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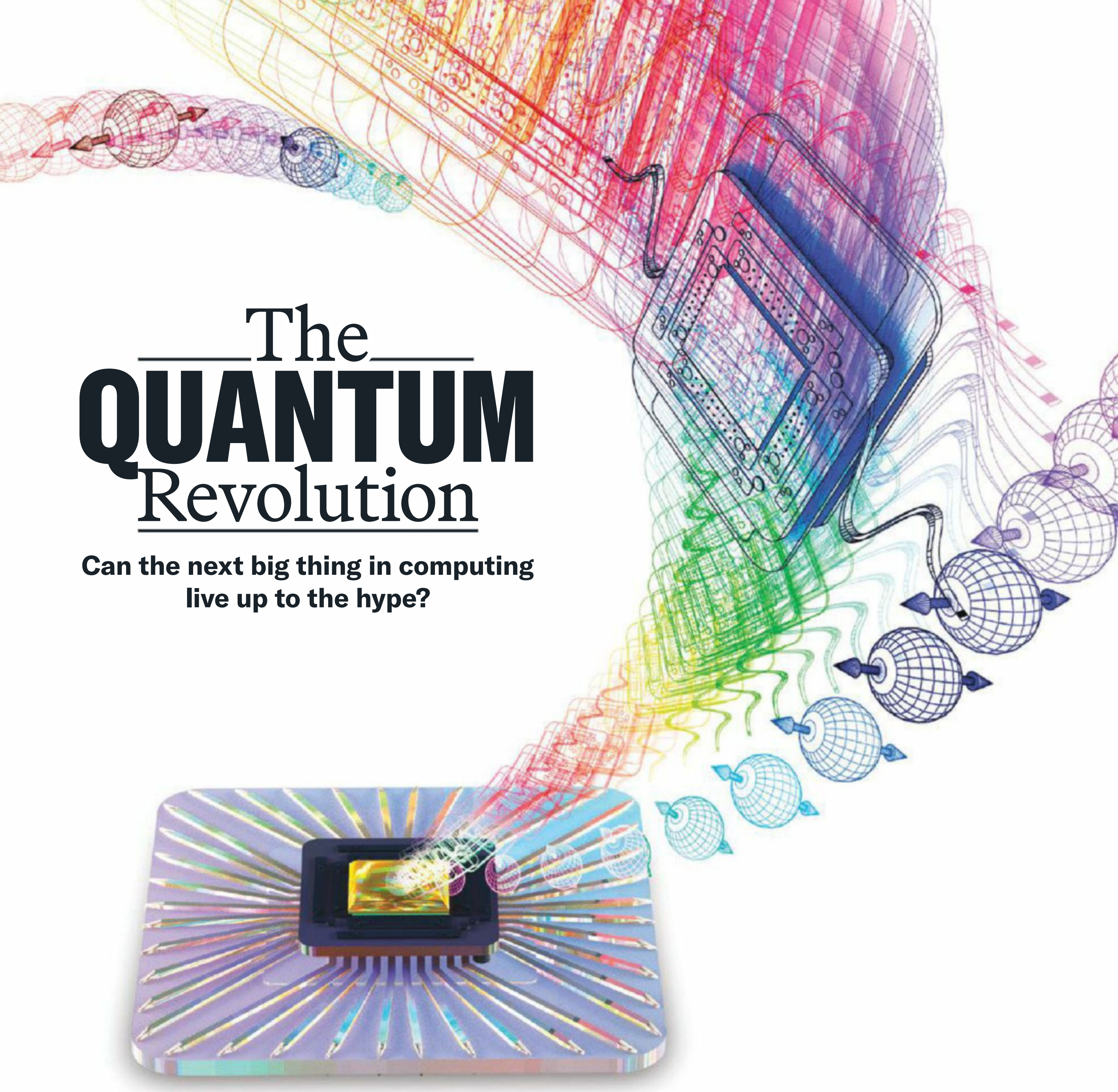
A New Race to the Moon

Lost Roads of the Roman Empire

The Scariest Problem in Math



The QUANTUM Revolution

Can the next big thing in computing live up to the hype?

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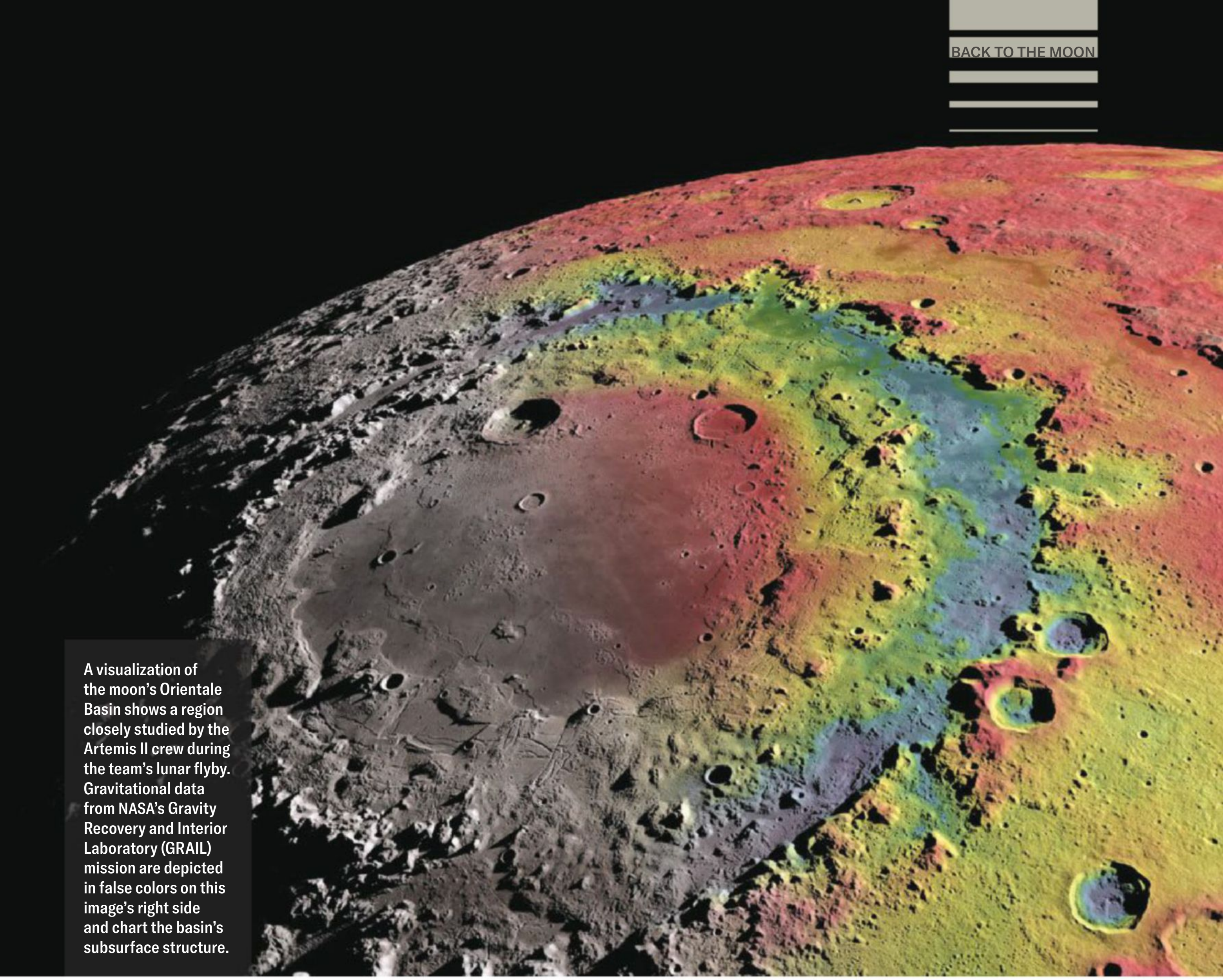


A visualization of the moon's Orientale Basin shows a region closely studied by the Artemis II crew during the team's lunar flyby. Gravitational data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission are depicted in false colors on this image's right side and chart the basin's subsurface structure.

NASA's Scientific Visualization Studio

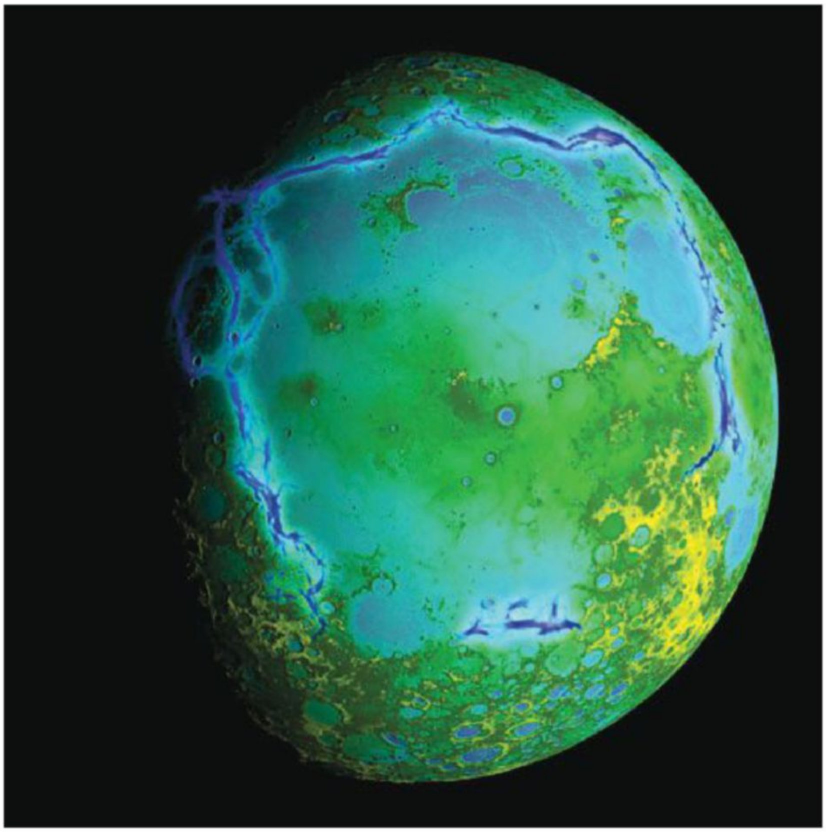
Lunar Geology

If NASA's ambitious lunar-exploration plans succeed, scientists will cover the moon with sensors—and find answers to several long-standing questions about the inner solar system BY ROBIN GEORGE ANDREWS

AT NASA'S "IGNITION" EVENT this March in Washington, D.C., the agency's administrator, Jared Isaacman, made it clear that Artemis II is only the beginning of a larger U.S. effort to populate the moon with astronauts and resource-prospecting robots. If this quest advances at the breakneck pace Isaacman desires, then Earth's celestial sidekick will also become a source of profound scientific revelations.

Despite the moon's proximity, we know surprisingly little about it with much certainty. The Apollo astronauts hauled back moon rocks and left behind a few short-lived geological experiments, but most of our lunar knowledge comes from moon-orbiting satellites, telescopic observations from Earth and the handful of sample-return missions undertaken recently by China.

Robin George Andrews is a volcanologist and science writer based in London. His most recent book is *How to Kill an Asteroid* (W. W. Norton, 2024). Follow him on X @SquigglyVolcano



A false-color topographic lunar view centers on Oceanus Procellarum, the largest expanse of frozen lava on the moon. Based on data from NASA's Lunar Reconnaissance Orbiter, as well as the space agency's GRAIL mission, the blue border structures are thought to be ancient, lava-flooded rift zones buried underneath Oceanus Procellarum's volcanic plains.

NASA/Colorado School of Mines/MIT/GSFC/Scientific Visualization Studio

Plenty of researchers are itching to use the moon as a Rosetta Stone for studying the origin and evolution of our world and the solar system at large. Earth's tectonics, volcanism, oceans, atmosphere and life have all erased the geological records of the planet's earliest eras. But the moon, lacking such tumult, has preserved its historical evidence. That makes the silvery orb "a perfect geological laboratory," says Sara Russell, a planetary scientist at London's Natural History Museum. With new lunar access, here are the biggest mysteries moon-focused scientists are hoping to solve.

How is the moon still geologically alive?

The churning heat deep within planets and moons is what gives them geological "life," from volcanic eruptions and earthquakes to the uplifting of mountains and the excavation of ocean basins. But when the heat wanes, a world dies, geologically speaking.

Scientists know of three main ways for those metaphorical fires to keep burning. Planets and moons possess a certain amount of primordial heat left over from the collisions of bodies that formed them. Decaying radioactive elements also emit heat. And the tidal forces that knead a world's innards like dough produce frictional heat.

The moon is much smaller than Earth, so its primordial heat should have leaked into space long ago. Lunar samples and theoretical models suggest it doesn't have a hidden abundance of radioactive elements. And careful calculations show that Earth's gravitational pull shouldn't be causing significant lunar tidal heating. Yet shallow quakes still shake the moon, and age estimates based on crater counts along its pockmarked surface suggest it was volcanically active as recently as 100 million years ago—which, on geological timescales, is yesterday.

Scientists, naturally, have questions. "Is the moon still volcanically active?" asks Thomas Watters, a senior scientist at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies in Washington, D.C. To find out just how much geological life still lingers there, and why, "we need to get a better look at the moon's internal structure," Watters says.

To delve to the (geological) heart of the matter, scientists want to know the moon's deepest secret: what's happening at its most abyssal depths. "Does the moon have a solid core or a liquid core?" asks Yuqi Qian, a lunar geologist at the University of Hong Kong. "We still don't know."

With seismometers, scientists can use moonquakes (caused by either internal rumblings or meteoroid strikes) to effectively perform a CT scan of the moon's deep subsurface. But the seismometers that the Apollo astronauts placed on the moon stopped working in 1977. Even if they were still operating, they're all located in just one patch of the moon's nearside. "We don't have any seismometers deployed on the farside," Qian says.

That's about to change. If current projections are to be believed, the Artemis IV mission will put astronauts on the moon in 2028. When those crewmembers reach their landing site near the moon's south pole, they'll tote along a cutting-edge seismometer package called the Lunar Environment Monitoring Station. Eventually, as part of a NASA initiative called Commercial Lunar Payload Services, robots will deploy a network of sensors on the moon's farside called the Farside Seismic Suite. "Artemis astronauts will be laying down some of the first nodes of a global seismic network," says Nicholas Schmerr, a seismologist and planetary scientist at the University of Maryland, College Park. (China may make its first crewed landing somewhere on the moon's nearside, and those astronauts will probably bring seismometers as well.)

Seismometers aren't only great at interrogating the mysteries of the lunar interior; they can also be used to work out just how seismically active the moon is today. Moonquakes, which at their strongest can persist for hours, could imperil a future moon base. "You don't want to think of the moon as this benign place," Watters says. "You really need to understand whether you have threats to long-term infrastructure from seismic activity."

To understand the moon's geological heartbeat, samples, too, will be vital. Rocks carried home by China's robotic lunar-sample-return missions, Chang'e 5 and Chang'e 6, indicate that the moon hosted active volcanism until at least two billion years ago. Widening our view to the moon's more recent history requires nabbing more youthful material from its surface. For now, Qian says, "we don't have samples younger than that."

Scientists also hope future landings will locate and sample expunged sections of the moon's mantle, the primeval underbelly of the lunar crust. If mantle rocks proved to be riddled with by-products of radioactive decay, it would probably mean the moon's interior is richer in heat-generating radioisotopes than scientists had thought—thus explaining why it's still convulsing long past its geological expiration date.

How did the moon form?

The moon's most popular origin story involves Theia—a Mars-size protoplanet—smashing into the primordial proto-Earth, with the debris from both bodies quickly coalescing into the moon. This account isn't just a fable: it's backed up by robust computer simulations grounded in plenty of geochemical evidence. Samples of the moon's mantle, though, could further test this theory—and geophysical observations could address the moon's weirdest feature.

The nearside is covered in vast, dark splotches of cooled volcanic rock called mare (Latin for "sea"). The farside looks more like Mercury: a crater-filled land of jagged mountain ridges. Why is the moon so two-faced?

One possible explanation comes from an idea called Earthshine. Eons ago, when the moon formed, its orbit was 15 times closer to Earth than it is now. At some point the moon became tidally locked, meaning one hemisphere (the nearside) always faced Earth. And because back then our planet was a seething ball of magma, the lunar nearside should have gotten baked like crème brûlée, turning molten and bubbly. Streams of vaporized rock whooshed around the moon, cooling and raining down on the farside to create its thick, lumpy crust. A network of seismometers, especially on the farside, could reveal hidden clues to the lunar past. "What is the structure of the moon?" Russell asks. "This is important to find out because it will help us understand how the moon first formed from the debris of a giant impact and then evolved."

Where did the moon's water come from?

NASA wants to set its astronauts down near the lunar south pole because that's where permanently shadowed craters hold some amount of water ice—a potential resource for hydrating humans, growing crops and making rocket fuel at a permanent moon base. It's no coincidence, then, that lunar prospecting was a hot topic at NASA's Ignition event. Astronauts could, in principle, descend into the treacherously dark and cold craters themselves to take a look, but most of this water divining will be conducted by robots.

NASA's Volatiles Investigating Polar Exploration Rover will use its instruments to sniff out subsurface water, then drill to confirm its suspicions. And NASA's next-generation moon buggy—or Lunar Terrain Vehicle—will do something similar while either being piloted by astronauts or autonomously navigating the surface. And on an upcoming crewed mission, astronauts are set to bring along the Lunar Dielectric Analyzer, an instrument that can detect electrical currents in the ground below, which can reveal the presence of ice. "This will really help us understand where water is on the moon and in what form," Russell says.

The search for water isn't just pragmatic. Scientists still don't really know where Earth's water came from. Ice-rich comets and drier asteroids are the two prime suspects. Geochemical studies of meteorites and Earth's oceans suggest that asteroids were the more likely vector, but the case is far from closed. Consulting the moon's relatively pristine terrain—much of which has been frozen in time for billions of years—could help solve this mystery. "If there's any water ice on the moon, its signal might be more primitive," Qian says. And because Earth and the moon have a very similar ancient history, "the origin of water on the moon is likely to be the same as the origin of water on Earth," Russell says. All scientists need to do now is find it. ●

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