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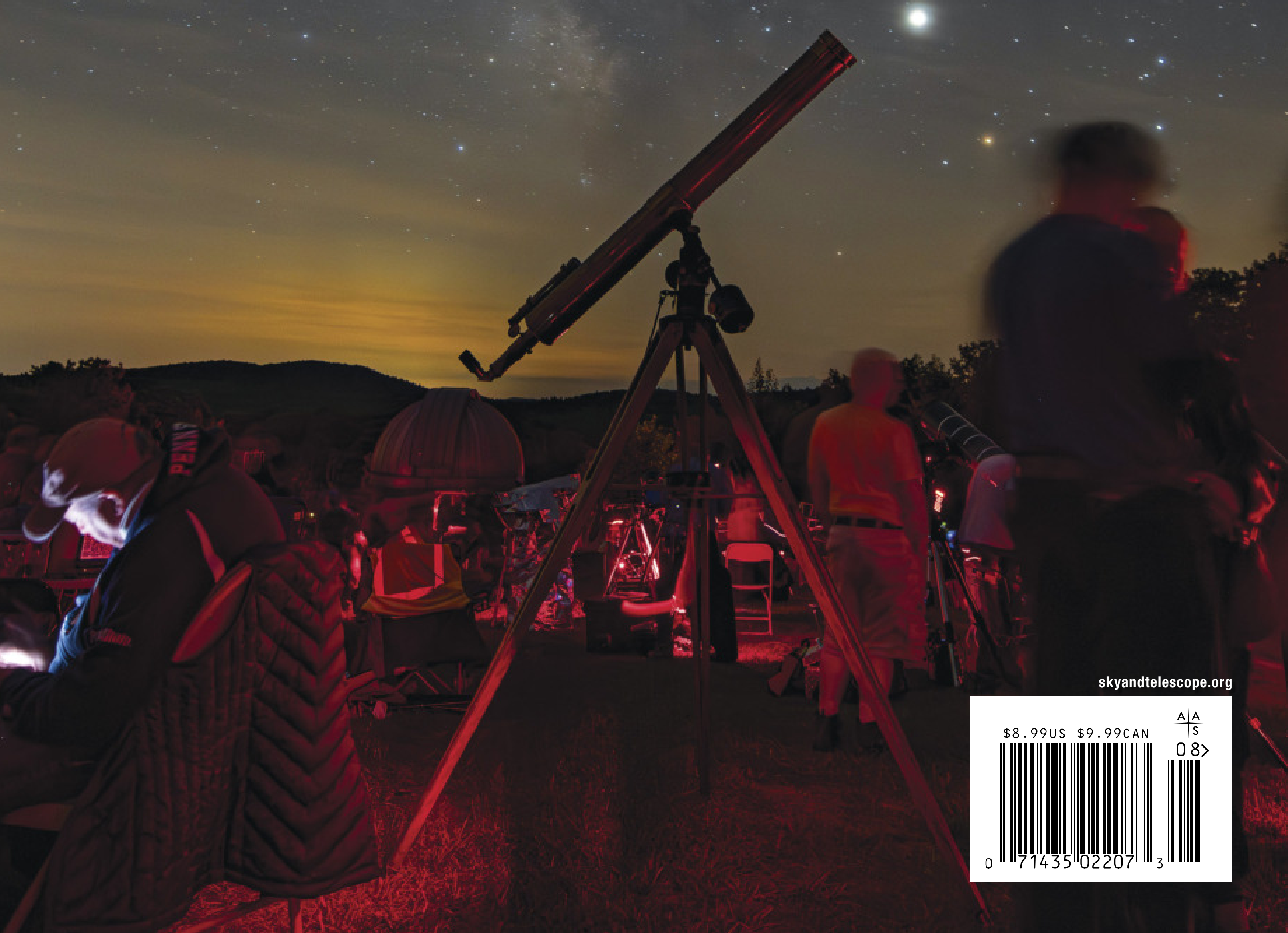

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 by Javier Barbuzano

SHAKE, RATTLE, a

Conquered by dust, the Insight lander has ended its mission after giving us an unprecedented look at seismic activity on the Red Planet.

"My power's really low, so this may be the last image I can send. Don't worry about me though: my time here has been both productive and serene. If I can keep talking to my mission team, I will — but I'll be signing off here soon. Thanks for staying with me."

This was the farewell message from @NASAInSight, the official Twitter account of NASA's Insight lander. For four years, the spacecraft had studied the interior of Mars in an unprecedented way. But dust accumulating on the lander's solar panels had been steadily reducing their power output, to the point that the craft was no longer able to charge its batteries. The image posted with the tweet looked like a car-crash scene from *Mad Max*, a fish-eye view of dust-covered gadgets strewn over an arid landscape.

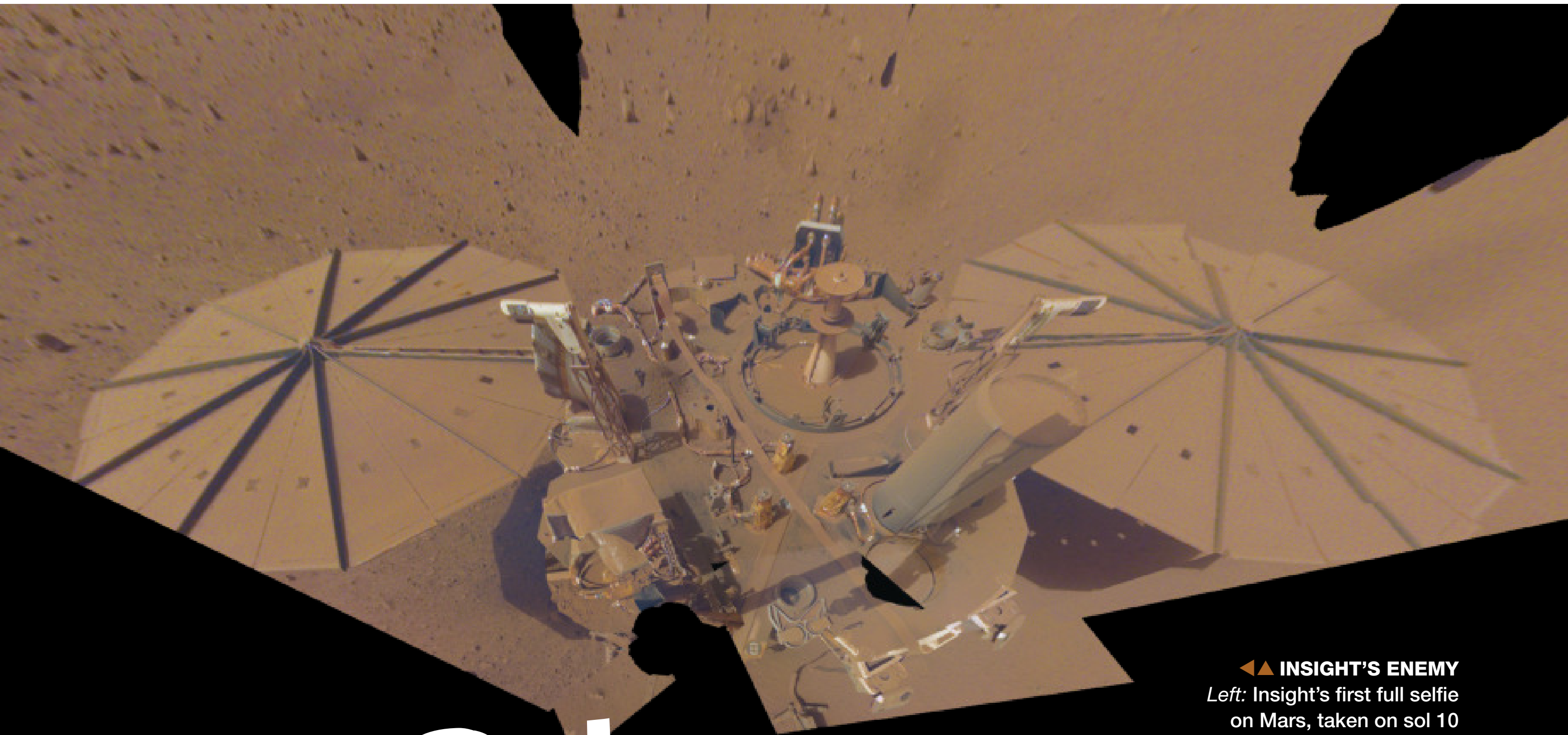
Just two days later, on December 21, 2022, NASA announced that the spacecraft had failed to communicate with mission controllers at the Jet Propulsion Laboratory (JPL) in California. The agency declared the mission over.

"We've thought of Insight as our friend and colleague on Mars for the past four years, so it's hard to say goodbye," said the mission's principal investigator, Bruce Banerdt (JPL), in a press release.

Although Insight doubled its initial life expectancy of two years, Banerdt and the mission team had hoped it would live far longer. But the solar panels' output had started declining almost immediately after landing. Other solar-powered missions have fortuitously had their panels cleared by occasional wind gusts, but the breezes in Insight's location, while strong, didn't remove enough dust. The grime kept building up, until it completely blocked the sunlight.

Nevertheless, Insight was largely a success. It was the first spacecraft to use a seismometer on the Martian

FIRST AND LAST SHOTS OF LANDER: NASA / JPL-CALTECH (2)



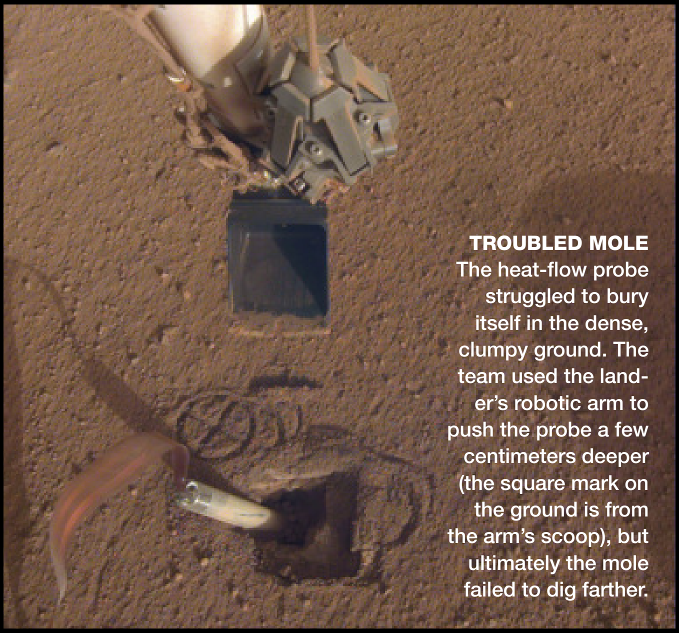
nd ROLL

INSIGHT'S ENEMY *Left:* Insight's first full selfie on Mars, taken on sol 10 (December 6, 2018) shows its clean solar panels and deck, with its science instruments still on top. *Right:* The lander's final selfie, from sol 1211 (April 24, 2022), shows it so covered in dust that it's hard to see it against the landscape.

surface to detect the equivalent of an earthquake — a *marsquake* — and opened an entirely new window into the planet's interior. In only a few years, Insight revealed the size of Mars's crust, mantle, and core — something that took 30 years for terrestrial seismology. But it has also left scientists with new puzzles about how Mars formed and how its atmosphere works today.

Off to a Bumpy Start

Insight (Interior Exploration Using Seismic Investigations, Geodesy and Heat Transport) landed on Mars on November 26, 2018, on the relatively flat lowlands of western Elysium Planitia. Its mission was to study the deep interior of Mars. Mars is arguably the most studied planet in the solar system, but previous observations have been of the surface, or what lies above or just beneath. Scientists know little about the planet's inner structure. Yet, this interior holds the answers to how the planet formed and evolved over the last 4½ billion years and, by extension, could tell us many things about the formation of the solar system as a whole.



TROUBLED MOLE The heat-flow probe struggled to bury itself in the dense, clumpy ground. The team used the lander's robotic arm to push the probe a few centimeters deeper (the square mark on the ground is from the arm's scoop), but ultimately the mole failed to dig farther.

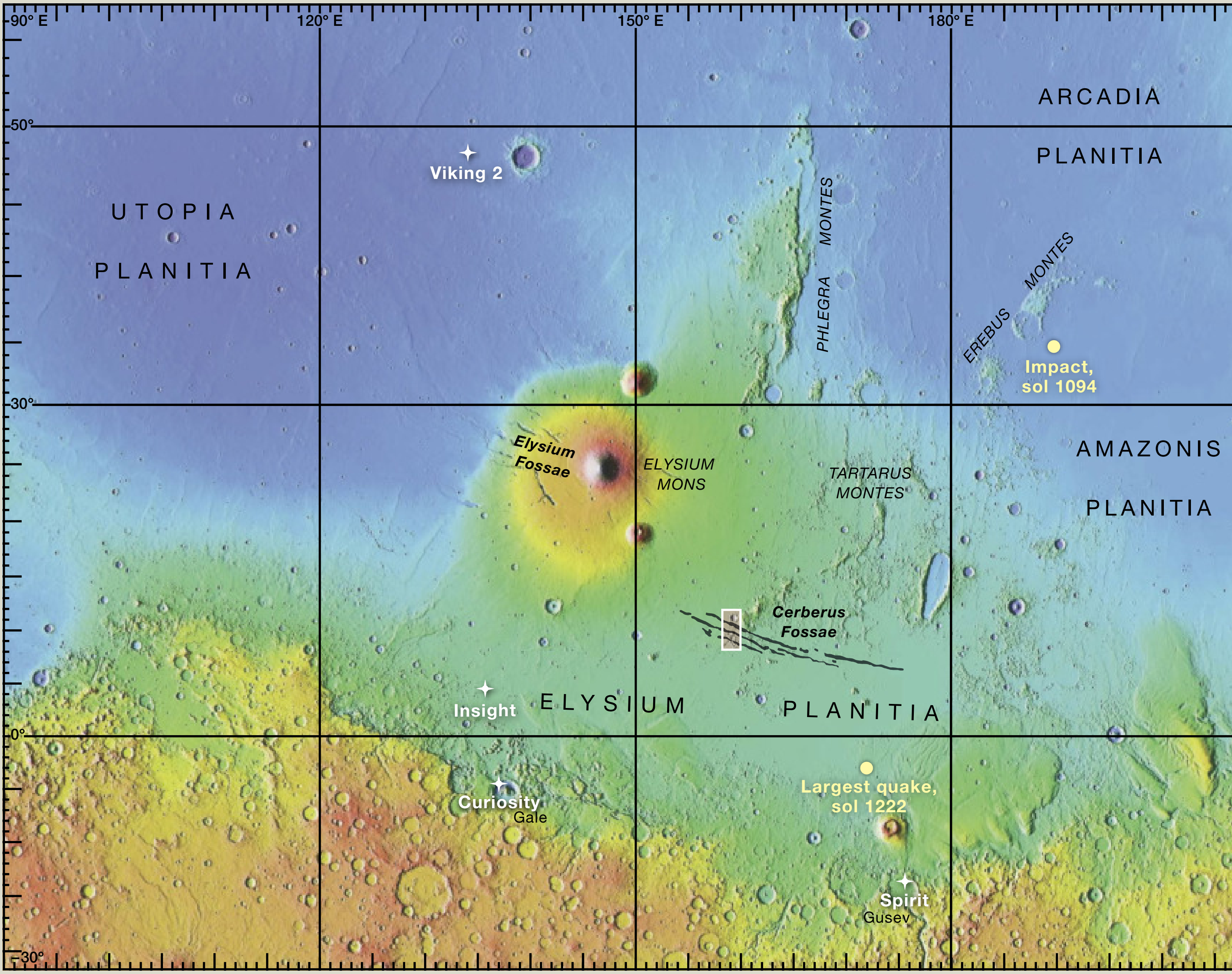
NASA / JPL-CALTECH

Insight carried three main scientific instruments: A seismometer to record marsquakes, a thermal probe to measure the heat escaping from the planet, and a tracking device to study the orbit of Mars with exquisite precision. It also had a robotic arm to put the instruments on the ground, two cameras, and a wide array of sensors to measure wind speed, atmospheric pressure, local magnetism, and other environmental parameters.

The Heat Flow and Physical Properties Package (HP^3) relied on a self-burying device, nicknamed "the mole," to drag a ribbon-like cable studded with temperature sensors to a depth of 5 meters. Its goal was to measure the heat flow from the planet's interior and the thermal properties of the ground. The mole, a pointy metallic cylinder 2.7 centimeters (about an inch) wide and 40 centimeters (16 inches) long, housed a spring-loaded weight that would wind up and hammer the mole downwards with each impact.

The ground beneath Insight wasn't mole-friendly, though. The device had been designed for sandy terrains like those encountered by previous surface missions: It needed friction

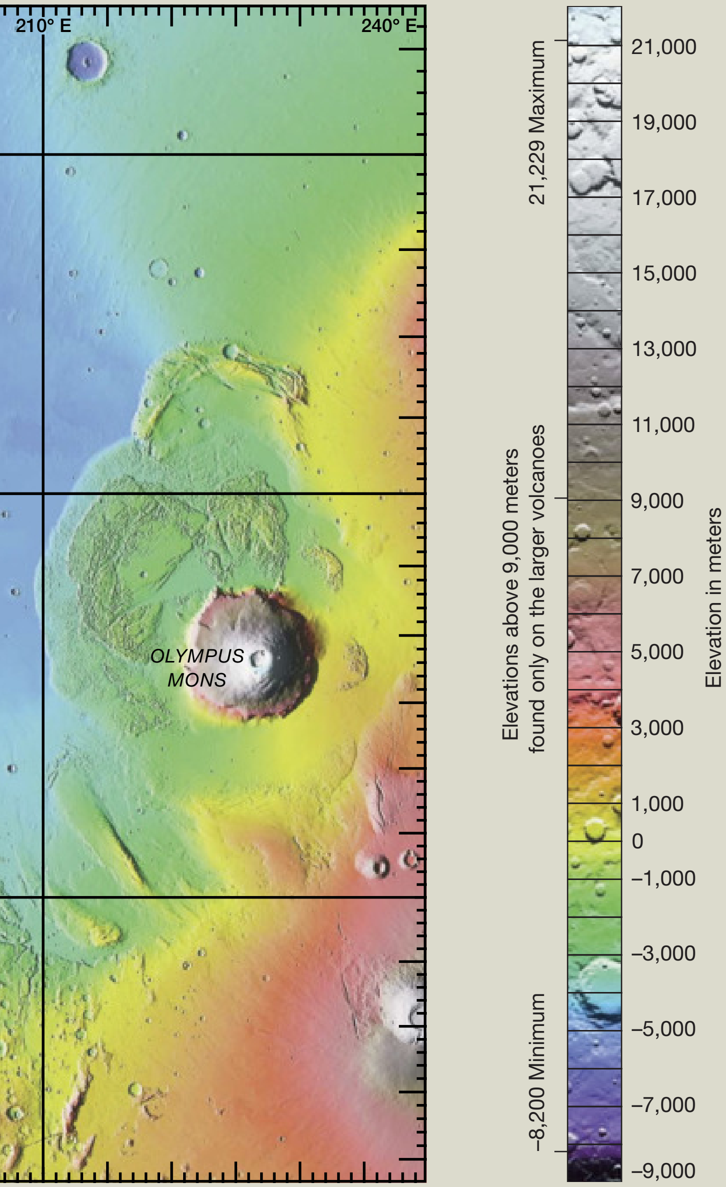
CERBERUS FOSSAE *Below:* Insight landed in Elysium Planitia, north of the Curiosity rover. Most of the marsquakes it detected originated around an extensive fault system called Cerberus Fossae (black lines, box shows close-up section), which is as long as California's San Andreas fault zone. But some of the largest seismic events came from farther away, including the Christmas Eve impact (sol 1094) and a 4.7-magnitude shaker on sol 1222. *Opposite:* Made with data from the Mars Express orbiter, this close-up shows the boxed part of the trench system.

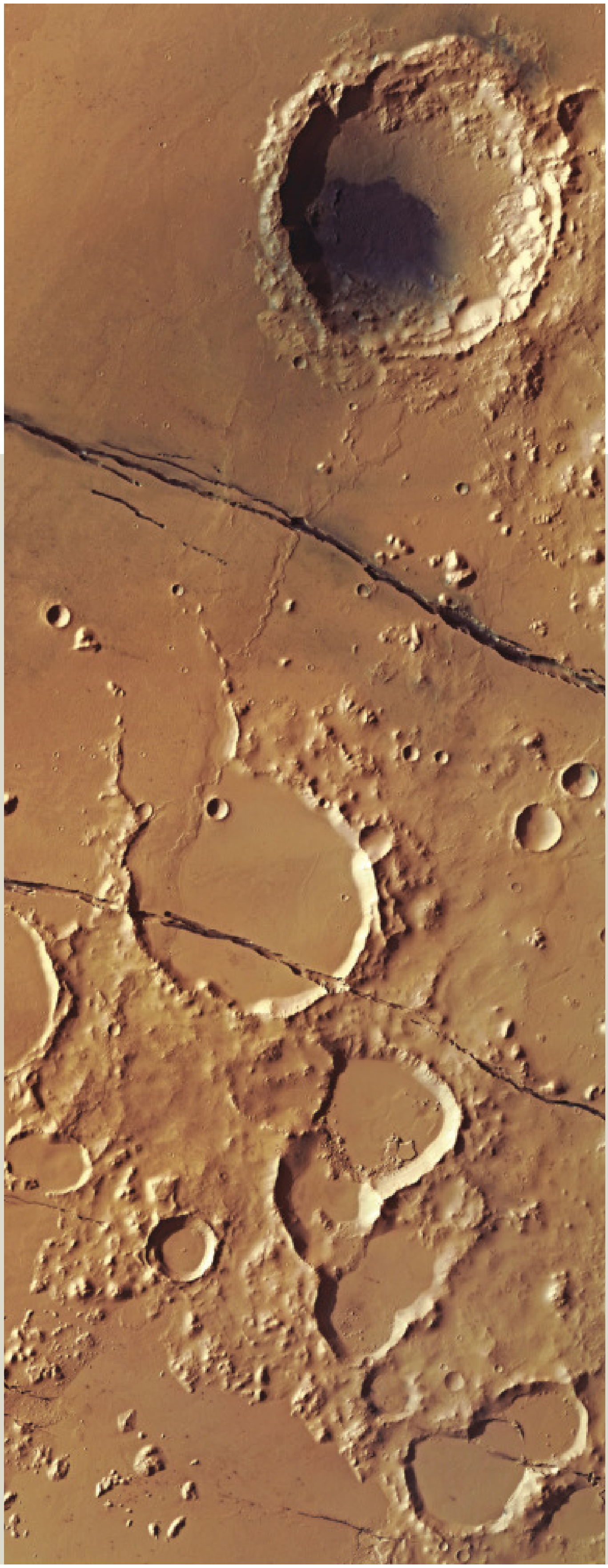


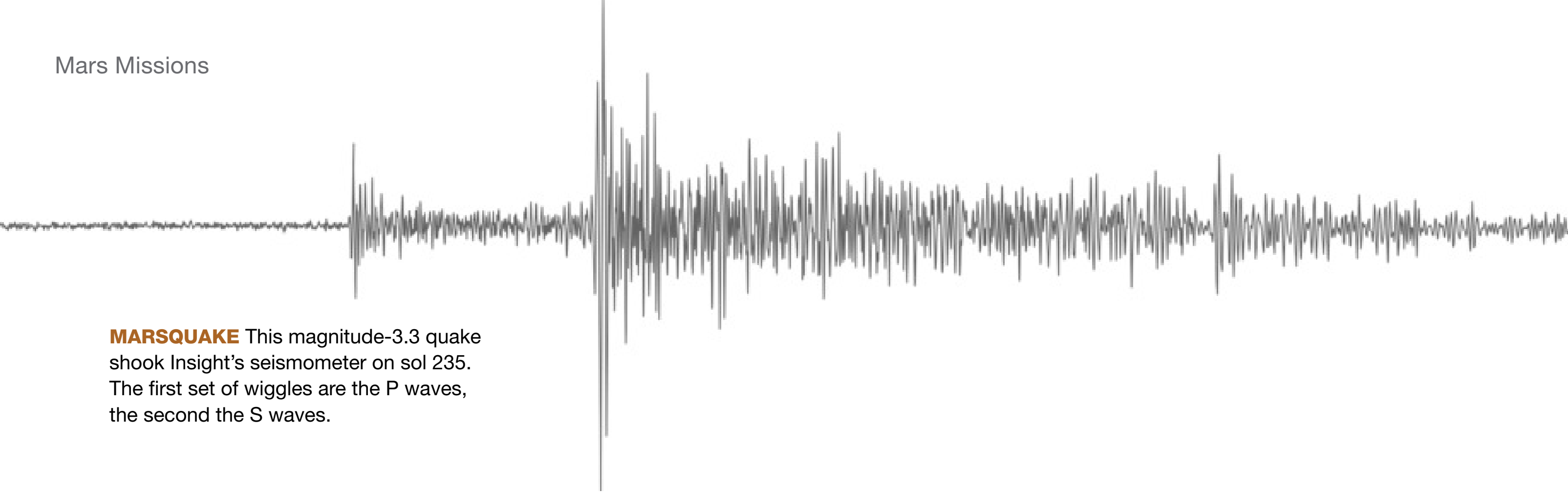
with loose particles to absorb the recoil from the hammering in order to drill. Instead, the landing site was a hard, clumpy terrain, and the mole just bounced in place.

The mission team tried using Insight's robotic arm to help the struggling mole bury itself. They pushed it from different angles, scooped dirt on top of it, and even shoved it into the hole and pinned it with the arm's scoop. It failed to pull itself even an inch farther. The Insight team officially gave up on January 9, 2021, after almost two years of frustration.

It wasn't all in vain, though. The mole measured the thermal conductivity of the uppermost layer of soil. Its hammering also provided a seismic source that allowed the seismometer to collect information on the uppermost layer of the ground and to measure the velocity of seismic waves in the Martian regolith.







MARSQUAKE This magnitude-3.3 quake shook Insight's seismometer on sol 235. The first set of wiggles are the P waves, the second the S waves.

Ready to Rumble

As the mole struggled, the seismometer — the real bread and butter of the mission — listened to the murmurs from the Martian underground.

Insight's Seismic Experiment for Interior Structure (SEIS) is the all-terrain vehicle of seismometers. "We were able to provide a seismometer as good as the best portable seismometer on Earth, except that it's able to survive the space environment, very cold temperatures, radiation, et cetera," says Philippe Lognonné (Institute of Earth Physics of Paris), SEIS's principal investigator.

SEIS, like other seismometers, uses a system of pendulums to measure movement caused by seismic waves, which occur when something makes the ground vibrate. It's extremely sensitive, able to detect movements smaller than the size of an atom — so sensitive, in fact, that it needed special shielding from ambient noise and temperature changes in order to operate.

SEIS found that, seismically speaking, Mars is very different from Earth. The first thing scientists noticed is that it's very quiet. On Earth, oceans create a constant seismic buzz that masks faint quakes at long distances. But on Mars, the seismometer could pick up quakes 100 times weaker than it would on Earth.

Researchers could not take full advantage of the seismic silence, though. Mars is very windy, and the seismometer — although covered by many isolating layers and a wind dome — was essentially exposed to the elements. As the wind hit the lander, it wiggled and rattled, transmitting vibrations to the ground. Luckily, the wind died out at night almost like clockwork, leaving a window of six to eight quiet hours when most of the quake detections occurred.

The first quake appeared on Sol 128, after two months of nail-biting wait. It was a faint, 2nd-magnitude tremor, which would be undetectable to human beings on Earth. Before the end of the mission, SEIS recorded 1,319 quakes, with magnitudes ranging from 1 to 4.7. Only a handful of them were above magnitude 4, powerful enough to jingle windchimes but probably not to wake you up at night.

The number of quakes is at the lower end of pre-Insight expectations, showing that marsquakes are both less powerful and less frequent than earthquakes. On Earth, moving tectonic plates constantly produce quakes. But Mars has a single plate, a thick crust that has been cooling and contracting for billions of years like a raisin. The built-up tension occasionally breaks the crust and creates *thrust faults*, where one side of the fault jumps on top of the other. This process accounts for one-third of the total seismic energy released on Mars.

Quakes on Mars also last longer than on Earth. While earthquakes last seconds or minutes at most, marsquakes typically last tens of minutes. Moonquakes, detected by seismometers deployed during the Apollo missions, linger for hours after the initial shake. The key difference is the attenuation produced by a warm interior and liquid-filled pore spaces, two factors that hinder seismic waves. Mars occupies a middle ground between Earth and the Moon in this regard.

4.7
Magnitude of largest marsquake Insight observed (on sol 1222, or May 4, 2022)

Like on Earth, quakes generate two types of seismic waves. *Surface waves* travel on the surface and can only reveal details about the crust and upper layers. *Body waves* travel through the interior of the planet and tell us about its deep structure. They come in two flavors: primary or P-waves, which are compressional waves and travel faster, and secondary or S-waves, which oscillate perpendicular to the direction of propagation and are slower. Researchers can use the difference between the speeds and arrival times of P-waves and S-waves to find the source of quakes. The waves also reveal the properties of the rocks they passed through.

Cerberus Fossae

To the scientists' astonishment, Insight's marsquakes had a favorite source: Cerberus Fossae.

Cerberus Fossae is a fault network 1,200 kilometers long, located 1,500 km east of Insight's landing spot. It's one of the youngest features on the Martian surface, thought to have started forming just 10 million years ago. Scientists suspect ongoing volcanism in the area. Satellite images have revealed lava fields and ash deposits, some of them younger than 50,000 years — not even the blink of a geologic eye.

The flanks of Cerberus's faults don't slide laterally past each other, like in California's San Andreas zone, but seem to be pulling away from each other, opening gaps in the ter-

NASA / JPL-CALTECH

rain. This area was the source for about 90% of all the quakes Insight detected, accounting for half of the total seismic energy released on the planet as a whole. The large number of quakes shows that the faults are still opening today.

"To produce these opening faults you need an active mechanism," says Insight team member Simon Stähler (Swiss Federal Institute of Technology Zurich). "More and more people are becoming convinced that this could be due to an upwelling in the mantle, a so-called plume."

Mantle plumes are powered by heat coming directly from the mantle-core boundary. They are made by hot but solid rock — not magma — that over long periods, maybe hundreds of millions of years, is plastic enough to flow. Once the plume reaches the bottom of the crust, it pushes from below, opening the fractures. Its heat can also melt rock, creating magma pockets that can produce volcanism.

On Earth, mantle plumes are related to volcanism far from plate boundaries, in places such as Hawai'i. Since there's no plate tectonism on Mars, mantle plumes seem like the most plausible driver of volcanism.

Adrien Broquet and Jeffrey Andrews-Hanna (both at University of Arizona) argue that they've found evidence that this is what happens at Cerberus Fossae. They decided to look at the wider picture, puzzled by the intense seismic activity and recent volcanism.

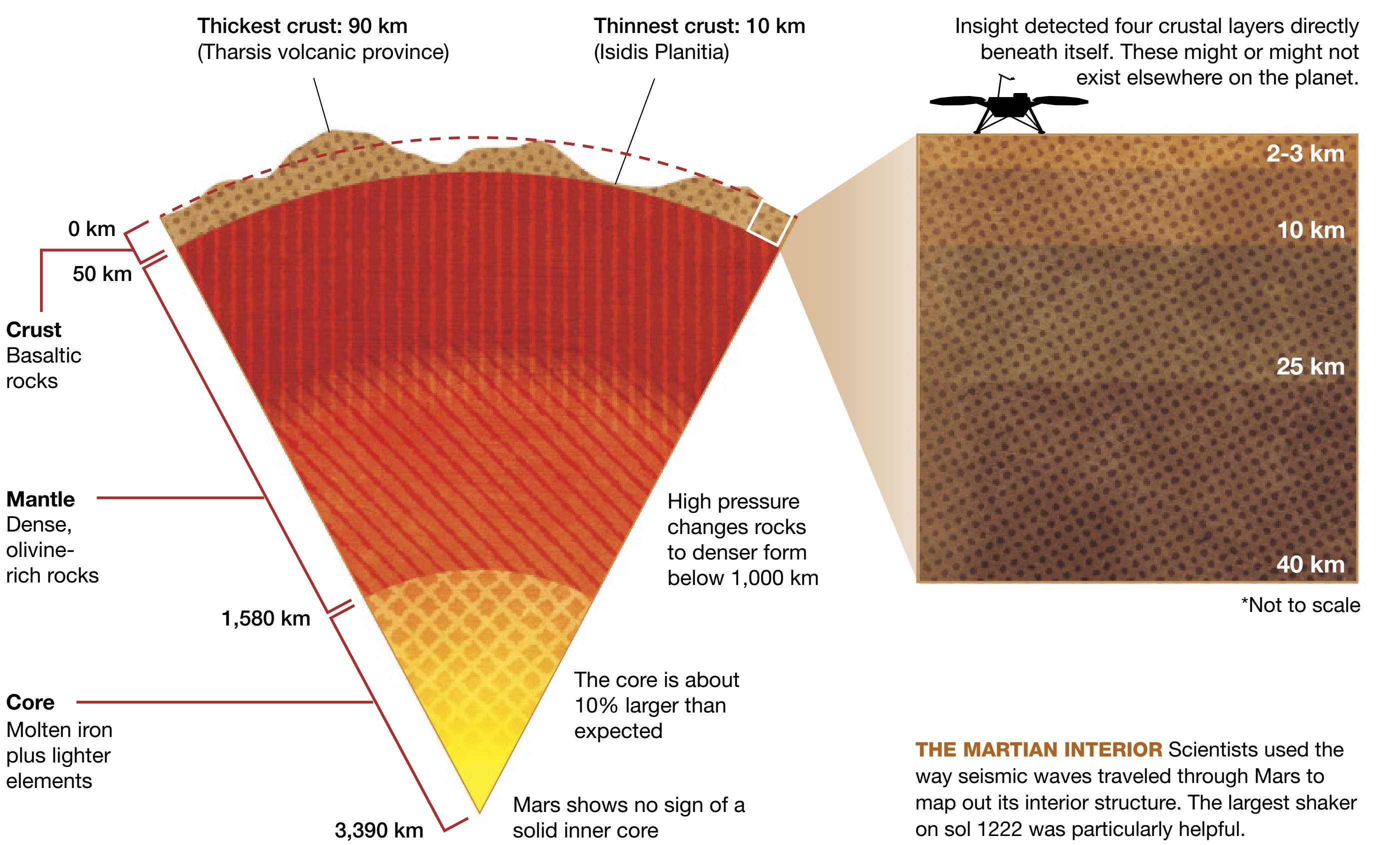
Using satellite observations, they realized that Elysium Planitia, the flat region that includes both Cerberus Fossae and the Insight landing site, rises up to 2 km over the vast northern lowlands, forming a very broad dome. They also spotted subtle gravitational variations, pointing to a build-up of material coming from the deep. More revealing, they saw that the floors of impact craters in the area, instead of being flat, are tilted in the direction of the plume, showing that the ground has moved after the craters formed.

All the evidence points to a mantle plume that is actively uplifting today. It could be as large as 4,000 km wide — roughly the size of the contiguous United States. "That's not something you'd expect from a planet that is cooling," Broquet says.

"It's a bit surprising because it requires quite a bit of activity in the Martian mantle, and for that you need a certain amount of heat," Stähler says. "Since Mars is smaller than Earth, you'd have expected it to cool quicker and generally be much colder in the interior, and that's something people will have to wrap their heads around to explain."

A Multi-layered Planet

Seismic waves are like a flash of light illuminating the planet's interior. As they move through different materials, their speed changes and they are refracted, the same behavior we see with light waves. If the material's properties change abruptly, the waves bounce off and produce echoes, revealing discontinuities that often mark the transitions between the main layers of a planet.



THE MARTIAN INTERIOR Scientists used the way seismic waves traveled through Mars to map out its interior structure. The largest shaker on sol 1222 was particularly helpful.

LEAH TISCIONE / S&T

Insight's measurements confirm that, like Earth, Mars has a crust, mantle, and core. This is unsurprising. But what *is* surprising are some of the details.

The crust is a planet's outermost solid shell. The average crustal thickness on Mars is about 50 km, with a minimum of 10 km in Isidis Planitia and a maximum of 90 km in the Tharsis volcanic province. Earth's crust ranges from 20 km under the oceans to 80 km in its thickest areas.

Insight has detected four distinct layers in the crust directly beneath it. The uppermost layer is only 2 to 3 km deep, and seismic waves travel very slowly through it (at about 1 km/s, or 2,000 mph), revealing that it's very dry, very porous, and likely heavily fractured by meteorite impacts. This layer could be a local feature below Insight's landing site. There are two more discontinuities below, at about 10 and 25 km, but their properties aren't very clear. At 40 km a weaker discontinuity, the *Moho*, marks the end of the crust and the beginning of the mantle.

The *lithosphere* is the upper layer of rigid rock where convection can't happen. It includes the crust and part of the upper mantle. The Martian lithosphere is 500 km thick, twice that beneath Earth's oldest continents. This was expected, since the Martian lithosphere is ancient and has been cooling for a very long time, whereas on Earth plate tectonism continuously recycles this top layer.

The lithosphere acts like a lid that prevents heat loss from a planet's interior. Knowing its thickness, researchers have estimated the planet's heat flow — what HP^3 wanted to measure — to be between 14 to 29 milliwatts per square meter. This is slightly more than expected, but it's still three to five times lower than Earth's.

Deeper down, the mantle looks like a fairly homogeneous layer of silicate rock some 1,500 km thick. On Earth there is a clear distinction between the upper and lower mantle at a depth of 600 km, where the mineral olivine transforms into bridgmanite, a mineral that only forms at very high pressure. The Martian mantle doesn't reach the pressure necessary for this change, although it likely has a weaker discontinuity around 1,000 km, where olivine transforms to wadsleyite. Without the bridgmanite discontinuity, convection in the Martian mantle is largely unhindered, allowing heat from the core to reach the surface more easily.

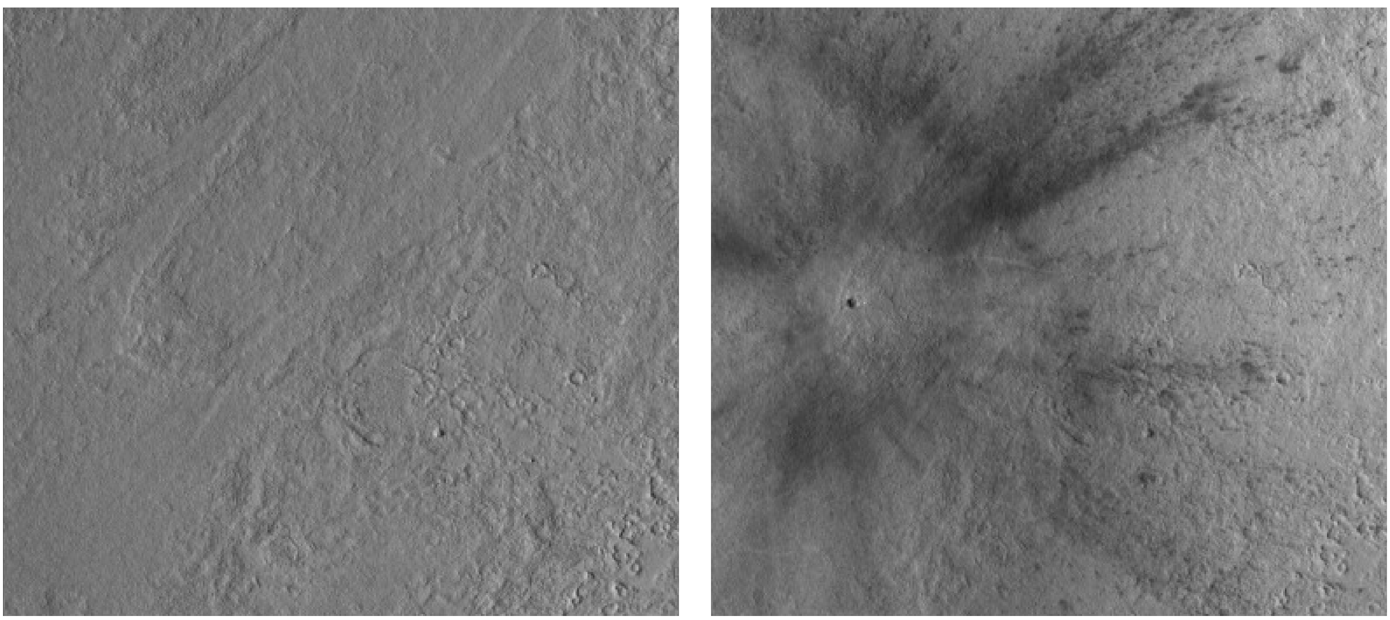
Insight has also confirmed that Mars has a liquid core. S-waves cannot penetrate fluids, so when they reach the core they reflect back to the surface. The Martian core is unexpectedly large, with a radius between 1,780 and 1,810 km. Compared with our planet's interior, Mars's core is proportionally the same size (about half the radius). But Earth has a solid inner core and liquid outer core, and scientists have found no sign of a solid inner core on Mars yet.

The newfound size means the core is less dense than expected. Mars's core, like Earth's, contains heavy elements such as iron and nickel. But the lower density implies that lighter elements such as sulfur, hydrogen, oxygen, and carbon are a significant part of the core's recipe.

Such a composition, however, does not bode well for planet-formation models. Planetary scientists don't think large quantities of light elements were available for the terrestrial planets as they formed. Plus, to get to the estimated core density of about 6 g/cm^3 would require adding more than 25% sulfur to a pure iron core, which seems unreasonable.

"At the moment geochemists — the people who think [about] how the planets are built — are really unhappy with this result," Stähler says.

One explanation is that Mars might have formed very early in the history of the solar system, at a time when more



NASA / JPL-CALTECH / MSSS (2)

▲ **COSMIC PUNCH** Taken before and after a meteoroid struck, these orbiter images show the impact in Amazonis Planitia on sol 1094 that sent seismic waves traveling through Mars to Insight's seismometer, some 3,500 kilometers away.

light elements were available for planet formation before the solar wind blew them away. Or maybe Mars accreted smaller planetary bodies from the outer solar system, which brought the light elements with them.

A third explanation is the presence of a molten layer of rock at the bottom of the mantle, which would seismically behave like the fluid core, making it look larger than it really is. This idea is still being explored, though.

Hit Me Baby One More Time

On Christmas Eve of 2021, Mars shook more violently than usual. SEIS detected a 4th-magnitude marsquake, among the most powerful recorded. It was the first event to produce surface waves. The epicenter wasn't in Cerberus Fossae, though, but 3,500 km northeast from Insight in Amazonis Planitia, a low, flat plain bordering the vast polar basin.

Two months later, scientists poring over images from the Mars Reconnaissance Orbiter (MRO) spotted a big blotch in this same region. Images revealed a 150-meter-wide crater, surrounded by a large blanket of ejected material that stretched up to 37 km away. Such an impact, scientists estimated, must have been produced by a meteorite 4 m to 12 m in diameter. The crater was 21 m deep and excavated water ice that had lain buried underground, visible as white spots in the satellite image that disappeared over time as the ice sublimated.

Liliya Posiolova (Malin Space Science Systems), the operations lead for MRO, remembered that Insight had reported a large seismic event and realized this impact could be the culprit. Daily weather images taken by another camera on MRO confirmed the date of the impact.

Inspired, Insight researchers looked for similar events in their records, finding that a 4.1-magnitude event that occurred on Sol 1000 (September 18, 2021) was a good candidate. When MRO looked at its epicenter, 7,500 km from Insight, they found a cluster of new craters, the largest 130 m wide.

The surface waves produced by these impacts traveled through the shallower part of the crust to reach Insight. Surprisingly, the waves traveled at roughly the same speed through the northern and southern hemispheres. The topography of the two Martian hemispheres is radically distinct, with a low-lying north that might have hosted oceans and a rugged south made of highlands. On Earth, the oceanic and continental crusts have different densities, something that doesn't seem to be true on Mars.

Weather, Wind, and Dust

As it sat on Elysium Planitia, Insight did more than sense quakes. It also produced an unprecedented set of meteorological records. It measured the atmospheric pressure and wind speed uninterruptedly for over a Martian year, watching conditions change from second to second.

But one thing the lander *didn't* see is dust devils, small dusty tornadoes that are commonplace in other Martian

TIME TO SLEEP This image from sol 1436 (December 11, 2022) is one of the last Insight took before it ran out of power. The seismometer's 69-cm-wide protective dome appears at center.

NASA / JPL-CALTECH

locations. Insight registered thousands of the pressure drops associated with dust devils, but not one was caught on camera — even though vortexes shook the lander and left visible tracks around it.

"We have many theories, but we really don't know why we haven't seen a single dust devil," says José Antonio Rodríguez-Manfredi (Center for Astrobiology, INTA-CSIC, Spain), principal investigator for the lander's temperature and wind sensors. Insight has taken daily images of the ground to track how the winds move dust and pebbles over time, and while there's plenty of dust at the landing site, there are still few clues as to why the dust seems reluctant to become airborne in this area. "This is one of the things we don't understand yet."

But there was still enough dust to impact the lander. After four years on Mars, the dust build-up on Insight's solar panels finally blocked more light than the craft needed to recharge its batteries. Ingenious efforts to lower energy consumption and clean the solar panels were eventually not enough, and Insight entered a hibernation state called "dead bus mode," in which everything is disconnected except the circuit that charges the batteries. In the unlikely case that a wind gust clears some of the dust from the solar panels, the spacecraft is ready to resume charging and send a message home: "I'm alive!"

Meanwhile, scientists will keep exploring Insight's data. Currently we are between the second and third generation of Insight results, says Stähler. The first one, he explains, comprised the first observations right after landing, the second included odd or surprising findings, and the third one will consist of new hypotheses to explain all that doesn't add up. "We are entering the third generation of Insight results right now," he says.

JAVIER BARBUZANO is a freelance science journalist who covers astronomy and geoscience.