

Hot Idea

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The Oldest Moon Rocks



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--- Rocks from the lunar crust provide new clues to the age and origin of the Moon and the terrestrial planets.

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Anorthosites, rocks composed almost entirely of plagioclase feldspar, are the oldest rocks on the Moon. They appear to have formed when feldspar crystallized and floated to the top of a global magma ocean that surrounded the Moon soon after it formed. Not all ages determined for anorthosites, however, are as old as we expected--one appeared to be only 4.29 billion years old. While 4.29 billion years sounds very ancient, a magma ocean ought to have solidified well within 100 million years of lunar origin about 4.55 billion years ago. One possibility is that the young ages reflect impact events, not the original time of igneous crystallization. My colleagues Lars Borg (University of New Mexico) and Larry Nyquist and Don Bogard (Johnson Space Center) and I studied an anorthosite (rock 67215) relatively rich in pyroxene, allowing us to determine a precise crystallization age of 4.40 billion years. But even that age might have been affected by the subsequent shock heating event that reset the low-temperature components in this rock about 500 million years after it formed.

By examining data for all of the previously dated lunar anorthosites, we were able to show that plagioclase feldspar is more prone to shock damage than are the pyroxenes in these rocks, so we plotted only the pyroxene data for four different anorthosites on a samarium-neodymium isochron diagram. These data fall on a well-defined line indicating a crystallization age for the anorthosites of 4.46 billion years, consistent with very early, widespread melting of the Moon. Other data for 67215 show that it comes from a relatively shallow depth in the crust, giving us clues to the structure of the lunar crust. Studies like this one are filling in the picture of how the initial crust of the Moon formed, which in turn sheds light on the formation of the terrestrial planets.

Reference:

Norman, M. D., Borg, L. E., Nyquist, L. E., and Bogard, D. D. (2003) Chronology, geochemistry, and petrology of a ferroan noritic anorthosite clast from Descartes breccia 67215: Clues to the age, origin, structure, and impact history of the lunar crust. *Meteoritics and Planetary Science*, vol 38, p. 645-661.

Keystone for Understanding the Origin of Planetary Systems

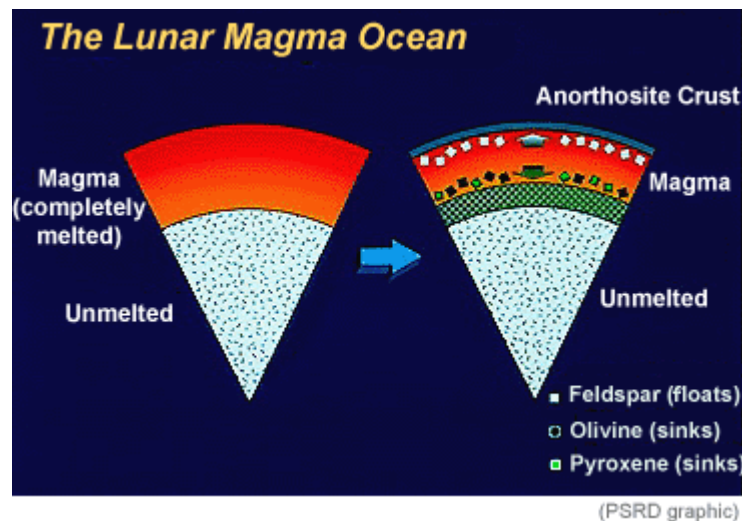
Understanding the origins of planetary systems is one of the most central and challenging questions in planetary science. The idea that the planets in our Solar System were assembled from a rotating disk of dust and gas known as the [Solar Nebula](#) is reasonably well established, but in detail we know surprisingly little about the actual events that lead to construction of the planets.

[Chondritic](#) meteorites have revealed an impressive portrait of conditions in the early nebula (see [PSRD](#) articles [Dating the Earliest Solids in our Solar System](#) and [The First Rock in the Solar System](#)), whereas igneous meteorites such as the eucrites provide a glimpse of what the early planets may have looked like (see [PSRD](#) article [Asteroidal Lava](#)

[Flows](#)). The compositions and textures of [eucritic](#) meteorites show that some asteroids were extensively molten, and it would not be surprising if similar processes occurred on the early planets. However, asteroids are relatively small bodies and the existence of now-extinct radioactive isotopes such as ^{26}Al and ^{182}Hf (see [PSRD](#) article [Hafnium, Tungsten, and the Differentiation of the Moon and Mars](#)) in some igneous meteorites show that their parent bodies must have cooled rapidly and experienced little geological activity since they formed. Although igneous meteorites provide important information about what was happening on small bodies in the early Solar System, they provide only a general guide to the nature of events that built the larger planets.

The internal structure and chemical compositions of the terrestrial planets provide intriguing clues to their origins, but the record of early events on Earth, Venus, and Mars has been obscured or erased by billions of years of geological activity. Processes such as [convection](#), volcanism, [weathering](#), and [erosion](#) have largely obliterated the primary signatures that would inform us about the mechanisms and timing of planetary formation in the inner Solar System. Fortunately, nature has provided a keystone that links the record of early nebular events preserved in meteorites with the subsequent geological evolution of the terrestrial planets, and that keystone is the Moon. For example, volcanism on the Earth and Moon overlapped in time for about a billion years, yet the Moon's crust is sufficiently old that it preserves direct evidence for planetary-scale events that occurred before the Earth's surface stabilized. In effect, the surface of the Moon is a time capsule that carries a record of the physical processes that created and modified the terrestrial planets.

An essential step in unraveling some of the early planetary history was the acquisition of samples from the Moon by the [Apollo](#) and [Luna](#) exploration missions. While photographs and remote sensing data provide useful information about distant bodies, having real samples from the Moon available for detailed laboratory studies has revealed aspects of the geological evolution of the planets which otherwise could only be imagined. For example, the first studies of Moon rocks inspired John Wood (Smithsonian Astrophysical Observatory) to boldly imagine the idea that terrestrial planets must have been extensively molten soon after they formed.



The concept that the Moon melted substantially (possibly completely) when it formed, nicknamed the "magma ocean concept" is a fundamental tenet of lunar science.

This global melting event produced a stratified Moon with a low-density crust formed by accumulation of the mineral plagioclase overlying a higher density mantle of olivine and pyroxene. Meteorite impacts have reworked the lunar crust extensively over the past 4.5 billion years, and most of the rocks returned from the Moon are [breccias](#). Although these breccias preserve important clues to lithologic and compositional diversity in the lunar crust and the impact history of the Earth and Moon, deciphering the primary record of crustal evolution from these rocks is difficult because they are mechanical mixtures of unrelated rocks.

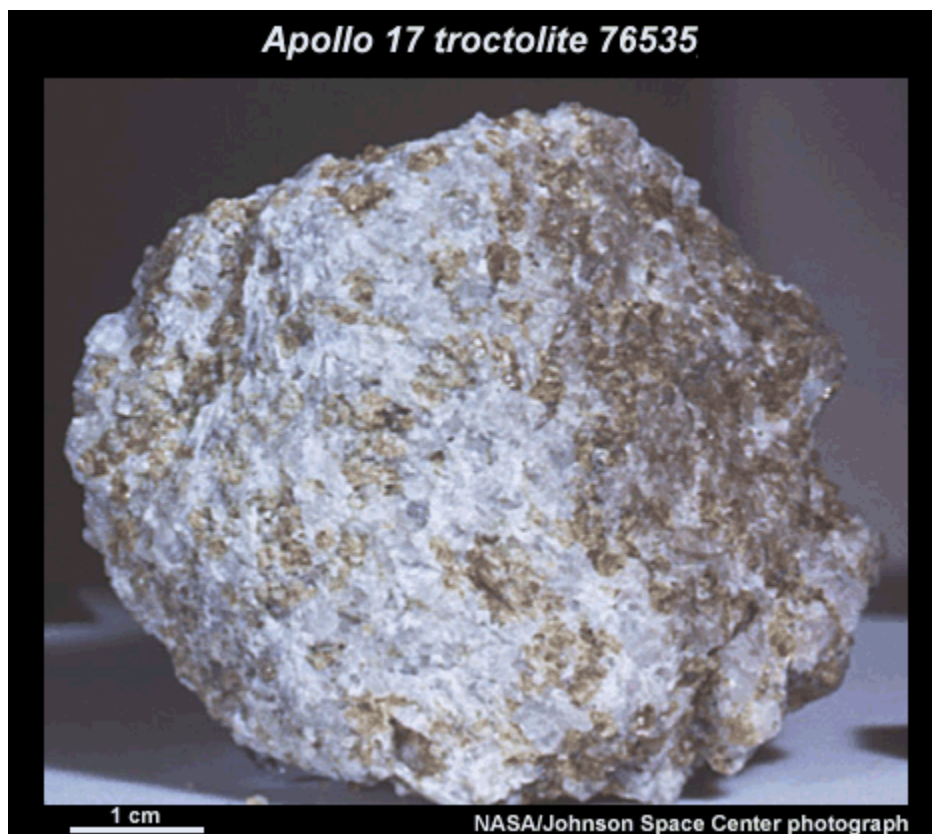


67016 is an impact breccia that was collected from the rim of North Ray crater, Apollo 16. It consists of fragments of plagioclase (white) and glass (dark gray). Rock fragments in breccias like these tell us a great deal about the early history of the Moon.

Fortunately, the primary record of the early crustal genesis and evolution on the Moon has not been completely destroyed. Lunar scientists have developed criteria such as low abundances of siderophile elements (which are present in high concentrations in most meteorites relative to common igneous rocks) and other chemical and petrographic data, to identify a suite of rocks thought to represent primary igneous cumulates from the lunar highlands. These cumulate rocks are rich in plagioclase, and most are classified as anorthosites (>90% plagioclase), norites (plagioclase plus low-Ca pyroxene) and troctolites (plagioclase plus olivine). The anorthosites are usually referred to as 'ferroan' after the iron-rich compositions of their olivines and pyroxenes, whereas the norites and troctolites have more magnesian mineral compositions.



15415 is an anorthosite (more than 90% plagioclase feldspar) collected by the Apollo 15 crew in the Hadley-Apennine region.

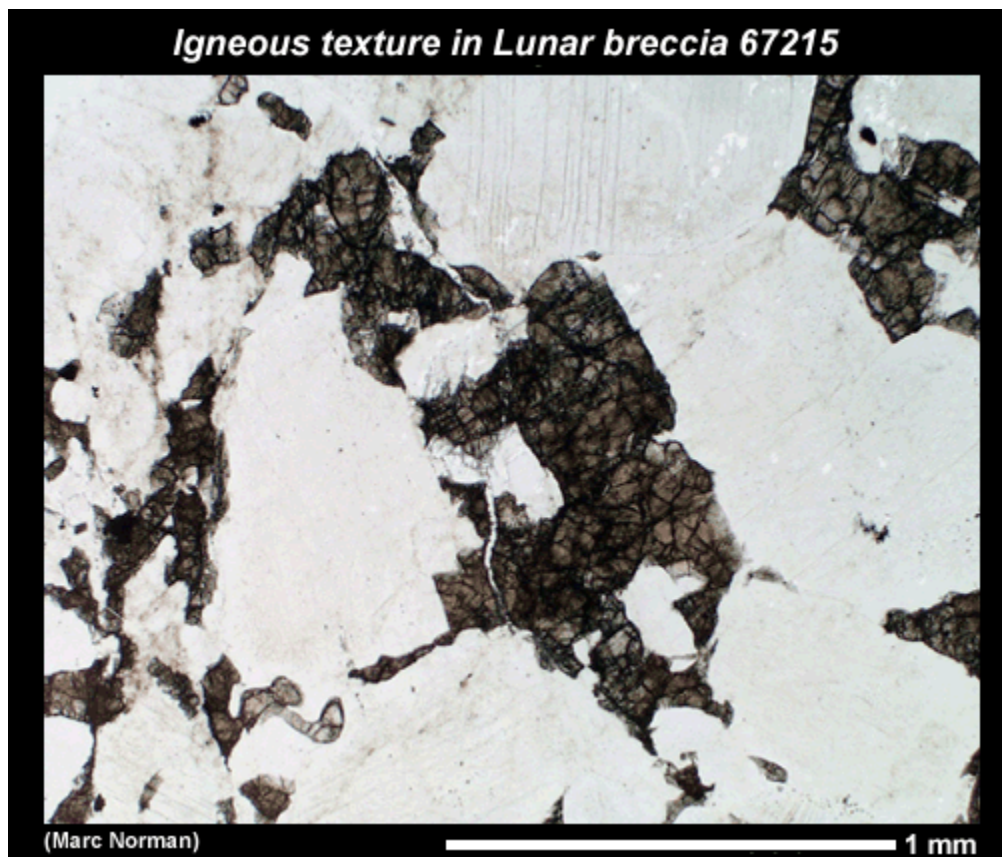


76535 is a troctolite (plagioclase plus olivine) collected by the Apollo 17 crew in Taurus-Littrow.

Age of the Lunar Crust

Lunar anorthosites in particular have assumed a key role in our understanding of the early history of the Moon because lunar geochemists think that these rocks crystallized directly from the global magma ocean. The ages and chemical compositions of lunar anorthosites therefore provide ground truth tests for theoretical models of planetary accretion and differentiation. We have measured the isotopic and trace element compositions of lunar anorthosites to provide better information about how and when they formed. Precise crystallization ages of lunar anorthosites are difficult to determine. The long history of meteorite impacts into the lunar crust has disturbed or reset their K-Ar and U-Pb isotopic compositions. The fact that most lunar anorthosites are, by definition, composed almost totally of plagioclase makes it difficult to obtain enough sample for mineral isochrons using more robust systems such as ^{147}Sm - ^{143}Nd . Our work has focused on a small group of lunar anorthosites that have enough pyroxene to enable mineral isochrons to be determined.

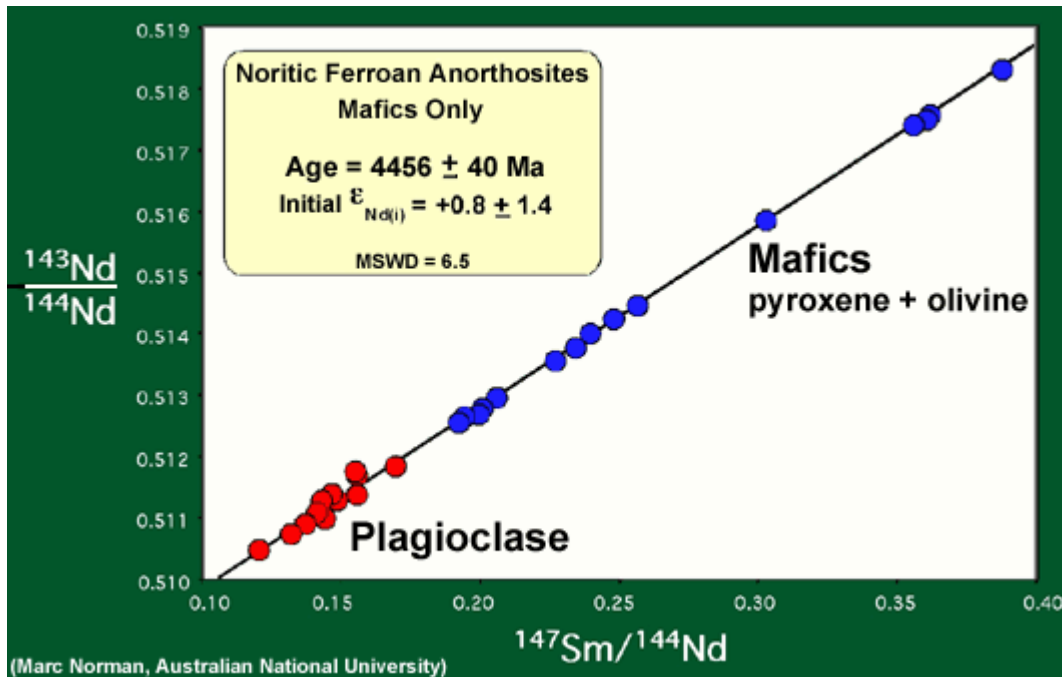
Recently we reported the results of a study on a clast of ferroan noritic anorthosite from Apollo 16 breccia 67215. This clast is especially interesting as it has one of the best-preserved igneous textures of any lunar anorthosite (see photo below), and it was found in a type of breccia collected around North Ray crater in which ancient crustal rocks have been found by Chantal Alibert, Malcolm McCulloch, and myself in a previous study back in 1994. Mineral compositions and trace element characteristics of this clast show that it is genetically related to the main group of lunar ferroan anorthosites. Our isotopic analyses of plagioclase and pyroxene separated from 67215c produced a ^{147}Sm - ^{143}Nd mineral isochron indicating a crystallization age of 4.40 ± 0.11 billion years. This very old age supports the idea that lunar anorthosites formed early in the history of the Moon, most likely by crystallization from a magma ocean.



Photomicrograph image showing the igneous texture of the clast of ferroan noritic anorthosite from Apollo 16 breccia 67215.

These results also help explain some puzzling features of previous isotopic studies on other lunar anorthosites. Prior to this study, Sm-Nd isochrons had been obtained on only three other lunar anorthosites, and these gave an unexpectedly large range of ages (4.29-4.54 Ga; Carlson and Lugmair, 1988; Alibert et al, 1994; Borg et al., 1999). This range of ages provoked a strong challenge to the idea that all of these rocks crystallized from the magma ocean, and lead to

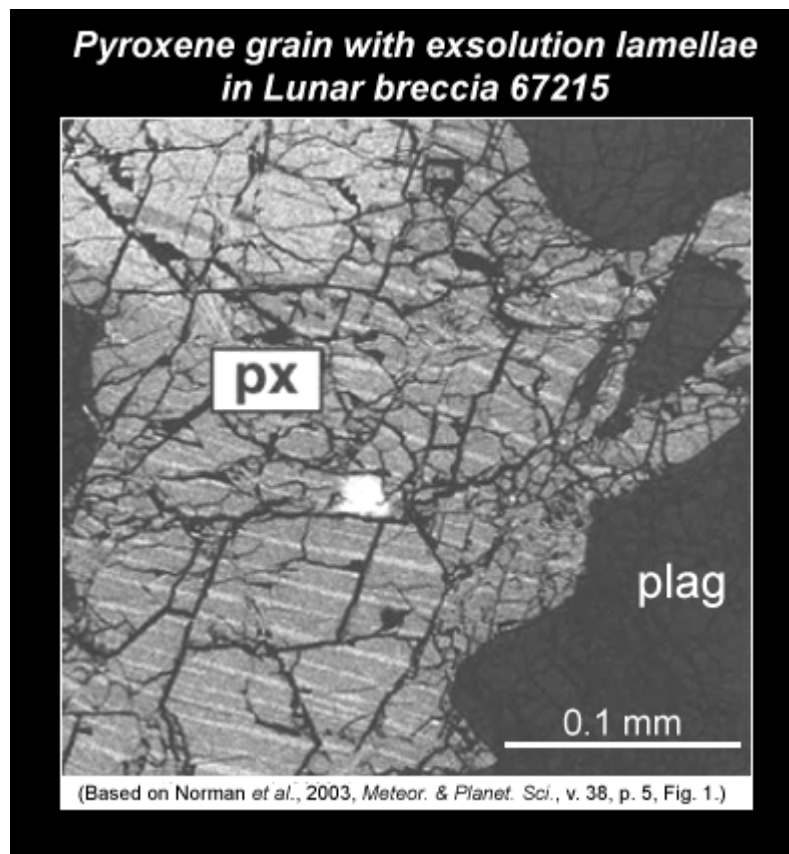
proposals for alternative styles of lunar evolution perhaps involving formation of the crust through a series of smaller, unrelated magmatic events. However, we found that the range of ages reported by the previous studies could be explained by subtle disturbance of the Sm-Nd isotopic compositions in plagioclase separated from the anorthosites, and that the pyroxenes and olivines from these rocks defined an age of 4.46 ± 0.04 billion years (see graph below). This may represent a robust estimate for the primary crystallization age of the earliest lunar crust.



Isochron plot for Nd and Sm isotopes in lunar anorthosites. The blue circles are for pyroxene crystals in four lunar anorthosites. The red circles are for plagioclase feldspar. The pyroxene data define a very precise line, the slope of which defines the age, 4.456 billion years. Plagioclase data scatter more because of chemical exchange of Sm and Nd caused by reheating by a large impact event that seems to have affected almost all anorthosites. Pyroxene is more resistant to isotopic exchange, and so records the original crystallization age of these rocks.

Structure of the Lunar Crust

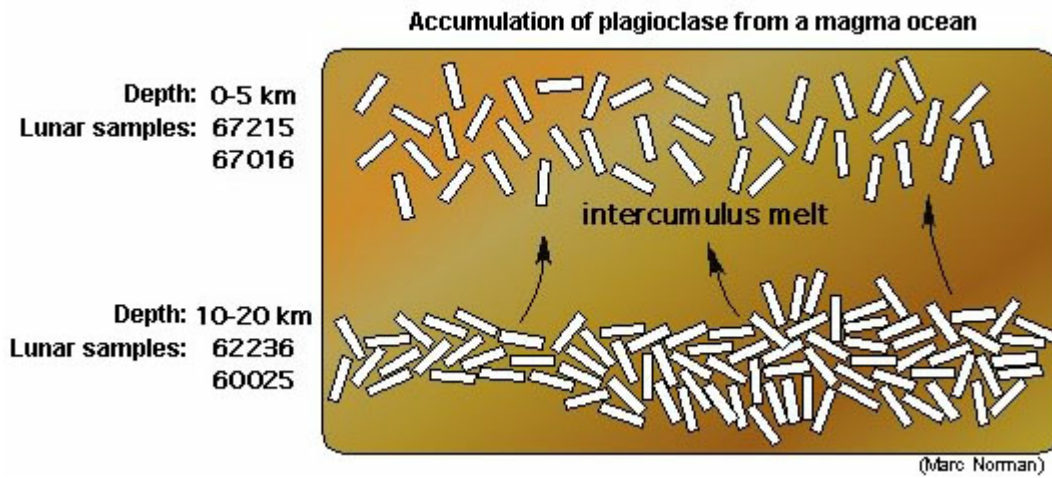
In addition to placing better limits on the age of the Moon, the mineralogy and textures of 67215c also provide interesting information about the overall structure of the lunar crust. The fine-scale [exsolution](#) lamellae in the pyroxenes of 67215c (see photo below) are consistent with crystallization of this rock at relatively shallow depths within the lunar crust (<0.5 km). This contrasts with the petrographic characteristics of some other lunar anorthosites, which I. S. McCallum (University of Washington) and his colleagues show are more consistent with slow cooling at much greater depths (10-20 km).



A backscatter photomicrograph image showing the [exsolution](#) lamellae (light gray stripes) in pyroxene in the ferroan noritic anorthosite clast from the Apollo 16 breccia 67215.

The petrographic characteristics of lunar anorthosites can be combined with recent remote sensing studies of the spatial distribution of lithologic units exposed in lunar craters and basins (Hawke *et al.* 2003; Wieczorek and Zuber 2001) to produce a generalized view of lunar crustal stratigraphy. The primary upper crust appears to contain a complex mixture of rock types having affinities with both ferroan anorthosites and the more magnesian norites and troctolites. This heterogeneous upper crust appears to be underlain by regionally extensive layers of relatively pure anorthosite at mid-crustal depths.

In this context, 67215c and the other ferroan noritic anorthosites may represent samples of relatively shallow anorthositic crust that formed by accumulation of plagioclase along with some magma. Petrologists call the magma that occurred between large plagioclase crystals "trapped melt." In contrast, other lunar anorthosites may have formed at greater depths and contain very little trapped melt. If all of these samples crystallized from a common magmatic system, as suggested by their coherent mineralogical, isotopic, and trace element characteristics, this magma must have been at least 20 km deep, and probably >45-60 km deep to account for the lack of complementary mafic and ultramafic cumulates in the lunar crust. Such a deep magmatic system supports the idea that a global magma ocean was present on the Moon soon after it formed.



As the anorthosite crust accumulated by plagioclase floatation in the lunar magma ocean, shallower regions contained more magma (called "trapped melt") between the plagioclase crystals than in deeper zones.

Origin of the Earth and Moon

Having a good date for the age of the lunar crust provides an important constraint on the timing of planetary evolution in the inner Solar System, and helps us understand the way that planetary systems form. This becomes especially important as we begin to discover different types of planetary systems around other stars, and try to predict which types of planets might have structures and compositions most like our own, and therefore represent potentially habitable worlds.

The ^{147}Sm - ^{143}Nd isotopic compositions of lunar ferroan anorthosites indicates that the primary lunar crust formed about 100 million years after the oldest datable materials found in primitive meteorites precipitated from the solar nebula. As crystallization of a lunar magma ocean is likely to have been relatively fast, this implies that assembly of the Moon was a relatively late event during the formation of the Solar System. Such a scenario is consistent with the planetesimal accretion hypothesis in which the origin of the Moon was intimately linked to the early evolution of the Earth through gigantic collisions between proto-planets.

Additional Resources

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