

**ISOTOPIC COMPOSITION OF LUNAR SOILS AND THE EARLY DIFFERENTIATION OF THE MOON.** M. C. Ranen and S. B. Jacobsen, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford St. Cambridge, MA 02138, USA, (ranen@fas.harvard.edu).

**Introduction:** The isotopic composition of the Lunar Highlands crust is still not well defined. This study will measure Hf-W, Rb-Sr, Lu-Hf, and <sup>147,146</sup>Sm-<sup>143,142</sup>Nd on a suite of 14 lunar soils from the Apollo 14 and Apollo 16 missions. The overall goal of this project is to estimate the isotopic composition of the average lunar crust in order to constrain timescales and magnitude of magma ocean crystallization.

**Initial ε<sub>Nd</sub> of highland materials?:** Only three Sm-Nd isochrons have been reported on highland rocks from the Apollo 16 mission [1,2,3]. Models of magma ocean crystallization predict that the ancient highland rocks, ferroan anorthosites (FANs), should have a <sup>147</sup>Sm/<sup>144</sup>Nd ratio that is subchondritic, having a negative (ε<sub>Nd</sub>)<sub>i</sub>. However, all three of these samples have (ε<sub>Nd</sub>)<sub>i</sub> ranging from +0.85 to +3.5. This has caused the theory of crust formation by plagioclase flotation in a global magma ocean to be questioned. Recently, anorthositic clasts in two lunar meteorites were found to have negative (ε<sub>Nd</sub>)<sub>i</sub> values, of which one, Y86032, has an ancient age of 4.4 Ga [4]. Thus, the true isotopic composition of the lunar highland crust is still not well known. This knowledge is imperative to any quantitative theory of magma ocean crystallization.

**Lunar soils as tracers for the average crust:** Much like terrestrial geochemists use sediments to estimate the average isotopic composition of the continental crust, it is possible to infer the average isotopic composition of the lunar crust using samples from the lunar regolith. Billions of years of impacts from meteorites have struck and mixed the lunar surface creating a regolith that ranges in depth from 5 to greater than 15 m. Even though lunar soils have had a complex history, soils can give a better average composition than individual rocks. Based on data from the Lunar Prospector and Clementine missions, Joliff et al. [5] proposed that the lunar crust is made up of three terranes, the Procellarum KREEP Terrane (PKT), Feldspathic Highlands Terrane (FHT) and the South Pole-Aitken Terrane (SPAT). Together, the FHT and the PKT make up 95% of the lunar crust with the FHT alone comprising 85% of the crust. Having representative samples of both terranes will allow a better estimate of the average isotopic composition of the total lunar crust. The Apollo 16 mission is the only mission that landed in the ancient highland crust while Apollo 14 soils are thought to be representative of the PKT

[6]. Thus, 14 soil samples from both Apollo 14 and Apollo 16 were studied with hopes that representative end members of both the FHT and the PKT would be found in these samples. Table 1 lists the lunar soil samples received. All samples have a mass of ~ 100 mg.

Sample	Specific	Parent
14141	175	25
14163	913	772
14259	651	130
14260	90	60
60006	416	32
60006	417	116
60007	512	19
60007	513	80
60009	2072	2031
60009	2073	2036
60009	2074	2057
60010	479	9
60010	480	91
60010	481	110

**Methods:** Each sample was dissolved in full. One percent of the solution was set aside for trace element work [7], ten percent was set aside for isotope dilution studies and the rest is being used to measure the isotopic composition of Sm, Nd, Rb, Sr, Lu, Hf, and W. An ion exchange separation technique was developed that utilizes a primary column to separate the elements into several groups and each element of interest is further purified using separate two column procedures.

**Table 1:** Lunar Soils Studied

**High Precision Mass Spectrometry:** A new GV Isoprobe-P multi collector mass spectrometer will be used for Lu, Hf, and W measurements. A GV Isoprobe-T multi collector thermal ionization mass spectrometer will be used to measure all isotopes of Sr, Gd, Sm, and Nd. The Isoprobe-T is able to resolve anomalies in <sup>142</sup>Nd to an accuracy of better than 3 ppm, while the Isoprobe-P is better than 5 ppm.

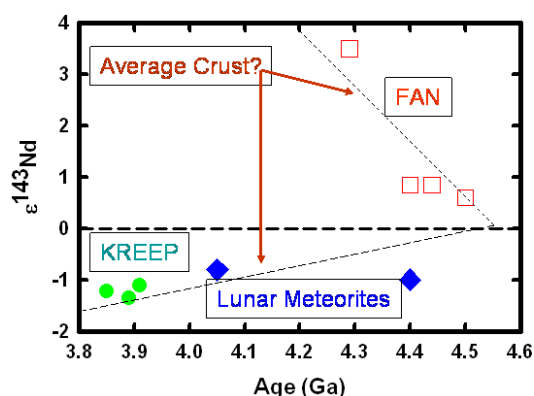
**Neutron capture effects:** Neutron capture effects are well established and large for Sm and Gd in lunar soils [8,9]. Specifically, <sup>149</sup>Sm is systematically depleted in lunar samples while <sup>150</sup>Sm is enriched relative to terrestrial standards. Nyquist et al. [10] detail how neutron capture at the surface can alter both Sm isotopic ratios as well as give rise to small changes in <sup>142</sup>Nd and how to correct for these effects. Anomalies resulting from the decay of <sup>146</sup>Sm are small ( typically <1ε) and therefore effects of neutron capture on <sup>142</sup>Nd must be properly corrected. All isotopes of Gd and Sm will be measured on unspiked aliquots in order to calculate the neutron fluence that each sample has encountered. From this, neutron capture corrected <sup>142</sup>Nd/<sup>144</sup>Nd ratios are to be calculated. A controversy over measured W isotopes has also arisen because of

neutron capture effects [11,12]. One possibility is the  $^{181}\text{Ta}(n,\gamma)^{182}\text{Ta}(\beta^-)^{182}\text{W}$  reaction from cosmic irradiation accounts for the extremely large  $^{182}\text{W}$  anomalies seen in some lunar samples (up to  $\varepsilon_{\text{W}} = +11$ ). Another possibility is that  $^{181}\text{TaH}$  production in the mass spectrometer may account for the excess  $^{182}\text{W}$ .

**Discussion:** The depth of the lunar magma ocean is still a controversy in lunar science. Estimates for the depth of the magma ocean range from 20 km to the entire radius of the Moon. We [13] proposed using isotopic mass balance to constrain the depletion of the lunar mantle relative to the crust. By dividing the Moon into three separate reservoirs (1) bulk Moon and undifferentiated mantle, (2) a depleted mantle, and (3) an enriched crust, the mass fraction of depleted mantle can be solved by using

$$X_3 = \frac{M_3}{M_2 + M_3} = \frac{\varepsilon_2 \times c_1}{(\varepsilon_2 - \varepsilon_3) \times c_3}$$

for any long lived isotopic system such as Rb-Sr, Sm-Nd, or Lu-Hf. A range for  $M_3$ ,  $\varepsilon_2$ ,  $c_1$ , and  $c_3$  can be estimated from existing data. However, the average epsilon value of the lunar crust is so unconstrained by the lack of data that it cannot be truly estimated within any major uncertainty. Measuring the isotopic composition of these lunar soils will allow for a better understanding of the relative depletion or enrichment of the crust compared to the bulk Moon. Figure 1 shows previously measured data on different suites of crustal rocks and establishes the uncertainty of the average anorthositic crust.



**Figure 1.**  $\varepsilon_{\text{Nd}}$  evolution of lunar ferroan anorthosites

Extinct nuclides measured in the Apollo 16 soils in particular will provide more detail on timescales of lunar differentiation.  $^{182}\text{Hf}$  has a half life of 9 Myr while  $^{146}\text{Sm}$  has a half life of 106 Myr. The  $^{182}\text{Hf}$ - $^{182}\text{W}$  system can constrain timescales of early fractionation and/or core formation while the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  system can give information about the time that each mantle and crustal source finally crystallized from the magma

ocean. Comparing  $\varepsilon_{\text{W}}$  with  $\varepsilon_{^{142}\text{Nd}}$  in the lunar crust will constrain both the timing of the Moon forming impact as well as the core formation and magma ocean crystallization. This will be the first Sm-Nd data reported on lunar soils. Data measured for long-lived isotopic systems such as Sm-Nd, Lu-Hf and Rb-Sr will be used to determine the average isotopic composition of the lunar crust helping to constrain the initial depth of the lunar magma ocean by isotopic mass balance. Data on extinct isotopes such as  $^{182}\text{W}$  and  $^{142}\text{Nd}$  once corrected for neutron capture effects will shed light on the timescale of formation of the original lunar crust as well as the crystallization of the KREEP reservoir, thought of as the last crystallization product of the Lunar Magma Ocean.

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