

The Earth–Moon late-accretion conundrum

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The distribution of iron-loving elements between the mantles of the Moon and Earth may differ from established belief, suggest two studies that determine the hafnium–tungsten ratio and sulfide–silicate melt partitioning of elements in the lunar mantle.

The mantles of the Moon and Earth have many compositional and isotopic similarities. Nevertheless, the abundances of elements that preferentially partition into metal, termed siderophile elements, are notably different between them. It has been proposed that the lunar mantle hosts substantially fewer highly siderophile elements (HSEs) than the terrestrial mantle¹. In addition, the isotopic abundance of tungsten ¹⁸²W, a decay product of the short-lived hafnium isotope ¹⁸²Hf,

is slightly higher in the lunar mantle than in the terrestrial mantle². The similarities in stable isotopes are now mostly in line with giant-impact models of the Moon's formation^{3,4}. There are, however, multiple hypotheses to explain the differences in the abundances of HSEs, including less impactor retention on the Moon⁵ and the stochastic nature of planetary accretion⁶.

In this issue of *Nature Geoscience*, Thiemens et al.⁷ and Brenan et al.⁸ together suggest that the siderophile-element composition of the lunar mantle is less constrained than previously thought.

Lunar basalts (Fig. 1) contain about 100-times less HSEs than their terrestrial counterparts¹. With the current understanding of sulfide-undersaturated lunar mantle melting and basalt formation, sub-nanogram HSE concentrations in the mantle source of lunar basalts were proposed¹, around 40-times lower than in the Earth's mantle⁹. This Earth–Moon difference is interpreted to reflect disproportionate late accretion of primitive matter after core formation, with an estimated mass of 1.5×10^{19} kg being added to the Moon (0.02% of its mass) versus about 2×10^{22} kg to the Earth (0.5% of its mass)^{1,6,9}. The inferred additions of impactor material constrain the Earth and Moon to having had indistinguishable abundances of ¹⁸²W before late accretion. This is inconsistent, however, with recent models of Moon formation by a giant impact, which predict a significant difference in ¹⁸²W abundance^{2,10,11}.

Low-Ti mare basalt
Apollo 12 mission
(sample no. 12009)

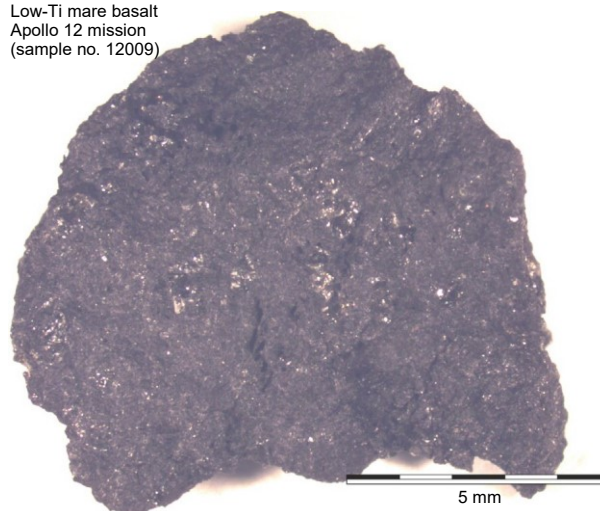


Fig. 1. Lunar basalts are invaluable probes of the Moon's silicate mantle composition. Thiemens et al.⁷ and Brenan et al.⁸ trace back fractionation processes during lunar basalt formation and reveal insights into the timing of iron core formation and subsequent addition of impactor material on the Moon.

Knowledge of the Hf/W ratio of a given planetary reservoir is a prerequisite for interpretation of ¹⁸²W variations in terms of differences in formation time. This is not trivial, however, because of the different geochemical behaviour of W and Hf during planetary-differentiation processes.

Thiemens et al. analyse the Hf and W mass fractions in lunar samples with high precision, revealing that although the Hf/W ratio varies between different rock types, that of lunar basalts can be explained by the composition of their respective mantle source and subsequent fractionation processes. They quantify the fractionation processes and narrow down the bulk silicate Moon's Hf/W ratio to a range of 30 to 50. This result is important, because such a high Hf/W ratio would result in strong radiogenic ingrowth of ¹⁸²W from decay of ¹⁸²Hf within its short lifetime, until 60 million years after Solar System formation. Previous assessments proposed lower Hf/W ratios, closer to that found for the bulk silicate Earth.

Among the different possibilities to explain the Hf/W ratio and ¹⁸²W abundance of the bulk silicate Moon, Thiemens et al.

advocate a scenario of early lunar core formation and conclude that the ¹⁸²W excess in lunar rocks can be explained by the decay of now extinct ¹⁸²Hf in the lunar mantle. This explanation is novel because it implies that lunar core formation was the predominant control on the Hf/W ratio, and thus on the W isotopic composition of the silicate Moon. However, the extent of equilibration between metal and silicate during the Moon-forming impact and its effect on Hf/W and the W isotopic composition are not well constrained^{10,11}. From this point of view, the isotopic evolution and the influence of late accretion on the ¹⁸²W abundance of the lunar mantle remain ambiguous.

In contrast to W, HSEs partition almost completely into metal during core formation. Therefore, the HSE abundances in the lunar mantle should provide more definite estimates of the mass of late-accreted matter. Assessing the Moon's HSE inventory from basalt compositions, however, requires knowledge of phase relations during partial melting of the mantle. In this regard, the abundance and speciation of the moderately

siderophile and volatile element sulfur in the lunar mantle is important. Residual sulfide phases would retain significant quantities of HSEs and diminish the utility of lunar basalts as a measure of late accretion¹².

Brenan et al. report experiments on the solubility of sulfur in silicate melts and the sulfide–silicate melt partitioning of HSEs for a model lunar basalt composition. They find that at the reduced conditions of the lunar interior, the basalt source is likely to be saturated in a sulfide melt phase. Since sulfide retains some HSEs more than others, lunar basalts should have significant fractionations between different HSEs. Because these fractionations are not observed, Brenan et al. suggest that most lunar basalts may be contaminated with minute amounts of unfractionated HSEs from impactor material in the lunar megaregolith.

Thus, the true HSE content of the lunar mantle could be veiled by residual sulfide and contamination with impactor debris. The mantle could therefore host a larger range of HSE abundances, which in principle now includes mass fractions of late accretion as high as predicted from moderately siderophile and volatile elements¹³.

Thiemens et al. and Brenan et al. differ in their appraisal of the processes that exert the dominant control on siderophile-element abundances in the lunar mantle and the resulting implications for the evolution of the Earth–Moon system. Thiemens et al. argue that lunar differentiation is the main control and imply that late accretion might be insignificant, whereas the results of Brenan et al. suggest that late accretion onto the Moon could have been more substantial than we thought.

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