UNDERSTANDING THE GEOCHEMICAL EVOLUTION OF AN ASYMMETRIC MOON.

L. E. Nyquist, Mail Code KR, NASA Johnson Space Center, Houston, TX 77058, laurence.e.nyquist@nasa.gov.

Introduction: Major ambiguities remain in our current understanding of the geochemical evolution of the moon. That situation arises partly because (a) our geochemical and isotopic data sets for mare basalts are overly influenced by samples from the Procellarum KREEP Terrain (PKT [1]), and (b) samples of the highland crust useful for isotopic studies are limited in both quantity and quality. Future missions returning lunar samples should target those areas likely to contain mare basalts not influenced by the PKT, and/or a suite of crustal samples most likely to faithfully reveal the processes of lunar crustal formation.

Radiogenic evolution of initial ^{87}Sr/^{86}Sr: Radiogenic ^{87}Sr from decay of the long-lived natural radioactivity ^{87}Rb present in lunar rocks causes the ^{87}Sr/^{86}Sr ratio to increase with time from its starting value in the bulk Moon. Fig. 1 plots the initial ^{87}Sr/^{86}Sr ratios in lunar basalts vs. their time of crystallization, and illustrates ^{87}Sr/^{86}Sr growth for a bulk, undifferentiated Moon with Rb/Sr ~ 0.013 [2], "depleted" mantle reservoirs with Rb/Sr ~0.0027, and "enriched" crust/mantle reservoirs with Rb/Sr ~ 0.05. These reservoirs are represented by lunar meteorite LAP02205 [3], a basalt fragment returned by Luna 16 (L-16) [4], and lunar "KREEP" (K, REE, and P rich rocks, [2]), respectively. A basalt fragment returned by Luna 24 (L-24) [5] and the "YAM" lunar meteorite basalts MIL 05035 and A-881757 [6] plot near the L-16 growth curve. Most mare basalts, including those from the Apollo missions (A11, etc.), were derived from mantle reservoirs depleted in Rb/Sr compared to the bulk Moon.

Variation of mantle Rb/Sr with location: The data of Fig. 1 suggest that Rb/Sr in the mantle reservoirs of the lunar basalts varies with selenographic location. Fig. 2 plots source region Rb/Sr ratios vs lunar longitude of the known or estimated (YAM [6], LAP 02205 [3]) sampling sites. The overall data set is strongly influenced by the atypical PKT, which contributes basalts with Rb/Sr as high as ~0.05.

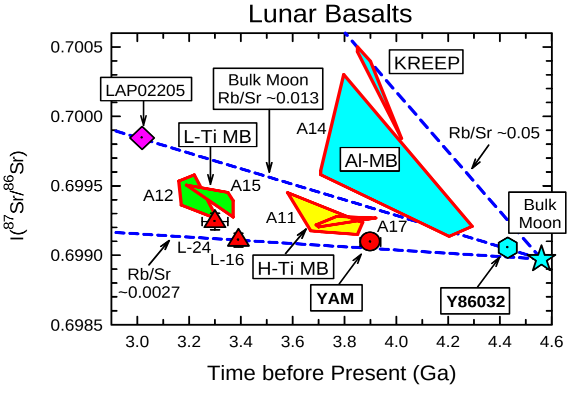

Figure 1. Initial ^{87}Sr/^{86}Sr in some lunar rocks vs. their ages. Data from [1,2] except where noted.

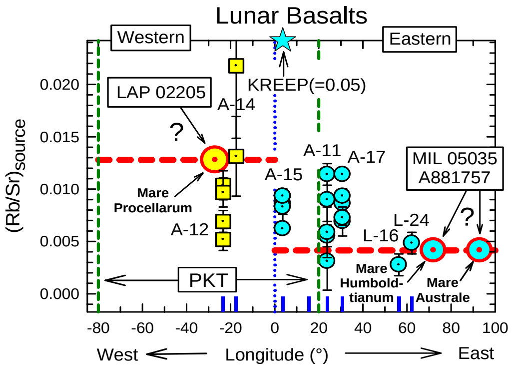

Figure 2. Estimated source Rb/Sr for lunar basalts vs. longitude of known or estimated sampling sites.

Radiogenic evolution of initial ε_{Nd} values: For the Sm-Nd element pair, radiogenic ^{143}Nd from decay of ^{147}Sm causes the ^{143}Nd/^{144}Nd ratio to increase with time from the starting value of the bulk Moon analogously to the Rb-Sr case. Both Sm and Nd are Rare Earth Elements (REE), which are particularly useful for geochemical modeling, so initial ^{143}Nd/^{144}Nd values are usually expressed as ε_{Nd}, the deviation in parts in 10^4 from a reference value for chondritic meteorites of the same age. REE are not easily separated from one another, so the relative abundances of REE in chondrites are likely to be representative of the bulk Moon. Fig. 3 shows ε_{Nd} values for the lunar rocks of Fig. 1, and Fig. 4 shows source-region Sm/Nd ratios vs. longitude. The only Sm-Nd data for an eastern basalt of known location is for the L-24 VLT basalt [5]. However, the YAM meteorites MIL 05035 and A-881757 likely originated from either Mare Humbodtianum or Mare Australe [6]. If so, some eastern basalts come

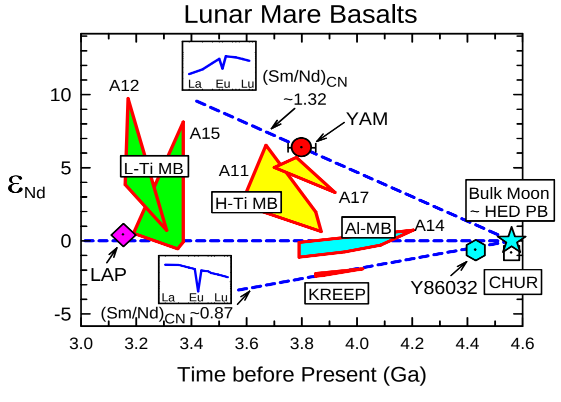

Figure 3. ε_{Nd} in some lunar rocks vs. their ages. Data from [2] except where noted.

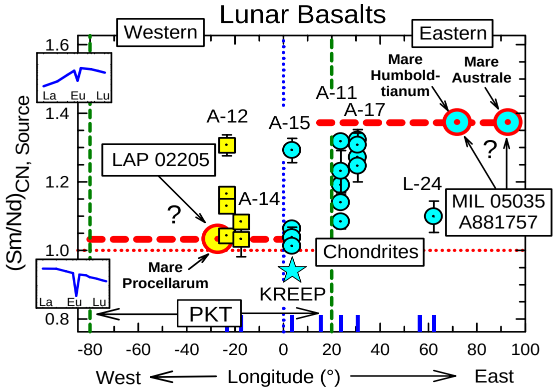

Figure 4. Estimated source region Sm/Nd for lunar basalts vs. longitude of known or estimated sampling site.

from source regions with highly depleted LREE (Light REE, i.e., La, etc.) like the source regions of the A11 and A17 basalts.

Initial ε_{Nd} of Lunar Crustal Rocks: Fig. 5 shows ε_{Nd} values for some Apollo 16 Ferroan Anorthosites (FANs) compared to those for highland lithologies in the Yamato 86032 lunar meteorite of likely lunar farside origin [7]. Y86032 data also are used in Figs. 1 & 3 because they are likely to be most representative of the lunar crust. The Y86032 isotopic data are consistent with formation of the corresponding lithologies as part of an anorthositic lunar crust formed via plagioclase flotation from a Lunar Magma Ocean (LMO). That is, initial ε_{Nd} for these lithologies are consistent with radiogenic growth of ^{143}Nd in an environment in which the Sm/Nd ratio is always $\leq$ the chondritic value, i.e., chondrite-normalized $(Sm/Nd)_{CN} \leq 1$. In contrast, the elevated ε_{Nd} values of some A16 FANs require some part of their isotopic evolution to have occurred in an environment with $(Sm/Nd)_{CN} \geq 1$, inconsistent with a strictly magma ocean environment.

Discussion: Because the easternmost basalts give no evidence of highly differentiated, late-stage differentiates from the LMO ("urKREEP", etc.) in their mantle source regions, radiogenic heating from decay of U, Th, and K could not have provided the heat required for their petrogenesis by partial melting as is widely assumed for basalt genesis. Mantle overturn of urKREEP into their source regions is unnecessary, but mantle uplift (convection?) seems a likely cause of pressure release melting. Further, an earlier episode of remelting of overturned mafic cumulates [8] could account for the positive ε_{Nd} values of A16 ferroan anorthosites from the "outer" Feldspathic Highlands Terrane (FHT,O [1]), but is not required by ε_{Nd} of the Y86032 lithologies. Negative ε_{Nd} for the Y86032 lithologies, combined with the presence of previously unrecognized crustal lithologies in Y86032, led [7] to suggest the possibility of assymetric development of the LMO. Whether this suggestion is correct, or whether the variation in ε_{Nd} for highlands rocks simply reflects local variations in the FHT due to postmagma ocean petrogenesis [8], remains to be determined.

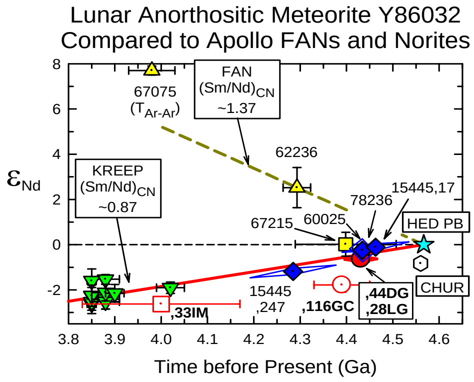

Figure 5. ε_{Nd} for some lunar crustal rocks [7] and lunar KREEP.

Conclusions: The PKT should be avoided in future missions returning lunar samples. The probable derivation of previously unrecognized Y86032 lithologies (Fig. 6) from the lunar farside highlands (FHT, A [1]) combined with the probable existence of magnesian anorthosites like the Dhofar 489 lunar meteorite (D489MAN in Fig. 6) there [9], suggests evidence for the putative LMO also is most likely preserved there. Further, the isotopic systematics of a farside sample are less likely to be disturbed by impacts than samples from the nearside central highlands (e.g., A16).

References: [1] Jolliff B. L. et al. (2000) *JGR, 105*, 4197-4216. [2] Nyquist L. E. et al. (2001) *The Century of Space Science*, Kluwer, 1325-1376. [3] Nyquist L. E. et al. (2005) *LPS XXXVI*, Abstract #1374. [4] Papanastassiou D. A. and Wasserburg G. J. (1972) *EPSL, 13*, 368-374. [5] Wasserburg G. J. et al. (1978) *Mare Crisium: The View from Luna 24*, 675-678. [6] Nyquist L. E. et al. (2007) *LPS XXXVIII*, Abstract #1702, submitted. [7] Nyquist L. et al. (2006) *GCA 70*, 5990-6015. [8] Longhi J. (2003) J. Geophys. Res., 108, 10.1029/2002JE001941. [9] Takeda H. et al. (2006) *EPSL 247*, 171-184.

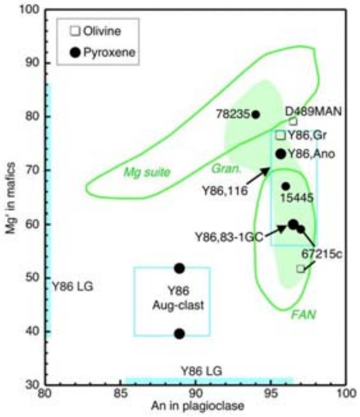

Figure 6. mg' in mafic minerals vs. An in plagioclase for Y-86032 lithologies and some other lunar crustal rocks [7].