

Hf/W insights into the primeval Moon

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Abstract

The Moon formed in the aftermath of a giant impact of a planetesimal into the growing proto-Earth. The timing of this event is a key event in the early history of our Solar System and Earth. Age estimates for lunar formation are subject to ongoing debate. These ages estimates vary between those who believe in an “old Moon,” (which formed between 30 and 70 Myrs after solar system formation) and those who believe in a young Moon (from ca. 80 to 200 Myrs after solar system formation). The Moon bears an excess in ^{182}W compared to the Earth, and grasping the nature of this excess is a key step towards a more profound understanding of the Earth-Moon system. We present high-precision isotope dilution measurements of relevant trace elements for a wide range of lunar samples, with an emphasis on High Field Strength Elements (HFSE). By coupling these with recent HFSE crystal/silicate melt partitioning data relevant to lunar magmatism, we find that the lunar mantle bears a resolvably higher Hf/W ratio than the bulk silicate Earth. We can therefore explain the ^{182}W excess observed in lunar samples as the result of the radiogenic ingrowth of ^{182}W that resulted from the decay of the still extant ^{182}Hf , implying that the Moon must have formed while the Hf-W decay system was extant.

1. Introduction

Lunar rocks provide a snapshot of the early solar system, and insights into the processes involved during planetary formation and differentiation. These processes require an understanding of the differentiation events of the Moon, such as core formation, the crystallization of the Lunar Magma Ocean (LMO), and generation of lunar mare basalts. This understanding is best achieved by combining observations and data obtained from natural samples, with data from experimental studies dealing with lunar magmatism. We pursue this by exploring redox-sensitive trace element behavior during lunar magmatism and modeling its implications for Hf-W chronometry. Tungsten and U, for example, are

regarded as behaving geochemically identical during partial melting in the Earth’s upper mantle. However, mineral/melt experimental partitioning data have shown that U and W are less incompatible at more reduced $f\text{O}_2$ conditions, such as those prevalent during lunar mantle melting [1,2]. The higher mineral/melt partition coefficient of W^{4+} relative to W^{6+} will significantly affect the overall compatibility of W in lunar mantle residual phases during partial melting. This, in turn, will fractionate W from U and other High Field Strength Elements (HFSE). Therefore, we combined whole-rock high-precision HFSE and Hf-Nd isotope data in lunar samples with core formation, crystallization, and aggregate fractional melting models to better understand the petrogenesis of major lunar rock types and quantify the lunar W budget with implications for the ^{182}W systematics of the Earth and the Moon.

2. Methods

Lunar samples were obtained from the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM), including 7 high-Ti mare basalts and soils, 14 low-Ti mare basalts, 2 ferroan anorthosites (FANs), and 7 KREEP-rich samples. Mixed HFSE and U-Th isotope tracers were added prior to digestion. The elements of interest were isolated for analysis on the University of Cologne’s MC-ICP-MS following the methods of [4]. External precision and accuracy for elemental ratios determined by isotope dilution are typically better than $\pm 1\%$ for U/W and Th/W (2σ r.s.d.). Typical blanks during the course of the measurements were better than 50 pg for W, 60 pg for U, 30 pg for Th, and 30 pg for Hf. These blanks proved negligible, with blank uncertainty derived propagated errors less than $\pm 1\%$. Our Lunar Magma Ocean fractionation model was created based on a cumulate crystallization sequence [3]. To define the starting composition for the silicate Moon we modeled the geochemical constraints for the variation of major- and trace-element and Nd, Sr, and Hf isotope features of the lunar sample suite reported in the literature [4,5]. For W, an additional mass balance between the estimate of its content in the

bulk silicate Moon after core formation was performed [6], considering different core mass fractions (1-3% of the total mass of the Moon). Trace element crystal/silicate melt partition coefficients for pyroxene, plagioclase, and olivine were selected considering the variation of TiO₂ exhibited by lunar mare basalts [2] and the effect of fO₂ on the behavior of W [1,2]. Ilmenite/silicate melt trace element partition coefficients are an average of the high-Ti experiments listed described by [7].

3. Results and Discussion

Our data for low-Ti mare basalts U/W range between 1.6 to 2.6 and Hf/W between 30 to 50. Within individual groups the low-Ti basalts are fairly uniform (U/W generally varies by 0.1, Hf/W by ca. 5). Amongst the high-Ti mare basalts, the Apollo 17 samples show variable Hf/W up to 150 and correlated U/W up to 2.3, clearly distinct from the A11 high-Ti basalts (Hf/W of 40 to 60 and U/W between 1.5 and 2.2) and all low-Ti basalts. Similarly, most samples show Zr/Nb between 14 and 18 while A17 high-Ti mare basalts fall below 10. Melting models (continuous & fractional melting, ± residual metal) and the within-group homogeneity of low-Ti mare basalts imply that the source compositions per group are virtually identical but differ from group to group. This agrees with the distinct Hf-Nd isotopic and extended HFSE features found amongst different groups of low-Ti mare basalts, which require similarly distinct mantle sources [4,5]. A unique A17 high-Ti mantle source implied by Hf-Nd isotopes [5] is compatible with variable Hf/W and correlated U/W of A17 basalts given the likely presence of residual Fe-Ti oxides and metal at the source [1,2]. Across our samples, we find a uniformly elevated Hf/W in the lunar samples, corroborating previous studies [e.g. 10].

The assumption that W is less incompatible than Hf during the formation of LMO cumulates, which became the source of lunar mare basalts [1,2,5], requires a re-evaluation of the Hf/W of the lunar mantle. The mineral constituents of the low-Ti mantle sources preferentially retain W over Hf and U during LMO crystallization at the low lunar fO₂. Therefore, the measured Hf/W of low-Ti lunar mantle sources define minimum estimates of the Hf/W in the sources and, by inference, of the bulk LMO as well as of the silicate Moon. When modeling source compositions from the measured

samples, it can be inferred that the Hf/W of the bulk silicate Moon is higher than that of the bulks silicate Earth, at least by 20-30%.

There are three broad scenarios that can account for the elevated Hf/W of the Moon. The first scenario holds that a late veneer of material with a Hf/W of ~1 lowers the Hf/W of the Earth-Moon system. As the Earth is struck by a proportionally larger amount of material, the bulk silicate Earth's ratio is lowered to 25.6, while the Moon retains a uniformly higher Hf/W closer to the original Hf/W of the system. The second explanation holds that the Moon forming event occurs while ¹⁸²Hf is extant, and the Earth's Hf/W is lowered following lunar formation by ongoing core formation and increasingly oxidized conditions on the Earth. The final explanation holds that the Moon forms while ¹⁸²Hf is extant, and the formation of the lunar core elevates the silicate Moon's Hf/W signature.

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5. References

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