THE ISOTOPIC COMPOSITION OF THE LUNAR CRUST AND THE AGE AND ORIGIN OF THE MOON: EVIDENCE FROM LUNAR SOILS. S. B. Jacobsen[1], M. C. Ranen[1], R. Chakrabarti[1], J. Farkaš[1], S. Huang[1], R. Parai[1], G. Yu[1], A. Zindler[1]. [1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138 (jacobsen@neodymium.harvard.edu).

Introduction: Most of the effort to understand the earliest differentiation and formation of the Moon is based on isotopic work on mare basalts or lunar highland rock samples. Lunar soils may provide good average compositions of large areas of the lunar crust. Here we report isotopic results on a number of lunar soil samples to further evaluate theories for the early differentiation, age and formation of the Moon.

Fourteen soils from the Apollo 16 and Apollo 14 missions are studied. They were chosen to be representative of both the Feldspathic Highland Terrane (FHT**,** Apollo 16) and the Procellarum KREEP Terrane (PKT**,** Apollo 14). Since mare volcanism accounts for less than 2% of total crustal volume the majority of the crust is made up of a combination of the FHT and PKT. The lower crust may be different but is most likely some mixture of FANs and rocks of the Mg-suite.

Trace Element Study: Trace element data show that the Apollo 14 soil samples have a high KREEP component as evidenced by the very high REE concentrations as well as large negative Eu anomalies. Most Apollo 16 soils, while having an order of magnitude lower REE concentration, still have a significant KREEP component that gives rise to a negative Eu anomaly. Only one sample (60009,2074) has the positive Eu anomaly and a low Nd concentration characteristic of the lunar highlands and is likely close to a true signature of the plagioclase flotation crust.

Stable Isotope Compositions: Large mass-dependent fractionations of O, Si, S, and K (although the bulk Solar System is homogeneous in K) isotopes have been reported in lunar soils suggesting enrichments in the heavier isotopes [1,2]. The largest reported effects were for O and Si isotopes extracted from the soils by reaction with fluorine. The proposed mechanisms for such isotopic fractionations include: 1) local volatilization by sputtering and associated gravitational segregation as well as "sticking" of heavy isotopes; 2) thermal volatilization upon impacts and re-deposition; and 3) formation of volatile compounds in chemical reactions after solar wind implantation. In laboratory sputtering experiments, large isotopic fractionations have been observed in Ca [3] and Mg [4] suggesting that if sputtering is the main mechanism for fractionation isotopes of light elements in lunar soils, it should be observed in Ca and Mg isotopes in lunar soils. However, in contrast to the isotopes of O, Si, S, K, lunar soils display little or no fractionation of Ca [5] and Mg isotopes (max. 1.9‰/amu in one soil #66081 [6]). If thermal volatilization and re-deposition is the main fractionation mechanism, Ca isotopes may not be fractionated due to its more refractory nature. However, Mg, which has a similar volatility as Si, would be expected to show large fractionation, but no such effects are observed in lunar soils [6]. Lunar soils represent average compositions for various quantities of the lunar crust. Absence of sputtering and impact-related fractionation in Si, Ca and Mg isotopes in lunar soils makes them potentially valuable samples for estimating the bulk Si, Ca and Mg isotopic compositions for the Moon. We are thus investigating the use of bulk measurements of these samples for further establishing the stable Si, Ca and Mg isotopic compositions of the Moon. So far, our stable Si, Ca and Mg isotope data for lunar samples are identical with all other inner Solar System objects and therefore do not indicate any special connection between the Moon and Earth's mantle.

Sm-Nd Isotopic Measurements of Lunar Soils: Sm and Nd isotopes were measured both with a GV Isoprobe P MC-ICP MS and a GV Isoprobe-T TIMS. Sm isotopes were normalized using an exponential law with $^{147}Sm/^{154}Sm = 0.5918$. Figure 1 presents ^{149}Sm and ^{150}Sm isotope data for each soil studied. These data were used to estimate neutron capture corrections to the Nd isotopic compositions of the same samples.

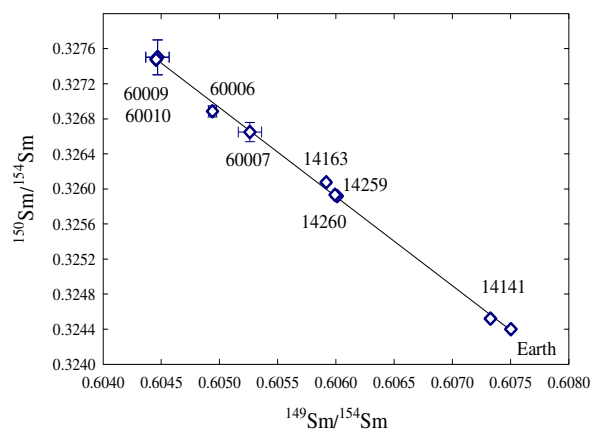

Figure 1. Sm isotopic variations in lunar soil samples showing the effect of ^{149}Sm burnout to ^{150}Sm.

Nd isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$ and corrected for mass fractionation using an experimentally derived law. The samples were run using the same method as the standard and the ion beam was kept at a constant intensity of 2V for ^{142}Nd. Each

Nd sample was run to exhaustion which allowed for some repeat measurements. Deviations (ε_{142Nd}) are calculated from the average of our NdA standard as measured by TIMS. The average ε_{143Nd} of the lunar crust is well constrained by these data as all samples measured have ε_{143Nd} values in the range of -15 ±1. The highland "end member", sample 60009, 2074, having the lowest ε_{143Nd} (-15.84), is within range of all other measured soils. The lack of scatter in ε_{143Nd} supports a single value for the ε_{143Nd} of the enriched lunar crust (defined as FAN + KREEP). We propose that this value of -15 ±1 can be confidently chosen to represent the lunar crust.

Further (as shown in Figure 2) ^{147}Sm-^{143}Nd model ages, with respect to the lunar depleted mantle evolution, yield values ranging from 3.80 Ga for the highly enriched samples from the PKT, to 4.46 Ga for the lunar highlands end member of the FHT. The 3.8 Ga age likely represents production of KREEP type melts at the time of the terminal lunar cataclysm, while the 4.46 Ga age likely represents a lower limit to the mean age of the lunar highlands crust.

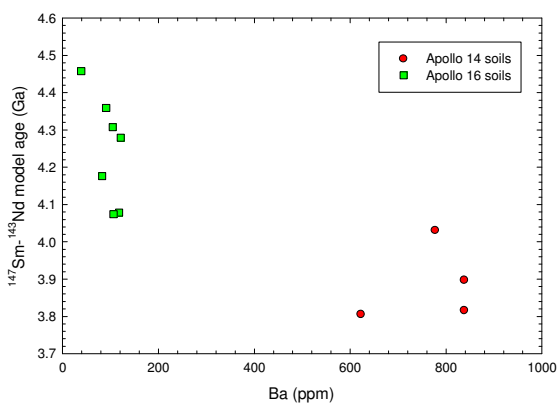

Figure 2. ^{147}Sm-^{143}Nd model age versus highly incompatible element enrichment (Ba) in lunar soil samples.

^{142}Nd and the Timescale of Early Lunar Differentiation: A large body of data for long-lived chronometers (Sm-Nd, Rb-Sr, U-Th-Pb) suggests formation and early differentiation of the Moon within 50 to 100 Ma after Solar System formation. In contrast, the first two detailed ^{146}Sm-^{142}Nd studies [7, 8] suggested lunar differentiation more than 200 Ma after Solar System formation. However, a whole-rock ^{147}Sm-^{143}Nd isochron for the lunar samples measured by Rankenburg et al. [8] yields a best fit line that corresponds to an age of 4.49 Ga, or 70 Myr after the formation of the Solar System. This again calls into question the significance of a >200 Myr formation interval inferred from the ^{142}Nd/^{144}Nd data. New ε_{142Nd} data for lunar soils are plotted in Figure 3 and compared to the ^{147}Sm-^{143}Nd model ages. There is perhaps a suggestion that the largest negative ε_{142Nd} values are for the samples with the oldest ^{147}Sm-^{143}Nd model ages. Such large ^{142}Nd effects would suggest formation and differentiation of the Moon within the first 50 Ma of the Solar System. Neutron capture corrections on the ^{142}Nd/^{144}Nd data are large, however, and must be further carefully scrutinized. The apparent >200 Myr ^{146}Sm-^{142}Nd isochrons of [7, 8] most likely do not represent magma ocean crystallization but rather a later events causing substantial late Sm-Nd fractionation as is also required for the KREEP component in the soils.

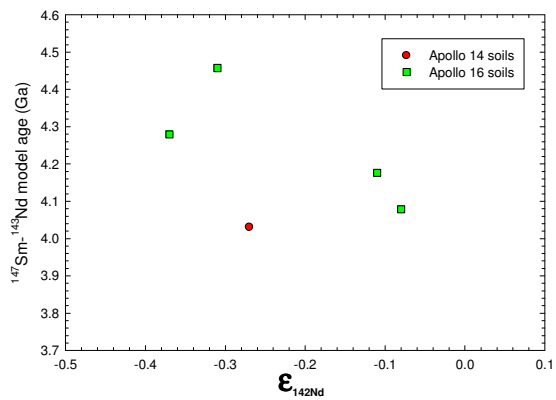

Figure 3. ^{147}Sm-^{143}Nd model age versus ^{142}Nd/^{144}Nd variations (corrected for neutron capture effects) in lunar soil samples.

Discussion and Conclusions: The trace element and isotope data show that our lunar soil samples span the entire range of compositions from an >4.46 Ga old, almost pure highland end-member to a ~3.8 Ga KREEP end member. Our stable Si, Ca and Mg isotope data for lunar samples are identical with all other inner Solar System objects and therefore do not indicate any special connection between the Moon and Earth's mantle. Our limited ^{142}Nd/^{144}Nd data on lunar soils suggest that ^{146}Sm-^{142}Nd systematics in the Moon may reflect both early > 4.46 Ga and late (3.8 Ga) Sm/Nd fractionation in the lunar mantle.

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