Scientists solve a long-standing mystery surrounding the moon's 'lopsided' geology

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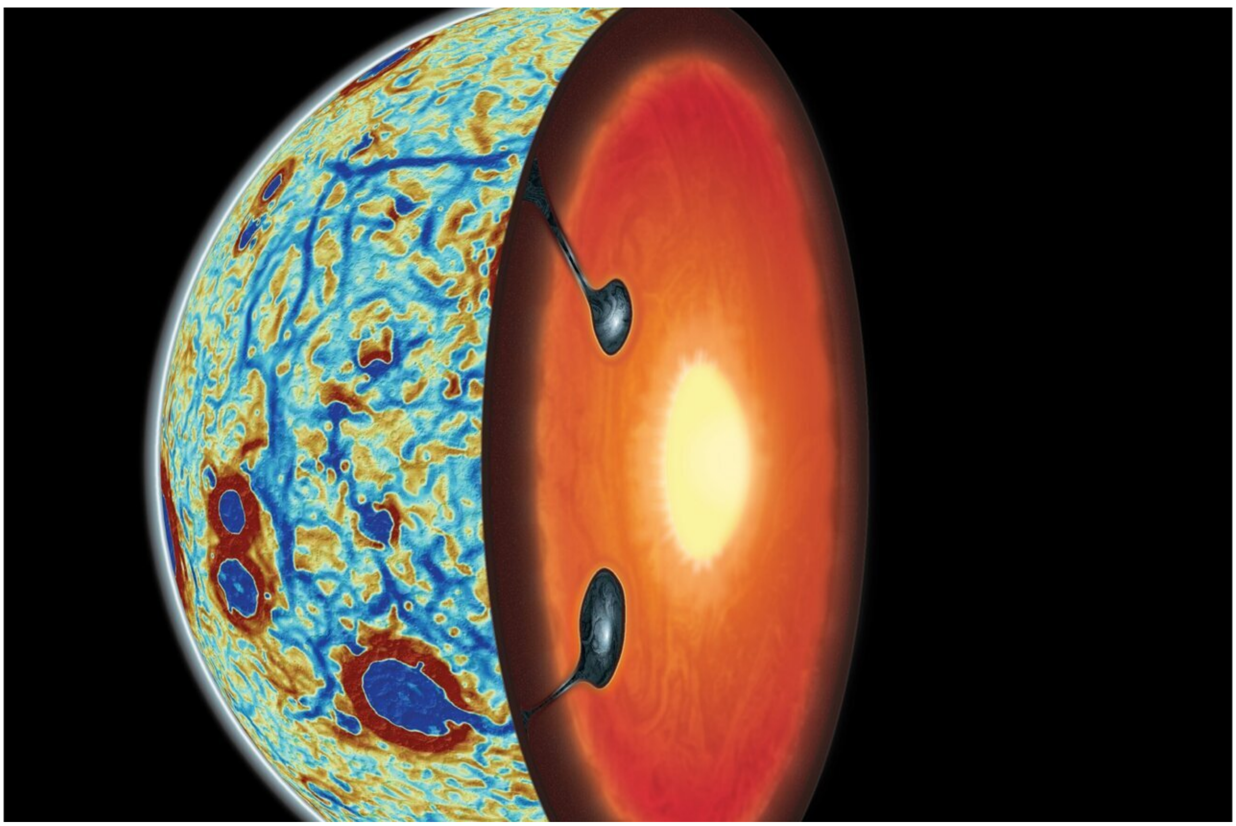


Schematic illustration with a gravity gradient map (blue hexagonal pattern) of the lunar nearside and a cross-section showing two ilmenite-bearing cumulate downwellings from lunar mantle overturn. Credit: Adrien Broquet/University of Arizona & Audrey Lasbordes

About 4.5 billion years ago, a small planet smashed into the young Earth, flinging molten rock into space. Slowly, the debris coalesced, cooled and solidified, forming our moon. This scenario of how the Earth's moon came to be is the one largely agreed upon by most scientists. But the details of how exactly that happened are "more of a choose-your-own-adventure novel," according to researchers in the University of Arizona Lunar and Planetary Laboratory who published a paper in *Nature Geoscience*.

The findings offer important insights into the evolution of the lunar interior, and potentially for planets such as the Earth or Mars.

Most of what is known about the origin of the moon comes from analyses of rock samples, collected by Apollo astronauts more than 50 years ago, combined with theoretical models. The samples of basaltic lava rocks brought back from the moon showed surprisingly high concentrations of titanium. Later satellite observations found that these titanium-rich volcanic rocks are primarily located on the moon's nearside, but how and why they got there has remained a mystery—until now.

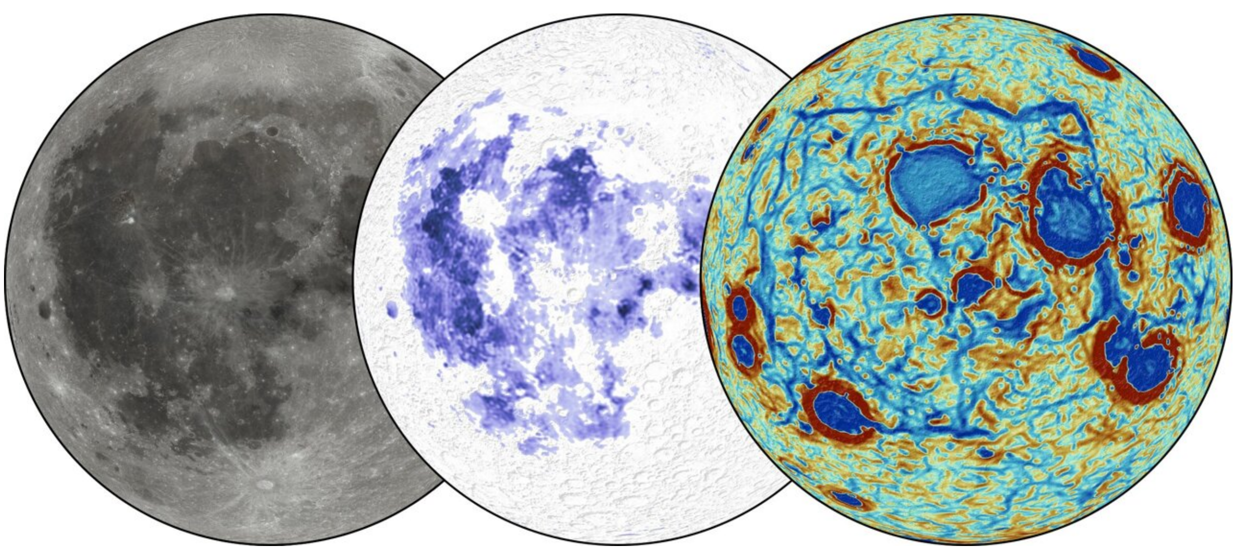
Because the moon formed fast and hot, it was likely covered by a global magma ocean. As the molten rock gradually cooled and solidified, it formed the moon's mantle and the bright crust we see when we look up at a full moon at night. But deeper below the surface, the young moon was wildly out of equilibrium. Models suggest that the last dregs of the magma ocean crystallized into dense minerals including ilmenite, a mineral containing titanium and iron.

"Because these heavy minerals are denser than the mantle underneath, it creates a gravitational instability, and you would expect this layer to sink deeper into the moon's interior," said Weigang Liang, who led the research as part of his doctoral work at LPL.

Somehow, in the millennia that followed, that dense material did sink into the interior, mixed with the mantle, melted and returned to the surface as titanium-rich lava flows that we see on the surface today.

"Our moon literally turned itself inside out," said co-author and LPL associate professor Jeff Andrews-Hanna. "But there has been little physical evidence to shed light on the exact sequence of events during this critical phase of lunar history, and there is a lot of disagreement in the details of what went down—literally."

Did this material sink as it formed a little at a time, or all at once after the moon had fully solidified? Did it sink into the interior globally and then rise up on the near side, or did it migrate to the near side and then sink? Did it sink in one big blob, or several smaller blobs?



The lunar near side with its dark regions, or "mare," covered by titanium-rich volcanic flows (center) makes up the moon's familiar sight from Earth (left). The mare region is surrounded by a polygonal pattern of linear gravity anomalies (blue in image on the right) interpreted to be the vestiges of dense material that sank into the interior. Their presence provides the first physical evidence for the nature of the global mantle overturn more than 4 billion years ago. Credit: Adrien Broquet/University of Arizona

"Without evidence, you can pick your favorite model. Each model holds profound implications for the geologic evolution of our moon," said co-lead author Adrien Broquet of the German Aerospace Center in Berlin, who did the work during his time as a postdoctoral research associate at LPL.

In a previous study, led by Nan Zhang at Peking University in Beijing, who is also a co-author on the latest paper, models predicted that the dense layer of titanium-rich material beneath the crust first migrated to the near side of the moon, possibly triggered by a giant impact on the far side, and then sunk into the interior in a network of sheetlike slabs, cascading into the lunar interior almost like waterfalls. But when that material sank, it left behind a small remnant in a geometric pattern of intersecting linear bodies of dense titanium-rich material beneath the crust.

"When we saw those model predictions, it was like a lightbulb went on," said Andrews-Hanna, "because we see the exact same pattern when we look at subtle variations in the moon's gravity field, revealing a network of dense material lurking below the crust."

In the new study, the authors compared simulations of a sinking ilmenite-rich layer to a set of linear gravity anomalies detected by NASA's GRAIL mission, whose two spacecraft orbited the moon between 2011 and 2012, measuring tiny variations in its gravitational pull. These linear anomalies surround a vast dark region of the lunar near side covered by volcanic flows known as mare (Latin for "sea").

The authors found that the gravity signatures measured by the GRAIL mission are consistent with ilmenite layer simulations, and that the gravity field can be used to map out the distribution of the ilmenite remnants left after the sinking of the majority of the dense layer.

"Our analyses show that the models and data are telling one remarkably consistent story," Liang said. "Ilmenite materials migrated to the near side and sunk into the interior in sheetlike cascades, leaving behind a vestige that causes anomalies in the moon's gravity field, as seen by GRAIL."

The team's observations also constrain the timing of this event: The linear gravity anomalies are interrupted by the largest and oldest impact basins on the near side and therefore must have formed earlier. Based on these cross-cutting relationships, the authors suggest that the ilmenite-rich layer sank prior to 4.22 billion years ago, which is consistent with it contributing to later volcanism seen on the lunar surface.

"Analyzing these variations in the moon's gravity field allowed us to peek under the moon's surface and see what lies beneath," said Broquet, who worked with Liang to show that the anomalies in the moon's gravitational field match what would be expected for the zones of dense titanium-rich material predicted by computer simulation models of lunar overturn.

More than 50 years ago, Apollo astronauts brought basaltic lava rocks back from the moon with surprisingly high concentrations of titanium. Later, satellite observations found that these titanium-rich volcanic rocks are primarily located on the moon's nearside - but how and why they got there has remained a mystery – until now. Credit: NASA

Lopsided moon

While the detection of lunar gravity anomalies provides evidence for the sinking of a dense layer in the moon's interior and allows for a more precise estimate of how and when this event occurred, what we see on the surface of the moon adds even more intrigue to the story, according to the research team.

"The moon is fundamentally lopsided in every respect," Andrews-Hanna said, explaining that the near side facing the Earth, and particularly the dark region known as Oceanus Procellarum region, is lower in elevation, has a thinner crust, is largely covered in lava flows, and has high concentrations of typically rare elements like titanium and thorium.

The far side differs in each of these respects. Somehow, the overturn of the lunar mantle is thought to be related to the unique structure and history of the near side Procellarum region. But the details of that overturn have been a matter of considerable debate among scientists.

"Our work connects the dots between the geophysical evidence for the interior structure of the moon and computer models of its evolution," Liang added.

"For the first time we have physical evidence showing us what was happening in the moon's interior during this critical stage in its evolution, and that's really exciting," Andrews-Hanna said. "It turns out that the moon's earliest history is written below the surface, and it just took the right combination of models and data to unveil that story."

"The vestiges of early lunar evolution are present below the crust today, which is mesmerizing," Broquet said. "Future missions, such as with a seismic network, would allow a better investigation of the geometry of these structures."

Liang added, "When the Artemis astronauts eventually land on the moon to begin a new era of human exploration, we will have a very different understanding of our neighbor than we did when the Apollo astronauts first set foot on it."

More information: Adrien Broquet, Vestiges of a lunar ilmenite layer following mantle overturn revealed by gravity data, *Nature Geoscience* (2024). DOI: 10.1038/s41561-024-01408-2.
www.nature.com/articles/s41561-024-01408-2

Provided by University of Arizona