TUNGSTEN ISOTOPES AND THE ORIGIN OF THE MOON.

T. Kleine[1] and T. S. Kruijer[1], [1]Institut für Planetologie, University of Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany (thorsten.kleine@wwu.de).

Introduction: The Moon is generally thought to have formed from hot debris ejected by a giant impact on Earth [1]. During this event mantle and core material from the impactor mixed with material from proto-Earth's mantle. These three components likely had different ^{182}W compositions, reflecting the distinct accretion and differentiation histories of the impactor and Earth. The ^{182}W composition of the Moon, therefore, reflects the distinct ^{182}W signatures in the impactor and Earth, and the proportions of these components in the Moon. As such, the lunar ^{182}W composition provides unique insights into the origin of the Moon [2-5].

The ^{182}W composition of the Moon has proven difficult to determine, however, owing to cosmic ray-induced neutron capture reactions affecting ^{182}W [6]. Two recent studies have determined precise pre-exposure (i.e., unaffected by neutron capture) ^{182}W compositions for KREEP-rich samples [3, 4], and showed that these samples exhibit a ~25 ppm ^{182}W excess over the present-day bulk silicate Earth. However, no lunar samples other than KREEP have been analyzed, and so it remains unclear as to whether (i) (radiogenic) ^{182}W heterogeneities exist within the Moon and (ii) the 25 ppm ^{182}W excess for KREEP is representative for the bulk Moon.

To address these issues, we obtained new ^{182}W data for several non-KREEP lunar samples. Using these data we will define the bulk ^{182}W composition of the Moon and use this composition to evaluate current formation models for the Moon.

Methods: The samples selected for this study include one Mg-suite sample (77215), two low-Ti (12004, 15495) and six high-Ti mare basalts (10057, 70017, 70035, 70215, 75035), as well as lunar meteorite Kalahari 009. For all samples we obtained high-precision ^{182}W data using the Neptune *Plus* MC-ICPMS at Münster [3]. To monitor cosmic ray-induced effects, we also determined Hf isotopic compositions and Ta/W ratios [3].

Excess ^{182}W in the Moon: After correction for cosmic ray-induced effects on ε^{182}W, all samples have indistinguishable ^{182}W compositions, with a mean ε^{182}W = 0.26±0.03 (Fig. 1). This ^{182}W excess of the Moon over the present-day bulk silicate Earth is consistent with the effect resulting from disproportional late accretion to the Earth and Moon [3, 4]. Mathematical removal of the late veneer from the ^{182}W composition of Earth's mantle, using a mass of the late veneer as derived from highly siderophile element systematics, shows that prior to late accretion the Earth's mantle has a ε^{182}W of ca. 0.25, exactly the value measured for the Moon. Thus, our data confirm that immediately after its formation, the Moon and Earth's mantle had nearly identical ^{182}W compositions [3, 5].

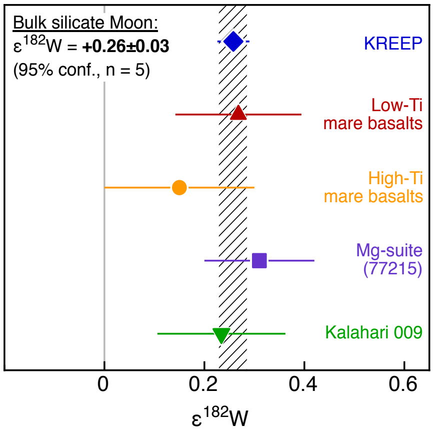

Figure 1: Pre-exposure ε^{182}W of lunar samples obtained in this study. ε^{182}W is the parts-per-10,000 deviation of ^{182}W/^{184}W from the standard.

***Expected* ε^{182}W of the Moon:** In order to assess the significance of the nearly identical ^{182}W compositions of Earth's mantle and the Moon immediately following the giant impact, we calculated the *expected* ^{182}W composition of the Moon in various giant impact scenarios. Similar calculations have been done previously, showing that the ^{182}W composition of the Moon can be reproduced [2], most likely by invoking a Mars-sized, highly reduced impactor [5]. However, here we take a different approach and assess the *likelihood* of producing nearly identical ^{182}W compositions for the Earth's mantle and the Moon.

In the calculations we made the following assumptions: the metal-silicate partition coefficient for W in the impactor was between 5 (i.e., an 'oxidized' impactor) and 100 ('reduced' impactor); the time of core formation in the impactor was between 5 and 20 Ma after solar system formation; the impactor-to-Earth mass ratio was between 0.04 and 0.15; the mass fraction of impactor core material in the Moon was between 0 and 0.025. In the calculations, we varied these parameters randomly within the given range of values. In addition, we varied the mass fraction of impactor core material that equilibrated with the Earth's mantle between 0 (no equilibration) and 1 (full equilibration).

The results of the calculations are shown in Fig. 2 for two different mass fractions of impactor material in the Moon (the dots represent more than 16,000 outcomes of the calculations). The results show that in both cases the observed composition of the Moon is within the field of calculated compositions, but the results also show that in most cases a larger ^{182}W excess for the Moon is calculated. The probability to obtain the nearly identical ^{182}W compositions of the Earth and Moon is only ~5% if the Moon predominantly consists of proto-Earth material, and is reduced to ~1% if the Moon mostly derives from the impactor (Fig. 3).

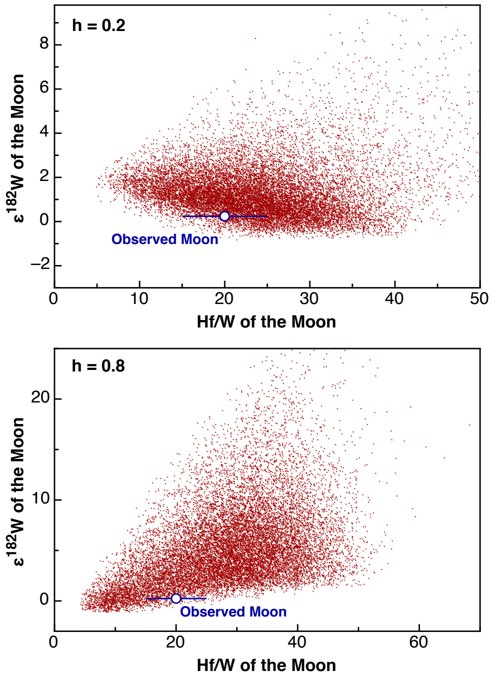

Figure 2: Expected ε^{182}W of the Moon in two different giant impact scenarios. h is the mass fraction of impactor material in the Moon.

Implications for the origin of the Moon: Although the nearly identical ^{182}W compositions of the Moon and the Earth's mantle could be coincidence, the probability of this is uncomfortably low. Nevertheless, if the ^{182}W similarity is in fact coincidence, then it is more likely that the Moon predominantly derives from the proto-Earth's mantle. However, although this is possible [7, 8], dynamically it is far more likely that the Moon would largely consist of impactor material. Thus, we are left with the dilemma that two low probability cases have to be invoked to account for the ^{182}W composition of the Moon.

Given the difficulty to account for the ^{182}W composition of the Moon suggests that additional processes might have been important. It has recently been proposed that the Procellarum basin on the Moon formed by a giant impact [9]. Mass balance calculations show that this impact might have lowered the ^{182}W composition of a significant portion of the lunar mantle by up to ~1 ε^{182}W. If the lunar samples analyzed to date would all derive from this modified area, then the Moon might initially have had a larger ^{182}W anomaly, as predicted by our calculations. Clearly, more work is needed to understand ^{182}W in the Moon and its bearing on lunar origin.

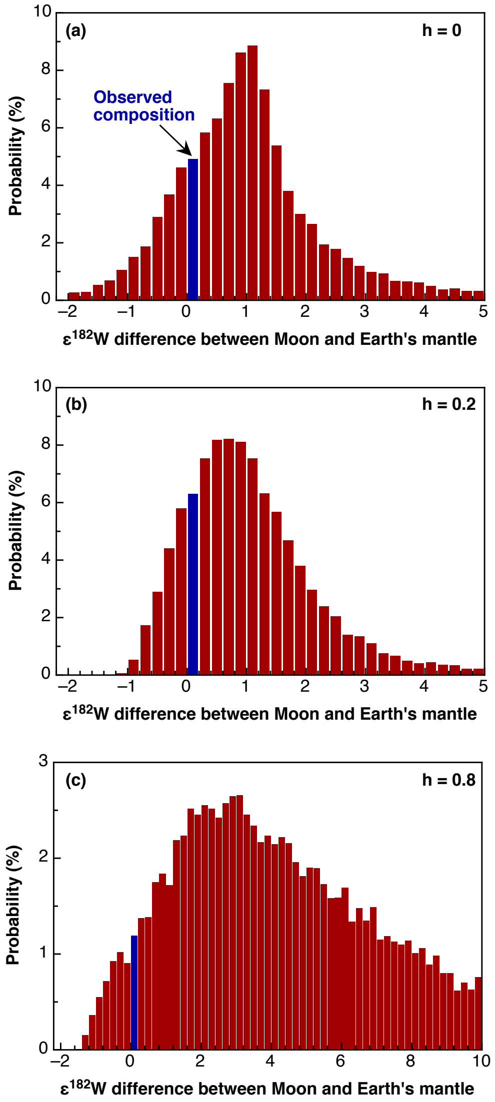

Figure 3: Histogram showing the expected ε^{182}W difference between the Moon and Earth's mantle.

References: [1] Canup, R.M. and E. Asphaug (2001) *Nature, 412, 708-712.* [2] Dauphas, N. et al. (2014) *PTRS 372, 20130244.* [3] Kruijer, T.S. et al. (2015) *Nature, 520, 534-537.* [4] Touboul, M. et al. (2015) *Nature, 520, 530-533.* [5] Wade, J. and B.J. Wood (2016) *EPSL, 442, 186-193.* [6] Leya, I. et al. (2000) *EPSL, 175, 1-12.* [7] Canup, R.M. (2012) *Science, 338, 1052-1055.* [8] Cuk, M. and S.T. Stewart (2012) *Science, 338, 1047-1052.* [9] Zhu, M.H. et al., this meeting.

Acknowledgements: We gratefully acknowledge NASA and CAPTEM for providing samples, and the Deutsche Forschungsgemeinschaft for funding through TRR 170.