REDETERMINATION OF THE Sm-Nd AGE AND INITIAL ε_{Nd} OF LUNAR TROCTOLITE 76535: IMPLICATIONS FOR LUNAR CRUSTAL DEVELOPMENT.

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Introduction: Lunar troctolite 76535 is an old lunar rock predating the era of the lunar cataclysmic bombardment, but its radiometrially determined ages have been discordant [1-3]. The most recent multi-chronometer study [4] gave preferred ages of 4226±35 Ma and 4236±15 Ma from a ^{207}Pb/^{206}Pb isochron and an U-Pb upper concordia intercept, resp. We derive an age of 4323±64 Ma from Sm-Nd data reported by [4] for the bulk rock and three mineral separates. They derived an age of ~4.38 Ga from combined Rb-Sr data [3,4] by omitting data for olivine separates. ^{39}Ar-^{40}Ar ages of ~4.2 Ga are summarized by [5].

New ^{147}Sm-^{143}Nd data presented here give an age of 4335±71 Ma in agreement with the Sm-Nd age from [4], whereas ^{146}Sm-^{142}Nd data give a model age T_{LEW} = 4439±22 Ma. Further, initial ε^{143}Nd for 76535 conforms to the ^{143}Nd evolution expected in an urKREEP [6] reservoir, consistent with inheritance of urKREEP Sm-Nd systematics via assimilation. We show that urKREEP Sm-Nd systematics require the lunar initial ε^{143}Nd to exceed the Chondritic Uniform Reservoir (CHUR) value [7], but are consistent with evolution from initial ε^{143}Nd like that of the HED meteorite parent body as defined by a 4557±20 Ma internal isochron for the cumulate eucrites Y-980433 and Y- 980318 [8].

^{147}Sm-^{143}Nd isochron: Nine ^{147}Sm-^{144}Nd analyses determine an isochron corresponding to an age of 4335±71 Ma and ε^{143}Nd = 0.23±0.44 (Fig.1). Two data points lie sufficiently far from the fitted isochron to warrant their exclusion from the regression. With these exceptions, the data lie within ~1 ε-unit of the isochron. The MSWD = 22 and may represent response of the Sm-Nd system to post-crystallization events.

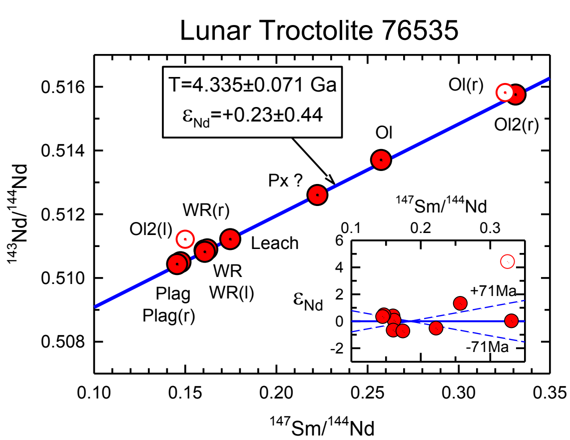

Figure 1. ^{147}Sm-^{143}Nd isochron for 76535.

^{146}Sm-^{142}Nd isochron: New ^{146}Sm-^{142}Nd data are shown in Fig. 2. Ten data points determine an isochron slope corresponding to initial ^{146}Sm/^{144}Sm (I(Sm)) = 0.0034±0.0005 with MSWD = 1.9. A model age T_{LEW} = 4439±22 Ma is calculated by reference to I(Sm) = 0.0076 [9] for the 4558 Ma angrite LEW 86010 [10] and a ^{146}Sm halflife of 103 Ma [11].

Crystallization Age: We suggest that the Sm-Nd chronometers most accurately give the crystallization age of 76535. We note that a "three-point" ^{207}Pb/^{206}Pb isochron age of 4343±72 Ma is derivable from the data of [4] by regressing their whole rock residue (WR) data with the data for both plagioclase separates PL-1 and PL-2 (*cf.* [4], Fig. 5), as corrected for the measured Pb blanks. Alternatively, ages of 4338±30 Ma for PL-1 plus PL-2 alone and 4226±35 Ma for WR, PL-1, and OL-P were reported by [4]. Considering the Pb data for WR plus both plagioclase samples may be more appropriate. Pb should be more compatible in plagioclase than in olivine or pyroxene, but the blank-corrected Pb concentration in Ol-P (40.1 ppb) exceeded that in PL-2, the reverse of expectation. Moreover, the percentage of Pb blank correction for Ol-P (3.7%) exceeded that for PL-2 (2.3%). Further, the blank correction for PL-2 was comparable to that for WR, and only ~2.3 times that for PL-1. Finally, lower blank-corrected Pb concentration for PL-2 (26.8 ppb) than for PL-1 (44.2 ppb) provides no rationale for further blank correction [4].

Significance of (T, ε_{Nd}) relationships: Fig. 3 compares (age(T), ε^{143}Nd) parameters for 76535 to other samples that are enriched in the urKREEP component. Data are from JSC (78236 [12], 72275 [13], 76535 [14]), and UCSD (15386 [15]). ^{143}Nd evolution in the urKREEP reservoir(s) is shown for μ =

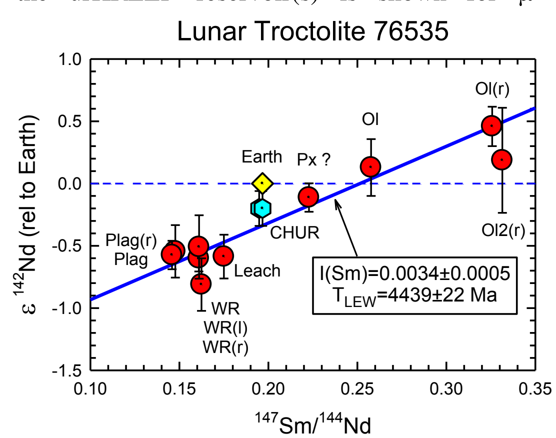

Figure 2. ^{146}Sm-^{142}Nd isochron for 76535.

$^{147}Sm/^{144}Nd$ = 0.172 (red line). The Apollo samples are either KREEP basalts or Mg-suite rocks. KREEPy mare basalt NWA 2977, probably derived from the Procellarum KREEP Terrane (PKT), extends the (T,ε^{143}Nd) correlation to ~3.1 Ga ago. That these diverse lunar rock types exhibit the same pre-magmatic, sub-chondritic, radiogenic ingrowth of ^{143}Nd in their source reservoirs is consistent with their assimilation of large proportions of their Nd from "semi-infinite" sources of urKREEP residua. The $^{147}Sm/^{144}Nd$ ratio in materials from the last ~5% crystallization of parent magma systems of bulk lunar composition is expected to show little variation (*e.g.,* [16]). In the case of a global Lunar Magma Ocean (LMO), the (T, ε^{143}Nd) correlation can be extrapolated to the time when the LMO had reached ~90-95% crystallization. For rapid LMO crystallization near the solar system age of ~4568 Ma, an initial lunar ε^{143}Nd = 1.1±0.2 is predicted, within the error limits of initial ε^{143}Nd for the paired cumulate eucrites Y-980433/318 (Y98) [8]. Hf-W systematics constraining crystallization of the LMO to 62(+90,-10) Ma after formation of the solar system [23] constrain ε^{143}Nd to the range +0.6 to +0.9ε.

Two-stage model for Nd-isotopic evolution: Fig. 4 models evolution of ε^{143}Nd and ε^{142}Nd in urKREEP source(s) from assumed initial values. For initial ε^{143}Nd like that in the Y98 cumulate eucrites, the modeled evolution prior to crystallization of 76535 gives μ = 0.159, nearly identical to measured μ = 0.161 post-crystallization. Similar μ-values of ~0.15-0.17 can account for evolution to ε^{142}Nd for 76535 for a non-chondritic, Earth-like initial ε^{142}Nd. These results illustrate the possibility of (a) early lunar formation, accompanied by early formation of LREE enriched urKREEP, and (b) measured $\varepsilon^{142,143}$Nd > CHUR for lunar highland rocks.

Implications: Although these Nd-isotopic results for troctolite 76535 are permissive of a "young", ~4.4 Ga moon with initial Nd isotopic composition near chondritic values, the lunar age must be greater than that of the oldest zircon, 4417±6 Ma [17]. Also, the young 4360±3 Ma age of 60025 [18] when viewed in combination with concordant Sm-Nd and Rb-Sr ages of 4.47±0.07 Ga for lunar anorthosite 67075 [19,20] and Sm-Nd data for bulk anorthosites suggests variability in the ages of lunar anorthosites. Key observations are: (a) urKREEP reservoirs were produced contemporaneously, or nearly so, in diverse lunar locations, (b) urKREEP-enriched Mg-suite rocks are contemporaneous, or nearly so, with lunar anorthosites. These observations can be explained by an initial LMO followed by post-magma-ocean genesis of lunar anorthosites [21] as well as of Mg-suite lunar highland rocks (*e.g.,* [22]).

References: [1] Bogard D. D. et al. (1975) *EPSL, 26,* 69-80. [2] Lugmair G. W. et al. (1976) *PLSC 7,* 2009-2033. [3] Papanastassiou D. A. and Wasserburg G. W. (1976) *PLSC 7,* 2035-2054. [4] Premo W. R. and Tatsumoto M. (1992) *PLSC 22,* 381-387. [5] Meyer C. Jr. (2012) *Lunar Sample Compendium (online).* [6] Warren P. H. and Wasson J. T. (1979) *Rev. Geophys. Space Physics 17,* 73-88. [7] Jacobsen S. B. and Wasserburg G. J. (1984) *EPSL 67,* 137-150. [8] Nyquist L. E. et al. (2011) *Antarct. Met. XXXIV,* 64-65. [9] Nyquist L. E. et al. (1994) *Meteoritics, 29,* 872-885. [10] Lugmair G. W. and Galer S. (1992) *GCA 56,* 1673-1694. [11] Friedman A. M. et al. (1966) *Radiochim. Acta 5*, 192-194. [12] Nyquist L. E. et al. (2008) *LPS XXXIX,* Abstract #1437, updated. [13] Shih C.-Y. et al (1992) *EPSL 10,* 203-215. [14] This study. [15] Carlson R. W. and Lugmair G. W. (1979) EPSL 45, 123-132. [16] Snyder G. A. et al (1992) *GCA 56,* 3809-3823. [17] Nemchin A. (2009) *Nature Geosci., 25,* 133-136. [18] Borg L. E. et al. (2011) *Nature 477,* 70-72. [19] Nyquist L. E. et al. (2010) *LPSC41, Abstract #1383.* [20] Nyquist L. E. et al. (2010) Global Lunar Conf., http://www.iafastro.net/download/congress/GLUC-2010/DVD/full/ [21] Longhi J. (2003) *JGR. Vol. 108, No E8,2.* [22] Elardo S. M. et al. (2011) *GCA 75,* 3024-3045. [23] Touboul M. et al. (2009) *Icarus 199,* 245-249.

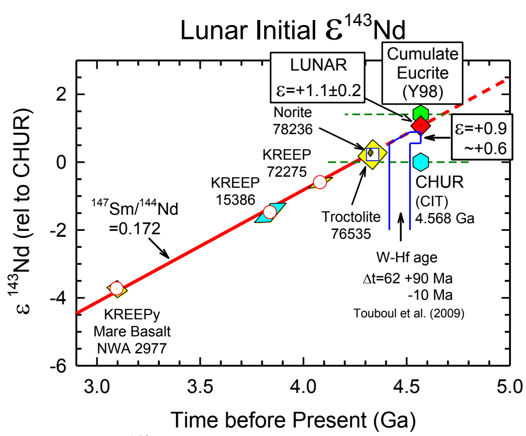

Figure 3. (T, ε^{143}Nd) for urKREEP-enriched samples including mare basalt NWA 2977.

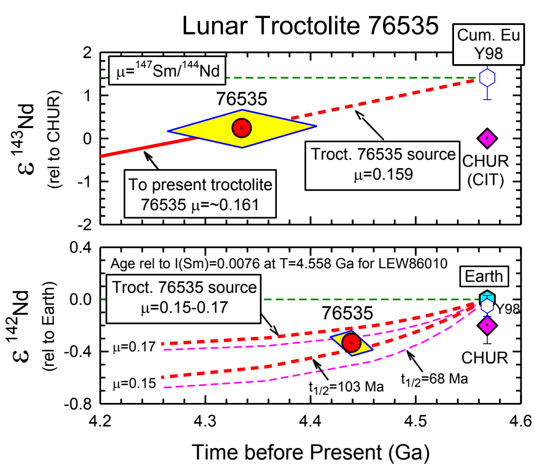

Figure 4. Hypothetical isotopic evolution for ^{143}Nd (top) and ^{142}Nd (bottom) in a simple two-stage model.