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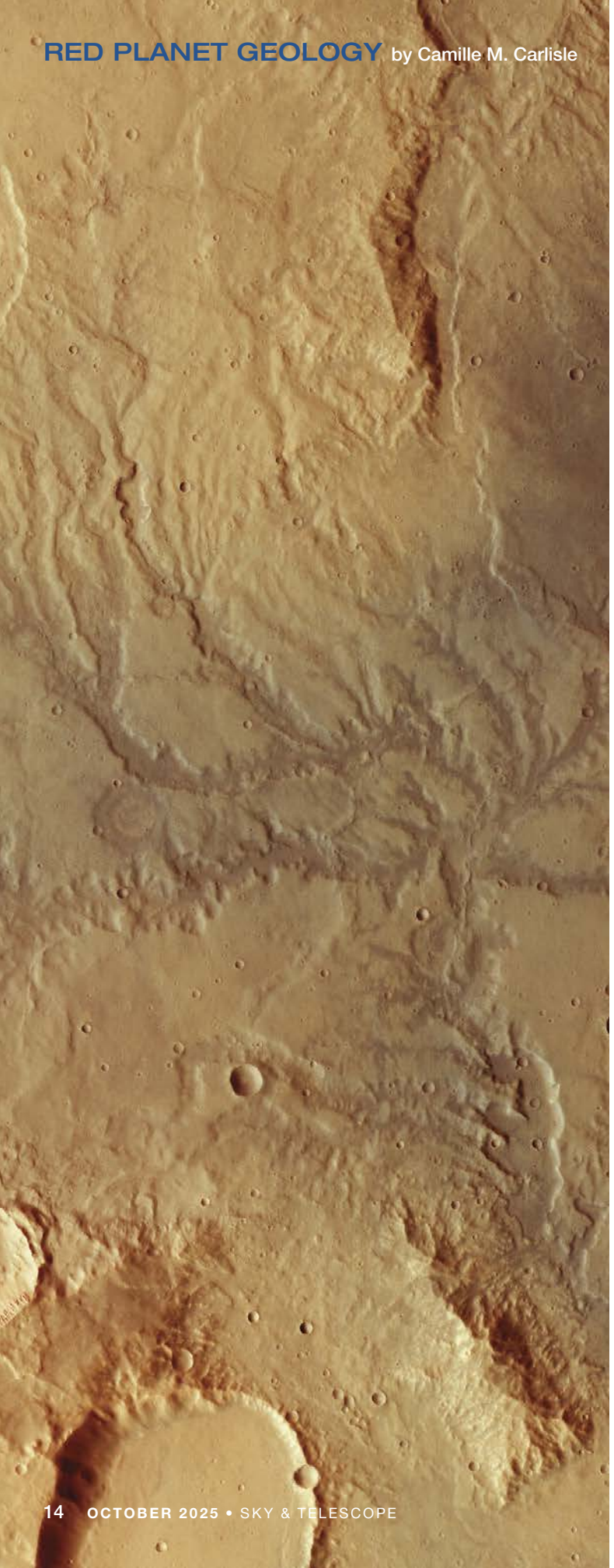


When Rive

Water carved the terrain of ancient Mars in sporadic bouts of activity that scientists are striving to explain.

Mars today is a frozen wasteland. Countless craters pockmark the terrain, including scars from some of the heftiest planet pummelers the early solar system let fly. More than half the surface is at least 3 billion years old, preserving the Red Planet's geologic history like a rare book.

This ancient landscape tells the story of a different Mars than the one we see today. Scientists have found roughly 70,000 valleys splayed across the surface, some linked in networks that meander for thousands of kilometers. Valleys play connect-the-dots with craters, flowing over rims in ways that suggest lakes once filled — and sometimes spilled out of — the basins. One network stretches all the way from the impact-beaten highlands near the south pole to the smoother equatorial lowlands, some 8,000 km (5,000 miles) away.

Since their discovery in the 1970s, these valley networks have provided abundant evidence that water once flowed on Mars's surface. (For various reasons, the liquid had to be water.) But poor little Mars can't sustain liquid water today: It has lost nearly all of its atmosphere. That's due at least in part to the solar wind, which stripped the planet's gaseous shroud away like dandelion fluff caught in a child's breath. The carbon dioxide air is now so thin that the atmospheric pressure is less than 1% that of Earth's, and average surface temperatures are far below freezing. What water remains lies trapped in polar ice caps or in the ground.

To explain the valleys crisscrossing its terrain, Mars must have had a radically different climate between 3 and 4 billion years ago. For decades, scientists have debated what that environment looked like and what enabled its existence, a debate sometimes summed up as "warm and wet versus cold and icy."

Now, however, better observations and calculations have transformed the conversation. Scientists are increasingly seeing ancient Mars as a world that suffered climate whiplash, bouncing time and again between clement and frigid conditions. Glaciers, rivers, rain — the planet seems to have had them all. Yet how water's many manifestations worked together to sculpt the landscape, and what mix of causes spurred the climatic swerves, remain half-exposed enigmas.

◀▶ **ANCIENT WATERWAYS** *Left:* This composite image from the Mars Express orbiter shows an eroded valley system in the planet's southern highlands. The topography suggests water flowed downhill from north (top) to south, carving valleys up to 2 km (1 mile) wide and 200 meters (650 feet) deep. *Right:* A simulated side view, based on terrain data.

rs Ran Through It

Mixed Messages

The valleys stretch primarily across the southern highlands, the primeval, rugged land that covers two-thirds of the planet. Some networks branch like great carved trees. In many cases, the tributaries start near the peaks of topographic divides, just as watersheds do on Earth. Their appearance suggests that the water that made them often came from rain or snowmelt.

But although the valleys are widespread, they don't carve as deeply or as extensively as researchers would expect if they had formed during prolonged warm and wet conditions.

Surface minerals also suggest liquid water had a limited presence. Although there's evidence of erosion by water, and there are clays created by water's interaction with rocks, the mineralogy doesn't match what we'd see if water cavorted across the planet for hundreds of millions of years. The mineral olivine, for instance, alters quickly in contact with water, transforming into other things. Yet olivine is all over Mars.

Long-lasting liquid water would also have created vast deposits of carbonate rock, through the interaction of minerals and carbon dioxide both dissolved in the water. The lack of ubiquitous carbonates has long been one line of evidence indicating that Mars lost its CO_2-rich atmosphere to space, instead of by chemically stuffing it into the crust (*S&T:* July 2018, p. 14). Researchers have recently found far more carbonates than they once thought existed, and they are currently debating the implications. Yet they still see nothing like the marine deposits on Earth.

Thus, although scientists have no doubt that there was lots of liquid water on Mars between 3 and 4 billion years ago — enough to cut valleys into rock and fill crater lakes and maybe even an ocean in the northern lowlands (still an open question) — that water wasn't active for very long. "Nobody that I know of thinks it was warm for a billion years," says Briony Horgan (Purdue University).

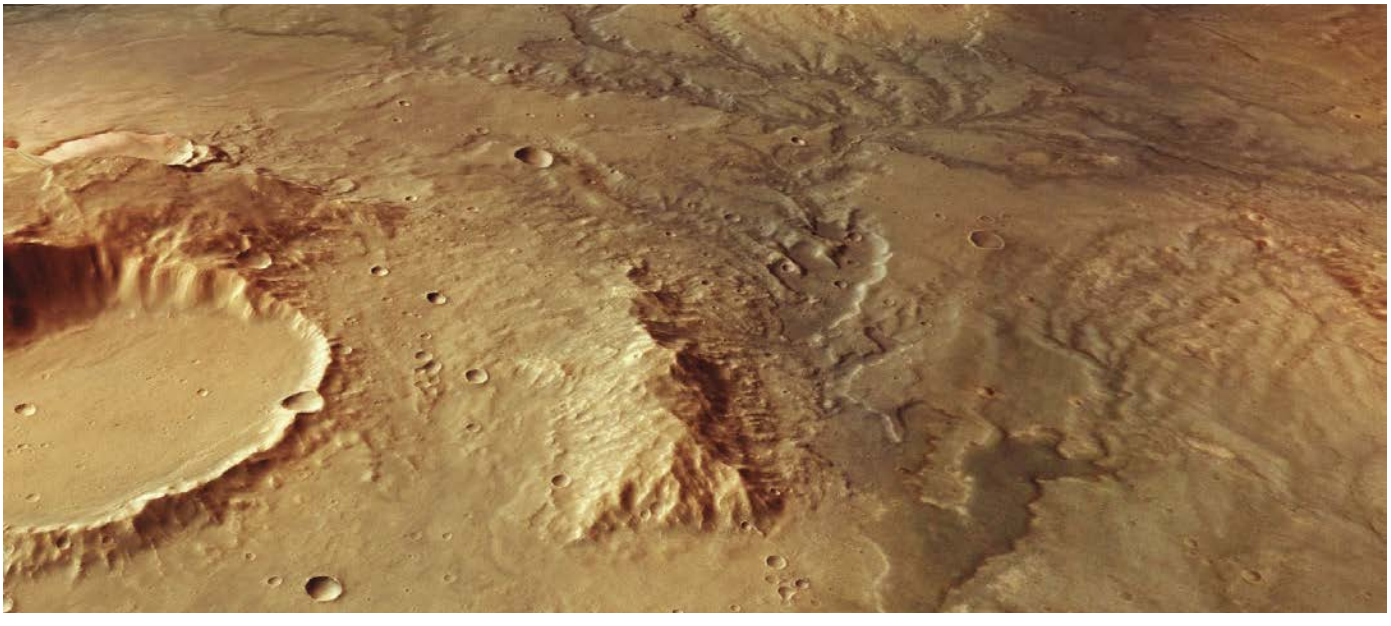
Instead, much of the Mars scientific community has converged on an episodic scenario, in which the planet was on-again, off-again habitable. Estimates vary, but clement conditions might have lasted between 100,000 and 10 million years cumulatively, with each interval stretching for some 10,000 to 1 million years. There might have been up to 100 different eras during which water flowed.

It's Cold Outside

Mars lies half again as far from the Sun as Earth does, and the early Sun was fainter than today's. So in order to sustain liquid water, ancient Mars would have needed a boost of more than 60 kelvin (110°F) in greenhouse warming — around double the greenhouse effect on present-day Earth, and nine times greater than the effect on present-day Mars.

Awash in Riddles

The peak of valley formation occurred 3.7 billion years ago, at the transition between an older geologic period known as the Noachian and the more recent Hesperian period. There should have been widespread ice sheets in the southern high-



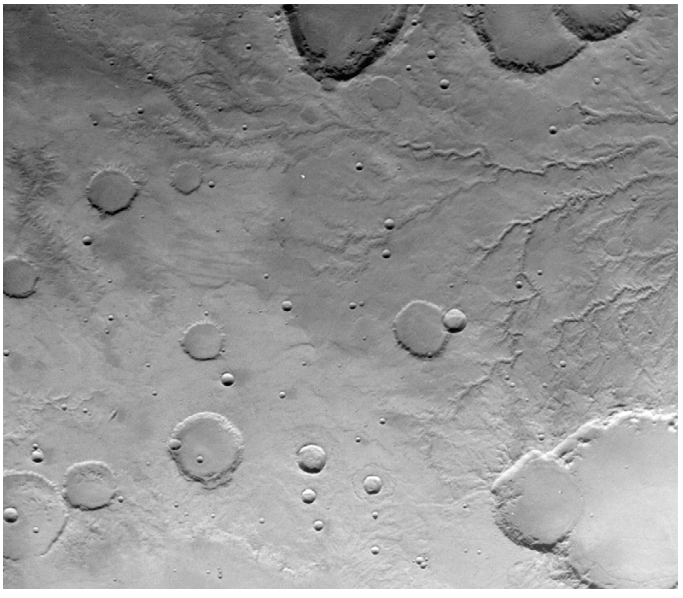
lands around this time. The highlands' terrain rises several kilometers above the younger northern plains, a stark contrast that makes the planet look two-faced.

During the Late Noachian, when the valley networks were forming in earnest, the planet's atmosphere was thicker, with a surface pressure of perhaps half a bar to a full bar (where 1 bar is the pressure at sea level on Earth). In a thick enough atmosphere, air will cool with elevation, as it does on Earth. The coldest places become "traps" where water vapor in the air freezes out as ice and snow.

"If you have an active water cycle, water is always going to want to travel to cold-trap regions," says Robin Wordsworth (Harvard University). Water would inevitably accumulate in the southern highlands as ice. "Then when you combine that with melting events driven by climatic warming, there's just a natural feedback that will allow water to cycle through the system." The water would flow down to lower elevations, carving valleys and filling lakes as it went, then evaporate and travel back to the highlands to reset the cycle.

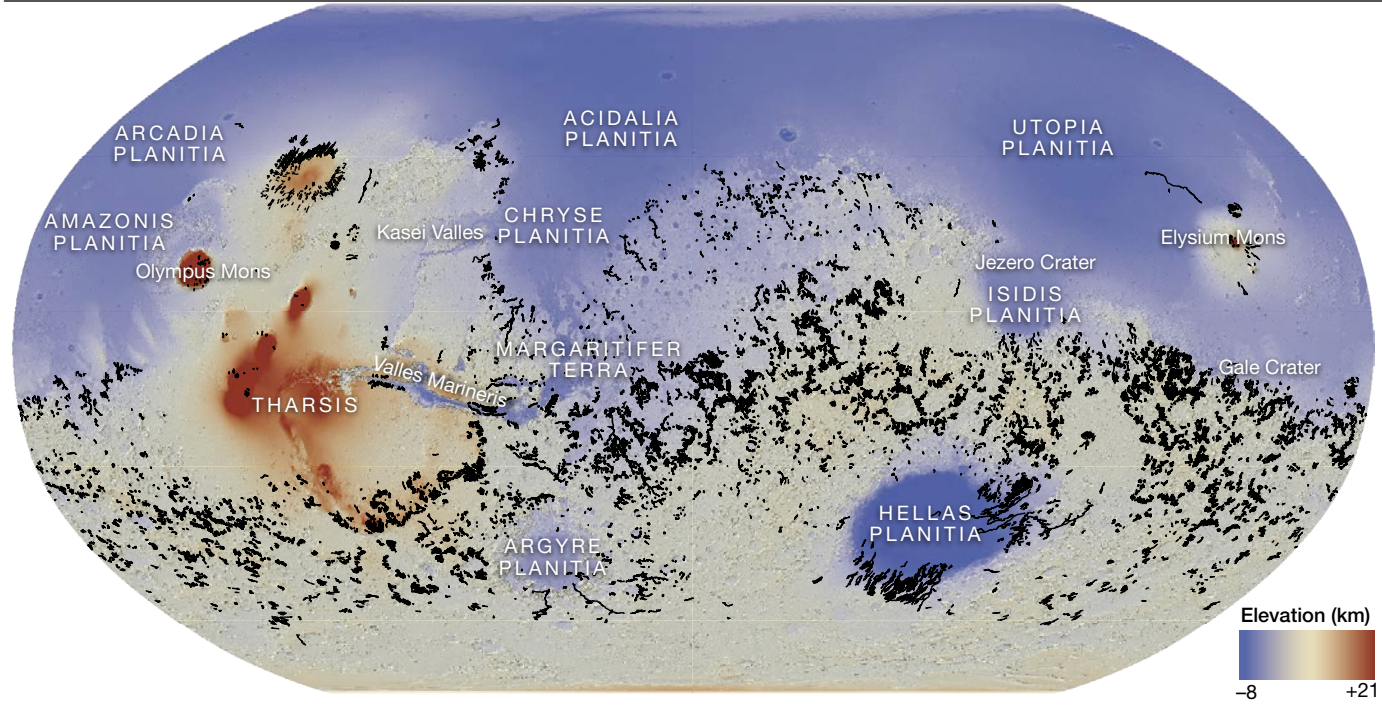
We see signs of ancient ice sheets on Mars, such as the Dorsa Argentea Formation at the south pole. This geologic feature includes *eskers*, sediment ridges that build up within subglacial drainage channels. Other glacial features appear at mid-latitudes and even in some places near the equator, along the boundary between highlands and lowlands.

The ice sheets would have played their own role in sculpting valleys. Some valleys appear to have been carved not by rivers but by meltwater flowing beneath glaciers, where it cut channels into the underlying rock. These features indicate that Mars did not have to be warm to make every valley; water wielded a variety of chisels.



▲ **EARLY SIGNS** This Viking 1 image from 1976 shows the Paraná Valles, a valley network in Margaritifer Terra. The image spans about 250 km. North is lower right, higher terrain is to the south.

But scientists disagree about the impact glaciers had on Mars during this era. There's no sign of large-scale glacial landscapes like those we see on Earth, where long-gone



▲ **VALLEYS GALORE** Scientists have so far found tens of thousands of valleys across Mars. They lie primarily in the southern highlands, which rise several kilometers above the northern plains. The volcanic Tharsis plateau also reaches to high elevations; it was likely already in place during the era of valley formation (debate continues). Like the southern highlands, Tharsis experienced glaciers. Mars's dramatic topography would have influenced climates on multiple scales, making it difficult for researchers to disentangle what the ancient environment looked like.

1970S NETWORK; JPL / NASA; GLOBAL MAP: ANNA GRAU GALOFRE

ice sheets scoured and eroded the ground, leaving distinct mounds of debris.

"Even at the rover scale, we just haven't seen any deposits or anything that we would associate with glaciation, with icy environments," Horgan explains. "Everything we see looks like there was just liquid water on the surface."

Perhaps, some argue, that's because the highlands were never covered in ice, and early Mars was persistently warm. Others have suggested that the glaciers' bases were so cold that they froze to the rock instead of melting and sliding.

A third possibility is that Mars's weaker gravity changed how meltwater drained from beneath its glaciers. Mars is a much smaller planet, and its surface gravity is only one-third that of Earth. Martian glaciers should thus sit less heavily on the landscape, enabling stable drainage channels to form beneath the ice and reducing friction between the ice and ground, Anna Grau Galofre (Laboratory of Planetology and Geosciences, Nantes, France) and others have suggested.

These channels would siphon water away, preventing sliding and erosion. As a result, the team concluded, glacial erosion on Mars should be much lower than on Earth — perhaps anywhere from 20 to 400 times slower. Martian glaciers' primary fingerprints would be the remnants of this drainage system, including channel networks and eskers much like the valleys and ridges found in the southern highlands. That could explain why on Mars we don't see the same glacial landscapes we find on Earth.

Think Indiana, Not Antarctica

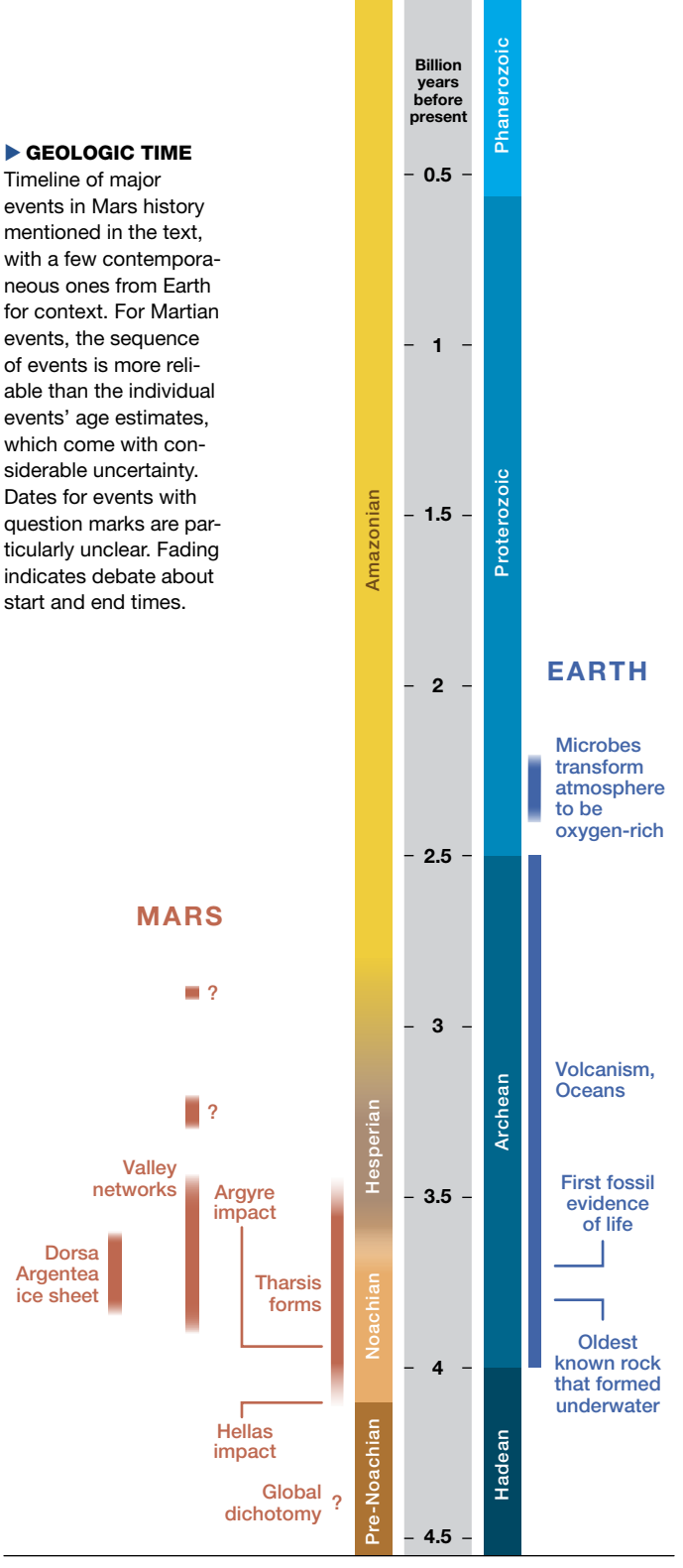
Still, ancient Mars cannot have always been icy. Mineral evidence favors the presence of warm, rainy conditions at least some of the time.

Scientists have found more than 100 outcrops of clay-rich rock that date from roughly the same era as the valley networks. These *weathering profiles* can be 200 meters (700 feet) thick. On Earth, deposits like these form when rain seeps down into the soil and breaks up minerals. The water drags the resulting clays downward with it as it slowly leeches through the ground.

Such clay stacks require lots of water to develop. We usually see terrestrial ones in tropical climates where the ground is tectonically stable and stays in place long enough for water to sit and act. But with no tectonic activity or quick erosion to erase these outcrops on Mars, a semi-arid climate would suffice to create them — something like the U.S. Midwest and its rainstorms, says Horgan.

The clay outcrops cluster in the mid-latitudes, and they appear at lower elevations and closer to lakes than valleys do. Whereas the valleys would have formed where the ground was susceptible to erosion, the clay stacks formed where it wasn't and where water could pool.

"The big takeaway we have right now on the geology side is, I don't know the way to produce both the valley networks and the weathering profiles that we see with just snow and ice," Horgan says. "It really does have to be warm and raining."



▶ GEOLOGIC TIME
Timeline of major events in Mars history mentioned in the text, with a few contemporaneous ones from Earth for context. For Martian events, the sequence of events is more reliable than the individual events' age estimates, which come with considerable uncertainty. Dates for events with question marks are particularly unclear. Fading indicates debate about start and end times.

These clay stacks couldn't have formed beneath glaciers, she adds. On Earth, glaciers' daily and seasonal melt cycles unleash intense amounts of water, which create a silica goo very different from the minerals in the outcrops.

NASA's Curiosity rover has also seen signs that ice-free water once existed on the Red Planet. For more than a decade now, the rover has been climbing a towering sediment mound in Gale Crater near the equator, trundling through the planet's geologic history as it travels upward. The rover has

BEATRIZ INGLESSIS / *S&T*, SOURCES: W. K. HARTMANN / *ICARUS* 2005, C. I. FASSETT & J. W. HEAD III / *ICARUS* 2008, R. D. WORDSWORTH / *ANNUAL REVIEW OF EARTH AND PLANETARY SCIENCES* 2016, A. GRAU GALOFRE ET AL. / *ICES IN THE SOLAR SYSTEM* 2024, R. D. WORDSWORTH ET AL. / *NATURE GEOSCIENCE* 2021

▲ **WEATHERED ROCK** Over time, surface water leached down through this basaltic ash deposit in Madagascar, transforming the bedrock (gray) into oxidized rock (red). On Mars, we don't see as much evidence for oxidation, so the weathering profiles don't look quite as red.

found evidence for multiple lakes, each at a different geologic time and lasting for an uncertain duration.

Recently, the rover drove over a lake deposit with wave-created ripples. The only way for wind-spurred waves to have stirred ripples in the lakebed is if the lake was at most 2 meters deep and its surface was ice free.

"That rules out a whole class of scenarios that are loosely Antarctica-like," says Edwin Kite (University of Chicago). Antarctica has some 600 lakes beneath its ice sheets, and Kite had previously thought such ice-covered lakes might be a possibility for Mars. This new result eliminates that option, at least for Gale. "You have to have open water."

NASA's Perseverance rover, meanwhile, has been exploring a shallower crater called Jezero, in which lakes came and went. Scientists chose Jezero in part because it's the end point for the area's valley networks, which flowed into the crater, dropped their entrained sediment, and created a large delta. As the rover has climbed to higher elevations, the rocks around it have transformed from those seen in deep lakes to rivers to big flood deposits. It's unclear whether the latter would be from glacial melting or larger climatic change.

The confusing lines of evidence make it difficult to assemble a clear picture of the ancient Martian environment. "It's closer to the feeling a few years before all the puzzle pieces fit together," says Kite. "All these hard-to-explain observations are piling up."

The confusion is compounded by the fact that conditions would have changed with time and from place to place. "It's a *planet*, right?" says Horgan. "It should have had many different things going on at different times, and you can imagine ice sheets coming and going. . . . The question is, why?"

Chicken Little Was from Mars

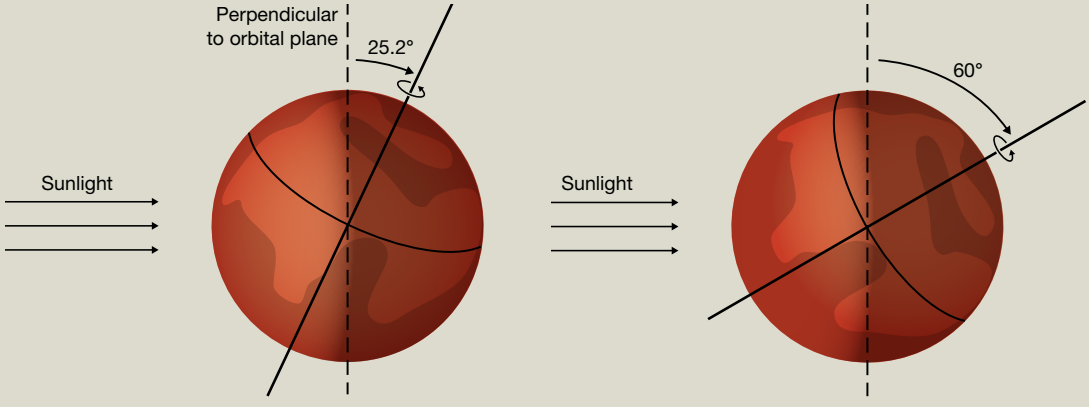
One driver of worldwide climate change is variations in the tilt of a planet's spin axis. These changes happen because the planets tug on one another as they revolve around the Sun. Thanks to the stabilizing presence of our large moon, Earth's rotation axis holds pretty steady, with an *obliquity* (tilt) of about 23° with respect to the plane of its orbit.

Mars has no such guardrail. The tilt of its rotation axis swings over hundreds of thousands of years, ranging from 0° to 60°, perhaps more. Although Mars's current obliquity is similar to Earth's, the average is likely around 40°.

When the obliquity is low, like now, the Red Planet's poles stay cold and icy. But at angles greater than about 40°, summer finds sunlight beating down on those same regions. The resulting heat wave melts the ice. Carbon dioxide releases into the air, raising the atmospheric pressure, and water migrates toward the now-colder equator, where it freezes. This climate transition happened as recently as a few million years ago, when mountain glaciers formed in the tropics.

Because the obliquity seesaw is a chaotic process, scientists can only trace the behavior back some 20 million years into the past. More distant forecasts must rely on statistics and geologic evidence. It's therefore unclear how obliquity played with (or contributed to) bouts of clement climate during the era of valley formation. Strong seasonal changes might have enabled water to melt even when the yearly average temperature was ostensibly far too cold for liquid water, for instance.

▶ **LEANING PLANET** Mars's spin axis is currently tilted about 25° from being perpendicular to its solar orbit *(left)*. But this angle, called obliquity, oscillates over time and may reach 60° *(right)*. The obliquity variations change which regions receive the most intense sunlight and where ice collects on the planet's surface. The diagram shows southern summer.



The variations would also have cast Mars into and out of ice ages. "Landscapes that carried water early in Mars's history may have been glaciated later on during one of these ice ages," Grau Galofre explains. "Some regions of the mid-latitudes most likely have seen both glacial and [river] processes throughout Mars's history." The giant Hellas Basin, for instance, likely contained a glacier during periods when Mars's tilt was severe, but the ice sheet disappeared when the planet reoriented to a lower angle. Areas near the south pole, meanwhile, may have had glaciers, rivers, and water flowing beneath ice sheets, all at the same time.

But the chaotic obliquity wasn't the only factor shaping the ancient climate. Back when the valley networks were forming, the Sun was fainter. At that time, Mars received only one-third as much sunlight as Earth does today. Although the Red Planet had a thicker atmosphere back then, even a full bar (or more) of carbon dioxide wouldn't have been enough to warm the planet. Too much CO_2 can, ironically, have a chilling effect.

The atmosphere can even collapse. Cool the planet a little at lower obliquities, and the carbon dioxide gas will begin to condense as surface ice at the poles — particularly the southern one, which rises to a much higher elevation than the northern one. A thinner atmosphere transports heat less effectively, and so the pole cools more, creating a runaway effect in which the sky literally falls. And it happens *fast*, within a few hundred years.

Counterintuitively, atmospheric collapse might have helped create some valley networks. The carbon-dioxide ice cap would have formed on top of a pre-existing water-ice cap. Last year, Peter Buhler (Planetary Science Institute) suggested that the thick, CO_2-ice sheet could have served as a thermal blanket, helping warm the water ice beneath it. The resulting meltwater would have snuck out from beneath the cap as ice-encrusted rivers, flowing like oozing lava into the gigantic basin Argyre and filling it with an ice-topped sea as voluminous as the Mediterranean. From there, the water spilled out again and wound its way equatorward until finally draining into the Margaritifer Terra plains, thousands of kilometers from the south pole (*S&T:* Apr. 2025, p. 11). The innovative scenario could explain the extensive valley system branching across that part of Mars.

But given the evidence for intermittent warm and wet conditions, one or more greenhouse gases besides carbon dioxide and water likely helped Mars out at least some of the time.

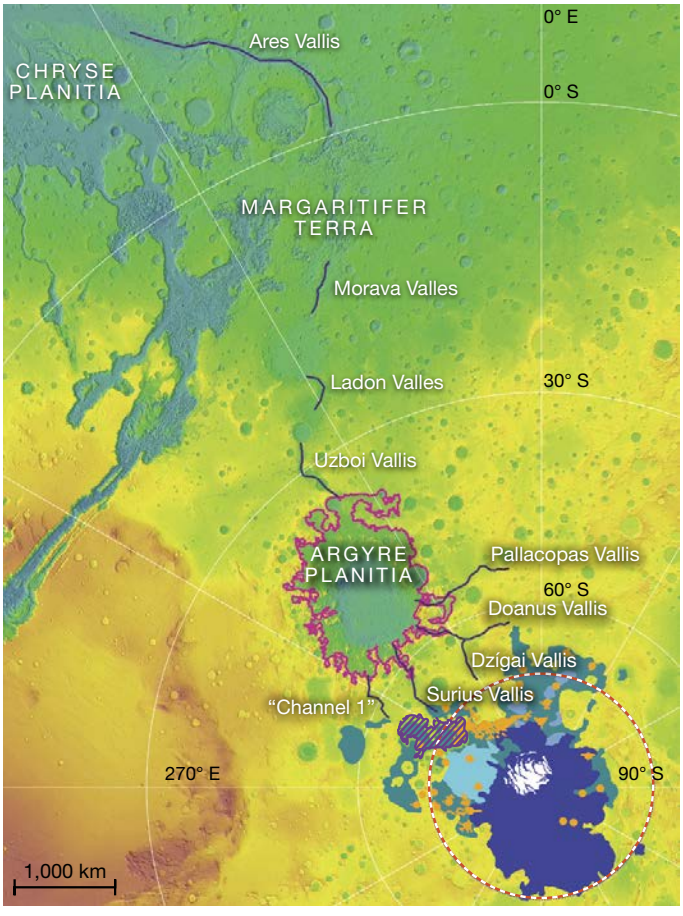
One solution is hydrogen. Mars's crust is basalt, a type of volcanic rock that's also the most common rock type in Earth's crust. If you throw a bunch of water at basalt, it'll chemically modify the rock and create hydrogen gas. The planet's lower gravity means the crust should be more porous, too, enabling water to infiltrate the ground and interact with minerals there to make hydrogen.

Hydrogen would also come from volcanism itself. Ancient Mars had plenty: Widespread lava flows cover terrain from the Noachian and Hesperian periods. As it wells up from below, molten rock carries with it gases, trapped as bubbles, that escape as the magma reaches the surface. Scientists think the Martian mantle contains a higher fraction of hydrogen than Earth's does, meaning the gases spewed out would contain a higher proportion of hydrogen.

It's possible that multiple sources of hydrogen would be enough to temporarily boost the greenhouse effect and create warm, humid climates, Danica Adams (Harvard), Wordsworth, and others recently proposed. It remains unclear whether other molecules that contain hydrogen, such as methane, could also contribute.

Cold Storage

The era of valley-network formation marks the beginning of Mars's transition to a cold, arid climate. Over time, liquid



▲ **GIANT RIVER SYSTEM?** A vast valley network connects Mars's south pole to the lowland plains of Margaritifer Terra and Chryse Planitia. Recent research suggests this network might have formed when a sheet of carbon-dioxide ice built up over the pole, helping to melt underlying water ice that then snuck out and meandered, ice-encrusted, for thousands of kilometers. The underlying topography map spans elevations of several kilometers.

P. B. BUHLER / JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS 2024

JEZERO Ancient waterways spilled into Jezero Crater, leaving evidence like the delta at the center of this image. The Perseverance rover climbed up this delta to reach the crater's rim. The inset below is a simulated side view, created by draping camera data over a terrain model. Jezero itself is about 45 km wide.

JEZERO FLOW: ESA / DLR / FU-BERLIN / NASA / JPL-CALTECH; B&W: NASA / JPL-CALTECH / USGS

water huddled at lower and lower elevations, likely due to a dwindling greenhouse effect that left the high places too cold for water to move and carve the terrain. The planet experienced several major climate transitions. Rivers and lakes appeared and disappeared with increasing scarcity.

Eventually, the planet dried out. Today, besides the occasional asteroid impact, the only thing notably shaping Mars's surface is wind. It sweeps across parched terrains, kicking up grains left by long-gone glaciers, rivers, and volcanoes. Dust storms shroud the sky and kill solar-powered craft. As the Sun traverses butterscotch-hued heavens, the wind and its dust devils are the only things scouring the landscape — a landscape with its past freeze-dried on its surface, waiting for us to decipher it.

Reading that history is a slow process. Scientists have barely had time to dig into Perseverance's data, Horgan says. And over the next couple of years, both Curiosity and Perseverance will traverse terrains with ages we've never explored on the ground before — Curiosity to younger deposits, Perseverance to older ones. Perseverance is now atop Jezero's rim and ambling among extremely old rocks, including fragments of pre-Noachian crust that were scooped out by impacts and dropped there. "They really do date from the dawn of Mars geology, which is wild," Horgan says.

Scientists have precious little information about this period. "It could be the first few hundred million years of Mars history are the most habitable," Kite says. "But we just don't have a good surface record, because that record's been buried." These chunks of ancient crust might preserve evidence of that early time.

So far, Perseverance has collected more than two dozen samples, from a variety of rock types, and is leaving them in tubes on the ground for future pickup and return to Earth. On Earth, scientists can see and handle rocks and run tests with a host of sophisticated lab equipment. They can determine things like the atmospheric composition and ambient temperature when the minerals formed. They can't load all those capabilities on a rover.

"Sample return is really, really, really important," Wordsworth says. "It's absolutely vital."

Yet NASA has struggled to devise a workable sample-return strategy, and as of press time the Trump administration's proposed budget would nix funding for a mission. For now, there's no plan for reclaiming the tubes of rock and air.

Mars scientists hope that changes. "If we can actually get the samples back, [it] would be just absolutely phenomenal," Horgan says. "Those samples piece together how the atmosphere degraded."

When the samples finally make it home, the Red Planet's history won't just sit preserved on a surface some 200 million kilometers away — it'll sit in the palm of our hands.

■ Science Editor **CAMILLE CARLISLE** would never, ever, ever want to live on Mars, but she'd love to hold a Martian rock nabbed by a robot and brought back to Earth.