Mars Globe

Sky & Telescope's Mars Globe, 3rd Edition

Produced in cooperation with NASA and the U.S. Geological Survey

SKY & TELESCOPE

NOTES AND SPECIFICATIONS

The *Sky & Telescope* Mars Globe is the result of a two-year collaboration with planetary scientists at the U.S. Geological Survey's field center in Flagstaff, Arizona. This 12-inch globe portrays the planet at a scale of approximately 1:22,250,000 (1 inch = 350 miles or 570 km). It includes about 140 feature names approved by the International Astronomical Union.

BASIC MARS DATA

Equatorial radius	3,396 km (2,110 miles)
Polar radius	3,376 km (2,098 miles)
Mass	6.42×10^{26} g (0.11 Earth's)
Sidereal rotation period	24.6229 hours ($24^h 37^m 22^s$)
Mean density	3.93 g/cm^3
Surface gravity	3.7 m/s^2 (0.38 Earth's)
Surface temperature	−125°C to 20°C (−195°F to 68°F)

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The Surface of Mars

Michael H. Carr

Figure 1. The Hubble Space Telescope obtained this sharp view of Mars in 2003, when the planet was slightly closer to Earth than at any time in the past 60,000 years. The bright area known as Arabia Terra (above center) is wedged between dark Sinus Merdiani at left and Syrtis Major at right. The large impact basin Hellas appears below them, to the upper right of the ice-covered south-polar cap.

We have long been fascinated by Mars. Its red color, periodic brightenings, and slow looping movements across the starry background make it particularly distinctive in the night sky. But during the last 200 years our fascination with Mars has been stimulated largely by the prospect that life may exist there — and by the certainty that it will be the first planet to be visited by humans.

Our perception of Mars has changed greatly over the past century. In the early 1900s it was widely believed that advanced civilizations had developed there and that long linear markings, seen by many observers, were canals built to transport water from the poles to the parched equatorial deserts. As the 20th century progressed, belief in intelligent life dimmed considerably — yet even as late as the early 1960s, maps of Mars prominently portrayed canals and oases. In addition, many astronomers continued to believe that seasonal changes in the planet's surface markings *(Figure 1)* could be due to changing vegetation patterns.

This perception of a world hospitable to life changed dramatically in the 1960s, when we were able to determine Mars's surface temperature and when Mariner 4 flew by the planet and returned the first close-up pictures. These revealed an apparently lifeless, cratered landscape somewhat resembling that of the Moon, an impression seemingly confirmed by the subsequent flybys of Mariner 6 and 7 in 1969. Our perception changed again in 1971, however, when Mariner 9 reached Mars and went into orbit around it. Contrary to earlier explorations, this spacecraft revealed the complex, very *un*-Moonlike planet that we know today. Most surprising of all was the observation of ancient, dry riverbeds, which suggested that, despite today's extremely cold temperatures, the surface had warmer conditions and abundant liquid water in the past.

In 1976 twin Viking landers safely reached the surface. Although their complex life-detection instruments failed to detect any present or past biological activity, the mission's accompanying orbiters found abundant evidence confirming the former presence of liquid water, an essential requirement for life.

Subsequently, an unexpected source of new information about Mars came to light. Several researchers suggested that a handful of meteorites found on Earth had come from Mars, a suspicion confirmed when gas trapped in the meteorites was found to have isotopic and chemical compositions identical to the Martian atmosphere's as measured by Viking. More than 50 of these Martian meteorites have now been recognized. One of them, designated ALH84001, differs from the others in being very ancient — more than 4 billion years old. In 1996 NASA researchers announced that they had found microscopic structures, organic molecules, magnetic particles, and carbonate minerals in this meteorite, which taken together, they claimed, indicated a biologic origin. The consensus now is that all of these features have plausible nonbiological origins.

Nevertheless, the properties of ALH84001 indicate that conditions on early Mars were more Earthlike than they are today. This realization, combined with the recognition that life started very early on Earth, and that life forms thrive in conditions formerly thought uninhabitable, have enhanced the prospects that some form of life may have started on Mars and possibly even survived to the present in protected niches.

All of this has stimulated renewed interest in exploring

Mars, despite the fact that at present it's a dry, cold world very unlike the wet warm Earth. Mars Pathfinder reached its surface in 1997, Phoenix landed in 2008, and the twin rovers Spirit and Opportunity began their extended treks in 2004 *(Figure 2)*. Meanwhile, a small fleet of craft has been viewing the entire planet from orbit with a wide array of high-resolution instruments: Mars Global Surveyor (launched 1996), Mars Odyssey (2001), Mars Express (2003), and Mars Reconnaissance Orbiter (2005).

While many of the geologic processes that have shaped the Red Planet are familiar to us on Earth, the results on Mars are spectacularly different. Huge volcanoes have accumulated atop broad regional bulges. Extensive fault systems disrupt the surface. Vast canyons slice across the landscape. Episodic floods of enormous magnitude and widespread glaciation have modified large areas of the surface.

Why does the geology of Mars differ so much from that of Earth? There are three main reasons. First, Mars is much smaller than Earth (their equatorial radii are 3,396 km and 6,378 km, respectively). As a result, the Martian interior must have cooled relatively quickly after forming, thereby resulting in less volcanic activity than on Earth. Second, Mars has not experienced plate tectonics (the cyclic overturn of its crust). It therefore lacks analogs to many of Earth's most prominent features — great mountain chains such as the Andes and the Himalayas, deep oceanic troughs, and mid-oceanic ridges, all of which form at plate boundaries.

Third, Mars's very thin atmosphere and its distance from the Sun (1½ times Earth's) keep surface temperatures very low, averaging −60°C (−76°F) at the equator and as low as −125°C (−195°F) at the poles. These low temperatures have inhibited the activity of liquid water, resulting in low erosion rates for most of Martian history and the survival of very ancient features on the surface. Still, the presence of some water-worn features indicates that Mars experienced episodes of warmer conditions in the past, particularly very early on.

Figure 2. The exploration of Mars is now being conducted both from orbit and from the planet's surface. This ground-level view from the rover Spirit shows an outcrop in the Columbia Hills, located inside 160-km-wide Gusev crater. These rocks have been highly altered over time by sulfur-rich, aqueous fluids. In contrast, younger, fresher-looking basalts sit atop the surrounding plains.

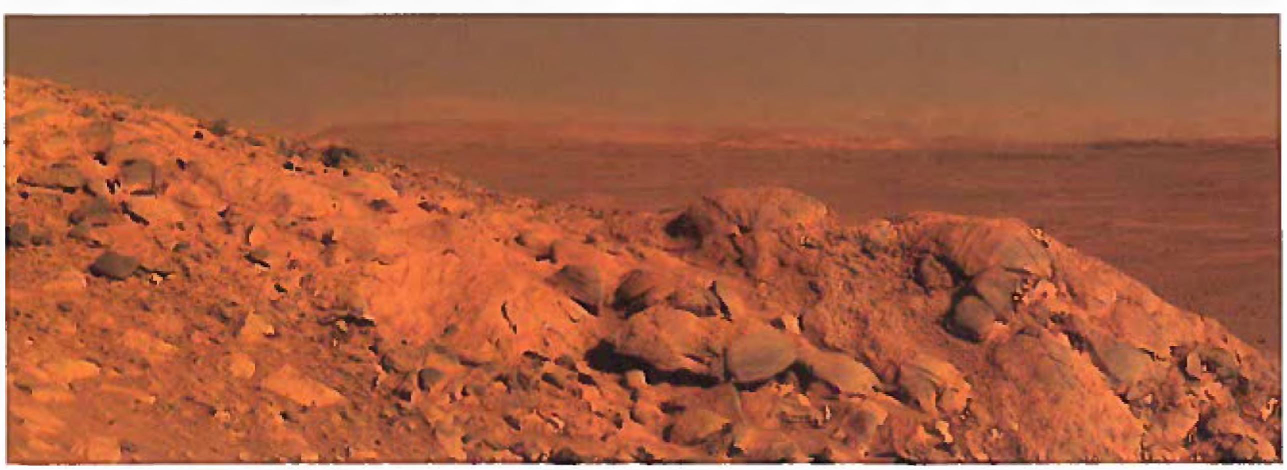
Let's take a closer look at the planet's landscape by expanding on these geologic themes.

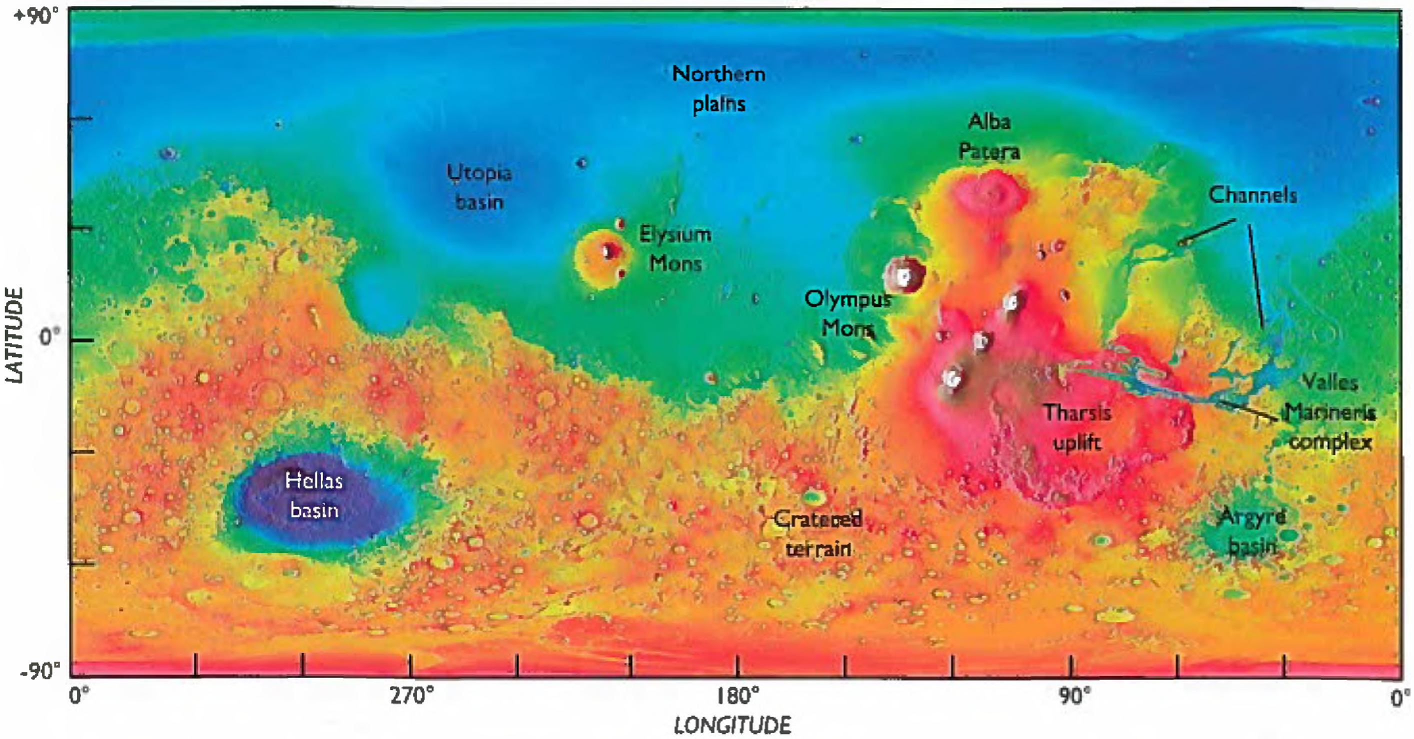
CRATERED HIGHLANDS

A remarkable aspect of the Martian surface is the distinct asymmetry, or dichotomy, between its northern and southern halves *(Figure 3)*. Almost the entire southern hemisphere is high-standing and heavily cratered, while much of the northern hemisphere is topographically low and sparsely cratered. The average elevation difference between the two hemispheres is 6 km. Why is this so?

We know that the Moon, and by implication the entire inner solar system, experienced an early period of heavy meteoritic bombardment that ended around 3.8 billion years ago, after which the cratering rate was very low. The southern highlands of Mars are heavily cratered and thus must have survived from this early era. Several large impact basins stand as testament to the intensity of the bombardment. Hellas, the largest of these, is roughly 2,200 km across. Its formation would have had devastating environmental effects, heating the young planet's surface by hundreds of degrees and depositing tens of meters of molten rock over the entire globe. The current consensus is that the hemispherical dichotomy on Mars was likewise caused by a gigantic impact very early in the planet's history. The collision created an immense crater that encompassed much of the northern hemisphere and has since been partly filled with younger materials.

Martian impact craters differ from those on the Moon. Lunar craters typically have coarse, hummocky ejecta (material thrown out by each impact) close to the rim. In contrast, the ejecta around most Martian craters is deposited as thin sheets, each with a rounded outer margin clearly defined by a low ridge *(Figure 4)*. The pattern resembles what happens when pebbles are dropped into mud — an apt analogy, because many geologists think that the distinctive patterns around Martian craters resulted because of water or ice in the ground at the time of impact. The water-infused ejecta continued to flow outward after being deposited on the ground around the crater. In support of this idea, we see numerous places where the ejecta has flowed around obsta-





cles that were in its path. An alternative explanation is that the distinctive patterns around Martian craters results from the ejecta's interaction with the atmosphere.

Observations by the Spirit rover in Gusev crater (184.5°W, 14.5°S) and spectral observations from orbit reveal that the highland rocks are complex. Unaltered rocks, mostly variants of basalts, are interbedded with pulverized deposits called megabreccias that formed by large impacts and sediments. Most of the rocks have undergone some aqueous alteration, which has reduced some of the rocks at Gusev to soft, spongy remnants. Detection by orbiting spacecraft of hydrated clay minerals in many highland locales is a further indication of the warm, wet conditions on early Mars under which chemical weathering could occur. Clay minerals are not detected in younger terrains except where impacts have unearthed the underlying older materials.

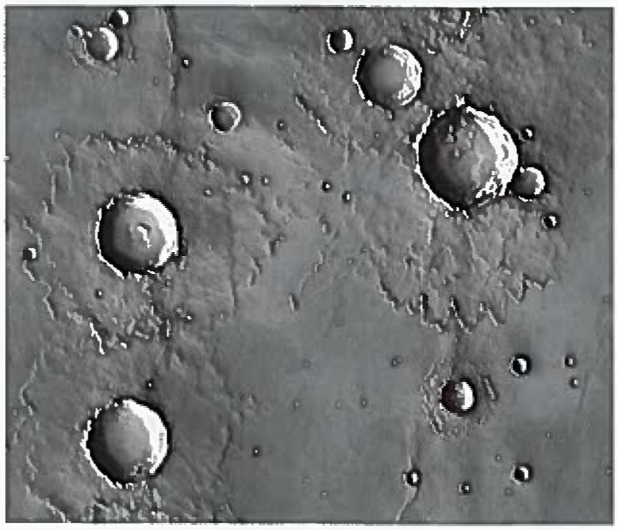
PLAINS

Extensive plains dominate Mars's northern hemisphere and also occur in isolated, low-lying patches in its southern half. They differ from the highlands mainly in being sparsely cratered. Therefore, they clearly postdate the period of heavy bombardment but have a wide range of ages. The most heavily cratered plains, such as those of Lunae Planum, probably formed more than 3½ billion years ago — shortly after the end of heavy bombardment. By contrast, some very sparsely cratered plains in and around Tharsis are probably less than 100 million years old.

Many of the equatorial plains, particularly those in the volcanic regions of Tharsis and Elysium, consist of enormous lava flows stacked one on top of the other *(Figure 5)*. In some areas flows are not visible, but numerous ridges like those on the lunar maria are present; such plains also

Figure 3. In this portrayal of Martian topography, reds and yellows denote high areas while blues and greens show low areas. Note the striking dichotomy between the planet's cratered highlands to the south and the low-lying sparsely cratered plains to the north. The hemisphere at right is dominated by Tharsis, a huge volcanic pile upon which sit the planet's tallest volcanoes. The vast canyons of Valles Marineris extend eastward from the center of Tharsis. The most prominent feature in the other hemisphere is Hellas, a 2,200-km-wide impact basin. Just north of the equator is the volcanic feature Elysium surrounded by plains.

Figure 4. Impact craters in Lunae Planum. As is typical of Martian craters, material ejected during each impact is arrayed in lobes outlined by low ridges. The pattern is very different from that around lunar impact craters — either because of the properties of the surface materials or because of the presence of an atmosphere. Although these craters are probably billions of years old they are almost perfectly preserved, implying extremely low erosion rates. The largest crater is 20 km across.



appear to be volcanic, though other origins are possible. On all of these plains, impact craters have the distinctive flow-ejecta patterns described earlier.

Many low-lying plains, particularly those at high latitudes, do not have the lava flows and ridges just described. They exhibit a wide array of landforms, such as polygonal fractures *(Figure 6)*, that closely resemble those seen in terrestrial permafrost and glaciated regions. Many of the northern plains are at the end of large flood channels (described later). Large bodies of water must have been left in the low-lying areas when the floods ended. Some scientists have proposed that Mars could have once had ocean-sized bodies of water, as evidenced by long linear features speculated to be shorelines. The bodies of water left after the floods probably froze rapidly to form massive ice deposits — hence the array of landforms that resemble terrestrial glacial features. Results from orbiting spacecraft and on the ground *(Figure 7)* suggest that water ice must lie close to the surface beneath large plains areas in the north and south polar latitudes.

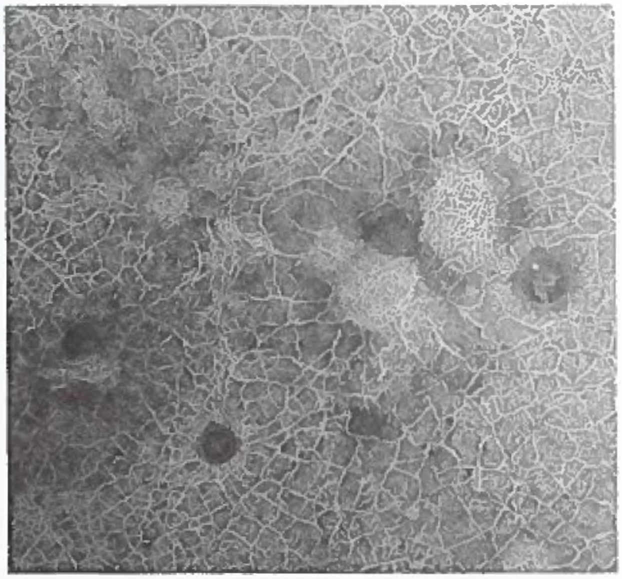


Figure 6. Many of Mars's high-latitude plains are imprinted with a polygonal fracture pattern (here highlighted by frost within the fractures). The polygons range widely in scale, from a few meters to 1 km across. On Earth patterns like these are found in permafrost regions containing ground ice. When temperatures fall in winter, the ice contracts and cracks into the characteristic polygons; in summer the openings fill with water or sand, then the process repeats the following winter. It's unlikely that these Martian cracks filled with water in summer, though the pattern nonetheless is a strong indicator that subsurface ice is present.

VOLCANISM

Among Mars's most impressive features are its volcanoes. Straddling the dichotomy boundary in the western hemisphere is the region called Tharsis, centered on the equator at 105°W *(Figure 3)*. Tharsis is a vast volcanic pile roughly 4,000 km across and 10 km high at its center. Although this pile, commonly called the Tharsis bulge or plateau, appears to have largely accumulated by the end of heavy bombardment, the region has been the focus of much of the volcanic activity for the planet's entire history. The enormous mass of Tharsis has deformed the crust, resulting in a vast system of fractures radial to the bulge. The largest volcanoes are on or at the edge of the bulge, and the bulge's surface is comprised mostly of lava flow on lava flow, many of them so crater-free as to suggest geologically recent eruptions. A much smaller bulge in Elysium (25°N, 210°W) with smaller volcanoes — though still large by terrestrial standards — has also been the site of at least intermittent volcanic activity throughout the planet's history.

On the northwest flank of Tharsis are three large volcanoes (Arsia Mons, Pavonis Mons, and Ascraeus Mons), and just beyond its northwestern edge is Olympus Mons, the tallest volcano on the planet *(Figure 8)*. All four volcanoes are enormous. The main edifice of Olympus Mons is 550 to 600 km across, rises up to 24 km above its surroundings, and is outlined by a cliff over 8 km high in some spots *(Figure 9)*. To the north of Tharsis lies Alba Patera, which though only a few kilometers high is more than 1,500 km across. For comparison, the largest volcano on Earth — Hawaii's Mauna Loa — is 120 km across at its base and has a summit "only" 9 km above the ocean floor.

Olympus Mons and its like-size siblings resemble large terrestrial shield volcanoes such as those in Hawaii. Each

Figure 5. Most of the plains of Tharsis consist of lava flows stacked one upon another. Here a 4-km-wide flow, which erupted from the flanks of Pavonis Mons then spread over the adjacent plains, runs diagonally through the image. In the middle of the flow is a vaguely outlined channel that transported lava to the flow front. The flows resemble those seen on the flanks of large terrestrial volcanoes, but most are much larger and imply higher eruption rates. Illumination is from the left.

has a large summit pit, or caldera, and numerous long flows and leveed channels cascade down its flanks. The main difference between the Martian edifices and their counterparts on Earth is size. Martian summit calderas are 10 to 100 times wider than terrestrial ones, probably because larger magma chambers lie beneath the summits. The flank flows and associated features are likewise 10 to 100 times longer; Mars's lower gravity may play a role here, but it appears that the rate and volume of the young planet's eruptions were simply much higher than those on Earth.

The large size of the volcanoes themselves probably results mainly from the lack of plate tectonics on Mars. Hawaii's shield volcanoes have relatively brief active lifetimes because the Pacific plate on which they stand is constantly moving to the northwest. Once separated from its magma source in the mantle, below the plate, a Hawaiian volcano falls silent and a new one forms to its southeast. The result is a line of ever-older extinct volcanoes that stretches northwestward from Hawaii across the Pacific Ocean.

In contrast, volcanoes on Mars remained over their mantle sources and continued to erupt and grow as long as magma was available. Compared to elsewhere on Mars, few impact craters are superimposed on the large shield volcanoes in Tharsis and Elysium, which suggests that these mountains' current, topmost surfaces are relatively young. However, evidence from surrounding flows suggests that the volcanoes have been accumulating for much of Martian history. Thus the planet's large shield volcanoes might actually be quite old, despite their young surfaces.

Not all Martian volcanoes have shield shapes. Some have relatively little vertical relief. Alba Patera has already been mentioned; others are found close to the large impact basin, Hellas. Tyrrhena Patera, northeast of Hellas, is very different from any of the volcanoes so far discussed. It is surrounded by deeply eroded, stratified deposits. Most probably, the eruptions of Tyrrhena Patera consisted primarily of ash rather than lava. In this respect, the volcano more resembles Mount St. Helens than Mauna Loa. Other volcanoes in Tharsis *(Figure 10)* are puzzling in that their flanks exhibit numerous fine channels that could have been carved by water, lava, ash flows, or some other agent.

All of the known Martian meteorites are volcanic rocks, and the youngest of these solidified only 180 million years old. Geologically this is very young, implying that Mars is volcanically active today. However, because this activity now occurs at a much lower rate than it does on Earth, volcanic eruptions are likely to be spaced hundreds, even thousands of years apart — so we are unlikely to ever see one as it happen.

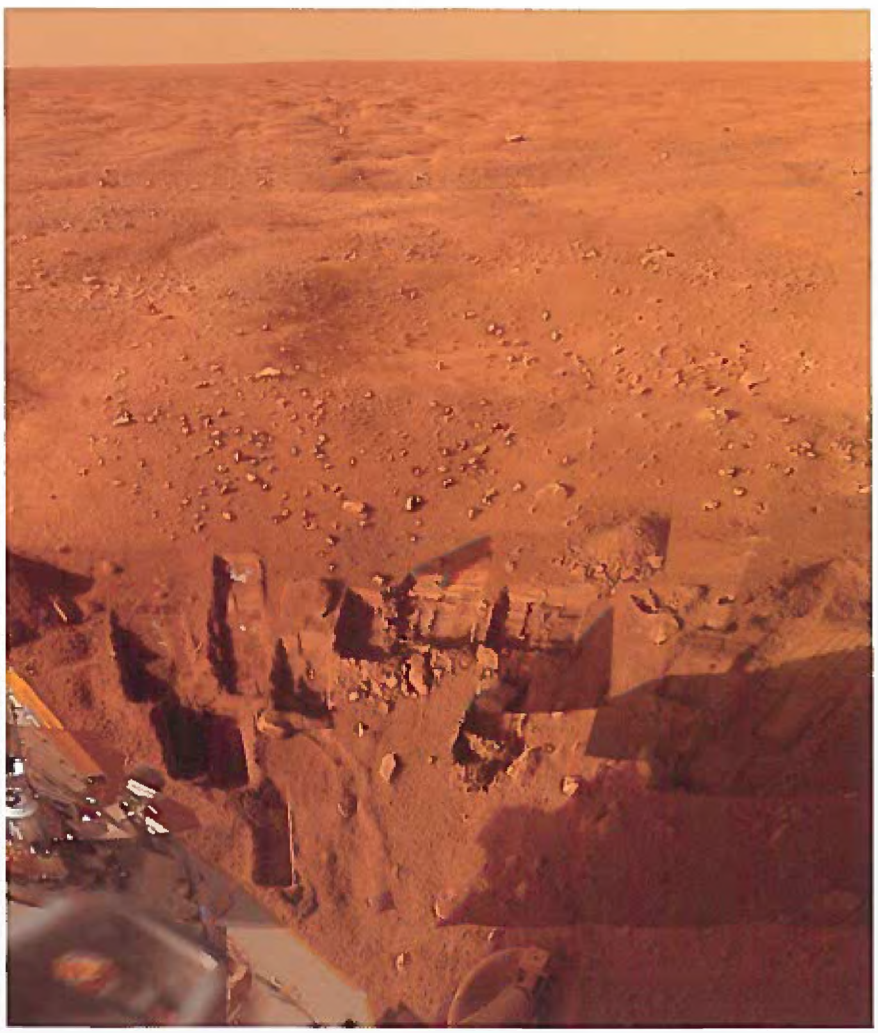


Figure 7. The landscape at left shows a polygonal pattern in an arctic plain near the north polar region of Mars. In the foreground are several trenches dug by the Phoenix lander. Although not obvious, this plain consists of a thin topping of dirt overlying a thick bed of water ice, as seen in the close-up above of some freshly excavated trenches. In fact, observations from orbiting spacecraft hint that water ice lies buried under vast tracts of the planet's north and south polar regions.

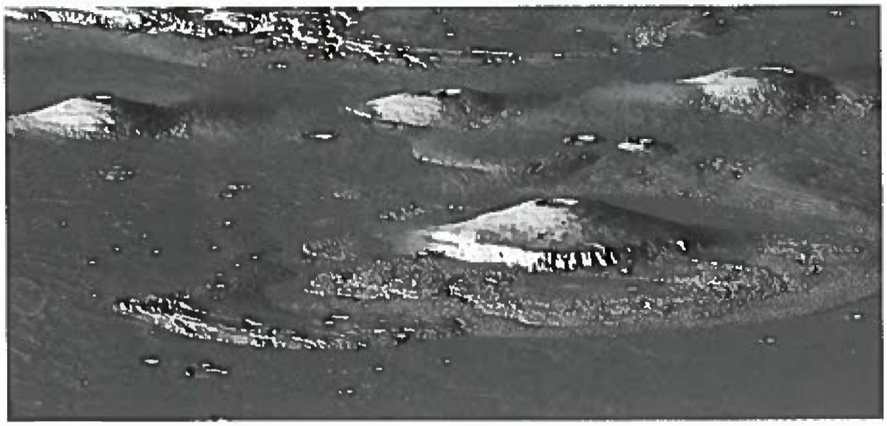


Figure 8. A topographic representation looking southeast across the Tharsis plateau, with vertical relief exaggerated three times. Olympus Mons (foreground) is 550 km across and 24 km (78,000 feet) high. The cliff along its base is itself 9 km (29,000 feet) high. Huge tongues of highly textured terrain, just visible in front of the cliff, were perhaps caused by a series of collapses of the volcano's outer flanks. In the distance are (left to right) Ascraeus Mons, Pavonis Mons, and Arsia Mons — all likewise huge volcanoes by terrestrial standards. Beyond them lies Valles Marineris.

CANYONS

To the east of Tharsis, just south of the equator, is a vast system of canyons collectively known as Valles Marineris *(Figures 11, 12, 13)*. The system begins in the west with Noctis Labyrinthus, at the summit of Tharsis, and extends about 4,000 km eastward until the canyons merge with areas of what is termed chaotic terrain (described later). Depths range from 2 km at the east and west ends to at least 9 km in the central section, where three parallel canyons merge to create a chasm more than 600 km wide. To the north is a large, closed canyon, Hebes Chasma, entirely isolated from the others. West of the central section the canyons are poorly graded and consist mostly of lines of mutually intersecting closed depressions. To the east the canyons are better graded and merge into large, seemingly water-worn channels with teardrop-shaped islands and streamlined walls.

Linear scarps, completely enclosed depressions, truncated spurs on the walls, and poorly graded floors together indicate that the canyons formed largely by faulting along fractures radial to Tharsis. They therefore differ fundamentally from large terrestrial depressions, such as the Grand Canyon, which form mainly by water erosion. However, while the dominant canyon-forming process on Mars was faulting, other processes played secondary roles. Deep branching side valleys in many places *(Figure 12)* and the streamlined islands at the eastern end are strongly suggestive of enlargement by water erosion. Elsewhere the canyons have been widened by enormous landslides.

One of the most intriguing aspects of the canyons is the presence, in places, of thick stacks of layered, sulfate-rich sediments. These are particularly common in Hebes Chasma and in the central section of the canyons where the Ophir, Candor, and Melas chasms merge. Although we have no ground-level views of these deposits, they probably resemble the sulfate-rich material explored by the rover Opportunity in Meridiani Planum. One possibility is that sulfate-rich groundwater episodically erupted into the canyons along the bounding faults, thereby creating lakes that later evaporated, leaving behind sulfate deposits. It has been suggested, further, that lakes within Candor and Ophir chasms drained catastrophically to the east. This would explain the pattern of erosion of

Figure 9. The huge shield volcano Olympus Mons covers an area the size of Arizona. Its peak is up to 24 km above the surrounding Tharsis plateau. At the volcano's summit is a conspicuous caldera, a complex nest of craters 80 km across. A caldera forms when magma rising toward the surface stalls and fills a chamber beneath the summit. Once the magma finally erupts, the chamber collapses, which enlarges the caldera. Long before spacecraft discovered its true nature, Olympus Mons and the clouds that frequently attend it were recognized by telescopic observers as a bright spot on Mars named Nix Olympica (Snows of Olympus).

Figure 10 (left). Not all the volcanoes in Tharsis are analogs to terrestrial shield volcanoes. Ceraunius Tholus (bottom of image) has a densely channeled surface with few visible flows. The channeling suggests that the surface is composed of easily erodible material such as ash. The cause of the channels is controversial. Possibilities include erosion by water and erosion by nuess ardentes — hot, dense clouds of ash. The outer flanks of the volcano are covered by younger lava flows, and the number of impact craters superposed on the volcano flanks suggests a surface older than those of the large Tharsis shield volcanoes. We may be seeing just the summits of two old, larger shields.

Figure 11 (right). The vast canyon complex called Valles Marineris splits Mars's equatorial region for more than 4,000 km. It begins at the crest of the Tharsis bulge with Noctis Labryinthus, the strange polygonal network at left (west), continues eastward as an interconnected series of enormous steep-walled rifts, and empties to the north at its east end in the dark-hued region known as Margaritifer Sinus. This view of Mars is not a complete hemisphere; it is the "fisheye" view that would be seen from an altitude of 2,500 km.

the canyon-floor sediments and the previously mentioned fluvial features common at the "downstream" (eastern) end.

Layered, sulfate-rich deposits, resembling those in the canyons, occur in several places in the highlands to the east of the canyons. The one explored by Opportunity is several hundreds of meters thick and buries more than 500,000 square kilometers of highland terrain. It consists mostly of sand and silt-size grains of basaltic minerals, silica, and sulfates left by evaporating brines.

The source or sources of all this sediment remain one of the greatest geologic enigmas on Mars. Because of the great number of layers and their relatively even thickness *(Figure 14)*, it is highly unlikely that they resulted from volcanic eruptions. More likely, these sediments were likely deposited by the wind (though some might have formed in rivers and lakes) during repetitive changes in climatic conditions due to cyclic changes in the planet's obliquity (spin-axis tilt).

CHANNELS

Most of Mars's large flood channels occur to the north and east of the giant canyons and converge on Chryse Planitia *(Figure 15)*. Many of the channels emerge from what geologists term chaotic terrain. These are areas of jostled blocks situated 1 to 2 km below the surrounding landscape and surrounded by an inward-facing cliff. They appear to have formed by collapse of the surface *(Figure 16)*. Some areas of chaotic terrain merge westward with the canyons; other areas are completely isolated from the canyons. Large channels emerge out of these chaotic areas and extend thousands of kilometers northward across Chryse Planitia until they merge with the low-lying plains at high northern latitudes. Other large channels emerge from box canyons to the north of the main east-west canyon complex. Some of the box canyons and chaotic depressions contain thick stacks of layered sulfate rich deposits like those in the canyons. All these channels emerge full size from areas of chaos and have few, if any, tributaries. They tend to be narrower and more deeply incised where they cross cratered highlands, broader and shallower where they cross plains. Their paths are easily recognized by scour marks and numerous teardrop-shaped islands *(Figure 17)*.

The abrupt beginnings, lack of tributaries, abundance of sculpted landforms, and strong resemblance to terrestrial flood features all suggest that these channels did not form

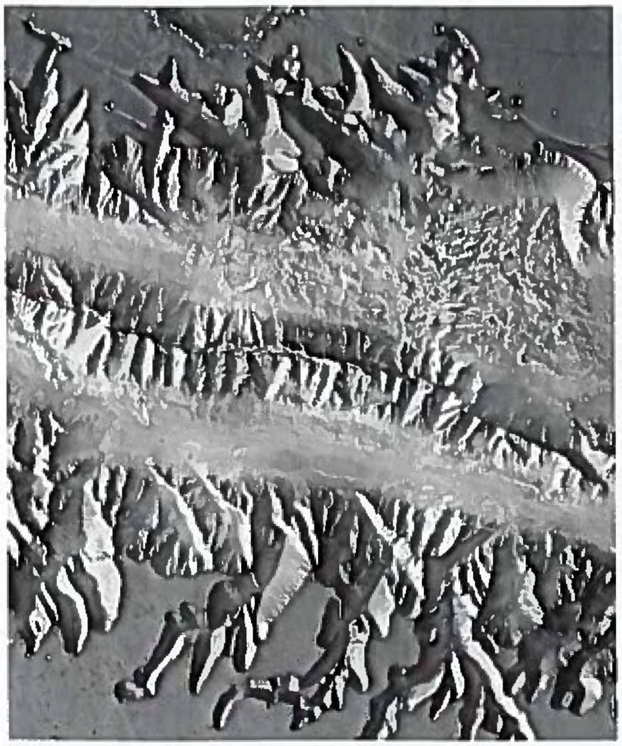
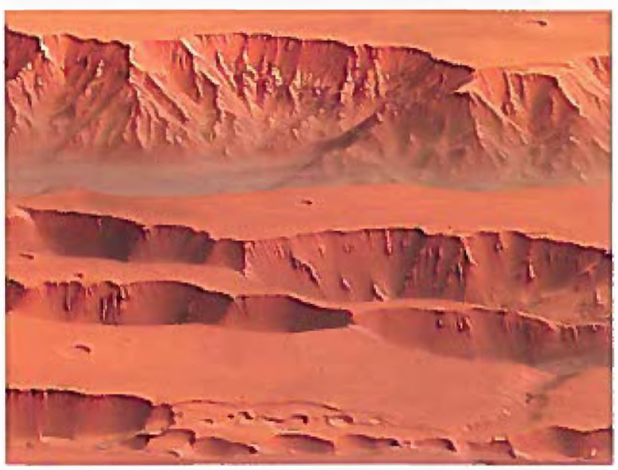


Figure 12. A 290-km-wide section of Ius Chasma. The canyon here is roughly 8 km (26,000 feet) deep. It consists of two down-faulted sections separated by a central spine. The south wall is deeply eroded to form side canyons that are comparable in size to the Grand Canyon in Arizona. Lack of deposits where the side canyons intersect the flat floor of the main east-west canyon suggests that the side canyons formed as the main canyon deepened. Although the main canyon probably formed by faulting, the side canyons more likely formed by water erosion. To the right the north wall has collapsed in a huge landslide.

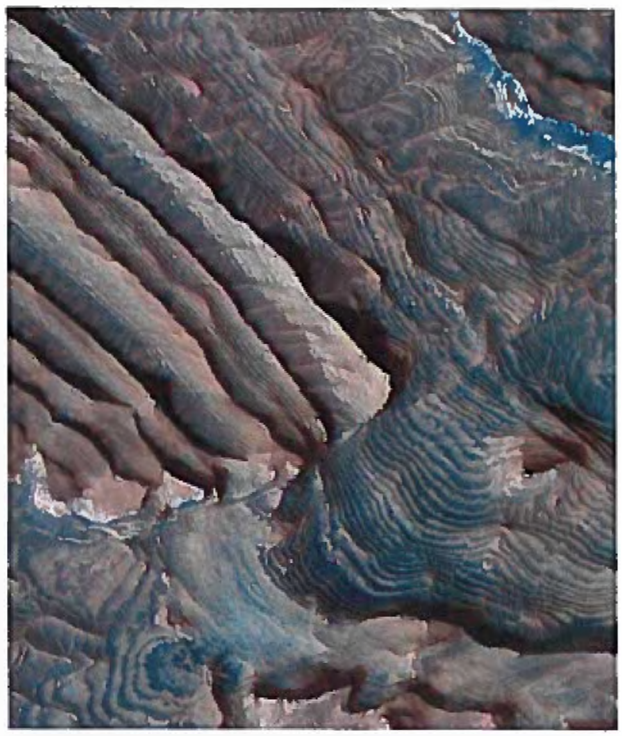
Figure 13. A perspective view of a portion of Coprates Chasma, the easternmost section of the Valles Marineris canyon system. The north wall, seen at top, reaches heights of 9½ km (31,000 feet) high, but the canyon becomes shallower toward the east (only 5 km deep). A long portion of the north wall is strikingly linear, which strongly supports the suggestion that the relief of the canyons was created largely by faulting. Farther east the canyons merge with large channels with streamlined islands. These observations suggest that the canyons on occasion contained lakes that drained to the east. In the foreground are chains of craters caused by collapse (much like sinkholes).



by slow erosion of running water but instead resulted from catastrophic floods. One of the largest floods known on Earth eroded the Channeled Scablands of eastern Washington State about 10,000 years ago. Numerous branching channels, tens of kilometers wide, are thought to have formed within a few days when a large ice dam collapsed, thereby releasing water from a large lake in what is now western Montana. Peak discharges in the Channeled Scablands floods were an estimated 10 million cubic meters per second, a thousand times the average discharge rate of the Mississippi River.

The Martian floods appear to have been even larger than those that carved the Channeled Scablands and likely had at least two causes. One, already mentioned, is the catastrophic release of water stored as lakes within the canyons; a second is catastrophic eruption of groundwater under high pressure. This is implied by the sudden emergence of large channels from local areas of chaotic terrain. If groundwater were trapped beneath a thick permafrost zone, pressures could have become so great that the water broke through the overlying seal. Rapid escape of water from the underground aquifer would have caused the host rock to disintegrate and be carried along in the flood; the surface then collapsed into the vacated volume, creating the chaotic terrain. Relative ages determined from crater densities indicate that most of the floods occurred 3 to 3½ billion years ago. However, a few events continued episodically until the recent geologic past.

Figure 14. Among Mars's greatest geologic enigmas is the deep, widespread layering that covers much of the planet. This false-color image shows rhythmic bedding inside Becquerel crater, located at 22°N, 8°W in Arabia Terra. The sediments consist of "bundles" of 10 layers, each about 3.6 m (12 feet) thick, which apparently result from 100,000-year-long swings in the obliquity (tilt) of the planet's spin axis that become especially pronounced every million years. These swings change the global energy balance, causing water and CO_2 to move into the polar regions and back out again.



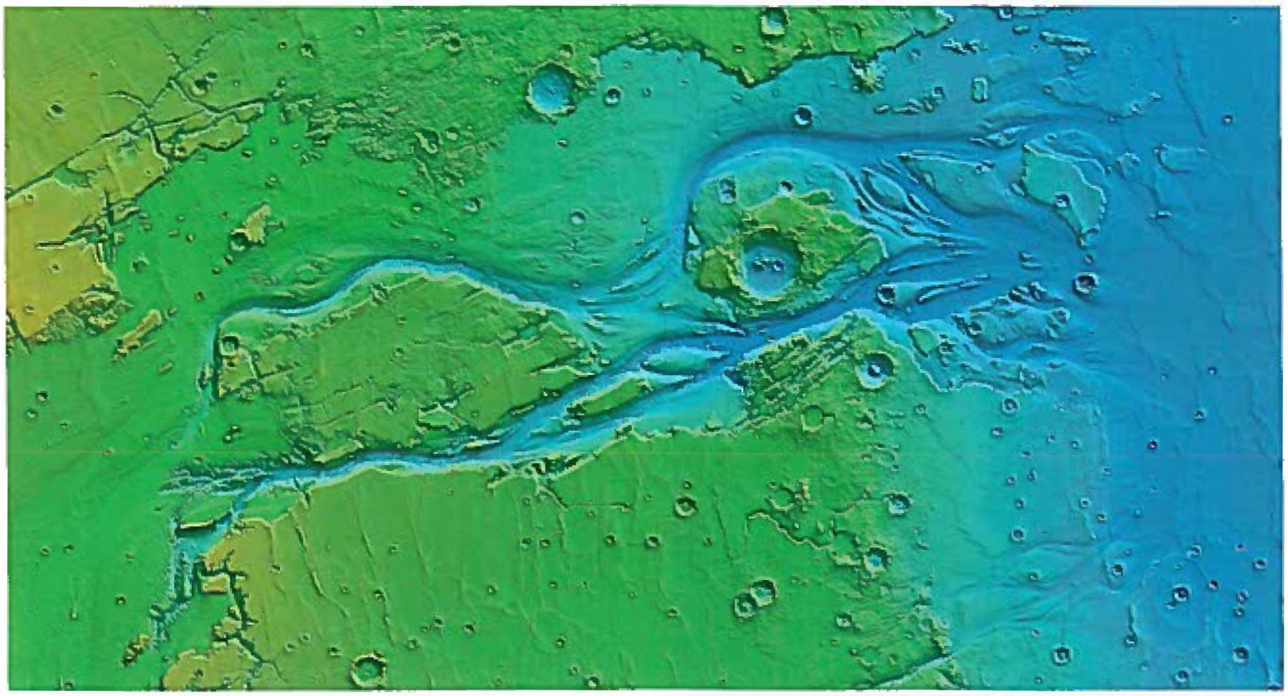


Figure 15. Kasei Valles, the largest system of outflow channels on the Red Planet. This topographic map is 1,800 km wide. The channel emerges from a broad, shallow, north-south depression, Echus Chasma, just off the image at lower left. It then splits into two branches up to 2½ km deep and cuts across Lunae Planum until it reaches Chryse Planitia, where the branches merge to form an eroded swath 600 km across, rich in sculpted landforms such as teardrop-shaped islands. Evidence of the flood can be traced another several hundred kilometers, off the image to the upper right, deep into the northern plains. Enormous discharges are implied by these dimensions, possibly more than 1,000 times the average discharge of the Mississippi River. The source of the water that cut this enormous feature is puzzling in part because its beginnings are hidden beneath young lava flows from Tharsis.

If the channels were formed by large torrents of water, then large volumes of water must have been left at their ends when the floods ended *(Figure 18)*. Geologists have looked for evidence of ancient oceans at the ends of the channels in the lowest lying areas of the northern plains. Some researchers point to linear features that might mark ancient shorelines; others point to muted impact craters perhaps partly buried by flood-borne sediments; and still others point to features that resemble those found under terrestrial glaciers. But the evidence for the presence of oceans or seas remains equivocal. Also puzzling is what ultimately happened to all the water that flowed through the channels. The planet's known water reservoirs, such as the polar deposits discussed later, are not large enough. So most likely the water is now underground, either as ice in the shallow subsurface *(Figure 7)* or as groundwater at greater depths.

VALLEYS

Branching valley networks, which are common throughout the ancient cratered highlands, differ from the flood channels in that they are much smaller, have numerous tributaries *(Figure 19)*, and increase in size downstream instead of starting abruptly. Many created delta-like deposits where they entered depressions *(Figure 20)*. Thus they are more akin to normal terrestrial river valleys. Most of the networks are more open than typical terrestrial valley networks, but clustering is not uncommon *(Figure 21)*. Although drainage densities vary greatly, valley networks are found almost everywhere in the cratered highlands but only in a few places on younger terrains. It appears that whatever process created them was more effective very early in the planet's history.

The striking resemblance of the valley networks to terrestrial river systems strongly suggests that they formed by slow erosion of modest-sized streams fed by rain or snow. Since such streams would freeze rapidly in Mars's current climate, so warmer conditions must have prevailed during the era when most of the networks formed. The discovery of alteration products such as clays in these ancient terrains supports the notion of more clement conditions. (In contrast, the floods described earlier involve such huge discharges and formed so quickly that freezing would be insignificant even under present climatic conditions.)

If a warmer climate did prevail very early in the planet's history, it did not last long, for the amount of fluvial erosion is limited and localized. While the oldest craters are heavily eroded, younger craters are not. Even delicate textures on craters billions of years old are preserved *(Figure 4)*. Moreover, individual trunk channels did not have time to extend themselves, capture streams from adjacent basins and thus control the drainage over large areas (as has occurred with the Mississippi and Amazon rivers, for example). The absence of large drainage basins on Mars indicates that fluvial action was either brief, very intermittent, or not truly analogous to what occurs here on Earth. Nearly all the available data — location of valleys on old terrains, patterns of

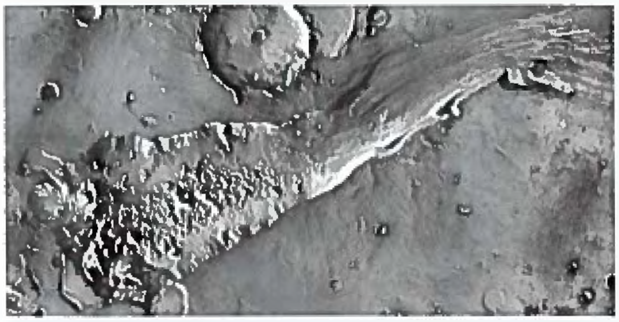


Figure 16 (top left). The source of the outflow channel Ravi Vallis. This 20-km-wide channel emerges full size from a rubble-filled depression, and there are no tributaries. Groundwater likely erupted under pressure and flowed eastward to cut the channel. The eruption was likely short lived, and the ground collapsed after the eruption to form the depression.

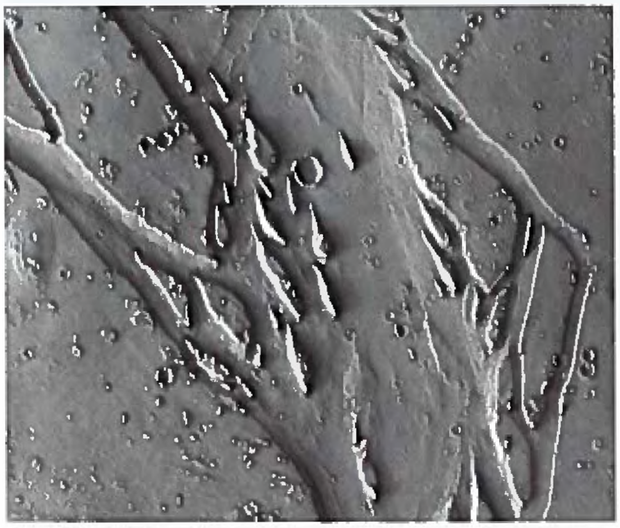


Figure 17 (center left). A cluster of water-carved islands in an outflow channel southwest of the volcano Elysium Mons. Flow was from the bottom northward. Teardrop-shaped islands such as these are common on the floors of many of the large outflow channels. They formed where divergence of flow around an obstacle, such as an impact crater, left a long tail pointing downstream and deeply scoured ground between the islands.

dissection, erosion rates, aqueous alteration — are consistent with an early warm, wet epoch followed by a cold era that has persisted for most of Martian history.

Frankly, we do not have a satisfactory explanation for the valley networks. Almost all researchers agree that these waterways formed by slow erosion from running water, as terrestrial river valleys do, and that warm conditions were required. The problem is achieving these warm conditions when the planet was very young and occasionally later on (to explain rare young valley networks). Climate modelers point to the difficulty of having warm conditions on early Mars because of the lower luminosity of the early Sun, and the poor greenhouse created by Mars's thin CO_2 atmosphere. Suggestions include large impacts (to inject water into the atmosphere and create temporary heating), eruption of greenhouse gases into the atmosphere during large volcanic events, and wide climatic swings caused by changes in the tilt of the planet's spin axis. Finding the answer(s) has important consequences for the possibility that life could have started on Mars.

Some water-worn features may be forming in the present epoch despite the cold conditions. Fresh appearing gullies are incised into many steep slopes such as crater

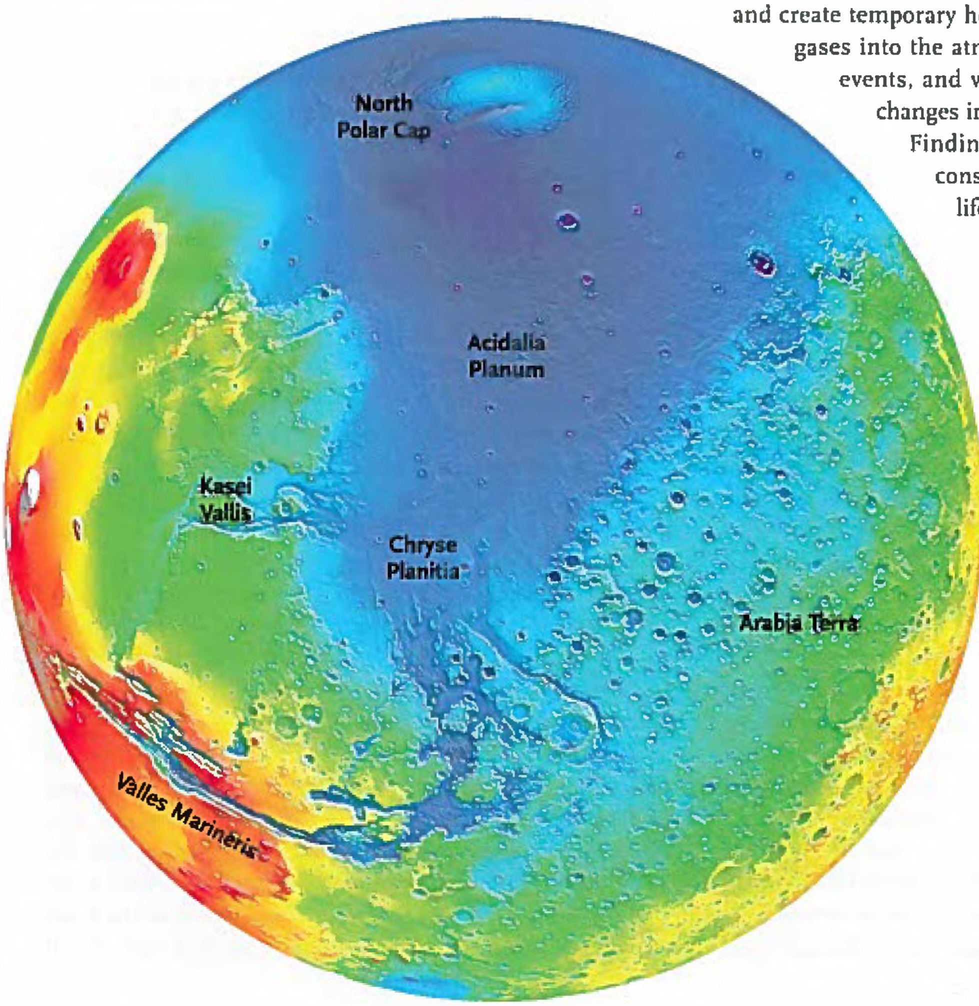


Figure 18. Orthographic view centered on Chryse Planitia at 30°N, 40°W. Valles Marineris (at lower left) transitions into chaotic terrain from which emerge several large channels that extend northward, merge with Kasei Valles, then fade away into the northern plains. Visible at the top are the layered terrains of the north pole. The water that cut the channels must have pooled in the low-lying areas, but the extent of the ponded waters, their lifetimes, and their fates are all unknown.

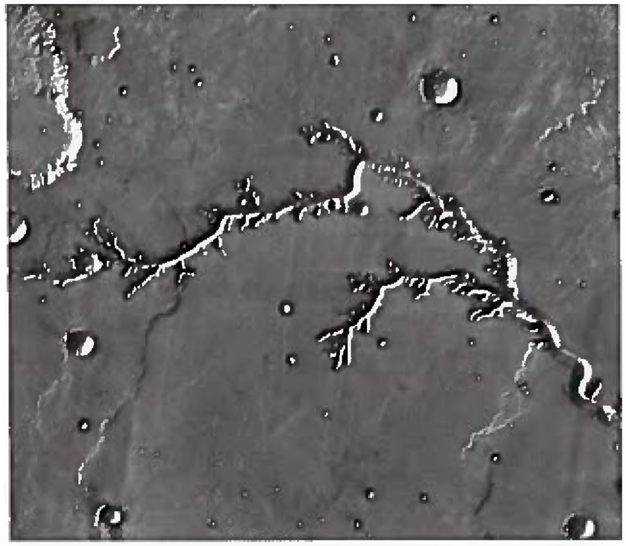
walls *(Figure 22)*. Most are meters to tens of meters wide and hundreds of meters long and have many characteristic that suggest they formed by erosion of running water. When they were first discovered, many geologists thought groundwater seepage might be the cause. But this now appears unlikely. Instead, a plausible possibility is that they result from the melting of snow that accumulates on slopes during periods of high obliquity (described in the next section).

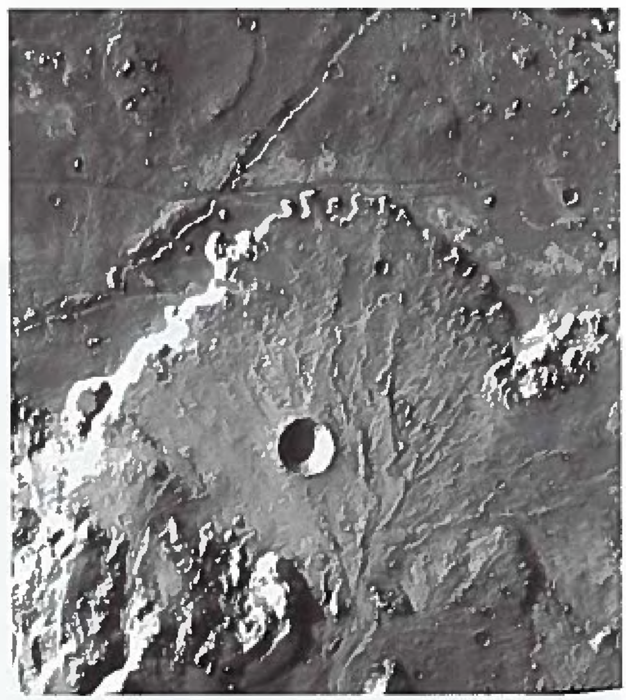
OBLIQUITY AND ICE IN THE POLAR REGIONS

At both poles a 3-km-thick stack of finely layered deposits extends outward from the pole to about the 80° latitude circle *(Figure 23)*. In the south they rest on the cratered highlands; in the north on plains. The layering is clearly visible around the edges of the deposits and in the walls of deeply incised valleys that curl out from the poles *(Figure 24)*. Infrared and radar observations show that the deposits consist almost entirely of water ice. The layering is caused by variations in the amounts of intermixed dust. The deposits bear few impact craters, indicating that they are geologically very young.

During Martian winter, carbon dioxide condenses at the poles to form a seasonal cap roughly 1 m thick. Because winter in the south is longer and colder, its cap grows larger, extending to the 45° latitude band and incorporating almost a third of all the atmospheric CO_2. As the two seasonal caps wax and wane *(Figure 25)*, carbon dioxide migrates back and forth between the two hemispheres. In the north the seasonal cap almost completely disappears in summer to expose a residual water-ice cap. In the south, a residual CO_2 cap remains even in midsummer, within which small patches of water ice lie exposed.

Away from the poles any water ice on the surface will tend to sublimate (change directly from ice to vapor) and then





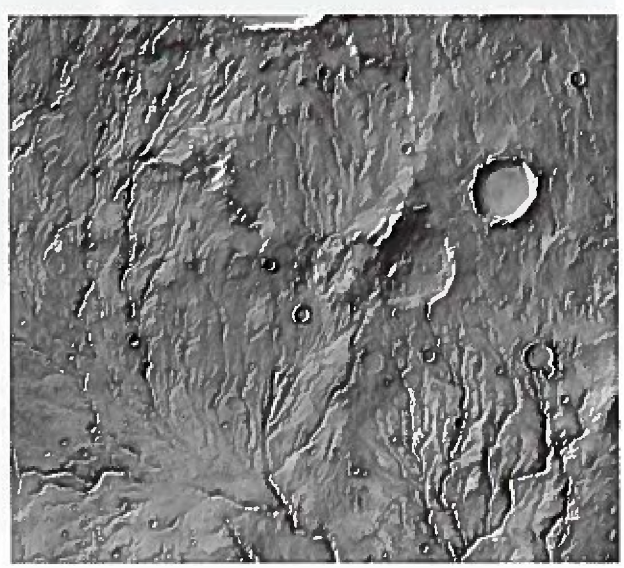


Figure 19 (top right). Nirgal Vallis, seen here, was the first branching valley network to be clearly seen from orbit. It is deeply incised into what is probably a lava plain and has tributaries that have abrupt alcove-like terminations, all characteristics of terrestrial valleys fed mainly by groundwater springs. The valley is somewhat unusual in that it cuts lava plains rather than heavily cratered terrain, which suggests that it is younger than a typical valley network. The large crater in the upper right is 25 km across.

Figure 20 (center right). A delta in Holden Crater (27°S, 34°W). A valley has cut through the south rim of the crater, just visible at the bottom of the picture, and deposited its sediment load as a 10-km-wide fan within the crater. At the time the crater likely contained a lake. Low ridges mark the paths of former channels across the delta probably because coarse debris on the former channel floors was resistant to erosion. Many such deltas are seen throughout the ancient highlands, particularly where channels cut through a crater rim. They suggest that lakes were common during the early era when the valley networks formed.

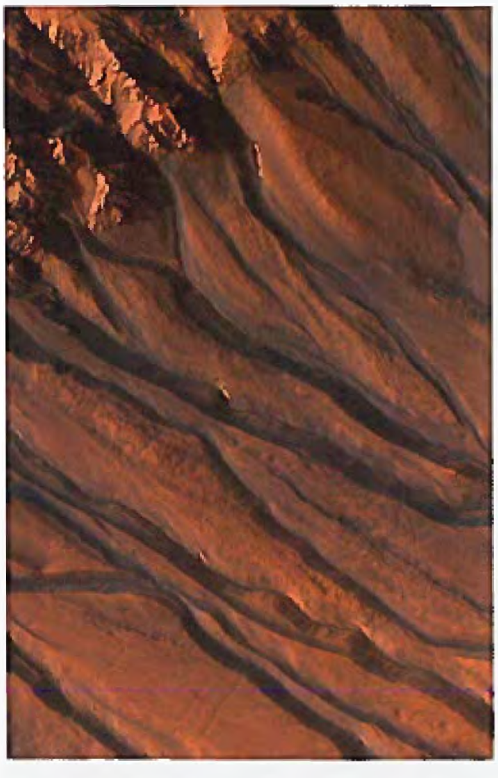
Figure 21 (bottom right). Warrego Vallis is one of the most densely dissected areas of the planet, and it contrasts markedly with the much more open drainage system of Nirgal Vallis (Figure 19). The close-spaced streams are unequivocal evidence of precipitation of rain or snow followed by surface runoff.

precipitate as ice at the poles. At equatorial latitudes ground ice is very unstable — even if it is buried well below the surface. At latitudes poleward of 30° to 40°, water ice sublimates where exposed but is stable just below the surface. We should expect, therefore, to find evidence for ground ice at high latitudes but not at low latitudes — and indeed we do. Orbital instruments have detected ice just below the surface almost everywhere at latitudes poleward of 60°, and the Phoenix lander found ice just below the surface at 68°N *(Figure 7)*.

A number of geologic features have also been attributed to the presence of ground ice. At latitudes of 30° to 50°, crater rims and other features tend to be more rounded and subdued than are those nearer the equator, and subtle flow lines suggest downslope movement of materials. A strong possibility is that the presence of ground ice at these higher latitudes enables this transport. In addition, in these same latitude bands, aprons of material extend tens of kilometers away from almost all steep slopes, as though the material had flowed away from the slopes. In places the aprons wrap around obstacles in their path or converge at gaps *(Figure 26)*. Ground-penetrating radar carried by orbiting spacecraft shows that the aprons consist almost entirely of water ice. They are, in effect, glaciers. However, their source remains controversial. Some researchers claim that ground ice was shed from the steep slopes and accumulated into the glacier-like features; others claim that the ice accumulated after precipitating from the atmosphere.

The stability of water ice on the Martian surface is sensitive to the obliquity (tilt) of the planet's spin axis. Earth's obliquity is essentially fixed at 23½°, but that of Mars can range widely over geologic time. Right now it is 25°, similar to Earth's, but in the past 10 million years it has ranged between 15° and 45°. Over longer time scales the obliquity might have exceeded 70°. At such high values, each pole faces the Sun continuously during the long Martian summer. As a consequence, ice would be driven from high latitudes and deposited at lower latitudes.

During periods of low obliquity, the process reverses, creating accumulations of ice at the poles. So as the obliquity swings between high and low values, the thick polar ice deposits periodically sublimate and reform (hence their young age). The polar layering seen today is probably is a record of changes in the obliquity in the recent past, much as tree rings provide evidence of Earth's seasonal cycles. Gullies on steep crater walls might also provide evidence for these climatic swings. During high-obliquity periods, ice



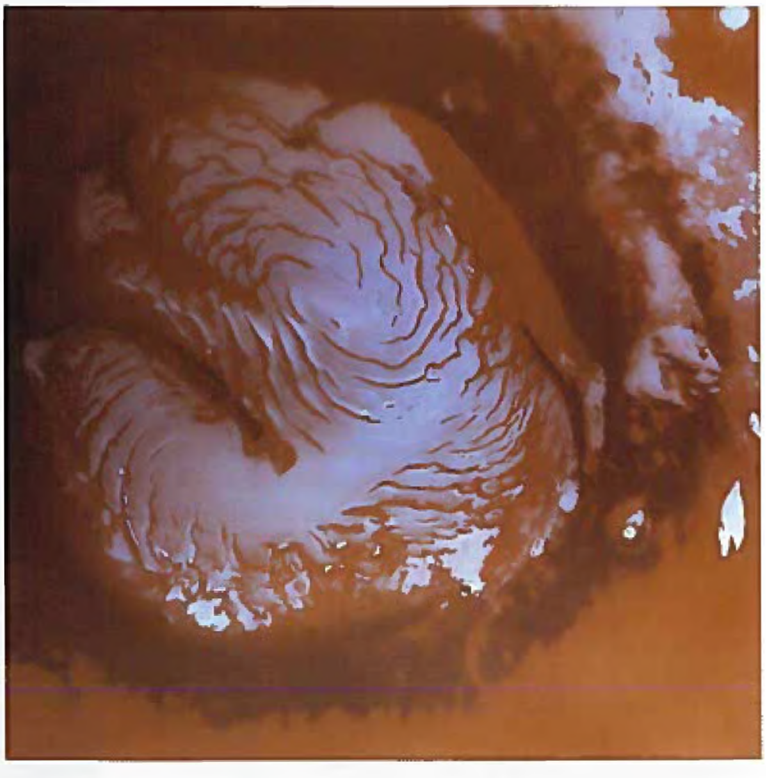


Figure 22 (left). Gullies cut into a crater wall in the southern highlands of Mars. The gullies emanate from the rocky cliffs near the rim's crest (upper left) and show meandering and braided patterns typical of water-carved channels. The origin of the gullies is controversial, however. While they appear to be cut by water, the planet's current climate makes the generation of enough liquid water to cut gullies very difficult. Alternately, it has been suggested that they formed by melting of snow and ice during periods of high obliquity.

Figure 23 (right). View looking down on the residual north polar ice cap, which is roughly 1,100 km (680 miles) across. It is surrounded by layered deposits that are up to 3 km thick and comprised mostly of water ice. Too fine to be seen in this image, the layers are exposed around the edge of the deposits and in the walls of deep valleys that spiral out from the pole. Surrounding the layered deposits is a vast dune field composed mostly of gypsum.

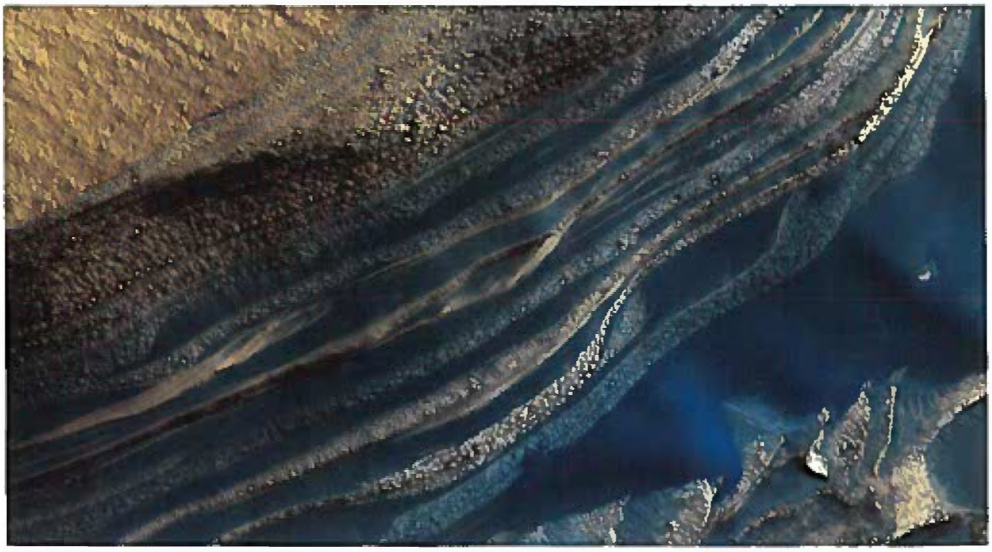


Figure 24. Chasma Boreale is a large canyon cut into the thick dust-and-ice layers that surround Mars's north pole. The fine-scale layering stands out especially well along the scarp seen in this false-color view. The layering is caused by variations in the amounts of dust intermixed with the ice as the deposits accumulated during periods of low obliquity when the mean annual temperatures at the poles are their lowest. During periods of high obliquity, ice sublimates away, thereby allowing the dust to be blown away.

might accumulate on shaded crater walls during winter and then melt in summer, creating enough liquid water to destabilize the slope and form a gully.

WIND

Although the atmospheric surface pressure on Mars is less than 1% that on Earth, wind is one of the few agents for change that can be seen in action. Many of the changes in the planet's surface markings, observed telescopically for centuries, are wind-driven: loose material is removed in dark areas, and it accumulates in bright areas. Even amateur telescopes reveal the local and global dust storms that periodically sweep across the planet's disk.

Now, with the benefit of detailed images from orbiting spacecraft, we see wind-formed features, particularly dunes, in almost all depressions such as craters and river valleys. In some areas, such as around the north pole and in Meridiani Planum *(Figure 27)*, vast dune fields extend for hundreds of kilometers. In other areas, the surface materials have been sculpted by the wind into streamlined forms. Dust devils have been seen from orbit and imaged by rovers on the ground.

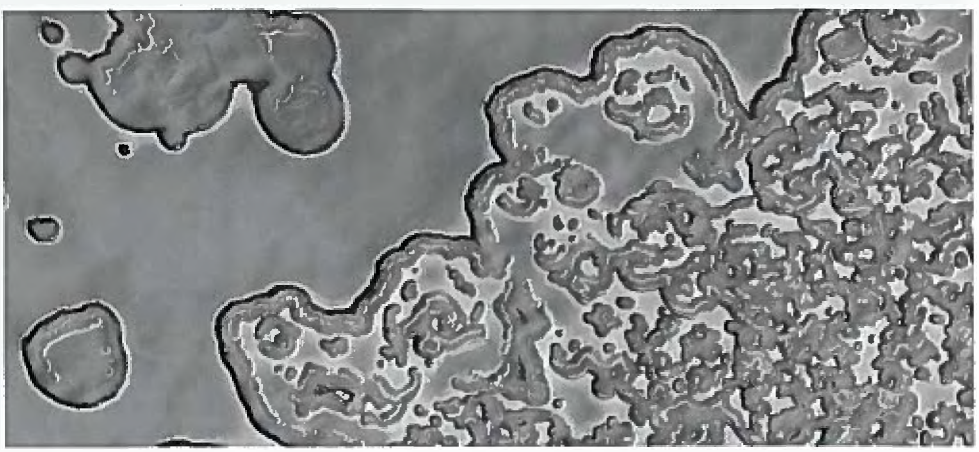
One reason for the abundance of wind-blown debris is the lack of oceans. On Earth, most fine-grained material is ultimately deposited in the sea, whereas on Mars most of the dust particles produced by erosion, impacts, and volcanism tend to remain on the surface and are thus available for the wind to move around. Moreover, on Earth most dunes consist of quartz sand, whereas the vast dune fields found on Mars mostly consist of basaltic minerals or sulfates. The ones surrounding the north pole, for example, are rich in gypsum ($CaSO_4 \cdot 2H_2O$). Yet, despite exposure to billions of years of wind action, the Martian surface has endured relatively little wind erosion. Instead, the same accumulations of loosely consolidated material get blown around over and over again.

SUMMARY

In some important ways, Mars resembles Earth. The planet has an atmosphere (albeit a thin one) and has been both volcanically and tectonically active. Water has eroded parts of the surface and reacted with materials there to produce weathering products. Ice and wind have also modified the surface.

Yet the two planets remain profoundly different. Earth's geology is controlled by plate tectonics. New crust continually forms at mid-ocean ridges; mountains chains and ocean trenches form where plates collide. In contrast, there are no crustal plates on Mars, so many of the geologic features

Figure 25. This "Swiss cheese" pattern forms in the Martian polar regions (here in the south) when a relatively high, smooth surface layer of frozen carbon dioxide (dry ice) breaks up into depressions tens to hundreds of meters across. Most likely, this pattern forms as the ice sublimates when the temperature warms during local summer. Year to year changes in the pattern suggest that the residual CO_2 cap is slowly dissipating to expose an underlying water-ice cap.



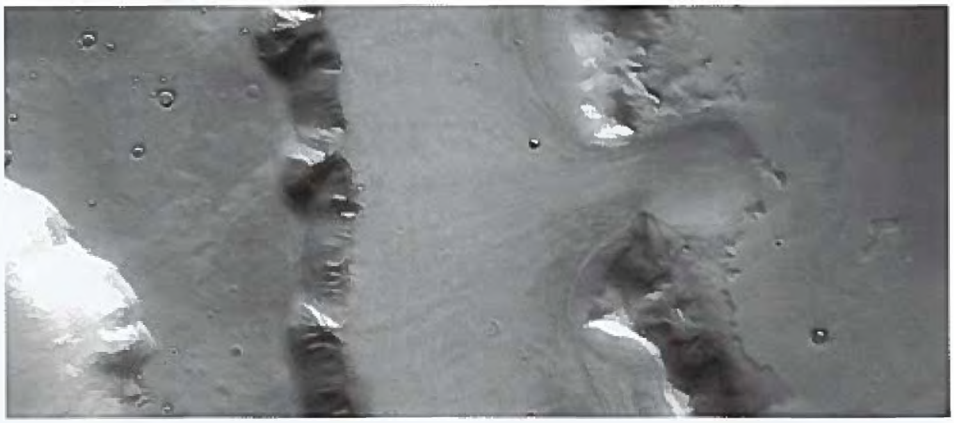


Figure 26. An ice flow originating at a cliff at the left side of the image has been deflected through a gap in an obstructing ridge. Such flows are common at the base of cliffs at mid-latitudes on Mars. When first observed, the flows were thought to be ice-rock mixtures, but more recent data from ground-penetrating radar show that they consist almost entirely of ice. The source of the ice is unclear, but these flows may be yet another manifestation of effects of high obliquity.

familiar to us are absent. Instead, this lack of plate movement allows many Martian features such as volcanoes and fault troughs to grow to enormous sizes. And though water has eroded some parts of the Martian surface, its total effect in sculpting the surface is secondary to the effects of impact and volcanism. The result is a spectacular planet on which geologic features of enormous scale, variety, and age are almost perfectly preserved.

A crucial issue, of course, is whether any form of life ever developed on Mars. The prospects now seem much better than they were in the late 1970s and early 1980s, following the negative results from the Viking mission. Recent work shows that the most primitive life forms on Earth live in hydrothermal environments. Researchers have suggested that either that life started in these niches or that only those life forms viable in such environments survived early conditions on Earth and they gave rise to all subsequent life.

Hydrothermal environments may have been common on early Mars. We know liquid water was present and that the planet was volcanically active — a combination that must have resulted in widespread hydrothermal activity. We don't yet know whether life did start on Mars, or whether it could have survived to now in protected niches. Learning the answer will almost certainly require a sustained exploration program including both on-site experimentation and the return of samples to Earth for comprehensive analysis.

Figure 27. Tracks left by the Opportunity rover as it crossed the dunes that cover much of the Meridiani Planum.