land heavy and large loads on Mars, which it fulfilled upon landing. In this regard, Curiosity has paved the way for the dispatch of equipment and large infrastructures necessary for future human explorations of the planet. Experience in precision landing techniques also provides the first steps in developing the ability to send astronauts to a specific location safely and reliably. A better understanding and characterization of the radiation levels on the surface of Mars will help mission planners understand the potential risks faced by any future astronaut crews and design methods to protect their health.
Curiosity has been working on these targets for over 3,000 sols, a milestone passed on January 12th. Over this long period, the rover's instruments have made significant contributions to achieving the four main scientific objectives of the Mars Exploration Program. In particular, it confirmed that, in a remote time, there were rather impetuous streams on the Martian surface. Scientists didn't have to wait long to get this confirmation - just over a month after landing. In fact, Curiosity only needed to travel a short stretch of the Martian surface to make this fundamental discovery. After completing the instrumental tests at the Goulburn site



Clouds over Gale Crater seen by Curiosity on May 7, 2019, using its black-and-white Navigation Cameras (Navcams). These are likely water-ice clouds about 19 miles (31 kilometers) above the surface. [NASA/JPL-Caltech]



The sites where Curiosity has observed rock formations originating from the prolonged flow of water. The images from Link and "Hottah", in particular, unequivocally show the bed of ancient streams. [NASA/JPL-Caltech/Univ. of Arizona]



Overall view of Gale Crater with Mount Sharp in the center, both originating from the impact of an asteroid. The ellipse represents the area within which Curiosity could have landed; the blue section is instead its itinerary. [NASA/JPLCaltech/ESA/DLR/FU Berlin/MSSS] and observing probable traces of sediments formed as a result of the action of the water, Curiosity set off towards Glenelg, the first planned objective of its mission and a geologically interesting site due it being the confluence of three different types of land. It was enough to cover only about 50 of the 500 meters that separated Goulburn from Glenelg to reach a site, called Link, characterized by the presence of a rock spur with inclusions of gravel and pebbles, whose origin can only be traced back to the flow of water. At that point, Curiosity advanced further to look for even more obvious traces of a remote hydrological structure. After traveling another 60 meters, it reached a second spur of rock, called "Hottah",

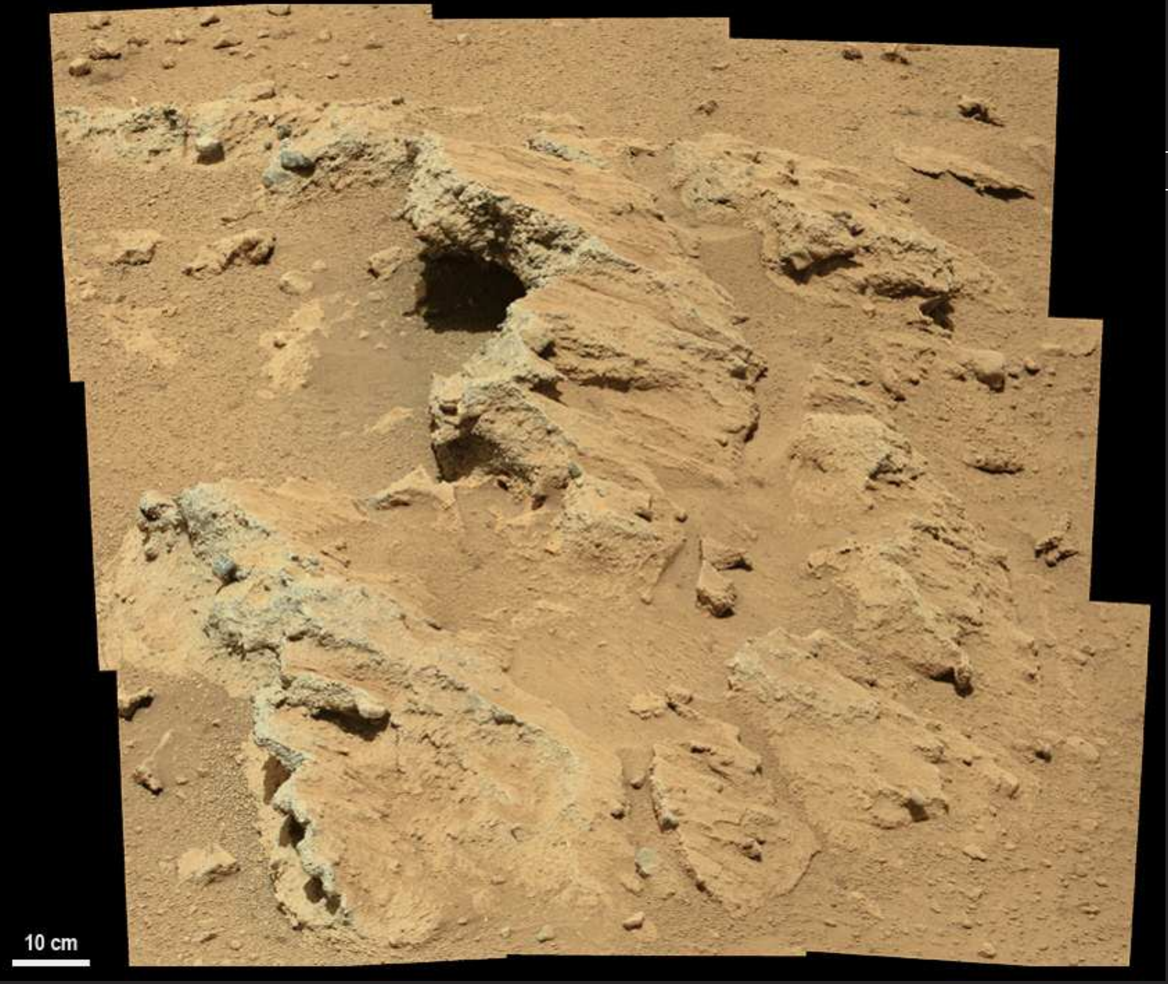
Remains of an ancient Martian stream, at the Link site. The sharp shape of some rocks is indicative of the direction of water flow. The scenario is marked by the erosion of the most exposed fractured parts, which show an abundant pouring of gravel. Below, a comparison between an enlargement of the Link bed with the bed of a terrestrial stream. The conglomerate sediments, the type of cementation, the smoothing of the gravel and the erosion of the matrix are virtually identical. [NASA/JPL-Caltech/MSSS and PSI]

where researchers had, for the first time, the absolute certainty that water flowed on Mars in the distant past. Hottah is a slab of rock that rose from the ground following a probable meteorite impact and is made up of gravel and pebbles cemented together in a sandy matrix, a formation that geologists call a sedimentary conglomerate. The characteristics of gravel and pebbles are completely similar to those of gravel and pebbles modeled and transported by homologous terrestrial waterways, so much

This view of Hottah is a mosaic of images taken by the right (telephoto-lens) camera of the Mastcam on Curiosity during the 39th Martian day, or sol, of the rover's work on Mars (Sept. 14, 2012 PDT/ Sept. 15 GMT). Here, billions of years ago, a stream flowed. [NASA/JPL-Caltech/ MSSS]

so that the individual elements in both scenarios have smoothed and rounded surfaces from mutual collisions and rolling in torrential shores. Very interesting is also the fact that Hottah shows evident traces of erosion following its lifting from the ground, which suggests that the slab (1) was formed as a result of sedimentation of material carried by water, (2) was then hit by a meteorite that lifted it from the stream bed and (3) was subsequently eroded by the water that continued to flow above it. As shown by the images presented here, on the front of the slab crack there are some small but clearly blunted pebbles and part of the gravel has fallen below the fault to form a small deposit. This scenario indicates a slow washout of the sandy matrix. Some grooves left by the last streams of water in and around the rocky outcrop are also clearly visible, a sign of a gradual drying up of the stream.

Researchers estimate that thousands of years, if not millions, are needed to create a landscape with Hottah characteristics, confirming that the flow of water on Mars was not an ephemeral phenomenon. From the size and shape of the conglomerate rocks, and from the size of loose gravel and pebbles, information can be obtained on the speed and depth of the stream's water. Geologists at the Planetary Science Institute, engaged in the interpretation of what Curiosity discovered, are inclined to believe that the water reached, depending on the points of the stream, heights of between a few centimeters and almost a meter, and that its speed was about 1 m/s. Only a watercourse of this capacity would have

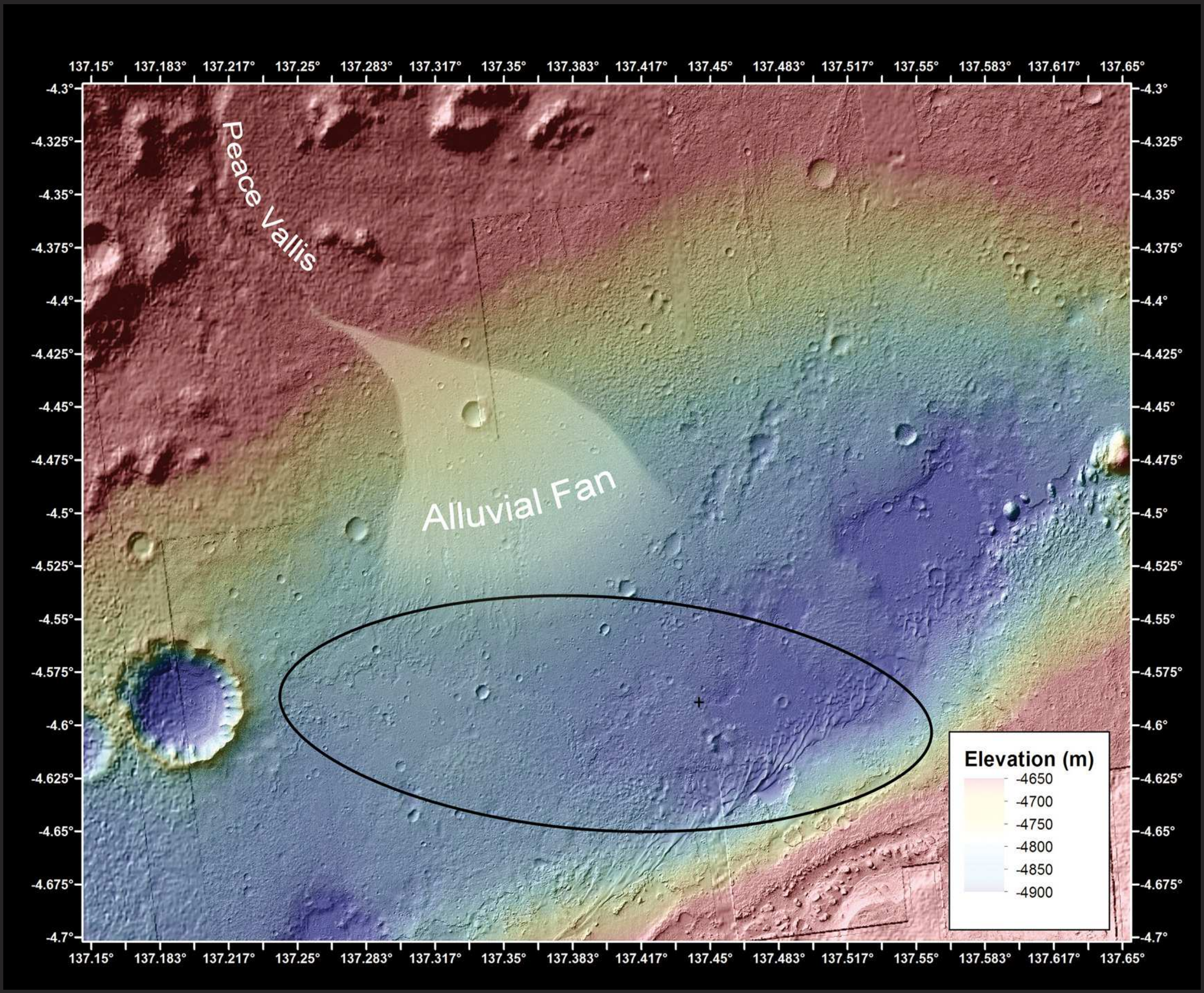


Left and below, close-up views of Hottah reveal more details of the outcrop. Broken surfaces of the outcrop have rounded, gravel clasts, such as the one circled in white, which is about 1.2 inches (3 centimeters) across. Erosion of the outcrop results in gravel clasts that protrude from the outcrop and ultimately fall onto the ground, creating the gravel pile at left. [NASA/JPL-Caltech/MSSS]

been able to move and shape pebbles that the images show, which reach four cm in size – a non-negligible size amounting to a non-negligible Martian weight. Not even the smallest gravel can be deposited through mechanisms other than those dominated by water.

For example, it is unthinkable that the Martian wind smoothed and transported all of that material. In short, there is no doubt that Curiosity has identified the first dry stream on the surface of Mars, confirming once and for all the existence of free water on the surface in very remote times.

About a year after this pivotal discovery, Curiosity's exploration also proved with certainty that an area of Gale Crater called Yellowknife Bay housed a lake and that this lake lasted long enough to house ele-



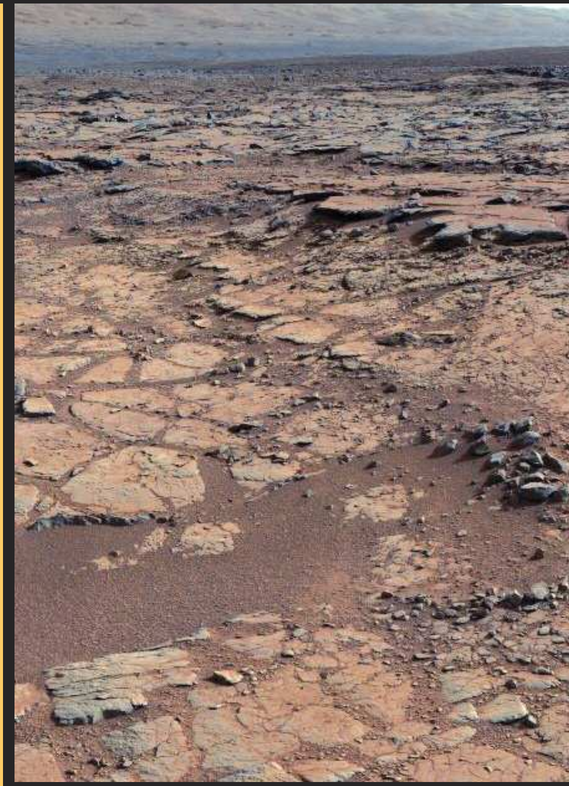
Elevation map of the alluvial delta, fed through Peace Vallis, which originated the dry streams discovered by Curiosity. The cross inside the ellipse indicates the rover's landing site, very close to the sites of Link and Hottah. [NASA/JPL-Caltech/Univ. Of Arizona, ASU]

mentary life forms. This discovery confirmed the dominant view of the history of Mars, which indicates that there were cool, calm waters where clay minerals could form about 4 billion years ago. That environment, which was favorable to life, then experienced a growing drought that made those waters increasingly acidic and brackish. Understanding where and how those clay minerals formed within Gale Crater could provide the chronology of the lake it hosted. The longer this lake lasted before evaporating, the more likely it is that it may have harbored elemental life forms. A key question was whether Yellowknife Bay's clay minerals formed earlier than the lake's supposed epoch.

A second important question concerns where these clays formed. They may have formed outside what could be the crater's bottom, such as on the crater ring, by the action of simple temporary streams. Alternatively, they might have formed on the bottom of the crater due to the action of lake waters, starting from rocky fragments rolled along the slopes and from dust carried by the winds. Since the raw material is substantially formed by volcanic minerals in both cases and since their transformation into clay

MARS SCIENCE LABORATORY SCIENCE INSTRUMENTS

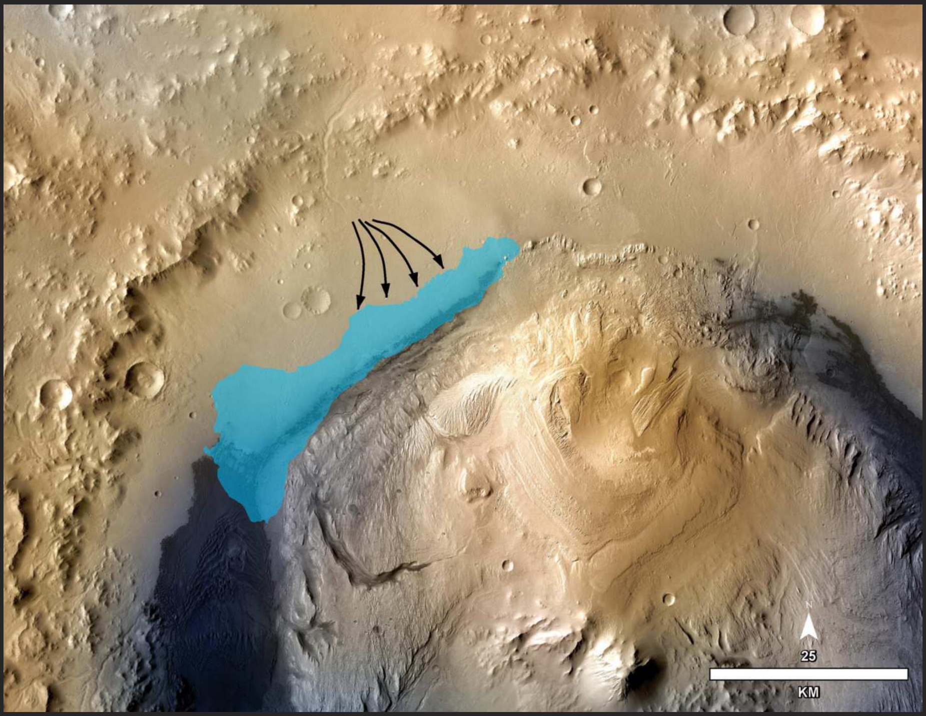
- **Mastcam (Mast Camera)**
The Mast Camera, or Mastcam for short, takes color images and color video footage of the Martian terrain. The images can be stitched together to create panoramas of the landscape around the rover.
- **MAHLI (Mars Hand Lens Imager)**
The Mars Hand Lens Imager, called MAHLI, is the rover's version of the magnifying hand lens that geologists usually carry with them into the field. MAHLI's close-up images reveal the minerals and textures in rock surfaces.
- **MARDI (Mars Descent Imager)**
The Mars Descent Imager, nicknamed "MARDI," shot a color video of the terrain below as the rover descended to its landing site. The video helped mission planners select the best path for Curiosity when the rover started exploring Gale Crater.
- **APXS (Alpha Particle X-Ray Spectrometer)**
The Alpha Particle X-Ray Spectrometer is called APXS for short. When it is placed right next to a rock or soil surface, it uses two kinds of radiation to measure the amounts and types of chemical elements that are present.
- **ChemCam (Chemistry and Camera)**
The Chemistry and Camera tool is known as ChemCam. ChemCam's laser, camera and spectrograph work together to identify the chemical and mineral composition of rocks and soils.
- **CheMin (Chemical and Mineralogy)**
The Chemical and Mineralogy instrument, or CheMin for short, performs chemical analysis of powdered rock samples to identify the types and amounts of different minerals that are present.
- **SAM (Sample Analysis at Mars)**
The Sample Analysis at Mars tool is called SAM. SAM is made up of three different instruments that search for and measure organic chemicals and light elements that are important ingredients potentially associated with life.
- **RAD (Radiation Assessment Detector)**
The Radiation Assessment Detector is also known as RAD, and is helping prepare for future human exploration of Mars. RAD measures the type and amount of harmful radiation that reaches the Martian surface from the sun and space sources.
- **DAN (Dynamic Albedo Of Neutrons)**
The Dynamic Albedo of Neutrons tool, called DAN for short, looks for telltale changes in the way neutrons released from Martian soil that indicate liquid or frozen water exists underground.
- **REMS (Rover Environmental Monitoring Station)**
The Rover Environmental Monitoring Station is nicknamed REMS, and it contains all the weather instruments needed to provide daily and seasonal reports on meteorological conditions around the rover.
- **MEDLI (Mars Science Laboratory Entry Descent and Landing Instrument)**
The Mars Science Laboratory Entry Descent and Landing Instrument is called MEDLI. MEDLI measured the heating and atmospheric pressure changes that occurred during the descent to help determine the effects on different parts of the spacecraft.



Some of the main geological structures investigated by Curiosity in Yellowknife Bay. John Klein and Cumberland are two of several sites where the rover drilled into the rocks to extract dust for analysis in its in-house laboratory. [NASA/JPL Caltech/MSSS]

minerals involves the dissolution in water of some of their characteristic elements, such as calcium and sodium, an overall scarce presence of the latter in the vicinity of the clays would indicate that the process took place through stirred waters, able to totally disperse the washed-out elements into the environment. On the contrary, if the clay sediments still contain certain types of elements, it means that the geochemical action that led to their formation took place in calm waters and in a more recent period than that of the first scenario.

Curiosity has confirmed that the clay sediments of Yellowknife Bay originated in accordance with the second scenario and that the particles that then gave rise to the minerals in question were transported to the bottom of the lake by the waters of some streams before undergoing significant chemical actions by water. The slow evaporation of the lake and the not exces-



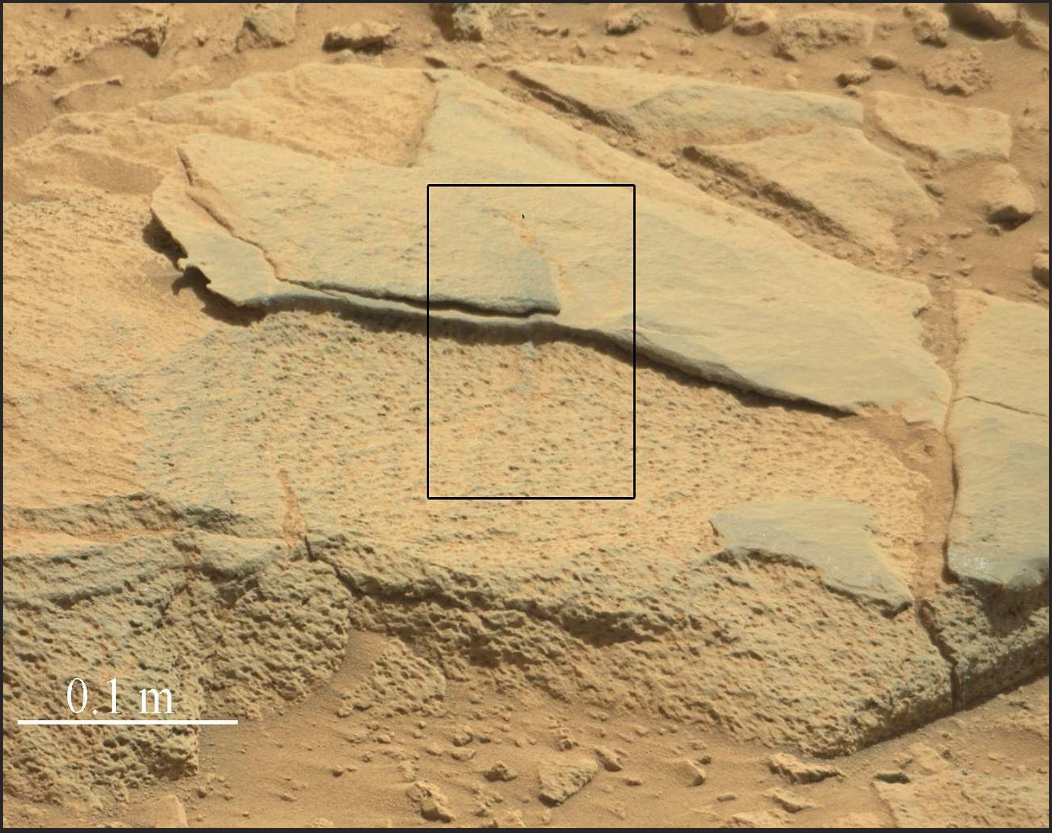
Possible extension of the lake identified by Curiosity in Gale Crater. Squeezed between the crater rim and Mount Sharp, the lake would stretch into the circular valley, covering a small portion of it. The same thing may also have happened in other areas of the same crater or in other craters. [NASA/JPL Caltech/MSSS]

Overview that offers a view of the dry lake in which Curiosity has found concrete evidence of a remote habitability of Mars. In the foreground, on the right, large sandstone can be seen, located in what can be called the edge of Yellowknife Bay. [NASA/JPL-Caltech/MSSS]

sively aggressive Martian atmospheric and geological agents have ensured that those deposits have been very well-preserved to this day, despite their very ancient origin. This peculiarity is typical of Mars, while on Earth it is extraordinarily difficult to find rocks dating back to those same periods. By examining the isotope ratios of some elements, geologists were able to estimate the age of a slab of clay minerals called "Cumberland", which was found to have formed between 3.86 and 4.56 billion years ago, confirming an extremely remote origin of Gale Crater and also of the lake that found its seat there.

Researchers estimate that the lake may have been preserved until at least 3.6 billion years ago, but its slow evaporation may not have spelled the end of any microbial life

Below, one of the many holes that Curiosity has dug in the Martian rocks. The rock drilled here was named "John Klein". [NASA/JPL Caltech/MSSS]



The rock "Ithaca" shown here, with a rougher lower texture and smoother texture on top, appears to be a piece of the local sedimentary bedrock protruding from the surrounding soil in Gale Crater. [NASA/JPL-Caltech/MSSS]

that appeared in it. The analysis of the data collected by Curiosity has also shown that the clay sediments of Yellowknife Bay are rich in iron and sulfur, elements that together with the clay form a mineral called smectite. This mineral forms in waters with neutral pH and low salinity, the ideal habitat for a primitive terrestrial life form called chemolithoautotrophs. These bacteria draw energy directly from the rock material by exploiting the oxidation of inorganic compounds, with sulfur and iron at the center of their diet, while using the supply of carbon that exists directly from an atmosphere rich in carbon dioxide. In a sense, chemolithoautotrophs are powered by a sort of battery, and that kind of power supply was available in Yellowknife Bay. All this demonstrates that the geological environment of young Mars was conducive to the emergence of life. Since the age of the rock structures of Yellowknife Bay are a little older than expected, those conditions have then lasted until more recent times than previously believed. If we then consider that hydrogen, oxygen and nitrogen have also been identified in the dry lakebed in addition to the elements already mentioned, we find all the prerequisites for microbial life to have proliferated in that environment and in other similar environments. But any confirmation in this sense can only come from Curiosity's successors, starting with Perseverance. ■

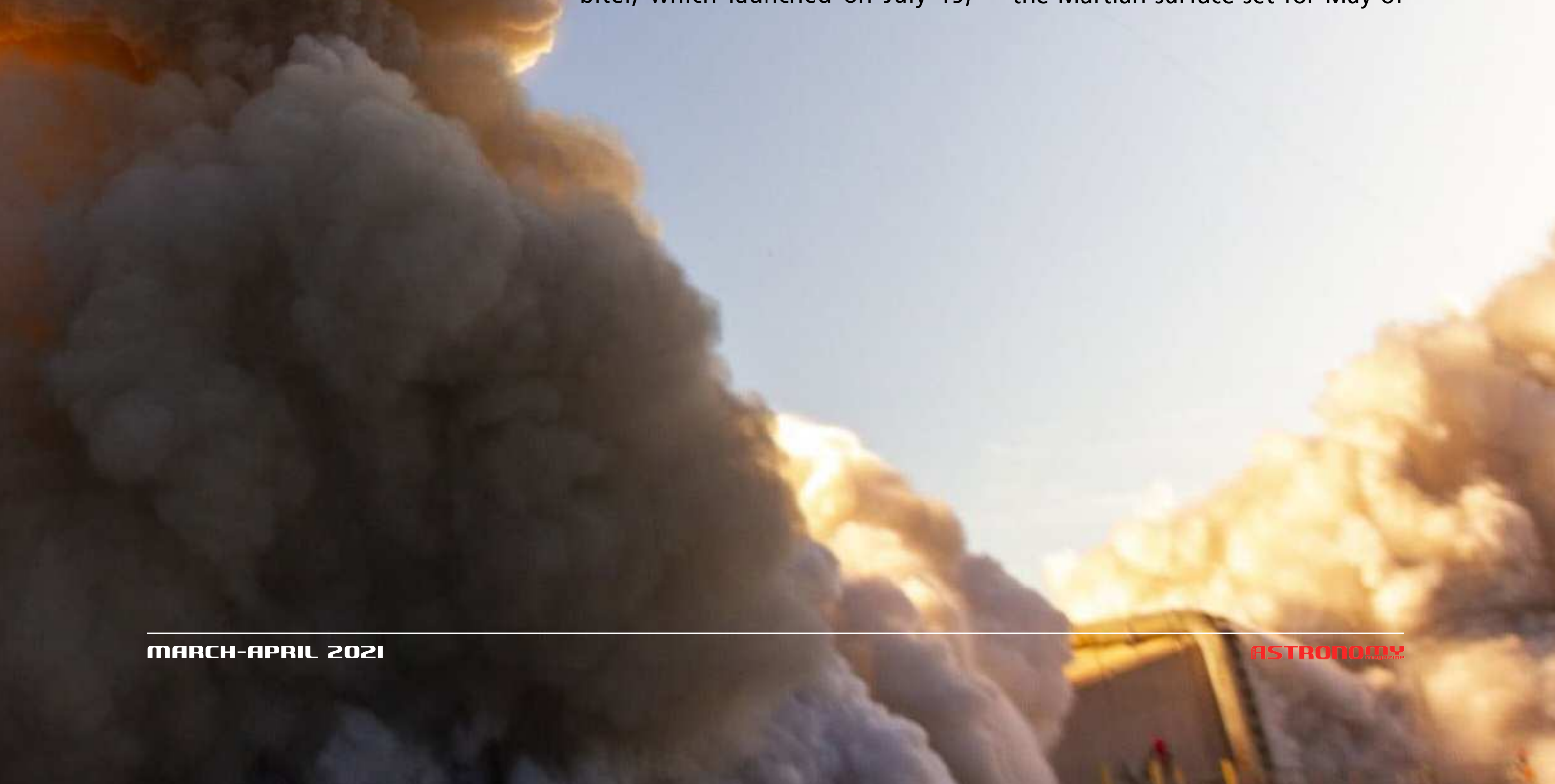
NASA's Curiosity Mars rover recorded this sequence of views of the sun setting at the close of the mission's 956th Martian day, or sol (April 15, 2015), from the rover's location in Gale Crater. The four images shown in sequence here were taken over a span of 6 minutes, 51 seconds. This was the first sunset observed in color by Curiosity. [NASA/JPL-Caltech/MSSS/Texas A&M Univ.]

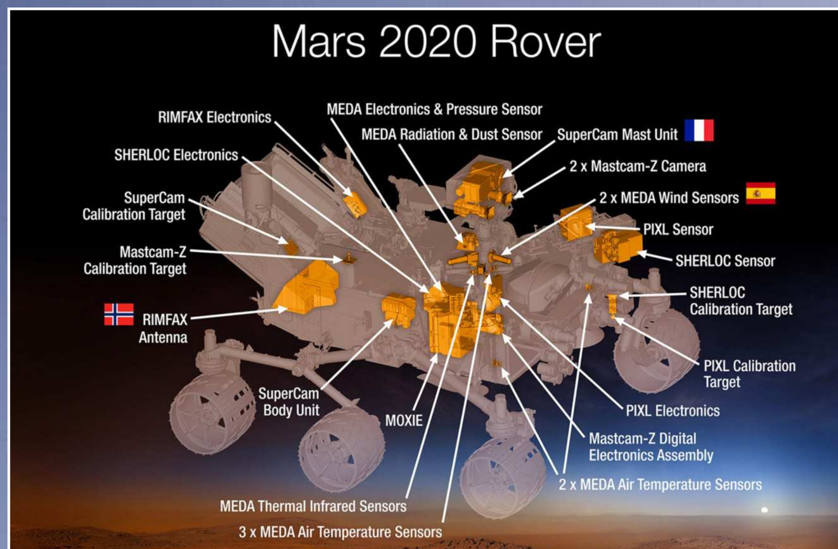
Perseverance

by Damian G. Allis ❖ NASA Solar System Ambassador

Efficient interplanetary travel is all about timing. Within a span of just nine days, three travelers from Earth, all launched in July 2020, have found themselves either inserted into Martian orbit or, most recently, present on its surface. This clustering of missions is, of course, not by coincidence – the nearby and near-circular orbits of Earth and Mars result in periodic windows for relatively short and fuel-efficient travels. This particular path for Earth and Mars, their Hohmann transfer orbit, greatly reduces overall fuel requirements and transit times,

The launch on a ULA Atlas V rocket of Mars 2020 from Cape Canaveral on July 30, 2020. [NASA]





Scientific equipment on Perseverance, with international collaborations labeled. [NASA/JPL]

but then requires that missions be absolutely ready when the window opens for launch – else risking a mission delay of 26 months, the time between these ideal Earth-Mars launch windows.

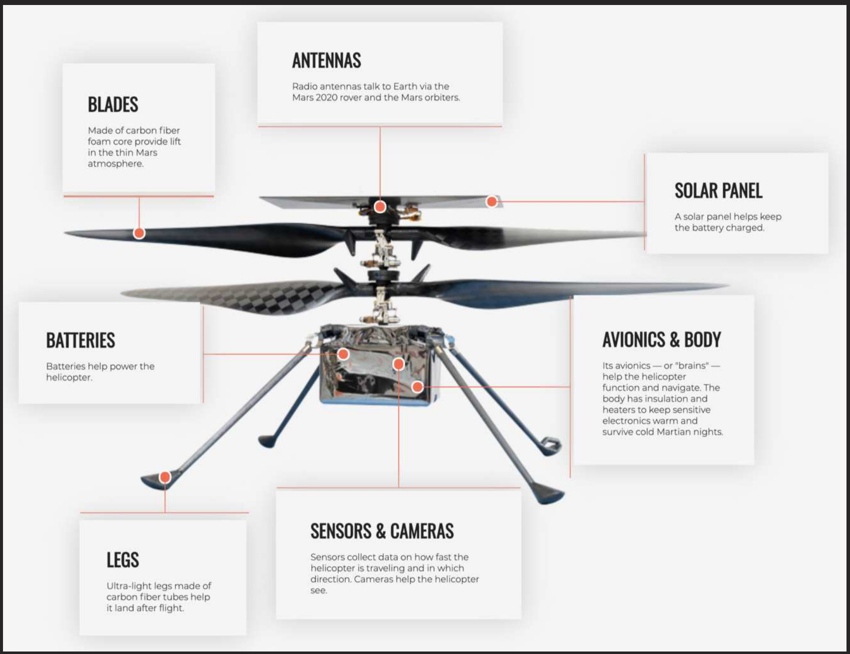
The first arrival this month was the United Arab Emirates' "Hope" orbiter, which launched on July 19, 2020 and entered orbit on February 9, 2021. With a mission to study the Martian atmosphere and climate, the UAE has established itself as a nation with the technical know-how to be among the few "first-firsts," having their first Mars mission work successfully the first time. The second mission is China's Tianwen-1, launched on July 23, 2020 and in orbit as of February 10, 2021, with a planned lander descent to the Martian surface set for May of

Together with the Perseverance rover, the Ingenuity helicopter landed on Mars this past February 18th. Its mission is to demonstrate the first powered flight on another planet, taking to the Martian skies in Spring 2021. [NASA/JPL-Caltech]

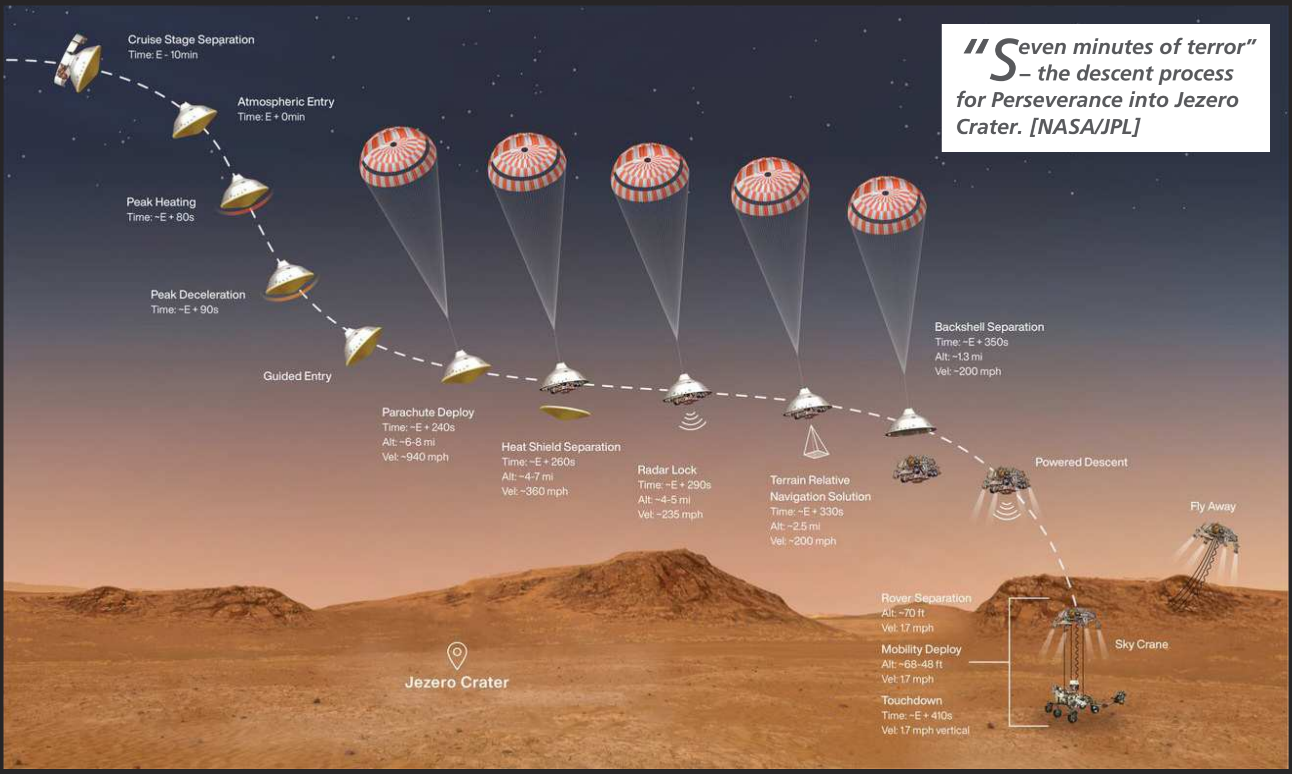
this year. Within the lander is a rover equipped with cameras, a spectroscope, meteorological equipment, and ground-penetrating radar. If all goes well, China will be only the third nation to successfully land on Mars (behind the Soviet Union and United States) and only the second nation to successfully land a mobile laboratory.

Among Martians and Mars enthusiasts alike, the most famous scientific organization on the planet's surface is NASA. On February 18th, the next mission in the NASA Mars Exploration Program, Mars 2020, delivered a number of new scientific instruments in a single rover to study the history and possible future of Mars habitability, as well as to specifically search for evidence of past microbial life on the Martian surface. The Perseverance rover ("Percy" for short), like Hope and Tianwen-1, are launched by a single entity but are international efforts in terms of the several countries producing different scientific instruments, with facilities in France, Norway, and Spain providing or co-developing some of Percy's onboard scientific hardware.

Just as Pathfinder and Sojourner were the first tests of a lander and undemonstrated rover, Perseverance is a first test of a demonstrated rover design and undemonstrated powered flight. Packed underneath Percy is "Ingenuity" – a small and lightweight helicopter set to be the first aerial device to travel over and survey another planet. With a total of five planned flights over the course of 30 days, Ingenuity and its successors offer the possibility of greatly extending the distances that a rover can travel by providing much higher resolution imaging of troublesome surface features than is possible from either orbit or from the rovers themselves, all while producing some of the most remarkable drone photography ever recorded. These aerial scouts can also provide hi-res imaging to aid in the selection of interesting features, thereby also reducing the target selection times and potentially greatly increasing the rate of scientific discovery.



The main structural components of the Ingenuity helicopter, scheduled for up to five flights in one month. [NASA]

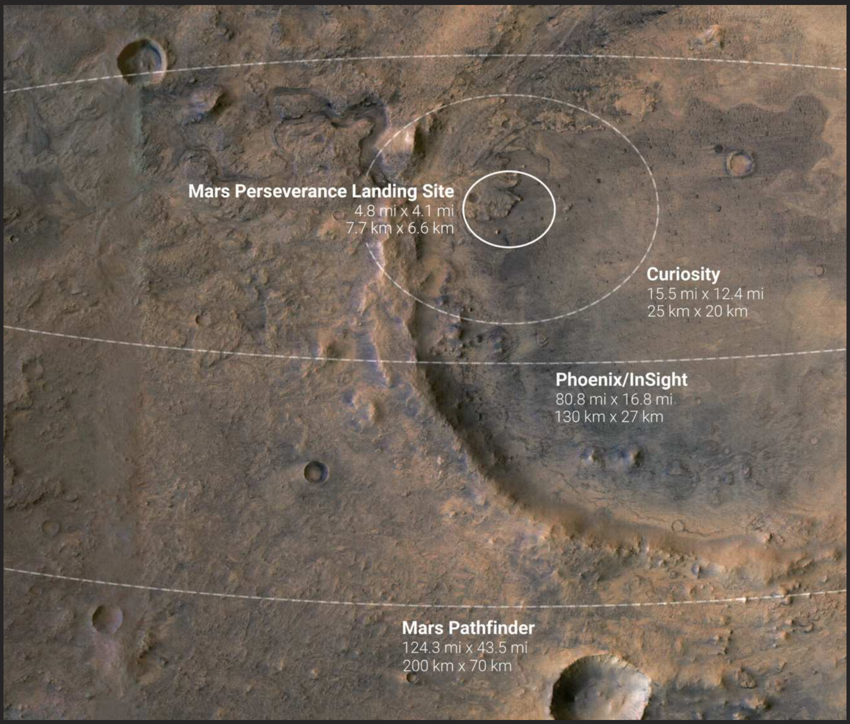


"Seven minutes of terror" – the descent process for Perseverance into Jezero Crater. [NASA/JPL]

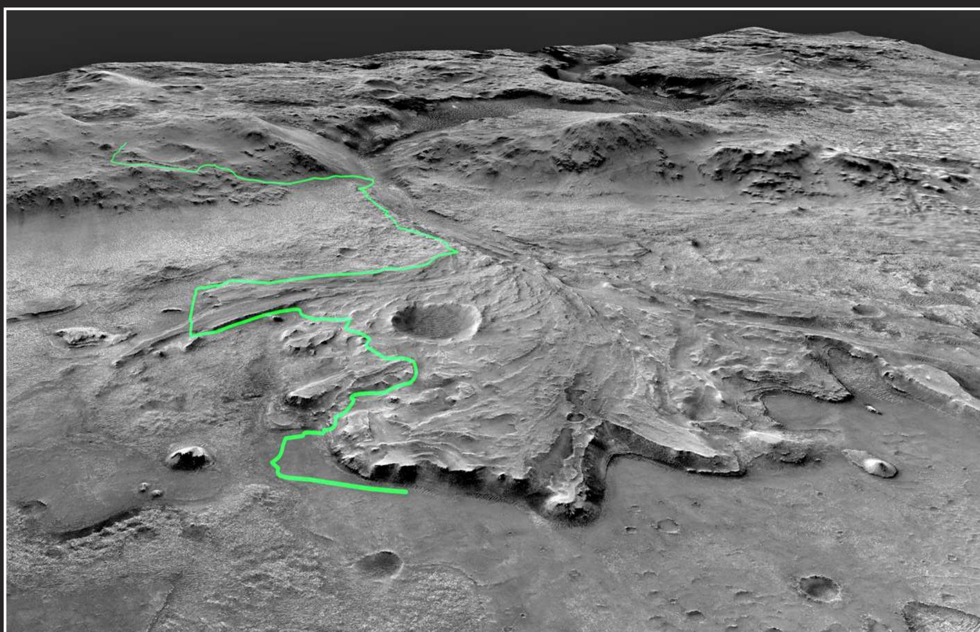
Mars 2020 is one more step in support of the larger Mars Exploration Program that has included all of the missions featured in this issue. The Perseverance rover has four mission objectives that clearly emphasize the bio-centric focus of NASA's current Martian interests:

(1) "Looking for habitability" – in this case, the search is for data about past habitability in further support of our current models of ancient Mars as a warmer, wetter, and potentially life-supporting planet.

(2) "Seeking biosignatures" – we



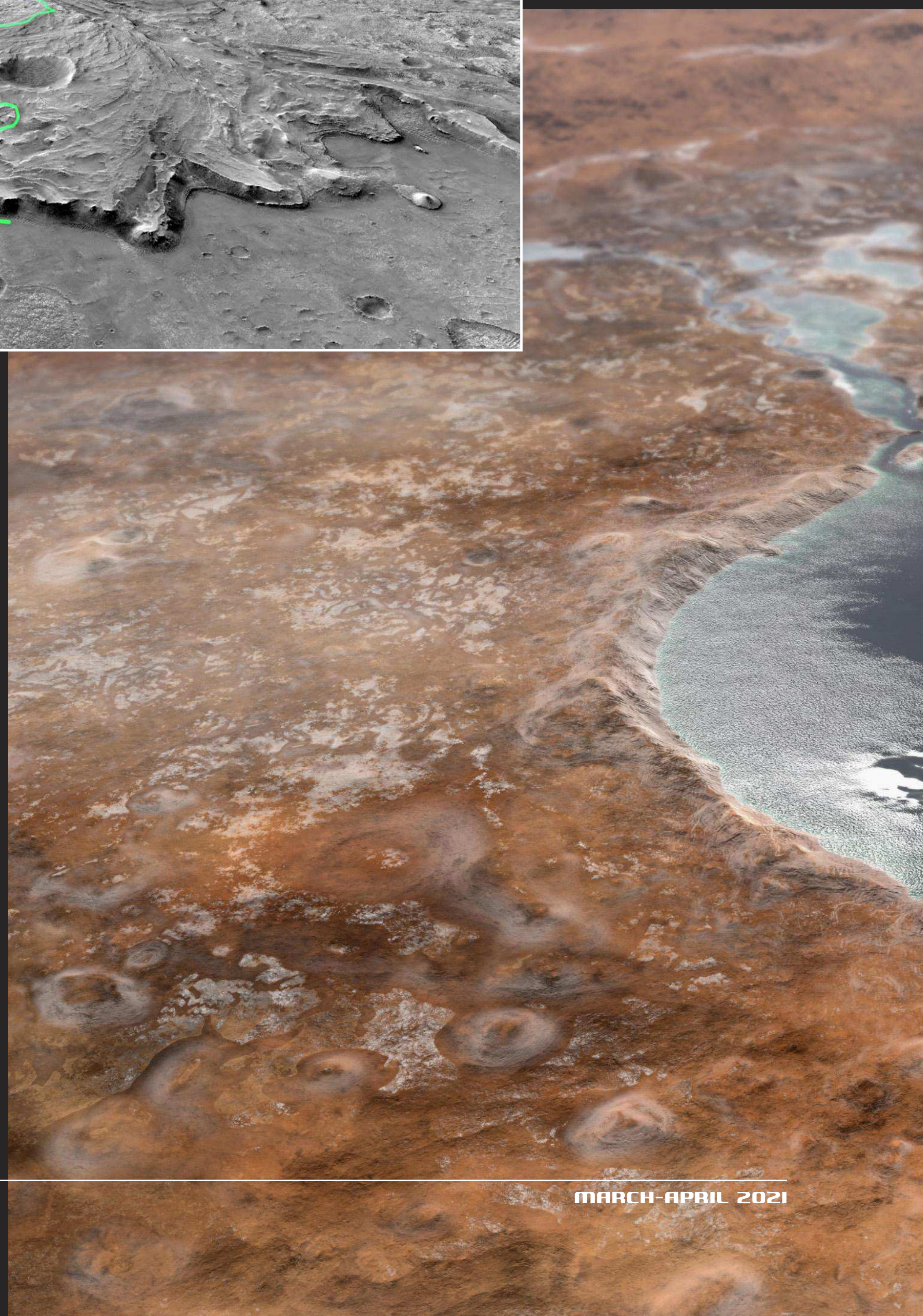
The landing ellipses for several past Mars missions, centered on the planned landing region for Perseverance. Changes to lander descent technologies and guidance have greatly reduced the descent uncertainties and enabled increasingly targeted deliveries of rovers to selected locations. [NASA]



This annotated mosaic depicts a possible route the Mars 2020 Perseverance rover could take across Jezero Crater as it investigates several ancient environments that may have once been habitable. [NASA/JPL-Caltech]

must always qualify that such searches are strongly biased towards the kinds of lifeforms we have on Earth and the evolutionary processes that resulted in what we observe today. That said, our own explorations here on Earth have greatly expanded the kinds of lifeforms to look for, with the increasing number of identified species we refer to as extremophiles dramatically expanding the range of amazing conditions under which life can proliferate.

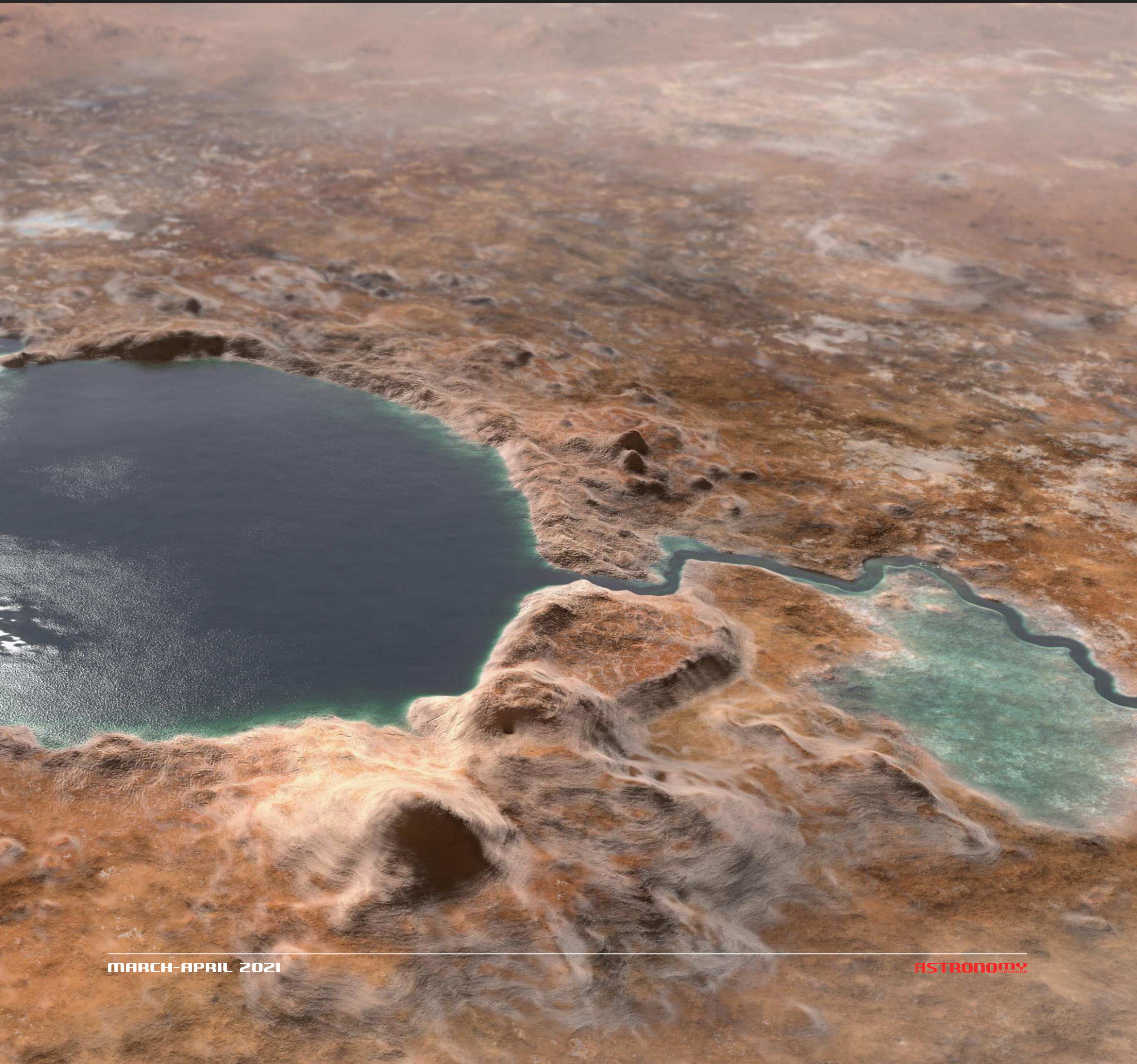
(3) "Caching samples" – this objective makes clear that NASA intends on having future missions explore much more of the Martian surface and that it also intends on performing much more exhaustive analyses here on Earth – or, at least, somewhere nearby. This separation of the scientific instruments that perform analysis from the future collection and delivery hardware that will deliver samples back to

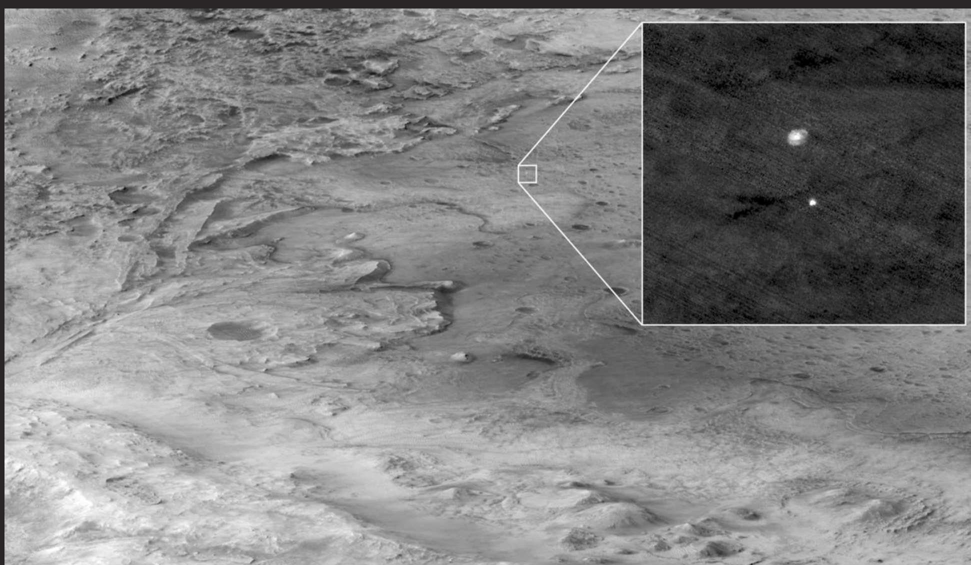


An artist's concept of Jezero Crater at a time billions of years in the past, when rivers filled the crater depth to form a standing lake while also depositing clays and other materials that exist in the form of dry deltas to this day. [NASA/JPL-Caltech/ASU]

us means that neither mission has to sacrifice payload or precious space to accommodate both. For the samples collected by Percy, the "fetch rover" (although one can only imagine that such a collection mission would be far more efficient with a more advanced version of Ingenuity) and return vehicle are currently slated to bring this precious cargo back to Earth in 2031.

(4) "Preparing for humans" – the most exciting news about our moon this past decade was the identification of water ice on its surface, meaning a potential fuel supply is



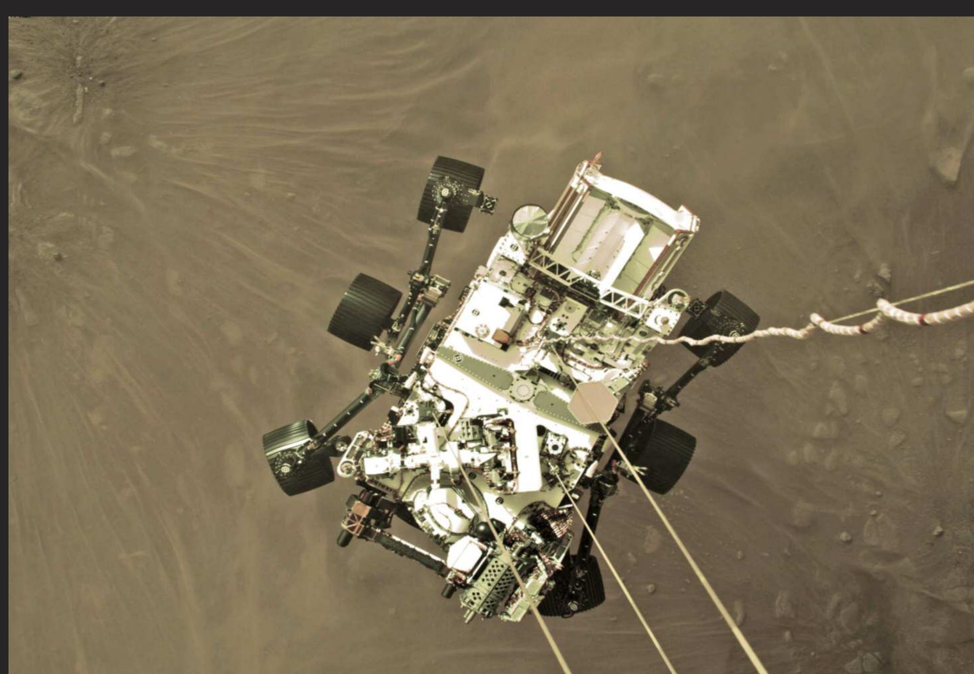


The descent of Perseverance as captured by the High Resolution Imaging Experiment (HiRISE) camera aboard the Mars Reconnaissance Orbiter. At image left, the mission-target river delta within Jezero Crater. [NASA/JPL-Caltech/University of Arizona]

accessible for missions that could then launch from a body with a fraction of Earth's gravity. On Mars, we have accessible water ice for both fuel and drinking, but also a thin atmosphere from which the right equipment could convert carbon dioxide into oxygen – after which the process of compressing and storing oxygen for future use is something we already do on Earth every day. This test is being performed within the Mars Oxygen ISRU Experiment (MOXIE) to determine if future explorers could simply make breathable oxygen out of, certainly in the case for Mars, thin air.

The delivery of an advanced mobile laboratory to a desolate and featureless location is about as useful as delivering a rover with minimal capabilities to an ideal location. To that end, probes such as the Mars Reconnaissance Orbiter have been used to scour the Martian surface for years in search of locations of great geological interest and, for Percy, potential past biological habitability.

The chosen location for Percy is Jezero Crater, the focus of an extensive article in the Jan/Feb 2020 issue. In Mars' ancient past, Jezero Crater hosted at least one lake into which several rivers flowed, two of which produced



Taken from the descent stage, a snapshot of Perseverance rover from about two meters above the Martian surface. This image was sent down the coiled umbilical into Percy for later transmission before the descent stage disconnected from the rover and flew off to a safe distance. [NASA/JPL-Caltech] deltas rich in clay deposits – perfect for storing biological markers or, potentially, even fossils. It is hoped that the Mars 2020/Jezero Crater combination of technology and location will lead to great discoveries at an accelerated pace. While this advanced rover still lacks the dexterity and spontaneity that a human researcher trained in geology would bring to the study of the Martian surface, advances in automation, machine learning, and scaling mean that some future vehicular laboratory on par with a living scientist may, in fact, still be delivered and doing science before any mission with a human crew does find their way to the surface.

For space scientists and enthusiasts alike, the launches of July 2020 and anticipated arrivals in February 2021 were a welcome break from the ongoing COVID pandemic.

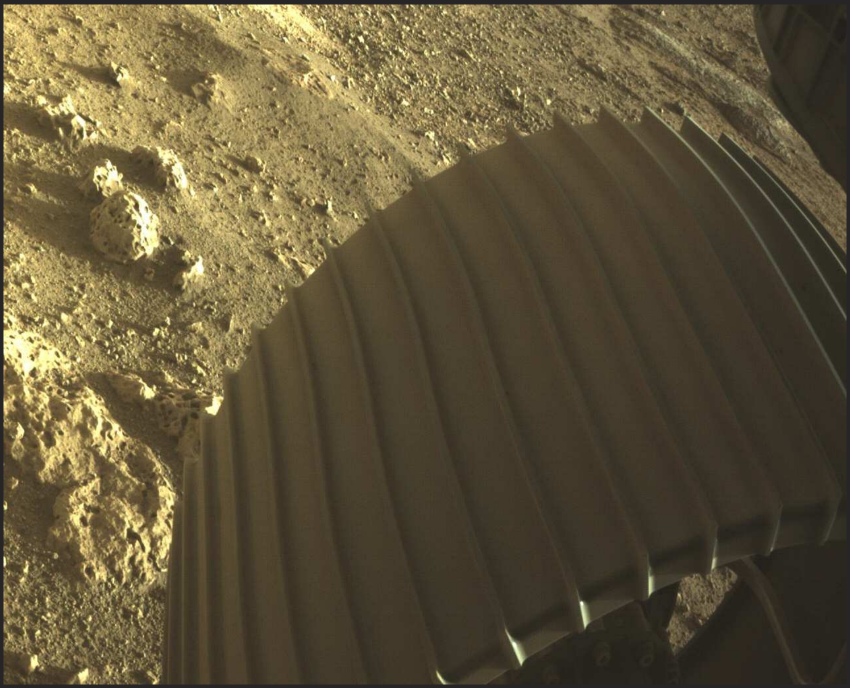
NASA's Mars 2020 Perseverance mission captured thrilling footage of its rover landing in Mars' Jezero Crater on Feb. 18, 2021. The real footage in this video was captured by several cameras that are part of the rover's entry, descent, and landing suite. The views include a camera looking down from the spacecraft's descent stage (a kind of rocket-powered jet pack that helps fly the rover to its landing site), a camera on the rover looking up at the descent stage, a camera on the top of the aeroshell (a capsule protecting the rover) looking up at that parachute, and a camera on the bottom of the rover looking down at the Martian surface. The audio embedded in the video comes from the mission control call-outs during entry, descent, and landing. [NASA/JPL-Caltech]

On the local afternoon of February 18th at NASA Mission Control, seven months and 292 million miles (472 million km) of anticipation abruptly transitioned into "seven minutes of terror," the phrase NASA mission specialists have used to describe the time during which the Perseverance delivery system entered orbit, deployed its parachute, jettisoned its aeroshell heat shield, and initiated its retro-rocket/skycrane system to slowly winch the rover to the ground be-

The first two images, taken through transparent lens covers, from Perseverance Hazard Cameras (Hazcams) after landing. [NASA/JPL-Caltech]

fore cutting ties and flying off to some safe distance. At a distance of 11 light minutes from Earth, such a precision landing could not be guided by humans from Mission Control. Instead, the delivery was the product of all of the associated hardware and, as explained by Deputy Project Manager Matt Wallace, about two million lines of code processing 30,000 control, sensor, and landing parameters. The Percy landing was, by all accounts, picture-perfect. While the superstitious might attribute this to the now-famous NASA "lucky peanuts" seen being consumed by some on live feeds to ward off the ghosts of

The first high-resolution, color image to be sent back by the Hazard Cameras (Hazcams) on the underside of NASA's Perseverance Mars rover after its landing. [NASA/JPL-Caltech]



This high-resolution image shows one of the six wheels aboard NASA's Perseverance Mars rover, which landed on Feb. 18, 2021. The image was taken by one of Perseverance's color Hazard Cameras (Hazcams). [NASA/JPL-Caltech]

failed missions past, this same manner of delivery was equally flaw- less nine years prior for Curiosity.

By the end-of-feed, the official NASA YouTube channel reported 12 million views for the descent, landing, and celebration at Mission Control upon confirmation and delivery of the first two images. These first two images, taken through the transparent lens covers of two engineering cameras at the front and back of the rover, revealed a successful landing on a flat area with several exposed rocks ready for analysis and, in the distance, a view of the ancient river delta that was the intended landing target for the mission.

During the post-landing press briefing, NASA Associate Administrator Thomas Zurbuchen shouted for joy *"Here's for the contingency plan!"* as he ripped the small stack of papers that served as the roadmap for an unsuccessful landing.

Further analysis of the landing position revealed that Percy was about 2 km to the southeast of the target delta, near-or-at the boundary of two regions known as the "mafic floor unit" and "olivine-bearing unit." This itself was excellent news for geologists, as this landing area marks the boundary region between two different types of rocks and features. In short order, the actual landing location was determined and released. Within 24 hours, color images of the uncapped engineering cameras were reported. In a feat of timing, the same Mars Reconnaissance Orbiter that aided in finding an ideal landing site for Perseverance's mission also captured Percy's descent after parachute deployment above its final landing location. The following days were a wealth of diagnostic data and, of course, stunning images. With the scientific mission now active, we await the many downloads from what is currently the most sophisticated machine to ever exist on a planet that is, so far as we now know, entirely populated by only machines.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