Introduction: Recent dating of Mg-suite troctolite 76335 has shed more light on early lunar chronology. Troctolite 76335 has an age of 4278 ± 60 Ma and an initial $\varepsilon_{143}^{Nd}$ value of 0.06 ± 0.34 (Fig. 1). The relatively young age and near-Chondritic Uniform Reservoir (CHUR) initial $\varepsilon_{143}^{Nd}$ value of 76335 prevent it from lying within error of the trend defined by Mg-suite norites with negative $\varepsilon_{143}^{Nd}$ values relative to CHUR and younger KREEP samples [1,2]. There are three possible explanations for this unexpected result. The first reason is that the $^{147}$Sm-$^{143}$Nd isotopic systematics of troctolite 76335 have been disturbed and do not accurately reflect the true age and initial $\varepsilon_{143}^{Nd}$ value of this Mg-suite sample. The second is that the norites and troctolites are not isotopically related. The third involves the assumption that the bulk Nd isotopic composition of the Moon is equivalent to CHUR.

Discussion: The $^{147}$Sm-$^{143}$Nd isotopic systematics of lunar materials, specifically those of highland rocks, are often scrutinized because of the effects of impact-induced thermal metamorphism [e.g., 3]. In the case of troctolite 76353, the $^{87}$Rb-$^{85}$Sr age (4570 ± 70 Ma) [4] is much older than the $^{147}$Sm-$^{143}$Nd age (4260 ± 60 Ma) [5] and the Ar-Ar age (4260 ± 20 Ma) [6]. The Ar-Ar age, and by default the $^{147}$Sm-$^{143}$Nd age, is often considered the metamorphic age while the $^{87}$Rb-$^{85}$Sr age is thought to be the crystallization age, despite the fact that the $^{87}$Rb-$^{85}$Sr age of 76353 has yet to be reproduced [e.g., 7]. For 76335, the $^{147}$Sm-$^{143}$Nd isotopic systematics yielded a six-point isochron, while the $^{87}$Rb-$^{85}$Sr data held no determinable age significance. However, the 76335 $^{147}$Sm-$^{143}$Nd isochron may have experienced rotation in response to thermal disturbance (i.e., a younger age and higher initial $^{144}$Nd/$^{148}$Nd ratio will be produced as a rock undergoes isotopic resetting). If 76335 experienced isotopic resetting, the initial $^{144}$Nd/$^{148}$Nd ratio would decrease as the age of 76335 increased. To evaluate the potential disturbance to the $^{147}$Sm-$^{143}$Nd isochron, we assumed rotation about the whole rock and no loss of rare earth elements during the disturbance. Due to the sub-CHUR $^{147}$Sm-$^{143}$Nd ratio of the whole rock, the initial $\varepsilon_{143}^{Nd}$ value of 76335 actually increases relative to CHUR with greater age (Fig. 1). Thus, the difference between the $^{147}$Sm-$^{143}$Nd isotopic systematics of 76335 and the KREEP evolution line of [1,2] cannot be explained by simple isochron rotation.

Given the established petrologic relationships between the Mg-suite norites and troctolites, it is expected that their sources should be isotopically related. However, the calculated initial $\varepsilon_{143}^{Nd}$ value for the norites and troctolites differ. This may imply that KREEP in the troctolites formed in a later differentiation event. Conversely, the KREEP signature in the troctolites and norites may both define a single trend which does not have a CHUR-like bulk Moon starting composition.

Figure 1. Time versus initial $\varepsilon_{143}^{Nd}$ value calculated for the source of each highland and KREEP-rich sample relative to CHUR. FANs plotted in yellow, Mg-suite norites in red, Mg-suite troctolites in green, and younger samples with KREEP signatures in gray. The KREEP source trend (blue line) is defined by Mg-suite norites with negative $\varepsilon_{143}^{Nd}$ values and younger KREEP-rich samples 14321, 15386, and NWA 773 [1,2]. Dashed blue line is an extension of this KREEP evolution line. This shows that the KREEP line of [1,2] does not intersect the HED parent body isotopic composition at a reasonable age. The green dashed line represents the calculated age and initial $\varepsilon_{143}^{Nd}$ value of 76355 based on whole rock $^{143}$Sm-$^{144}$Nd isotopic data assuming that the isochron rotated due to a disturbance. Note that rotation of the 76355 isochron would not intersect the KREEP line of [1,2]. This implies that the KREEP signature in the troctolite is different than the norite trend. However, if one uses the HED initial Nd isotopic composition for the Moon [12], and establishes a trend for the Mg-suite troctolites and norites, a calculated evolution line equivalent to a $^{143}$Sm-$^{144}$Nd ratio of 0.165 ± 0.017 is produced. The calculated ratio is similar to that calculated for KREEP (0.163) from [14]. This indicates KREEP formation at 4518 ± 85 Ma.
The assumption that the bulk Nd isotopic composition of the Moon is equivalent to CHUR is problematic. First, multiple highland samples and ilmenite basalts indicate an originally positive $\varepsilon_{Nd}^{143}$ value for the bulk Moon [e.g., 8]. Data from multiple labs indicate that ferroan anorthosites (FANs) crystallized early with positive $\varepsilon_{Nd}^{143}$ values. Recent studies of meteorites and terrestrial samples show that the $\varepsilon_{Nd}^{142}$ values of meteorites are negative relative to CHUR [9,10]. The differences between the initial $\varepsilon_{Nd}^{143}$ value of CHUR and measured Precambrian terrestrial samples have also been investigated [11]. These samples show an apparent trend towards an initial $\varepsilon_{Nd}^{143}$ value of approximately +1 for the bulk Earth.

The fact that FANs have positive initial $\varepsilon_{Nd}^{143}$ values, as well as the uncertainties associated with using the CHUR Nd isotopic composition for the bulk Earth, allows the possibility of using a different initial Nd isotopic composition for the bulk Moon. In this case, we used the estimated bulk Moon Nd isotopic composition equivalent to that measured for the howardite-eucrite-diogenite (HED) parent body by [12] and proposed by [13]. A new KREEP evolution line was drawn using a linear regression of the Mg-suite samples (both norites and troctolites) with both positive and negative $\varepsilon_{Nd}^{143}$ values. This line has a $^{147}$Sm/$^{144}$Nd ratio of 0.165 ± 0.017, almost identical to that calculated for the KREEP composition proposed by [14]. This new evolution line intersects the HED parent body isotopic composition at 4518 ± 85 Ma, indicating the time of KREEP formation.

**Implications:** One benefit to using an HED initial Nd isotopic composition for the bulk Moon is that the $^{147}$Sm-$^{144}$Nd isotopic systematics of the majority of the Apollo 16 FANs may now be explained by a lunar magma ocean model. The FANs may now also have a LREE-enriched source region, which is implied by their geochemistry. This indicates that 62236 is the only truly disturbed FAN measured to date. The new HED initial Nd isotopic composition accounts for the relatively old age and positive $\varepsilon_{Nd}^{143}$ value of Mg-suite norite 15445 [17]. In addition, the age determined for KREEP formation is concordant with the $^{176}$Lu-$^{176}$Hf isotopic systematics of lunar zircons [15].

There are a few disadvantages to using an HED initial Nd isotopic composition for the bulk Moon. For example, if the KREEP $^{147}$Sm-$^{143}$Nd isotopic signature is uniform throughout the Mg-suite, this implies that any differences in the source region lithology that could have been reflected in the REE signature of the rocks is erased by the interaction with KREEP. In addition, the relationship shown between the Mg-suite norites and the younger KREEP-rich rocks in the KREEP line of [1,2] is not reinforced by this model. In fact, the new KREEP source evolution line ($^{147}$Sm/$^{144}$Nd = 0.165 ± 0.017 in Fig. 1) does overlap the KREEP-rich samples 14321 and 15386, but does not overlap olivine cumulate NWA 773. This implies that the Mg-suite and other KREEP-rich rocks do not share the same evolutionary history. The new KREEP line is also not as constrained as the KREEP source evolution line proposed by [1,2].

**Conclusions:** The isotopic study of Mg-suite troctolite 76335 confirmed the CHUR-like initial $\varepsilon_{Nd}^{143}$ value of troctolite 76355 [5]. This implies that (1) both troctolites 76335 and 76535 are disturbed, (2) KREEP in the troctolites differentiated later than for norites from a CHUR-like Moon, or (3) the assumption that the Moon has a CHUR initial Nd isotopic composition is in error. Rotation of the $^{147}$Sm-$^{144}$Nd isochron for 76335 about the whole rock will not explain the differences between the isotopic compositions of the Mg-suite troctolites and norites. There is no geochemical evidence that the KREEP component found in troctolites is different from the KREEP component in norites. An initial Nd isotopic composition of the Moon equal to that of the HED parent body appears to be more likely than an initial bulk Moon composition equal to CHUR. A new KREEP evolution line can be drawn through the Mg-suite norites and troctolites with a slope equal to a $^{147}$Sm/$^{144}$Nd ratio of 0.165 ± 0.017. This new evolution line corresponds to a KREEP reservoir formation age of 4518 ± 85 Ma, and explains the positive initial $\varepsilon_{Nd}^{143}$ values of most FANs and norite 15445 [17].

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**References:**