3 Mars: The Abode of Life?

On the drive up Interstate 15 from Los Angeles towards Las Vegas, as the land begins to ascend and give entry to the city of infinite dreams and dross, one can take a detour from the journey and turn at the small town of Baker ("Gateway to Death Valley"). The environment that continues north along the scenic California State Route 127 is almost indistinguishable from that of Mars, except for the few straggly plants that hug the road and other places with just a little moisture. Vast ranges of sanded plains greet jagged mountains and dry lake beds. The terrain is so Mars-like, that a mock-up of the Mars Science Laboratory *Curiosity* was tested there in 2012, a year after the actual rover was launched (Figure 3.1). Engineers moved the car-sized vehicle over the desert to see how its wheels would fare in the sandy soil of Mars. *Spirit*, one of JPL's earlier Mars Exploration Rovers, had gone to its final resting place in 2009 after one of its wheels got stuck in the martian sand after more than six years of studying the surface of Mars. The other Rover, *Opportunity*, is still going strong at the time of writing.

The cautious and ingenious engineers at JPL weren't going to let a similar fate overtake *Curiosity*. Their mock-up, with a mass of only about 38% of the real thing to account for the lower gravity on Mars, was beset with challenging situations similar to those expected on Mars. It was driven up and over the sides of sand dunes, and into the deepest, softest sand imaginable. The wheels of *Curiosity* were engraved with giant treads with immense gripping power, and in a flight of flair and fancy, the prototype was engraved with the letters JPL. When NASA Headquarters saw that they banned it from the final model. Under the "one NASA" policy, the entire Agency had to share in the glory. But the clever engineers at JPL struck back: they embedded the Morse code symbols for JPL in the tire, so the

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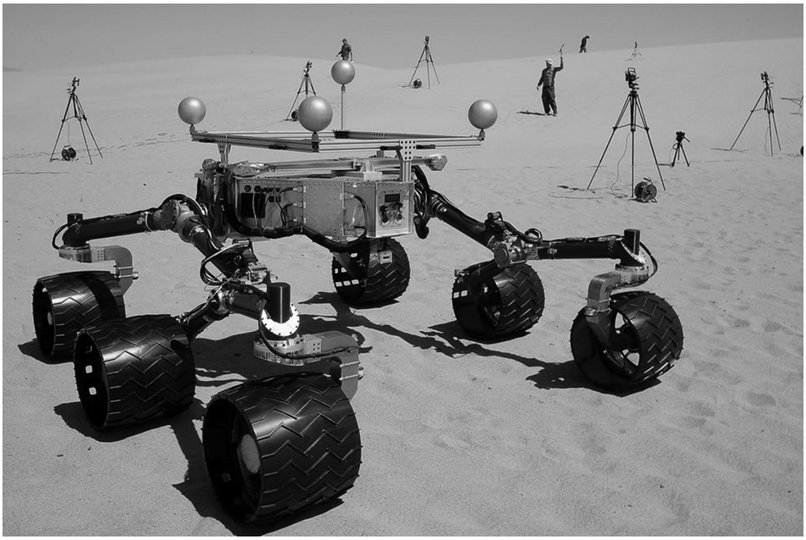

FIGURE 3.1 JPL engineers testing the wheels of the Mars Science Laboratory *Curiosity* in the Dumont Dunes, about 30 miles north of Baker, California. The sandy terrain is similar to the challenging conditions found on the surface of Mars. The wheels are 20 inches wide. NASA/JPL-Caltech. See plate section for color version.

true geeks' code is engraved in endless trails all over the martian sands.

But in spite of the Mars-like terrain found on Earth, early explorations of the real Mars dealt a series of blows to our fantasy of finding a planet just like our own. As a young girl in July of 1965, I remember being glued to our tiny black and white television to await the return of the first pictures of Mars sent back from *Mariner 4*. I had been raised on a hearty diet of science-fiction classics that painted Mars as a hospitable – or at least habitable – place populated by various races of humans or human-like creatures. Robert Heinlein's *Podkayne of Mars* featured the adventures of a space-faring spunky female teenager (what an antidote to the vision of the NASA's Mission Control in the 1960s, with orderly rows of buzz-cut engineers in crisp white shirts and pocket protectors!), and his *Stranger in a Strange Land* described a spiritually superior, non-consumerist culture of an advanced race of

Martians. Ray Bradbury's *Martian Chronicles* serialized the demise of a human civilization on the Red Planet, as Mars is known because of its color, even to the naked eye. One of the stories in the *Chronicles* irked me even back then, before a feminist consciousness had gripped my generation. In the chapter entitled "The Silent Town," a miner left behind by his fellow earthlings goes in search of any other human being, preferably a woman. The male chauvinist guesses that the most likely place for a woman to be is in a beauty salon, and of course that is where he finds her. But this woman is not beautiful: Bradbury caricatures her as an overweight battle ax, pursuing the poor miner, the last man on a dying planet. It was a bad story, but it showed again that even sordid human dramas could play out in outer space.

I was fascinated by another chapter in Bradbury's book, "The Green Morning," which described the overnight greening of Mars from a barren wasteland to a lush forest. This story foretold the rise of the Mars Underground, a somewhat undercover group of NASA and university scientists that arose in the 1970s and 1980s to advocate "terraforming" Mars into an Earth-like planet. The technological challenges are huge, and not even the most optimistic scientist would predict an overnight transformation. I first became aware of the ideas of this group in 1989 when Chris McKay, an astrobiologist at NASA Ames Research Center, gave a talk after receiving the Urey Prize of the American Astronomical Society's Division for Planetary Sciences (DPS). My Cornell mentor Carl Sagan bestowed the award upon McKay, and then modestly stepped away: he was at the height of his celebrity at the time, but he still attended our professional meetings. All the kitchen staff were agog at his presence. It is traditional for recipients of this award, which is given each year to the most promising early-career planetary scientist in the world, to give a scientific address at the annual meeting of the DPS. At the end of McKay's talk, he showed a series of images of Mars being terraformed from the desert planet it is today into a successively more Earthlike world: wetter, warmer, and cloudier. The last slide of the talk illustrated a Mars with oceans, cloud patterns, and green land. From the normally polite audience, there were some derisive snickers, but there were also some oohs and aahs of appreciation.

And of course there was H. G. Wells's *War of the Worlds*, which had residents of New Jersey panicking in the streets when the story was read on the radio by Orson Welles in 1938 on the day before Halloween. As I waited for those pictures from *Mariner 4* to arrive, in the back of my mind there was also the fading paradise on Mars painted by Percival Lowell (1855–1916), the nineteenth and twentieth century American astronomer.

Lowell was a Boston Brahmin, descended from a prominent line of colonial bigwigs. The mill town of Lowell, Massachusetts was named after Francis Cabot Lowell, a family member who was one of the first industrialists to envision the factory as the efficient manufacturing system that was to become characteristic of the capitalism of the twentieth century. By the mid-nineteenth century the city's mills employed thousands of immigrant laborers. The Chinese-speaking, cigar-smoking, Pulitzer prize-winning poet Amy Lowell was Percival's sister, and his brother A. Lawrence Lowell was the president of Harvard from 1909 to 1933. The latter's legacy revolves in part upon his effort to preserve White Anglo-Saxon Protestant (WASP) privilege at Harvard: he famously attempted – and succeeded – to limit the Jewish enrollment to 15%. He also opposed the nomination of Louis Brandeis, the first Jew appointed to the Supreme Court, banned African–Americans from freshman dorms, and purged the campus of gay men, an action that was unearthed only in 2002, and that tragically led many of the men to commit suicide (and was ironic, as Amy was probably gay).[1]

In 1894, Percival decided to devote a large portion of his family's fortune to building an observatory in the cool dry highlands of Flagstaff, Arizona, which was not a state until 1912. He had become interested in astronomy and was drawn to the writings of Camille Flammarion (1842–1925), a French astronomer and spiritualist who believed Mars was inhabited by an intelligent race that had previously communicated with Earth. Flammarion is perhaps best known for his

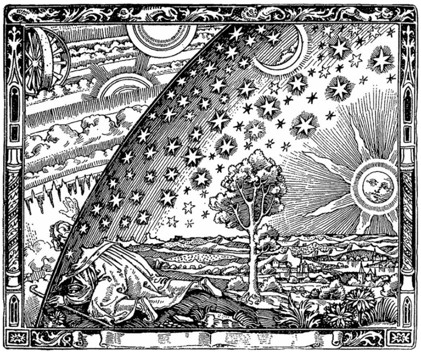

FIGURE 3.2 Flammarion's iconic image of the seeker.

production of an 1888 wood engraving that depicts a medieval pilgrim – perhaps an avatar for anyone seeking knowledge or enlightenment – penetrating the heavens to behold the inner workings of the cosmos (see Figure 3.2). The meaning of the scene beyond the sky is debatable: among the interpretations are that it includes the merkavah (upper left), the mystical chariot of Ezekial that inspired medieval Jewish kabbalists, or that it is simply a concrete depiction of the orbits of the planets. In any case, astronomers throughout the last century have considered – and we still consider – the print inspirational, part of the lore that underlies astronomy as being a search for the ultimate workings of the universe.

Lowell had also heard of the discovery in 1888 of "canali" on the surface of Mars by the Italian astronomer Giovanni Schiaparelli. The Italian word means "channels," natural bodies of water, but the word was translated as "canals," a word that implies a man-made sluiceway. Soon after Lowell installed the 24-inch refracting telescope built by fellow Bostonian, Alvan Clark, the ace telescope maker of his day, he began to produce drawings depicting a complex system of canals and dots on the planet (Figure 3.3). Lowell believed the canals were conduits bringing water from the martian polar caps – which are clearly visible through a telescope and follow a seasonal pattern similar to the Earth's – to a dry, dying civilization in the temperate zones. The dots at the intersections of the canals were "oases" in the martian desert. Lowell also claimed to see seasons: as the polar

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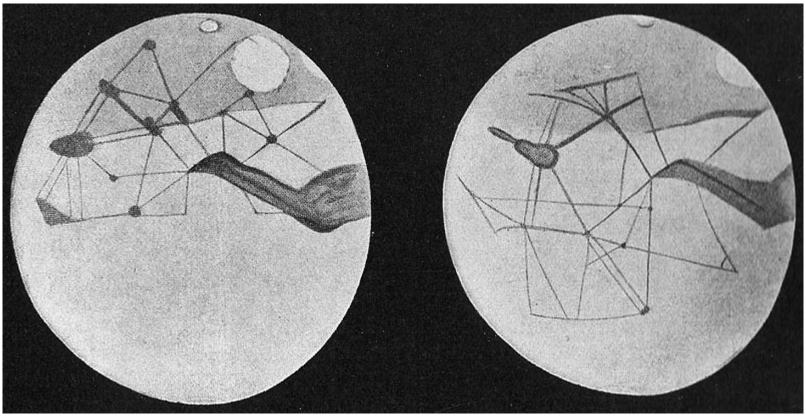

FIGURE 3.3 Drawings by Percival Lowell of the canals, oases, and advancing green spring vegetation on Mars (top).

caps retreated in the spring he could see a blanket of green spreading toward the equator. Lowell published three books describing in detail his passionate beliefs about an advanced civilization on Mars: *Mars* (1895), *Mars and Its Canals* (1906), and *Mars as the Abode of Life* (1908).

Almost as soon as Lowell popularized his ideas of civilized life on Mars, other astronomers attacked his observations and his credibility. Eugene Antoniadi turned the larger 33-inch telescope at Meudon University toward Mars and declared the canals to be optical illusions. Alfred Russel Wallace (1823–1913), the British biologist best known for his independent discovery of the theory of evolution, published a book *Is Mars Habitable?* (1907) that demolished Lowell's claims. Wallace showed that fundamental physical principles precluded the existence of a system of canals and intelligent life on Mars. The planet was much colder than Lowell claimed, and the atmospheric pressure at the surface was too low for water to exist as a liquid. If there were water, it would have been detected in the atmosphere by terrestrial telescopes. When a 60-inch telescope was built on California's Mount Wilson in 1908 and trained on Mars, the canals were shown to be systems of separate dark patches. The human eye tends to organize such

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patches into linear, continuous structures. Psychologists even have a term for this tendency to see patterns when none are there: apophenia. The canals were indeed optical illusions, and Lowell's observation of vegetation advancing in the spring – if it were real – may have been a large dust storm of the sort we now know periodically envelopes Mars.

Lowell's ideas seem even more ridiculous today, but his critics have overlooked one aspect of his work: he was an early environmentalist, a visionary who harped on about the need for sustainability. *Mars as the Abode of Life* was prescient in its tone about the need to preserve land, water, and resources. He speaks of a nearly global desert on Mars, beautiful but fatal to its inhabitants:

> A vast expanse of arid ground, world-wide in its extent . . . Their bare rock gives them color, from yellow marl through ruddy sandstone to blue slate . . . But this very color, unchanging in its hue, means the extinction of life . . . Pitiless indeed, yet to this condition the Earth itself must come, if it last so long. With steady, if stealthy, stride, Saharas, as we have seen are even now possessing themselves of its surface. It is perhaps not pleasing to learn the manner of our death. But science is concerned only with the fact, and Mars we have to thank for its presentment.[2]

Over a hundred years have passed since Lowell wrote these words, and the deserts have continued their inexorable march across the face of the Earth.

But as I sat in my family's living room in July 1965, I was hoping to see canals and other wondrous sights on Mars. In the popular mind, the idea of canals and Martians had never really vanished. Science-fiction literature considered civilizations and clement environments on Mars as established canon. About this time I read a report in *Life* magazine about a scientist who built a small chamber under martian conditions and was able to keep primitive terrestrial plants and animals alive in it. But *Mariner 4*'s first fuzzy pictures of the martian surface showed craters like those on the surface of the lifeless

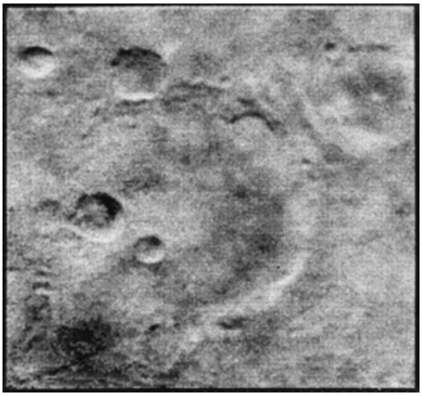

FIGURE 3.4 The best image returned by *Mariner 4*, showing a dead, cratered surface. NASA/JPL-Caltech.

Moon (see Figure 3.4). The march of scientific discovery had peeled away layers of hope and longing, painfully, and decisively. I hadn't been so devastated since the Yankees lost to the Pirates in 1960.

Two more flybys of Mars were executed by *Mariners 6* and *7* (*Mariner 5* flew to Venus), and these craft showed more of the same: craters and desolate landscapes. Our view of Mars as Earth's planetary twin was being deflated even further, just as it had for Venus only a few years earlier. After the failure of *Mariner 8* during launch, *Mariner 9* was successfully inserted into Mars orbit in 1971. It was the first spacecraft to achieve orbit around a planet other than the Earth. *Mariner 9* was also the first in a succession of Mars missions that dug us out from the hole in which we found ourselves after *Mariner 4*. With an orbiting spacecraft, we could finally get a global view of Mars. Except the planet was engulfed in a giant dust storm when it arrived. After the storm cleared, *Mariner 9* revealed a Mars that had once been much wetter, and possibly warmer, in the past. In fact, there was evidence that erosional processes occuring on the Earth, such as flooding, wind erosion, and volcanism, had also sculpted the surface of Mars. Figure 3.5 shows a massive floodplain on Mars that resembles terrestrial features such as the Scablands of eastern Washington State. These massive terrestrial flood plains were formed after natural dams restraining giant bodies of collected glacial water burst at the end of the last ice age 11,000 years ago. And then there is Vallis

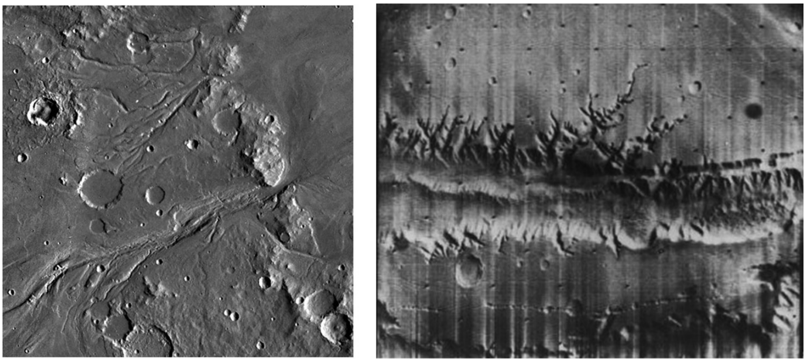

FIGURE 3.5 *Mariner 9*'s discovery of the relics of water erosion on Mars. On the left is a floodplain and associated debris fan, and on the right is the first image of Vallis Marineris obtained by a spacecraft. NASA/JPL.

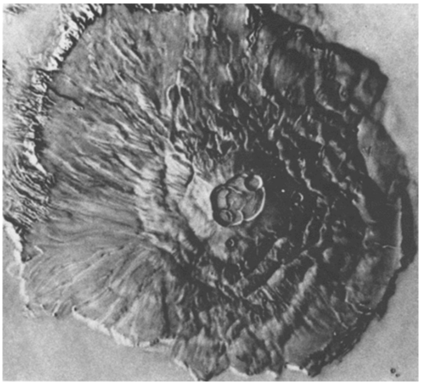

FIGURE 3.6 A *Mariner 9* image of Olympus Mons, the largest volcano on Mars. NASA/JPL-Caltech.

Marineris (Valley of the Mariners): a big gash in the surface of Mars that dwarfs the Grand Canyon and is heavily eroded by running water (Figure 3.5).

We also got a view of pimple-like volcanoes dotting the surface of Mars. Olympus Mons, the largest, is a shield volcano, an immense structure built from successive lava flows (see Figure 3.6). The pancake domes on Venus (Chapter 2) are other examples of this type of volcano. These features arise from conduits filled with molten rock moving up from a planet's interior: they are not part of the superprocess of plate tectonics. The best known shield volcanoes on the

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Earth comprise the Hawaiian Island Chain. Olympus Mons dwarfs the Big Island – at 17 miles above the mean surface level of Mars, it is more than two and a half times the height of Mauna Kea, measured from the sea floor. Just recently, scientists counted craters – our classic way of figuring out how old surfaces are, as older surfaces have more impact features as they have been exposed to space longer – on the flanks of Olympus Mons to discover that the volcanic activity that created this mountain lasted from about 115 million to just 2 million years ago: a blink of an eye in geologic time. What this discovery means is that Olympus Mons is likely to still be active. It may be a dormant volcano waiting to erupt at any time, a possibility made even more real by the recent discovery of martian methane, a component of volcanic gas.

What Lowell got right was his description of the desert-like conditions on Mars, and now we know the vast sandstorms and dune fields that characterize terrestrial deserts are prevalent on Mars. There are even dust devils on Mars (see Figure 3.7). Planetary geologists have been able to deduce global wind patterns on the surface of Mars from the orientation of its Earthlike dunes. The erosion of the surface of Mars by wind is going on today: the global dust storm that greeted *Mariner 9* on its arrival at Mars is a fairly frequent occurrence.

Another Earthlike feature of Mars is its polar caps, which can be easily observed from the Earth (their melt was the putative liquid that filled Lowell's canals), and which wax and wane with the seasons like those on the Earth. The tilt of Mars's axis is similar to that of the Earth – 25 degrees vs. 23 degrees – and since the tilt of the Earth's axis is what causes the seasons, it isn't surprising that Mars has seasons, too. There are permanent polar caps on Mars, which consist of water ice, and transient caps of carbon dioxide or dry ice (the south polar cap has some permanent dry ice as well), which sublimates in the spring and condenses in the fall. As sunlight creeps up on the ice cap in the spring, violent winds and stormy clouds filled with dust, sand, and even snow sweep up from the surface. The spring heating and release of carbon dioxide is so rapid, that geysers of gas with entrained sand

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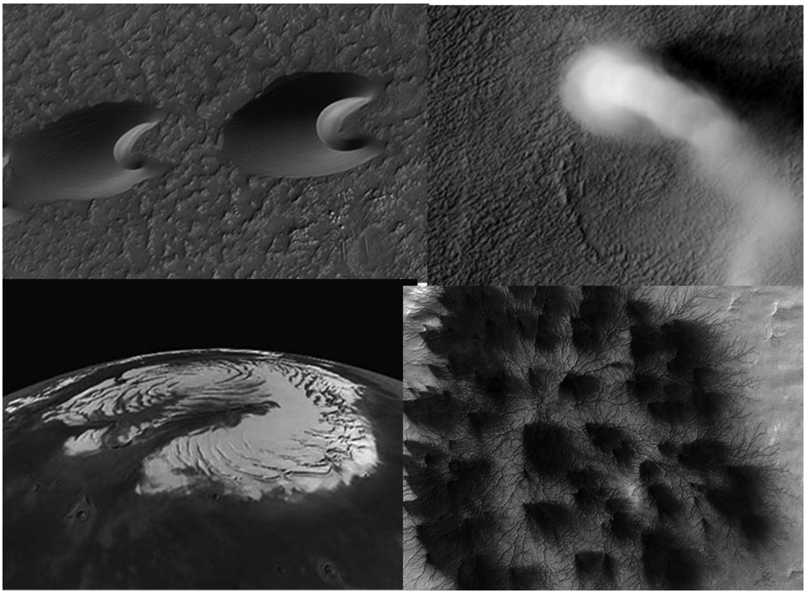

FIGURE 3.7 Marvelous sights on Mars, three of which have terrestrial analogues. Clockwise from the upper left: Barchan dunes, crescent-shaped features common on terrestrial deserts, including California's Kelso dune field in the Mojave desert near Baker, California; a dust devil; spiders on the south polar cap; and the northern polar cap of Mars. Only the spiders are not seen on Earth. NASA/JPL-Caltech/University of Arizona.

and darker minerals sprout up on the pristine cap to form strange features known as "spiders." Nothing quite like them appears on the Earth, but they make their appearance in the outer Solar System on Triton, as we shall see in Chapter 9.

In 1976, NASA sent two landers, *Viking I* and *Viking II*, to the surface of Mars to determine if life did indeed exist there. When these landers executed their experiments, they showed rather convincingly that there were no organic compounds above the one part per billion level in the upper few centimeters of the surface. The landers also reported on the extreme environment of Mars, with temperatures falling to –120°F (–84°C) at night. So, for a while, the debate subsided surrounding the position of Mars as the abode of life. Mars was seen

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FIGURE 3.8 JPL's Tim Parker with his contour map of the northern regions of Mars, showing the extent of a global ancient ocean. Photo by the author. See plate section for color version.

as a desiccated, dry desert, bombarded by ultraviolet radiation. But the spacecraft put into orbit – *Viking Orbiter* – and later missions, continued to show Mars as a past water world.

Ever so slowly, Mars began to wake again. My JPL coworker Tim Parker began to see evidence for global oceans on Mars in the distant past – vast shorelines encircling the smooth basins of ancient bodies of water. He compared remnant shorelines left in the vicinity of Lake Bonneville, the huge prehistoric lake that was the predecessor of the Great Salt Lake, and coastal environments in Antarctica. Clear analogies were there: Mars revealed remnants of debris flows that were deposited above upsloping terrain that looked like the shores of ancient oceans; there was evidence of boulders and rocks pushed by large masses of floating ice; and many craters had been eroded by water on their "seaward" sides. Parker put together a contour map of Mars to show the ancient global ocean covering its northern regions: it was miles deep, comparable to terrestrial oceans (Figure 3.8). Parker

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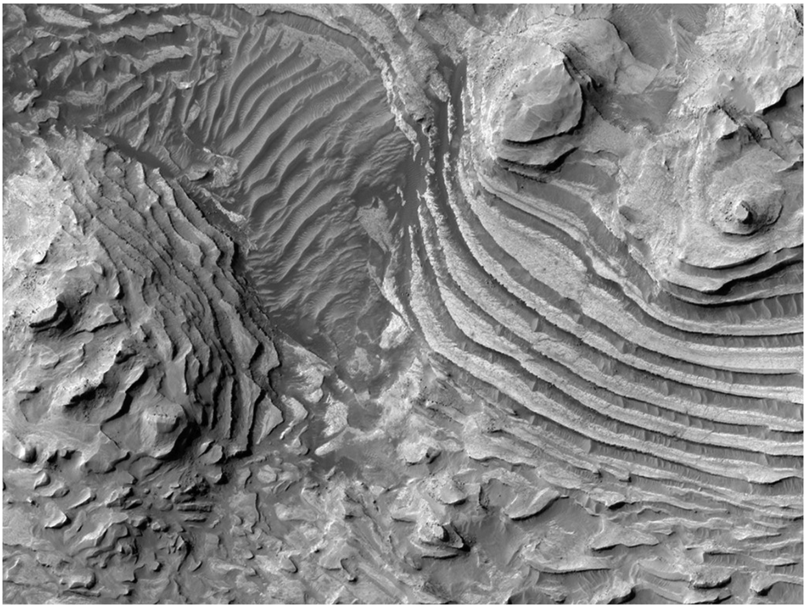

FIGURE 3.9 Sedimentary deposits in the Meridiani Planum region of Mars. NASA/JPL-Caltech/University of Arizona. See plate section for color version.

believes it was sustained by ice-rich impacting bodies brought to Mars during the Late Heavy Bombardment, which ended about 3.8 billion years ago. When the source stopped the water escaped because of the lower gravity on Mars. To quote Parker: "Earth and Venus hogged all the mass, so Mars became just a little bit more interesting than Mercury." As we shall see later, other scientists believe most of the water is still there, trapped in the martian crust. There is also a fair amount trapped in the polar caps: work led by JPL's Jeffrey Plaut showed that all the water in the caps could fill a global ocean nearly 40-feet deep.

Even if the global ocean hypothesis initially aroused some skepticism among scientists, orbiting spacecraft revealed extensive layered deposits, strongly suggesting successive deposits of sediments borne by liquid water. Figure 3.9 shows a spectacular image of such deposits returned by the HiRISE camera on the *Mars Reconnaissance Orbiter*.

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Scientists have speculated that life arose on Mars early in its history when it was warmer and liquid water was abundant. Life arose on the Earth almost as soon as it could, right after the subsiding of impacts by space debris during the period of Late Heavy Bombardment that stripped away the Earth's atmosphere and ocean. Mars dwells just outside that sweet spot of celestial mechanics: the "habitable zone" around a star where the temperature is just right for water to exist as liquid. Liquid water is the most important condition for life as we know it: NASA has coined the mantra "follow the water" to describe its search for extraterrestrial life. A planet's distance from its sun is the main factor in determining the temperature of the surface, but there are many others: does it have an atmosphere to hold in and buffer heat? Does it rotate sufficiently fast to prevent cycles of baking and chilling? Is its surface dark or bright (dark surfaces absorb more heat and are thus hotter)? Does its atmosphere possess the heat-trapping greenhouse gases such as carbon dioxide and methane? The latter is what killed Venus's chances of being a tropical paradise: its runaway greenhouse effect has raised its surface temperature from a value very close to that of the Earth's to that of an Italian pizza oven (its slow rotation rate is also a problem). Also critical is a planet's size. Martian gravity is only 38% of the Earth's, so it is much easier for its atmosphere, including water vapor, to escape.

As conditions on Mars deteriorated to become the cold, dry desert of today, could any life forms that arose have "hunkered" down in a protected subsurface environment? Such "hunkerers" are abundant on Earth. Life persists in practically every inclement environment, from the bowels of the Earth – at least two miles down – to very salty, acidic, or boiling water, to the depths of Antarctica's oceans, subsurface lakes, and glaciers, and to the upper atmosphere. The Antarctic's frigid Lake Whillans, which lies under an ice sheet a half a mile thick, is home to thousands of different types of bacteria. Do similar "extremophiles" exist in hidden enclaves on Mars? There is good evidence that much of the liquid that once coursed over the surface of Mars has not even been lost to space but is stored as ice

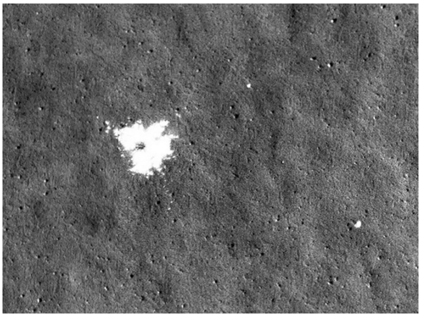

FIGURE 3.10 A fresh crater on Mars showing ice excavated from beneath the surface. NASA/JPL-Caltech/University of Arizona.

underneath its surface. For example, an image of a fresh crater on Mars obtained in 2008 by the HiRISE camera shows a massive excavation of subsurface ice, a possible habitat for primitive life forms (Figure 3.10). As we have observed more favorable conditions on Mars, possibly even ones that are habitable, the thrust of our research has moved into the search for primitive life forms, either alive or dead, as well as geologic evidence for past standing water.

Another path of revitalization for the search for life on Mars began in 1996 when the late David S. McKay of NASA's Johnson Space Center and his colleagues studied the martian meteorite ALH84001 and found several strands of evidence that pointed to life on Mars early in its history. This meteorite was found in Allan Hills, Antarctica, and the oxygen atoms trapped in its vesicles were identical to those found in the martian atmosphere, as measured by the *Viking* landers. Thousands of years ago, a large impact on Mars sent chunks of rock into a trajectory that eventually brought these pieces to Earth. McKay and his colleagues not only detected chemical traces characteristic of life in the rock, including complex hydrocarbons, and clay and magnetite deposits formed in ways similar to those produced by terrestrial bacteria, but there is what appears to be a fossilized bacterium that had once been on the surface of Mars (Figure 3.11).This intriguing fossil of so-called nanobacteria – creatures that are one-thousandth as thick as a human hair – were found along tiny cracks in the meteorite adjacent to the mineral deposits, cracks that could have supported running water. Each piece of evidence was not strong on its own

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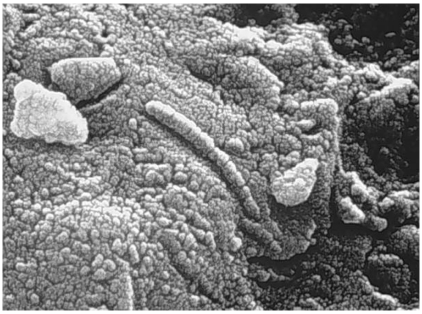

FIGURE 3.11 The martian meteorite ALH84001 showing a putative fossil of a tiny bacterium. NASA.

but, taken together, they provided a compelling argument that this meteorite from Mars once harbored primitive life. Soon on the heels of McKay's announcement, scientists began to criticize every argument. The chemicals were all due to geologic rather than biological processes, or they were terrestrial contaminants, said the naysayers. Furthermore, the nanobacterium – the existence of such creatures is even controversial on Earth – was just a mineral crystal. Even though most planetary scientists ended up on the side of skepticism, McKay's team's discovery energized the field of searching for life on Mars. Again, intelligent speculation and disagreement advanced science.

The series of rovers that trekked over the martian surface provided another key piece of evidence for past habitable environments on Mars: ground truth for sedimentary rocks and minerals that could only have formed in an evaporating ocean or lake bed (Figure 3.12). The tiny *Sojourner* and then the Mars Exploration Rovers, *Spirit* and *Opportunity*, and finally the daringly giant and sophisticated Mars Science Laboratory, *Curiosity* – which dug and delved through the patina of windblown dust that seems to coat everything on Mars – uncovered unmistakable evidence for evaporate deposits: minerals formed in the presence of water. The Mars orbiters, *Mars Odyssey*, *Mars Global Surveyor* (MGS), and the *Mars Reconnaissance Orbiter* (MRO), sent back stunning global views of these same minerals. Carbonates, magnetite, clays, and salts were all there, formed in the same way as they are on Earth, in the presence of water. Moreover, the layered deposits observed by *Curiosity* could only have been formed by

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FIGURE 3.12 Extensive sedimentary formations on the surface of Mars shown by the *Curiosity* rover. NASA/JPL-Caltech. See plate section for color version.

sediments set down on the bottom of a lake over tens of millions of years: these lakes were not transient or limited in scope. The driller on *Curiosity* uncovered hematite, a mineral usually formed from an aqueous solution, and which *Odyssey* and *Global Surveyor* showed covered extensive regions on other parts of Mars. Hematite was also found by *Opportunity*, much of it in the shape of "blueberries" or spherules that are formed in solution with water (see Figure 3.13; "Moqui marbles" from the Utah deserts are formed in the same way). The global views provided by the Mars Orbiters, coupled with the ground-truth provided by the Mars Rovers and *Curiosity's* drill, completed the picture. Mars had a sustained watery past. As *Curiosity* Project Scientist, John Grotzinger of Caltech, says about the Gale crater that is the mission's stomping grounds: it is "a system of

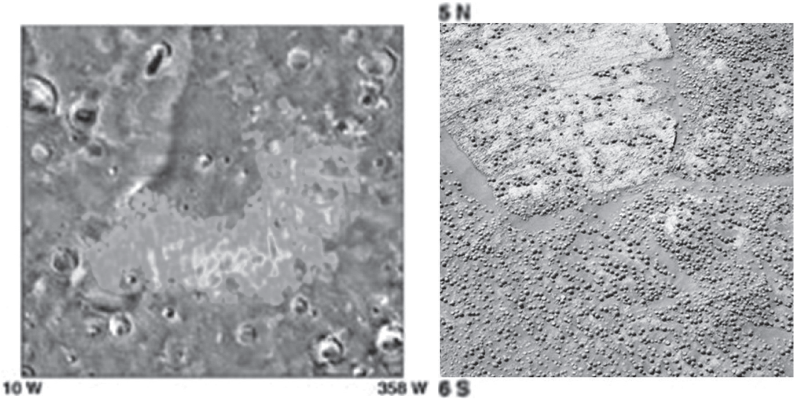

FIGURE 3.13 (Left) An image derived from data returned by the thermal infrared spectrometer (TES) on the *Mars Global Surveyor* showing extensive deposits of hematite, a mineral formed in the presence of water. Higher abundances are hotter colors. (Right) An *Opportunity* image of "blueberries," hematite concretions that are believed to form from watery solutions. NASA/JPL-Caltech/Arizona State University. See plate section for color version.

alluvial fans, deltas, lakes, and dry deserts that alternated probably for millions if not tens of millions of years as a connected system" (*NY Times* Dec. 9, 2014: p. D6). Furthermore, all the elements for a habitable environment were in place: water, energy, and the prebiotic elements of carbon, hydrogen, oxygen, nitrogen, and phosphorus. The only missing element – at least as we know so far – is life itself.

But perhaps even more spectacular than the evidence for standing water early in the history of Mars was the discovery of active gullies on Mars. The HiRISE camera caught an image of deep gullies on the rim of Hale Crater, a typical example of the many found on Mars (Figure 3.14). Some show evidence for fresh and repeated flows, and they look very similar to gullies that form in the California deserts after periodic heavy rains and flash flooding. Scientists originally thought the gullies were formed by running water, as they are on the Earth. Perhaps these features provided the needed evidence for habitable regions near the surface – or even on the surface – of Mars. But the gullies did not form in the warmest regions of Mars:

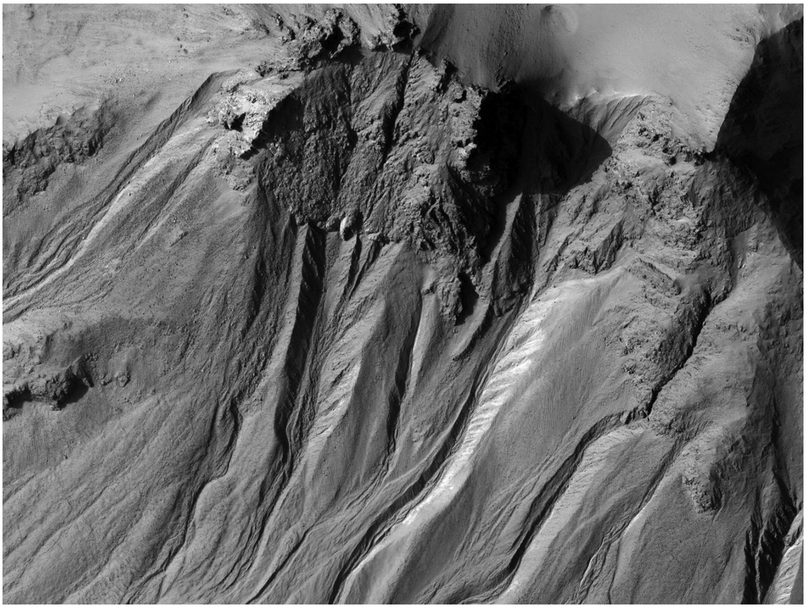

FIGURE 3.14 A HiRISE image of recent martian gullies in the Hale Crater. The image is 77 × 93 miles. NASA/JPL/University of Arizona.

the ambient temperatures were not nearly high enough to sustain liquid water. Some scientists thought that the gullies were formed by the successive freezing and thawing of carbon dioxide. The march forward to seek habitable environments on Mars was dealt a teasing glimmer followed by a setback. But then scientists found the presence of perchlorate – a salt – at the gullies. This martian salt acts as an antifreeze for subsurface ice, just as salt scattered on wintry roads melts the ice and snow. These gullies are a far cry from the canals of Lowell – but they are still intriguing and speak of a Mars with an active surface and abundant subsurface ice.

One of the most significant lines of investigation for possible life on Mars has been the elusive search for methane. Methane would not last long on the surface of Mars – ultraviolet light would destroy it after only a few years – so if it's there it must be continuously created. There are three possible sources for martian methane: volcanoes (or at least gentler outgassing from below the surface); chemical changes in

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minerals that produce methane; or life. Early life on Earth did not produce or need oxygen: terrestrial primitive bacteria thrived in oxygen-starved environments and often produced methane as their metabolic output. Thus, if methane is present on Mars, it would provide possible evidence for primitive bacteria similar to those extant on the early Earth. In 2003, two groups reported the presence of trace amounts of methane but, in 2013 the *Curiosity* rover didn't find any at all. Then just a year later, NASA announced the discovery of small amounts of methane (seven parts per billion, on average) on the surface of Mars. The presence of methane on Mars is sporadic! The most pedestrian explanation of chemical reactions in minerals or outgassing may win out, but it is quite possible that methane is a marker for methane-producing bacteria (methanogens, in biologists' lingo) yet to be discovered or, alternatively, active volcanoes. *Curiosity* will continue to monitor the presence of methane to solve this ongoing scientific puzzle.

No discussion of life on Mars would be complete without mention of the "Face on Mars" and its imitators, such as the "Inca City" and the "Airport." In 1976, the *Viking 1* orbiter imaged the Cydonia region on Mars, and a poorly resolved mesa appeared to have rough human features (Figure 3.15). Despite disavowal by all planetary scientists that the face was a relic of an intelligent race, a "Face on Mars" club of gullible fans arose, supported by books and "analysis." Nearby "pyramids" provided further "proof" that the face was the vestige of a past civilization on Mars.

These hoaxes – and more generally all forms of pseudoscience – follow common themes. First, they are sources of profit and fame for those who espouse them, as we saw for Velikovsky's wild claims about Venus. Whole industries have been built around pseudoscientific books and speaking gigs involving the Face. Another usual claim is that NASA and "government scientists" are covering up the truth. Whenever there is an encounter at Mars, a group of nutty protestors shows up at the entrance to JPL, protesting our secrecy. Even if a reasonable person could believe that thousands of maverick, itchy

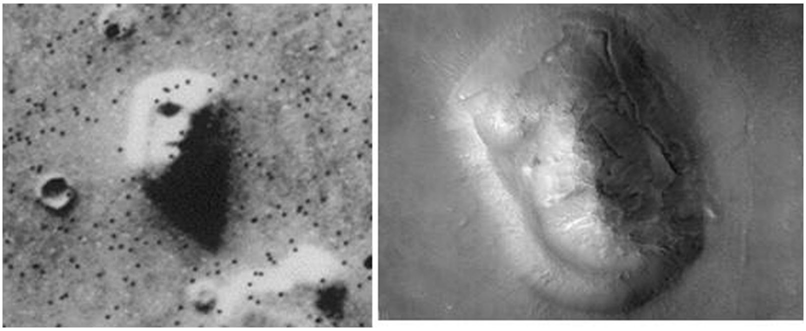

FIGURE 3.15 (Left) *Viking 1* image of a mesa in Cydonia with shadows that suggest human features (the black dots are data drop-outs). (Right) A *Mars Global Surveyor* image of the same mesa under much higher resolution, showing that natural crags and gullies are responsible for the humanoid features. NASA/JPL-Caltech/Malin Space Science Systems.

scientists would shut up, why should we? If we found even slight evidence for extraterrestrial life, our budgets would increase tenfold, or more. NASA didn't keep the research on the Mars meteorite ALH84001 secret, and in fact it rekindled interest in life on Mars (our budgets increased only slightly). Finally, the scientific method dictates that as evidence is gathered, one must modify models to fit the new data. No amount of evidence will convince the "Face" crowd and their intellectual kin that they are wrong. The *Mars Global Surveyor* obtained images of the "Face" showing it was a hill of eroded gullies and other natural irregularities. But the "Face" enthusiasts persist in their claims.

Other fanciful items found on Mars include an image taken by *Mariner 9* that mission scientists jokingly referred to as the "Inca City," but which seemed to have stuck in the public imagination as a "thing" (Figure 3.16). When scientists looked at the "big picture" they noticed that the "city" was actually a maze of cracks created by a giant impact crater. The most likely explanation for the formation of the city – the "Occam's razor" explanation – is the infilling of cracks by lava and the subsequent wasting away of less resistant surrounding rocks. An "Airport Terminal" (Figure 3.16), also imaged by

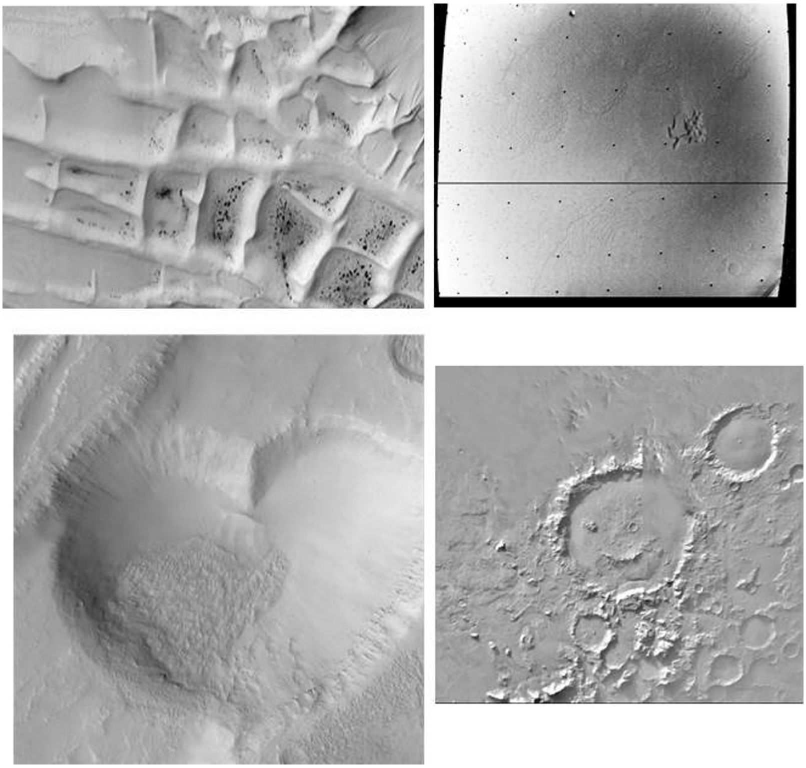

FIGURE 3.16 Fanciful images from Mars. At the top left is the "Inca City," originally observed by *Mariner 9* and shown here through the eyes of the camera on the *Mars Global Surveyor*. The top right shows the original *Mariner 9* image of the "Airport Terminal" (the black dots are fiducial marks, not landing airplanes). At the bottom left is a heart-shaped crater, perhaps formed by an irregularly shaped asteroid, and on the right is a smiley face, with "eyes" and "mouth" formed by smaller craters and ridges. NASA/JPL-Caltech/Malin Space Science Systems.

Mariner 9, which its fans claim has runways and parking areas for planes, is a collapsed lava tube or underground cave to the geologist's eye. So far, there are natural explanations for all the exotic features seen on Mars, but a small group of profiteers continues to publish books and give lectures on their obviously incorrect explanations.

Not to be outdone, and to anticipate and preempt some of the crackpot claims – and also to show we do have a sense of fun and romance – NASA scientists have sent out on purpose some of the fanciful features uncovered by spacecraft. For example, on one Valentine's day, NASA sent out an image of a heart-shaped crater on Mars, and later a smiley face (Figure 3.16). There is also a "Mickey Mouse" shaped crater on Mercury. Luckily we weren't sued by Disney, who guards the copyrighted image of Mickey jealously.

Even before the "Face" appeared in the public imagination, the idea of artifacts left by past civilizations on Mars had crept into the common mind. Mars has two moons, Deimos and Phobos ("Fear" and "Terror"), tiny objects that are possibly captured asteroids. In its family of moons, Mars is completely unlike that of the Earth. Phobos (Figure 3.17) orbits around Mars so rapidly that a Martian would see it rise and set three times each martian day, which at 24 hours 37 minutes is very Earthlike. As a 1959 April Fool's joke, the amateur astronomer Walter Scott Houston reported that Dr. Arthur Hayall of the University of the Sierras discovered that both moons of Mars were artificial satellites. (The professor and the school are both fictitious.) He based the claim on a putative decay in their orbits, suggesting they were hollow and thus artificial, possibly a vestige of a past civilization. The respected Soviet astrophysicist, Iosif Shklovsky, who in 1966 published the classic *Intelligent Life in the Universe* with Carl Sagan, didn't get the April Fool's joke – my Russian colleagues tell me the holiday is celebrated in Slavic countries, even during the Soviet period – and produced his own measurements and modeling that supported the hoax, which survived in one form or another for years.

With a little bit of scientific sleuthing, the broad history of Mars has been revealed. Mars even has its own geologic time scale to capture this history in a nutshell. The 4.6 billion year history of the Earth and of all life on it is described by the shorthand of the Geologic Time Scale, a listing of all the ages of our planet (many have passed into common use: pre-Cambrian, Jurassic, Cretaceous, etc.). Although to students on basic geology courses the scale seems like pointless memorization, it is really just a way of holding the world and

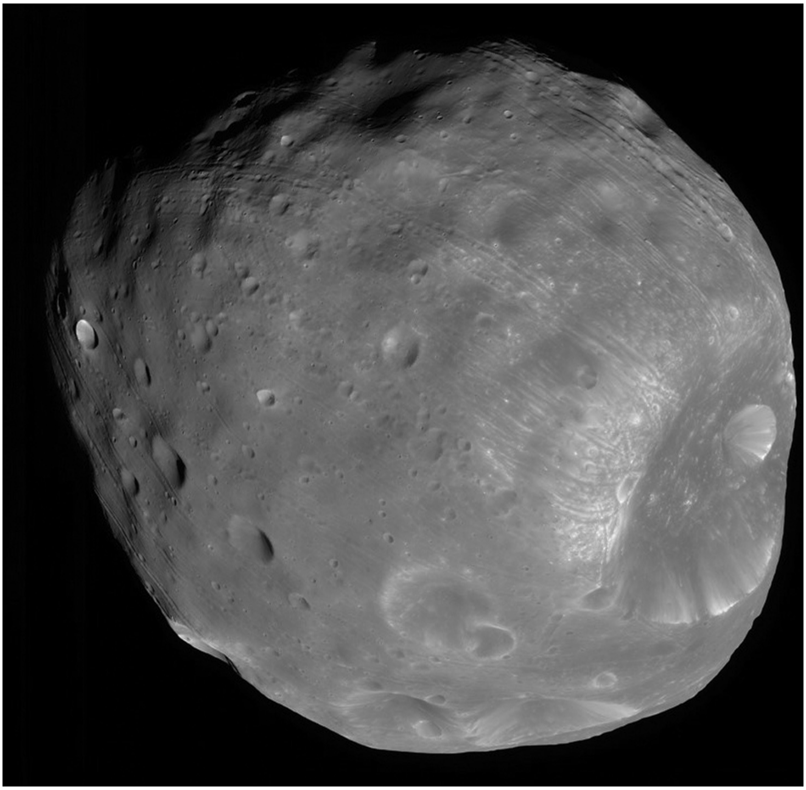

FIGURE 3.17 HiRISE image of Phobos, one of the two moons of Mars. It is 14 miles wide (Demos is 7.7 miles wide). The striations coming from the crater, named Stickney after Angeline Stickney Hall, the wife and collaborator of Asaph Hall, who discovered Phobos in 1877, may be related to it, or to tidal forces acting on the moon. NASA/JPL-Caltech/University of Arizona.

all that ever happened on it in the palm of your hand. To a scientist the word "Cretaceous" evokes tropical lands; "Silurian" just sounds like watery seas that were teaming with life, ready to crawl out onto the land; and "Pennsylvanian" had to have occurred when all that coal was formed.

Mars's geologic time scale is sketchier than that of Earth, but it is also a shorthand method to scope out the main train of events that occurred on the planet. As on the Earth, the time periods are named

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after geographical regions that underwent key events that happened during that period. The earliest events in Mars occurred during the Noachian (named after Noachis Terra – Land of Noah), an appropriate name for a time when the planet harbored abundant water on its surface. The Hesperian period (named after Hesperia Planum, Plain of the West, from one of Schiaparelli's original names) lasted from 3.7 to 3 billion years ago and was characterized by catastrophic flooding and volcanic activity. Finally, the Amazonian (named after Amazonis Planitia – Plain of the Amazons) was a period of increasing quiescence, as the gasping planet lost its water and its volcanoes went to sleep.

But Mars may surprise us yet. There is the teasing evidence that it may harbor extremophiles or other primitive life forms. Its volcanoes may come to life sporadically. Many scientists think that Mars possesses a tremendous amount of water in its crust – estimates range from 6 to 27% of Earth's amount, which is vast if one considers Mars has only 15% of Earth's surface area (but about 50% of its *land* surface area). Over thousands of years, the tilt of the rotational axis of Mars changes drastically – it has no large moon like ours to temper the irregular wobble of its axis – so that sunlight on previously frozen terrain may release ice and even water. But then there are the martian dust storms that dwarf anything on Earth (these storms are probably what Lowell mistook for the advance of green vegetation in the martian spring), the dust devils and dunes, bone-cold frigidity, and an atmosphere that is less than a hundredth that of the Earth's. Will all our teasing evidence for habitable zones, or microbial life, hold up only until the hammer of additional evidence comes down?

We have completed two phases of the exploration of Mars, and we are now on the cusp of the third. The first is that period that every astronomical body goes through: astronomers trying to tediously squeeze information from points of light or blurry disks with fuzzy features open to interpretation. During the current era of space exploration, especially with the rovers, we are studying Mars as a geologic world. We have come full circle: leaving the Mars of science fiction, but returning "to know the place for the first time," in the words of T. S. Eliot. But there will be a third stage in time yet to come: beholding Mars for its mythic beauty. The landforms of Mars look uncannily like those of the Canyonlands of southern Utah, first studied geologically by John Wesley Powell (1834–1902) after the Civil War. Everett Ruess (1914–1934?), the young artist, writer, and explorer who mysteriously disappeared in the Canyonlands in 1934, was the first non-Native person to appreciate this area for its beauty. Writing in a letter to a friend he says "the burning Sun beats down on silent, empty desert . . . long walls of sandstone mesas reach away into the distance, the shadows in their fluted clefts the color of claret. Before me the desert drops sheer away into a vast valley, in which strangely eroded buttes of all delicate and intense shadings of vermilion, orange, and purple, tower."[3] Future explorers will pen similar words as they peer out into the canyons, plains, and valleys of Mars. What we have learned so far places the planet far from the vision of Percival Lowell, but what we find in the future will be more wonderful as we continue our explorations. Poet-explorers of the future will accept Mars on its own terms, not as a "habitable body" fit to conform to our own ideas, but as its very own world. To quote Ruess again, "My burro and I . . . are going on and on, until, sooner or later, we reach the end of the horizon."[4]

NOTES

1 Wright, W. *Harvard's Secret Court*. 2006. St. Martin's Press.

2 Lowell, P. *Mars as the Abode of Life.* 1908. Excerpts from pp. 134–135.

3 Ruess, E. *On Desert Trails*. 2000. Gibbs-Smith Publisher. pp. 45–46

4 Ruess, E. *Ibid*. p. 8