THE AGE OF THE MOON AND LIFETIME OF ITS MAGMA OCEAN - NEW CONSTRAINTS FROM W ISOTOPES IN LUNAR METALS. M. Touboul[1], T. Kleine[1], B. Bourdon[1], H. Palme[2], and R. Wieler[1]. [1]Institute for Isotope Geochemistry and Mineral Resources, Department of Earth Sciences, ETH Zürich, Clausiusstrasse 25, 8092 Zürich, Switzerland (touboul@erdw.ethz.ch), [2]Institut für Mineralogie und Geochemie, Universität zu Köln, Zülpicherstr. 49b, 50674 Köln, Germany.

Introduction: ^{182}Hf-^{182}W chronometry is well suited to constraining the timescales of lunar differentiation because large Hf-W fractionation occurred during crystallization of the lunar magma ocean [1-3]. Variations in the ^{182}W/^{184}W of lunar whole-rock whole-rock samples were interpreted to indicate formation and differentiation of the Moon during the effective life-time of ^{182}Hf (i.e., within the first ~60 Ma of the solar system) [1-4]. This time constraint, however, is inconsistent with results from ^{146}Sm-^{142}Nd chronometry that indicate a much longer lifetime of the lunar magma ocean [5, 6]. The ^{182}W/^{184}W of lunar whole-rock samples does not only reflect ^{182}Hf-decay but also cosmogenic production of ^{182}W, mainly by neutron capture of ^{181}Ta during cosmic-ray exposure of the lunar surface [7]. The dominant ^{182}W component in most lunar rocks is cosmogenic, compromising a reliable interpretation in terms of ^{182}Hf-^{182}W chronometry. Here we present W isotope data for lunar metals from a comprehensive set of lunar rocks and show that these metals do not contain any measurable Ta-derived ^{182}W. These data are used to better constrain the Hf-W record of early lunar differentiation.

Results: We separated metals from 5 high-Ti basalts, 4 low-Ti basalts and 2 KREEP-rich samples. The purity of the metal separates was checked under the binocular. The metals were dissolved in 6 M HCl-0.06 M HF and W was separated from its sample matrix using standard ion exchange techniques. All isotope measurements were performed using the Nu Plasma MC-ICPMS at ETH Zurich. The ^{182}W/^{184}W ratios of the samples are determined relative to a terrestrial W standard and are expressed as ε_W, which is deviation in parts per 10^4. ^{183}W/^{184}W ratios were used as a monitor of accurate measurements. They agree for all samples analyzed here to within ±0.2 ε units (ε is parts per 10^4) with the terrestrial standard. Ta/W ratios of metal separates are estimated using their Hf/W ratios, determined by isotope dilution on 5% aliquots, combined with Ta/Hf ratios of whole rocks. Cosmogenic corrections of ε_W, calculated using these Ta/W ratios and exposure ages, were applied to all samples and were usually below ~0.1 ε units.

All samples analyzed here have identical ^{182}W/^{184}W ratios within ±0.32 ε units (2 SD) and agree with previously reported data for metals from KREEP-rich samples [1]. These data combined average at ε_W=0.09±0.10 (2 SE, n=15). In contrast to earlier reports [1, 2, 4] we do not find elevated ^{182}W/^{184}W ratios for low- and high-Ti mare basalts.

Discussion: The identical ^{182}W/^{184}W ratios for pure metal separates reported here indicates that are no ^{182}Hf-induced W isotope variations among KREEP and the mare basalt sources. Elevated ^{182}W/^{184}W ratios in low- and high-Ti mare basalts reported earlier likely reflect the presence of small cosmogenic ^{182}W components in the analysed fractions.

The homogeneous ^{182}W/^{184}W ratios of all lunar samples in spite of strongly fractionated Hf/W ratios in their source areas [3, 8] indicates that the equilibration of W isotopes within the lunar magma ocean continued for more than ~60 Ma after the start of the solar system. This is no longer in conflict with Sm-Nd constraints regarding the lifespan of the lunar magma ocean. The rapid crystallization required by the earlier W isotope data [1, 2, 4] implied that some ^{147}Sm–^{143}Nd ages for ferroan anorthosites [9, 10] and the ^{146}Sm-^{142}Nd model age [5, 6] of the lunar mantle reflect events that were not associated with the primordial differentiation of the Moon. With the revised Hf-W time constraint pesented here, however, this is no longer required and the aforementioned Sm-Nd ages could possibly date processes associated with the primordial differentiation of the lunar mantle. This would suggests that the lunar magma ocean was largely solidified as late as ~215 Myr, as given by its ^{146}Sm-^{142}Nd model age [5, 6].

The apparent presence of ^{182}Hf-induced ^{182}W variations within the Moon was used as an argument that the Moon formed within the first ~60 Ma of the solar system [1, 2, 4]. Our new data, however, indicate that there are no ^{182}W/^{184}W variations within the lunar mantle, such that formation of the Moon during the lifespan of ^{182}Hf is no longer required, although it can not be excluded. An alternative approach to date the formation of the Moon uses the Hf/W and ^{182}W/^{184}W ratios of the bulk lunar and terrestrial mantles. The best current estimates for the Hf/W ratios of the lunar and terrestrial mantles are 26.4±1.5 (2σ) and 19.7±1.6 (2σ), respectively, and these Hf/W ratios were established by core formation in the Moon and Earth. Using these estimates, the virtually identical ^{182}W/^{184}W ratios of the bulk lunar and terrestrial mantles require that core formation in the Moon and Earth were completed later than ~45 Ma, otherwise a ^{182}W excess would have developed in the lunar compared to the terrestrial mantle. This new age constraint for core formation in the Moon also provides the earliest time the giant impact could have occurred and Earth's core could have completely been segregated. This new age constraint is inconsistent with termination of Earth's accretion at ~30 Myr [11] and also difficult to reconcile with the <30 Myr ^{146}Sm-^{142}Nd model age for differentiation of Earth's mantle [12]. Our new age constraint, however, is consistent with most U-Pb model ages for the Earth [13].

All successful simulations of the giant impact predict that ~80% of the Moon is derived from impactor material [14], such that any W isotope differences between the proto-Earth and impactor should be apparent in the composition of the Moon. The difference in initial ^{182}W/^{184}W between the lunar and terrestrial mantles, however, is smaller than ~0.5 ε units. Similarly, the identical O isotopic compositions of the Earth and Moon in spite of widespread O isotopic heterogeneity among all other inner solar system objects are unexpected. This has been interpreted to reflect accretion of the Earth and Moon at the same heliocentric distance [15] but this scenario cannot account for the identical W isotope compositions of the lunar and terrestrial mantles. Hence, unless the Moon is almost entirely derived from terrestrial material, lunar and terrestrial materials equilibrated in the aftermath of the giant impact. It has been shown that such equilibration is possible for O isotopes [16] but its effectiveness in equilibrating W isotopes remains to be investigated.

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