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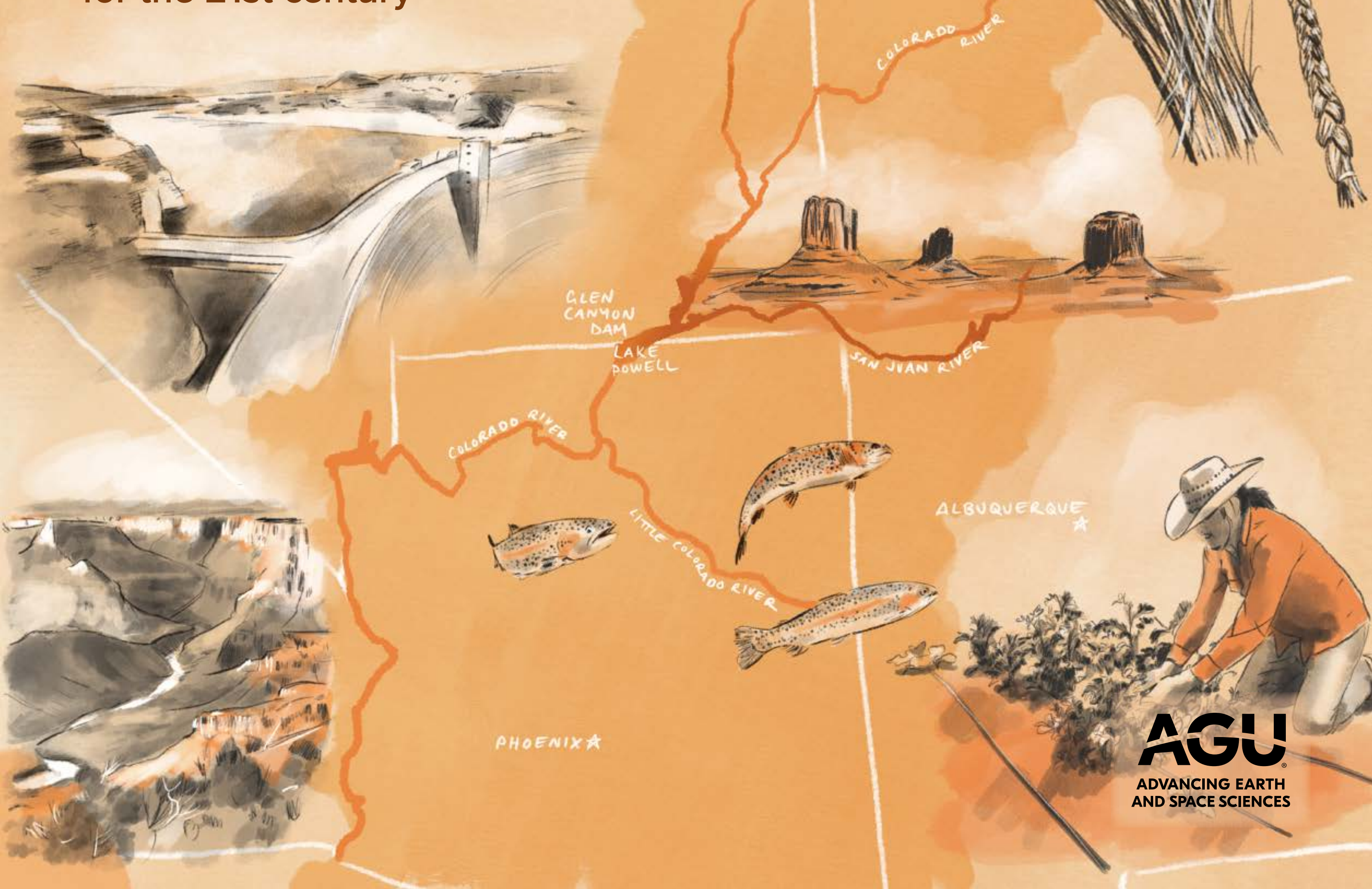

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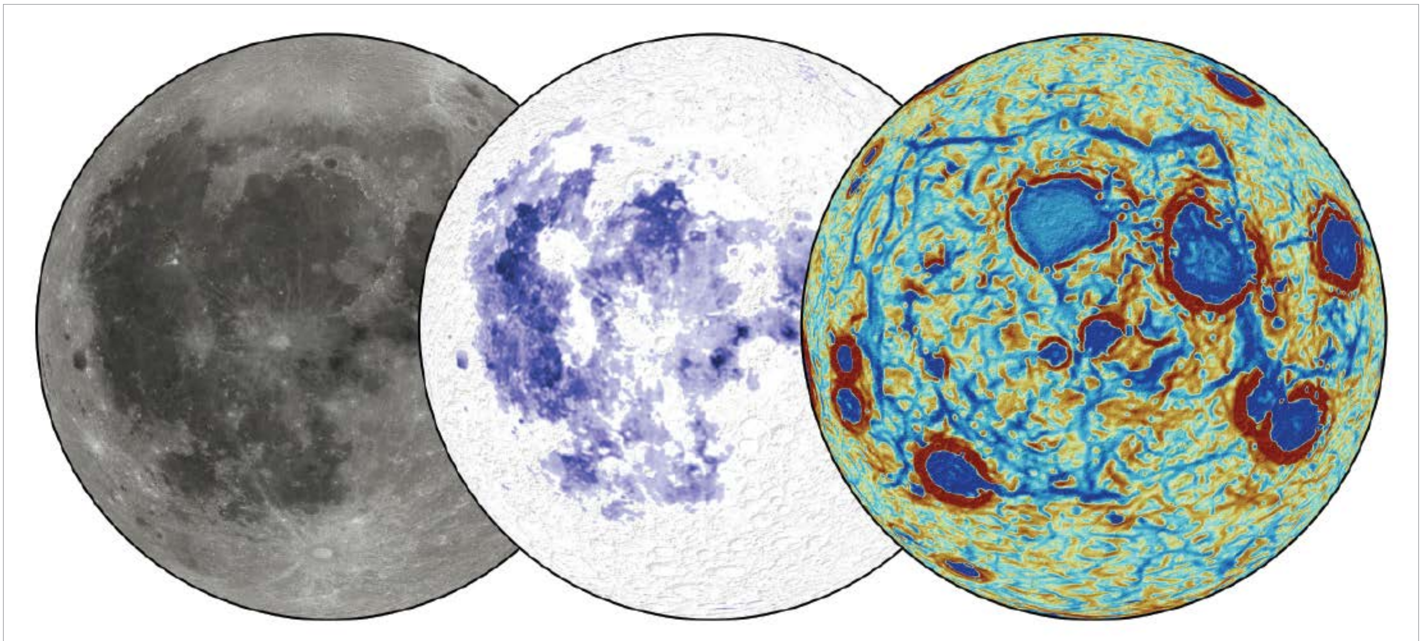
The Moon's Mantle Did a Flip—and Scientists May Now Have Evidence



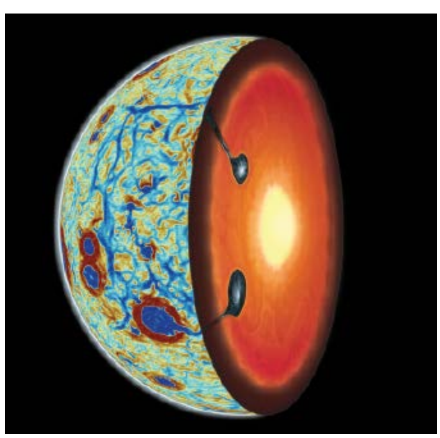
The familiar view of the Moon from Earth (left) shows its nearside dominated by dark volcanic plains, called maria (middle). These maria are surrounded by a mysterious pattern of anomalies (visible as blue lines in a recent gravity map, right). Scientists believe that these lines might be remnants of dense material that sank deep within the Moon billions of years ago. Credit: Adrien Broquet/University of Arizona

For decades, scientists have been intrigued by a strange twist in the Moon's history. Toward its last stages of formation, the lunar mantle likely flipped: Minerals that had formed at its top sank to the bottom, in a process called lunar mantle overturn. The idea emerged from simulations based on the analysis of lunar rocks brought back by the Apollo missions.

Now a new study published in *Nature Geoscience* offers the first evidence supporting the theory (bit.ly/mantle-overturn).

Four and a half billion years ago, a collection of gases and rocks—remnants of a massive collision between Earth and another object—coalesced into a molten ball that would become the Moon. The lunar surface was initially made up of a vast magma ocean. As it cooled, a natural sorting process began. Metals solidified first, forming the lunar core. Then, minerals started crystallizing, with the denser ones sinking toward the center and the lighter ones rising to the surface and forming the Moon's early crust.

However, during the final stages of crystallization, something peculiar happened. The small bit of remaining magma at the top of the mantle crystallized, forming a layer of ilmenite, a titanium-rich mineral denser than the underlying rock. Scientists theorize that this layer eventually sank, essentially flipping the mantle.



An ilmenite layer may have cascaded into the Moon's mantle in the past. Credit: Adrien Broquet/University of Arizona & Audrey Lasbordes

"You have the top of the mantle that goes down, and then whatever was underneath, that goes up," said Adrien Broquet of the German Aerospace Center in Berlin, who helped lead the new investigation during his time as a postdoctoral researcher at the University of Arizona.

Scientists think that after it sank, some of the ilmenite melted and eventually returned to the surface as titanium-rich lava flows, which were sampled by the Apollo astronauts. This has been the leading theory for the past 50 years, but evidence of the sinking process has been missing.

Matching the Evidence

Researchers realized that NASA's GRAIL (Gravity Recovery and Interior Laboratory) mission, which flew more than a decade ago, might have captured a snapshot of the vestiges of the ilmenite sinking process.

In 2012, GRAIL used two orbiting spacecraft to measure tiny variations in the Moon's gravitational pull. It detected a polygonal pattern of gravity anomalies produced by dense rocks surrounding lunar maria, the dark patches of basalt on the lunar surface's nearside.

Though scientists had been puzzled by the polygonal shapes revealed by GRAIL, it wasn't until one of the new study's team members did a series of computer simulations of how a sinking ilmenite layer would behave that they connected the two. The shapes formed by the sinking ilmenite in the simulations matched what the gravity data were revealing.

The dense rocks spotted by GRAIL are likely the last remnants of the ilmenite layer, which didn't sink uniformly, according to the researchers. Instead, because of the thickness of the underlying mantle, the ilmenite fractured into flat sheets that cascaded downward in a series of waterfall-like structures. These "falls" eventually froze in place as they cooled, preserving their unique form for billions of years.

If true, the gravity data would be the first physical evidence of the ilmenite layer's existence.

"This is one of the most important gravity signals that we have on the Moon, and it was completely unexplained," Broquet said. "This is going to help a lot in future modeling of this process."

Scientists think that the structures left behind by the cascading ilmenite can shed light on the properties of the lunar mantle at the time they formed, the mantle's viscosity in particular. "These ilmenites are sinking into the mantle, but as the Moon cools down, some of these cascades will freeze," Broquet said.

He compared the process to heating a thick liquid, like honey, in a pot: As it gets hotter, it flows more rapidly and forms smaller bubbles. If it cools down suddenly and the bubbles are preserved, they can reveal how quickly the liquid was flowing. Similarly, the geometry of the frozen ilmenite cascades can tell scientists how easily the lunar mantle flowed billions of years ago.

"It's a very interesting idea, but it's very tricky to prove or disprove," said James Tuttle Keane, a planetary scientist at NASA's Jet Propulsion Laboratory who wasn't involved with the new study. (Keane is a science adviser for *Eos.*) "You can create a lot of models to explain gravity observations, and so it's hard to use gravity data alone to separate these things out," he said. Additional observations could put these ideas to the test, whether from modeling, analyzing gravity data, or, ideally, showing that samples from these regions have different geochemistry, Keane added.

When and Where

The researchers dated the ilmenite sinking event by looking at the ages of lunar impact basins. The ilmenite cascades are disrupted by the oldest impact basins on the Moon's nearside, which formed around 4.22 billion years ago, suggesting that the cascades formed earlier. The timing of the sinking is coherent with the later uptick in volcanic activity that brought to the surface the titanium-rich lava flows sampled by the Apollo missions, the authors said.

GRAIL did not detect similar anomalies on the Moon's farside, which has a thicker crust.

"This is one of the most important gravity signals that we have on the Moon, and it was completely unexplained."

This could mean that the features are there but at a depth where GRAIL couldn't detect them. Another possibility is that the ilmenite layer never formed on the farside. Or maybe it formed but migrated toward the nearside, Broquet explained.

A potential trigger for such migration could be a large impact, like the one that formed the South Pole–Aitken basin on the Moon's farside. If such an impact happened when the Moon was crystallizing, which is likely, according to Broquet, simulations show that such an impact can trigger a mass movement toward the antipode of the basin. This, Broquet said, "is exactly where we see the ilmenite in the nearside."

The target landing site for NASA's Artemis III crewed mission to the Moon is the South Pole–Aitken basin, offering an opportunity for collecting samples that could help in testing these ideas, he added.

By **Javier Barbuzano** (@javibarbuzano), Science Writer