# REDETERMINATION OF THE Sm-Nd AGE AND INITIAL $\varepsilon_{Nd}$ 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 radiometrically 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 $\varepsilon^{143}$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 $\varepsilon^{143}$Nd to exceed the Chondritic Uniform Reservoir (CHUR) value [7], but are consistent with evolution from initial $\varepsilon^{143}$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 $\varepsilon^{143}$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.

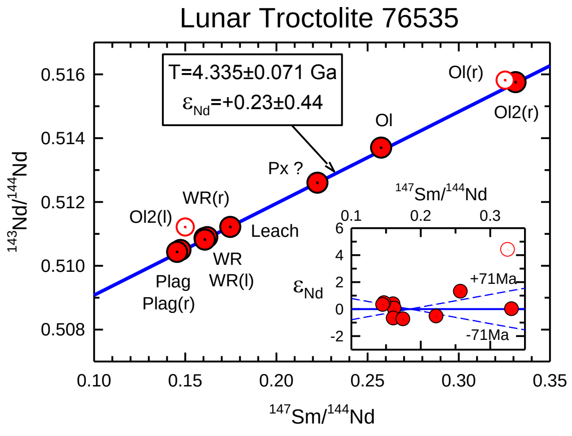

Figure 1. $^{147}$Sm-$^{143}$Nd isochron for 76535.

**$^{146}$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, $\varepsilon_{Nd}$) relationships:** Fig. 3 compares (age(T), $\varepsilon^{143}$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 =

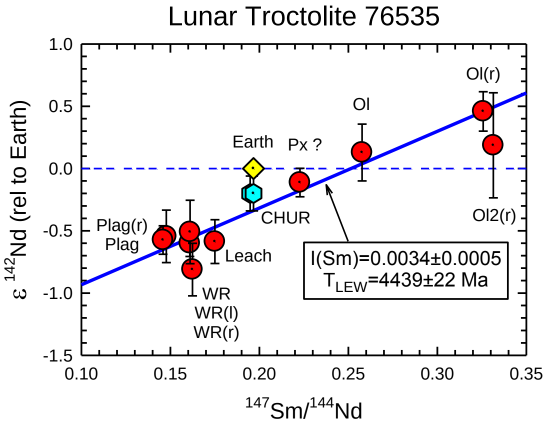

Figure 2. $^{146}$Sm-$^{142}$Nd isochron for 76535.

$^{147}$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,$\varepsilon^{143}$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, $\varepsilon^{143}$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 $\varepsilon^{143}$Nd = 1.1±0.2 is predicted, within the error limits of initial $\varepsilon^{143}$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 $\varepsilon^{143}$Nd to the range +0.6 to +0.9ε.

**Two-stage model for Nd-isotopic evolution:** Fig. 4 models evolution of $\varepsilon^{143}$Nd and $\varepsilon^{142}$Nd in urKREEP source(s) from assumed initial values. For initial $\varepsilon^{143}$Nd like that in the Y98 cumulate eucrites, the modeled evolution prior to crystallization of 76535 gives $\mu$ = 0.159, nearly identical to measured $\mu$ = 0.161 post-crystallization. Similar $\mu$-values of ~0.15-0.17 can account for evolution to $\varepsilon^{142}$Nd for 76535 for a non-chondritic, Earth-like initial $\varepsilon^{142}$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]).

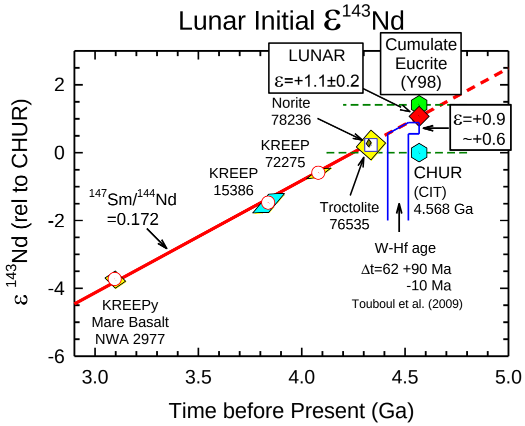

Figure 3. (T, $\varepsilon^{143}$Nd) for urKREEP-enriched samples including mare basalt NWA 2977.

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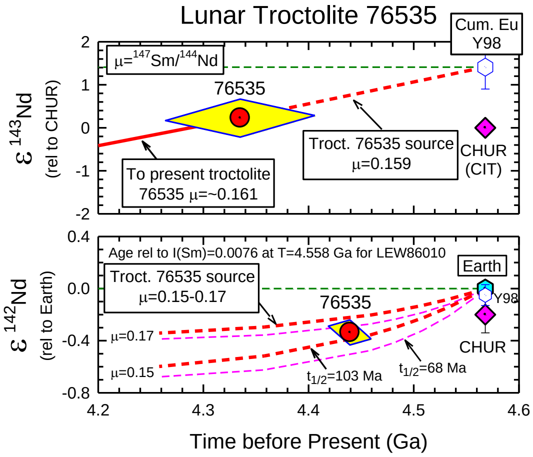

Figure 4. Hypothetical isotopic evolution for $^{143}$Nd (top) and $^{142}$Nd (bottom) in a simple two-stage model.