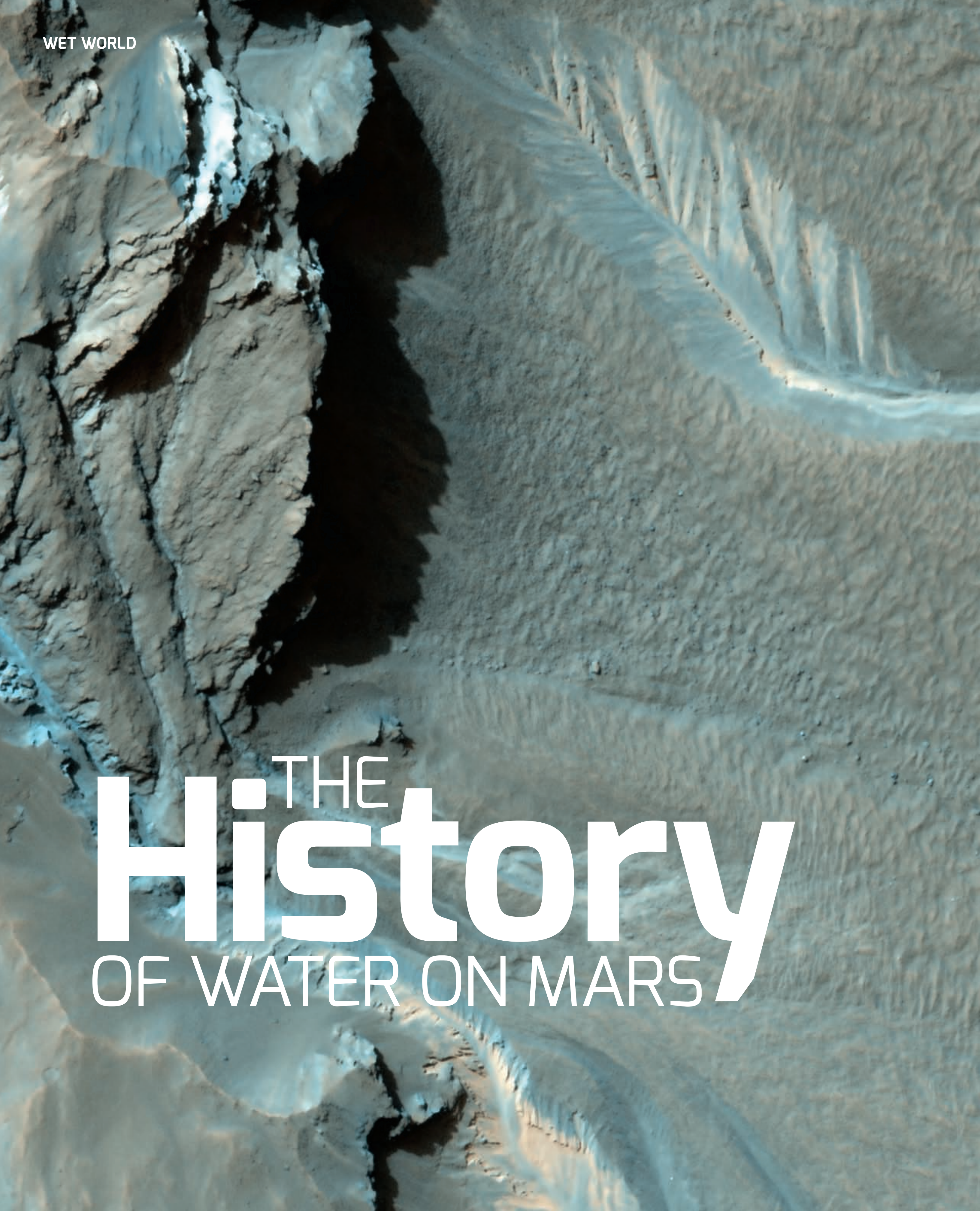
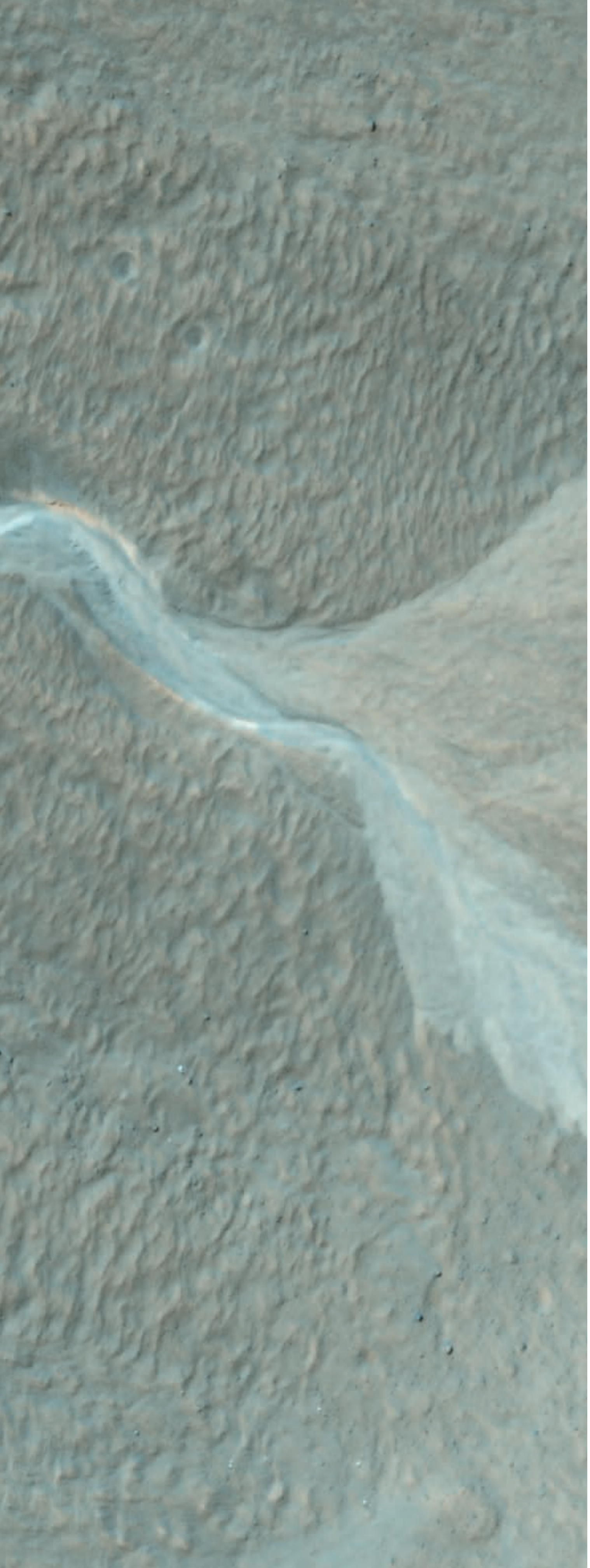


THE History OF WATER ON MARS



Emily Lakdawalla

How many times has NASA discovered water on Mars? We set the record straight.

Water on Mars? Again? Didn't we discover that already? NASA has "discovered water on Mars" so many times over the last two decades that some editors have forbidden their writers from covering the topic. Water on Mars today is easy for anyone to spot: you can see it plainly on Mars through a small telescope. The white polar caps are made mostly of water ice, as are the thin blue-white clouds.

In fact, water is everywhere in the solar system. The moons of the outer planets are made mostly of water ice, as are comets and trans-Neptunian objects. Water is bound into the minerals on asteroids and rocky planets. There is even water ice at the surface on the Moon and Mercury. If water is common, why are we fascinated with water on Mars?

It's because most people are not very interested in ice water, mineral-bound water, and intensely high-pressure water sealed under thick, icy crusts. We want running, swirling, pooling, eroding, dissolving, chemistry-facilitating liquid water. Beyond Earth, Mars is the only place where water has done nearly all of the myriad things that it does on Earth: it has rained, snowed, run off, eroded hills, filled basins, hosted chemistry, and glued sediments into rocks. These sedimentary rocks preserve the evidence of water's activity billions of years ago, revealing where water was and what it was doing.

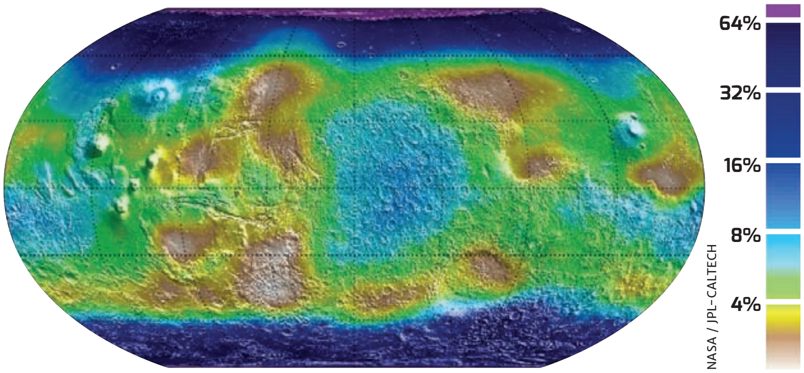
But Mars is not Earth and there are crucial unanswered questions. Did Mars's liquid water persist for millions of years or more in seas or oceans? And did its presence give life a chance to originate and, for a little while, flourish? If liquid water persisted on Mars, and we don't find evidence for life there, what does that mean? Those questions have motivated modern Mars exploration.

WATER EVERYWHERE, BUT NOT A DROP TO DRINK

Cold and hyper-arid, Mars is inhospitable today. Its atmospheric pressure is so low (less than 1% that at sea level on Earth) that an open container of water exposed on its surface would boil or evaporate faster than it would freeze.

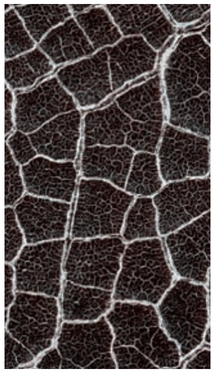
Gullies have formed on the interior rim of Hale Crater, just north of Argyre Planitia in Mars's southern hemisphere. One explanation for these gullies is flowing water, which might have deposited the bright material.

NASA / JPL / UNIVERSITY OF ARIZONA



NASA / JPL-CALTECH

NASA / JPL-CALTECH / UNIV. OF ARIZONA / MAX PLANCK INST. / ADDITIONAL PROCESSING BY EMILY LAKDAWALLA



NASA / JPL-CALTECH / UNIV. OF ARIZONA

Left: This map from Mars Odyssey's neutron spectrometer shows the location of water ice near the surface. As expected, there is lots of ice at high latitudes, but scientists were surprised by the relatively high abundance of subsurface ice around the equator. Center: The Robotic Arm Camera on NASA's Phoenix Mars lander took this shot of a flat slab of water ice just inches below the surface. Right: As on Earth, Mars's high latitudes often feature terrain shaped like polygons. Ice forms these polygons through complex processes involving the way water freezes, thaws, and exerts stress on its surroundings.

But water can be found nearly everywhere on Mars, not just in its polar caps.

Most of Mars's remaining water supply is hidden underground, frozen into a global ice table. In many places, the ice is deep below the surface, but in the vast northern lowland plains it lies just centimeters underground. Polygonally patterned ground hints at its presence. More evidence for near-surface ice came from NASA's 2001 Mars Odyssey orbiter, which detected large amounts of hydrogen buried in the top meter or so of soil.

This discovery prompted NASA to launch the Phoenix lander to Mars in 2007. When Phoenix's robotic arm imaged the lander's footpads on the fifth day after landing, scientists discovered that the retrorockets had exposed a flat layer of bright ice. Although the team had been expecting to find some ice, the surprising sight of such bright, pure ice inspired them to name the deposit "Holy Cow!"

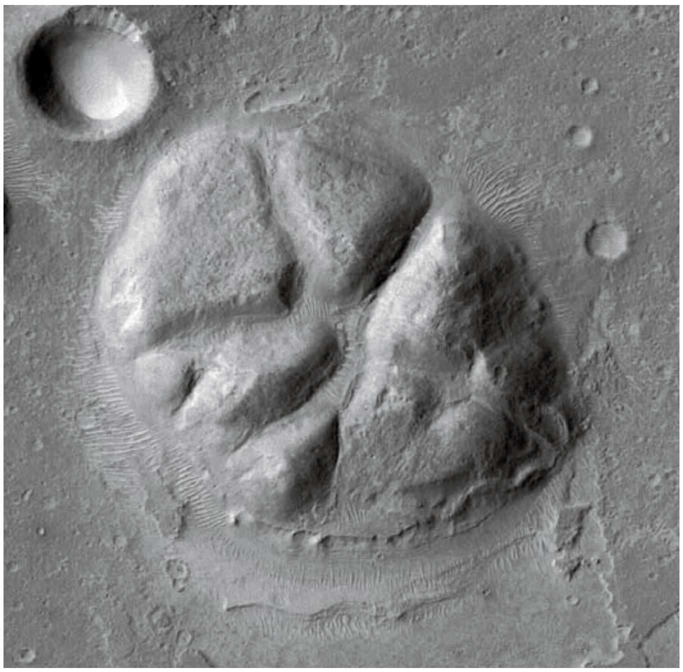
In addition, NASA's Mars Reconnaissance Orbiter (MRO) spotted 18 fresh craters whose centers are blue-white with pure, fresh ice. When researchers repeated the observations months or years later, the ice had either vaporized or been covered by settling dust.

Ice is so ubiquitous beneath the northern plains that NASA's Viking 2 lander — which touched down at latitude 48° north — might have been able to investigate it if scientists had only known it was there. If Viking 2 had been commanded to dig its trench just 4 inches (10 centimeters) deeper, it might have struck ice. After a journey of tens of millions of miles, we probably stopped 4 inches short, and the discovery of ground ice was delayed by a quarter century.

Other features on Mars hint at near-surface ground ice. Glacial landforms such as moraines and pingos dot both northern and southern landscapes. It's difficult to know whether they are active today, but their relative dearth of impact craters suggests the ice has moved in the geologically recent past.

But evidence for liquid water is harder to find. Year after year, we see small gully features form on steep, equator-facing canyon and crater walls. Are they carved by water flowing downhill? Not all scientists are convinced. Some speculate that they exist where salt-rich soil depresses the freezing point of water, making brines that melt at lower temperatures. The most recent work suggests that brines aren't needed; these gullies extend when, and only when, the uppermost layer of soil is at or above pure water's freezing temperature. But even if the gullies represent current sources of liquid water on Mars, they are transient, tiny, possibly salty trickles — hardly a paradise for life.

Mars Reconnaissance Orbiter took this image of a 2-mile-wide feature that looks like pingos found in Earth's Arctic regions. Pingos are mounds of ice covered by dirt and rocks.



NASA / JPL-CALTECH / MSSS

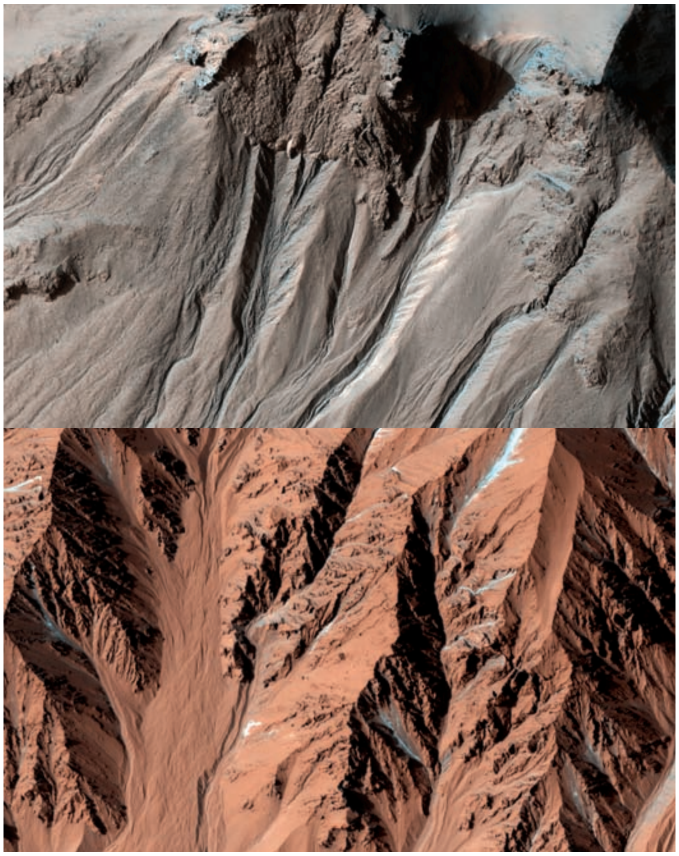
A WETTER PAST

Ancient Mars differed considerably from modern Mars, and its relics are everywhere. Like the Moon and Mercury, Mars bears ancient, cratered terrain, largely confined to its southern hemisphere, that is scarred by huge numbers of overlapping impact craters. The craters bear witness to a time when the entire solar system suffered through an intense bombardment by wayward asteroids and comets.

But look closely at the Moon, Mercury, and Mars, and you'll see the record of quite different histories. The Moon's cratered highlands have changed little since their formation. Mercury's cratered landscape has been flooded by countless volcanic eruptions and then wrinkled by planetary shrinkage. In contrast, Mars's southern highlands have been dissected by branching valleys.

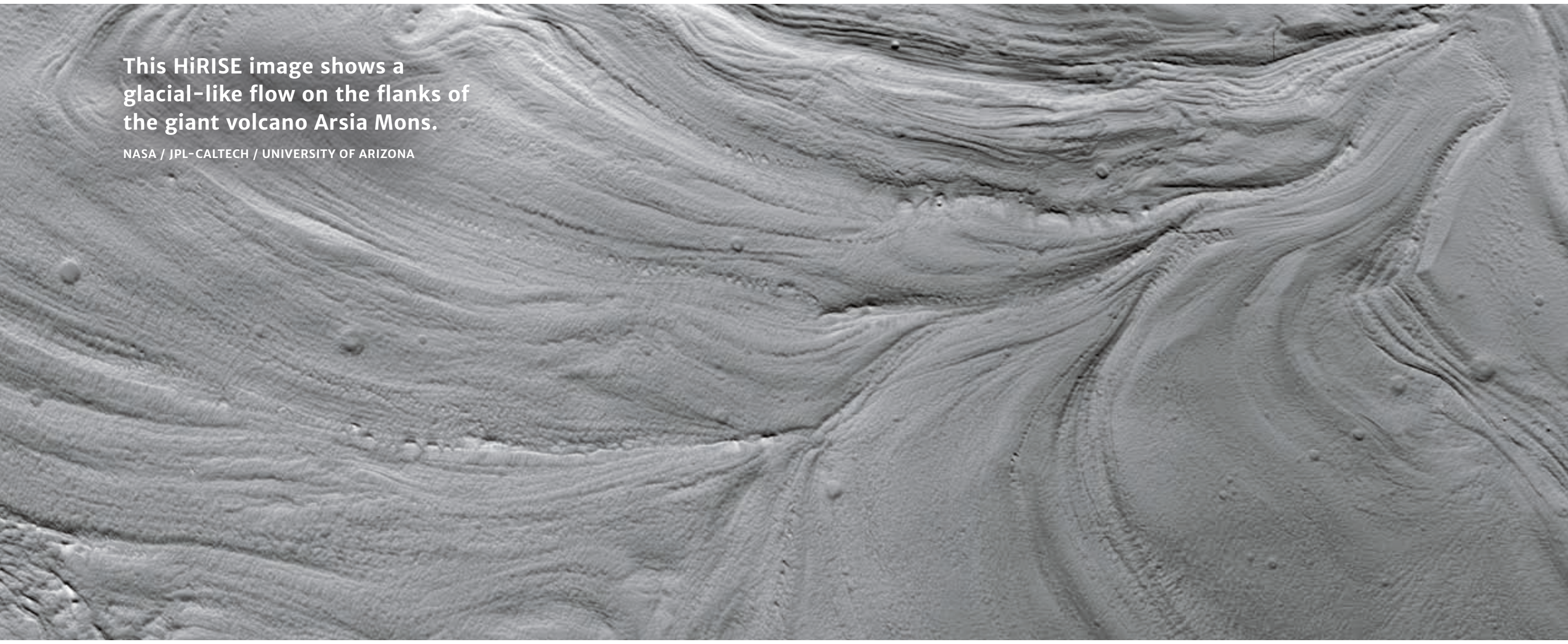
At first glance, Mars's valley networks look like terrestrial river systems. But when scientists examined them closely in Viking imagery, they seemed geologically primitive. The valleys had few branches, and large areas lacked any valleys at all. Many geologists concluded that the networks were produced by infrequent releases of groundwater. Perhaps the occasional large impact briefly thickened Mars's atmosphere, encouraging a few years' worth of greenhouse warming, rainfall, and runoff before the air thinned again, leaving Mars as cold and dry as before.

But new data have changed this view. Maps based on Mars Odyssey images show that the valleys link into densely branched drainage networks, with the smallest channels reaching right up to the divides between watersheds. Their complexity rivals Earth's river networks. Intriguingly, most valley networks appear to have formed within a narrow time span of perhaps 200 million years. And that 200 million years was relatively late — *after* Mars suffered most of its



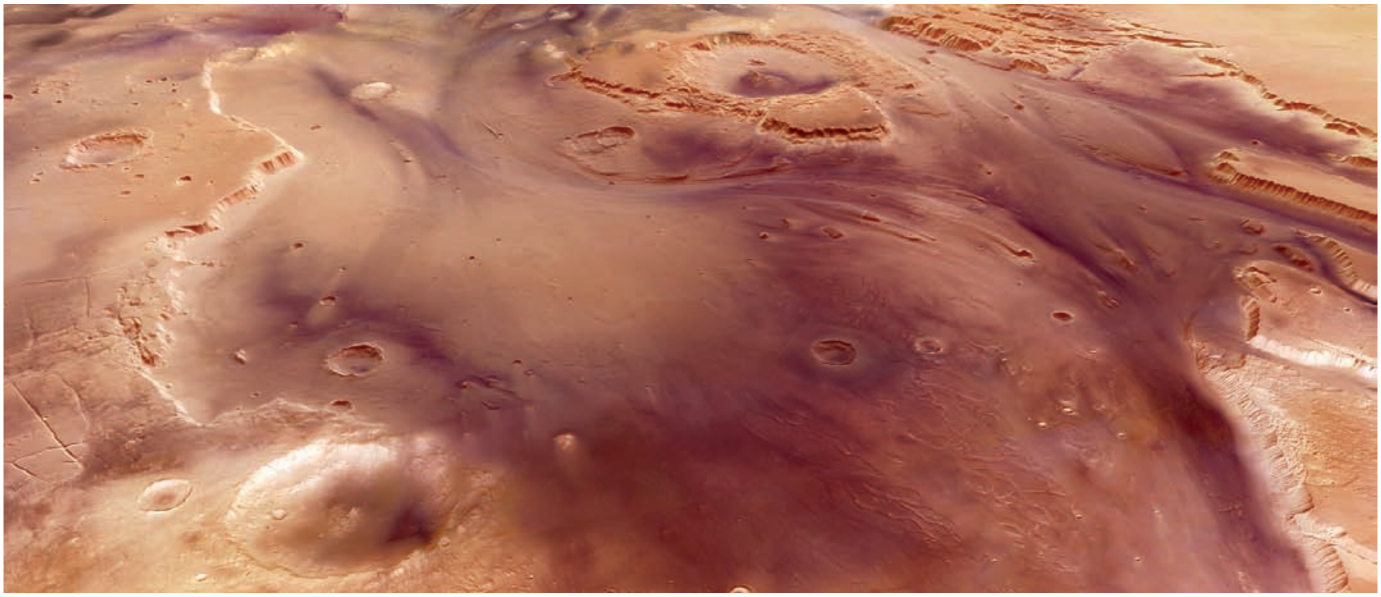
NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA (2)

High-resolution images taken from NASA orbiters have revealed numerous gullies on the Sun-facing walls of craters and canyons. Scientists are still debating their origin, but many geologists think they form when an aquifer of water bursts through a slope, creating a mini-avalanche of water mixed with sediments that flows downhill. These images come from the HiRISE instrument on MRO.



This HiRISE image shows a glacial-like flow on the flanks of the giant volcano Arsia Mons.

NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA



ESA / DLR / FU-BERLIN / GERHARD NEUKUM

After the river valleys dried up, Mars experienced occasional catastrophic floods, which carved deep, wide outflow channels such as Kasei Valles, imaged here by the high-resolution stereo camera on ESA's Mars Express orbiter.

major impacts around 3.8 to 3.6 billion years ago. Something other than impacts was responsible for the warm world that spawned the valley networks.

TURNING ON THE WATER CYCLE

Climatologists trying to explain a warm, wet early Mars run up against the "faint young Sun paradox." According to stellar-evolution models, the Sun should have been 30% fainter in its youth, while also producing more ultraviolet radiation that would have stripped away a carbon-dioxide-rich atmosphere. But if the valley networks actually formed late, after the major impacts, then they formed after the Sun had begun to burn brighter.

Mars's giant Tharsis volcanoes could have helped make Mars wet. The Tharsis region is a monstrous construct of overlapping volcanoes and lava flows that built up over billions of years. As impacts waned, volcanism started to dominate Mars's geology. The boundary between these ages is thought to be about 3.8 billion years ago (see page XX). Through Mars's middle age, volcanic eruptions pumped tremendous quantities of gases into the atmosphere, primarily water, carbon dioxide, and sulfur dioxide. These gases could have thickened the atmosphere just as a brightening Sun was warming Mars.

As Tharsis volcanoes were erupting, Mars's atmosphere grew faster than the Sun could destroy it. Water started to precipitate as snow or rain. Wherever it rained or the snow melted, running water wore away at Mars's soil. Water roiling with sediments quickly eroded environments that had been battered by impacts and decayed in hyper-arid conditions. The running water transported the sediment downstream. Water filled up craters such as Gusev and Gale to form lakes, and then they overflowed, flooding areas further downhill. Water eventually reached the great basin of the northern lowlands and perhaps even filled it up to form an ocean. And that's when a positive feedback cycle really got going. Basins full of water produced humid air that, when transported to higher elevations and cooler temperatures, dropped rain or snow.

Did a northern ocean ever exist? There's circumstantial evidence for shorelines — breaks in slope — around the northern lowlands. Geomorphologists have also mapped delta-like deposits at the termini of valleys and found that most cluster at a common elevation — a sign that they all emptied into a single ocean. But many scientists remain unconvinced; the question of whether Mars ever had a long-lived northern ocean remains hotly debated.

To see more images showing evidence for water on Mars, visit skypub.com/marswater. >>

PARADISE LOST

Even if Mars was once a paradise, this hospitable environment has since been lost. Valley-network activity waned over time. Any magnetic field Mars may have had was lost once the core cooled and solidified, and the planet's early thick atmosphere was stripped away by the solar wind (see page XX). The style of water erosion shifted from the valley networks to an entirely different kind of landform, the outflow channels. Outflow channels are enormous — up to 150 km wide and 2,000 km long — and must have been carved by catastrophic releases of massive quantities of water. They formed mostly during Mars's middle age, but a few have formed in geologically recent times.

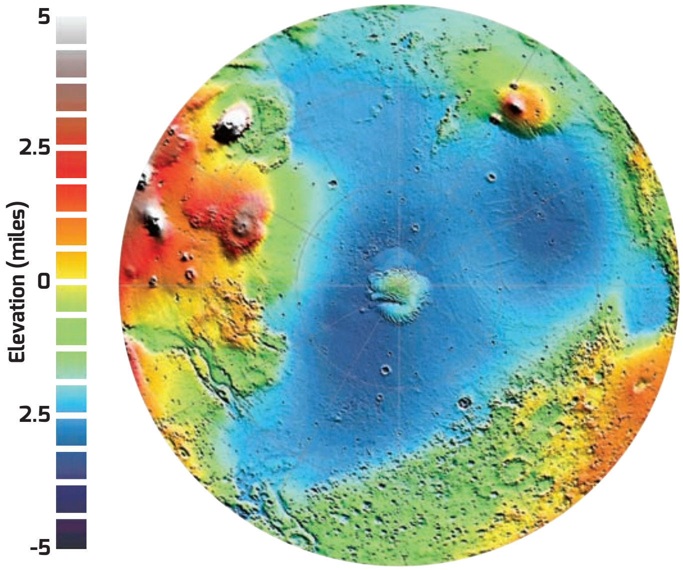
Unlike valley networks, outflow channels probably required a frozen climate. A thick cryosphere of ground ice could have trapped and pressurized vast quantities of liquid water. An impact or an underground squirt of volcanic magma could have suddenly broken or melted a direct path to the surface for an underground-lake's worth of high-pressurized water to traverse. This is particularly true in Mars's southern highlands: here, crater-forming impacts shattered the bedrock, leaving it highly porous and therefore able both to store lots of water and to release it all at once in catastrophic floods. Such floods might have temporarily filled Mars's northern basin, but the water was short-lived. In just a couple of years, the water might have seeped back underground, froze, or evaporated into the atmosphere, where it precipitated back out as rain, snow, or ice and got locked up in the cryosphere again.

And yet NASA's rovers have found evidence that Mars continued to produce sedimentary rocks even after its warmer, wetter climate shut down. All of the sedimentary rocks seen by Spirit and most of those seen by Opportunity formed after Mars's most ancient, wettest age. Sedimentary rocks usually require some water to form. Many of Mars's sedimentary rocks contain minerals whose crystal structures include water molecules or hydroxyl (OH^-) ions. What could have deposited these sediments and then cemented them into place? The answer may have to do with Martian climate change.

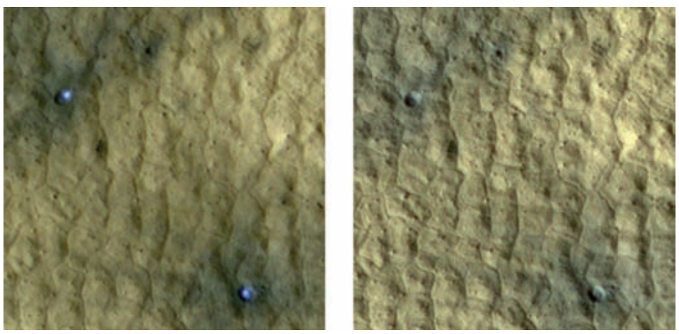
MILANKOVIĆ GOES TO MARS

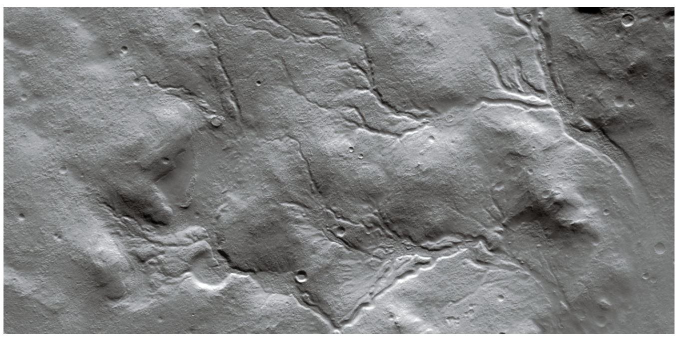
Earth's climate shifts from warmer to cooler on tens-of-thousands-of-year swings known as Milanković cycles, named for Serbian scientist Milutin Milanković who developed the idea in 1920s. Earth's axial tilt, along with the eccentricity and precession of its orbit, varies over a small range, which affects how much solar energy reaches Earth at different times in its seasons at different latitudes. Milanković cycles clearly influence Earth's climate; variations in isotopes of oxygen and carbon, plant activity, and the advance and retreat of glaciers all correlate strongly with the amount of solar insolation predicted by Milanković's theory.

Mars has even more extreme Milanković cycles. Mars's orbit can shift so that it's as much as 50% farther from the Sun at aphelion than at perihelion. And without the presence of a large moon to stabilize the orientation of Mars's rotational axis, at times the axis has been tilted nearly horizontal. In fact, Mars's current moderate axial tilt of only 25° is unusual. Mars spends more of its time with a relatively high tilt of 40° to 50°. During these periods, most of the planet bakes in near-continuous sunlight for half of the year and hides in darkness for the other half. Polar caps can't exist under these conditions; instead, any year-round water ice forms within a band encircling the equator. Climate variations move Mars's reservoir of frozen water back and forth from the poles to the equator. From time to time, conditions may allow ground ice to



Scientists constructed this topographic map of Mars's northern hemisphere using data from Mars Global Surveyor's laser altimeter. It clearly shows the remarkably flat, low-lying plain that covers much of the north. Many dried-up channels near the equator lead directly into this basin, prompting many scientists to conclude that the blue, flat area was once an ocean. NASA / JPL / GSFC





NASA / JPL-CALTECH / UNIVERSITY OF ARIZONA (3)

Left two: These two HiRISE images were taken 15 weeks apart in 2008. The leftmost image shows two mid-latitude craters with freshly exposed ice (bluish spots). But the ice vaporized over time, leaving just dust behind on the crater floors (right). The craters are about 13 feet across and 20 inches deep. Right: Narrow, branching valleys are common in Mars's equatorial regions. The preponderance of evidence suggests they were carved by rainfall-fed rivers about 3.5 billion years ago. This image was taken by Mars Odyssey's THEMIS camera.

flow more quickly than usual, creating some of the periglacial features at Mars's high latitudes.

Once in a great while, under marginal conditions barely more clement than today's, snowpack near the equator could melt to form short-lived flows of water. It may only occur during very brief intervals in the Milanković cycle, when Mars's axis is strongly tilted, its orbit is at its most eccentric, and when the equinoxes happen to line up with Mars's aphelion and perihelion. Then, and only then, for just a few weeks, a little water melts every day, trickles downward into the ground, and most likely freezes or vaporizes within the day.

Mars's loose, windblown dust is rich in highly soluble minerals such as sulfates and salts. The brief wetting could dissolve those minerals, and then glue the sand grains together with mineral cement. Piles of dust and windblown sand could then become frozen in time, locked in the position they held that one time when Mars's crazy orbital gyrations briefly synced to create a transient climate where snow could melt. Many of the bright sulfate sandstones studied by Opportunity exhibit large crossbeds typical of such windblown sands.

CURIOSITY FOLLOWS THE WATER

Under the rare climatic conditions that permit snow to melt anywhere on Mars, Gale Crater is one of the places where you would expect to find water. But melting water would've been an exceedingly rare event in a hyper-arid environment, happening only once every several millennia. Such an environment would not preserve evidence for ancient life, if such life ever existed.

Yet NASA's rover Curiosity has already found evidence for an even wetter environment. As Curiosity began its traverse across the floor of Gale Crater, it spotted rocks bearing rounded cobbles, too large to have been transported and rounded by wind. Those rocks must have tumbled in fast-moving streams. The first-drilled mudstones at the site named John Klein likely settled out of standing or very slow-moving water. Many of the rocks have been wetted at least once since they solidified. Mineral-saturated groundwater passed through, leaving its mark in the form of gypsum-filled veins. Did that water come from above, seeping downward from a crater-filling lake, or did it well up from below when the rocks were deeply buried? The Curiosity team is working to answer that question.

The current thinking is that the lowest part of Gale's central mountain dates to the valley network era, when Mars was warmer and wetter. The upper part formed later, and it probably consists of cemented windblown sands. The rocks in between would then record Mars's transition from hospitable to hyper-arid conditions. Gale Crater is thus a place whose rocks likely preserved evidence for every kind of climate that Mars ever had. As Curiosity climbs upward through Gale's stratigraphy, we hope its observations will verify or falsify our current understanding of Mars's past. ■

***Emily Lakdawalla** is senior editor and planetary evangelist for The Planetary Society. Find her at planetary.org/emily. This article is updated from a version that appeared in the September 2013 issue of* Sky & Telescope *magazine.*

Will Curiosity Find Evidence for Life?

MANY OBSERVERS openly hope that Curiosity will spot fossil evidence for Martian life. Sadly, even if Mars once teemed with life, Curiosity is unlikely to spot it. For one thing, it has no instruments capable of observing individual microbe-sized fossils. Preservation is a problem, too; even on Earth, it's exceedingly rare to find evidence for ancient life in nearly 4-billion-year-old rocks.

On the other hand, because Mars's geology largely shut down eons ago, its ancient rocks are in much better condition than Earth's. Martian rocks have suffered comparatively little insult from heat or pressure since they formed. At Gale Crater, Curiosity is examining rocks as old as life on Earth. Those rocks record conditions that might have been warm and wet. They are the kinds of rocks that could preserve the ingredients from which Earth life must have been made.

Even in the likely event that Curiosity finds no evidence for life on Mars, it's studying rocks that changed little over billions of years and that record the geologic and climatic conditions under which terrestrial life got its start. There's nowhere on Earth we can do that. Our best hope for understanding what things were like when life started on Earth rests, ironically, on another planet. Although we're curious about Mars for its own sake, we're ultimately studying it because it's the best place to answer the question: how did we get here?

CURIOSITY: NASA / JPL-CALTECH / MSSS; BACKGROUND: HIRISE

Hebes Chasma lies roughly 200 miles north of the vast Valles Marineris canyon system. Wind and water likely shaped the flat-topped mesa in its center. This view is a mosaic of eight images from ESA's Mars Express orbiter. The chasm is about 200 miles across east-west and 80 miles across north-south. It's nearly 5 miles deep. The numerous grooves suggest the material is easily eroded.
ESA / DLR / FU-BERLIN / GERHARD NEUKUM