THE HF-W AGE OF THE LUNAR MAGMA OCEAN. T. Kleine[1,2], K. Mezger[1], and H. Palme[3], [1]Zentrallabor für Geochronologie, Universität Münster, Corrensstr. 24, 48149 Münster, Germany (klaush@nwz.uni-muenster.de), [2]Institut für Isotopengeologie und Mineralische Rohstoffe, Departement für Erdwissenschaften, ETH Zürich, Sonneggstr. 5, 8092 Zürich, Switzerland (kleine@erdw.ethz.ch), [3]Institut für Mineralogie und Geochemie, Universität zu Köln, Zülpicherstr. 49b, 50674 Köln, Germany

Introduction: The early chemical differentiation of the Moon was dominated by the crystallization of a magma ocean. Determining the crystallization age of the lunar magma ocean (LMO) is critical for understanding the timing of Moon formation, melting, and subsequent differentiation and cooling. Currently, the most suitable isotope system for dating the crystallization of the LMO is the ^{182}Hf-^{182}W decay scheme, because the Hf/W ratios varied significantly between the different LMO reservoirs, and W isotope variations can have only been produced in the first ~60 Myr of the solar system [1]. Thus, information on early differentiation of the Moon is preserved in the ^{182}W/^{184}W of early-formed lunar reservoirs and is carried by lunar samples derived from any of these sources. A chronological interpretation of W isotope ratios for lunar whole-rocks and minerals, however, has been hampered by the neutron-flux induced production of ^{182}W from ^{181}Ta caused by the intense cosmic radiation reaching the surface of the Moon [2, 3]. Analyzing the metals of lunar samples can overcome this problem because metals do not contain significant Ta that could be converted to ^{182}W. We present W isotope data for metals from KREEP-rich and -poor highland breccias and low-Ti and high-Ti mare basalts. To investigate the effect of cosmogenic ^{182}W production in whole-rock samples, the W isotopes in some whole-rocks have also been analyzed

Results: All lunar metals display lower or similar ^{182}W/^{184}W than their respective whole-rocks, indicating a neutron-flux induced production of ^{182}W in samples having high Ta/W and/or long exposure ages. For instance, a whole-rock of the high-Ti mare basalt 79155 displays an exceedingly high ^{182}W/^{184}W of ~38 ε_W, whereas its metal has a ε_W of ~2.5. This ε_W difference results from the combined effects of a high Ta/W of ~20 and a prolonged exposure to cosmic rays of 79155. In contrast, samples having low Ta/W and/or short exposure ages display no ε_W differences between their whole-rocks and metals. Metals from the KREEP-rich and –poor highland breccias display indistinguishable ε_W values with an average of –0.4±0.2 (ε_W is the deviation of the ^{182}W/^{184}W from the terrestrial standard value in parts per 10,000). Metal and whole-rock from the low-Ti mare basalt 15475 have analytically indistinguishable ε_W that also agree with the neutron-flux corrected value for 15555 [3]. The average ε_W of the low-Ti mare basalt source based on these samples is 1.0±0.3. Metals from high-Ti mare basalts 72155 and 79155 have average ε_W values of 2.0±0.6

Discussion: The higher ^{182}W/^{184}W in the silicate-rich fractions relative to the metals cannot reflect radiogenic ^{182}W-production in the high Hf/W silicates because all lunar samples examined here formed by episodes of magmatism after ^{182}Hf was effectively extinct. Modification of the W isotope composition of lunar metals by contamination with meteoritic metal is unlikely because the W content of lunar metals is by two orders of magnitude higher than that of chondritic metal. Moreover, contamination with meteoritic metal provides no reasonable explanation for the systematic ε_W differences among lunar geochemical reservoirs. Late re-distribution of W isotopes between silicates and metal can be excluded because W diffusion from silicates into metal requires temperatures of >600°C [4] but lunar samples have not been re-heated to such high temperatures.

The W isotope data for the metals instead provide the indigenous W isotope composition of their sources and reveal W isotope differences among lunar geochemical reservoirs. The variations in ^{182}W/^{184}W correlate with the expected Hf/W for the different lunar reservoirs (i.e., KREEP has the lowest and high-Ti mare basalts have the highest Hf/W). We interpret this correlation as a isochron. The slope of this isochron corresponds to an initial ^{182}Hf/^{180}Hf of $(3.9 \pm 1.0) \times 10^{-6}$ (2σ, MSWD = 0.54), indicating that the last Hf-W fractionation between the different lunar geochemical reservoirs occurred 42±4 Myr after CAIs (used here to represent the start of the solar system). The Hf-W isochron for the lunar mantle is defined by the sources of KREEP and high-Ti mare basalts both of which formed at the very end of the crystallization sequence of the lunar magma ocean. The Hf-W age of 42±4 Myr after the start of the solar system thus most likely dates the final crystallization of the lunar magma ocean.

Conclusions: The ferroan anorthosites formed before complete solidification of the lunar magma ocean, implying that the earliest lunar crust must have formed before ~42 Myr after the start of the solar system. This result is consistent with the 4570±80 Ma Sm-Nd age for an anorthosite clast from lunar breccia 67016 [5] but contrasts with results from Sm-Nd studies that yield ages between 4400 and 4200 Ma for ferroan anorthosites, the KREEP and mare basalt sources [6]. These relatively young Sm-Nd ages thus cannot date the final crystallization of the lunar magma ocean or slow cooling of primordial material, but rather must record later re-melting and mixing events in the lunar mantle, which may be related to the convective overturn of early magma ocean cumulates [1, 6].

The Hf-W age of crystallization of the lunar magma ocean provides important constraints on the duration of planetary accretion in the inner solar system. Estimates based on dynamical simulations models are generally uncertain for the late stages of accretion and W model ages for core formation in Earth only provide the earliest time core formation in Earth can have ceased, but cannot constrain the end of Earth's accretion [7]. However, if the Moon formed at the very end of Earth's accretion, as is indicated by the most recent simulations of the giant impact [8], then the accretion of the terrestrial planets was completed in the first ~45 Myr of the solar system.

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