EVIDENCE FOR A COMMON INITIAL ^{176}Hf/^{177}Hf OF THE EARTH, MOON, AND CHONDRITES. P. Sprung[1,2], T. Kleine[1], and E.E. Scherer[3], [1]Institut für Planetologie, Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany, sprungp@wwu.de, [2]Institute of Geochemistry and Petrology, Clausiusstrasse 25, ETH Zurich, 8092 Zurich, Switzerland, [3]Institut für Mineralogie, Universität Münster, Corrensstr. 24, 48149 Münster, Germany.

Introduction: The ^{176}Lu-^{176}Hf systematics of ancient rock samples provide powerful constraints on the early silicate differentiation history of parent bodies [e.g., 1]. Defining the ^{176}Hf/^{177}Hf evolution of the bulk silicate part of planetary bodies is crucial to fully exploit this isotope tracer. The ^{176}Lu-^{176}Hf parameters of chondrites (CHUR) [2], are commonly considered adequate proxies when calculating the bulk ^{176}Hf/^{177}Hf evolution of terrestrial planets. This central hypothesis has been challenged, however, and an initial ^{176}Hf/^{177}Hf of the Bulk Silicate Earth (BSE) *ca.* 4 ε-units below CHUR at 4.567 Ga was proposed [3]. It was suggested that significant fractions of ^{176}Lu in chondrites underwent irradiation-induced, accelerated decay that significantly contributed 'excess ^{176}Hf' to chondrites but that such contributions were insignificant for the terrestrial building blocks [3].

The close isotopic similarity in Cr, W, and Ti between the Moon and the Earth [4-7] implies an intimate genetic link between their silicate portions. Thus, lunar Lu-Hf systematics offer a test for the competing initial ^{176}Hf/^{177}Hf BSE values: Any proposed lunar Lu-Hf parameters can be tested by comparing KREEP (*i.e.*, the residual liquid of the lunar magma ocean, LMO) model ages to other age estimates for LMO crystallization and KREEP formation, which consistently exceed 4.3 Ga [*e.g.*, 8-14]. Further, given the enriched character of KREEP, its initial ^{176}Hf/^{177}Hf value is the lower limit for the bulk ^{176}Hf/^{177}Hf of the Moon and the BSE at the time of KREEP formation.

Here, we test the competing initial ^{176}Hf/^{177}Hf BSE values using existing Sm-Nd and Lu-Hf data for KREEP-rich lunar samples [15] and data for 3 newly analyzed specimens. We show that the Lu-Hf systematics of KREEP require a ^{176}Hf/^{177}Hf$_{[4.567\ Ga]}$ of the terrestrial and lunar building blocks that is higher than that of [3] and conforms with that of CHUR.

Samples and analytical methods: Newly analyzed samples include: KREEP-rich soil (14163), and 2 basaltic clasts from KREEP-rich breccias (12010, 14321). To monitor neutron capture (NC) effects, non-radiogenic Hf isotope compositions were analyzed on spike-free powder aliquots. Sample preparation followed [15,16,17]. Isotope analyses were conducted on a Neptune *Plus* MC-ICPMS at the University of Münster. External reproducibilities (2 SD) were better than 30 ppm for ^{176}Hf/^{177}Hf. Replicate analyses (n≥5) yielded 95% confidence intervals below 5 and 9 ppm for ^{178}Hf/^{177}Hf and ^{180}Hf/^{177}Hf. Analyses of non-radiogenic Sm isotope compositions and Sm-Nd systematics are underway. All ^{176}Hf/^{177}Hf and the ^{143}Nd/^{144}Nd data from [15] are given as ε-values (parts per 10^4 deviations from CHUR [2]); all ^{180}Hf/^{177}Hf and ^{178}Hf/^{177}Hf values are reported as μ-values (ppm deviations) from terrestrial Hf. Still lacking some Sm isotope data, preliminary NC-corrections assume a neutron energy spectrum halfway between the most extreme lunar values [15,16].

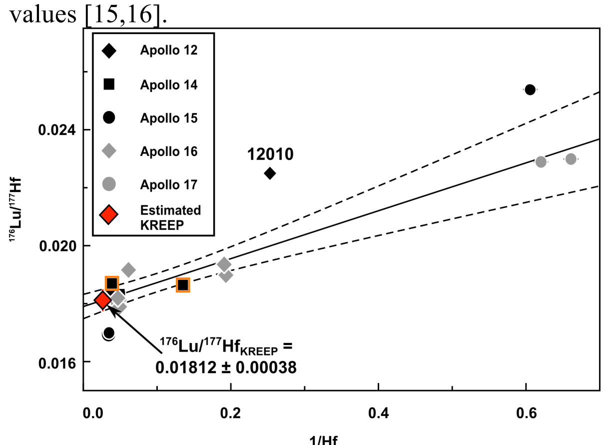

Fig. 1: ^{176}Lu/^{177}Hf vs. 1/Hf and new ^{176}Lu/^{177}Hf estimate for KREEP using data from [13,15,18] and including our new data for 14321 and 14163 (orange). Note that no analogous trend exists for ^{147}Sm/^{144}Nd vs. 1/Nd (not shown).

Results: Samples 14163 and 14321 display ^{176}Lu/^{177}Hf of *ca.* 0.0187 at Hf contents of 7 and 26 ppm, 12010 of *ca.* 0.022 at 4 ppm Hf (Fig. 1). Samples 14163 and 12010 show resolved, coupled μ^{178}Hf and μ^{180}Hf variations up to +225 and -380 ppm, typical of NC-induced effects [15,16], whereas sample 14321 lacks resolvable NC-effects. The εHf of 14321 of *ca.* -5 and the NC-corrected εHf value for 14163 at 3.9 Ga (typical age for KREEP-rich breccias [19]) overlap those reported in [15] including two samples that show no NC-effects (Fig. 2). In contrast, sample 12010 has an εHf value of *ca.* +26 at 3.9 Ga (not shown).

Discussion: The close compositional match of soil sample 14163 and the basalt clast from 14321 to previous data for KREEP-rich samples (Figs. 1, 2) implies that their compositions are also dominated by KREEP. In contrast, our 12010 split likely sampled one of the abundant mare basalt clasts in 12010 [20] and is thus excluded from the following discussion of KREEP.

Defining the ^{176}Lu/^{177}Hf of KREEP is crucial for obtaining accurate model ages. Because KREEP-rich rocks are mixtures of pure KREEP with various lunar rock types, all of which have lower Hf contents and higher $^{176}Lu/^{177}Hf$, an estimate for the composition of KREEP is found by projecting the linear regression in Fig. 1 to the inverse of the Hf content of KREEP [21]. Given the high Hf content of KREEP (*i.e.*, the low 1/Hf), this estimate is robust even for a large uncertainty on the true Hf content of KREEP.

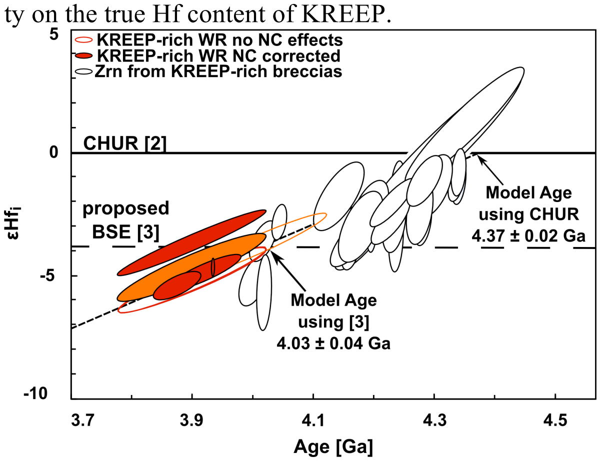

Fig. 2: εHf_i of KREEP-rich whole rocks (WR) from this study (orange) and [15] (red), KREEP zircon data (Zrn) from [11]. Dashed line: KREEP evolution using a $^{176}Lu/^{177}Hf$ of KREEP of 0.01812. Model ages only use whole rock data.

A total of 7 KREEP-rich lunar samples, three of which did not require any NC-corrections, overlap at an εHf of *ca.* -5 at *ca.* 3.9 Ga (Fig. 2). These data yield a Lu-Hf KREEP model age of 4.37±0.02 Ga (Fig. 2) using chondritic lunar bulk Lu-Hf parameters, which is in excellent agreement with Pb-Pb age constraints from KREEP zircons [10,11], and Sm-Nd KREEP model age estimates from [8,9] and that shown in Fig. 3. In contrast, any $^{176}Lu/^{177}Hf$ values feasible for KREEP yield unrealistically low Lu-Hf model ages of *ca.* 4 Ga (Fig. 2) for an initial lunar $^{176}Hf/^{177}Hf$ value equal to that proposed for the BSE by [3].

The new, non-radiogenic Hf isotope data for 14321 imply that the zircon Lu-Hf data of [11] lack significant NC-effects and substantiate their concordance with the data for KREEP-rich rocks. Thus, the collective data in Fig. 2 alongside those of [22], imply that the Moon cannot have had a strongly subchondritic initial $^{176}Hf/^{177}Hf$ as proposed by [3] unless the bulk lunar $^{176}Lu/^{177}Hf$ was markedly superchondritic (*ca.* 0.05), which has been ruled out [15].

Further support for *chondritic* $^{176}Hf/^{177}Hf_{[4.567\ Ga]}$ of the Earth- and Moon-building blocks comes from zircon data: In principle, the initial $^{176}Hf/^{177}Hf$ values of Hadean zircons constrain the ***maximum*** initial value for the BSE [e.g., 23], those of the oldest KREEP zircons constrain a *maximum* initial value for the Moon. If KREEP was ultimately derived from a primary reservoir (formed during LMO differentiation) having bulk lunar or more enriched (*i.e.,* lower) Lu/Hf, the lunar zircons also give a ***minimum*** $^{176}Hf/^{177}Hf_{[4.567\ Ga]}$ of the lunar building blocks. These limits bracket the CHUR value at 4.567 Ga, strongly suggesting that the Lu-Hf parameters of the Earth and Moon are chondritic.

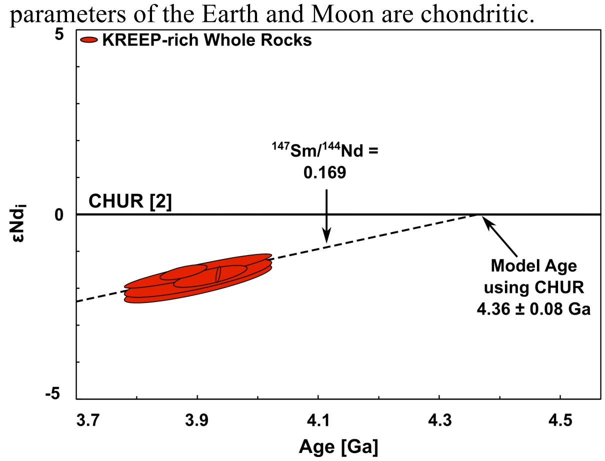

Fig. 3: εNd_i of KREEP-rich whole rocks from [15]. Dashed line: KREEP evolution using the weighted average $^{147}Sm/^{144}Nd$ of the displayed data of 0.196± 0.002.

Conclusions: The consistency of the Lu-Hf KREEP model age using chondritic lunar Lu-Hf parameters with other age estimates for the primordial lunar silicate differentiation and the Lu-Hf systematics of lunar and some Hadean terrestrial zircons strongly suggest that the BSE, the bulk Moon, and chondrites evolved according to the same Lu-Hf parameters.

References: [1] Patchett P.J. (1983) *GCA*, *47*, 81-91. [2] Bouvier A. et al. (2008) *EPSL*, *273*, 48–57. [3] Bizzarro M. et al. (2012) *G3, 13,* Q03002. [4] Lugmair G.W. and Shukolyukov A. (1998) *GCA, 62,* 2863–2886. [5] Touboul M. et al. (2007) *Nature, 450,* 1206–1209. [6] Touboul M. et al. (2009) *Icarus, 199*, 245–249. [7] Zhang J.J. et al. (2012) *Nat. Geoscie., 5*, 251–255. [8] Lugmair G.W. and Carlson R.W. (1978) *Proc. 9th Lunar Sci. Conf.,* 689–704. [9] Borg L.E. et al. (2013) *LPSC, abstract #1563*. [10] Nemchin A. et al. (2009) *Nature Geosci., 2*, 133-136. [11] Taylor D.J. et al. (2009) *EPSL, 279*, 157–164. [12] Boyet M. and Carlson R.W. (2007) *EPSL, 262*, 505–516. [13] Brandon A.D. et al. (2009) *GCA, 73*, 6421–6445. [14] Borg L.E. et al. (2011) *Nature, 477*, 70-73. [15] Sprung P. et al. (2013) *EPSL, 380*, 77–87. [16] Sprung P. et al. (2010) *EPSL, 295*, 1–11. [17] Münker C. et al. (2001) *G3*, *2*, 2001GC000183. [18] Münker C. (2010) *GCA*, *74*, 7340–7361. [19] Unruh D.M. and Tatsumoto M. (1984) *LPS XV*, 876-877. [20] Simon S.B. et al. (1985) *J. Geophys. Res., 90,* D75–D86. [21] Warren (1989) In: Moon in Transition: Apollo 14, KREEP, and Evolved Lunar Rocks, 149–153 [22] Gaffney A.M. and Borg L.E. (2013) *LPSC, abstract #1714*. [23] Harrison T.M. et al. (2008) *EPSL, 268*, 476–486.