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A neighborhood in space: finding the Moon's age to understand Earth's evolution

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How was the Earth formed? The age of its neighbor, the Moon, tells us much about the history of our planet. We propose a new method to more accurately estimate how old the Moon is by considering crucial early events, in particular crystallization of the lunar magma ocean.

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Understanding what made the Earth a habitable planet is an overarching goal of planetary sciences. Early events during the Earth's infancy set the initial conditions for its long-term evolution. The formation of its iron core and rocky mantle is one of those essential events. It was finalized in the aftermath of the collision of a large drifting rocky body onto the young Earth. The same collision hurled enough material into orbit to form the Moon: Earth's only satellite. There is hence a strong link between the Moon's birth and key events of Earth's youth. Scientists exploit this link to reveal our planet's history by looking into the Moon, which is less shy than the Earth when it comes to telling its age.

How come the Moon is easier to study than the Earth? — The Earth's surface is being constantly recycled, making it a forgetful planet. Even its oldest rocks do not go as far back in time as the Moon-forming event. In contrast, lunar material is well preserved and thus provides valuable clues about its earliest age. The oldest lunar rocks were formed through the crystallization of a magma ocean, which covered the surface early after its hot formation. Whoever wants to know when the Moon formed needs to know when its magma ocean crystallized and how long it took.

The end of the lunar magma ocean has previously been estimated to 4.36 billion years ago by measuring isotopic ratios in lunar samples that are considered as the end product of its crystallization. Isotopes are atoms of a given chemical element (like uranium or lead) having different masses. Some isotopes are stable, while others are unstable and turn into yet others, so-called "radiogenic". As this process, called radioactive decay, occurs at a constant rhythm, the ratio of stable (unchanged) to radiogenic isotopes provides a geological clock.

In this study, we simulated the cooling and crystallization of the ancient lunar magma ocean to estimate its lifetime. Because magma solidifies more easily at high pressure, the lunar magma ocean crystallized from the bottom up to the surface. Moreover, under the early Moon conditions, a floating crust formed atop the magma ocean, acting as a thermal lid and slowing down its cooling. This insulted magma ocean was kept hot by volcanism, fed by magma produced in the already-solidified part of the Moon's mantle. Taking all these effects into account in our simulations, we found that it took surprisingly long, 180 to 200 million years, for the lunar magma ocean to fully crystallize.

At this point, evaluating the age of the Moon seemed straightforward. However, we realized that the method previously used to infer the age of the end products of the magma ocean was conflicting with our finding of its long-lasting crystallization. Indeed, a baseline assumption of this method was that the magma ocean solidified very rapidly so that the radioactive decay during its crystallization was negligible. But this assumption no longer holds for a 200 million years-long magma ocean crystallization period. That is, using the traditional method to estimate the samples' age was like reading time on a stopwatch which did not start from 0. To fix this problem, we simulated the radioactive decay during the magma ocean crystallization. We found that the samples recording the end of the magma ocean solidification are actually younger than previously thought, by up to 100 million years, and that they suggest that the Moon formed between 4.45 and 4.40 billion years ago.

This research gives a new insight into how old the Moon is: the early lunar evolution, as illustrated by the magma ocean's lifetime, needs to be considered to more accurately interpret the age of the oldest lunar materials. Our estimate of the age of the Moon-forming impact agrees well with the dating of the end of the Earth's core formation. This dating has been challenged by alternative explanations of the underlying measurement. But the agreement with our estimate of the age of the Moon strengthens the hypothesis that it indeed records the formation of the Earth's core - a logical consequence of the massive melting occurring on Earth after a giant collision. This study is a great example of how much we can learn about our planet by studying its neighbor.