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Death of a Mars Rover

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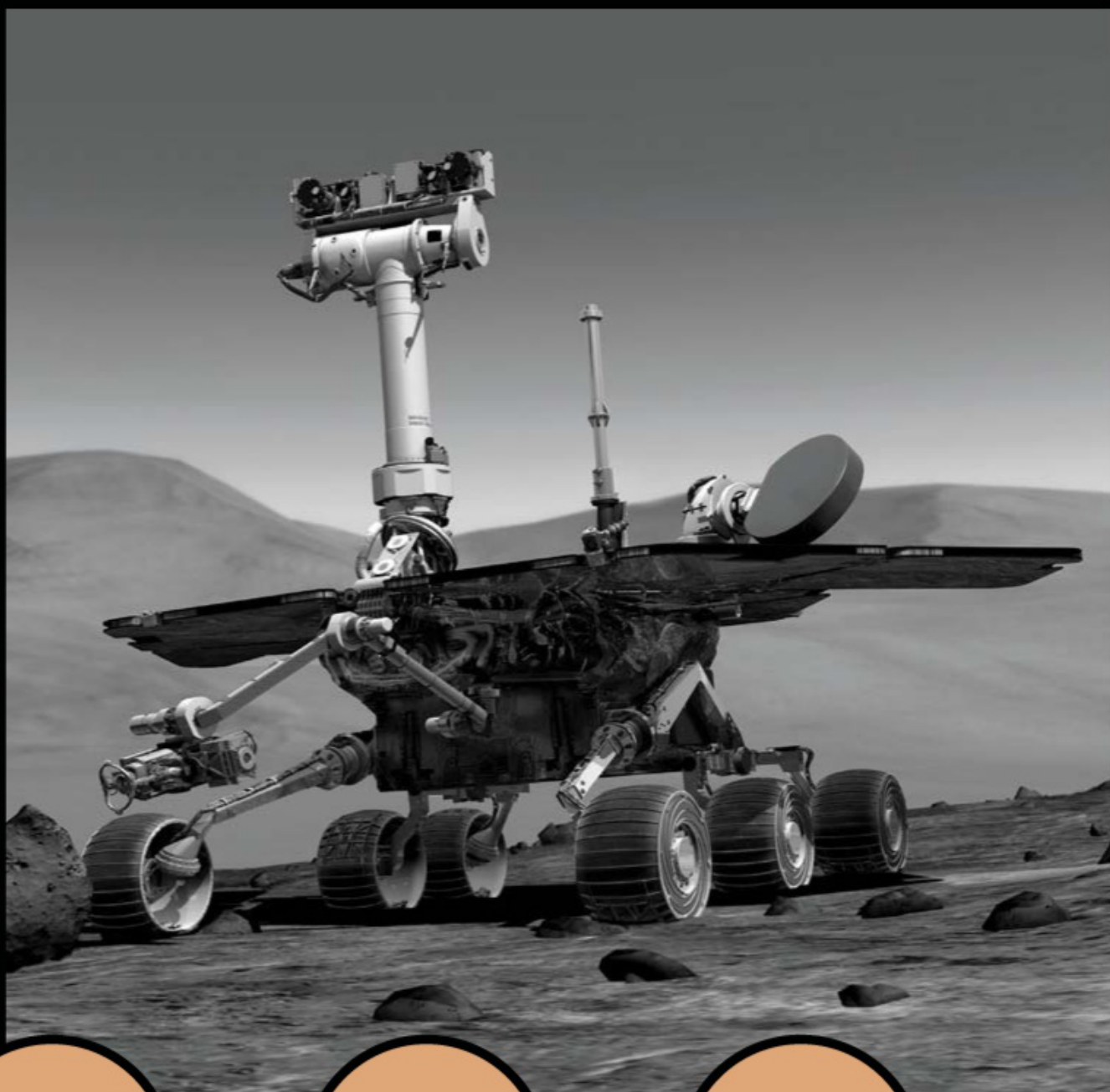
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Opportunity's End

The Martian rover's spectacular and heartbreaking saga helped rewrite textbook knowledge of the Red Planet.



14+
years
lifespan

217,594
raw
images

45
kilometers
traveled

32
degrees
(steepest slope)

“Opportunity had gotten through a lot of tough scrapes before, so we learned never to bet against the vehicle.”

—ABIGAIL FRAEMAN



◀▲ **THE ROAD TRAVELED** Opportunity looks back on its own tracks on two days in 2010: May 8th (*far left*) and August 4th (*above*). An artist's concept sits between.

The Martian winds were picking up — kicking dust, sand, and debris off the ground in a storm that would soon envelope the entire globe.

For weeks, amateur astronomers on Earth would swing their telescopes toward the Red Planet only to find its familiar surface features hidden under a thick veil of dust. The many satellites that orbit Mars would similarly image a hazy globe. And a beloved rover on the surface would fail to see the Sun, as daytime temperatures plummeted and the winds pummeled against it. Opportunity was in the heart of the storm.

On June 10, 2018, when the storm was well underway, NASA scientists asked the rover to take two photos of the Sun. But the images revealed nothing more than the faintest pinprick of light surrounded by a blackened sky. “By the time the dust storm was at its strongest, it was as dark for Opportunity at noon as it would be on a moonless night here on Earth,” says Tanya Harrison (Arizona State University). “I’m not sure we can even fathom a storm that severe on Earth — that just could completely black out the Sun.”

Little did scientists know at the time, those two photos would be Opportunity’s last. After the rover transmitted the images to Earth, it hunkered down for the dust storm. Scientists on Earth waited, hopeful that once the storm cleared the rover would pop back to life. But the intrepid explorer never stirred. In February 2019, NASA declared the mission complete.

“It’s almost like the death of a loved one,” says project manager John Callas (Jet Propulsion Laboratory). “You’re used to seeing that individual every single day and interacting with that individual. You have meals with them. You live your day with them. Suddenly, they’re gone.”

The Long Goodbye

Unaware of the coming tragic ending, the mood last September was hopeful — optimistic even — with many scientists expecting that the rover would pull through. “Opportunity had gotten through a lot of tough scrapes before, so we learned never to bet against the vehicle,” says deputy project scientist Abigail Fraeman (JPL). “Anything is possible.”

In the best-case scenario, the rover would simply wake up and phone home. “We were hoping that all we really had to do was wait and listen, and we were listening every day,” Callas says. More likely, however, was a scenario in which heavy dust had settled onto Opportunity’s solar panels, blocking the Sun and preventing the rover’s batteries from recharging. Here, too, scientists had hope: They expected that a heavy wind would clear away any settled dust, allowing the rover to rouse from its deep slumber.

But when the silence stretched into January, the team started to worry, convinced that there was another issue. It was possible that the rover’s internal clock had stopped keeping track of time. This would be a serious problem, because Opportunity wouldn’t know when to go into deep sleep at night and would instead just burn through the battery. Or perhaps one of the radio antennas was broken and the rover couldn’t send signals home, even if awake. So the team

started to exercise more extreme measures, sending Opportunity commands to restart its clock or communicate with the orbiters overhead by using different antennas.

Nothing worked. To make matters worse, February signaled the end of the winds and the beginning of colder, darker days, even near the equator. If Opportunity didn't stir before the seasons turned, the rover definitely wouldn't after.

So on the night of February 12th, scientists and engineers gathered at JPL where Thomas Zurbuchen, the associate administrator of NASA's Science Mission Directorate, announced that they would send the last commands to Opportunity that night. If there was still no response, he would declare the end of the mission.

Over the next two hours, the team sent four commands streaming toward the Red Planet. And for the most part, the spirit was jubilant: People hugged colleagues they didn't see often, they shared stories about the rovers, and they talked about how the rover had impacted their lives.

Mike Seibert, a former mission manager who left JPL in 2017, for example, got married on the anniversary of Spirit's launch day. Fraeman won a contest sponsored by the Planetary Society when she was in high school and scored a trip to JPL for the night Opportunity landed — a moment that encouraged her to become a planetary scientist. And Doug Ellison (JPL) was a multimedia producer for a medical company when he began stitching together mosaics from Spirit and Opportunity's publicly available images in his free time



▲ **THE SUN GOES DARK** This series of simulated images shows what Opportunity would have seen as the rising dust storm blotted out a mid-afternoon sky. Each frame corresponds to a measure of atmospheric opacity, called *tau*, of 1, 3, 5, 7, 9, and 11. The rover survived a 2007 storm with a tau somewhere above 5.5 (similar to the third panel from left), but the 2018 storm neared 11 (far right).

— a hobby that ultimately landed him a job directing Opportunity to take images of the Red Planet.

With a trip to the bar before the event and a never-ending number of stories to be told, the evening was akin to an Irish wake. But when the last command was sent, the room grew deadly silent as everyone waited 27 agonizing minutes (13.5 for the signal to reach Mars and 13.5 for a signal to return).

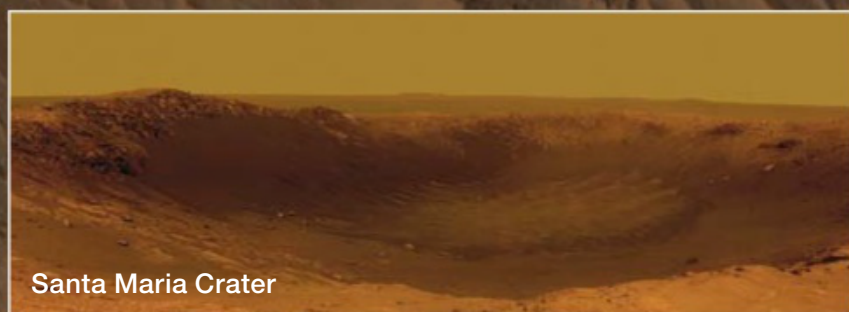
The countdown hit zero with no news.

“We knew with that final command, that this is it — this is over,” Harrison says. “And then a lot of people just kind of lost it. I stood in the corner crying, hugging Keri Bean (JPL) for a long time.”

DARKENING SKY: NASA / JPL-CALTECH / TAMU

THE TREK

Over the course of more than 14 years, Opportunity traveled some 45 km, visiting several craters, finding evidence of water-deposited bedrock, and seeing dust devils, among other sights.



Santa Maria Crater



Eagle Crater



Endurance Crater



Victoria Crater

In that moment, the team was forced to accept the inevitable. They were forced to say goodbye.

More than Machine

For those who see space-faring robots as gadgets of scientific discovery and nothing more, it may sound strange that so many considered the rover something analogous to a friend. Even the most calculated scientists tend to anthropomorphize Opportunity — better known as “Oppy” — and her twin, Spirit. And it’s easy to see why from merely a design standpoint: They were each about five feet tall and outfitted with a robotic arm and a neck topped with two eye-like science cameras, all eerily sentient-looking.

But Callas notes that not only did the rovers appear human, they had human-like qualities. “They were intrepid, they were dutiful, they were accomplished,” he says. “Sometimes they were recalcitrant. Sometimes they were funny. They were loyal. How could you not fall in love with them?”

And fall in love many of us did. Not only did the final command leave the rover team wistful, but it also inspired an outpouring of affection from much of the world. Opportunity trended on Twitter for days as scientists and non-scientists alike shared stories of the rover’s impact on them. Even former President Barack Obama posted a photo of the rover’s tracks to Instagram and congratulated the team.

But for many, it was the days after the final

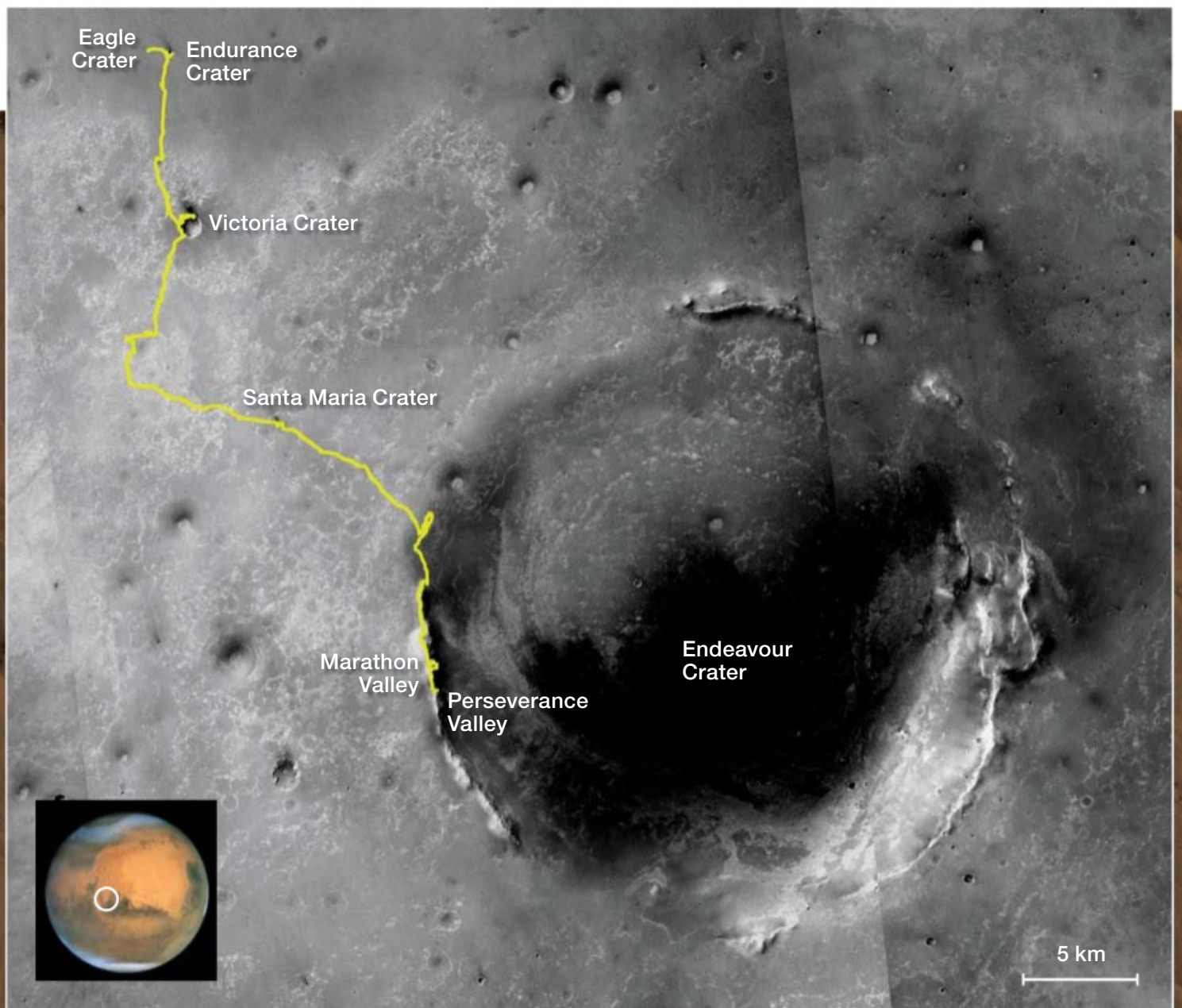
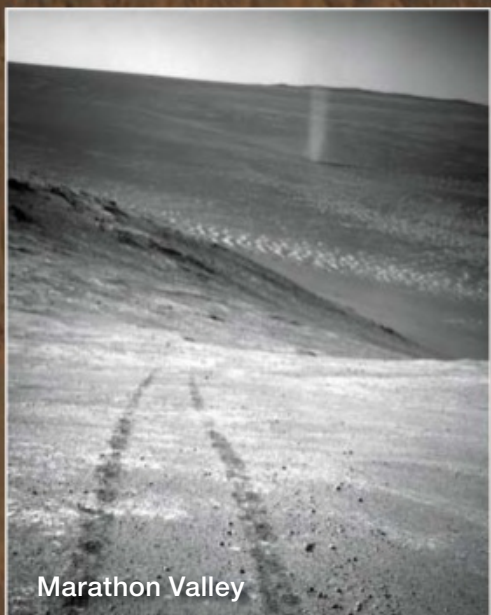
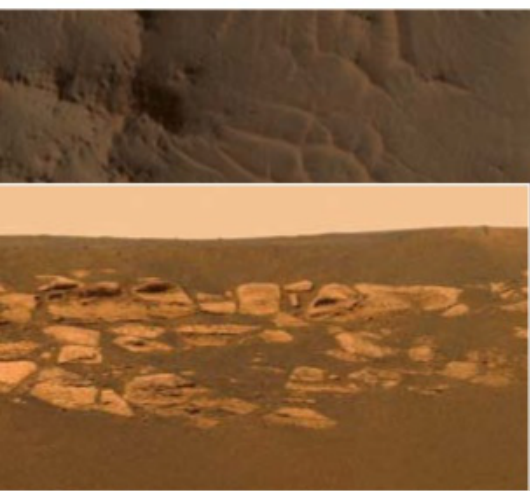
“Sometimes they were recalcitrant. Sometimes they were funny. They were loyal. How could you not fall in love with them?” —JOHN CALLAS

command that were harder. For more than a decade, the day-to-day lives of these scientists had revolved around Opportunity. Every morning they would check the status of the vehicle, plan rover operations, and prepare the commands. “You really do start to feel a connection to something that’s more than just a machine when you spend 15 years of your life making sure Opportunity is healthy, making sure her power is okay, making sure all the commands you’re sending are good,” Fraeman says.

Now, the team’s daily activities have shifted. “We come into work now and it’s like, ‘What do we do?’” Callas says. “It’s dramatic change.”

Seibert, who had a head start on mourning because he left in 2017, points out that the new daily routine likely won’t include the adrenaline rush that often came with working on the rovers. “You don’t have that little dopamine hit you get when every image comes down and shows whatever you

THE TREK: MAP: NASA / JPL-CALTECH / MSSS; GLOBE: NASA / CORNELL / SSI / STSCI / AURA; INSETS: EAGLE, ENDURANCE, AND VICTORIA: NASA / JPL-CALTECH / CORNELL (3); SANTA MARIA: NASA / JPL-CALTECH / CORNELL / ASU; MARATHON VALLEY: NASA / JPL-CALTECH; BACKGROUND MARS TERRAIN TEXTURE: NASA / JPL-CALTECH / UNIV. OF ARIZONA



planned the previous day was successful and you see a new piece of Mars,” he says.

Already, many team members are planning their next move. Some have been lucky enough to find jobs on other Martian projects, like Curiosity, the Insight lander, and the upcoming Mars 2020 rover. But now they have to bid farewell to the team, too. “Opportunity is metal, glass, and silicon,” Seibert says. “But the team that became a family to operate it — that’s what everyone is going to miss.”

Legacy Left Behind

But while mourning Opportunity, the team is also celebrating her achievements.

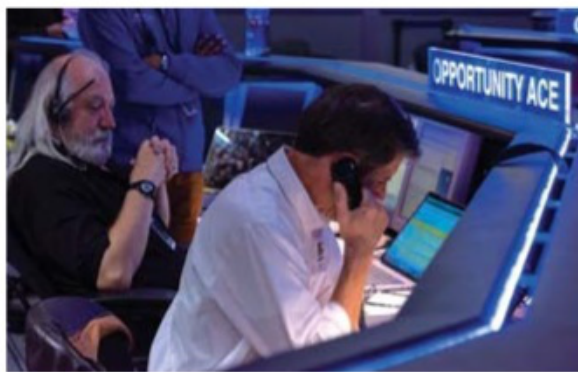
Opportunity and Spirit bounced onto Mars in January 2004, but their life expectancies were dramatically short. Engineers estimated that the rovers only had three months before so much dust accumulated on their solar panels that they both failed from lack of power.

Mars, however, intervened: Gusts of wind repeatedly wiped the solar panels clean and boosted power levels back up. That allowed Spirit to last for 6 years and Opportunity to last for more than 14. Their unexpectedly lengthy lifetimes allowed them to transform our vision of Mars.

Before the rovers tumbled onto the Red Planet, scientists had only seen signs from orbit that Mars had hosted liquid water in the past. But Opportunity’s first image revealed layered bedrock, which the team determined was probably sediments laid down by water.

Then, Opportunity stumbled upon tiny spherical grains, fancifully called blueberries, embedded within the sandstone. On Earth, similar orbs form when minerals dissolved in acidic groundwater solidify again in a different form. It was further evidence that Mars was once warm and wet.

“Then came the magnificent benefit of the extended mission,” Callas says. “As we drove this rover kilometers away from where we landed, we continued to see this evidence of liquid water. We’re not just talking about a puddle or a pond,



◀ **FAREWELL** Top: Mars Exploration Rovers project manager John Callas makes the call ending the Deep Space Network’s last listen for Opportunity, February 12, 2019. Bottom: Former mission manager Cindy Oda shares her experience working on the rover that same evening.

but we’re talking about at least kilometer-scale bodies of water on the surface.”

All in all, Opportunity drove more than a marathon on Mars — a distance that allowed the team to not only image extensive features carved by long-gone lakes but to actually drive back in time. Eagle Crater, where Opportunity landed, dates back to the Hesperian Period, 3.7 to about 3 billion years ago. In 2011 however, Opportunity reached Endeavour Crater, which formed in the Noachian Period, 4.1 to 3.7 billion years ago. It’s the oldest period yet studied on Mars.

Here Opportunity found signs of another ancient wet environment, but with water less acidic and more favorable to life. That find, coupled with Spirit’s discovery of hydrothermal vents, paints a tantalizing early portrait of Mars. After all, where there is both energy and water on Earth — such as within the geysers of Yellowstone or the hydrothermal vents of the ocean deep — there is life. Throw in the organic compounds that Curiosity later found on Mars, and the Red Planet seems to have once had everything organisms would need.

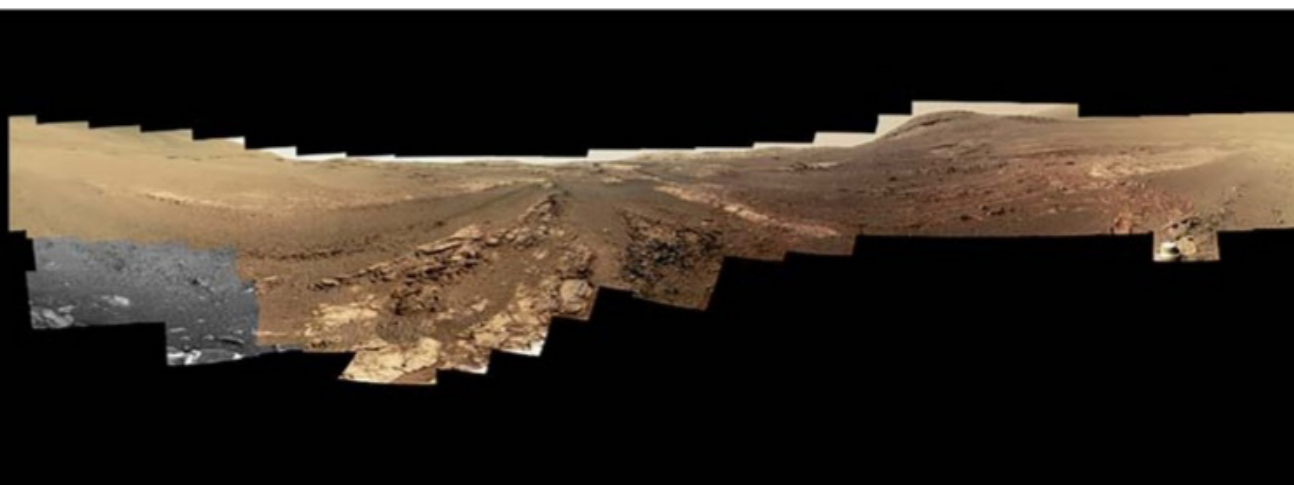
“You have the energy, you have the liquid water, you have the neutral pH, you have the warm temperatures, you have the thick atmosphere,” Callas says. “Boy, you don’t have to go much further than that to say, ‘This is physically habitable to support life as we know it.’”

Thanks to their extended forays, both rovers rewrote every textbook on Mars — and that is surely cause for celebration.

Opportunity Lost

“I always thought there were only two honorable ways for a mission like this to end,” says Steve Squyres (Cornell University), the principal investigator and godfather of the mission.

▶ **THE LAST HURRAH** This last 360° panorama of Perseverance Valley combines 354 images taken from May 13 through June 10, 2018. That same day, a global dust storm cut off the rover’s communications with Earth. The valley sits on the inner slope of Endeavour Crater’s rim, which rises in the distance. Had the rover survived, it could have followed the valley down to the crater floor.



PHONE CALL AND SHARING: NASA / JPL-CALTECH (2); LAST PANORAMA: NASA / JPL-CALTECH / CORNELL / ASU

“I always thought there were only two honorable ways for a mission like this to end. One is that we simply wear the vehicle out . . . and the other is that Mars just reaches out and kills it.” —STEVE SQUIRES

“One is that we simply wear the vehicle out, and that’s what happened with Spirit, and the other is that Mars just reaches out and kills it. And that’s what happened with Opportunity. To have a mission end after 14.5 years of science, being taken out by one of the worst dust storms to hit Mars in decades, you can walk away from that with your head held high.”

But no matter when a mission finally ends, some tantalizing discovery remains just beyond reach. Indeed, Opportunity was halfway down Perseverance Valley — a feature that looked like it had been carved by water — when the dust storm hit. And scientists were anxious to drive to the bottom, where sediments would have gathered, to further study the crater and verify that it was indeed sculpted by water and not by wind.

“It would have been the first opportunity we had had to look at a feature like this on the ground,” Fraeman says. Although scientists have spotted a number of similar gullies from orbit, they were excited to dive into one (literally) on the ground. If the hypothesis is true, then Fraeman suspects the groundwork would have helped the team better understand the history of water within the region, and perhaps across the entire Red Planet.

It also would have painted quite a vivid picture of the Red Planet’s wet past. Callas suspects that, if it really were carved by water, this valley might once have looked like the magnificent cascading waterfalls in Hawai’i. And while scientists might never answer this exact question, it points toward yet another legacy of the mission.

“We have made Mars familiar to the public,” Callas says. “They get an idea of what it’s like to be on the surface of Mars. It’s no longer this strange, distant, mysterious world.”

Although Opportunity played a large role in this legacy, it’s not hers alone. The rover is preceded in death by Spirit, and it is survived by Curiosity and the Insight lander. All in all, there are eight spacecraft from the world’s space agencies currently on or orbiting Mars, with a handful set to launch next year.

And that leaves scientists like Callas hopeful. He was 10 years old when Neil Armstrong walked on the Moon. “I was inspired by the Apollo program because I thought that there were no limits to what we can do,” he says. “These rovers are continuing that inspirational legacy. It’s the Apollo program of our day.”

■ Award-winning freelance science journalist **SHANNON HALL** still tears up when watching the video of Opportunity’s successful landing.

Read the team’s favorite stories from the mission: jpl.nasa.gov/opportunity-memories.

A Shortlist of Rover Discoveries

Both Spirit and Opportunity penned a new story of Mars — one that is overflowing with water and the necessary conditions to support life as we know it. Here are some of their most significant discoveries.

3

Acidic Waters When Opportunity first landed in Eagle Crater, the rover spotted layered bed-rock probably made from ancient sediments laid down by water. She also discovered the mineral hematite, which often forms in acidic water.



Blueberries At the start of her mission, Opportunity discovered tiny spherical grains embedded within the sandstone. Those so-called blueberries are thought to have formed in liquid water.



Hot Springs In 2007, Spirit accidentally churned up silica-rich soil, which typically forms within hot springs like those found in Yellowstone National Park on Earth. Scientists think that our planet’s early life might have developed in similar environments.

▲ BLUEBERRIES

The rover found these tiny mineral spherules in April 2004. They’re hematite-rich, and their shape suggests they formed in an ancient, watery environment.

7

Neutral Waters In 2010, Spirit found rocks 10 times richer in magnesium and iron carbonates than any other Martian rocks studied before. Such rocks can only form in an environment with neutral water.



Flowing Waters In 2011, Opportunity found bright-colored veins of gypsum in the rocks near the rim of Endeavour Crater. Because the mineral likely formed when water flowed through underground fractures in the rocks, it was the first sign of flowing water.