MILKY WAY HALO: Ghosts of Our Galaxy's Past
PAGE 22

THROUGH THE SCOPE: Hunt Dusty Galactic Cirrus
PAGE 30

TEST REPORT: 16-Megapixel Lucky Imaging Camera
PAGE 58

SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

Curiosity Update

PAGE 14

What We've Learned About Mars

Jupiter at Its Closest
PAGE 48

Amateurs Track Disintegrating Planet
PAGE 66

Perfect Your Narrowband Images
PAGE 36

APRIL 2017

SKY & TELESCOPE

skyandtelescope.com

Curiosity's Discoveries on Mars

After four Earth years on the Red Planet, the intrepid rover has found evidence of long-gone water and habitable environments.

NASA's Mars Science Laboratory, a.k.a. the Curiosity rover, is the most complex machine ever sent beyond Earth. Since its 2012 daredevil landing inside a broad crater called Gale, it has ventured 15 kilometers (9 miles) across the crater's interior, trundling 17 cameras, several spectrometers, a suite of weather sensors, and two miniature laboratories along as it investigates whether Mars was ever habitable.

A habitable environment needs three things: liquid water to facilitate chemical reactions, sources of energy and organic (that is, carbon-bearing) material, and long-term stability — time in which chemistry can take place in that water. It's better if the water is not so acidic or saline that it inhibits chemical reactions, and if a thick atmosphere or magnetic field (or both) shields the surface from harmful radiation.

Geochemists think the Red Planet had all these conditions early in its history. Evidence from recent orbiters suggests that the place to confirm such clement environments once existed is in Mars's oldest rocks, specifically in places where we can see clay minerals from orbit (*S&T:* Sept. 2013, p. 16). These clays formed when volcanic rocks were drenched in neutral or alkaline water, an environment in which microbial life could originate and prosper.

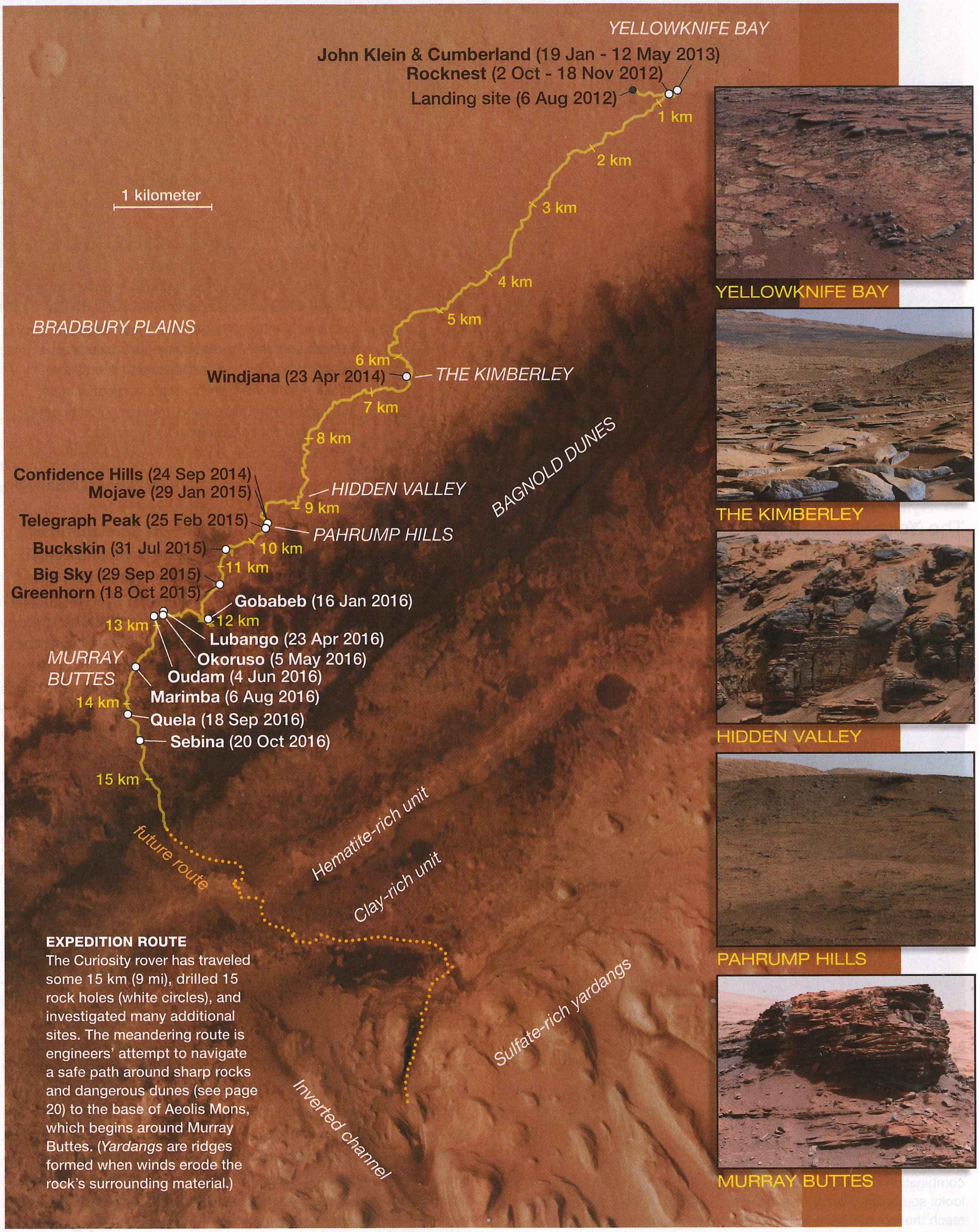
But the mission's scientists hoped to do more than study clays; they hoped to find sedimentary environments like placid ancient lakes, whose rocks would have had a chance of preserving any organic molecules that may have been in the ancient environment.

Curiosity's landing site offered a place to do that. One of the deepest holes on Mars, Gale is located just south of the equator, punching about 4 km deep into the boundary between Mars's southern highlands and northern lowlands. Gale displays clear evidence that water once flowed down its rim, depositing fans of sediment on the crater floor, and it also possesses a 5-km-tall central mound of layered sediments formally named Aeolis Mons. NASA's Mars Reconnaissance Orbiter had spotted spectral signs of clays, sulfates, and hematite (an iron oxide) in the mound's lowermost layered rocks, all of which form in different kinds of wet environments. Also, the stack was the thickest section of sedimentary rock seen on Mars, recording several potentially habitable environments that went, from bottom to top, in a roughly wet-to-dry order.

The grand challenge for Curiosity would be getting to those rocks.

SAY CHEESE Curiosity took this self-portrait at Buckskin in August 2015. The rover team white-balances images to make rock types easily identifiable, so landscapes shown here look slightly different on Mars.

NASA / JPL-CALTECH / MSSS



EXPEDITION ROUTE

The Curiosity rover has traveled some 15 km (9 mi), drilled 15 rock holes (white circles), and investigated many additional sites. The meandering route is engineers' attempt to navigate a safe path around sharp rocks and dangerous dunes (see page 20) to the base of Aeolis Mons, which begins around Murray Buttes. (*Yardangs* are ridges formed when winds erode the rock's surrounding material.)

YELLOWKNIFE BAY

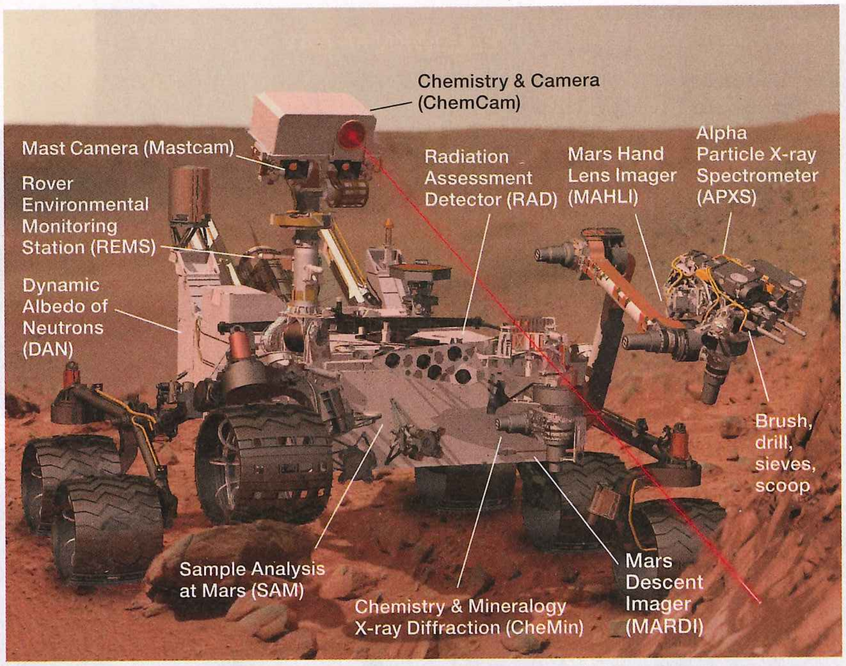
THE KIMBERLEY

HIDDEN VALLEY

PAHRUMP HILLS

MURRAY BUTTES

MAP: *S&T* GREGG DINDERMAN AND EMILY LAKDAWALLA, SOURCE NASA / JPL-CALTECH; INSETS: NASA / JPL-CALTECH / MSSS



Mars Science Laboratory

Curiosity's instruments perform four tasks: remote sensing, environmental sensing, contact science, and laboratory analysis. Remote sensing instruments include the Mastcam, color cameras, and ChemCam, which can determine the composition of materials up to 7 meters away by zapping them with a laser and then analyzing the resulting rock vapor. Environmental instruments include REMS, a suite of weather instruments; DAN, which searches for subsurface hydrogen by pulsing the ground with neutrons; and RAD, which measures incoming radiation. There are two science instruments on the end of the arm: MAHLI, a color camera; and APXS, which measures elemental composition. Finally there are two lab instruments that can ingest drilled rock powder: CheMin, which measures mineral composition; and SAM, which heats cups of sample in a high-temperature oven, measuring composition and isotopes to search for organics.

• Explore the rover at **https://is.gd/curiosityinst**.

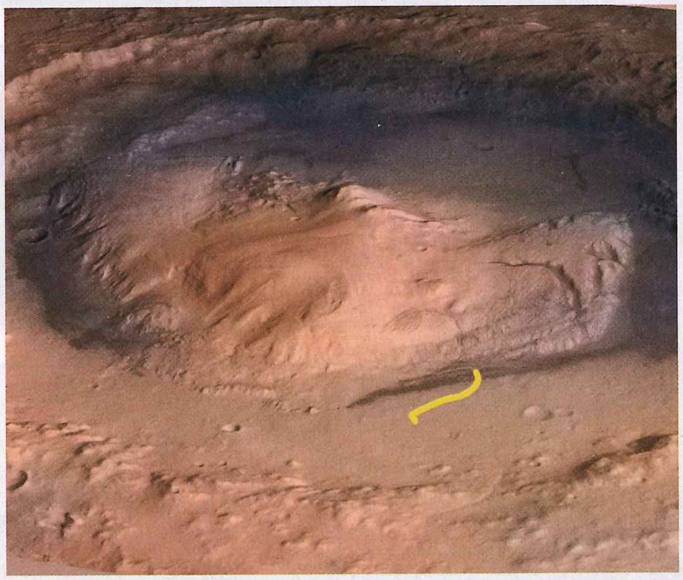
The Yellowknife Bay Campaign

For safety reasons, the engineering team landed the rover far from the mountain, in the flat rocks of the crater floor to its north. Access to the material they had traveled to Mars to study lay 8 km (5 mi) to the southwest, across a hummocky plain of mostly unexciting rocks and soil, then across a break in a dangerous band of active sand dunes (see below).

Near the landing site sat some light-toned rocks that appeared to be the end of a fan of sediment once carried by water that entered the crater from the northwest. Although there was no orbital signature of clay minerals, the appearance of this rocky expanse, named Yellowknife Bay, suggested that scientists might expect to find fine-grained sediments once deposited in standing water. Yellowknife Bay was in the opposite direction from the rover's planned route but held a chance of satisfying the mission's goals. So the science team made the tough decision to drive east instead of southwest. The rocks Curiosity initially encountered en route were mostly isolated boulders, but a few outcrops of bedrock jutted out of the ground. One rock type in particular thrilled geologists: *sedimentary conglomerate*. Seen at locations named Link and Hottah, it consists of loosely bound chunks of rock. The rounded pebbles in Gale's conglomerates offered clear evidence they had been tumbled in fast-moving water 10 to 100 centimeters deep — ancient Martian hillside streams.

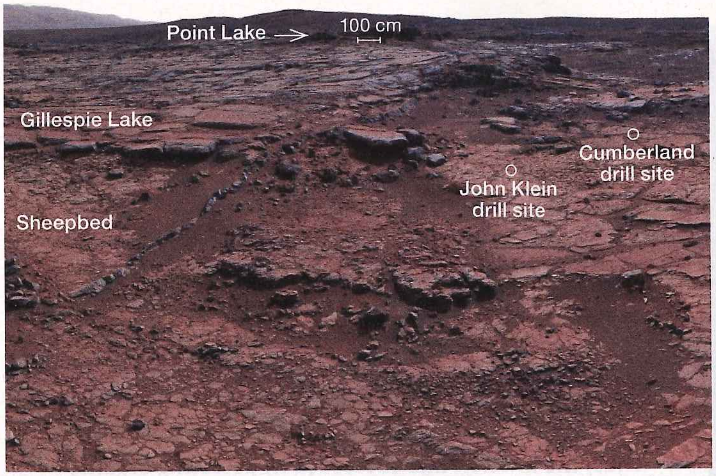
As the rover approached Yellowknife Bay, it entered a geological wonderland. At a site called Shaler: crossbedded, fine-grained sandstones speaking of sediment-rich streams fanning out across the landscape. At Point Lake: a massive, dark rock of enigmatic origin — was it volcanic or sedimentary? At Gillespie Lake: a coarse sandstone, its rounded grains made up of various minerals that must have been plucked from many sources in the plains outside Gale before riding down into the basin and being deposited there.

Finally, at the expanse's lowest point, Curiosity examined what the team named the Sheepbed member, a layered, light-toned rock crisscrossed by bright veins. The sediment was so fine that even Curiosity's highly magnifying MAHLI camera held as close as possible to the rock could not discern individual grains: It had once been silt or mud. Tiny grains



▲ **GALE CRATER** Curiosity landed in the northwest section of Gale, near the foot of its central mountain. This image is derived from a combination of elevation and imaging data from three Mars orbiters and looks southeast. Also shown is the approximate route the rover took to reach the mount's base (yellow). The crater is 154 km (96 miles) wide.

ROVER: NASA / JPL-CALTECH; CRATER: NASA / JPL-CALTECH / ESA / DLR / FU BERLIN / MSSS



▲ **YELLOWKNIFE BAY Left:** This mosaic of Mastcam images shows three major parts of Yellowknife Bay, where Curiosity took its first two drill samples (both in the Sheepbed mudstone). Point Lake is about 30 meters (100 feet) from the rover's location. **Right:** This close-up of the Link outcrop shows the gravel fragments that make up its conglomerate. The rounded bits most likely formed in quickly flowing water.

would've been suspended in the downhill flow and carried out into a lake until, in the still water, they slowly settled to the lakebed, trapping other materials floating nearby, possibly even organic compounds.

It was precisely the kind of environment that Curiosity had been sent to find.

The rover drilled in the Sheepbed rock twice, at sites the team named John Klein and Cumberland. The initial analysis by the Sample Analysis at Mars (SAM) instrument suite confirmed the rock was a mudstone, containing about 20% clay minerals that formed in direct contact with water (see page 21). And not the acidic, sulfate-rich water that the Spirit and Opportunity rovers had seen evidence of; this was gentler water, neither acid nor alkaline — the still, neutral water of a crater lake, an ancient habitable environment.

Methane with SAM

Success in hand, the team's next goal was to understand how Yellowknife Bay related to the crater's central mound — was it older or younger than the mountain? How different were the environments, and how many climatic turns did Gale's geologic story contain?

The rover now set off in a hurry. The Yellowknife Bay campaign, though productive, had taken seven months. Engineers estimated it would take about 200 "drive" sols — roughly another year, given that the rover doesn't drive every sol — to travel the 8 km to the entry point to the base of Aeolis Mons, or "Mount Sharp" as the team calls it (after beloved Caltech geologist Robert Sharp). And the nominal mission was only two years long.

Curiosity moved rapidly toward the mountain, covering nearly half the distance in the last six months of 2013. As the rover drove along, SAM periodically sniffed the air, searching for methane. Sunlight destroys methane in Mars's atmosphere in about 300 years, so if methane were present, its abundance should drop slowly. Yet Earth-based and orbiter observations had occasionally detected short-lived spikes, suggesting something — whether biotic or abiotic — was actively releasing and destroying methane on Mars. Curiosity's first several attempts to find atmospheric methane only set an upper limit of 1.3 parts per billion (ppb).

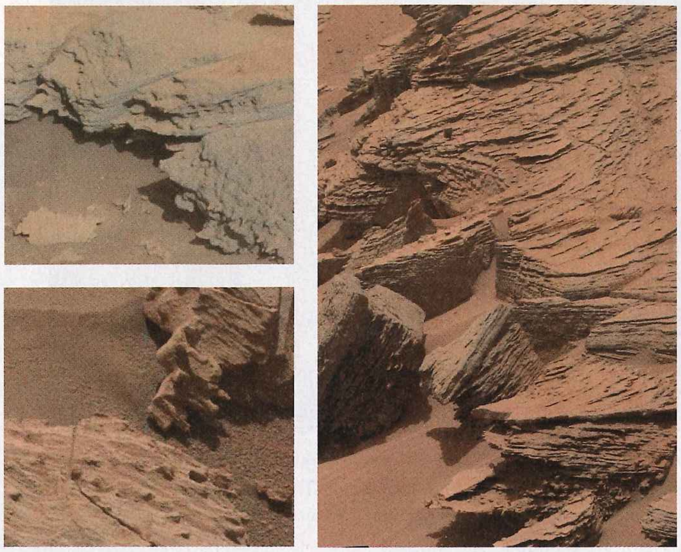
Suddenly, on sol 466, the rover detected a 5½-ppb surge. Methane abundance climbed rapidly over the next 60 sols. Then, in the next measurement on sol 573, the methane level had plummeted, back to less than 1 ppb.

What caused the methane spike? Researchers still don't know. But they've measured methane periodically at intervals ever since. Over two Martian years (45 months), they have seen its abundance shift seasonally: lowest (about 0.3 ppb) near southern winter solstice, rising to a high of around

◀ **JOHN KLEIN** Curiosity's first drill site, in the Sheepbed mudstone. The column of tiny dark dots is where ChemCam's laser sampled the rock's composition. Powder from the drilling process surrounds the hole.

◀ **SAM: MARTIAN LAB** The Sample Analysis at Mars suite analyzes elements and compounds separated from soil, rock, and atmosphere samples. The wheel moves small "cups" (test tubes) of powdered samples to the next analysis step. The majority of the system's 74 cups are quartz, which can be heated to release trapped atmospheric gases.

YELLOWKNIFE BAY, LINK, AND DRILL SITE: NASA / JPL-CALTECH / MSSS; SAM: NASA / GSFC



▲ **ERODED ROCK** Wind has worn down Gale's terrain, as seen in these rocks from Naukluft Plateau *(left top and bottom)* and Upheaval Dome *(right, near Pahrump Hills)*.

0.8 ppb in southern summer. After exploring many possible correlations, the SAM team now thinks that the seasonal variation in this tiny amount of methane *isn't* from microbes; instead, it's tied to seasonally varying levels of solar ultraviolet radiation breaking up organic material on the ground. Curiosity measures the intensity of sunlight with a deck-mounted UV sensor that's part of its REMS weather suite. A small amount of carbon-rich material rains year-round onto the ruddy terrain as micrometeorites. When Mars is closest to the Sun (a period coinciding with southern summer), the stronger-than-average sunlight breaks down organics into much smaller molecules, including methane, causing the seasonal methane cycle.

Isotopic Ages

As the rover drove, SAM's science team continued to perform different kinds of lab analyses on Cumberland material that had been "doggie bagged" inside some of the instrument's sample cups. By studying the amount of argon produced by potassium-40's radioactive decay, the researchers determined an age for the rocks of 4.2 billion years (give or take 350 million). Since these were sediments, this age represents that of the original rocks, once part of the highlands and crater rim, that were ground down and later deposited on Gale's floor.

At the same time, SAM measured another isotope of argon as well as those of helium and neon, produced when cosmic rays bombarded near-surface atoms in the rock. The amounts of these noble-gas isotopes showed that the rocks had only been exposed at the surface for 80 ± 30 million years. Together, the results mean that the rocks within Gale are old but — at least at Cumberland — have only been exposed recently, presumably by the activity of sandblasting winds that have eroded Gale's rocks into sometimes fantastic shapes. Such short exposure ages are good for organics-hunting scientists, because there's been less time for solar and cosmic radiation to break down any interesting molecules contained within the upper few centimeters of rock accessible to Curiosity's drill.

SAM also hunted for organics in the doggie-bagged Cumberland samples, and an analysis of one of them yielded the detection of chlorobenzene — a ring of six carbon atoms bonded to five hydrogens and one chlorine. Chlorobenzene likely formed when perchlorate ions present in the rock reacted with some hydrocarbon molecules. Perchlorate is a powerful oxidizer that was detected in modern Martian soil by the Phoenix lander. In water, perchlorate will attack complex organic molecules, breaking them into smaller pieces.

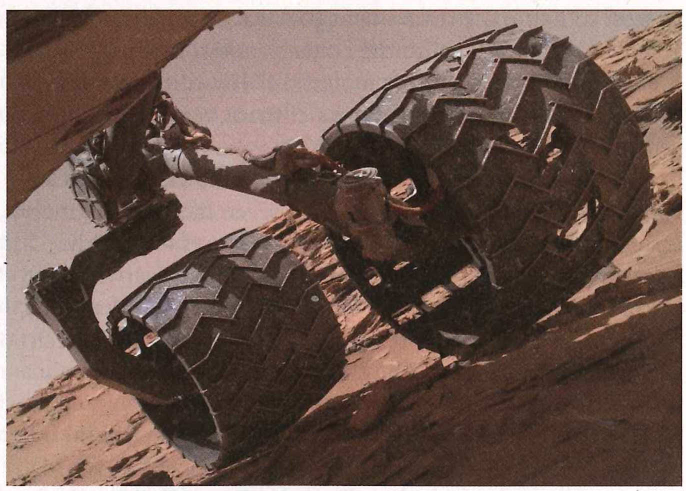
Thus, the mission had succeeded in detecting organic material locked within the rocks when they first formed, billions of years ago. If life had existed then, evidence of it could be preserved in Martian rocks — a promising find for future paleobiology missions.

Wheel Problems

The drive toward Mount Sharp took a toll on the rover: Mission engineers discovered serious damage to the wheels. The wind had eroded the hard rock of the crater floor into spiny prominences that stuck up like sharks' teeth; embedded in the ground, they neither shifted out of the way nor collapsed under the rover's weight. Instead, they speared the wheels like so many can openers.

The wheel damage put the brakes on the mission's rapid driving progress.

While the engineers drove more carefully and studied the problem, they steered the rover into sandy valleys among ridges of layered rock, heading for an interesting, striated-looking outcrop they named the Kimberley formation. Sticking to valleys rather than the plateau tops meant a twistier path



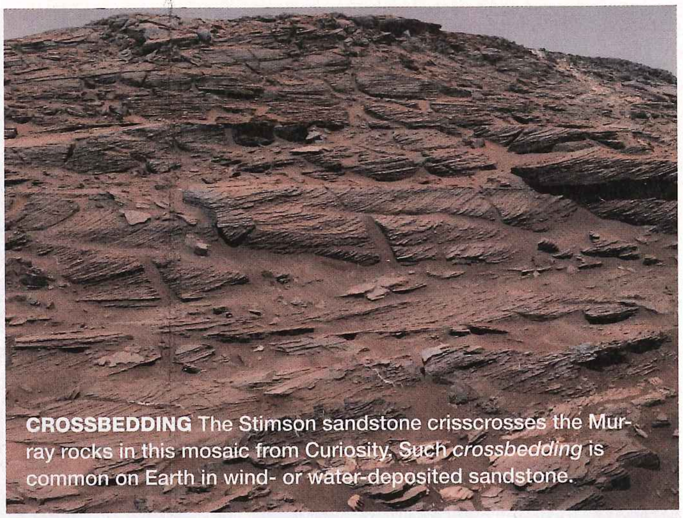
▲ **HOLEY ROLLER** Despite their careful design, Curiosity's wheels became increasingly punctured by pointy, immobile rocks the rover drove over. (The regular-shaped rectangular holes, on the other hand, are intentional: Scientists use the marks they leave in the rover's tracks to verify the distance the rover has traveled.)

ALL IMAGES: NASA / JPL-CALTECH / MSSS

toward Mount Sharp, in part because it limited how far ahead the rover could see. The driving pace slowed dramatically.

Pulling up to Kimberley, they discovered the striations to be eroded, tilted beds of sandstone. After much debate, the scientists determined the beds had formed in that tilted orientation, as the toes of deltas that formed when a fast-moving stream carrying sand particles emptied into a still body of water, dropping its sediment load. Isotopic age-dating revealed that the rocks had also been exposed for several tens of millions of years.

From there, the team proceeded cautiously, mapping the terrain ahead to plot a wheel-safe course. That often meant keeping to the edges of sandy valleys where the wheels could get traction but avoid pointy bedrock.



CROSSBEDDING The Stimson sandstone crisscrosses the Murray rocks in this mosaic from Curiosity. Such *crossbedding* is common on Earth in wind- or water-deposited sandstone.

Onward and Upward

Curiosity reached Mount Sharp in late 2014, just after an extension of its original two-year mission. In images the summit appeared to be as far away as ever, but the rover had never been aiming for the peak: It was after the layered sediments at the base.

Although the dunes continued to block the path to the mountain, their migration across the ground had scoured clean a 14-meter-thick section of rock that represented the very lowest — therefore, oldest — exposed strata of Mount Sharp. There scientists encountered another very fine-grained mudstone, called the Murray formation. Scientists had expected that the progression from streambed rocks seen near the landing site, to sandy deltas observed along the traverse, should end with fine-grained lake sediments. Their discovery at Mount Sharp validated the idea that billions of years ago, the crater's interior was a lake that slowly filled with sediment.

The Murray formation interfingered with the tilted beds of the Kimberley-like stream deltas but also climbed over them, showing this new rock was younger than the stuff Curiosity had explored before. The rover was, indeed, beginning to ascend Mount Sharp, fulfilling the promise of reading its layers like chapters in a book.

At a site called Pahrump Hills, the rover walked the outcrop as a human geologist would do, scoping it out, looping through a second trip to examine it in detail with MAHLI and APXS, and finally drilling in three locations. The Murray layers were incredibly thin and regular, the sort of sediments that form on Earth, when pulses of very fine sediment slowly settle in still lake waters. The number of muddy layers Curiosity has climbed imply that Gale's lake lasted for millions of years — longer if there were any gaps in the existence of the lake.

The Murray sediments also showed many other signs of water's action upon the rocks after burial: a network of thin veins of the salt calcium sulfate mixed with boron, which may suggest brine concentrated thanks to evaporation. Curiosity also found desert-rose-like mineral concretions. These can form after a sediment is buried deeply and begins to fuse into rock.

Departing Pahrump Hills, Curiosity drilled a final time into the Murray formation at Telegraph Peak and then headed westward, skirting the northern edge of the dune field and moving in and out of valleys, slowly ascending. At Buckskin, the rover discovered an unusual silica mineral called tridymite. On Earth, tridymite is only found in environments with low pressures but extremely high temperatures — typically, explosive, silica-rich volcanic eruptions. These kinds of volcanoes were not thought to exist on Mars. But geologists can't figure out any other way to make it. Another tantalizing clue to Mars's past.

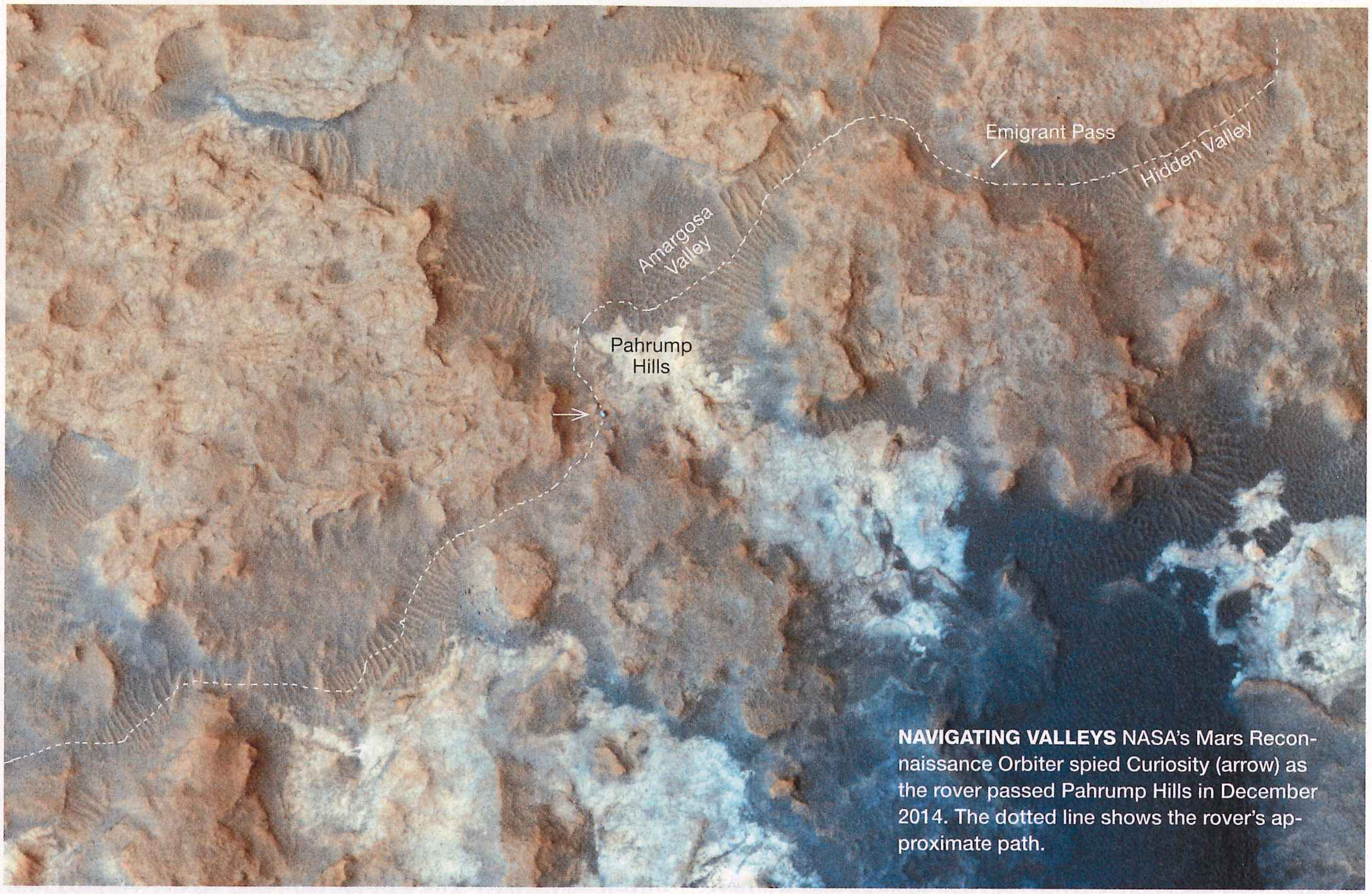
Near Buckskin, the rover had its first encounter with the next rock unit, named the Stimson formation. Stimson turned out to be a coarse sandstone, likely deposited by wind. It clearly cuts across Murray in a relationship called an *unconformity*: The Murray sediments were laid down, buried, turned to rock, exhumed, and eroded in some kind of arid environment where windblown sands then covered them up.

Cumberland's Atmospheric Window

One other discovery made in the Cumberland sample: The SAM team found evidence that Mars is missing some of its atmosphere. This was no surprise. Many different missions, most recently the MAVEN orbiter, have confirmed that Mars has lost (and continues to lose) its atmosphere to the stripping action of the solar wind (*S&T:* Sept. 2014, p. 20). The modern Martian atmosphere has six times as much deuterium — a hydrogen isotope with both a proton and a neutron in its nucleus — as single-proton hydrogen. The original ratio was probably closer to 1:1.

In Cumberland, Curiosity found a record of a Mars that had lost only some of its atmosphere, with a deuterium-to-hydrogen ratio of 3:1. Those ancient rocks therefore formed in a time when Mars hadn't yet lost its youth, under much thicker air.

NASA / JPL-CALTECH / MSSS



NAVIGATING VALLEYS NASA's Mars Reconnaissance Orbiter spied Curiosity (arrow) as the rover passed Pahrump Hills in December 2014. The dotted line shows the rover's approximate path.

Sedimentologists even found torn-up bits of Murray incorporated within the base of Stimson. There is probably a lot of time separating the formation of the Murray and Stimson units; the latter might well be the youngest rock that Curiosity will explore. Understanding these kinds of stratigraphic relationships will eventually enable the science team to tell the full story of the climatic evolution of Mars at the Gale Crater site. It's work that can only be done with field geology, at the outcrop level, from a rover or astronaut's point of view.

Beyond Buckskin, the rover drove up and onto the Stimson formation, crossing ridge after sandstone ridge. Fractures crosscut the Stimson exposures, but unlike previous fractures Curiosity had seen, these were surrounded by bright halos. Curiosity drilled the Stimson unit both inside and outside such a halo, at Big Sky and Greenhorn. In the halo (Greenhorn), the CheMin instrument found a rock containing silica-rich clays and not much else — its other chemical components had been leached out, as sometimes happens in highly acid groundwater environments on Earth. For a variety of reasons, the waters that leached the Stimson sandstone could not be the same as the ones that put sulfate veins in Murray's mudstones. How many different times have these rocks been buried and wetted? How much time separated each wetting episode?

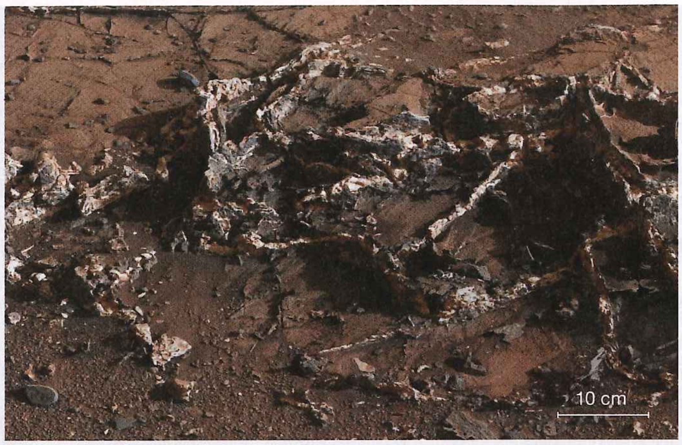
That last question can't really be answered with Curiosity's instruments; no dedicated age-dating instrument has yet been sent to Mars. One reason NASA's Mars 2020 rover will collect samples for eventual return to Earth is to permit geochronology experiments that will put numbers on these relative dates.

Curiosity finally turned toward the gap in the sand dunes on sol 1369 (June 12, 2016). Now the rover could head directly up the mountain, rather than skirting it. Through the summer of 2016, the rover drove among the spectacular landscapes of the Murray Buttes, knobs of Murray mudstone capped by Stimson sandstone. Martian wind whipping among the gaps between the buttes swept the ground free of dune sands, making a safe place for Curiosity to pass.

What's Next?

After four years of exploring, the science team has begun to understand elements of Gale's ancient history. Gale did host a lake for millions of years, one containing mostly neutral water, which occasionally dried and later refilled. Even after the surface became dry and inclement, percolating mineral-rich groundwater could have provided a persistent habitable environment for tens to hundreds of millions of years. While sometimes acidic, conditions still appear to have been hospitable to microbes — particularly those able to metabolize minerals' flow of electrons and survive deep in the cracked mudstone, away from sunlight. But searching for vestiges of life will have to wait for a future mission.

NASA / JPL / UNIVERSITY OF ARIZONA



▲ **PROTRUDING VEINS** This network of mineral veins juts up 6 cm (3 inches) above the surrounding rock. It formed when water moved through fractured rocks, depositing the minerals that now make up the veins. The surrounding rocks have eroded away to expose them.

Curiosity will soon be across the Bagnold dune field, and then it will still have another kilometer or so of Murray rock to cross before it finally reaches the next major transition: the "hematite ridge," a break in both the topography and the mineralogy where the rock is rich in this water-made iron oxide. Crossing that ridge, Curiosity will move up into a rock whose clays are concentrated enough to be visible to orbiting spectrometers. The rover will likely spend the rest of its second 2-year-long extended mission within these three main rock types, as it traverses and drills from site to site to understand how the mineralogical differences record changes in Mars's climate over time.

If Curiosity gets a third mission extension in late 2018, it might continue studying those rocks, or it could continue upward. The next major boundary it could encounter is a place where a channel once cut through Mount Sharp and emptied into Gale's ancient lake, forming what looks like a spreading, fan-shaped delta. The sediments deposited within that delta and the channel that fed it turned into rocks that were more resistant to erosion than the rest of Mount Sharp, so after eons of weathering, the channel now stands *above* the surrounding rocks. Curiosity could use that channel as a ramp to drive upward into the mountain, transitioning from a time in Martian history where clay minerals drew from neutral waters to a period when water was scarcer and rocks ended up more sulfate-rich.

Or not. Several things could limit the rover's lifetime. Its wheels are the least of its problems; with care they should last as long as they need to. Some instruments are already showing signs of their age. And the radioisotope power source is, inexorably, decaying. Within 14 years of fueling — or about 4,700 sols into the mission, roughly the current age of the Opportunity rover — it will no longer provide enough power to keep the rover alive even through sleep, and the rover's driving days will be over. Who knows, Opportunity may yet outlast Curiosity.

■ Currently writing a book on Curiosity, **EMILY LAKDAWALLA** has penned a Planetary Society blog at **planetary.org** for a decade. She thanks mission members Ashwin Vasavada, Paul Mahaffy, and Kathryn Stack Morgan for help with this article.

"MUDPIES" The mineral compositions of mudstones at 10 of Curiosity's drill sites differ significantly. (The rover's other five drill sites through 2016 were in sandstone.) Each pie chart displays the minerals in a drill sample. The diagonal represents the overall elevation change from Yellowknife Bay to the last sample, some 200 meters (700 feet). They're not a straight stratigraphy, however: Only the last four samples (Oudam, Marimba, Quela, and Sebina) were methodically spaced, each separated by 25 meters of elevation. The mineralogical variations in these mudstones may be due to differences in any or all of these factors: the source materials deposited by water that entered lakes, the processes of sedimentation and rock formation, and how the rocks were later altered.