

HALE CRATER on Mars may contain liquid water, as evidenced by streaks such as these lining steep hillsides inside the crater.

PLANETARY SCIENCE

man mars



in motion

**The surface of Mars changes all the time.
Is flowing water one of the causes?**

By Alfred S. McEwen

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Discoveries of water on Mars are now so common that the subject has become the butt of jokes among planetary scientists: “Congratulations—you’ve discovered water on Mars for the 1,000th time!”

Most of these findings have involved either visual evidence for ancient, long-gone water or evidence for present-day ice, vapor or hydrated minerals. The discovery of actual liquid water on the surface, in the present day, could change the course of Mars exploration. Where there is water on Earth, there is almost always life. Confirming the existence of water on Mars would therefore greatly improve the prospect of finding extraterrestrial life. This is the story of continuing efforts to uncover what role, if any, liquid water plays on Mars today.

The first credible evidence of modern-day water arrived in 2000, when NASA unveiled news that the Mars Global Surveyor (MGS) spacecraft had identified plentiful surface features that closely resembled gullies on Earth carved by flowing water. The Martian gullies suggested that “there may be current sources of liquid water at or near the surface of the red planet,” a NASA press release asserted at the time. The gullies drew the attention of many planetary scientists because they were

widely believed to form by running water or flows of wet debris.

Yet troubling questions soon arose. Tens of thousands of these gullies, some of them several kilometers long, dot slopes in the Martian middle latitudes, implying quantities of liquid that are very difficult to explain. The planet’s atmospheric pressure is so low, less than 1 percent of that on Earth, that pure water on the surface will rapidly freeze, evaporate or boil away.

Some researchers argued that the gullies must be relics of the past, when the planet experienced greater seasonal temperature swings. Then, in 2006, new data from MGS showed that light-colored material had spilled out of gullies just within the preceding few years. The gullies were not fossils after all.

Fortunately, as the gully intrigue began to swell, a capable new spacecraft had just arrived at Mars. The Mars Reconnaissance Orbiter (MRO) carries the High-Resolution Imaging Science Experiment (HiRISE), for which I am the principal investigator. The most powerful camera ever flown on an interplanetary mission, HiRISE would soon provide critical evidence about the gullies. But it would also give us something more.

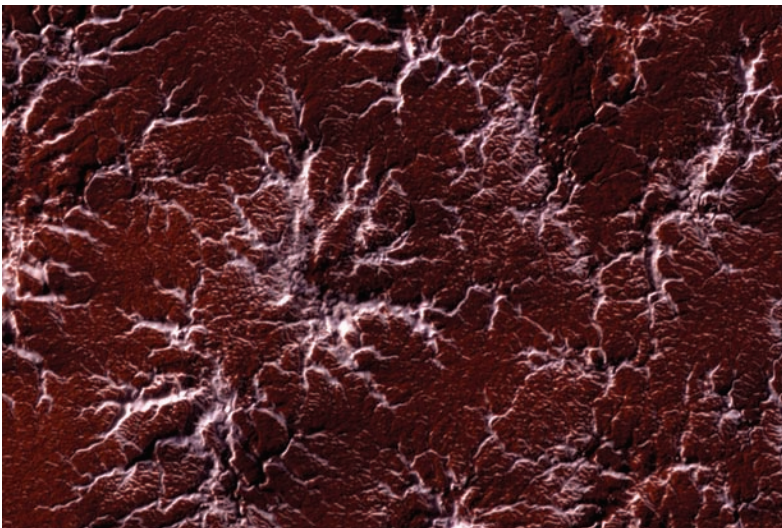
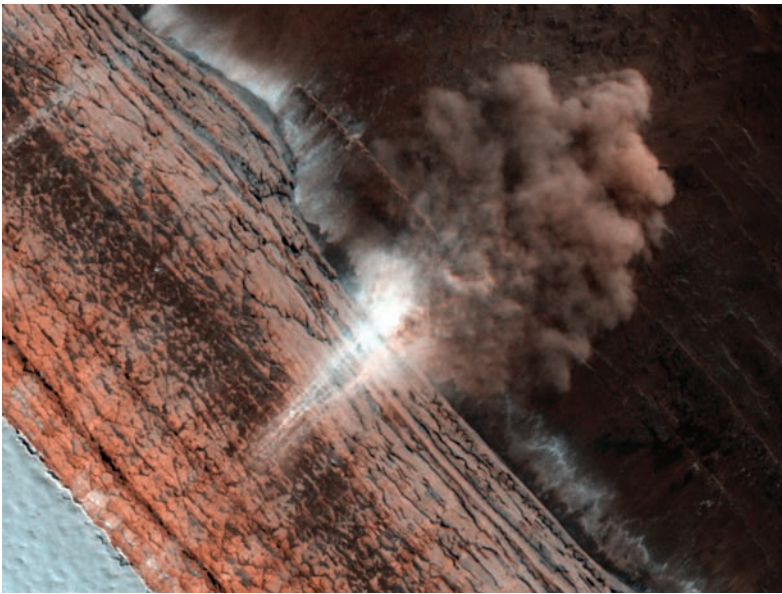
While MRO’s detailed new imagery unraveled the mysteries

IN BRIEF

High-resolution orbital imaging over multiple Martian years is revealing all manner of surface changes, some of which may involve liquid water.

Surface features known as gullies were once thought to require the presence of water, but recent evidence suggests otherwise.

A newly discovered class of features on warm slopes may mark the flow of salty water. These sites could be the best places to look for microbial life on Mars.



SURFACE ACTIVITY documented from orbit includes avalanches, “spiders” carved by carbon dioxide and a dust devil 800 meters tall (*top to bottom*).

of the gullies, a student in my laboratory discovered a perplexing feature of Mars’s surface that had never been seen before—streaks across the surface, flowing downhill, that grow slowly and change with the seasons in ways that suggest they are flows of liquid water. These streaks have turned out to be the strongest evidence for the presence of flowing water on Mars. They

trapped underneath dry ice. These are very unusual landforms, not seen on Earth, so it makes sense that they developed by an alien process.

In contrast, the gullies on Mars look so much like ravines or very large gullies on Earth that many researchers assumed they were shaped by Earth-like processes. Instead we would discover

have provided us with new ideas about how liquid water could exist in such a forbidding environment—and the best indication yet that Mars might still contain a niche near the surface in which life can survive.

FOREIGN BUT FAMILIAR

FROM ITS INCEPTION, we designed HiRISE with gullies and other small-scale structures in mind, and the camera has allowed us to examine these features in greater detail than ever before. HiRISE can photograph any part of the Martian surface, in color, at submeter resolution (0.25 to 0.32 meter per pixel). MRO can also precisely point the camera at a feature of interest on multiple orbits to look for changes in the landscape. In addition, the spacecraft can map the topography in stereo to create a three-dimensional view.

HiRISE’s combination of high-resolution stereo and color, along with repeated imaging over several Martian years, has dramatically improved our knowledge of the changing surface of the planet. We have documented wind-blown dust and sand, avalanches of rocks, frost and ice, and new impact sites dotting the surface [*see photographs at left*].

One of our very first HiRISE images from its mapping campaign showed a slope in the southern midlatitudes with the mysterious gullies that MGS had discovered. Much of the south-facing slope was still in the shadow of the crater rim at the time, during the southern winter season. Frost, primarily frozen carbon dioxide, largely covered the slope—except in some of the gully channels. This missing frost suggested that something was happening within the gully itself.

It took about two Martian years (nearly four Earth years) to catch numerous gullies in the act of changing, but the data eventually revealed a startling trend. The gullies became active—developing new alcoves, channels and fans—when carbon dioxide frost covered the ground. We had seen frozen carbon dioxide, or dry ice, in action before. In the polar regions of Mars, carbon dioxide’s seasonal sublimation (its change from a solid to a gas) produces bizarre cold jets, similar to geysers. On the layered deposits of ice and dust near Mars’s south pole, the sublimation of carbon dioxide creates “spiders,” radial networks of channels from the flow and erosion of gas

that they also can arise by a process that does not happen at all on the familiar terrain of Earth.

The carbon dioxide, my colleagues and I ultimately concluded, must trigger the formation of gullies by waterless processes, such as the sublimation of dry ice. These processes might cause rock and soil to flow downhill like a liquid.

Invoking dry ice frost as the cause of the gullies explained a number of mysteries. First, we had wondered why gullies formed predominantly on pole-facing slopes lying between 30 and 40 degrees south latitude and on all steep slopes poleward of 40 degrees south latitude. That pattern, it turns out, matches the seasonal distribution of carbon dioxide frost. Second, we could not explain why the gullies were far more active in the southern hemisphere than in the north. During Mars's current position in the cycle of orbital precession, southern winters are longer than northern winters, so more frost accumulates. When dry ice coats the ground, the surface and atmospheric temperatures stabilize at the carbon dioxide frost point, about -125 degrees Celsius. Pure water freezes at zero degrees C, so the season of dry ice frost is the least likely time of the year for liquid water to be present.

SOMETHING NEW UNDER THE SUN

I WAS BEGINNING to conclude that most of the surface erosion on Mars today was driven by carbon dioxide frost—that the idea of modern-day water on Mars might be “all wet.” At all latitudes on Mars, the surface shifts in response to dry environmental processes, such as the wind, but the most extensive changes take place in the region of seasonal carbon dioxide cover.

Then, in mid-2010, an undergraduate HiRISE researcher discovered something very different. Lujendra (“Luju”) Ojha was working to produce digital terrain models from stereo pairs of HiRISE images. I suggested that he use change-detection techniques on a stereo pair in an area where we had seen channel incision in a gully. The first image of the stereo pair was acquired two months before the second, and we wanted to find out if anything had changed in that brief interval. Ojha created the digital terrain model, then used those data to synthesize an overhead view, as if the orbiter had been looking straight down at its target. Finally, he compared the images to seek out subtle changes.

What Ojha found was puzzling. In the later image, many narrow, dark lines extended downhill from steep, rocky areas. Those streaks were absent from the first image.

I did not know what to make of the anomalous lines on the surface, so we gathered more information. First, we examined all stereo pairs acquired over steep slopes. We had already acquired hundreds of such pairs to study gullies, well-preserved impact craters and bedrock exposures. Among those images, we found other examples of the curious surface features. Each time we saw the same thing: dark lines, with no discernible topogra-

phy, on steep slopes near bedrock. All the images capturing these features were acquired in the southern midlatitudes on equator-facing slopes during the summer—the opposite season of when carbon dioxide drives surface activity.

Dark lines running downhill naturally makes us earthlings think of water or wet soils, but my colleagues and I chose to be cautious.

CAUGHT IN THE ACT

BEFORE WE COULD DETERMINE the cause of the streaky slopes, we needed to collect more evidence about when and where they occur. We suspected several things about these summertime flows: that they grew slowly and incrementally over a period of weeks or months, then faded or disappeared in the colder seasons, and then re-formed once more the next summer.

Because we did not recognize the warm-season flows until the second southern summer of MRO's residence at Mars, we had to wait until the third southern summer, in early 2011, to test our hypotheses. We picked six sites to intensively monitor for changes, and we spot-checked other ones. These observations confirmed our suspicions, and we published our findings in *Science* in August 2011.

In our *Science* paper, we called the flow features “recurring slope lineae,” or RSL, a purely descriptive name that does not assume we know their origin. If we had instead called them “water tracks,” we would have wrongly conveyed that we knew with certainty how they had come about.

By that time, however, we had become more convinced that water was somehow involved with this newfound

phenomenon. After all, RSL favored unusual environments: the middle latitudes, on especially warm slopes in the south, where the summers are hotter than in the north [*see box on opposite page*]. An instrument on the Mars Odyssey spacecraft has measured afternoon surface temperatures as high as 27 degrees C in such locations.

Temperatures above zero degrees C would seem perfectly adequate for liquid water, were it not for the thin Martian air, which forces pure water to rapidly evaporate or even boil away. Yet salty water is a quite different substance. The surface of Mars is very salty, as documented by every successful lander and rover, by spectrometers in orbit, and by the chemical analysis of Martian meteorites. Water flowing on the surface or in the subsurface of Mars must also contain high levels of salts.

When salty water cools, it either partially freezes into ice or precipitates some of its salts, or both. Whatever liquid is left over is now in its so-called eutectic composition, which is water with just the right salt concentration to remain liquid at the coldest possible temperatures. A salty brine of iron sulfate or calcium perchlorate (two common salts on Mars), in its eutectic composition, can remain liquid down to about -68 degrees C.

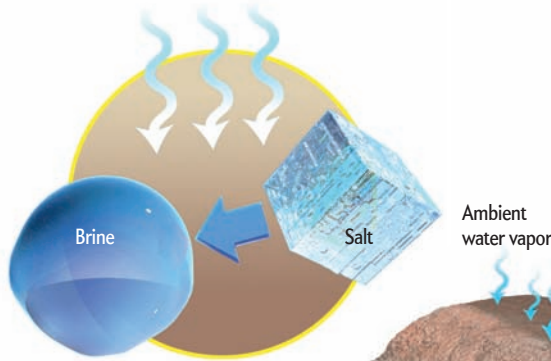
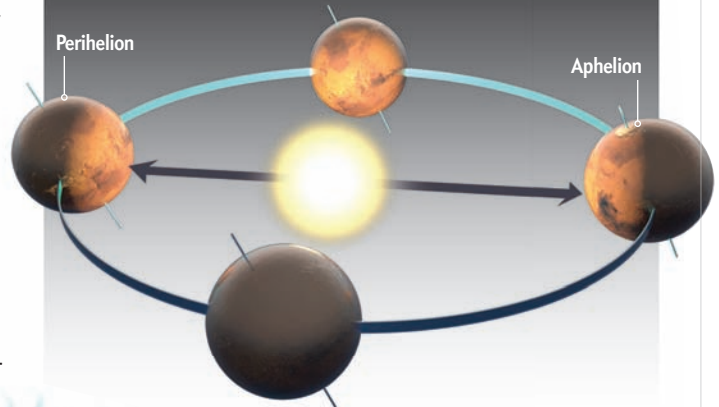
Newly discovered dark streaks on Mars have emerged as the strongest evidence for the presence of flowing water on the planet—and provide the best indication yet that Mars might still contain a niche in which microbial life can survive.

How Can Water Exist on Mars?

Planetary scientists are still debating what causes dark lines to appear annually on southern Martian slopes. But numerous lines of evidence, including the fact that these streaks are found on warm, sun-facing hillsides, implicate the seasonal melting of shallow deposits of salty frozen water. The slope cutaways (below) demonstrate possible mechanisms for delivering water ice to the shallow subsurface, where sunlight can melt it in warmer Martian months (right).

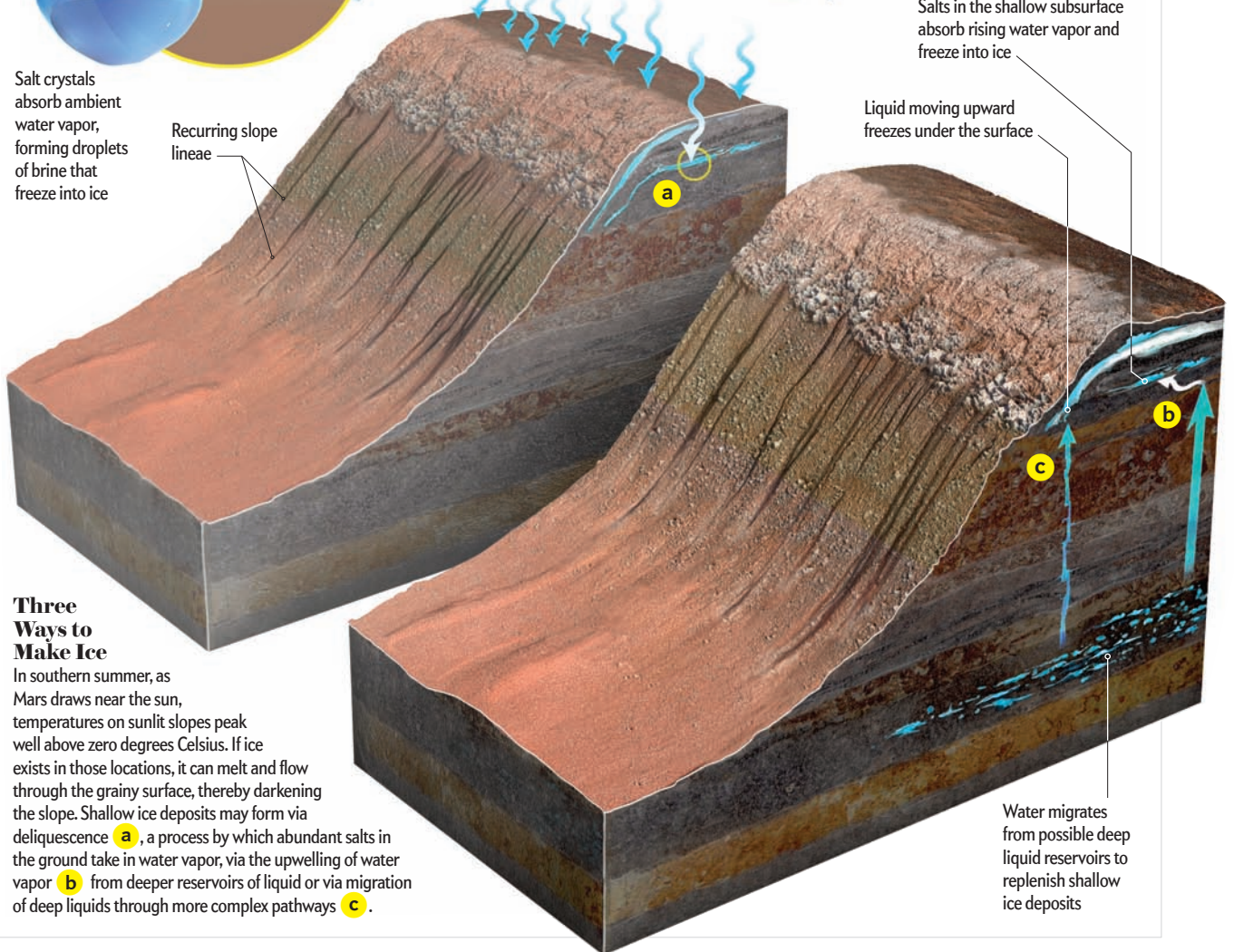
Southern Summer: The Great Thaw

Mars follows an elliptical orbit that carries the Red Planet significantly closer to the sun at perihelion (the closest point in its orbit) than at aphelion (the farthest point). Mars's orbital orientation shifts, or precesses, on timescales of tens of thousands of years; currently the planet reaches perihelion around southern summer, producing relatively hot summers on that hemisphere. Dark lines appearing on southern slopes during warm months could therefore represent melting ice.



Salt crystals absorb ambient water vapor, forming droplets of brine that freeze into ice

Recurring slope lineae



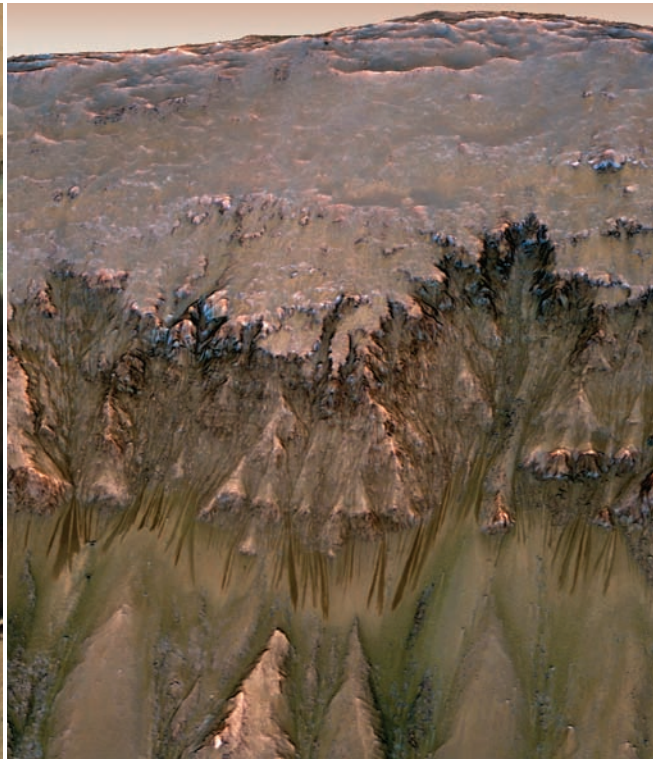
Salts in the shallow subsurface absorb rising water vapor and freeze into ice

Liquid moving upward freezes under the surface

Water migrates from possible deep liquid reservoirs to replenish shallow ice deposits

Three Ways to Make Ice

In southern summer, as Mars draws near the sun, temperatures on sunlit slopes peak well above zero degrees Celsius. If ice exists in those locations, it can melt and flow through the grainy surface, thereby darkening the slope. Shallow ice deposits may form via deliquescence **a**, a process by which abundant salts in the ground take in water vapor, via the upwelling of water vapor **b** from deeper reservoirs of liquid or via migration of deep liquids through more complex pathways **c**.



RECENT EPISODES of erosion or deposition in Martian gullies (*left*), presumably driven by dry ice frost rather than water, appear blue in a false-color image. Flowing water may, however, produce the recurring slope lineae streaking crater walls (*right*).

Furthermore, such eutectic liquids can survive environmental exposure much better than water can—they evaporate at less than one tenth the rate of pure water. The unusual properties of eutectic brines would make them far more stable on Mars than pure water, so we began to believe that these strange flows on warm slopes might, in fact, be the result of salty water.

Nevertheless, we followed the standard practice of pursuing multiple working hypotheses. Could some dry—or nearly dry—phenomenon explain these observations? No purely dry process, such as rockfalls or landslides, has been described that can account for the seasonality, the incremental growth and the sensitivity to temperature, and we had never seen anything like them on Earth’s desiccated moon.

Next we considered that volatile compounds such as water might be involved but only as minor players. If volatiles make soil particles stick together, the warmest temperatures could sublimate away that adhesive, thus releasing dry grains to flow downhill. (NASA’s Phoenix mission had encountered such stickiness in 2008, when soil stubbornly stuck to the inside of the robot’s inverted scoop instead of falling into the intake openings for the onboard instruments.) Yet that hypothesis could not explain why RSL show no topographic relief nor why they fade. Water that darkens the soil and flows only when warm, before freezing again at night, best explained the observations.

A watery origin for such surface activity would not be totally alien. In Antarctica, similar-looking water tracks do form from the shallow subsurface flow of salty brines. Tantalizingly, researchers have found microbes living in these Antarctic water tracks. So why not declare, “Eureka”? We have

learned from the gullies to be circumspect—appearances can be deceiving. (Interestingly, though, we have found many RSL near small channels or gullies, suggesting that some subset of the gullies may be carved by water after all.) Additionally, the terrestrial analogues can carry us only so far: Mars gets much colder at night than Antarctica does, so the active layer of unfrozen soil is much thinner.

CLAIMS OF WATER, WATER EVERYWHERE

WE WERE NOT THE FIRST, nor even the second, batch of researchers to suggest the presence of liquid water on modern-day Mars. Photographs from the Phoenix mission showed what looked like water droplets on the legs of the robotic lander. That idea seemed pretty crazy to me until I learned about deliquescence, a process by which salts absorb water from the atmosphere when both the temperature and relative humidity of the air are sufficiently high. If Phoenix’s retrorockets kicked up perchlorate salts when it landed, the conditions may have been right for the salts to absorb water and create droplets of liquid. I thought saltiness was a new paradigm for producing water on Mars until I realized that Robert B. Leighton and Bruce C. Murray of the California Institute of Technology had published this idea in 1966.

Deliquescence appears to be a tempting way to explain RSL, but the process produces very tiny amounts of water from the thin Martian air—not enough to flow down slopes unless some mechanism allows it to accumulate over time.

Perhaps melting subsurface ice is responsible for RSL. We know, based on the remote sensing of neutrons from orbit, that

the middle to high latitudes harbor shallow ice deposits. Some of the fresh impact craters we have discovered with HiRISE exposed this ice down to 40 degrees north latitude, somewhat closer to the equator than expected.

What are these ice deposits like? Surprisingly, the ice excavated from below the rock-strewn surface is remarkably clean, with very little soil mixed into the frozen layer. This means that the ice is not the product of condensation from the atmosphere, which fills the spaces between fine-grained regolith particles. Nor does it seem to be a remnant of snowfall, which does not last long on the surface before it sublimates away. Instead perhaps thin films of salty water migrate from below and refreeze into a clean subsurface ice layer.

This mechanism avoids various problems with sublimation. Because nonsalty ice sublimates much faster than frozen brine, almost all of the ice that formed in a past climate in the shallow subsurface would have sublimated away by now. Only the saltiest ice would remain. Steep sun-facing slopes may then absorb the warmth needed, in the summer, to melt the briny ice in places where it persists.

We have observations that support this idea. Peak RSL activity corresponds not to the peak surface heating but to peak temperatures in the shallow subsurface, which occur months later. On the other hand, if summer temperatures are warm enough to melt the briny ice, then the ice should disappear over time. Perhaps it *is* disappearing, and RSL are only active for a few Martian years or decades at each location, or maybe the water is somehow replenished [see box on page 63].

LOOKING FOR LIFE IN ALL THE RIGHT PLACES

AS OF YET, there has not been any direct identification of water at the RSL sites. The spectrometer on MRO is our best hope for accomplishing this, but it may lack the necessary spatial resolution to pinpoint such narrow stripes across the surface. To make matters worse, MRO's orbit ensures that the spacecraft observes perpetual afternoon on Mars, when water is probably not present or abundant at the surface. From lab studies, we now understand that salty water can be stable on the Martian surface during some seasons and at some locations, principally at two times of day: early morning and early evening. The relative humidity of the air decreases as it warms in the morning and increases as it cools in the evening. There may be brief periods when both the temperature and relative humidity are high enough for certain types of salts to absorb and hold on to water via deliquescence. In the evening, this process may happen after sunset, which is a difficult time to conduct targeted observations. In the morning, the deliquescence happens after sunrise, and the water persists even as the relative humidity drops substantially.

The ideal instrument for confirming or disproving that RSL

are formed by liquid water would be a spectrometer with a high spatial resolution (better than five meters, the width of the largest of the RSL) that we can use to observe at multiple times of day, including in the morning. Some of my colleagues and I presented such a mission concept at a recent workshop on future Mars exploration. The mission would also acquire imaging, topographic mapping and temperature mapping, all at high resolution. Such a spacecraft would allow us to confirm the presence of water (or not) and to say something about habitability. If we did not detect water, the phenomenon behind

RSL would require a different explanation—something perhaps even more surprising.

If RSL indeed reflect the presence of flowing liquid water, the natural next question is whether that water creates a habitable environment for some salt-loving microbe. We have learned much about extremophile organisms on Earth—species that can survive especially low or high temperatures, extreme aridity or salinity, high levels of radiation, and so on. We know that such organisms do not just survive but can actually reproduce at temperatures below -20 degrees C in certain liquids. Some eutectic solutions are not habitable (as far as we know), so it is not always true that where there is liquid water, there is life on Earth. Yet many of the RSL sites most likely are warmer than -20 degrees C down to a depth of a few centimeters for parts of summer

days. And Red Planet extremophiles, if they exist, may be even more tolerant than terrestrial microbes to Martian extremes.

The possible implications of a water-streaked Mars are immense. For now, my colleagues and I are still working to better understand the nature of RSL. We have identified many more sites with active RSL than we reported in our initial *Science* paper in 2011. Other researchers have conducted laboratory studies and Antarctic fieldwork to try to observe or replicate on Earth what HiRISE sees from orbit around Mars. We hope that our combined efforts will shed light on this newfound phenomenon and on whether flowing water is indeed the best candidate for its origins. Perhaps, among the myriad discoveries of water on Mars, the 1,001st time will be the charm. ■

In Antarctica, similar-looking water tracks form from the flow of salty brines in the shallow subsurface. Tantalizingly, researchers have found microbes living in these water tracks. But Mars gets much colder than Antarctica.

MORE TO EXPLORE

Evidence for Recent Groundwater Seepage and Surface Runoff on Mars. Michael C. Malin and Kenneth S. Edgett in *Science*, Vol. 288, pages 2330-2335; June 30, 2000.

Seasonal Flows on Warm Martian Slopes. Alfred S. McEwen et al. in *Science*, Vol. 333, pages 740-743; August 5, 2011.

Hydrological Characteristics of Recurrent Slope Lineae on Mars: Evidence for Liquid Flow through Regolith and Comparisons with Antarctic Terrestrial Analogs. Joseph Levy in *Icarus*, Vol. 219, No. 1, pages 1-4; May 2012.

SCIENTIFIC AMERICAN ONLINE

View a slide show of recurring slope lineae and other active surface features on Mars at ScientificAmerican.com/may2013/mars