

**D/H OF INTRUSIVE MOON ROCKS: IMPLICATIONS FOR LUNAR ORIGIN.** K.L. Robinson<sup>1</sup>, K. Nagashima<sup>1</sup>, and G.J. Taylor<sup>1</sup>, <sup>1</sup>Hawaii Institute for Geophysics and Planetology, University of Hawaii at Manoa, 1680 East-West Rd., Honolulu HI 96822. krobinson@higp.hawaii.edu

**Introduction:** Water has been detected in several types of samples from the lunar interior [1-6], as well as on the lunar surface and in agglutinate glasses from the regolith [7]. The D/H ratio of lunar water provides important clues about the source of that water. D/H measurement of the mineral apatite suggests that lunar interior water could be enriched in D with respect to Earth [4-6] while the D/H of water in agglutinate glasses reflects H-enriched solar wind [7].

The enrichment of D relative to H can take place as a result of a mass-dependent fractionation of H. H is lighter than D and is preferentially lost during degassing from a melt. Because of the strong dependence of H<sub>2</sub>O solubility on pressure, mare basalts would have degassed when they erupted. Thus, it is possible that the high D/H in apatites found in the mare basalts could reflect degassing rather than the D/H of lunar interior water. However, the extent of H<sub>2</sub>O degassing is not known. To avoid this uncertainty, we have analyzed H and D in intrusive rocks. The intrusive rocks formed at pressures where water would have been soluble in the melt, hence avoiding degassing, and thus present a more representative D/H of the lunar interior. About 1% water is soluble in basalt and rhyolite melts at ~1kbar, 2km depth on the Moon (calculated with [8]). This makes the intrusive rocks ideal for preserving H<sub>2</sub>O of their parent magmas and interior source region(s).

We have measured  $\delta D$  and water content of apatite in several intrusive rocks formed from KREEP basalt magmas. We performed the same measurements on residual glass in a KREEP basalt, to compare a degassed KREEPy sample to the supposed nondegassed intrusive rocks and to mare basalts.

**Samples:** The best definitively intrusive sample is the Mg-suite troctolite 76535, a plagioclase and olivine cumulate with minor pyroxene and accessory minerals including apatite [9]. Based on its coarse grain size and thermodynamic calculations, 76535 originated in a deep, large magma body, although the exact depth of origin is uncertain [9,10]. On the basis of REE concentrations in minerals in Mg-suite rocks [11] including 76535, Mg-suite magmas contained a KREEP component. We also analyzed KREEP basalt differentiates from smaller intrusions, felsites and quartz monzodiorites [5]. To test H loss during eruption we analyzed glass in KREEP basalt fragments in breccia 15358. The fragments have intersertal to intergranular textures and 11 to 18 vol% yellow glass, rather than

much smaller amounts of mesostasis present in other KREEP basalts [12].

Our focus has been on samples with a significant KREEP component in order to probe early lunar differentiation. Water is incompatible at low abundances, so it will become enriched in a crystallizing melt. Thus, KREEP or KREEP-rich magmas should be enriched in water when apatite crystallizes. However, measurements for evolved rocks [3-5] indicate that they contained very little water, which implies that the magma ocean contained little water [13].

#### Methods and Results:

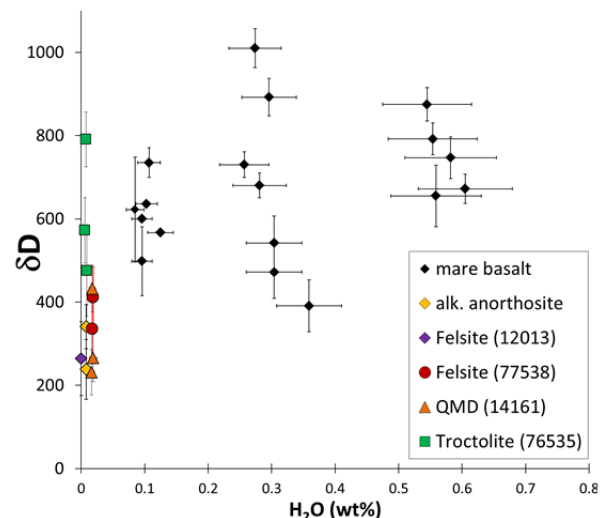


Figure 1.  $\delta D$  of lunar apatite vs. wt% H<sub>2</sub>O. Diamonds represent literature data from [4]. All other data is from this work and [5].

Apatites in troctolite 76535, 52 and -56; felsites 14321, 1047 and 77538, 16; and QMDs 14161, 7069 and -7373 were analysed in situ for D, H and <sup>18</sup>O on the UH ims 1280 ion microprobe using a ~2 or ~4 nA Cs<sup>+</sup> primary beam in three sets of measurements in May and Nov. 2011 and May 2012. H<sub>2</sub>O content of apatite samples was estimated from a H<sub>2</sub>O (wt%) vs. <sup>1</sup>H/<sup>18</sup>O calibration curve determined using 3 terrestrial apatite standards after [4,5]. The detection limit varied between runs depending on the primary beam current; higher current resulted in a lower detection limit. All apatite data is summarized on figure 1.

Residual glass in KREEP basalt clasts in 15358, 6 was measured for H, D, and <sup>30</sup>Si using a ~4 nA Cs<sup>+</sup> primary beam in March 2012. H<sub>2</sub>O content of the glass was determined using a H<sub>2</sub>O (wt%) vs. <sup>1</sup>H/<sup>30</sup>Si calibration

tion curve using 2 terrestrial basaltic glass standards. All data has been summarized on table 1.

Table 1. Ranges of measured H<sub>2</sub>O content and  $\delta$ D by rock type. The 2 $\sigma$  H<sub>2</sub>O and 2 $\sigma$   $\delta$ D shown are maximums for each set of measurements. DL: detection limit on H<sub>2</sub>O.

RockType	Felsite	QMD	Troctolite	KREEP glass
ppm H <sub>2</sub> O	175-190	160-190	60-85	60-95
2 $\sigma$ H <sub>2</sub> O	~55	~55	~10	~10
$\delta$ D (‰)	335-410	230-430	475-790	610-830
2 $\sigma$ $\delta$ D	~75	~55	~110	~85
DL (ppm)	~100	~110	~20	~10

**Discussion:** As shown in Fig. 1 and by other workers [4,6] lunar magmas are enriched in D. Although  $\delta$ D in mare basalts might have been modified by mass-dependent fractionation of H and D during eruption, the intrusive rocks indicate that their parent magmas, hence their mantle source regions, contained elevated D/H compared to Earth. Note that data for coarse-grained intrusive rock 76535 are in the range of  $\delta$ D values for mare basalts. We suggest that these data show that the lunar interior has higher  $\delta$ D than does Earth. However, uncertainty remains as to how enriched it is. To investigate this, we used our data for glassy KREEP basalts in 15358 to estimate how much fractionation would be required to raise terrestrial  $\delta$ D of -62.5 [14] to the average observed value in 15358 KREEP basalts (~730‰). This requires that 90% of the initial H<sub>2</sub>O be lost from the lava (Fig. 2). Beginning with  $\delta$ D like those in QMD (~230‰) and felsites (~400‰) requires loss of 55-70 wt% H<sub>2</sub>O. Assuming that our values for intrusive KREEP samples accurately reflect values in KREEP basalt mantle source regions, H<sub>2</sub>O loss is more likely to have been much lower than the 90% required if  $\delta$ D began with a terrestrial value. This suggests that water loss was equally modest for mare basalts, emphasizing that the lunar interior has elevated  $\delta$ D.

It is also possible that the moon accreted with high  $\delta$ D, or that high  $\delta$ D water was added very early in the moon's history. The protolunar disk could have inherited H<sub>2</sub>O with terrestrial  $\delta$ D, and undergone a subsequent fractionation as H was lost from the hot silicate gas [15]. Fractionation of D from H (preferential loss of lighter H) is consistent with the presence of heavy Zn isotopes in lunar samples [16]. An alternative is that a portion of the Moon's H<sub>2</sub>O inventory was added after the Moon had accreted, as argued by [4]. This would explain lower H<sub>2</sub>O in the magma ocean (as shown by low H<sub>2</sub>O in KREEPy samples) if the additional material was added after the magma ocean had crystallized. It would not explain the elevated  $\delta$ D in KREEPy samples. It would also require that the late-

accreting material had heavy Zn isotopes. This is not likely because Zn isotopes are strikingly similar in other solar system materials (Earth, Mars, and chondrites) [16]. The combination of enrichment in the heavy isotopes of the volatile elements H and Zn argues for vaporization during lunar formation.

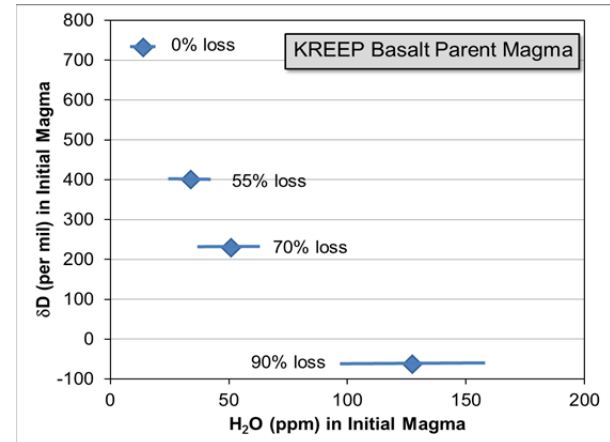


Figure 2. Calculation of degree of water loss required to obtain  $\delta$ D measured in 15358 KREEP basalt glass starting with observed terrestrial, QMD, and felsite  $\delta$ D and H<sub>2</sub>O abundances. Limits represent the range of measured H<sub>2</sub>O content in 15358 glasses.

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