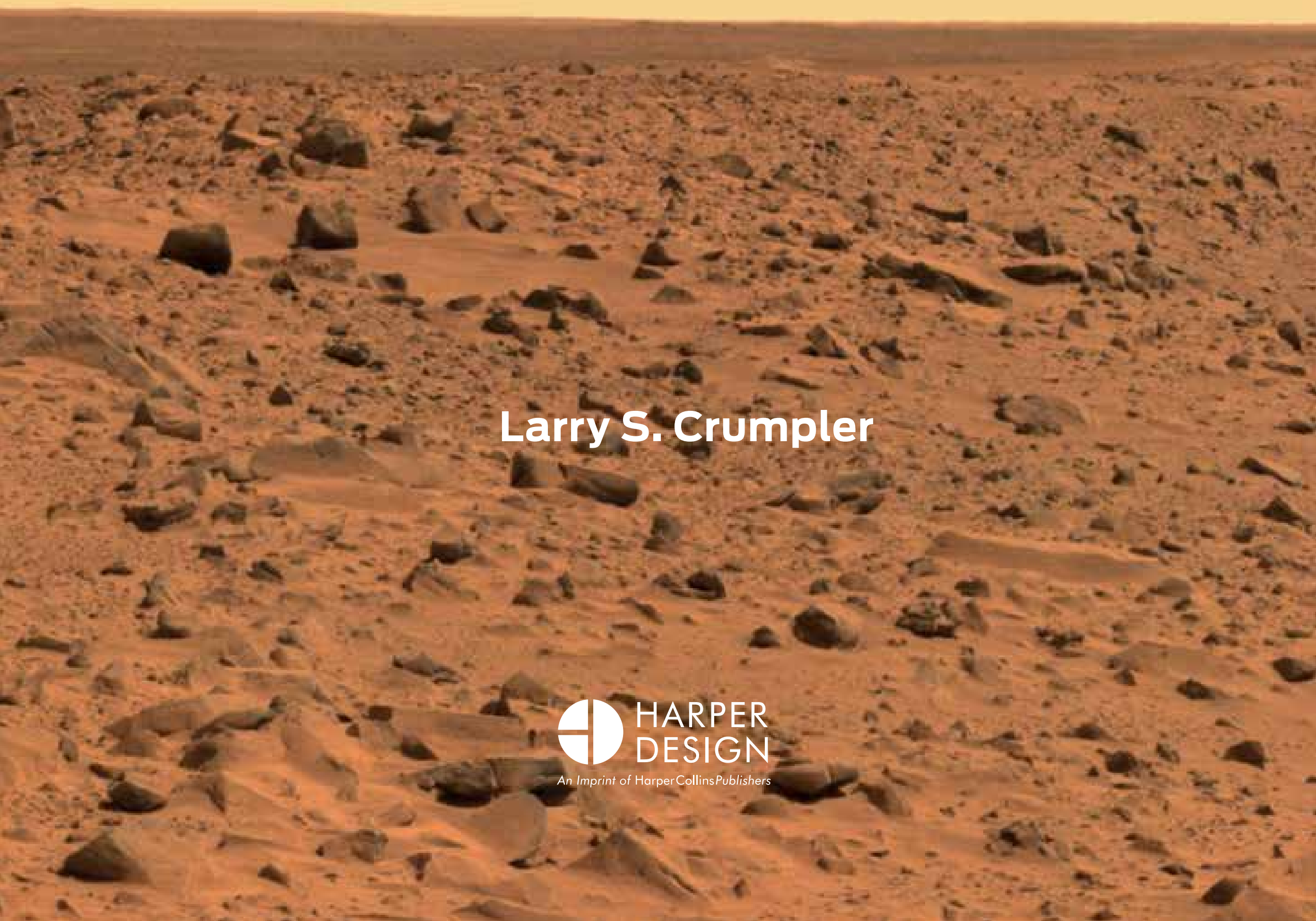
MISSIONS TO MARS

A NEW ERA OF ROVER AND SPACECRAFT DISCOVERY ON THE RED PLANET



Larry S. Crumpler

HARPER DESIGN
An Imprint of HarperCollinsPublishers

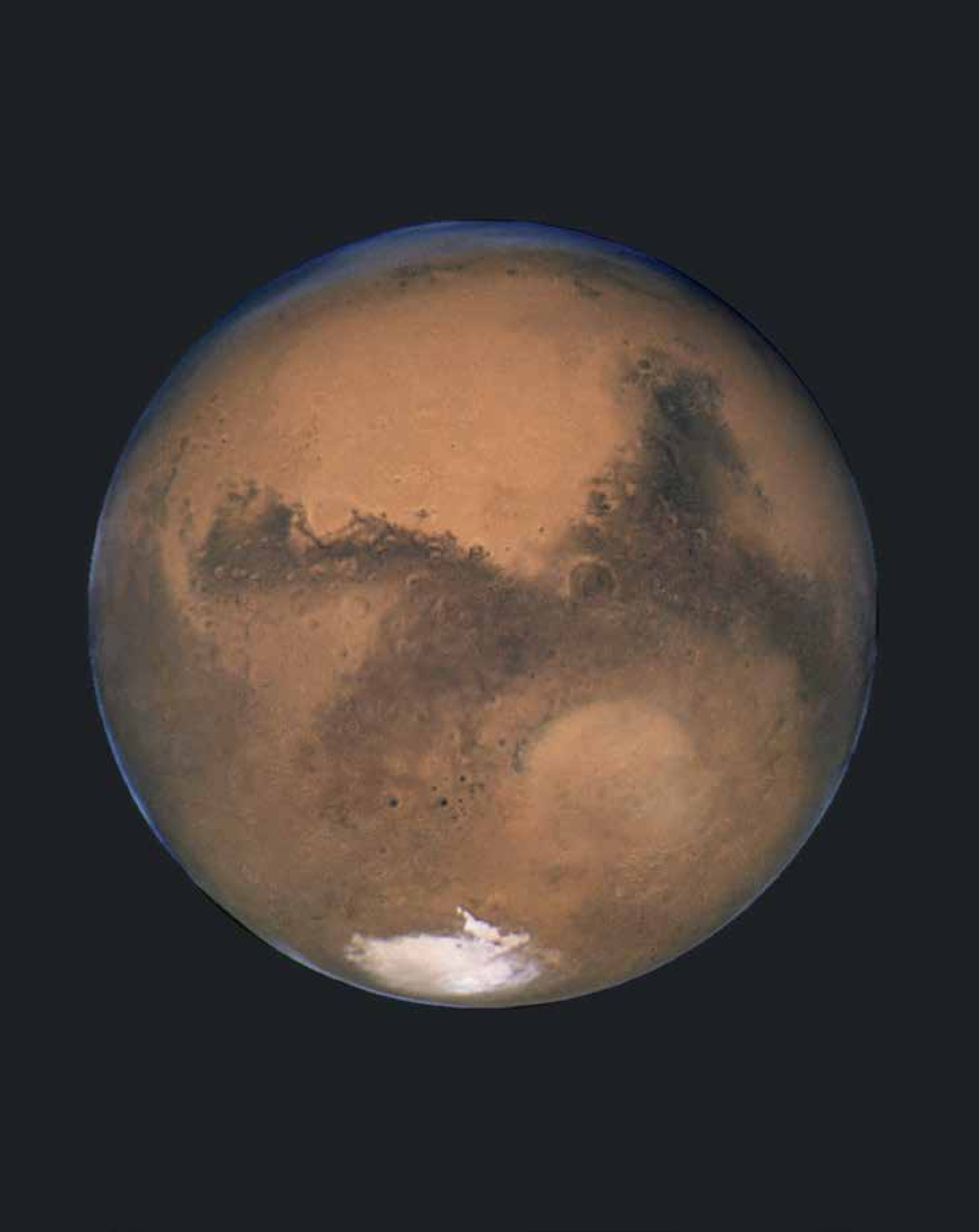
First published in 2021 by
Harper Design
An Imprint of HarperCollins*Publishers*
195 Broadway
New York, NY 10007
Tel: (212) 207-7000
Fax: (855) 746-6023
harperdesign@harpercollins.com
www.hc.com
Distributed throughout the world by
HarperCollins*Publishers*
195 Broadway
New York, NY 10007

ISBN 978-0-06-304736-5

Library of Congress Control Number: 2021025709

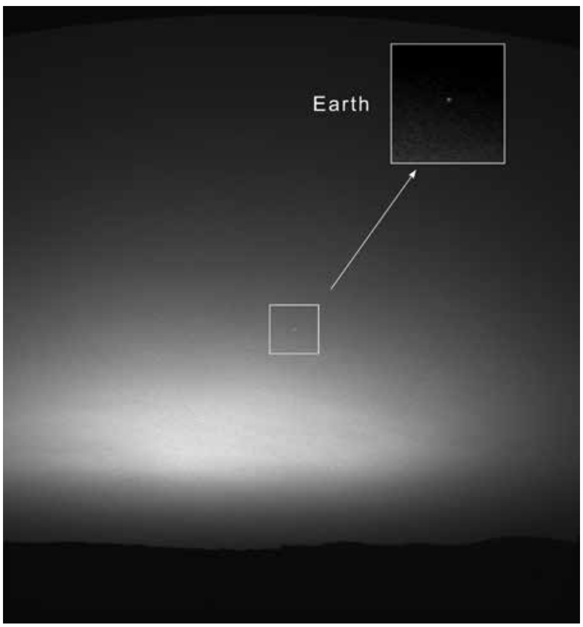
Printed in Malaysia

First Printing, 2021



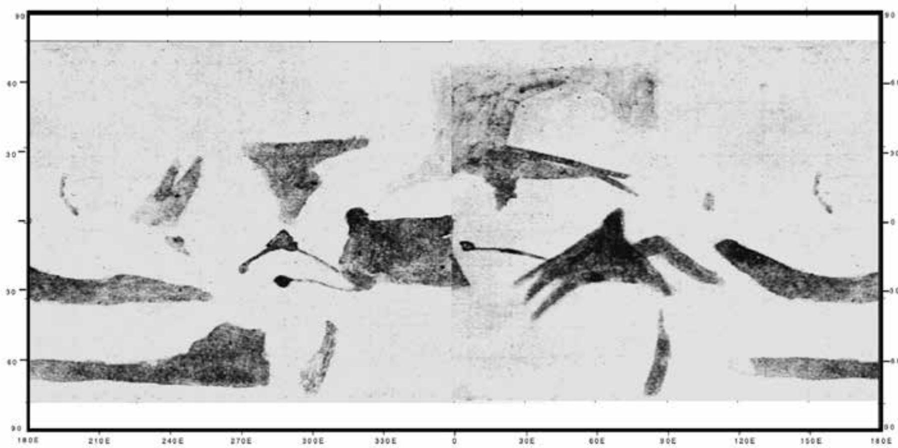
RIGHT: This was the view of Mars and the nearby Moon from Earth for centuries. This photograph of Mars in the evening sky was taken during the 2020 opposition. The view looks across the Rio Grande Valley from Rio Rancho toward the Albuquerque city lights.

BELOW: Sol (day) 63 image of the morning sky taken by Spirit rover one hour before sunrise. This is the first image of Earth taken by a spacecraft from the surface of Mars.

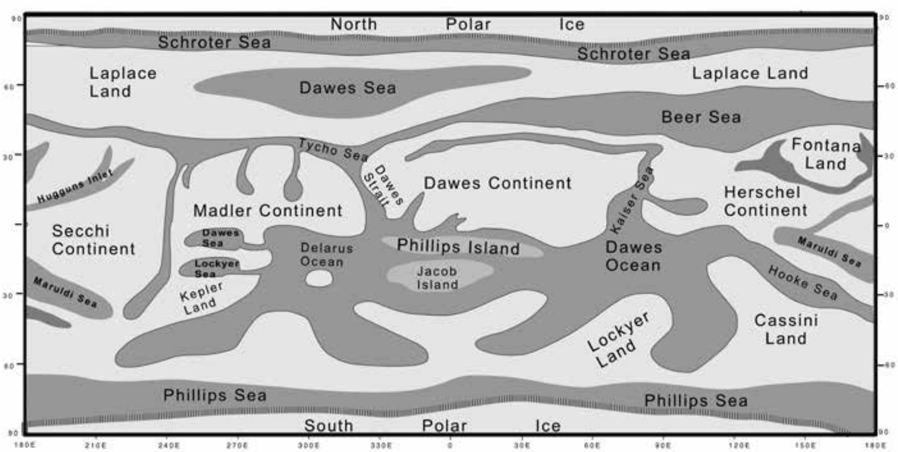


ABOVE: Sketches from the earliest efforts to view Mars through telescopes.

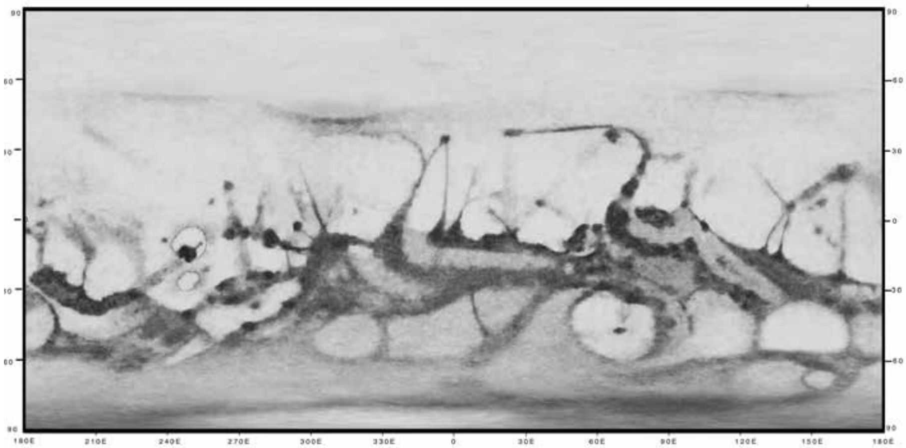
FIRST MAPS OF MARS



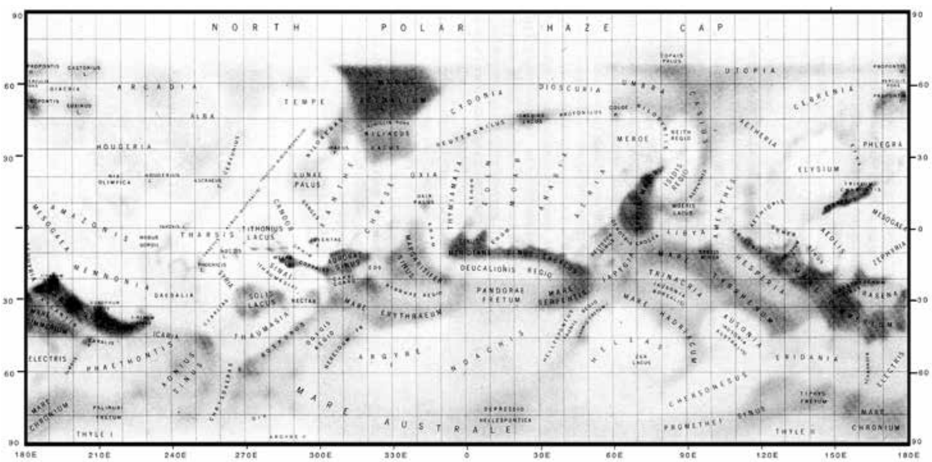
Beer and Mädler, 1830



Proctor and Dawes, 1865-67

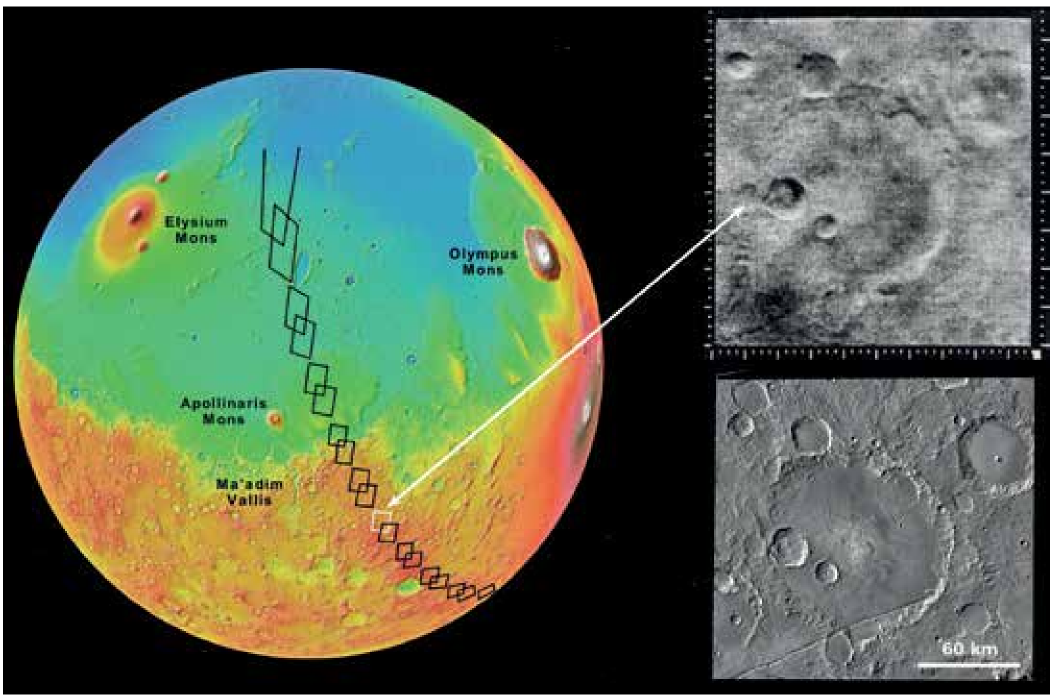


Antoniadi, 1909

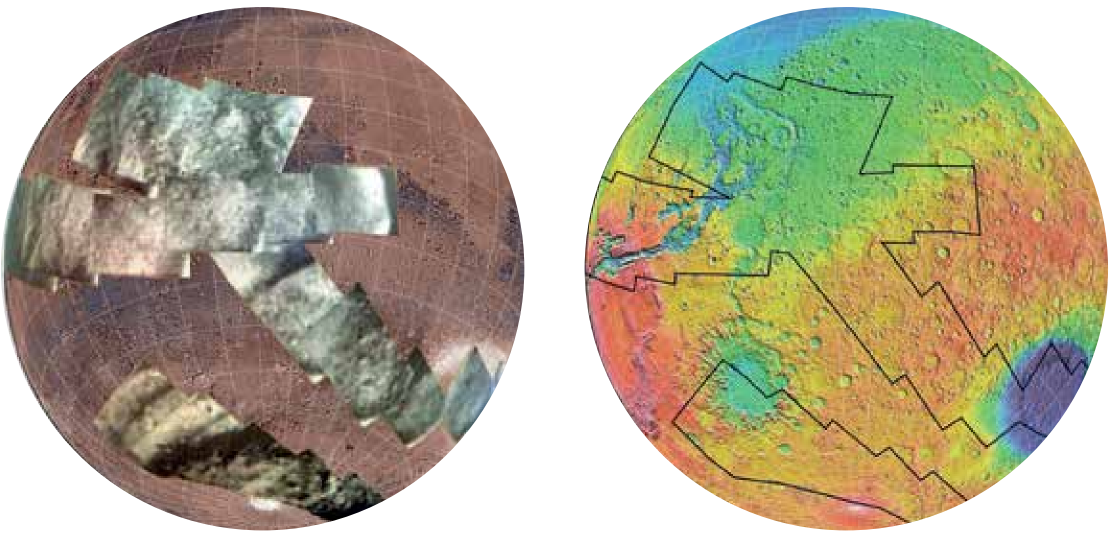


U.S. Air Force, 1962

ABOVE: The Mariner 4 spacecraft during assembly at Jet Propulsion Laboratory (JPL). Mariner 4 was the first successful spacecraft to fly by and image the surface of Mars.

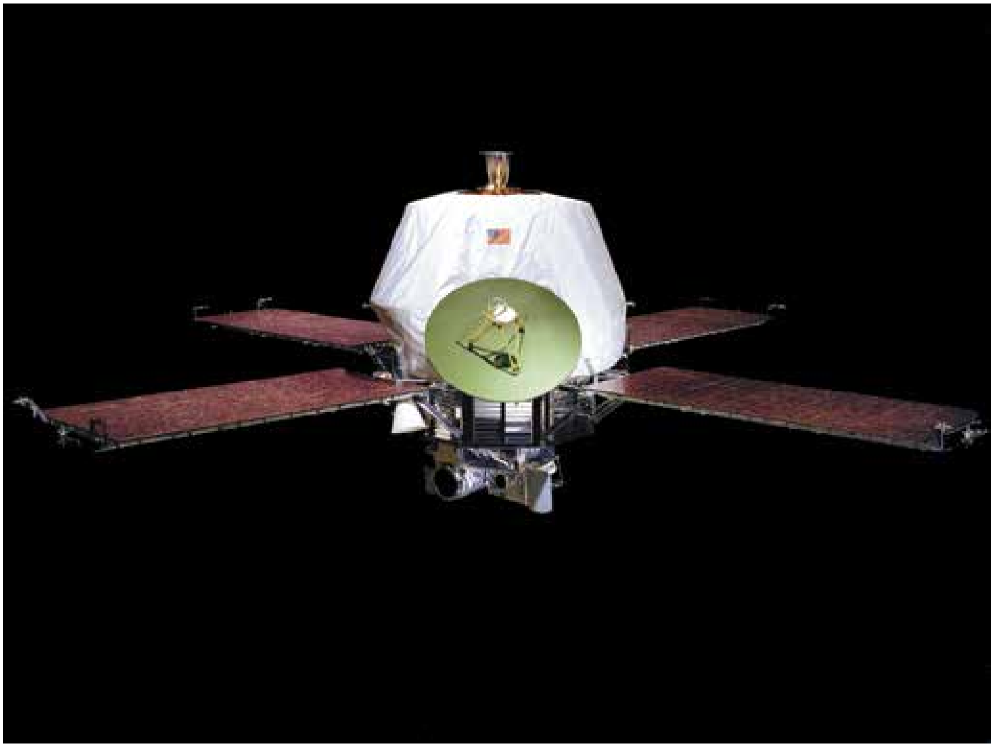


ABOVE: Footprints of all of the images acquired by Mariner 4 as it flew by Mars on July 15, 1965. **TOP RIGHT:** One of the clearest of the images acquired by Mariner 4, the 151-kilometer-diameter crater Mariner, from 12,600 kilometers above the surface. The image is 250 kilometers by 254 kilometers across and centered at 65ºS, 196ºE. **BOTTOM RIGHT:** A much higher-resolution version of the same scene acquired by the THEMIS camera of the later mission Mars Odyssey. The fracture on the bottom is Sirenum Fossae.



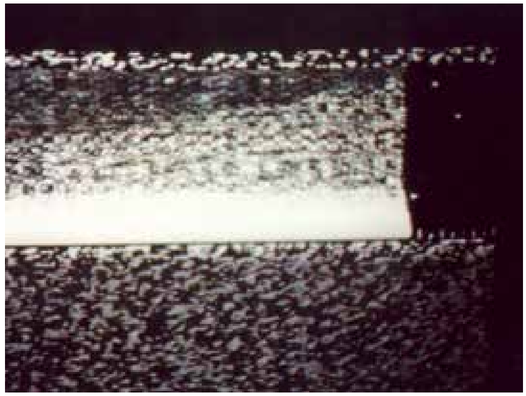
ABOVE: Mariner 6 and 7 images across Mars during a flyby in 1969. Once again a combination of factors obscured details in the more interesting areas such as the vast canyons while the cratered highlands were more clearly imaged.

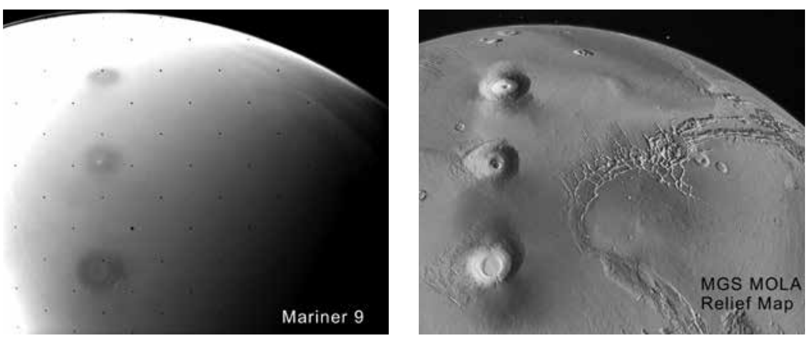
RIGHT: In 1971 Mariner 9 was the first spacecraft to successfully go into orbit about Mars, imaging over 85 percent of the surface. It revolutionized our understanding of Mars, revealing it to be far more exciting than the results of previous Mars flyby missions had indicated.



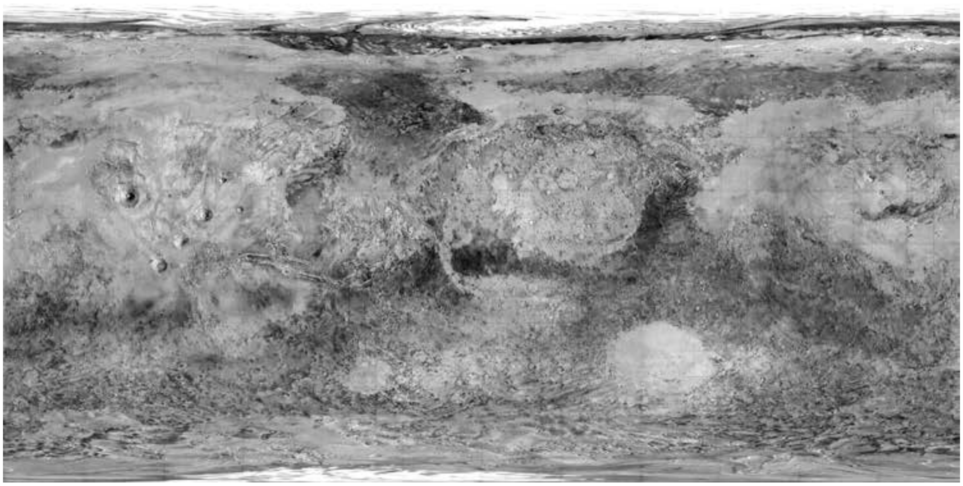
RIGHT: This partial image was returned by the Soviet Mars 3 following its descent and apparent landing on the surface of Mars on December 2, 1971, at 45ºS, 202ºE, in Ptolemaeus Crater. The image consists of about seventy scan lines and either shows the Martian horizon or is just radio static.

BELOW: Possible images of the Mars 3 lander on Mars acquired by the High-Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter in 2007.

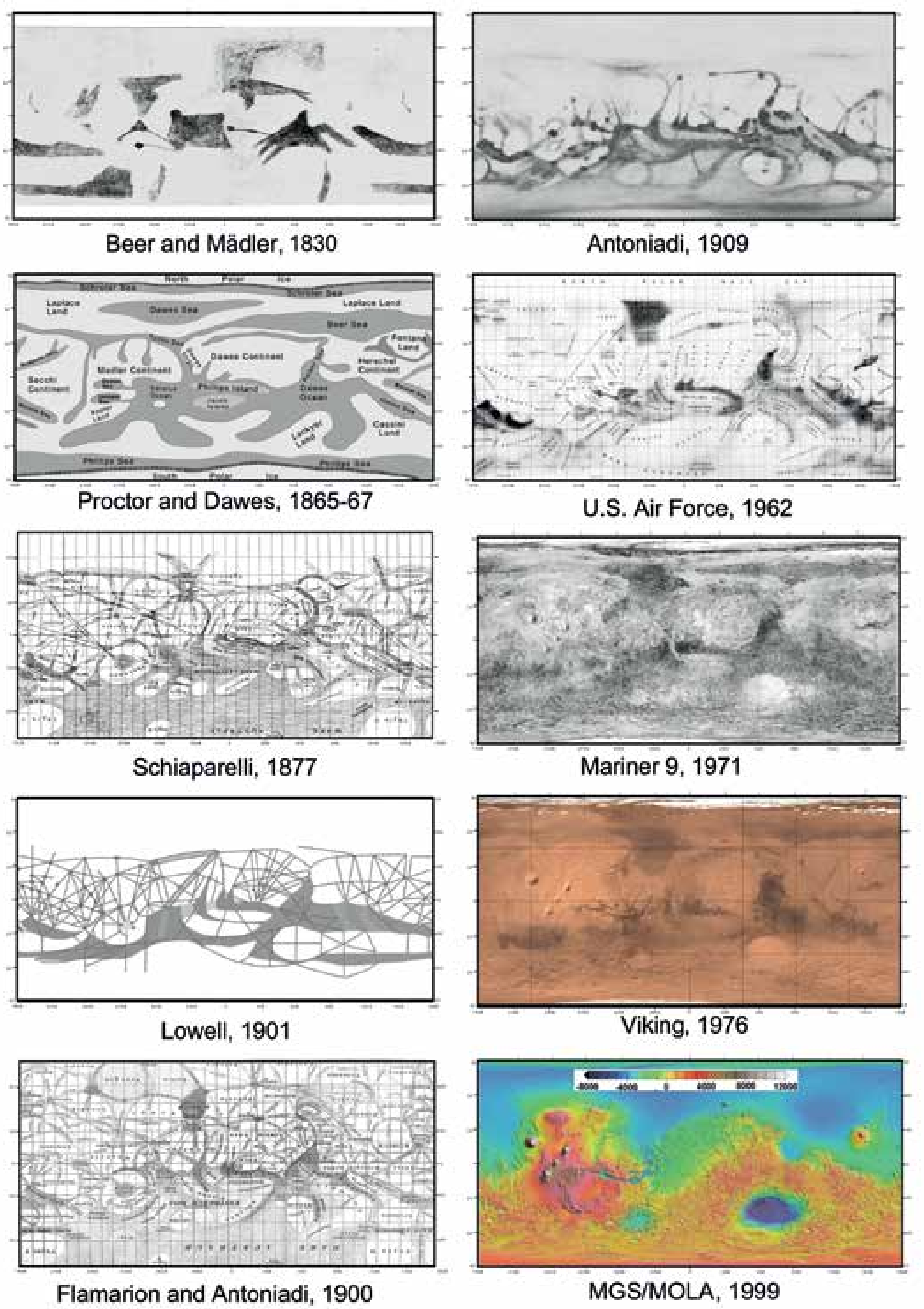




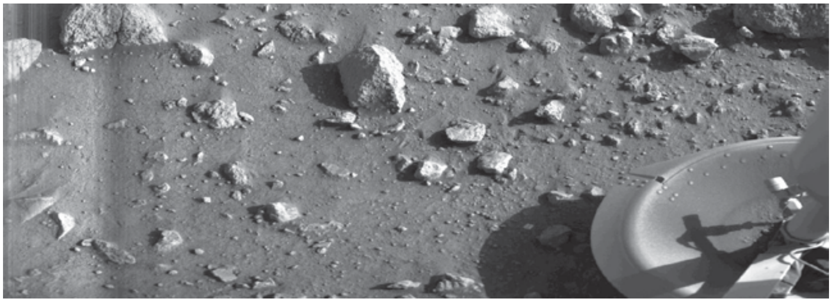
LEFT: The "discovery image" by Mariner 9 during its first orbits of the red planet showing three enormous volcanoes previously missed by flyby spacecraft. The volcanoes were sticking up through a global dust storm at the time. **RIGHT**: The same scene simulated with relief data from the Mars Global Surveyor Mars Orbiter Laser Altimeter instrument from the late nineties.



LEFT: Global airbrush map of Mars based on a mosaic of Mariner 9 images. Before the widespread use of digital-image manipulation methods it was common to produce maps using artistic airbrush renditions of features in actual images.

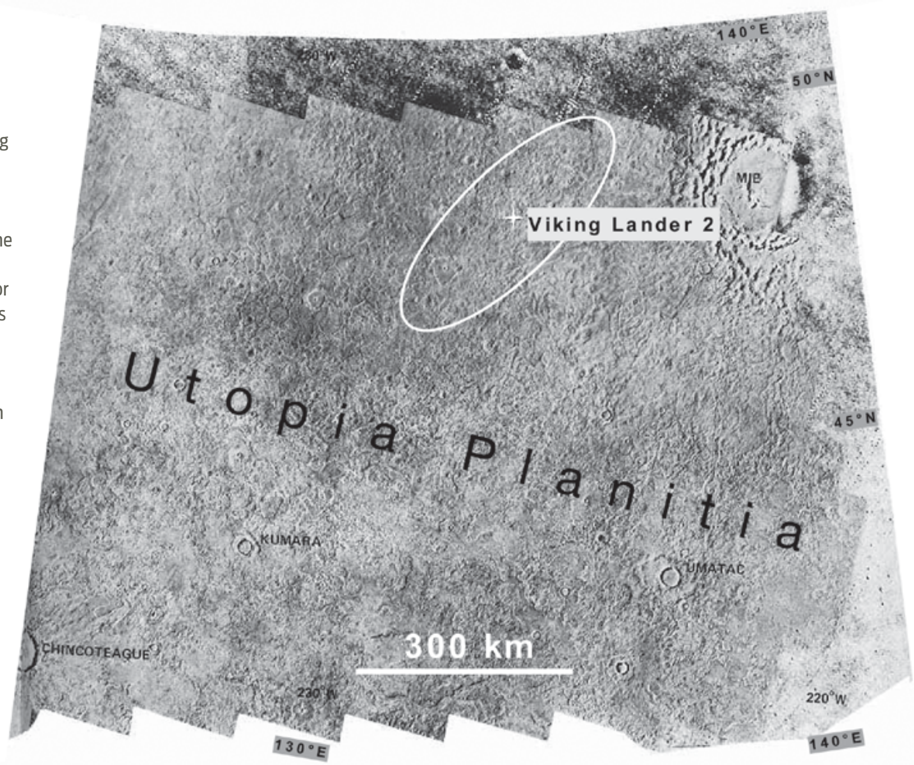


ABOVE: Compilation of Mars global maps. Early maps based on telescopic views of Mars were only able to resolve bright and dark permanent features. Later maps after Mariner 9 showed that the bright and dark features had little to do with the actual surface relief features of Mars. Modern Mars scientists mostly use the color-coded topography relief map from MGS/MOLA.



ABOVE LEFT:
The famous first image acquired by Viking 1 Lander after touchdown in July 1976.

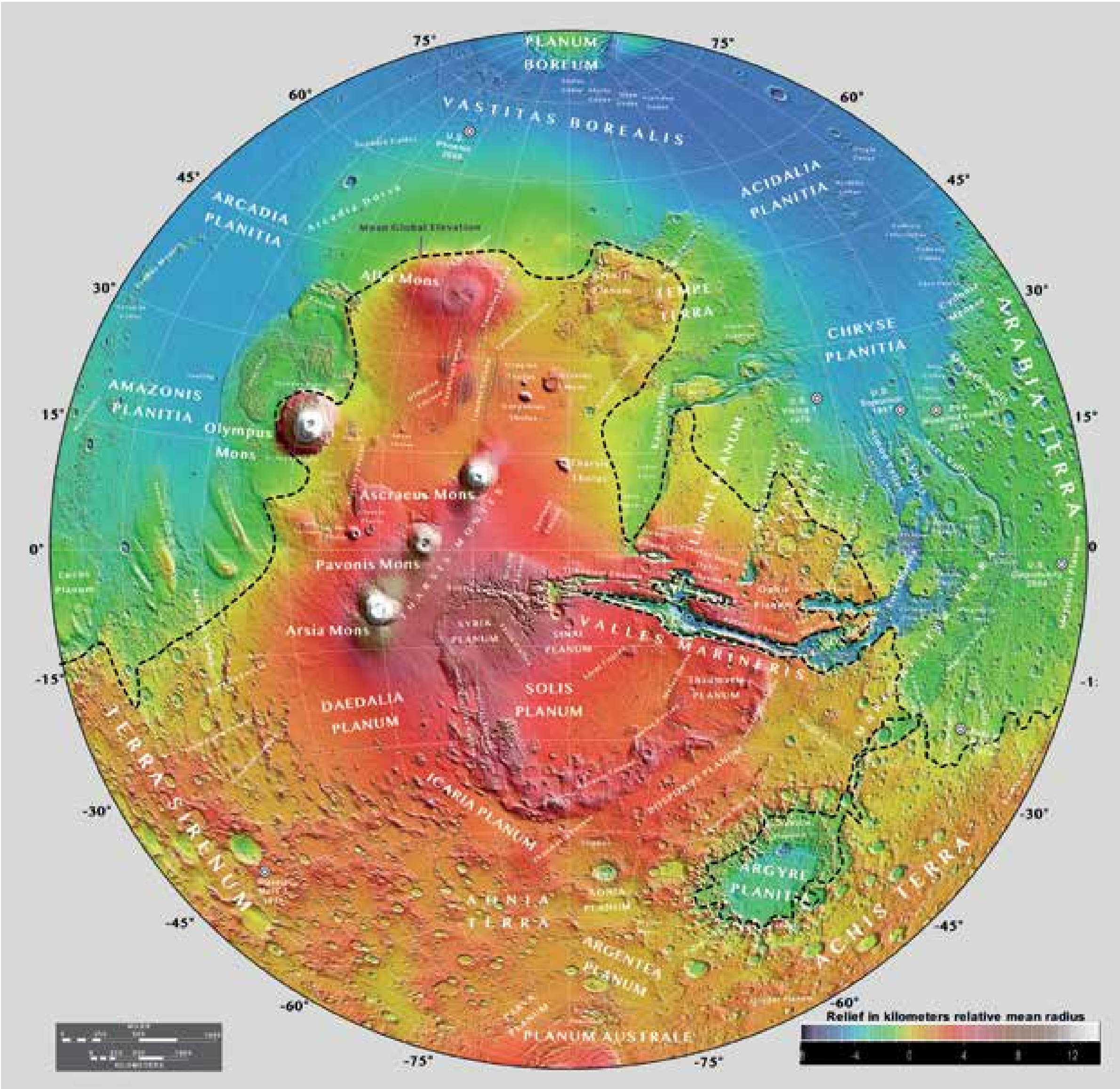
ABOVE RIGHT:
Part of the first color panoramic image of the surface of Mars as seen from Viking 1 Lander.



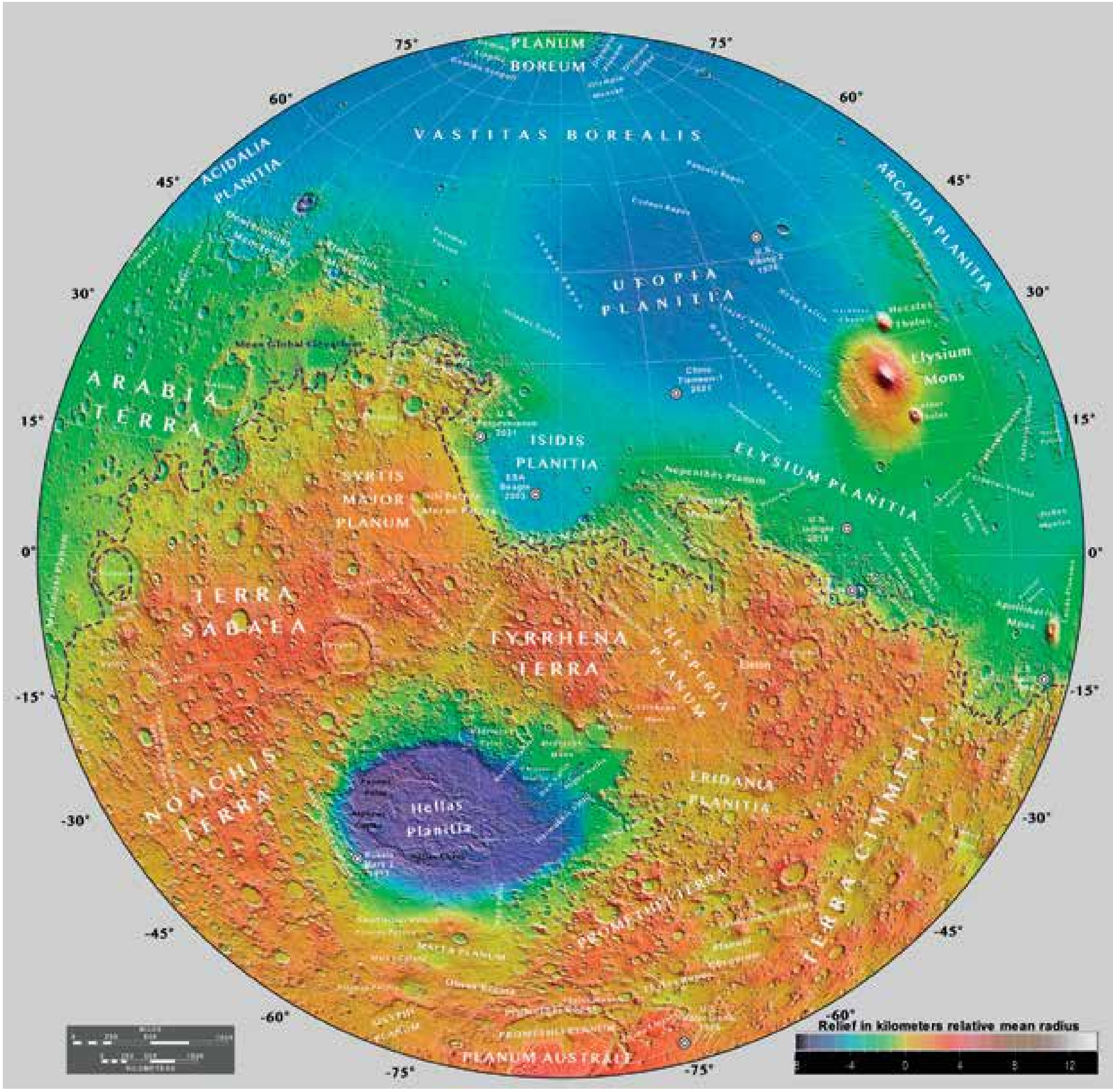
RIGHT: Controlled photomosaic of Viking Orbiter images covering part of Utopia Planitia. This illustrates the type of data we had for landing site selection in the final days before landing. The ellipse is centered on the area's highest probability of landing for the selected target. The site was selected in part by the author after frantic landing hazard analysis while the orbiter and lander were still attached and in orbit, awaiting certification of a landing site.

LEFT: First image taken by the Viking 2 Lander on the surface of Mars looking down at one of the landing footpads. This scene was up on the monitors at JPL the morning after the last landing site certification meeting and was the first evidence to the author that the landing had been successful. The rocks in the scene contain abundant gas bubbles, known as vesicles to geologists. This is a very familiar scene to anyone who has ever walked across an older lava flow on Earth and this looked shockingly identical to the rocks the author had walked on just a few weeks earlier in New Mexico.

ABOVE: Certificate of appreciation presented to the author at the end of the summer of 1976 and signed by Jim Martin, manager.



ABOVE: Western hemisphere of Mars.



ABOVE: Eastern hemisphere of Mars.

A TOUR OF THE MARTIAN LANDSCAPE FROM ABOVE

TO PROPERLY READ A MARS MAP, you need a program to recognize the players. The distinctions between some of these features can be academic, but many of them are of general interest and common enough that, as a start and a guide for exploring Mars maps, we can briefly outline a few of the alien-sounding names of Martian terrain. There are many other feature types than those listed here, but many of the most common refer to large features more likely to be encountered when looking over a Mars map, or are important in the narrative that follows, including:

> "Geography is an earthly subject, but a heavenly science."
> —EDMUND BURKE

- **Catena** (plural: *catenae*). A linear string of craters, either impact craters or pits. Pits sometimes occur along fractures or may be arrayed along the floor of a valley bounded on two sides by straight fractures.
- **Cavus** (plural: *cavi*). A depression with irregular margins. The irregular shape and absence of raised rims are not typical of impact craters, so these appear to be something else.
- **Chaos** (plural: *chaoses*). An area where the surface is a jumble of hills and scarps, sometimes in a gridded pattern, sometimes not.
- **Chasma** (plural: *chasmata*). An elongated depression/trough with steep sides.
- **Collis** (plural: *colles*). A small hill or knob. Usually these are clustered and, hence, colles on a map.
- **Crater.** A circular depression, often with raised rims created by an impacting body. The proper names assigned to larger Mars craters are derived from the names of prominent scientists who had contributed to the study of Mars. Craters smaller than sixty kilometers are named after villages of the world with populations of less than 100,000.
- **Dorsum** (plural: *dorsa*). A ridge or an elongated prominence.
- **Fossa** (plural: *fossae*). Ditch. Long, narrow, shallow depression. They generally occur in groups and are straight or curved.

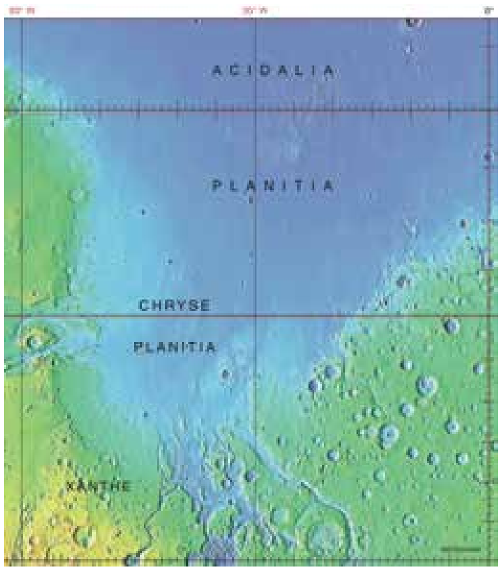
- **Labyrinthus** (plural: *labyrinthi*). Valley complex. Intricate, intersecting valleys, of which there is only one example, Noctis Labyrinthus.
- **Mensa** (plural: *mensae*). Flat-topped prominence with cliff-like edges.
- **Mons** (plural: *montes*). Mountain. A large topographic prominence or chain of elevations.
- **Patera** (plural: *paterae*). An irregularly shaped crater, with low relief that has scalloped edges, without raised rims in many cases, and sometimes with radiating channel-like features. It is not interpreted to be an impact crater.
- **Planitia** (plural*: planitiae*). Plain. Smooth, low area.
- **Planum** (plural: *plana*). Plateau. Smooth, elevated area.
- **Rupes** (plural: *rupēs*). A cliff or scarp that is straight or linear rather than sinuous.
- **Terra** (plural: *terrae*). An extended areal region or landmass. It is used in reference to the older, cratered highlands.
- **Tholus** (*plural*: *tholi*). An isolated steep or dome-shaped small mountain or hill.
- **Unda** (plural: *undae*). An area of dunes that are very wavelike in appearance.
- **Vallis** (plural: *valles*). A sinuous valley. These have the appearance of water-carved valleys. These are generally named after the word for Mars in various languages.
- **Vastitas** (plural: *vastites*). Extensive plain.

Then there are a host of smaller features or features that are less common:

- **Fluctus** (plural: *fluctūs*). A flowlike feature. Only one example of this type of feature is found on Mars, Galaxias Fluctus.
- **Labes** (plural: *labēs*). A feature that has the appearance of a landslide. The Latin meaning for labes is a “falling in” or “sinking in.”
- **Lingula** (plural: *lingulae*). Tongue-shaped feature.

- **Palus** (plural: *paludes*). A dark plain.
- **Scopulus** (plural: *scopuli*). A cliff or scarp that is irregular or lobate in appearance.
- **Serpens** (plural: *serpents*). A sinuous ridge.
- **Sulcus** (plural: *sulci*). A feature that has the appearance of a furrow, ditch, or wrinkle. These often occur in groups.

Those are long lists and they are also somewhat confusing and academic lists of strange terms. But they do represent an attempt to assign feature types to the post–Mariner 9 and Viking landscape menagerie. Although the names appear scientifically obscuring, they include some features that are worth taking a look at from the context of what we have determined about them in a geological sense. What was the significance of those features for understanding Mars? And what did we really know about them at this post-Viking mission point in the long-term exploration of Mars?

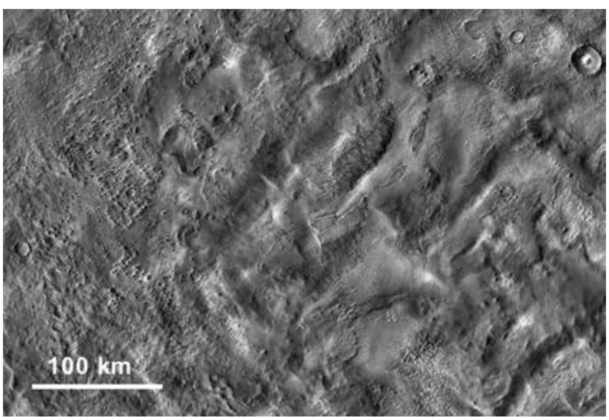


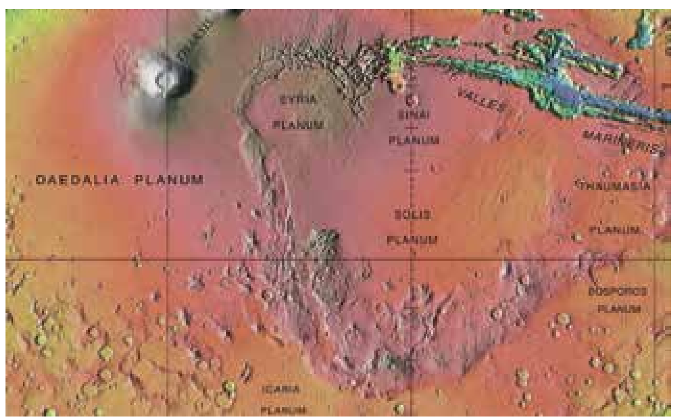
ABOVE: Color-coded relief map of the Chryse Planitia and Acidalia Planitia areas of Mars, site of the Viking 1 and Pathfinder landers.

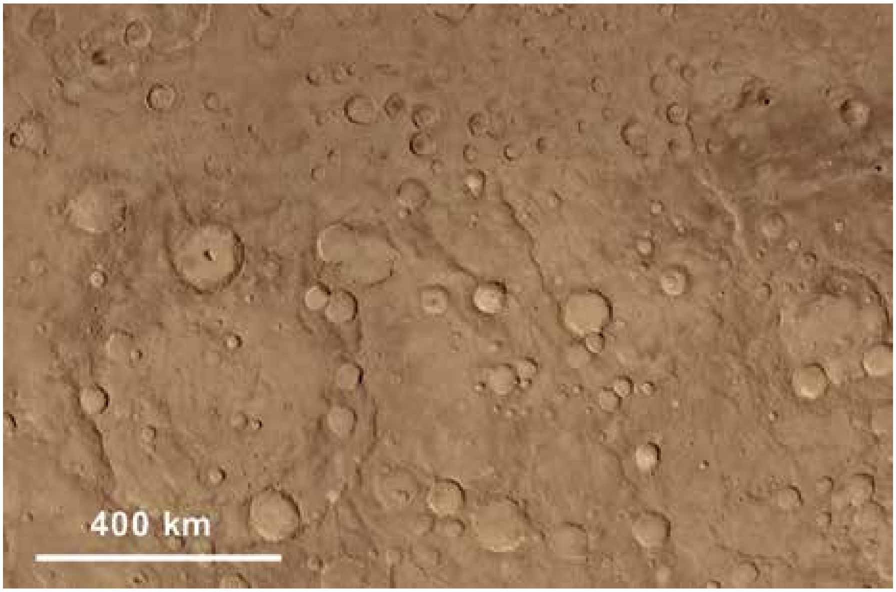
ABOVE: Unusual pitted mounds in the high latitudes of Mars such as this one over 100 meters across in Acidalia Planitia are interpreted as possible "mud volcanoes" driven by subsurface ice and gases. One of the gases could be methane, which is discussed in a later chapter.

BELOW LEFT: The floor of Hellas Planitia, one of the larger impact basins and the lowest surface on Mars. Because of the high southerly latitude it is thought that the complex terrain here is in part a result of ice and erosion processes.

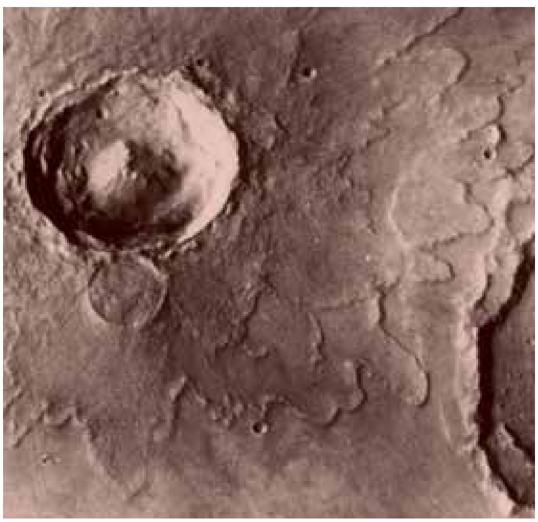
BELOW RIGHT: Color-coded relief map of the elevated plains of Solis Planum and Daedalia Planum.

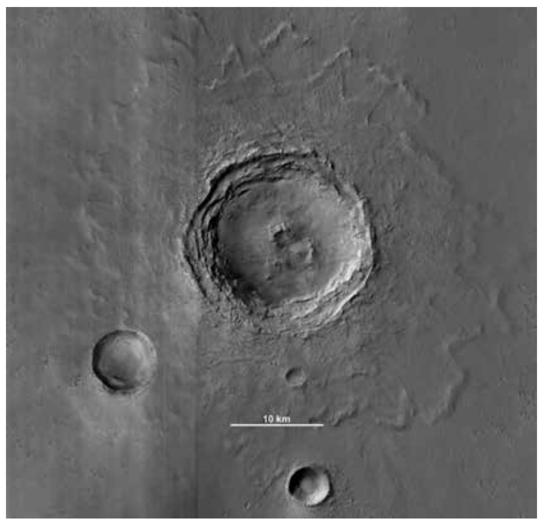






ABOVE: Viking Orbiter–based mosaic of the dusty and cratered highlands of Arabia Terra.

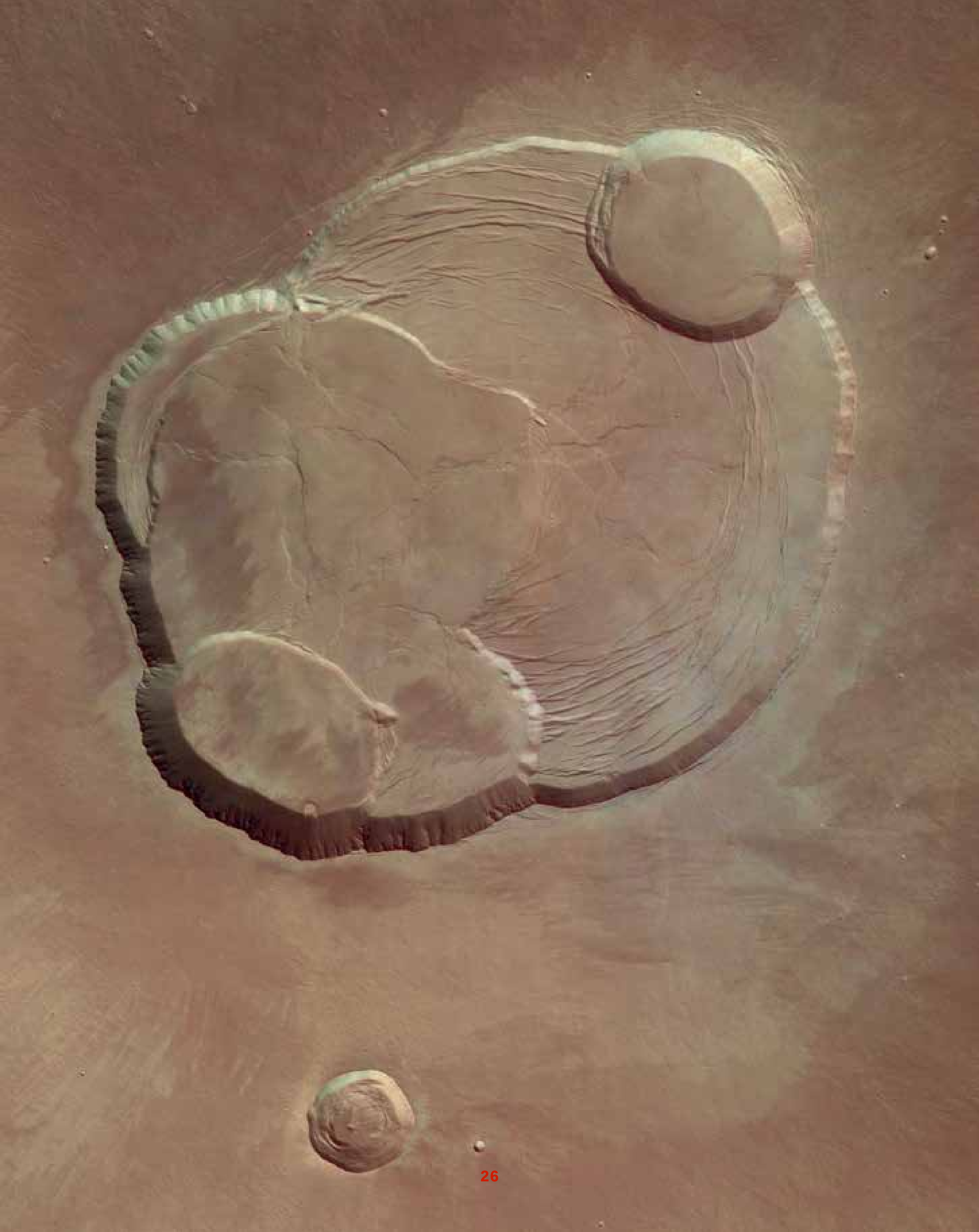


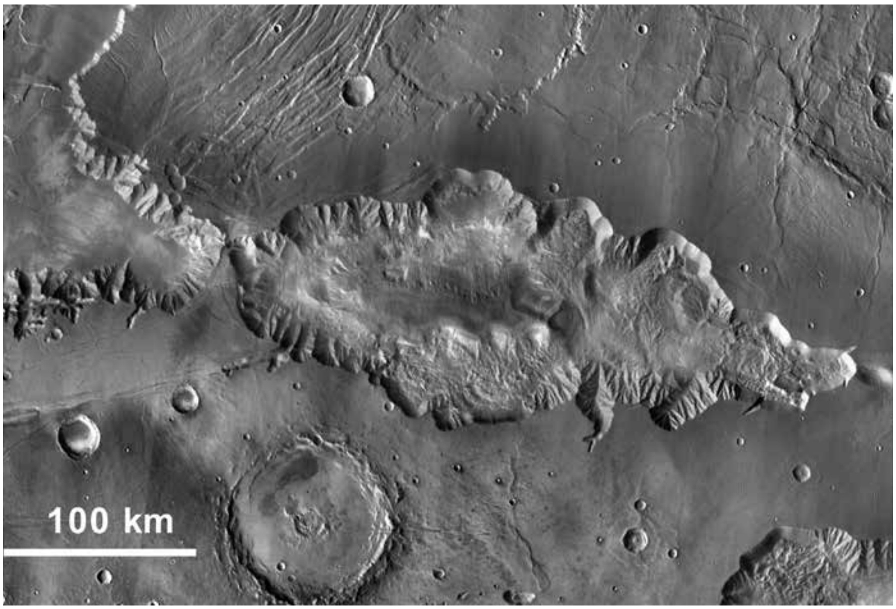


ABOVE LEFT: Historic original Viking Orbiter image of Yuty Crater located 2.4ºN, 34.2ºW. Yuty is a nineteen-kilometer-diameter crater, one of the first craters identified with unusual splash-like patterns of ejecta characterized by "ramparts" around the margins. **ABOVE RIGHT:** Santa Fe impact crater on Mars. Mosaic of MRO CTX and HiRISE images.

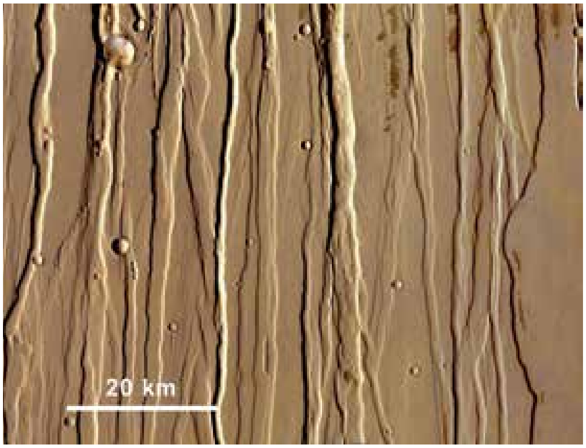
RIGHT: Famous Viking Orbiter image mosaic of Olympus Mons, twenty-two kilometers high and up to seven hundred kilometers across, it is the largest volcano in the solar system. It is an enormous shield volcano and one of the most famous landscape features of the red planet. Located at 18°N, 226°E in the Tharsis region.

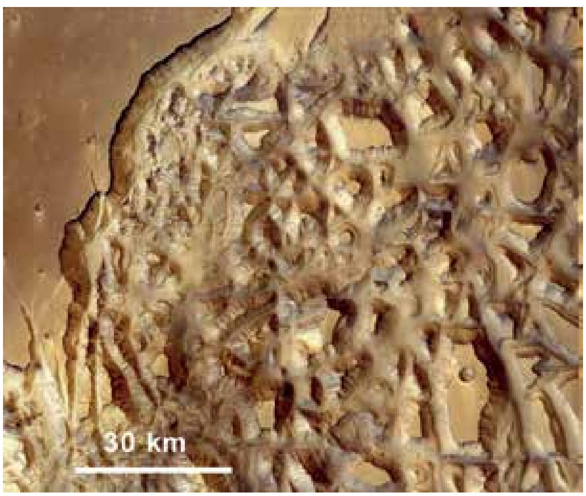
NEXT PAGE: Close-up of the Olympus Mons summit caldera.





LEFT: Hebes Chasma is a closed depression five to six kilometers deep, 320 kilometers long, and 130 kilometers wide just northwest of the great Valles Marineris canyon. On the left is Echus Chasma, which forms the upper reaches of the enormous outflow channel Kasei Vallis. On the floor of Hebes Chasma is a large mesa-like surface, Hebes Mensa, over five kilometers high that appears to consist of layered materials, probably sediments and debris that covered the chasma floor and nearly filled the chasma at one time.

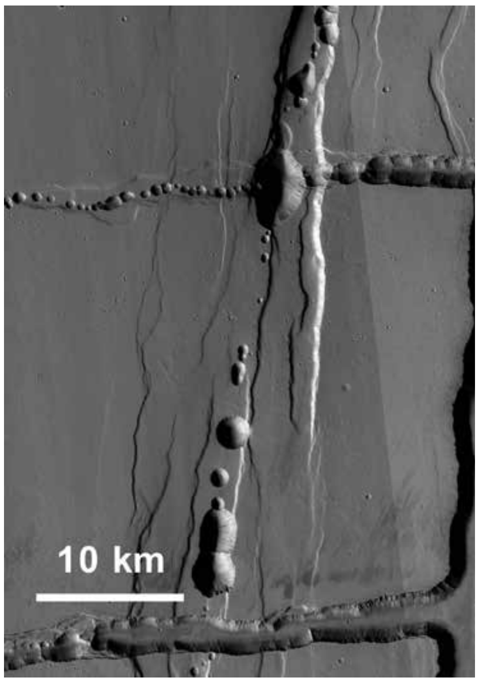




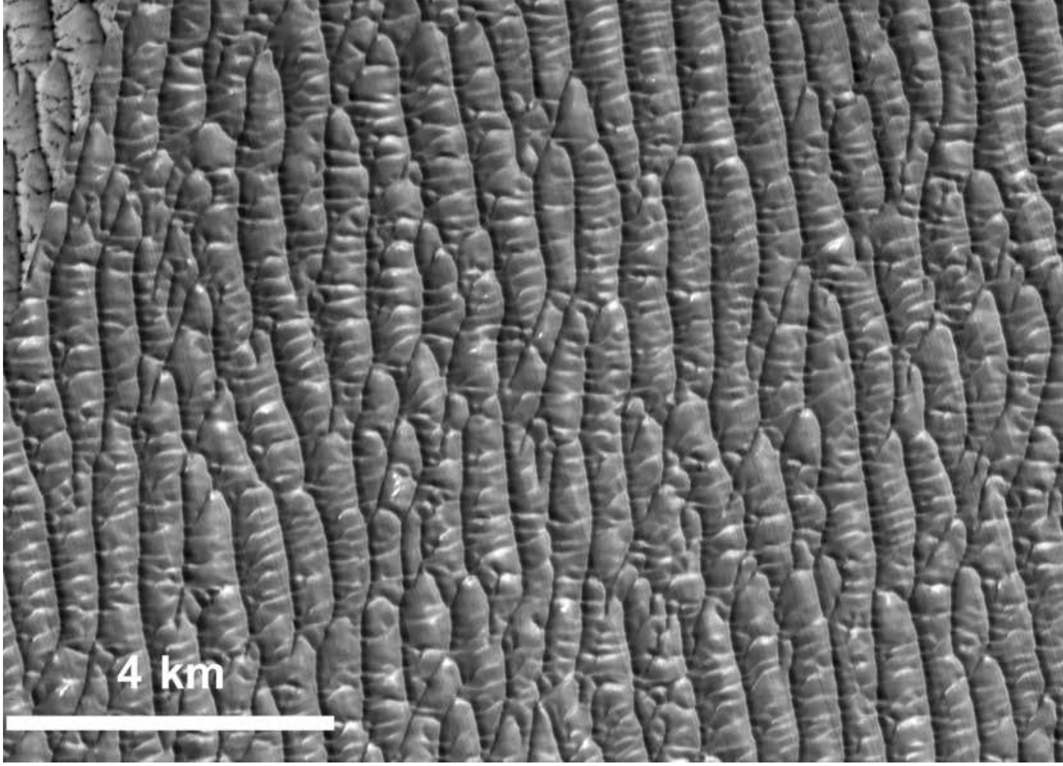
LEFT: Tractus Fossae, a series of tectonic troughs on the northern slopes of the Tharsis region.

BELOW LEFT: Hydraotes Chaos (1ºN, 36ºE) is located in the enormous and complex outflow region northeast of the end of Valles Marineris.

BELOW: Tractus Catena, located just under one thousand kilometers north of Ascraeus Mons, is an impressive series of pits arranged along part of Tractus Fossae, a fracture that is part of the extensive radial array of fractures around the Tharsis Montes.



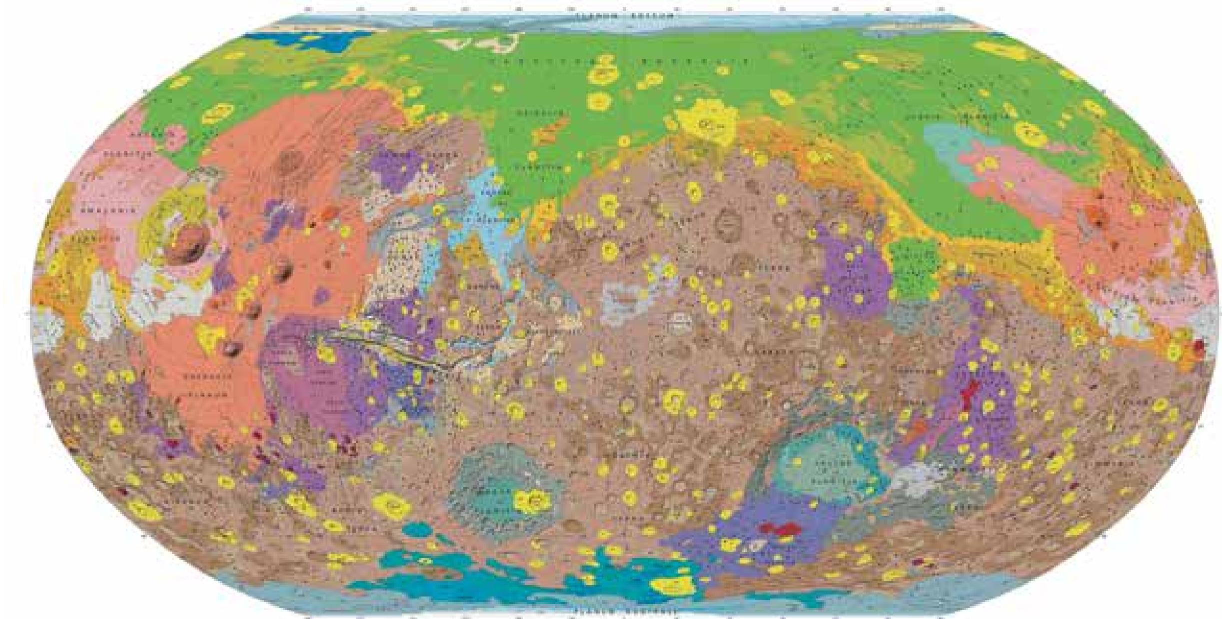
FAR LEFT: Pit opening about thirty-five meters across on the distal north slopes of Pavonis Mons, located at 3.7ºN, 248.5ºE. Sunlight through the opening is shining on a floor about twenty meters below the rim. **MIDDLE:** Another pit located on the southeastern margin of Elysium Mons. This one is 130 meters in diameter. **RIGHT:** Hypanis Vallis, a typical sinuous valley in the Xanthe Terra highlands. Location 9.5ºN, 315ºE.

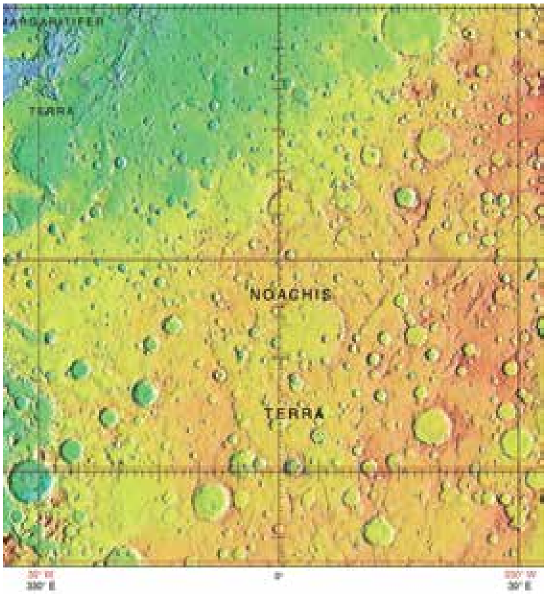


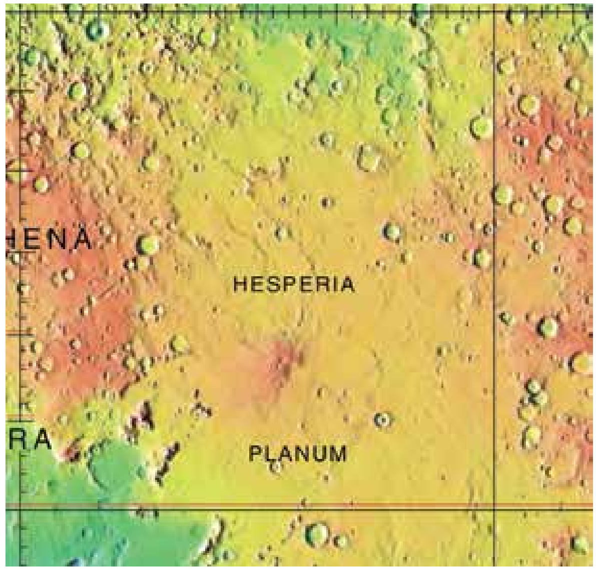
RIGHT: Olympia Undae is part of the vast sand sea surrounding the north polar plateau. Location 81ºN, 180ºE.

RIGHT: Field of barchan dunes on the floor of Arkhangelsky Crater located at 40.8ºS, 335ºE. This image is about five kilometers across.

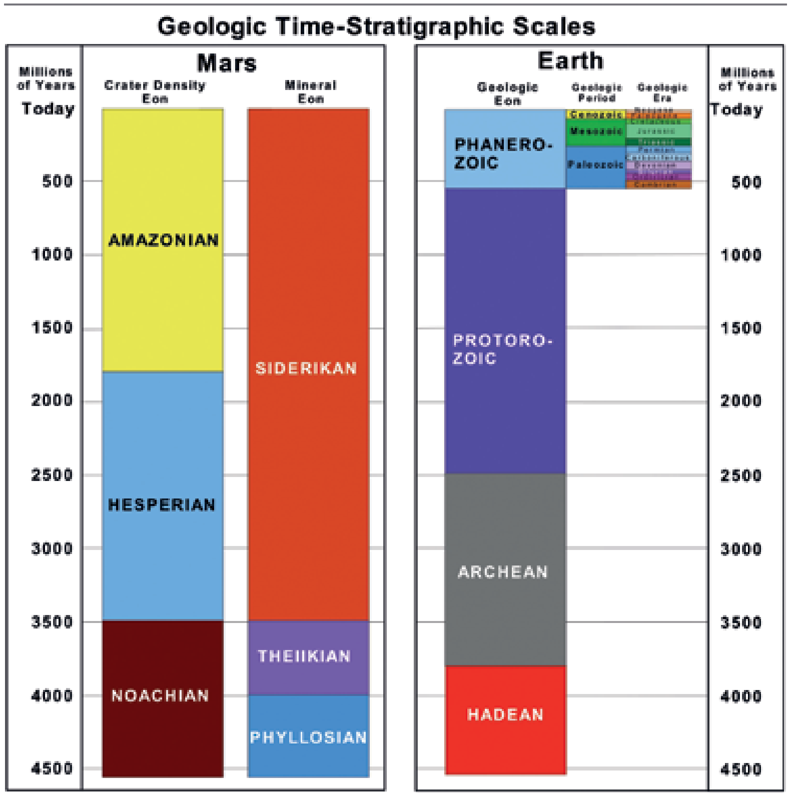
BELOW: Global geologic map of Mars. Different colors represent the variety of geologic surfaces and different ages as determined from analysis of thousands of images by many researchers over many years. This is the latest version released in 2014 of many maps produced over decades. Geologic maps like this one are accompanied by detailed descriptions of each unit and their interpretations based on extensive research analysis.







TOP LEFT: Color-coded relief map of Noachis Terra, the type area of the Noachian Eon in the Martian geologic time scale. **TOP RIGHT:** Color-coded relief map of Hesperia Planum, the type area of the Hesperian Eon in the Martian geologic time scale. **ABOVE:** Color-coded relief map of Amazonis Planitia, the type area of the Amazonian Eon in the Martian geologic time scale.



RIGHT: On the left are Martian geologic time scales, one based on the relative ages of surfaces and one based on the times during which certain types of minerals were forming. The scale on the right is the geologic time scale for Earth.

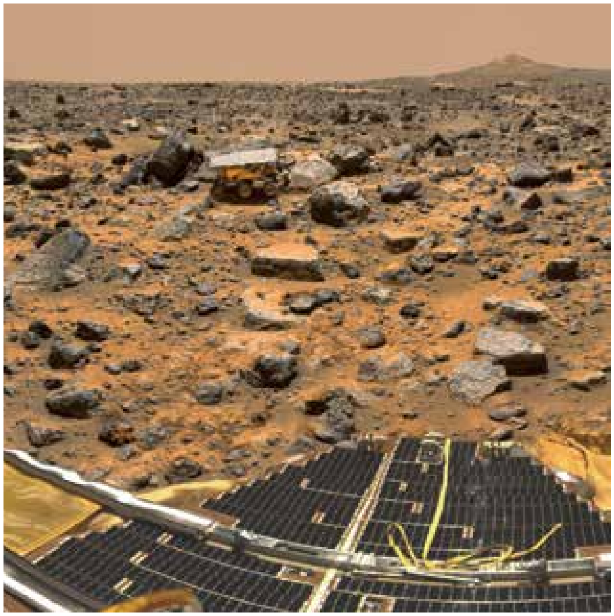
BELOW: Successful Mars spacecraft missions over the last eight decades. Many of us refer to the gap in exploration between Viking and Mars Global Surveyor, the late seventies to the midnineties, as the lost generation.

ABOVE: The Martian meteorite “Black Beauty,” or NWA 7034, is an usual sample containing traces of Martian water.

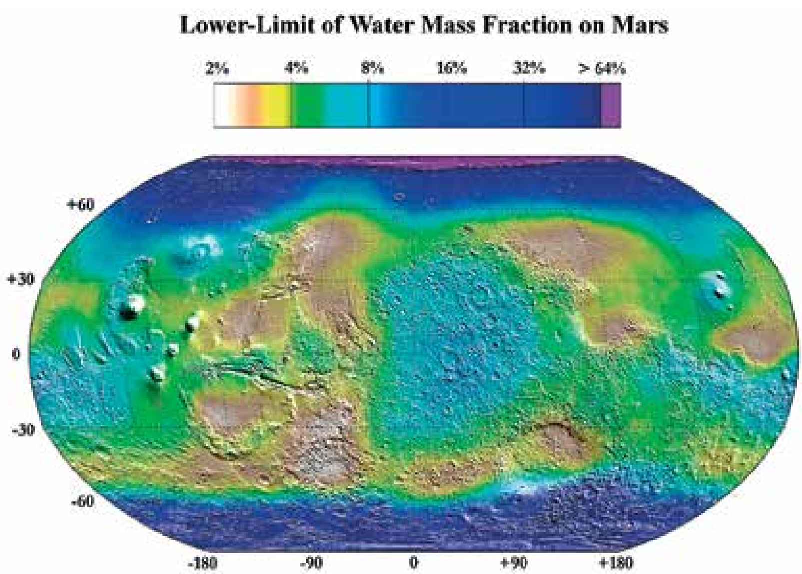
ABOVE: Phobos (left) and Deimos (right), moons of Mars as seen by the Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (HiRISE) camera in orbit about Mars.

TOP: One of the initial images from Mars Global Surveyor of small gullies on the inner wall of a crater. This became a major topic of debate and investigation in later missions.

ABOVE: Famous image of Nanedi Vallis in Xanthe Terra as seen by the Mars Orbiter Camera aboard the Mars Global Surveyor spacecraft. The valley is 2.5 kilometers wide at the rim. On the floor of the valley is a smaller two-hundred-meter-wide channel.



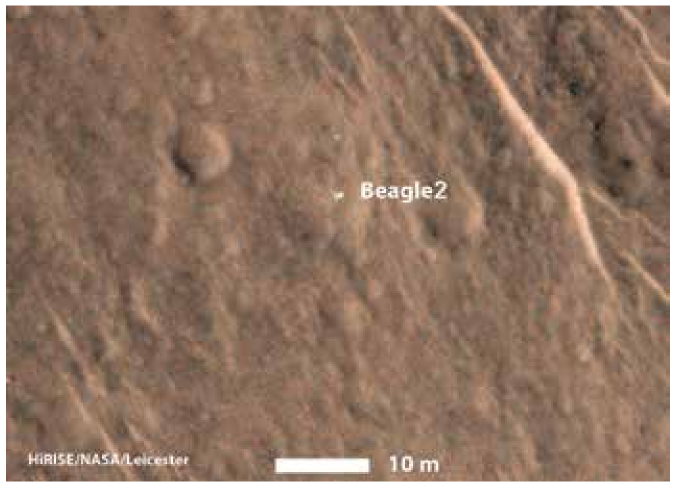
ABOVE: Part of the panorama acquired by the Mars Pathfinder lander. The terrain is exceedingly rocky. The Sojourner rover in this image was a small rover about the size of a microwave oven and the first rover operated on Mars.



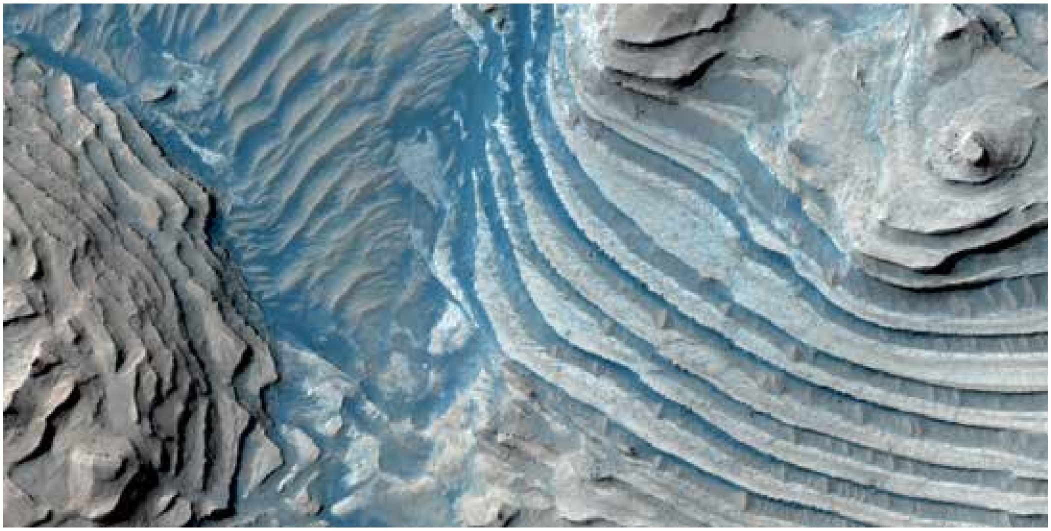
LEFT: Global map of the estimated lower limit of water content in the upper meter of the surface of Mars from the Gamma Ray Spectrometer, Mars Odyssey.

BELOW RIGHT: The Beagle 2 lander as it would be deployed on the surface of Mars.

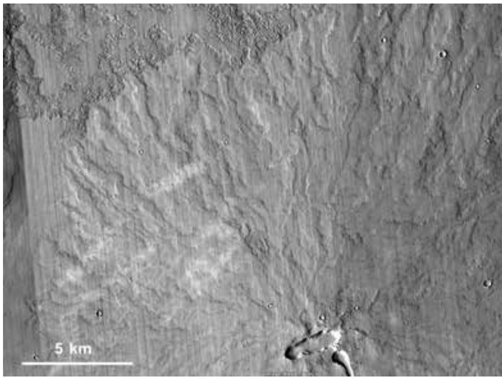
BELOW LEFT: MRO/HiRISE image of the Beagle 2 lander on the surface of Isidis Planitia, Mars. The lander was only a meter across. Close inspection of the image shows that the solar panels were only partially deployed.



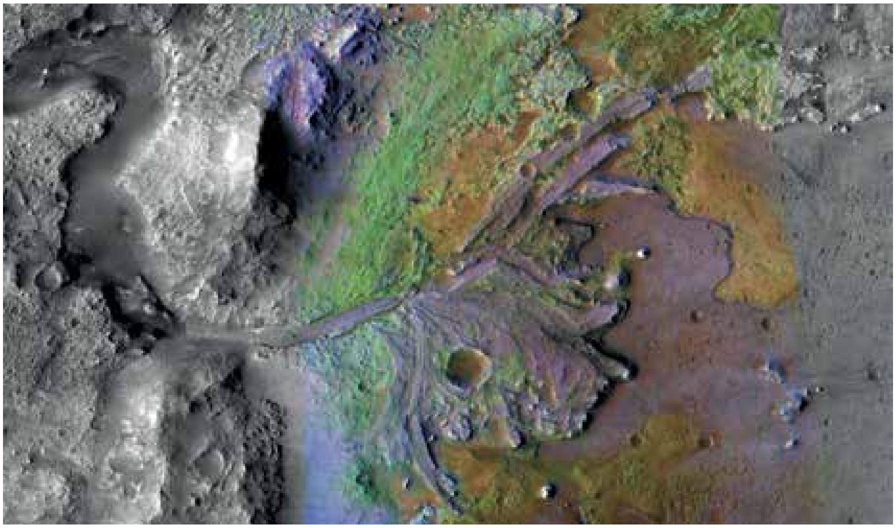
RIGHT: HiRISE image of sedimentary layers within a large crater in Meridiani Planum.

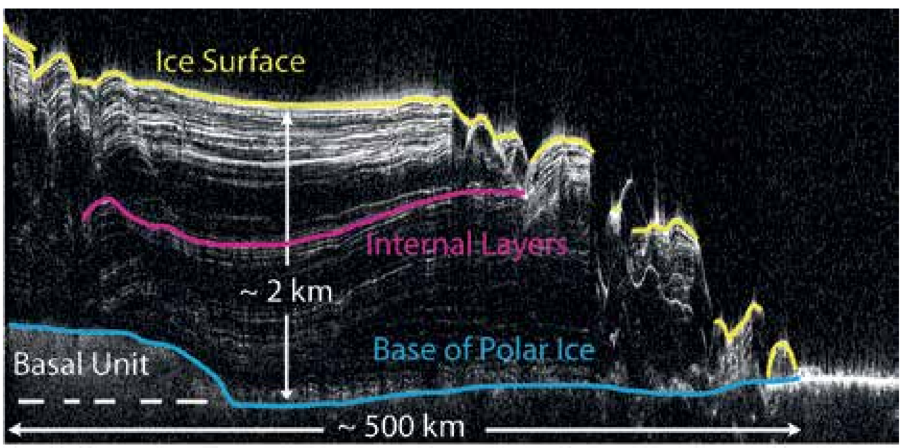


BELOW LEFT: Some lava flows in the Elysium region are so young that there are almost no impact craters, which means that they may be less than a million years old. This example is an area one kilometer across. **BELOW CENTER:** HiRISE image of the complex layering in the floor of Melas Chasma. **BELOW RIGHT:** MRO/CTX images cover larger areas than those acquired by MRO/HiRISE. CTX has revealed some interesting medium-scale volcanoes. An example is this small shield volcano with a small summit crater on the lower east slope of the Tharsis region between Pavonis Mons and Noctis Labyrinthus. Note the later lava flows that have flowed onto the lower slopes in the upper left.

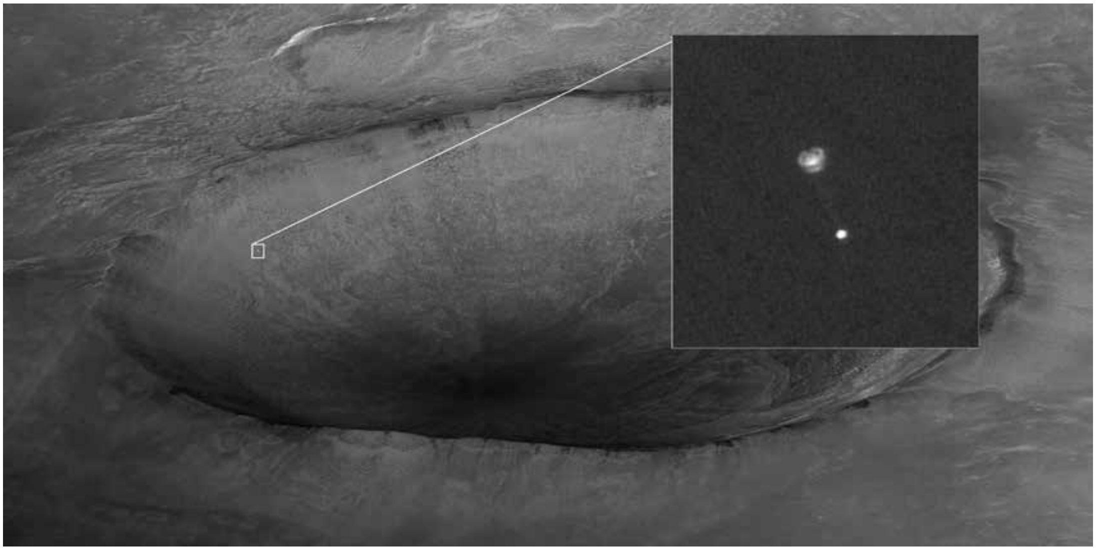


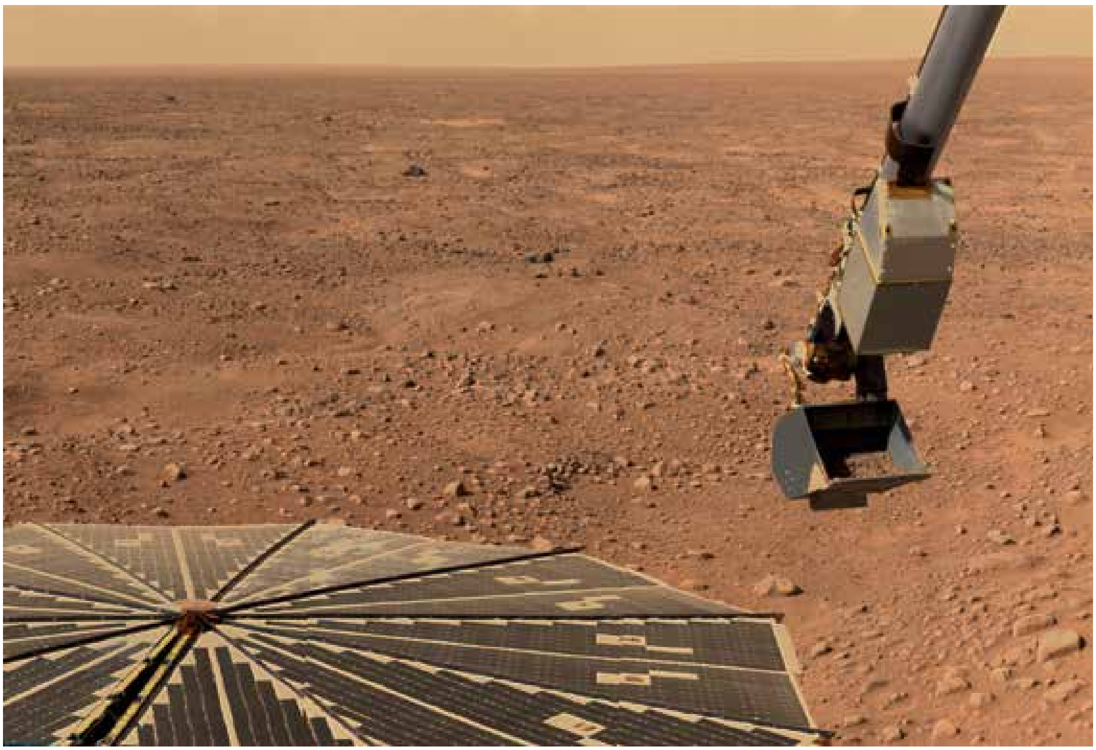
RIGHT: MRO/CRISM spectral image detections of different minerals overlain on an MRO/CTX image of Jezero Crater delta, exploration site for the Perseverance rover.





LEFT: MRO/SHARAD radar-sounding profile results across the north polar cap. The cap appears to be about two kilometers thick. The profile is 250 kilometers long, and the vertical scale is greatly stretched for visibility.

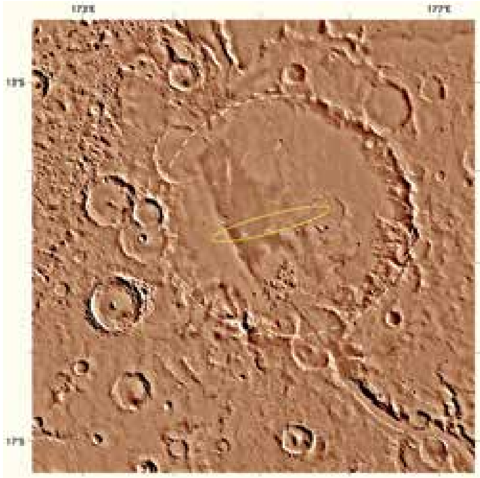




TOP: MRO/HiRISE image of the Phoenix lander on its parachute descending to the surface of Mars. The ten-kilometer crater Heimdal is in the background about twenty kilometers away. Inset shows a detail of the descending spacecraft. **ABOVE:** The Phoenix landing site acquired by the Surface Stereo Imager looking west during Phoenix's sol 16.

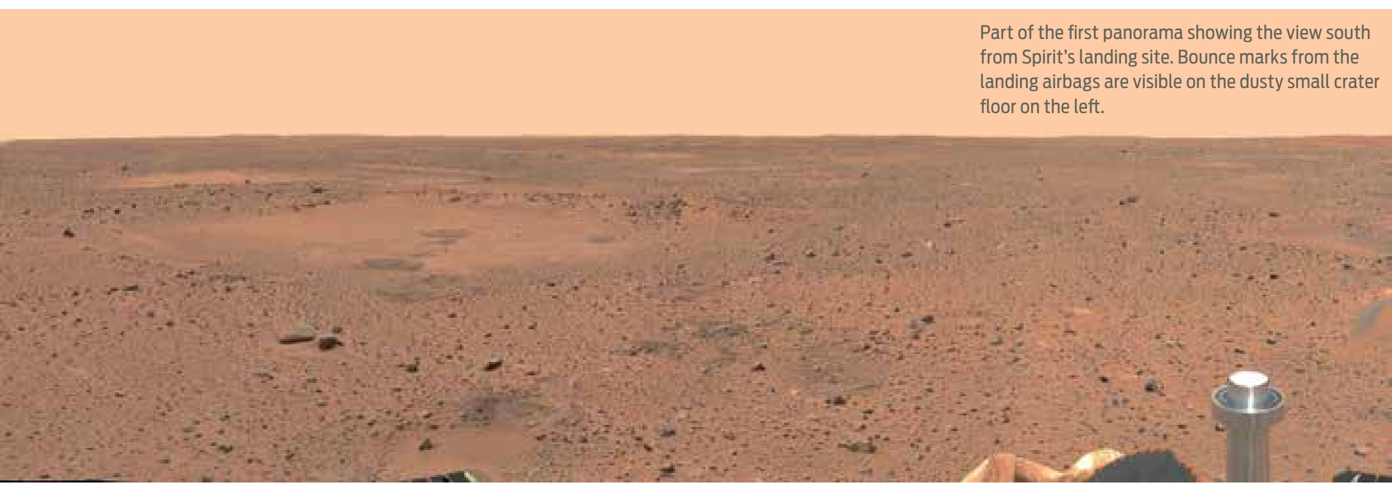
ABOVE: View underneath the Phoenix lander by the robotic arm camera on sol 142 showing a patch of ground ice exposed by the landing rocket blasts.

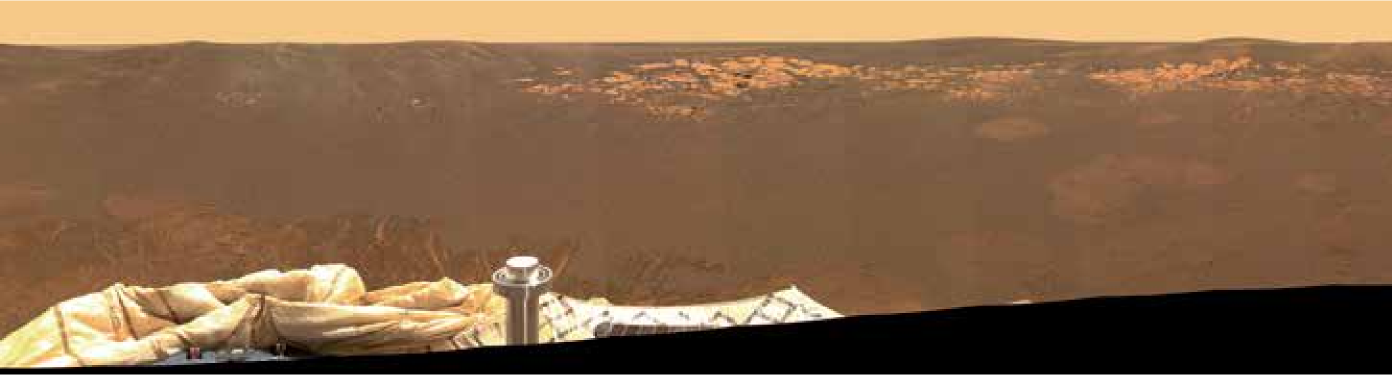
	THE GEOLOGIST IN THE FIELD . . .	THE ROVER ON MARS . . .
1	scans the terrain to look for an outcrop that may hold information about the rocks. This might take a minute or two.	takes some images, especially a panorama. This usually takes one sol.
2	walks toward a selected outcrop. This might take several minutes.	does what we refer to as an approach drive. This would be the next sol.
3	looks at the outcrop up close and selects a particular part of the outcrop that can be analyzed. This might take a minute or two.	takes some images of the outcrop just after completing the previous approach drive. Another sol has passed.
4	either whacks off a hunk of the rock outcrop with a rock hammer to get a look at the clean interior free of weathering or maybe just looks at it up close. This might take a minute or two.	reaches out with one of the instruments on the arm. The rock abrasion tool would be the equivalent of the rock hammer. Another sol has passed.
5	looks at the rock chunk that was broken off to assess the minerals and other useful characteristics. If it is an important rock, a sample might be taken and placed in a bag for later analysis in the lab. This might take up to five minutes.	uses its tools to do the mineral and chemical analysis right there, so there is no need to take a sample. Another sol has passed.
6	repeats the process, a traverse is made to the next outcrop, and so on.	repeats the process, a traverse is made to the next outcrop, and so on.
7	if the goal is to map the layout of different units and their relative timing, records these observations on a map, particularly how one rock type contacts another, so that overlapping relations are recorded.	if the goal is to map the layout of different units and their relative timing, records these observations on a map, particularly how one rock type contacts another, so that overlapping relations are recorded.



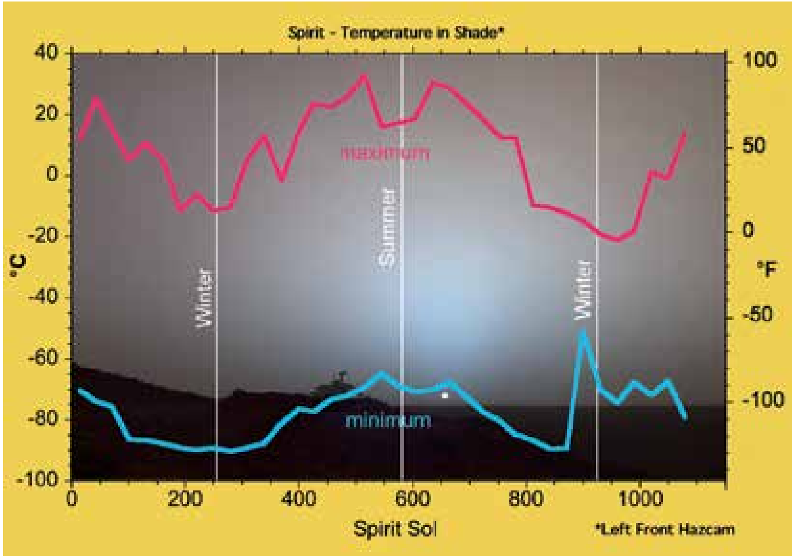
ABOVE: Viking image of Gusev Crater, more than 161 kilometers across. Shown in yellow is the prelanding ellipse indicating the probable area in which Spirit would land assuming a target near the ellipse center. The small star inside the ellipse indicates the final landing site location, which was ultimately a bit downrange from the center of the ellipse.

Part of the first panorama showing the view south from Spirit's landing site. Bounce marks from the landing airbags are visible on the dusty small crater floor on the left.



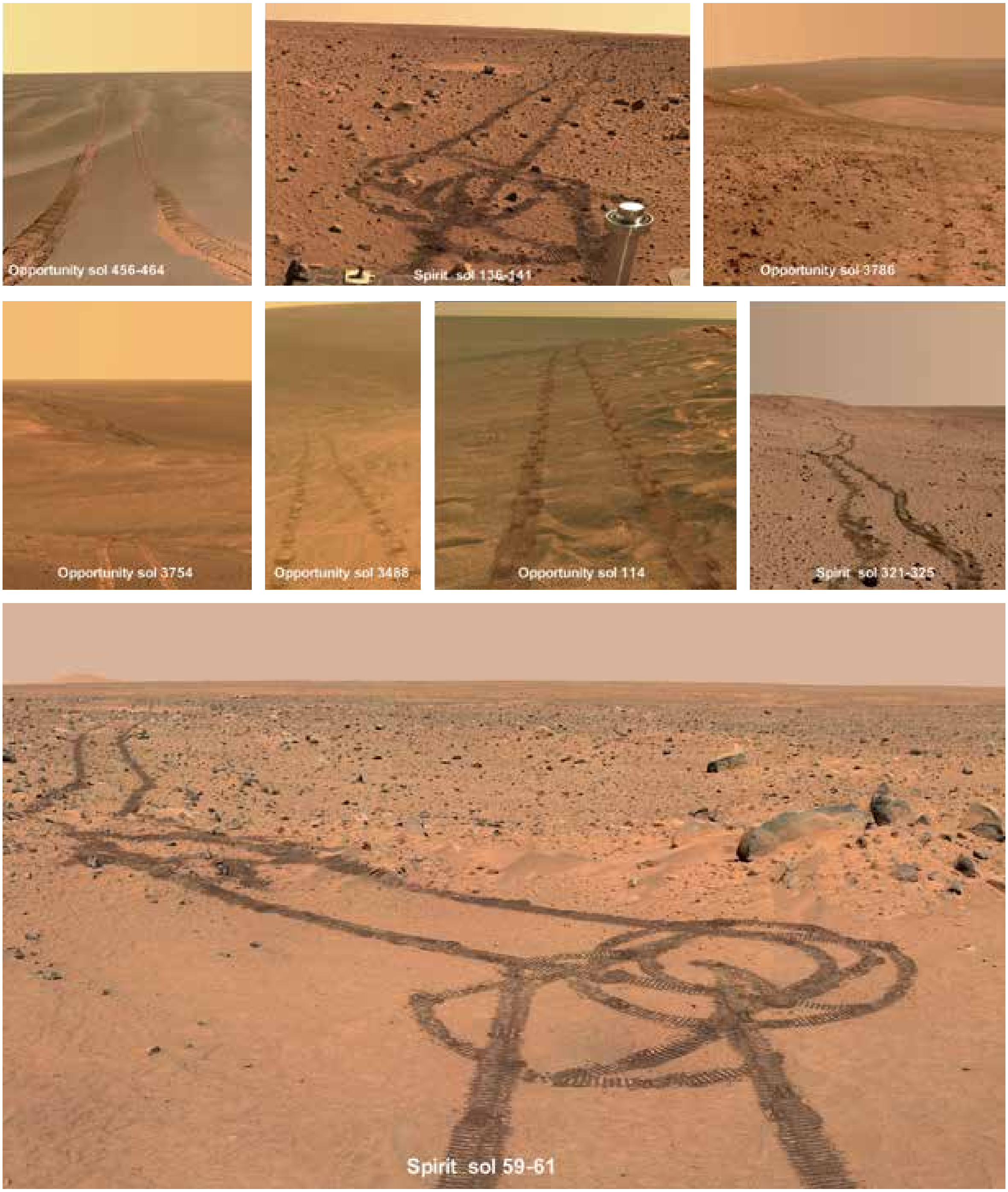


ABOVE: Part of the first panorama showing the view from Opportunity's landing site inside Eagle Crater. Outcrops of the Meridiani Planum sulfate-cemented sandstone are exposed inside the crater wall. Bounce marks from the landing airbags are visible on the dusty crater floor on the right. **BELOW:** Microscopic Imager view of the "blueberries" or hematite concretions on the surface of Meridiani Planum. Image is about 3.5 centimeters across.



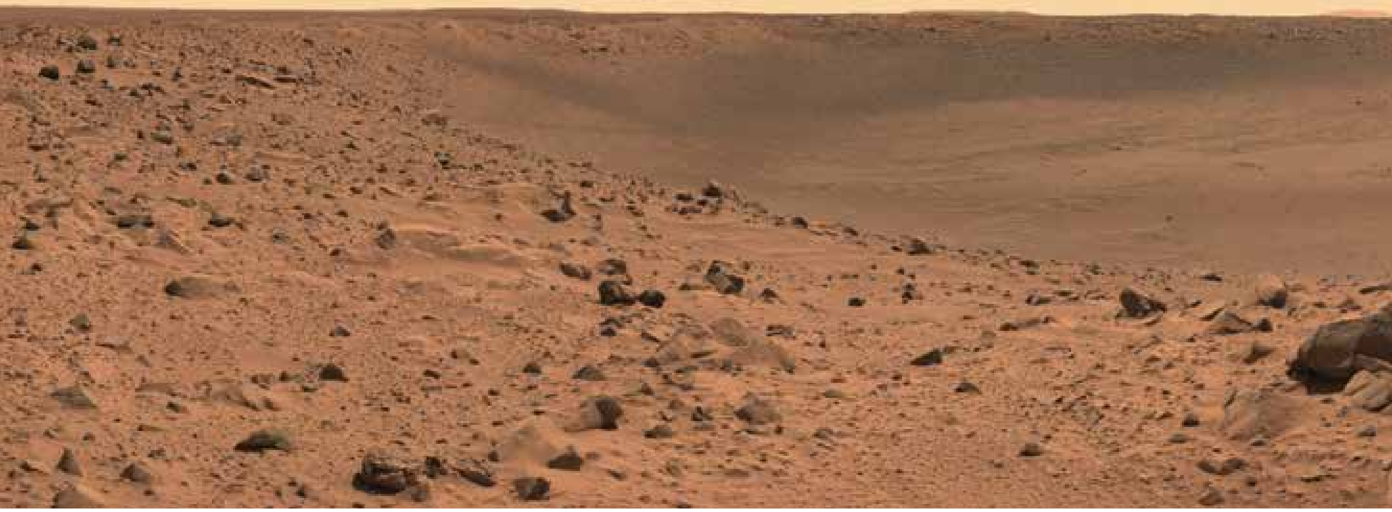
LEFT: Graph illustrating the daily maximum (high) temperatures in red and the daily minimum (low) temperatures in blue over the first eleven hundred sols on the Spirit rover front Hazcam cameras. Temperatures in the summer are moderate, but even in the summer the nighttime temperatures are similar to an Antarctic winter. Every night the temperatures fall nearly one hundred degrees, summer or winter.

ABOVE: The length of Opportunity's final total traverse, shown in yellow on a map of a moderate-size city for comparison.

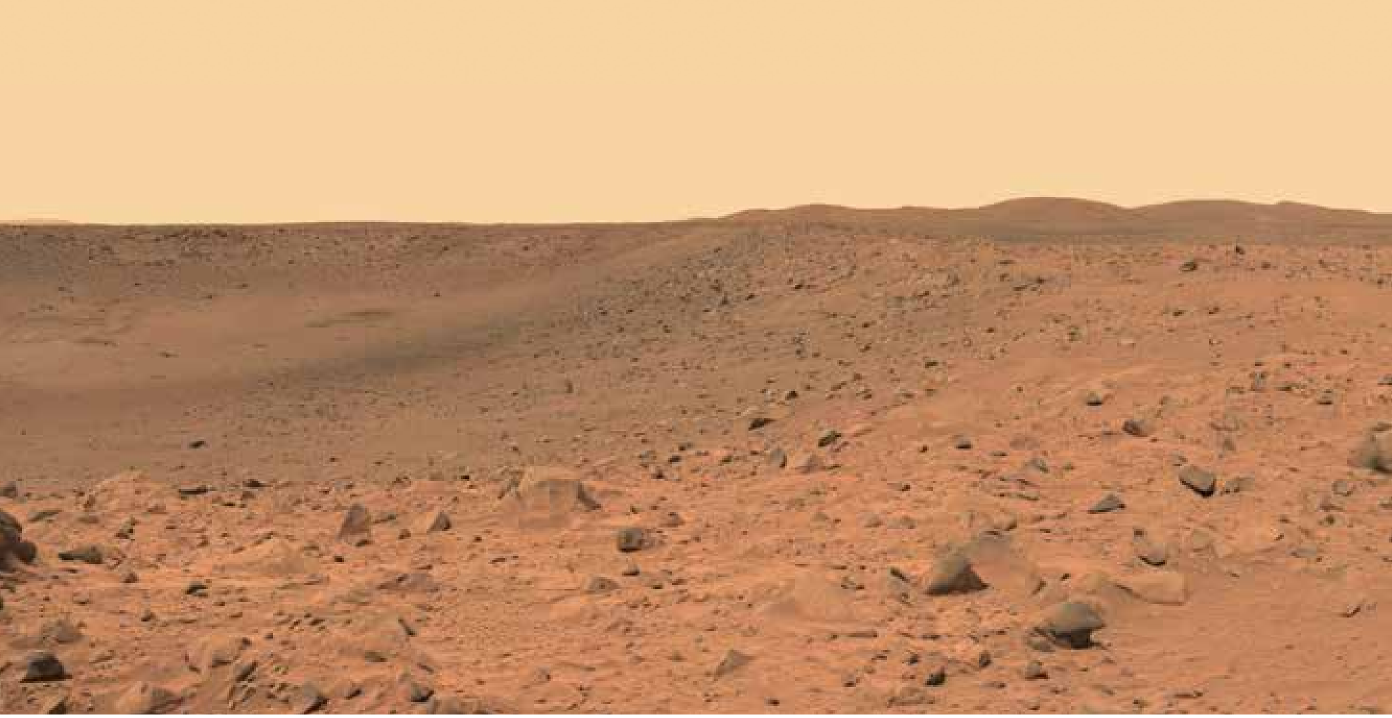


ABOVE: Collection of a few of the tracks left by Spirit and Opportunity in interesting places on Mars over the years.

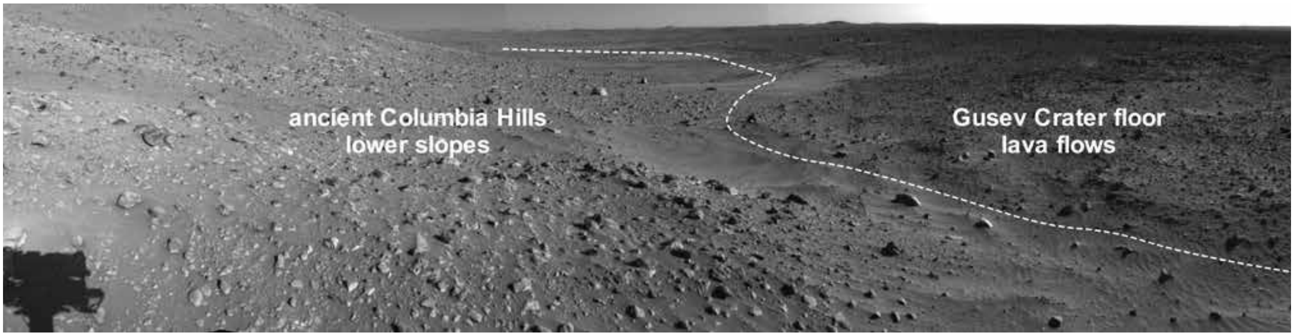
Comparison of panoramas taken on the rim of Bonneville Crater on sol 68 by Spirit **(TOP)** and on the rim of Barringer Meteor Crater, Arizona **(BOTTOM)**, by the author. Bonneville Meteor crater is 210 meters in diameter and fourteen meters deep. Barringer Crater is over 1.7 kilometers in diameter and 170 meters deep.



And looking into the crater the view was identical too: a deep bowl covered on the bottom with sediments and rising up all around to steep rocky outcrops just below the rim. It was a sense of complete similarity between two landscapes on two worlds millions of kilometers apart and I was standing in the same setting, one in person and the other by virtue of telepresence. My immediate conclusion standing there in the sunlight was that small craters are very similar wherever you go in the solar system.

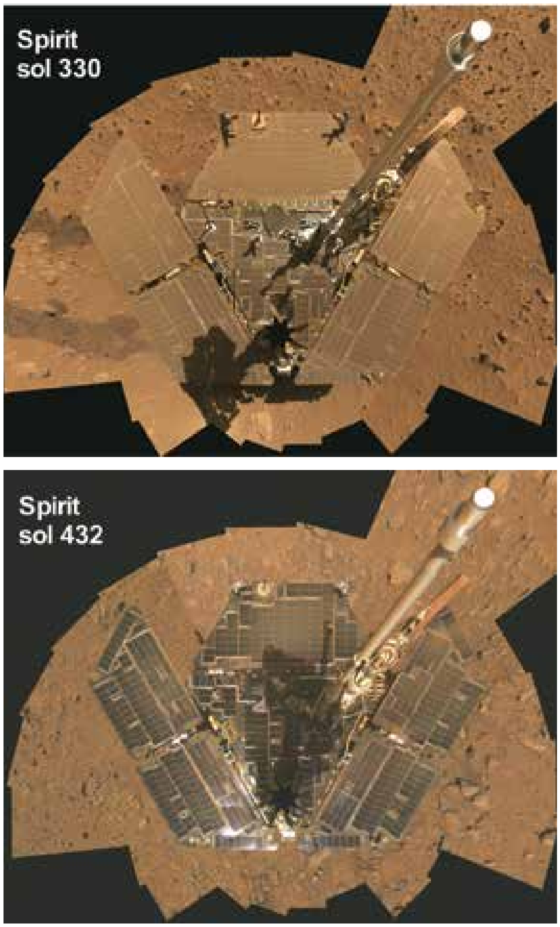


BELOW: Image of sedimentary layers of Burns Cliff acquired by Opportunity between sols 286–294 while exploring inside Endurance Crater.



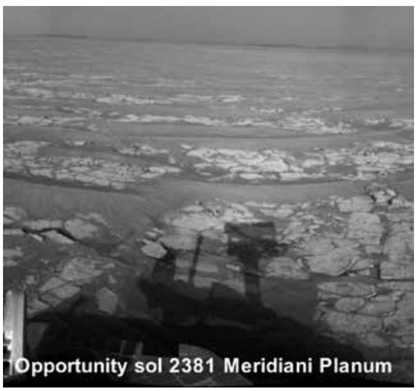
ABOVE: Part of a Navcam panorama looking south taken by Spirit on sol 156 after arriving on the "shores of its new world" in the Columbia Hills. The lava flows on the right date from the middle age of Martian geologic time, the Hesperian Eon, whereas the rocks of the Columbia Hills on the left date from the earliest geologic time on Mars, the Noachian Eon.

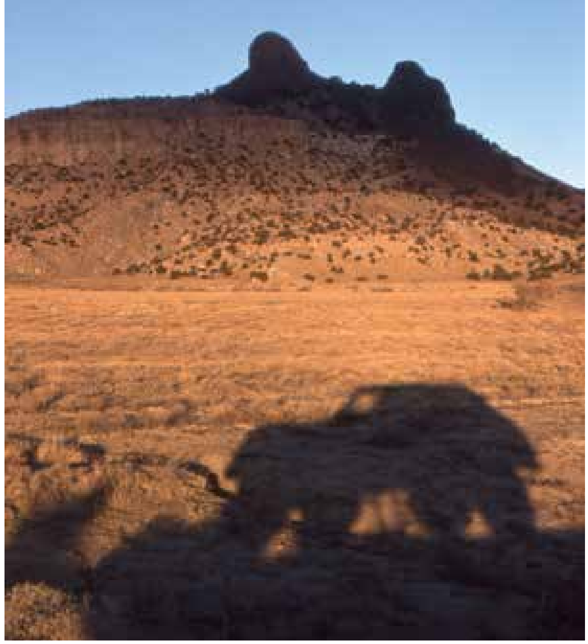
ABOVE: View of Opportunity's new world, the hills forming the rim of Endeavour Crater after arrival on sol 2,681. This is a false-color image with colors stretched to highlight contrasts.



ABOVE: Comparison of "selfies" taken by Spirit of its dust-covered solar panels on sol 330 and again on sol 432 after the panel-cleaning events of sol 419.

BELOW: Spirit views its shadow on the long road to the Columbia Hills seen in the far distance in this sol 124 post-drive image. Spirit would go on to eventually summit the highest peak in the Columbia Hills.

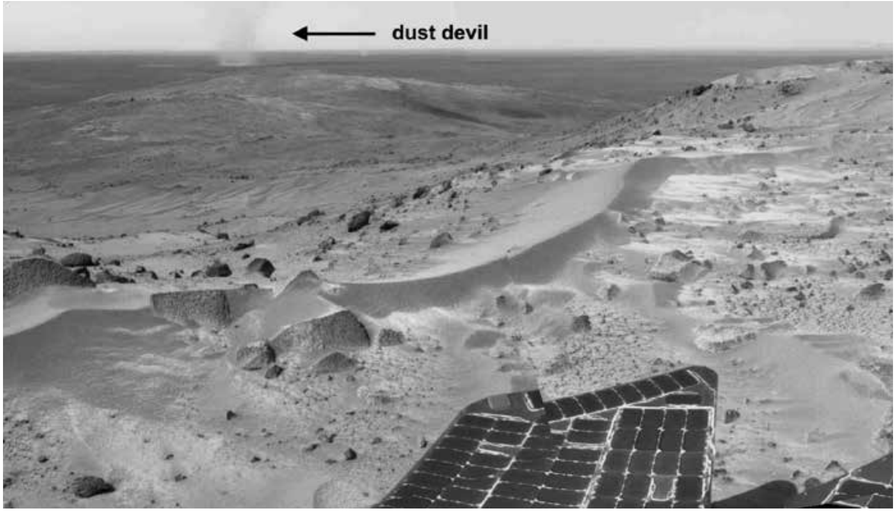




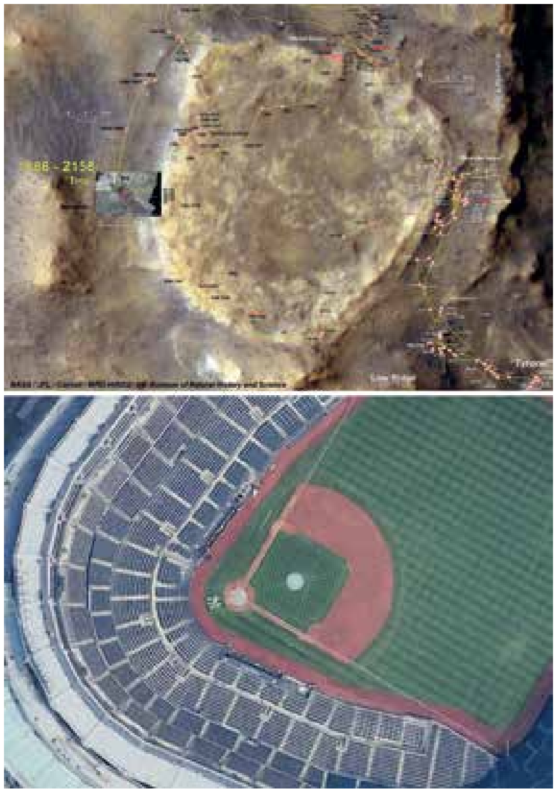
LEFT: Opportunity was an experienced taker of "shadow selfies." Over the course of the mission many such images were acquired as panoramas, which were taken at the end of each day's drive. **ABOVE:** Long shadows cast across the landscape at the end of a field trip to a Mars-like landscape in New Mexico are like the shadow selfies that Opportunity and Spirit saw at the end of their drives on Mars.

RIGHT: View north from near the summit of the Columbia Hills at the end of a drive on sol 581. A large dust devil can be seen in the plains west of the hills in the distance.

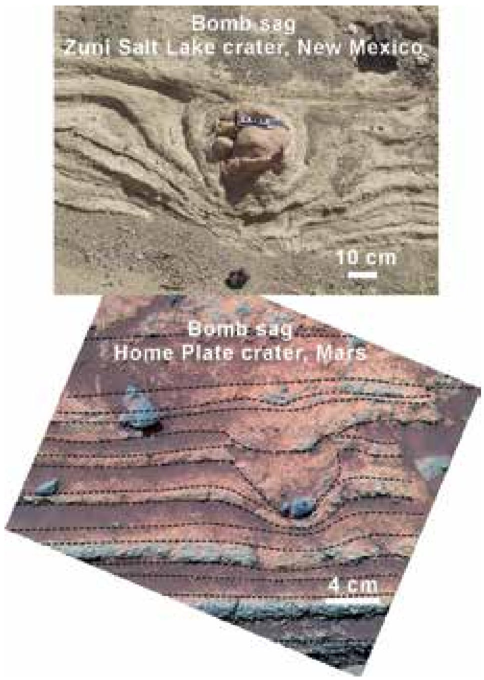
ABOVE: View north on Spirit's sol 454 of layers tilted downslope on the climb up the Columbia Hills. This scene was later modified to show a depiction of Spirit as it would have appeared in this scene during its traverse in the area. Larry's Lookout is behind the rover.



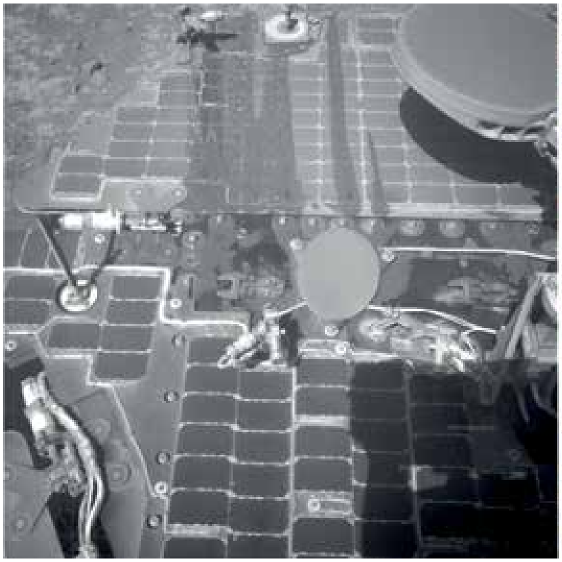
ABOVE: Opportunity's sol 3,894 "summit panorama" from the highest point in its traverse, the summit of Endeavour Crater's rim, "Cape Tribulation." The crater floor stretches twenty-two kilometers to the far rim in the distance. The rover's arm was held up into view **(INSET)** carrying the United States flag on a small metal motor shield made from a piece of the World Trade Center.

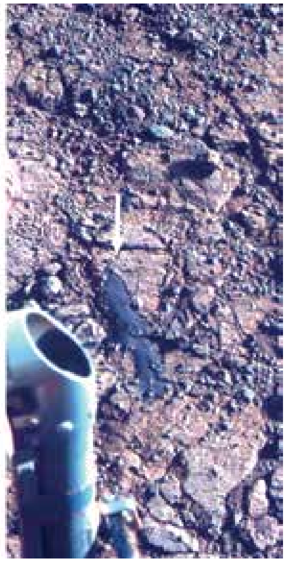


ABOVE: MRO/HiRISE image of Spirit's traverse around Home Plate and an overhead view of Yankee Stadium at the same scale.



Classic “bomb sag” type structure in the ash layers on the northwest margin of Home Plate **(BOTTOM)** compared with a similar feature in the ash layers of Zuni Salt Lake volcanic crater in western New Mexico **(TOP)**.



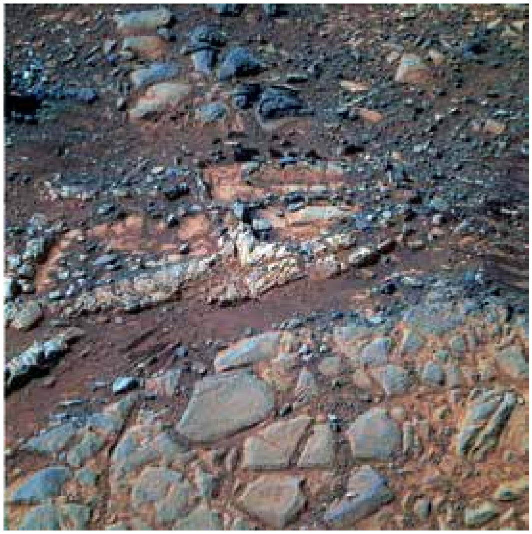


LEFT: Streams of sand draining off Opportunity's solar panels on sol 4,322 after a climb on a 30-degree slope. **RIGHT:** An image from sol 4,262 of one of the unusual dark sand puddles sitting on the surface. The sand appears to magically start at the top (arrow) and flow downslope.

ABOVE: Microscopic Imager documentation of a RAT grind on the rock Mazatzal on sol 82. Color was added from the Pancam image on sol 85. The grind circle is four centimeters across. The dark vertical band is an unground part of the original rock surface retaining the pre-grind "varnish."

TOP: The rock Route 66 acquired on Spirit's sol 100 shows just how dusty things are on Mars. The unusual pattern is the result of a series of brushing actions by the RAT to remove dust. It exposed the characteristic shiny "varnish" that occurs on many Martian rocks.

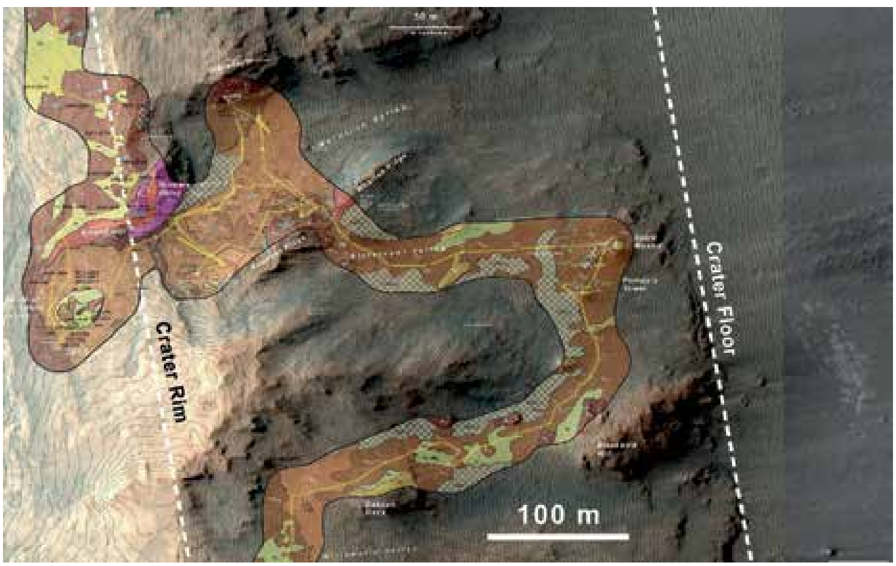
ABOVE: Petroglyph on basalt in Petroglyph National Monument, New Mexico. Petroglyphs are created by chipping off the dark desert varnish that forms on the surfaces of rocks in the desert Southwest and exposing the grayer rock underneath.



ABOVE: Image taken by Opportunity on sol 3,230 of an outcrop with a "boxwork" pattern of alteration along ancient fractures in the bedrock on the rim of Endeavour Crater. The image is about seventy centimeters across.

RIGHT: A vein of gypsum about two centimeters wide and forty-five centimeters long discovered by Opportunity on the rim of Endeavour Crater on sol 2,769.

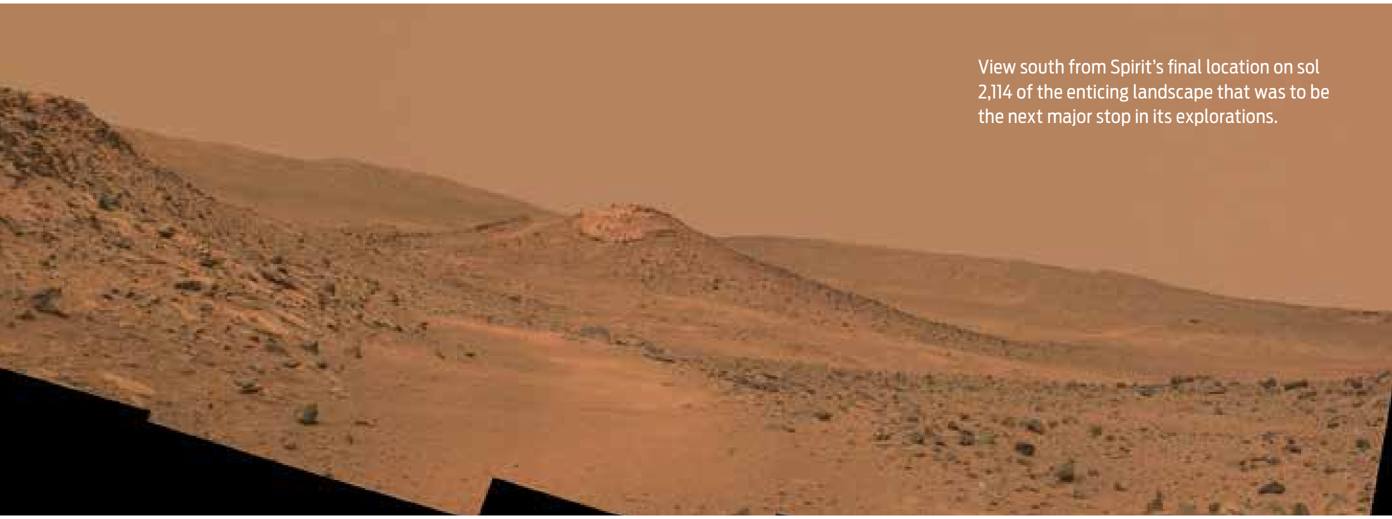
BELOW: This photo shows part of one of the first field geologic maps made from Opportunity observations. The photo was taken along its traverse out to a distance of twenty meters on both sides of the rover as it drove down Marathon Valley toward the floor of Endeavour Crater and then back out to the crater rim. Different colors represent different rock types identified from the rover along the rim of Endeavour Crater. Thin lines over the MRO/HiRISE base image are one-meter elevations.



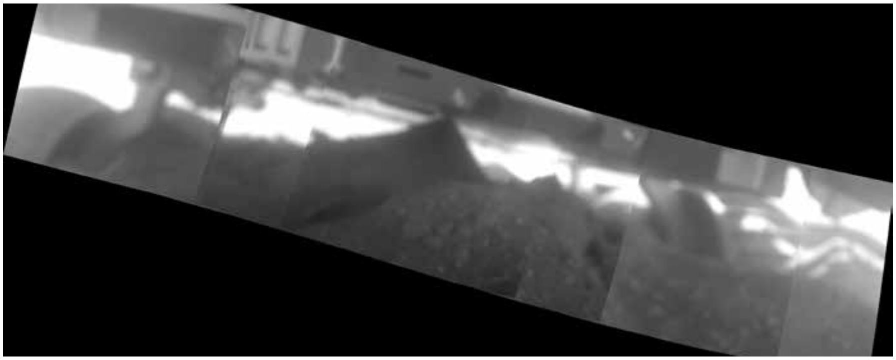
Images of dust devils crossing the Gusev Crater floor plains as seen by Spirit from its perch on the slopes of the Columbia Hills on sol 486 (**TOP;** colorized) and sol 456 (**MIDDLE**).

BOTTOM: View of a dust devil moving across the floor of Endeavour Crater captured while taking an end-of-drive Navcam panorama. This was just after a drive up Marathon Valley by Opportunity on sol 4,332.

ABOVE: A Martian dust devil captured in action crossing Amazonis Planitia. The plume is about eight hundred meters high and thirty meters in diameter.

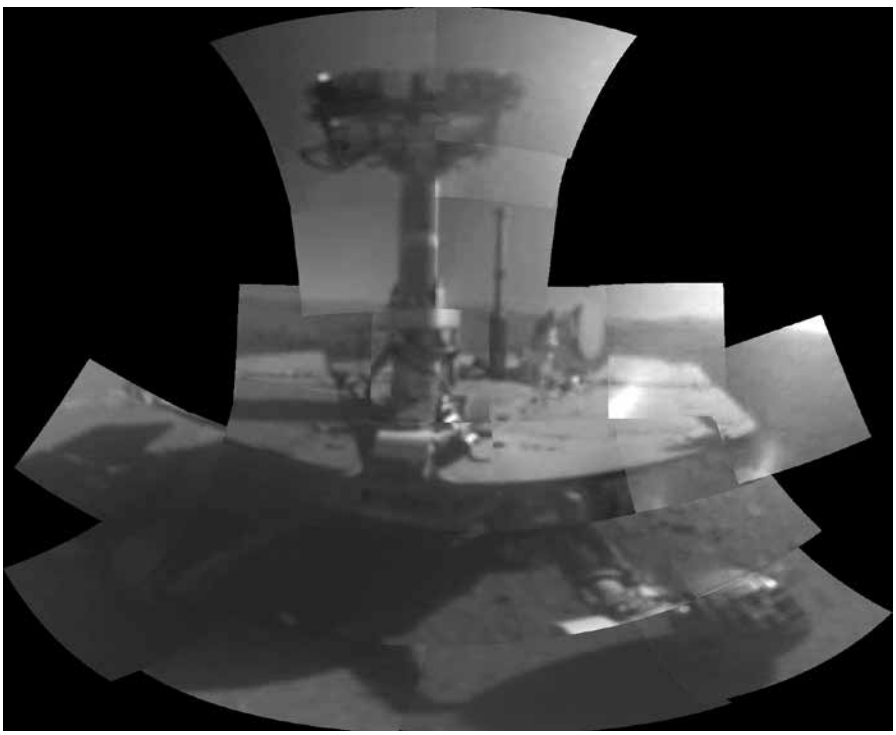


View south from Spirit's final location on sol 2,114 of the enticing landscape that was to be the next major stop in its explorations.

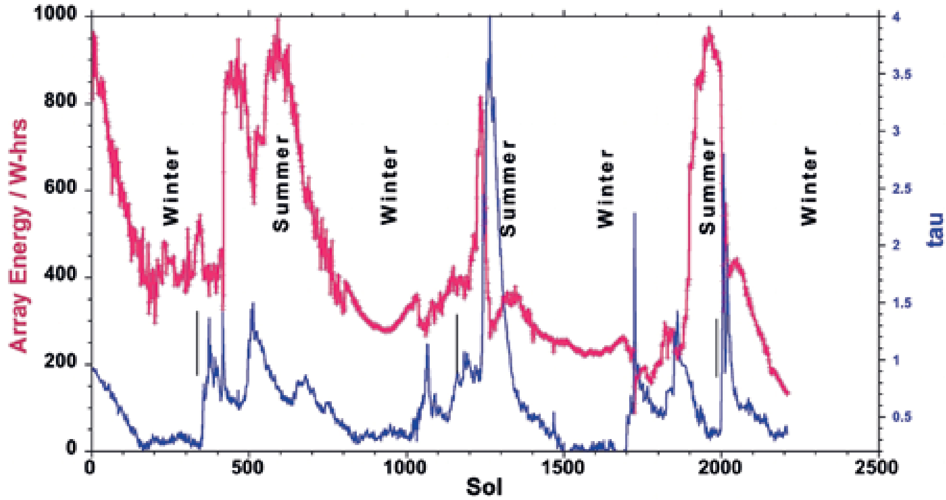


ABOVE: One of the first selfies made by Spirit on sol 1,925 using the Microscopic Imager on the end of the rover arm to investigate the proximity of a large rock threatening the underside while Spirit was trapped in deep sand at its last location.

LEFT: Image of the sunrise over the eastern rim of Endeavour Crater on Opportunity's sol 4,999. At this, its last location, it had traveled 45.1 kilometers over the surface of Mars and was about to celebrate its five thousandth sol on Mars. **RIGHT:** Composite of images taken by Opportunity showing the decrease in sunlight over 30 sols during the previous great dust storm of 2007. The numbers across the top indicate the increasing dust in the atmosphere.

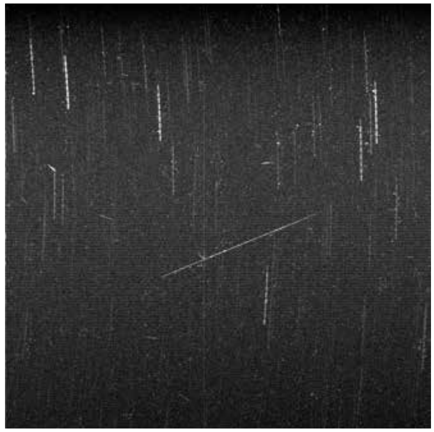


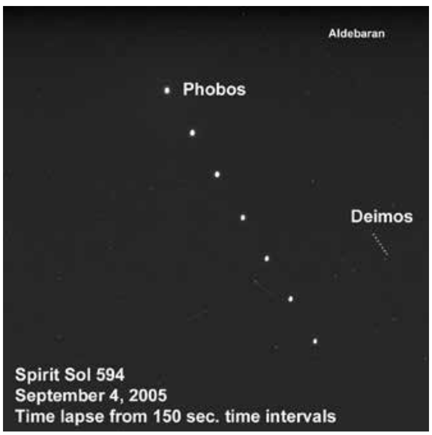
LEFT: The goodbye selfie taken by Opportunity using its Microscopic Imager on the end of its arm on its five thousandth sol on Mars.



ABOVE: Plot showing the energy output from the solar panels and the tau, or dust in the atmosphere, over the first 2,209 sols for Spirit.

A typical blue Martian sunset taken by Spirit as it climbed the slopes of the Columbia Hills on sol 489 near Larry's Lookout. This view is southwest, and the Sun is setting behind the southern rim of Gusev Crater eighty kilometers away.

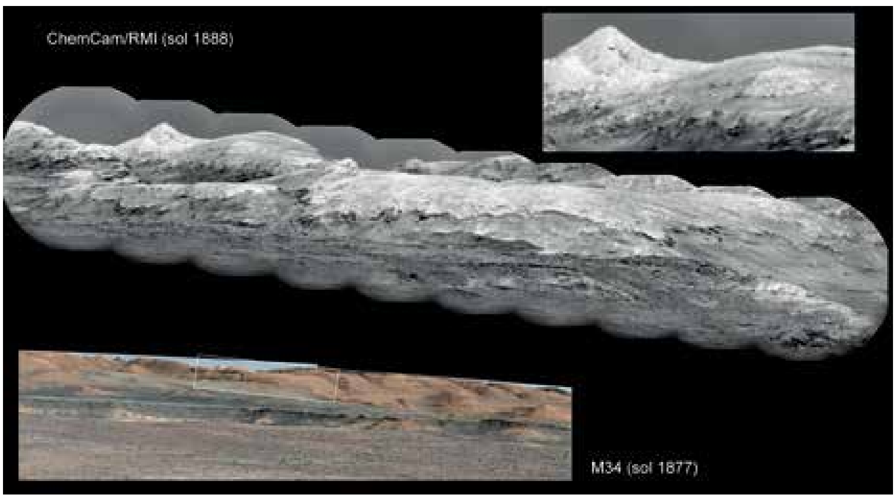




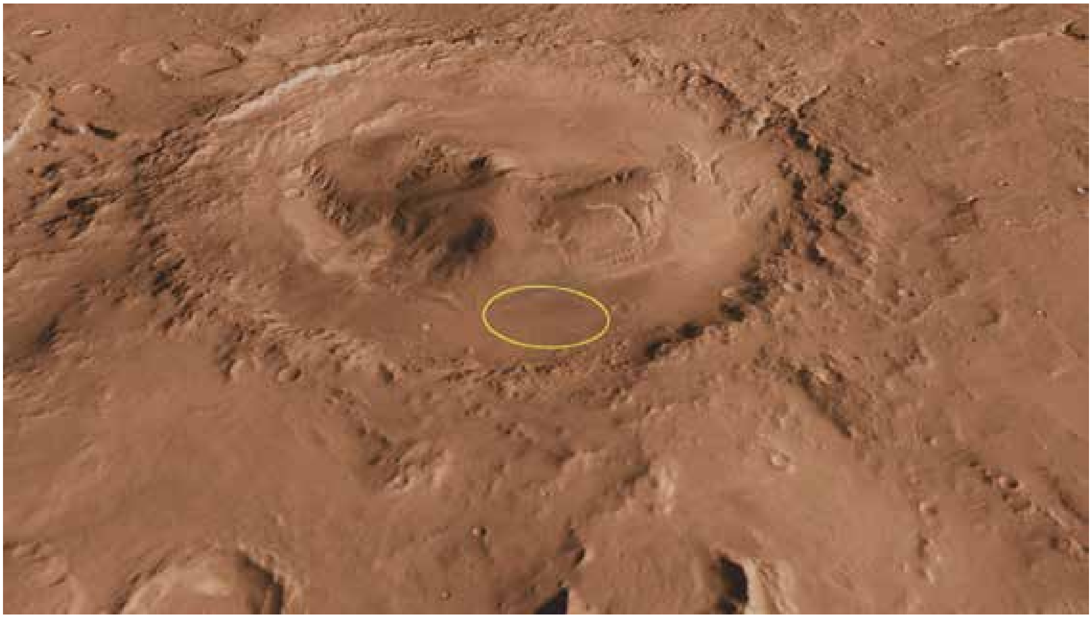
TOP LEFT: Early on the morning of sol 63 Spirit was imaging the morning predawn sky during its attempt to capture an image of Earth when it captured this strange streak. It was initially considered that it might be a satellite, perhaps even one of the old Viking Orbiters, but later we concluded that it was a likely meteor. **TOP RIGHT:** A composite of nine sixty-second exposures by Spirit during the night of sol 643 that captured another meteor. **BOTTOM LEFT:** Sequence of images taken 150 seconds apart from Spirit's "hilltop observatory" in the Columbia Hills on sol 594, showing the progression of the moons Phobos and Deimos across the Martian night sky. **BOTTOM RIGHT:** Spirit was quite the amateur astronomer and captured this eclipse of Phobos on the night of sol 675 as it passed into the shadow of Mars in the night sky. The images were taken about ten seconds apart as Phobos moved left to right across the sky.

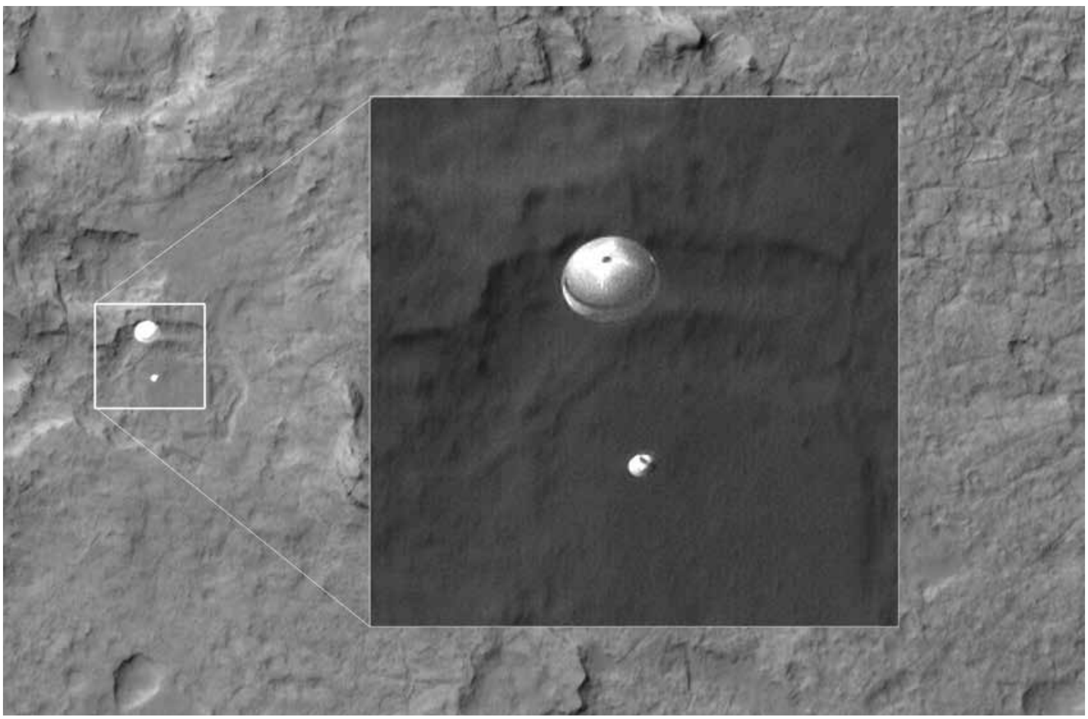
BELOW: View of the rock punctures in Curiosity's wheel taken on its sol 1,315 by the Mars Hand Lens Imager (MAHLI) camera.

Curiosity rover selfie taken on its sol 2,553. The image comprises fifty-seven individual images taken by the Mars Hand Lens Imager (MAHLI), a camera on the end of the rover's robotic arm.



LEFT: Image of the distant slopes of Mount Sharp (Aeolis Mons) in Gale Crater using the ChemCam Remote Microscopic Imager. Mastcam image at bottom shows the normal scene from Curiosity. The inset at upper right shows the detail within a small part of the RMI mosaic.

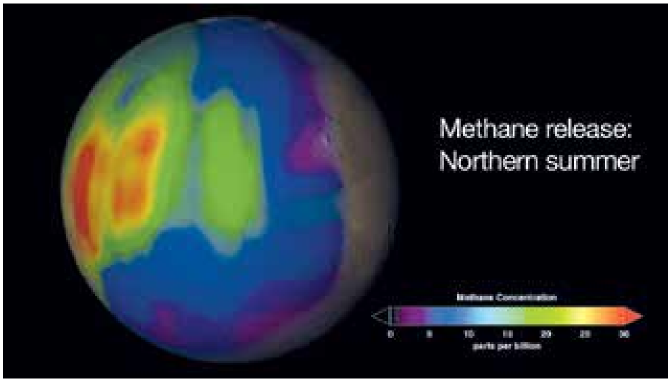


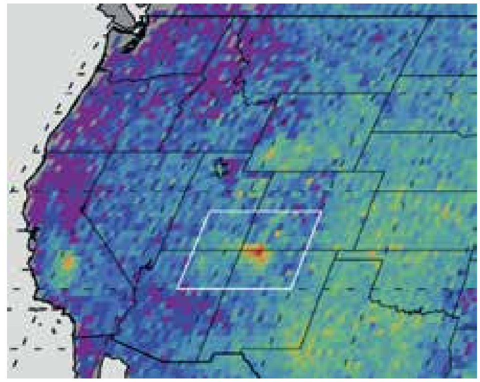


TOP: View looking obliquely south at Gale Crater showing the location of Curiosity's landing ellipse on the north floor of the crater. Gale Crater is 154 kilometers in diameter and has a peculiar layered mound in its center standing five kilometers above the crater floor. **BOTTOM:** This image of Curiosity descending toward the surface of Mars on its parachute was acquired by the MRO/HiRISE camera as its orbit carried it by the landing site during Curiosity's perilous descent to the surface.

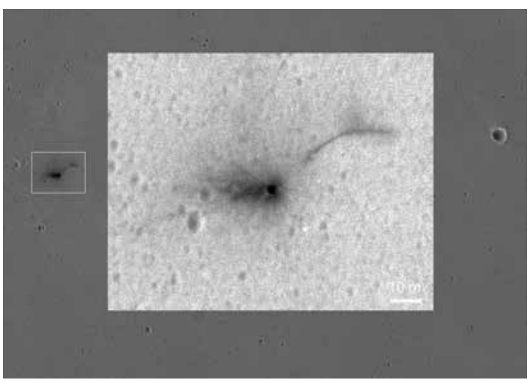
LEFT: A visualization of the extent of methane detection on Mars.

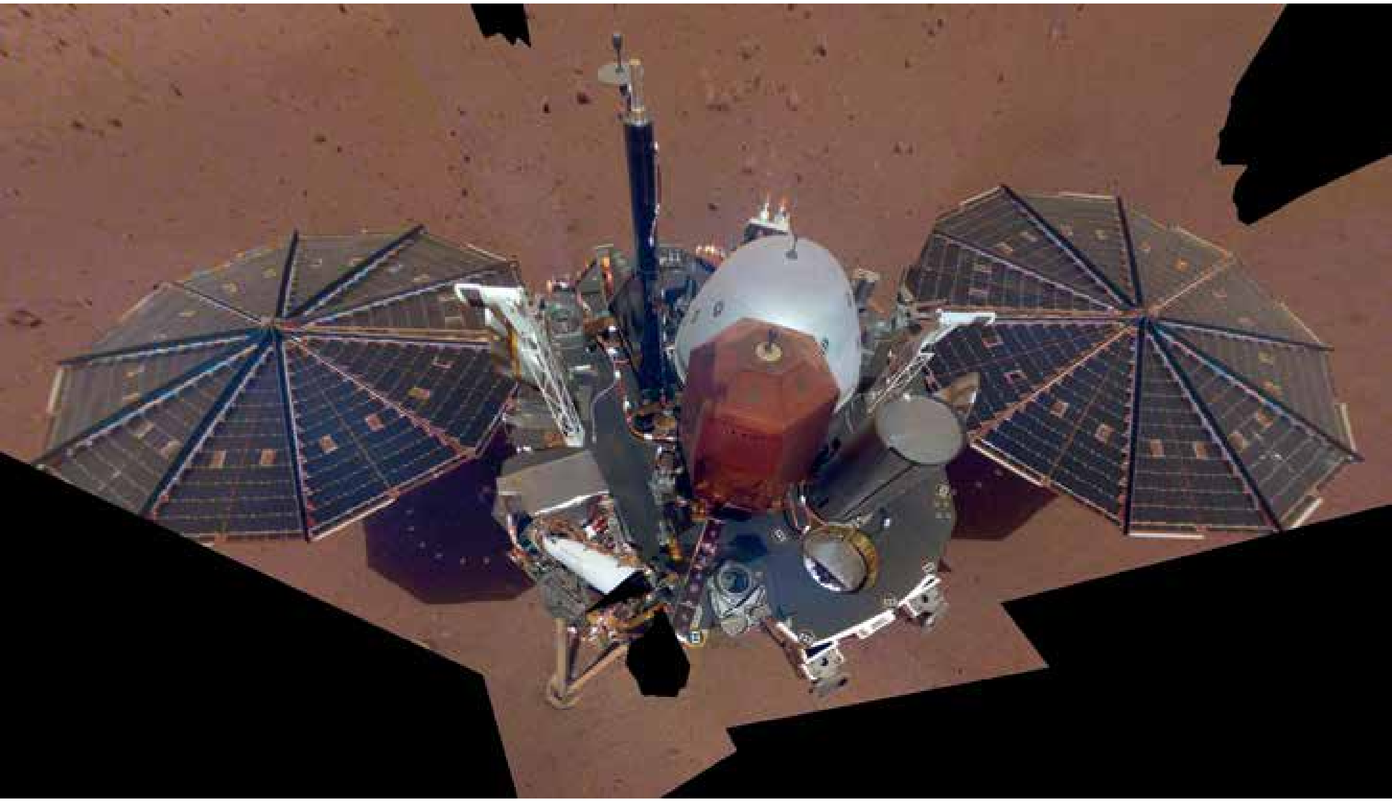
RIGHT: An image of methane concentrations in North America via a remote sensing satellite. The highest concentration is in an area of gas production in northwest New Mexico.





BELOW: Image of the ExoMars Schiaparelli lander crash site by the MRO/HiRISE camera.

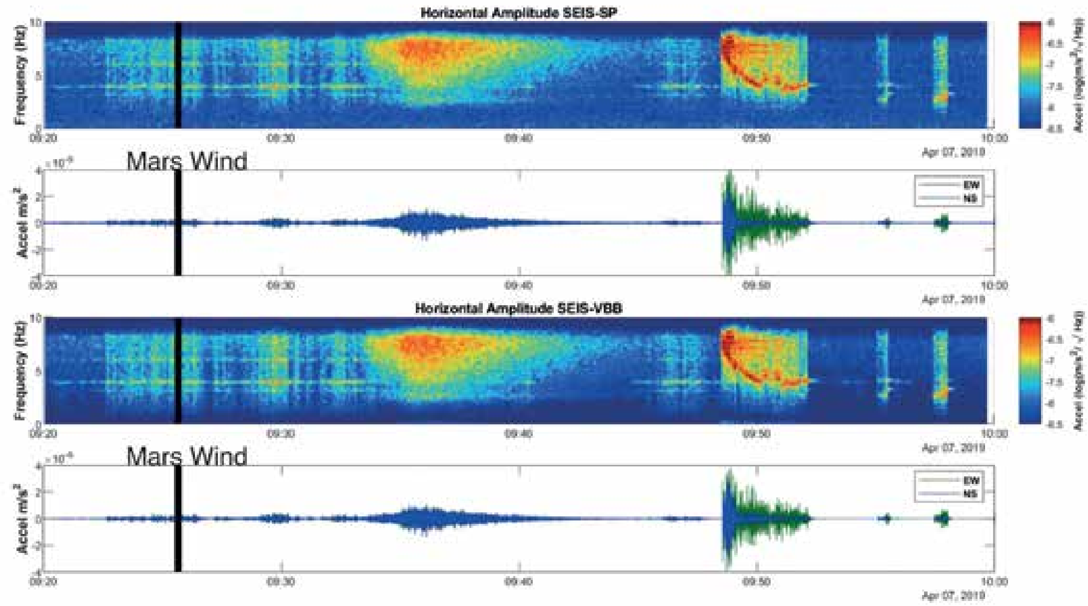


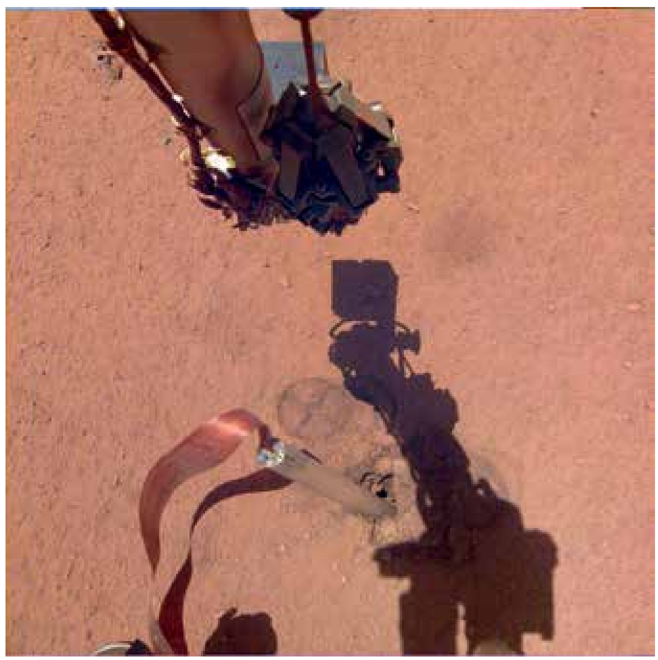


ABOVE: InSight lander selfie taken on its sol 10 after landing on Mars.

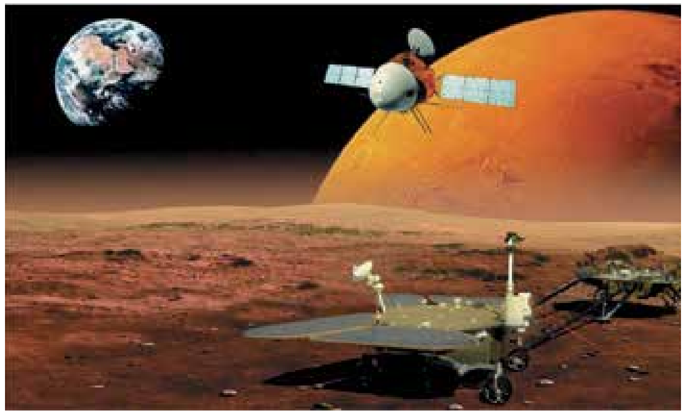
BELOW TOP: Part of a panorama acquired on sol 10 of the surface at the InSight site on Mars. The surface was selected specifically for low rock abundance and bland terrain.

BELOW BOTTOM: Image of InSight's seismic station deployed on the surface of Mars.

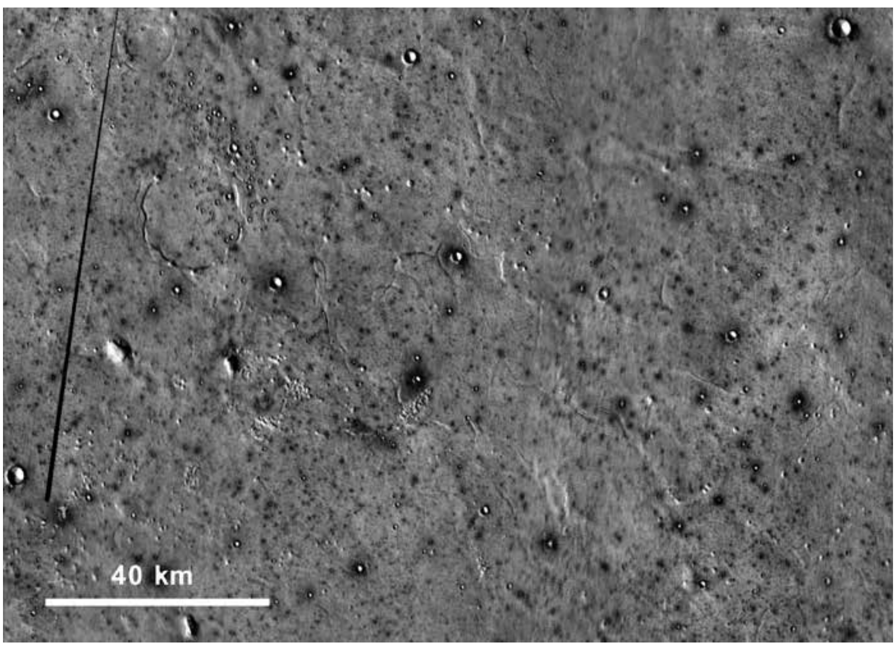




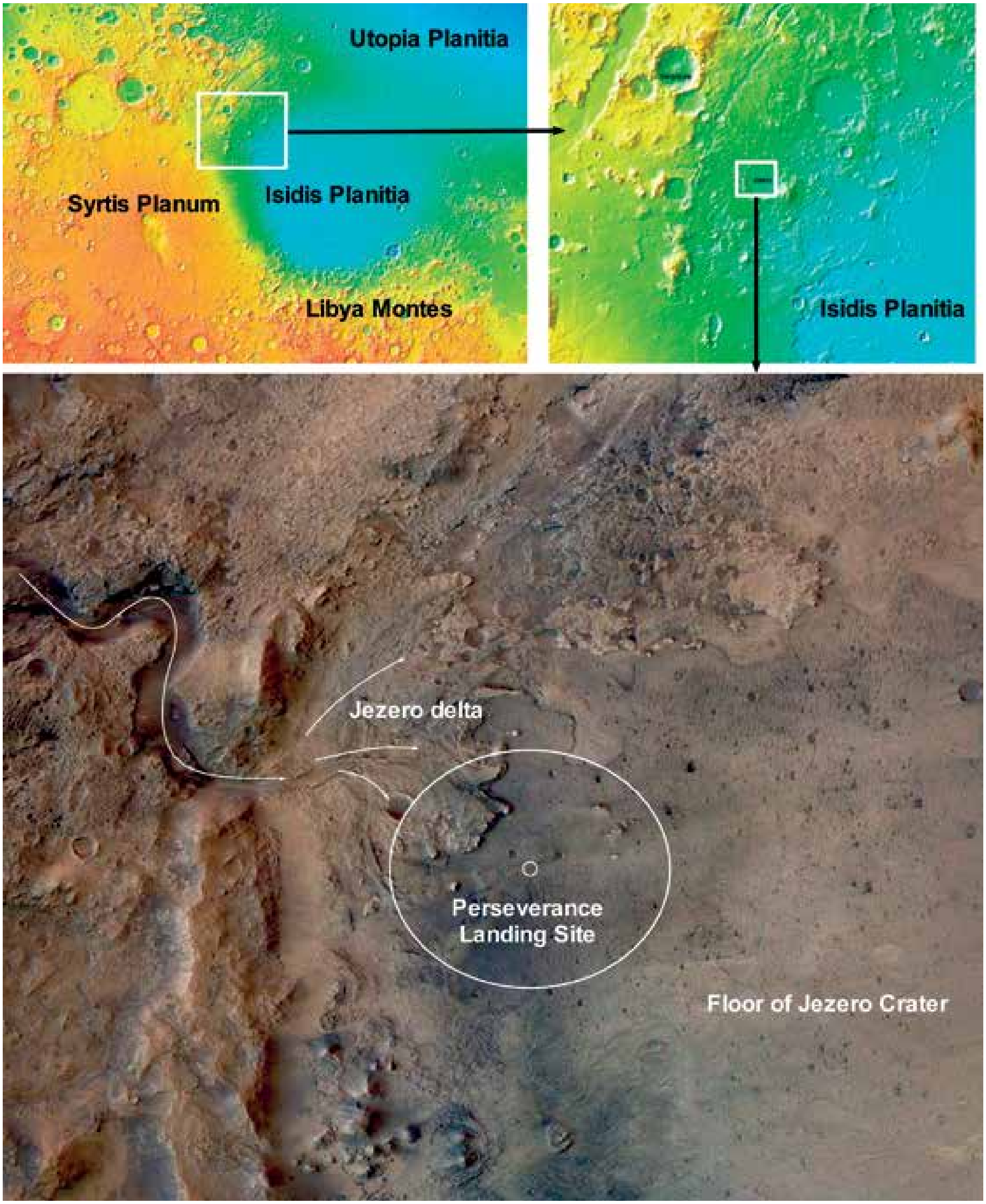
ABOVE: Seismic signal from InSight of a possible marsquake detected on its sol 128. A plot of wind at the same time is shown beneath the two seismic measurements in order to subtract from the total signal any disturbances in the surface due to wind. **RIGHT:** The silver-colored heat probe or "mole" as seen on InSight's sol 333 as the robotic arm was being used to assist the mole in



LEFT: Image taken by UAE Hope on arrival at Mars. **RIGHT:** Artist's publicity image of the Tianwen-1 orbiter and the Zhurong lander/rover at Mars.

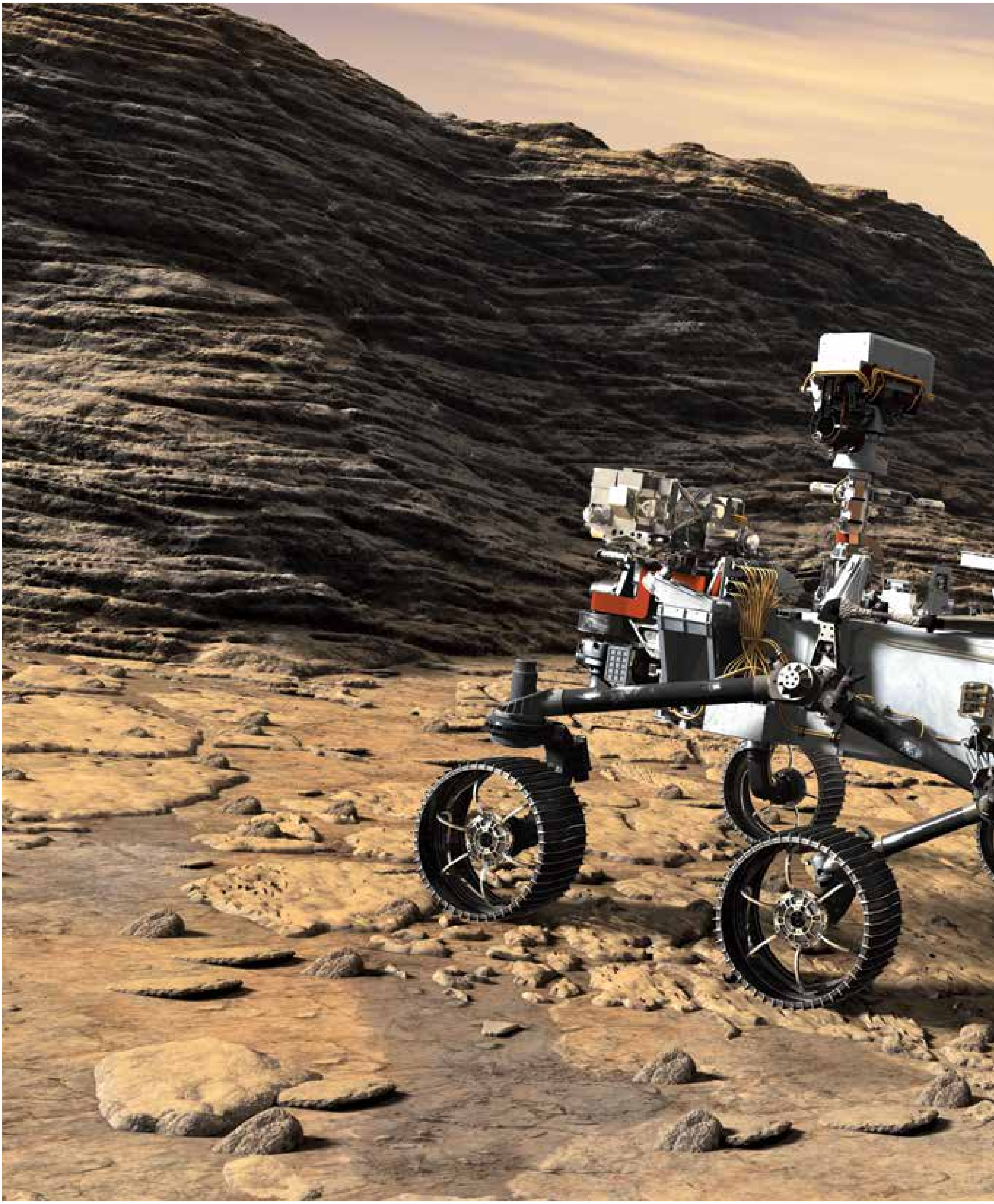


ABOVE: Odyssey/THEMIS image of the proposed Tianwen-1 landing site in southwestern Utopia Planitia.



ABOVE: The image on the upper right shows the location of the image on the upper right on the northwest margin of Isidis Planitia. The box in the upper right image shows the location of the image shown at the bottom. The landing site for the Mars 2020/Perseverance rover near an ancient delta within Jezero Crater on the northwestern margin of the Isidis basin.

ABOVE: The Mars helicopter Ingenuity in a clean room at JPL.



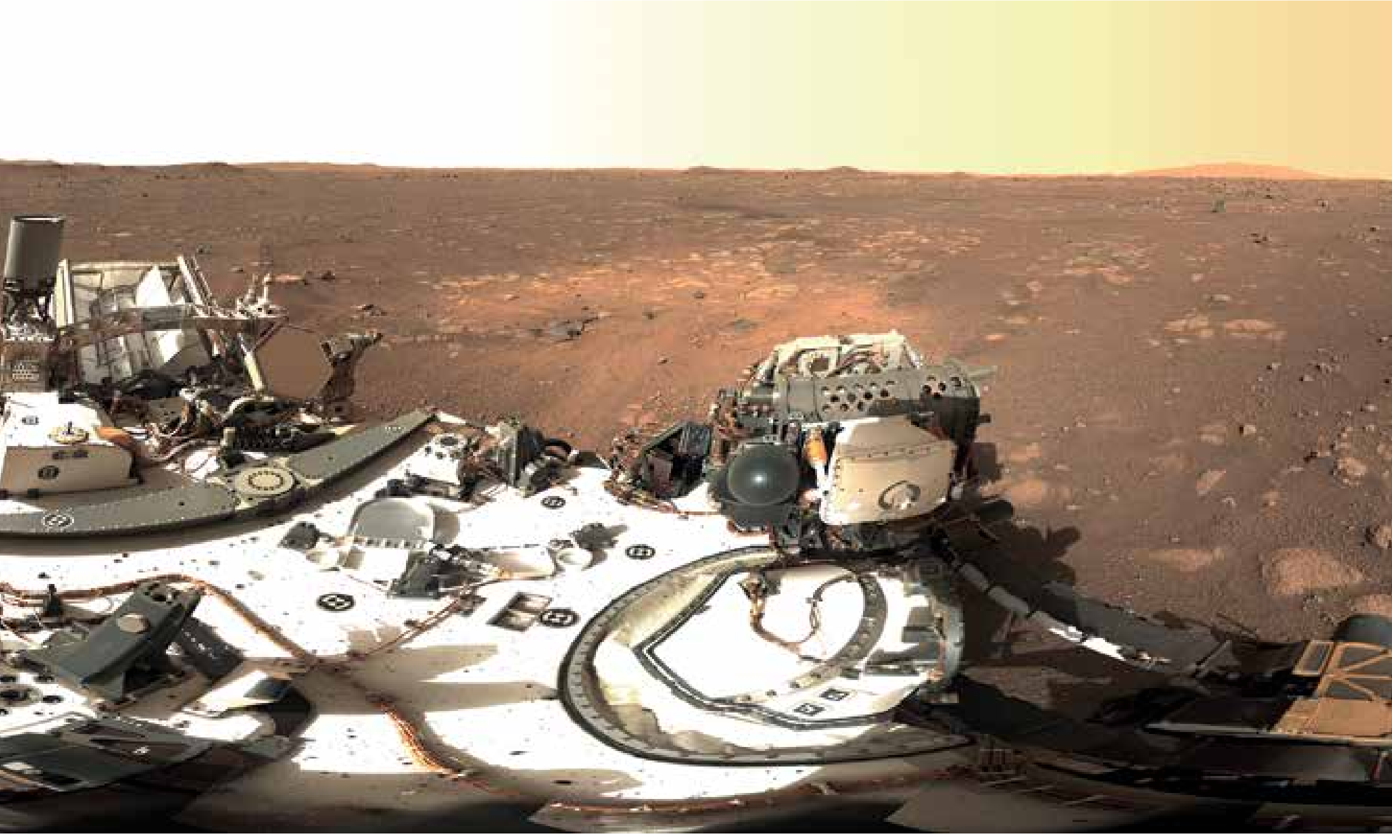
Artist depiction of the Mars 2020/Perseverance rover on the surface of Mars.

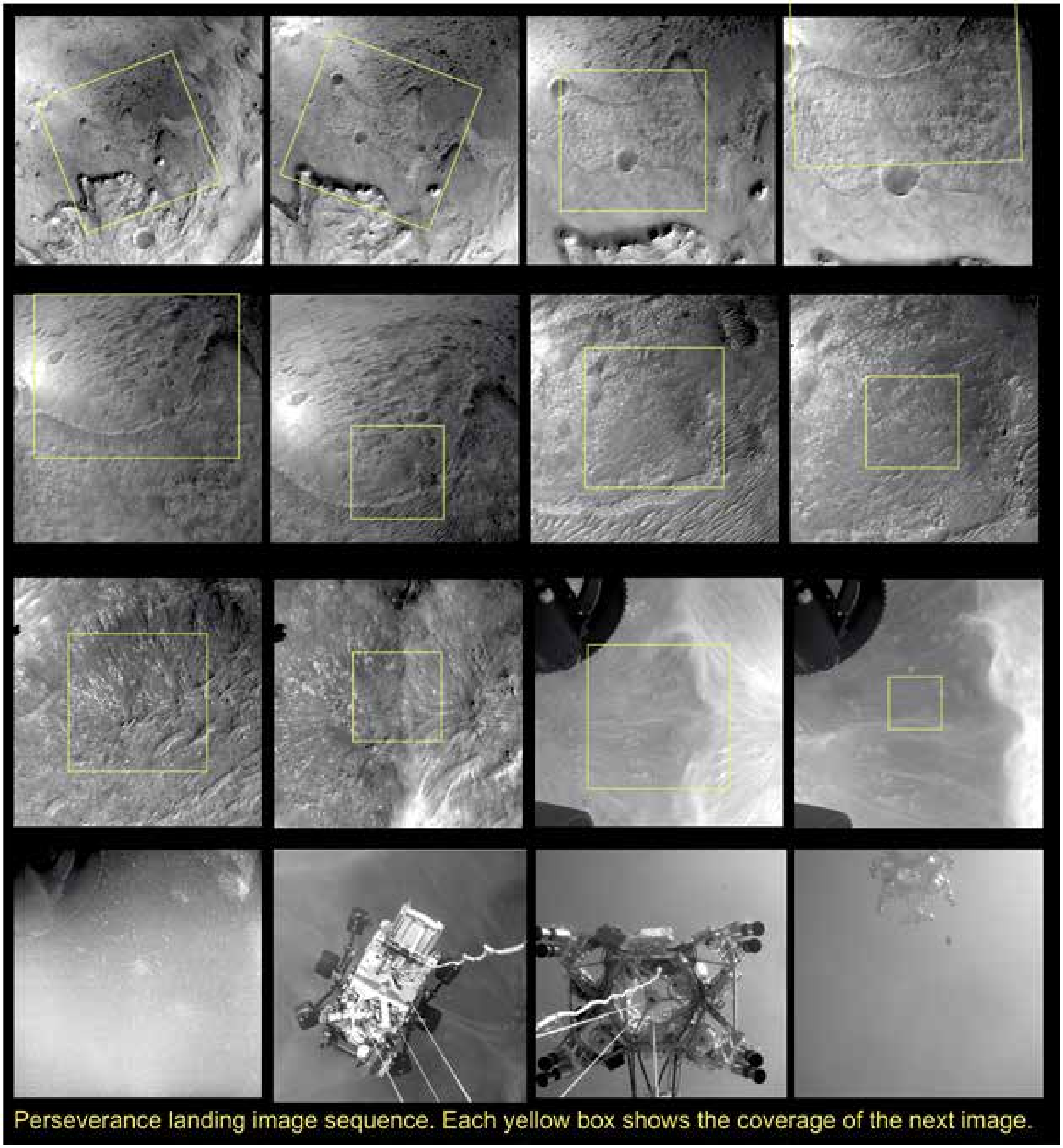
ABOVE: Part of the panorama acquired by Perseverance on sol 3, day 3 after the successful landing. This view is looking west toward a 200-meter-wide remnant of the sedimentary delta deposits in Jezero Crater two kilometers away and the mountainous rim of Jezero Crater fills the sky beyond. The rock in the closer middle ground is about two meters across and 130 meters away. **BELOW:** The Ingenuity helicopter flying on Mars on sol 61, its second flight, here hovering five meters above the surface as viewed by Perseverance high-resolution camera Mastcam-Z. The western rim of Jezero Crater forms the “mountains” in the distance.

ABOVE: Perseverance and Ingenuity on Mars in a "selfie" family portrait taken on sol 42 after placing Ingenuity on the surface.

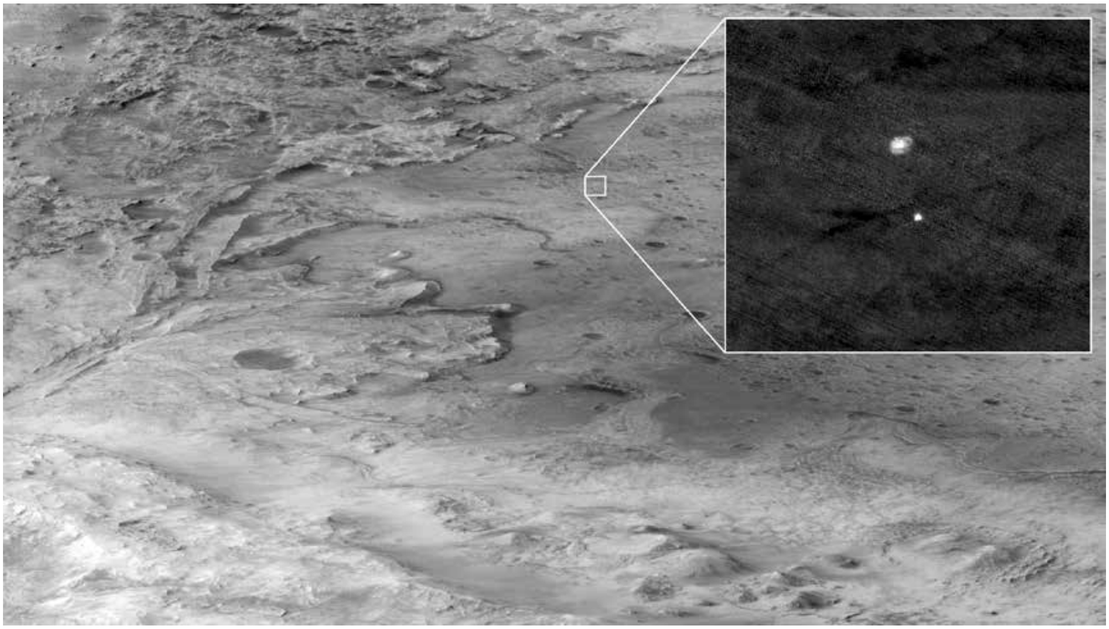

Mastcam-Z panorama from the landing site.

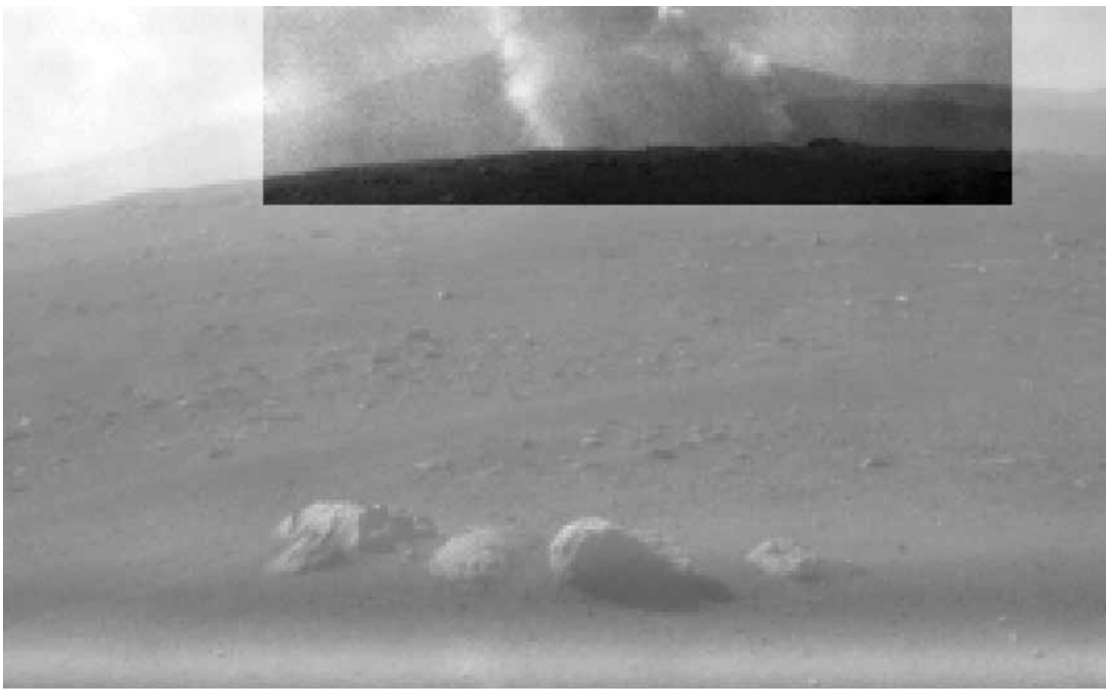
Mastcam-Z 110 mm zoom lens view of the Jezero delta margin from the landing site on sol 4.





ABOVE: Sequence of images from the Perseverance's landing approach.





TOP: Mars Reconnaissance Orbiter HiRISE camera view of Perseverance on it parachute and its way down to Jezero Crater. **BOTTOM:** The Hazcams on Perseverance captured this view of the plume rising over the local horizon from the crash site of the landing rocket stage.

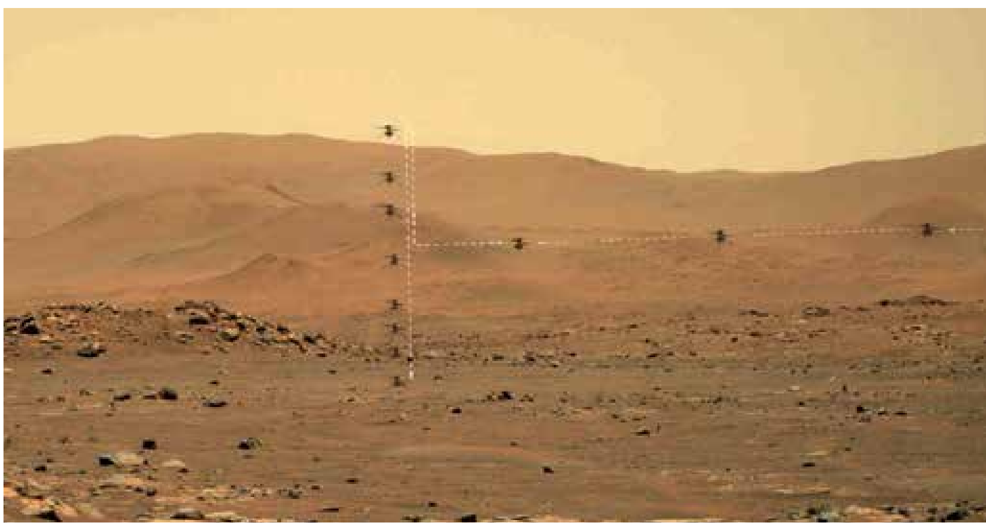
TOP LEFT: View of the parachute as Perseverance decelerated in the atmosphere during descent. The pattern of color segments spelled out a message in binary code: "Dare Mighty Things" along with the latitude and longitude coordinates of JPL. NASA/JPL-Caltech. **TOP MIDDLE:** Mastcam-Z view of the rocky escarpment east of Perseverance on its sol 62. **TOP RIGHT:** Ingenuity's downward-looking Navcam view of the ground as it flies over its "air field" on its third flight.

BOTTOM LEFT: Mastcam-Z view of the Mars helicopter "Ingenuity" awaiting its flight after being set on the ground by Perseverance. **BOTTOM MIDDLE:** Mastcam-Z view of the landform "Kodiak" several kilometers west of the landing site. Kodiak is thought to be a remnant of the Jezero delta. **BOTTOM RIGHT:** Ingenuiy's color camera looks out to the side during flight to capture a detailed view of the surface. Note rover tracks left during Perseverance's maneuvers prior to Ingenuity's flight tests.

LEFT: As Ingenuity approached its second and new airfield to the south of Perseverance on its fourth flight it acquired this color image of its destination landing site where it would land on its fifth flight a few sols later.

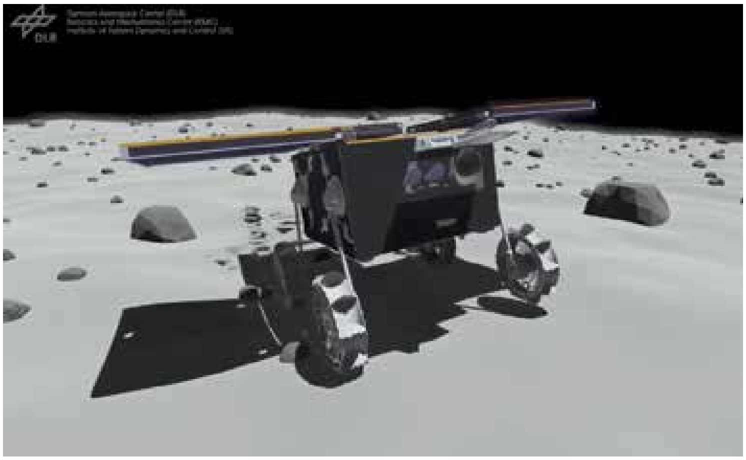
ABOVE: Ingenuity captured this color camera image of Perseverance 85 meters away. Outlined here is a white box in the upper left and expanded on the left. Ingenuity was flying about 5 meters off the ground on its third flight. The inset shows the orientation of Perseverance as seen in the image.

RIGHT: Sequence of images from the movie of Ingenuity's fifth flight to its landing site south of Perseverance.



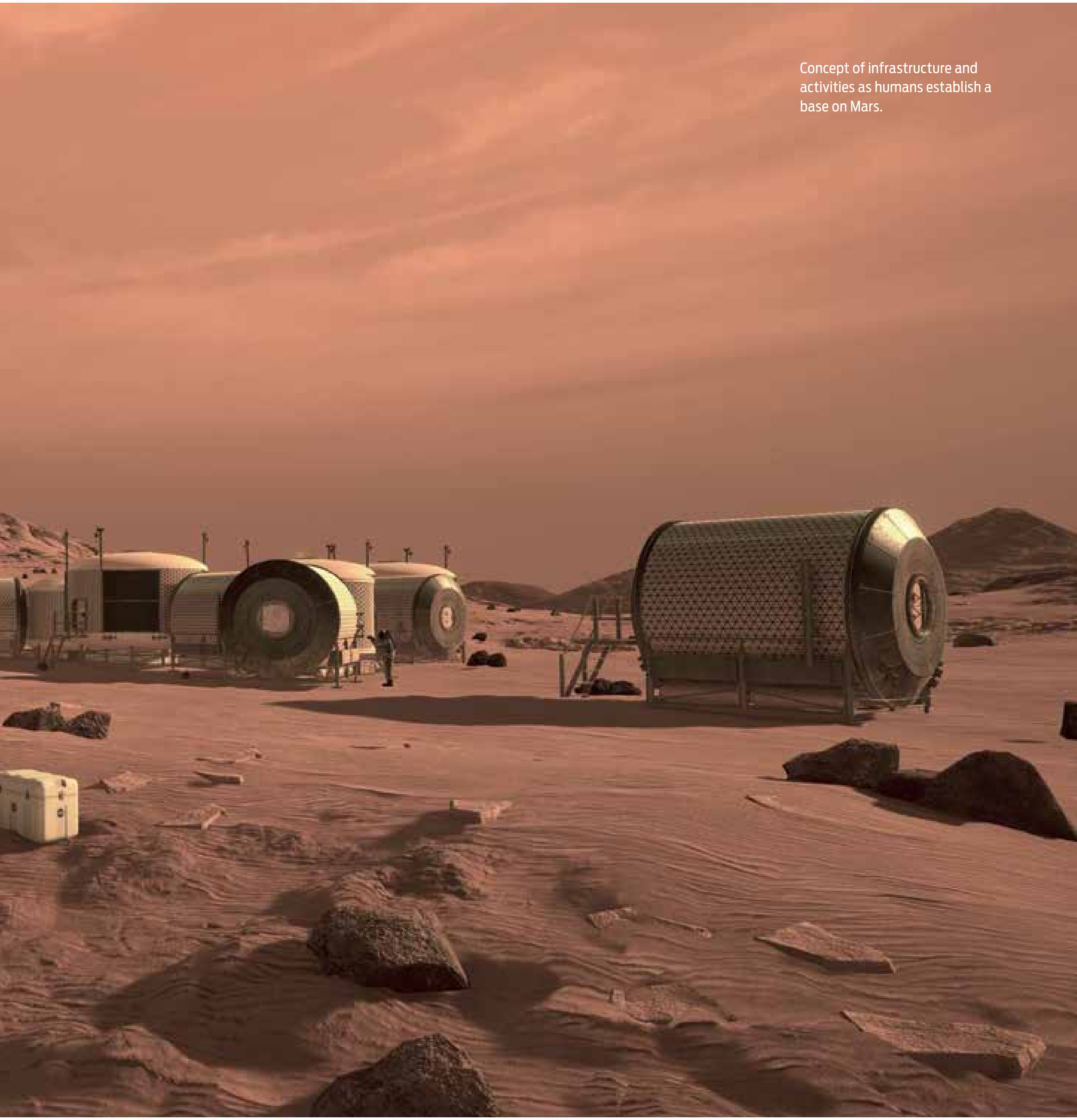
BELOW: Peculiar weathered–appearing outcrops in front of Perseverance on sol 66. The rocks are fractured, appear to have very granular and somewhat "crumbly" surfaces, and occur as polygons separated by fine-grained regolith. Mastcam-Z image.

LEFT: Matscam-Z image acquired on sol 68 looking north and east toward a large hill "Santa Cruz" 2.5 kilometers away.

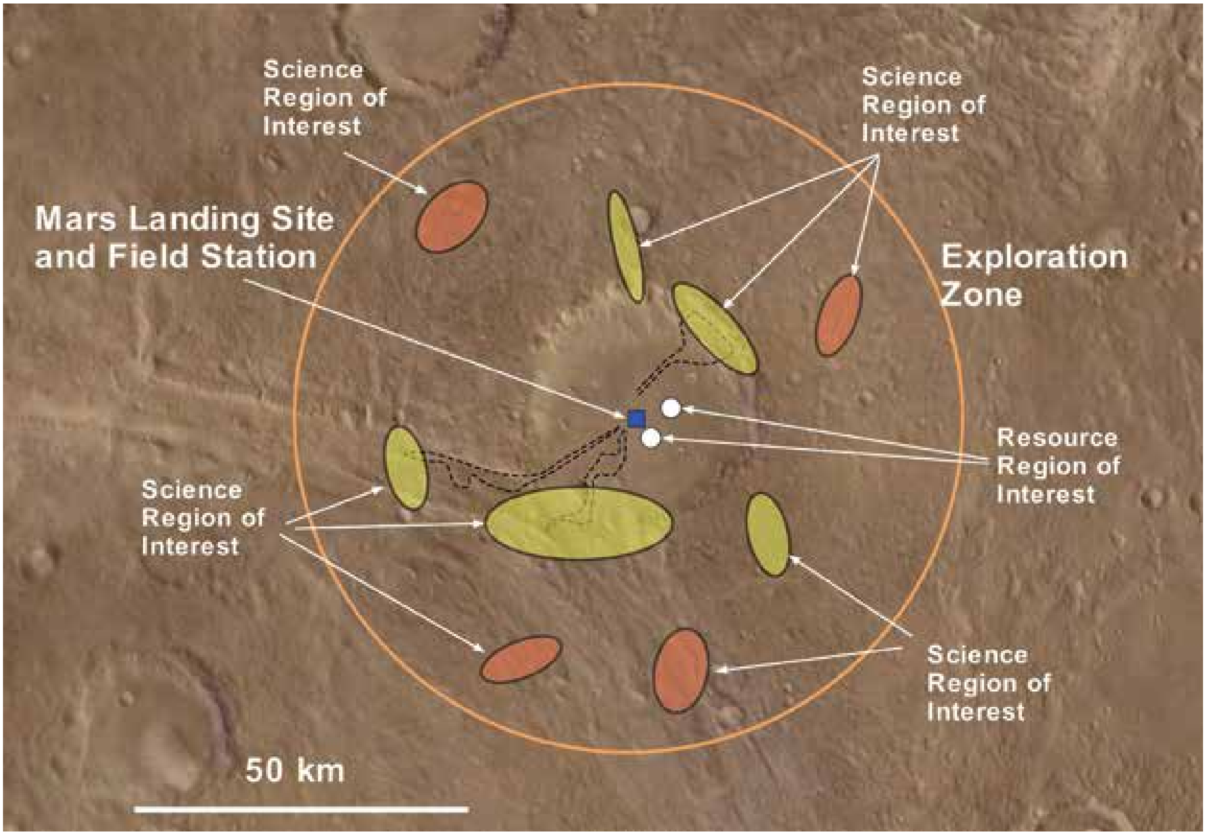


ABOVE TOP: Artist view of Rosalind Franklin rover on the Kazachok lander after arrival on the surface of Mars in the Oxia Planum region. **ABOVE MIDDLE:** Artist's rendering of the MMX Phobos rover after deployment to the surface for sample collection. **ABOVE BOTTOM:** Artist's concept of the MMX orbiter at Mars's moon Phobos.

ABOVE: Concept drawing of sample-return vehicle lifting off from the surface of Mars.



Concept of infrastructure and activities as humans establish a base on Mars.



ABOVE: Depiction of the “region of interest” concept as applied to Mars human landing site selection in the latest thinking about the priorities of a human Mars mission.

PHOTO CREDITS

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NASA, ESA, and STScl: 8

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Andrew Santangelo: 12 (top)

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NASA/USGS/MSSS/ESA/ DLR/ JPL/UA: 95 (top middle)

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China National Space Administration (CNSA): 288 (top right)

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JAXA/NASA: 309 (bottom right)

DLR: 308-309 (bottom middle)

NASA/JPL-Caltech/ASU/ MSSS: 300, 304-305 (bottom middle, top middle, 306 (bottom middle), 307 (bottom left, middle)

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RESOURCES

BOOKS

To learn even more about Mars and Mars missions, check out the books below.

Baker, David. *NASA Mars Rovers: 1997–2013 (Sojourner, Spirit, Opportunity, and Curiosity): An Insight into the Technology, History, and Development of NASA's Mars Exploration Roving Vehicles*. Sparkford, UK: Haynes Publishing, 2013.

Bell, Jim. *Postcards from Mars: The First Photographer on the Red Planet*. New York: Dutton Books, 2006.

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Coles, Kenneth S., Kenneth L. Tanaka, and Philip R. Christensen. *The Atlas of Mars: Mapping Its Geography and Geology*. New York: Cambridge University Press, 2018.

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Kieffer, Hugh, Bruce Jakosky, Conway Snyder, and Mildred Matthews, eds. *Mars*. Tucson: University of Arizona Press, 1992.

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McEwen, Alfred S., Candice Hansen-Koharcheck, and Ari Espinoza. *Mars: The Pristine Beauty of the Red Planet.* Tucson: University of Arizona Press, 2017.

Moore, Patrick. *On Mars*. London: Cassell, 1998.

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Squyres, Steve. *Roving Mars: Spirit, Opportunity, and the Exploration of the Red Planet.* New York: Hachette, 2005.

Wiens, Roger. *Red Rover: Inside the Story of Robotic Space Exploration, from Genesis to the Mars Rover Curiosity.* New York: Basic Books, 2013.

WEBSITES

To see more amazing pictures of Mars missions, check out these websites:

NASA Photojournal

https://photojournal.jpl.nasa.gov

Mars Odyssey THEMIS

https://themis.mars.asu.edu/gallery

Mars Reconnaissance Orbiter

https://mars.nasa.gov/mro/

https://www.nasa.gov/mission_pages/MRO/

MRO/HiRISE Images

https://www.uahirise.org

Spirit and Opportunity

https://www.nasa.gov/mission_pages/mer/

Spirit and Opportunity Images/ Data through MER Analyst's Notebook

https://an.rsl.wustl.edu/mer

Curiosity Rover

https://www.nasa.gov/mission_pages/msl/

InSight Mars Lander

https://www.nasa.gov/mission_pages/insight/main/index.html

Perseverance. Mars Rover

https://www.nasa.gov/perseverance

MAPS

If you want to see more maps of Mars, take a look at these resources:

Mars Geologic Map

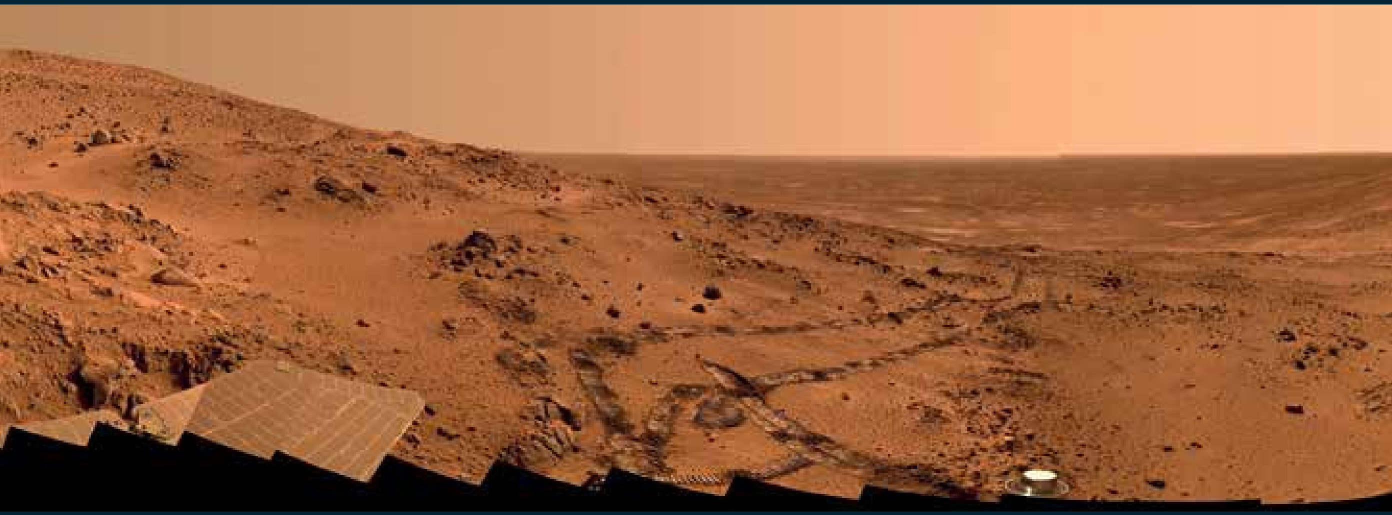
Tanaka, Kenneth L., James A. Skinner, James M. Dohm, et al. 2014. *Geologic Map of Mars*. 1:20,000,000 scale. US Geological Survey, Scientific Investigations Map 3292.

https://dx.doi.org/10.3133/sim3292; https://www.usgs.gov/media/images/geologic-map-mars

Mars 2020/Perseverance Landing Site

Sun, Vivian Z., and Kathryn M. Stack. 2020. *Geologic Map of Jezero Crater and the Nili Planum Region, Mars*. 1 sheet, 1:75,000 scale. US Geological Survey, Scientific Investigations Map 3464.

https://doi.org/10.3133/sim3464



Spirit's view of the surroundings in the Columbia Hills on Sols 410 to 413 (February 27 to March 2, 2005) from a position known informally as "Larry's Lookout."