

ISOTOPE SYSTEMATICS OF MG-SUITE TROCTOLITE 14321,1847. A. M. Gaffney,¹ L. E. Borg¹, J. B. N. Wimpenny¹, C. K. Sio¹, W. S. Cassata¹, N. E. Marks¹, C. K. Shearer², M. L. Miller³, C. D. Hilton⁴. ¹Lawrence Livermore National Laboratory, Livermore, CA, ²Institute of Meteoritics, University of New Mexico, ³Earth & Environmental Sciences, University of Rochester, ⁴Department of Geology, University of Maryland.

Introduction: Recent investigations of the chronology and isotope systematics of ancient lunar highlands samples, together with a re-evaluation of chronological data for highlands samples produced over the nearly 50 years since the first lunar samples were returned with the Apollo missions, have led to the hypothesis that lunar differentiation may have occurred at a relatively young time in our Solar System's history [1, 2]. This hypothesis is based on isotopic analyses of Mg-suite samples, ferroan anorthosite suite (FAS) samples, KREEP-rich samples and mare basalts that highlight the isotopically complementary nature of these materials, and also suggest the contemporaneous formation of the highlands samples, urKREEP and the mare basalt sources from a common geochemical reservoir around 4.34 Ga. Samples from Apollo 14, which is located in a high-Th region of the Procellarum KREEP Terrane, are under-represented in these isotopic datasets. In an effort to incorporate the geographical and geochemical breadth represented at Apollo 14 in this chronological hypothesis for lunar differentiation, we have completed isotopic analyses of an Mg-suite troctolite clast from breccia 14321.

Sample and analytical methods: We received an approximately 1 g allocation of a troctolite clast from 14321. The sample, 14321,1847, corresponds to the anorthositic troctolite clast 14231c1 described by [3]. The sample was gently crushed in a sapphire mortar and pestle, and sieved to produce 100-200 mesh and 200-325 mesh grain size fractions. These were passed through a Frantz magnetic separator to obtain separates of different magnetic susceptibility. The magnetic separates were hand-picked under a binocular microscope to remove visible impurities. Each hand-picked mineral fraction was dissolved, and 1% of each mineral fraction solution was analyzed by HR-ICP-MS to determine the elemental compositions. The sample fractions were spiked with mixed Rb-Sr and Sm-Nd (99.998% ¹⁵⁰Nd) tracers and Sm, Nd, Rb and Sr were purified using our established methods [1,4]. Isotopic analyses were completed using the Triton TIMS at LLNL. The Sm isotopic composition was analyzed using an unspiked aliquot of the <325 mesh sample fraction in order to evaluate the effect of neutron irradiation, which was determined to be negligible. An aliquot of a hand-picked plagioclase fraction was analyzed for Ar-Ar chronometry. Individual plagioclase and olivine mineral grains were also analyzed by electron microprobe and LA-ICP-MS to characterize elemental compositions.

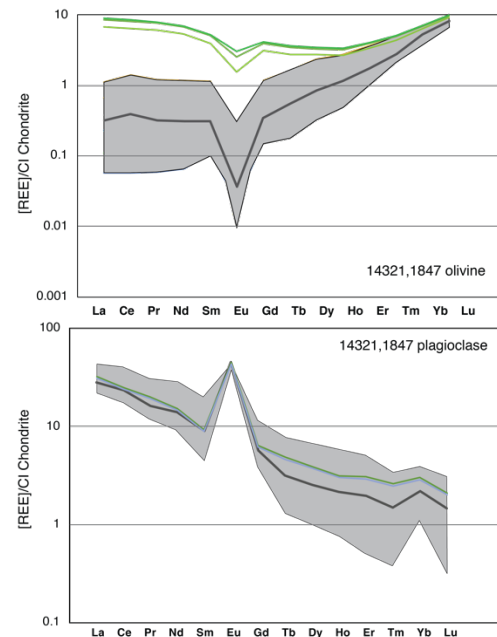


Figure 1. REE concentrations in olivine (top) and plagioclase (bottom) determined for bulk mineral separates (colored lines) and by LA-ICP-MS (bold gray lines and fields, representing averages and ranges, respectively, of in situ analyses).

Results and discussion: The chondrite-normalized REE patterns for the bulk whole rock fractions of 14321,1847 are generally similar to other Mg-suite samples [3, 5, 6]. The REE concentrations measured for the bulk mineral fractions by HR-ICP-MS show an anomalous pattern for the olivine fractions. Although the chondrite-normalized REE patterns illustrate the HREE enrichments typical for olivine, the olivine fractions are also enriched in LREE, which is atypical for magmatic partitioning of REE into olivine from a Mg-suite parental melt. The elemental data for the bulk mineral separates also show elevated P concentrations in the olivine mineral fractions, indicating that a trace component of a phosphate mineral is likely associated with the olivine fractions. This was confirmed through LA-ICP-MS analysis of individual mineral grains which show REE patterns in olivine that are typical of magmatic partitioning of REE into olivine (Fig. 1, upper). In contrast, the REE concentrations measured in the bulk plagioclase separates are essentially identical to the in situ plagioclase analyses by LA-ICP-MS (Fig. 1, lower); these REE patterns are also similar to those measured by SIMS in Apollo 14 norites [7]. These observations indicate that the plagioclase in 14321,1847 is relatively unaffected by the presence of trace phosphate minerals.

Because REE are strongly partitioned into phosphate minerals, and Rb is strongly excluded from phosphate minerals, this phosphate component affects dispersion of the mineral fraction data on the isochron diagrams (Figs. 2 and 3).

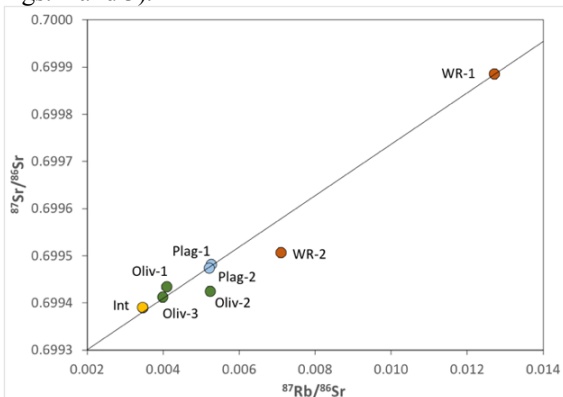


Figure 2. Rb-Sr isochron diagram for 14321,1847. Solid line is tie-line between Plag and WR-1 fractions, and corresponds to an age of 3784 ± 130 Ma.

The Rb-Sr systematics of plagioclase and WR-1 fractions are expected to be essentially unaffected by trace phosphate; a 2-point tie-line between these sample fractions yields an age of 3784 ± 130 Ma (Fig. 2). This is concordant with the Ar-Ar age of 3921 ± 42 Ma (MSWD = 5.3), and likely reflects an episode of re-equilibration during heating due to impact metamorphism.

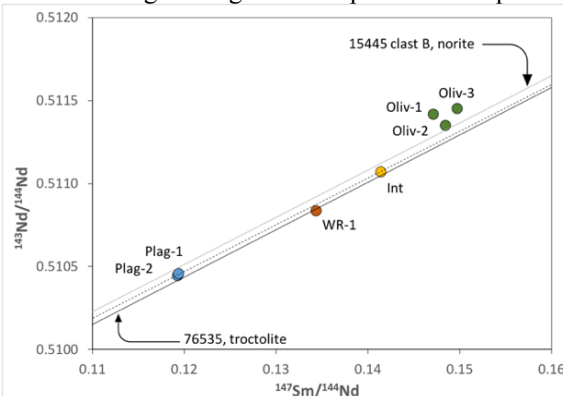


Figure 3. Sm-Nd isochron diagram for 14321,1847. Upper solid line is isochron for 15445,289 (4332 ± 79 Ma, data points not shown [8]). Lower solid line is isochron for 76535 (4307 ± 11 Ma, data points not shown [4]). Dashed line is tie-line between Plag and Int fractions, and corresponds to an age of 4246 ± 160 Ma.

The Sm-Nd isotopic data exhibit excess scatter and do not yield an isochron (Fig. 3). The WR-1 fraction lies on the extension of the isochron for troctolite 76535 and the plagioclase and intermediate fractions lie between the isochron extensions for 76535 and 15445 norite clast B, consistent with a common petrogenesis for these three Mg-suite samples. However, the plagioclase fractions have much lower $^{147}\text{Sm}/^{144}\text{Nd}$ than measured

for either of the other two samples, indicating that 14321,1847 crystallized from a more LREE-enriched parental magma. The observation that the olivine fractions, which have LREE contents dominated by trace phosphate minerals, are not co-linear with the plagioclase mineral fractions indicates that the phosphates are not cogenetic with the olivine and plagioclase phases. In other words, the phosphates are either a secondary phase or were isotopically altered after crystallization.

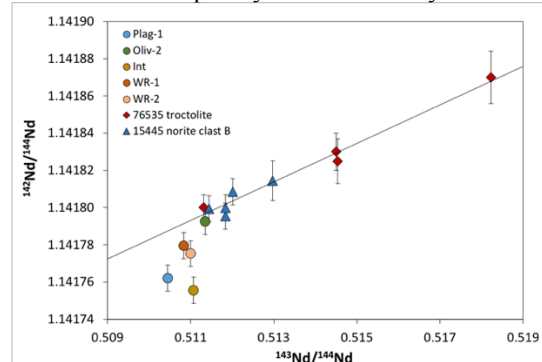


Figure 4. ^{142}Nd - ^{143}Nd variation among mineral separates for 14321,1847, 76535 [4] and 15445,289 [8]. Line represents regression through data for 76535 and 15445,289, and corresponds to an age of $4311 \pm 24/-29$ Ma.

The ^{142}Nd - ^{143}Nd variation among mineral separates of Mg-suite and FAS samples, as well as the sources of KREEP-rich samples and mare basalts, define a single linear array that is interpreted to represent their contemporaneous formation from a geographically widespread, chemically equilibrated magmatic source at $4337 \pm 20/-23$ Ma [8, 9, 10]. Figure 4 shows ^{142}Nd - ^{143}Nd variation among mineral separates from Mg-suite samples 14321,1847, 76535 and 15445 clast B. Although several of the fractions for 14321,1847 define a different linear array, the fact that these same data points do not define a linear array on the ^{147}Sm - ^{143}Nd isochron diagram indicates that the ^{142}Nd - ^{143}Nd array results from mixing rather than co-magmatic crystallization. The low $^{142}\text{Nd}/^{144}\text{Nd}$ value of the plagioclase fraction suggests that it was derived from an early-formed, incompatible element enriched reservoir that is not widely represented among lunar samples [e.g., 11].

References: [1] Gaffney & Borg (2014) *GCA* **140** 227-240; [2] Borg et al. (2014) *MAPS* doi: 10.1111/maps.12373; [3] Warren et al. (1981) *PLSC* **12B** 21-40; [4] Borg et al. (2017) *GCA* **201** 377-391; [5] Warren & Wasson (1980) *PLSC* **11** 431-470; [6] Shearer et al. (2015) *Am Min* **100** 294-325; [7] Papike et al. (1996) *GCA* **60** 3967-3978; [8] Gaffney et al. (2015) *LPSC* **46** abstr. #1443; [9] Gaffney & Borg (2014) *LPSC* **45** abstr. #1449; [10] Borg et al. (2018) *LPSC* **49** abstr. #2398; [11] Boyet et al. (2014) *GCA* **148** 203-218. This work performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.