

**OXYGEN ISOTOPE HOMOGENEITY OF THE MOON.** U. Wiechert<sup>1</sup>, A. N. Halliday<sup>1</sup>, D-C. Lee<sup>1</sup>, G. A. Snyder<sup>2</sup>, L. A. Taylor<sup>2</sup>, D. Rumble<sup>3</sup>. <sup>1</sup>Institute for Isotope Geology and Mineral Resources, Department of Earth Sciences, ETH Zentrum, Sonneggstrasse 5, 8092 Zürich, Switzerland. <sup>2</sup>Planetary Geosciences Institute, Department of Geological Sciences, University of Tennessee, Knoxville, TN 37996-1410, USA. <sup>3</sup>Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd., 20015 Washington, DC, USA. (email correspondence: [wiechert@erdw.ethz.ch](mailto:wiechert@erdw.ethz.ch))

**Introduction:** The recently developed hafnium-tungsten chronometer ( $t_{1/2} = 9\text{Ma}$ ) has significantly improved our understanding of the early history of the solar system. Negative  $\epsilon\text{W}$  values of iron meteorites indicate that core formation of their parent bodies occurred within 10 Ma after the solar system started [1]. In contrast, the chondritic tungsten isotope composition of the silicate Earth requires that terrestrial core formation was about 50 Ma late or accretion was slow [2,3]. The radiogenic  $^{182}\text{W}/^{184}\text{W}$  ratios of some lunar samples provide evidence that the moon formed by about 60 Ma, because after that time  $^{182}\text{Hf}$  was effectively extinct [4]. This age for the Moon is based on the assumption that the variable tungsten isotope compositions measured in lunar samples developed within the Moon by decay of former  $^{182}\text{Hf}$ . Recently Leya et al. [5] showed that a significant portion of  $^{182}\text{W}$  in some lunar samples has been produced from  $^{181}\text{Ta}$  by neutron capture but at least some of the radiogenic samples seem not to have a significant portion of cosmogenic  $^{182}\text{W}$  and, therefore, the constraints on the formation of the moon and the terrestrial core are still valid. However, it is also conceivable that the W isotope heterogeneity within the Moon might have been inherited from incomplete mixing of debris from the proto-Earth and impactor [4]. It has also been considered [4] feasible that perhaps the heterogeneity reflects incomplete admixing of chondritic W added to the moon after it formed. Although these possibilities were considered unlikely by Lee et al. [4] we have investigated them by searching for non-mass dependent oxygen isotope variation in lunar samples. It is well established that variations in  $\delta^{18}\text{O}$ - $\delta^{17}\text{O}$  reflect genetic relationships between meteorites [6] although the origin (nuclear or chemical) is not clear. Several decades ago it was claimed that lunar and terrestrial samples plot on the same mass dependent fractionation line in a three isotope plot [7]. So any O isotope heterogeneity must be at best small. We have re-investigated the oxygen isotope composition of lunar rocks because recently developed laser preparation techniques [8,9] have significantly improved the precision of measurements. We have included samples with both chondritic and more radiogenic tungsten isotope ratios.

**Samples and Procedures:** The oxygen isotope compositions of 33 lunar samples from different

Apollo missions have been analyzed using a high precision  $\text{CO}_2$  laser technique [7]. For most samples 1 to 5 small fragments with a total mass of between 1.5 and 2.5 mg were reacted with  $\text{BrF}_5$ . Fine-grained and powdered samples were melted in vacuum before fluorination in order to avoid losing material by violent reaction of the powder with  $\text{BrF}_5$  during laser heating. Only the powdered samples might be almost representative of bulk rock samples but this is of no consequence for this study. After all material was reacted, surplus  $\text{BrF}_5$  and other condensable gases were frozen in liquid nitrogen cold traps. The isotopic composition of the sample oxygen was analyzed on a Finnigan/MAT-252 gas source mass spectrometer injecting oxygen through a conventional dual inlet system. No corrections on mass 33 ( $^{17}\text{O}^{16}\text{O}$ ) were made because the high mass resolution of the mass spectrometer reduces scattering of  $^{32}\text{O}_2^-$ .

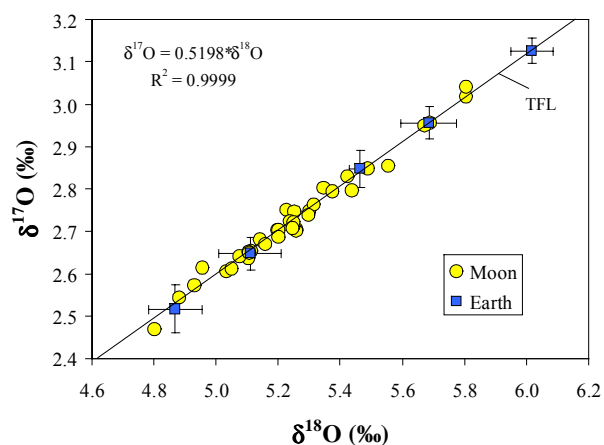


Fig. 1 Three-oxygen isotope plot of lunar and terrestrial samples. Data points for lunar samples reflect single analyses whereas terrestrial samples are averages of 2 to 10 single analyses. TFL-Terrestrial Fractionation Line.

We first analyzed 7 terrestrial samples with a wide range of  $\delta^{18}\text{O}$  from about 0 to 12‰ to be able to detect very small deviations from the mass dependent terrestrial fractionation line (Fig. 1). The linear equation calculated for the 7 terrestrial samples in  $\delta^{18}\text{O}$ - $\delta^{17}\text{O}$  space is  $\delta^{17}\text{O} = 0.5198 \times \delta^{18}\text{O}$  with a squared correlation coefficient of  $R^2 = 0.9999$ . Non mass dependent deviations are expressed relative to this experimentally

determined terrestrial fractionation line as  $\Delta^{17}\text{O} = \delta^{17}\text{O} - 0.5198 \times \delta^{18}\text{O}$ . A terrestrial olivine standard was analyzed together with the lunar samples in every run. 10 analyses of this olivine standard average  $\Delta^{17}\text{O} = -0.008 \pm 0.036$  ‰ and 4 analyses of UWG-2 give  $0.001 \pm 0.026$  ‰. Errors are given as  $2\sigma$ .

**Results and Discussion:** Neither highlands nor mare basalt samples with radiogenic W isotopic compositions display a difference in O isotope composition from lunar samples with chondritic W. Five ferroan anorthosites, 17 mare basalts, 1 KREEP basalt, 2 norites, 1 trocolite, 4 breccias and 3 soils investigated in this study plot on one single mass dependent fractionation line, which is, within error, identical to the terrestrial O isotope fractionation line (fig.1). The  $\Delta^{17}\text{O}$  values range from  $-0.034$  to  $0.037$  ‰ with an overall average of  $-0.0076 \pm 0.033$  ‰ ( $2\sigma$ ). Obviously the Moon is, within 60 ppm, homogeneous in oxygen isotope composition. There is no sign that the W isotope compositions are a reflection of incompletely mixed components from accretion during or after the impact that is thought to have formed the Moon (Fig.2). Therefore, the observed variations in W isotope ratios

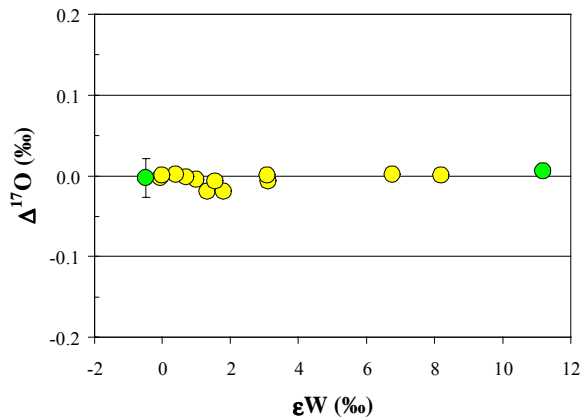


Fig. 2  $\epsilon\text{W}-\Delta^{17}\text{O}$  plot of lunar samples.

could be indeed a consequence of internal fractionation processes, i.e. segregation of spinel, titanates or other minerals with high Hf/W in a magma ocean immediately after the formation of the Moon. Such cumulate layers might have Hf/W ratios high enough to generate a radiogenic W reservoir within the Moon which would then be sampled by lunar volcanism long after  $^{182}\text{Hf}$  had decayed [4]. It can not be excluded, based on a homogeneous oxygen isotope composition of the Earth-Moon system, that the radiogenic W isotope ratios of the Moon do not reflect incomplete mixing of material from the impactor within the moon. Such a

model requires that the impactor and proto-Earth were very similar in oxygen isotope composition and that the oxygen isotope composition of the feeding zones for the two planets was, on average, identical. Assuming that a major proportion (50%) of the Moon is derived from the impactor then the oxygen isotope composition of the impactor could only deviate  $\leq 0.06$ ‰ from the terrestrial fractionation line. It is clear that no significant proportion of material from a martian or HED like source can have been mixed into the Moon.

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