



# Enstatite chondrites EL3 as building blocks for the Earth: the debate 1 over the $^{146}\text{Sm}$ - $^{142}\text{Nd}$ systematics

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**Enstatite chondrites EL3 as building blocks for the Earth: the debate  
over the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics**

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building blocks

**Abstract**

The  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  extinct decay scheme ( $^{146}\text{Sm}$  half-life of 103 My) is a powerful tool to trace early Earth silicate differentiation. Differences in  $^{142}\text{Nd}$  abundance measured between different chondrite meteorite groups and the modern Earth challenges the interpretation of the  $^{142}\text{Nd}$  isotopic variations found in terrestrial samples because the origin of the Earth and the nature of its building blocks is still an ongoing debate. As bulk meteorites, the enstatite chondrites (EC) have isotope signatures that are the closest to the Earth value with an average small deficit of  $\sim 10$  ppm in  $^{142}\text{Nd}$  relative to modern terrestrial samples. Here we review all the Nd isotope data measured on EC so far, and present the first measurements on an observed meteorite fall Almahata

Sitta containing pristine fragments of an unmetamorphosed enstatite chondrite belonging to the EL3 subgroup. Once  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios are normalized to a common chondritic evolution, samples from the EC group (both EL and EH) have a deficit in  $^{142}\text{Nd}$  but the dispersion is important ( $\mu^{142}\text{Nd} = -10 \pm 12$  (2SD) ppm). This scatter reflects their unique mineralogy associated to their formation in reduced conditions (low  $f\text{O}_2$  or high C/O). Rare-earth elements are mainly carried by the sulfide phase oldhamite (CaS) that is more easily altered than silicates by weathering since most of the EC meteorites are desert finds. The EL6 have fractionated rare-earth element patterns with depletion in the most incompatible elements. Deviations in Nd mass independent stable isotope ratios in enstatite chondrites relative to terrestrial standard are not resolved with the level of analytical precision achieved by modern mass spectrometry techniques. Here we show that enstatite chondrites from the EL3 and EL6 subgroups may come from different parent bodies. Samples from the EL3 subgroup have Nd ( $\mu^{142}\text{Nd} = -0.8 \pm 7.0$ , 2SD) and Ru isotope ratios undistinguishable from that of the Bulk Silicate Earth. EL3 samples have never been analyzed for Mo isotopes. Because these enstatite chondrites are relatively small in size and number, they are usually not available for destructive isotopic measurements. Average values based on the measurement of EL6 samples should not be considered as representative of the whole EL group because of melting and thermal metamorphism events affecting the Sm/Nd ratios and prolonged open-system history. The EL3 chondrites are the best candidates as the Earth's building blocks. These new results remove the need to change the composition of refractory incompatible elements early in Earth's history.

## 1. Introduction

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52       Variations in mass independent stable isotope ratios, also called nucleosynthetic  
53 anomalies, of refractory elements have become extremely useful to trace the origin of  
54 the different planetary bodies and their relative contribution into the building process  
55 of terrestrial planets (e.g., Warren, 2011). Enstatite chondrites appear to be the closest  
56 in isotope composition to terrestrial samples and carbonaceous chondrites the furthest.  
57 Enstatite chondrites and the Earth are undistinguishable for many isotope systems, i.e.  
58 Cr, Ti, O, Ni (see Dauphas, 2017 for a recent review), meaning that with the current  
59 level of precision no resolvable difference is observed between both materials. A  
60 small difference in Si isotopes does exist and this has been used against the Enstatite  
61 Chondrite Earth model (Fitoussi and Bourdon, 2012) but Si isotopes may have been  
62 fractionated during nebular processes and their isotope ratios may not faithfully  
63 reflect the initial composition of the starting material (Savage and Moynier, 2013;  
64 Zambardi et al., 2013; Dauphas et al., 2015). The only resolvable differences between  
65 enstatite chondrites and the Earth were reported for Mo and Ru isotope compositions  
66 (Burkhardt et al., 2011; Fischer-Gödde and Kleine 2017). The enrichment in s-process  
67 Mo for the Earth relative to chondrites suggests that the composition of the Earth  
68 cannot be reconstructed by any known combination of meteorites because it is itself  
69 an end-member in the mixing trend (Burkhardt et al., 2011). The initial composition  
70 of the Earth has become an issue for the use and interpretation of the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$   
71 short-lived isotopic systematic in meteorites and Earth rocks. An early fractionation  
72 of the Sm/Nd ratio during the lifetime of  $^{146}\text{Sm}$  ( $T_{1/2}=103$  Ma) would modify the  
73  $^{142}\text{Nd}/^{144}\text{Nd}$  signatures by radiogenic production. In 2005, the first high-precision  
74  $^{142}\text{Nd}$  measurements in chondrites revealed a difference of about 20 ppm with the  
75 modern terrestrial samples (Boyet and Carlson, 2005). Because both Sm and Nd are

lithophile elements under terrestrial redox conditions (Bouhifd et al., 2015), a differentiation event of the silicate Earth in the first 30 Ma of Solar System history has been proposed to explain this offset. One type of model considers that the bulk Silicate Earth (BSE) preserves a relative chondritic abundance of refractory lithophile elements. The early-depleted mantle reservoir (high Sm/Nd) served as the source for magmatism since its formation whereas the enriched reservoir remains isolated from mantle convection and is still untapped (Boyet and Carlson, 2005). Other scenarios proposed that the complementary enriched reservoir (low Sm/Nd) has been lost to space by collisional erosion of planetesimals (Caro et al., 2008; O'Neill and Palme, 2008) leaving the Bulk Earth depleted in incompatible elements and with a higher Sm/Nd ratio relative to the well-constrained average composition of whole-rock chondrites from the carbonaceous (CC), ordinary (OC) and enstatite (EC) chondrite groups (Bouvier et al., 2008).

These models have been challenged by the discovery of variations in mass independent stable Sm and Nd isotope ratios in whole-rock chondrites and their components (Andreasen and Sharma, 2006; Carlson et al., 2007; Gannoun et al., 2011; Brennecka et al., 2013, Bouvier and Boyet, 2016; Burkhardt et al., 2016). The isotope  $^{142}\text{Nd}$  is mainly produced by *s-process* but has a small contribution of *p-process*, estimated to be lower than a few percent (Arlandini et al., 1999; Bisterzo et al., 2011). The parent isotope,  $^{146}\text{Sm}$  is a pure *p-process* nuclide so any variation in the *p* production would affect the abundance of its daughter isotope  $^{142}\text{Nd}$  as well. Although we have undisputable evidences for different contribution of *s-process* isotopes in Solar System materials and measurable variations in the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios, the origin of the terrestrial  $^{142}\text{Nd}$  signature compared to the chondrite

meteorites is still unclear. The isotope signature of some ocean island basalts is difficult to interpret without an early event that would fractionate the Sm/Nd ratio of the bulk silicate Earth very early on in its history (Jackson et al., 2010). Here we re-evaluate the small isotopic variations measured in enstatite chondrites. Such meteorites were formed under reducing conditions and have a particular mineral assemblage. Importantly for interpreting their Sm-Nd systematics, half of the rare earth element (REE) budget is hosted in oldhamite (CaS), which is easily altered to Ca-sulphate by weathering (Croizat and Lundberg, 1995; Gannoun et al., 2011).

We have compiled all the Nd isotope data published on EC so far. We also present the first measurements on an observed fall Almahata Sitta containing fragments of the EL3 subgroup, such as the fragment MS-177. The fireball of Almahata Sitta fall was captured on camera in northern Sudan on October 7<sup>th</sup> 2008. Its trajectory was back-tracked to a small asteroid called 2008 TC<sub>3</sub> (Bischoff et al., 2010). Additionally, REE concentration measurements are presented for samples belonging to the two subgroups of enstatite chondrites (EH and EL). Since the identification of <sup>142</sup>Nd variations attributed to nucleosynthetic anomalies requires a comparison at the same Sm/Nd evolution, we present in detail two methods of calculations used for normalization of all chondrites to a common Sm/Nd and the difficulties inherent to the enstatite chondrite sub-groups. The <sup>142</sup>Nd/<sup>144</sup>Nd ratios are then compared to the corresponding mass independent stable Nd isotope ratios for each meteorite to establish their significance with respect to the distribution of nucleosynthetic anomalies amongst the chondrite groups. Finally, their potential contributions as Earth's building blocks are discussed.

## 2. Samples and Methods

### 2.1. Trace element contents in EC

Rare earth element concentrations have been measured for 12 EC from EH (4) and EL (8) sub-groups. The meteorite names and sample subgroups are reported in Table 1. Two techniques of dissolution have been used: 1) samples were digested in PFA Savillex® beakers using a mixture of concentrated HF-HNO<sub>3</sub> acids in 3:1 proportion at 120°C on hot plate during 48h; 2) samples were digested in individual Parr® pressure vessels in concentrated HF-HNO<sub>3</sub> (10:1) for 5 days at 155°C. In both cases, after drying down the samples, perchloric acid was added and evaporated on a hot plate to break down the fluorides. After successive dissolution/evaporation cycles in concentrated HNO<sub>3</sub>, samples were taken back into solution in PFA Savillex® beakers or in Parr® pressure vessels in 6M HCl. All measurements were performed using the Agilent 7500 quadrupole ICP-MS at the Laboratoire Magmas et Volcans (LMV) in Clermont-Ferrand, with the exception of Almahata Sitta MS-177 and Hvittis that were measured at the University Western Ontario using a Thermo iCAP Qc quadrupole ICP-MS. Both ICP-MS are equipped with He collision cells. Samples were measured in HNO<sub>3</sub> 0.5M- HF 0.05 M and HNO<sub>3</sub> 0.3M- HF 0.01 M in the two laboratories, respectively. Counts per second were calibrated using rock standards BCR-2, BHVO-2 or BIR 1a. The rock standards and a synthetic standard solution (CMS) were routinely analyzed to validate the efficiency of the digestion procedures and the accuracy and precision of the acquired data. Blank and standard solutions were measured every 4 samples. Both the external reproducibility estimated from

repeated measurements of the standards and the accuracy checked from certified rock standard analyses are lower than 5%.

## **2.2. $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ systematics and mass independent stable Nd isotopes**

Here we report new results for MS-177 (Table 2). After the Parr bomb digestion of the samples at the University of Western Ontario, following the methods detailed in Bouvier and Boyet (2016), an aliquot of about ~80% was used for isotopic composition, ~10% fraction was spiked with an enriched  $^{149}\text{Sm}$ - $^{150}\text{Nd}$  mixed spike to determine precisely the Sm/Nd ratios by isotopic dilution, and another 10% aliquot was used to determine Q-ICPMS REE concentrations. The Sm and Nd of the spiked fractions were purified and separated using a two-stage chemistry procedure (cationic AG50W-X8 and Ln-spec resins). This procedure was also used for a BCR-2 USGS basalt standard (aliquot of 1.1 mg) to ensure accuracy and reproducibility of our spiked and unspiked measurements. Both spiked Sm and Nd isotopic fractions were analyzed using a MC-ICPMS Neptune Plus at LMV.

The separation procedure for the Nd isotopic composition required 3 steps as described in Garçon et al. (2018). The Ce was separated from other trivalent REE using the oxidation of Ce to  $\text{Ce}^{4+}$  on Ln-Spec resin (Tazoe et al., 2007; Li et al., 2015). Then the separation between Nd and Sm was achieved on Ln-Spec resin using 0.20N to 0.25N HCl. Total procedural blanks are generally lower than a few tens of pg for Nd. The Nd isotopic compositions were measured as  $\text{Nd}^+$  using the LMV Triton Plus™ Multicollector Thermal Ionization Mass Spectrometer. For MS-177, Nd



isotope ratios were obtained in static mode following the method described in Gannoun et al. (2011a). Static measurements were preferred because the amount of Nd was small (~300 ng for MS-177) and dynamic routines require large sample size (e.g. 750 ng for the 4-line acquisition scheme developed by Garçon et al., 2018). In addition, we used a mass spectrometer equipped with new faraday collectors (6 month-old). No sign of deterioration of the faraday collectors was identified during the measurements. Ce and Sm contributions, monitored at masses 140 and 147 respectively, were lower than 3 ppm on masses 142 and 144 for both standard and sample measurements. Nd isotope ratios were corrected for mass fractionation to  $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$  using the exponential mass-fractionation law. The external reproducibility (2SD) calculated from 6 repeated measurements of the JNdi-1 standard is 5.6 ppm on  $^{142}\text{Nd}/^{144}\text{Nd}$ , 7.4 ppm on  $^{143}\text{Nd}/^{144}\text{Nd}$ , 4.4 ppm on  $^{145}\text{Nd}/^{144}\text{Nd}$ , 8.2 ppm on  $^{148}\text{Nd}/^{144}\text{Nd}$ , and 10.9 ppm on  $^{150}\text{Nd}/^{144}\text{Nd}$  (Table 2).

### 3. Results

The new REE data are reported in Table 1 and compared to published values from Gannoun et al. (2011b) and Barrat et al. (2014) in Figure 1. Data from Kalleyman and Wasson (1986) is not shown in Figure 1 because they reported the concentrations of only 5 REEs (La, Sm, Eu, Yb, and Lu), which is insufficient to define proper REE patterns. All EH samples have flat REE patterns with concentrations very similar to those reported in CI, except Kota Kota (EH3) that is enriched in LREE (Figure 1A). This split is the most visibly weathered in color and texture of our collection, and the meteorite was described as a strongly weathered EC by Leitch and Smith (1982). The measured sub-chondritic  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of Kota

200 Kota suggests that this sample has a complex history with several episodes of  
 201 fractionation of the Sm/Nd ratio (Gannoun et al., 2011b). Two EH samples display  
 202 unusual REE patterns: Galim (b) and LAP 0225 (Figure 1A, data from Barrat et al.  
 203 2014). They are classified as impact melt (IM) and their REE patterns are in  
 204 agreement with the petrological description of the samples (Michel-Lévy and Bourot-  
 205 Denise, 1988; Russel et al., 2004). EL samples present more variable REE  
 206 distributions. Most of EL3 samples display flat REE patterns with concentrations  
 207 ranging between 0.6 to 2 times the CI values. MAC 88180 is more enriched in REE  
 208 ( $\times 2$  CI) and has a negative Eu anomaly ( $\text{Eu}/\text{Eu}^* = \text{Eu}_{\text{CI}} / (\text{Sm}_{\text{CI}}^{1/2} \times \text{Gd}_{\text{CI}}^{1/2})$ ) of 0.7 (Figure  
 209 1C). Similar REE patterns have been obtained following the two dissolution  
 210 techniques. Almahata Sitta MS-177, which is the most depleted EL3 sample, has a  
 211 positive Eu anomaly of 1.5. The REE pattern for MS-177 is more similar to Adrar  
 212 Bous (EL5) with lower REE contents and large positive Eu anomalies ( $\text{Eu}/\text{Eu}^* = 1.3$ ).  
 213 EET 92063 has a REE pattern with similar characteristics but REE contents are even  
 214 lower and the Eu positive anomaly is higher (Figure 1D). This sample is described as  
 215 highly weathered and classified in an anomalous EL6 group by Barrat et al. (2014).  
 216 By contrast, all other EL6 samples display negative Eu anomalies and are called  
 217 “normal EL6” by the same authors. EL6 samples are all depleted in LREE relative to  
 218 HREE ( $(\text{La}/\text{Lu})_{\text{N}}$ ) up to 0.62. Chemical heterogeneities are observed within the same  
 219 sample. For example Hvittis has been measured 4 times and  $\text{Eu}/\text{Eu}^*$  varies from 0.8  
 220 to 1.0 depending on the split analyzed. Petrological observations show that all these  
 221 samples are strongly heterogeneous at millimeter to centimeter scale. Rare earth  
 222 element distribution in the different EC subgroups is presented in Figure 2. This time,  
 223 the database for REE in enstatite chondrites from Kallemeyn and Wasson (1986) is  
 224 included. All subgroups have similar Yb concentrations but different  $(\text{La}/\text{Sm})_{\text{N}}$  ratios.

Strong depletions in incompatible elements, hence low La/Sm ratios, are measured in EL6 samples and the two samples characterized by an unusual mineralogical assemblage (Galim (b) and LAP 0225). Then EL6 samples are clearly different from other EL samples. We note that the La/Sm ratios in EH are more variable and in average higher than those measured in EL3-5 samples.

Measured Nd isotope ratios for MS-177 are expressed in ppm deviation relative to the reference JNdi-1 standard ( $\mu$ -value) in Table 2 and all details on measurements (isotope ratios, intensity, interferences, etc) are available in Supplementary information (Table S2). This sample presents a small deficit of -11 ppm in  $^{142}\text{Nd}/^{144}\text{Nd}$  whereas all stable isotope ratios are identical within errors to the JNdi-1 standard values. The  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios calculated using the isotope dilution method are  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1381$  for the BCR-2 standard and 0.1897 for MS-177. Our repeated spiked Sm-Nd measurements of BCR-2 standard at LMV give an average of  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1381 \pm 0.0003$  (2SD,  $n=4$ ), thus a precision of 0.2%. This value is within literature values which range from  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1357$  to 0.1396 and identical within errors with the most recent determination by ID TIMS at  $0.1379 \pm 0.0002$  (2SD; Li et al., 2012 and references therein). The initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio for MS-177 calculated at 4.568 Ga is  $\epsilon^{143}\text{Nd} = +0.06 \pm 0.25$  when normalized to the initial for the Solar System composition using the chondrite average (CHUR)  $^{147}\text{Sm}/^{144}\text{Nd}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio values (Bouvier et al., 2008).

## **4. Discussion**

### **4.1. $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ systematics in enstatite chondrites**

250       The purpose of this paper is to take a more rigorous look at enstatite  
251 chondrites and their genetic relationship to the Earth. To compare the compositions of  
252 enstatite chondrites to other chondrite groups, we compiled all Nd data published on  
253 chondrites from this group so far, as well as new data. This compilation is provided in  
254 supplementary materials. Available data comes from 7 different publications: Boyet  
255 and Carlson (2005); Rankenburg et al. (2006); Carlson et al. (2007); Gannoun et al.  
256 (2011); Bouvier and Boyet (2016); Burkhardt et al. (2016); and Fukai and Yokohama  
257 (2017). For the studies using La Jolla Nd standard for the calculation of deviation in  
258 ppm relative to the terrestrial value ( $\mu\text{Nd}$ ), the data were recalculated relative to the  
259 JNdi-1 terrestrial standard. The two synthetic standards La Jolla and AMES record  
260 significant mass-dependent variability and then cannot be used as a reference either  
261 for the BSE or the modern mantle (O'Neil et al., 2008; Gautam et al., 2017; Saji et al.,  
262 2016). All the measurements have been obtained on large-size samples (1-2 g). The  
263 Nd isotope compositions obtained for the Allende CV3 chondrite using different  
264 methods of digestion (table-top acid-digested, Parr bomb acid-digested and alkali-  
265 fused acid-digested samples) are similar (Boyet and Carlson, 2005; Carlson et al.,  
266 2007). The complete digestion of refractory components may be an issue for some  
267 elements but not for Nd. Presolar SiC grains are a primary carrier of large Ba isotope  
268 anomalies and the destruction of these grains during the digestion is required  
269 (Bermingham et al., 2016). When measuring the Nd isotope composition of extra-  
270 terrestrial materials, an additional consideration is to take into account the potential  
271 neutron capture effects due to the interaction of materials with galactic cosmic rays.  
272 However previous studies have measured very small deviations in the  $^{149}\text{Sm}$   
273 abundance of chondrites which is one of the Sm isotopes having the largest thermal  
274 neutron capture cross section. This suggests that chondrites have not been

significantly affected by neutron fluence effects and that the correction on  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios is negligible or within the measurement precision (e.g. Boyet and Carlson, 2005; Bouvier and Boyet, 2016). McCoy-West et al. (2017) have determined the mass-dependent stable Nd isotope composition using a double spike technique. Chondrites and terrestrial samples have identical isotopic compositions with  $\delta^{146}\text{Nd}/^{144}\text{Nd} = -0.025 \pm 0.025\text{‰}$  (2SD; n=39) and  $\delta^{146}\text{Nd}/^{144}\text{Nd} = -0.022 \pm 0.034\text{‰}$  (2SD; n=30) respectively. These results imply that no bias is produced by the correction of instrumental mass fractionation effects when processing the raw data.

The first high-precision  $^{142}\text{Nd}$  measurements on chondrites have shown that differences in  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios existed among chondrite groups and that these variations were not correlated with changes of Sm/Nd ratios (Boyet and Carlson 2005). The new compilation combining all data measured on chondrites since 2005 leads to the same conclusion. The different groups of chondrites have different measured  $^{142}\text{Nd}/^{144}\text{Nd}$  values (Figure 3A). We note that results obtained from different chondrite fragments which were processed in different labs using different analytical techniques are in good agreement. On average carbonaceous chondrites (CC) have a  $\mu^{142}\text{Nd}$  of  $-31 \pm 20$  (2SD) ppm, ordinary chondrites (OC) of  $-16 \pm 9$  (2SD) ppm and EC of  $-12 \pm 21$  (2SD) ppm. Although standard deviations overlap, two sample t-tests strongly suggest that the three populations of chondrites are distinct from each other with p-values lower than 0.05 (p-value CC-OC =  $1.5 \times 10^{-8}$ ; p-value CC-EC =  $8.9 \times 10^{-10}$ ; p-value OC-EC = 0.004). Five samples have  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios far from the CHUR value of 0.1960 (dashed line in Figure 4A and 4B; Bouvier et al., 2008): NWA 2090 (CO3) and Tagish Lake (C2-ungrouped, not represented in the figure:  $^{147}\text{Sm}/^{144}\text{Nd}=0.148$ ) for CC, Adrian (H4) for OC (not represented in the figure:

<sup>147</sup>Sm/<sup>144</sup>Nd=0.137), and Kota Kota and Blithfield for EC. Moreover one EC sample displays an extreme  $\mu^{142}\text{Nd}$  value and this measurement has a large error bar (Abee:  $-44 \pm 17$  (2SE) ppm (Boyet and Carlson 2005). When all these samples are excluded from the averaging calculation, CC have a  $\mu^{142}\text{Nd}$  of  $-33 \pm 16$  (2SD) ppm, OC of  $-16 \pm 9$  (2SD) ppm and EC of  $-11 \pm 12$  (2SD) ppm. All these groups have similar measured Sm/Nd ratios even if a larger range is observed for EC (Figure 4A, B). When the same samples are selected, the mean <sup>147</sup>Sm/<sup>144</sup>Nd ratios of each group is  $0.1959 \pm 0.0046$  (2SD) for CC,  $0.1946 \pm 0.0033$  (2SD) for OC and  $0.1950 \pm 0.0084$  (2SD) for EC. The median values are equal to 0.1953, 0.1951 and 0.1952 for these 3 groups, respectively. CC and OC have normal distributions whereas EC present a larger scatter. These values are slightly lower than the CHUR value of  $0.1960 \pm 0.0004$  (2SD) defined from the average of unequilibrated chondrites (Bouvier et al., 2008) but are similar within uncertainties. Two sample t-tests further confirm that the mean <sup>147</sup>Sm/<sup>144</sup>Nd ratios of the three populations are undistinguishable from each other since p-values are much higher than 0.05 (p-value CC-OC = 0.9; p-value CC-EC = 0.3; p-value OC-EC = 0.3).

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The measured abundance of <sup>142</sup>Nd comes from two distinct contributions: its initial abundance and the quantity produced with time by the decay of <sup>146</sup>Sm. Since <sup>146</sup>Sm was alive only during the first 500 Ma of Solar System history, we can write the following equations:

$$^{142}\text{Nd}_{\text{meas}} = ^{142}\text{Nd}_{T0} + ^{146}\text{Sm}_{T0} \quad (1)$$

$$(^{142}\text{Nd}/^{144}\text{Nd})_{\text{meas}} = (^{142}\text{Nd}/^{144}\text{Nd})_{T0} + (^{146}\text{Sm}/^{144}\text{Nd})_{T0} \quad (2)$$

where  $_{meas}$  denotes the abundance or isotopic composition measured today in chondrites and  $_{T0}$  the initial abundance or isotopic composition at the time of formation.

These equations show that any fractionation of the Sm/Nd ratio during the  $^{146}\text{Sm}$  lifetime will significantly affect the measured  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios. In order to compare initial  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios between chondrites, the data are thus corrected from the  $^{142}\text{Nd}$  radiogenic production since the formation of the Solar System and normalized to a common chondritic evolution following the CHUR parameters defined by Bouvier et al. (2008). Two different methods of calculation can be used assuming a modification of the Sm/Nd ratio either early in the Solar system history or once the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics is extinct.

#### **Method A. $^{142}\text{Nd}/^{144}\text{Nd}$ corrected using measured $^{147}\text{Sm}/^{144}\text{Nd}$ ratios**

This correction is illustrated in Figure 5A. The  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio of the sample is calculated back in time to the age of the Solar System formation, *i.e.* 4.568 Ga (Bouvier and Wadhwa, 2010) using the *measured*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio. From this initial  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio, a modern value is recalculated using the CHUR  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of 0.1960 (Bouvier et al., 2008). Such a correction assumes that the modification of the Sm/Nd ratio occurred at the beginning of Solar System history *i.e.* when the chondrites form.

#### **Method B. $^{142}\text{Nd}/^{144}\text{Nd}$ corrected using measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios**

This correction, illustrated in Figure 5B, does not consider the *measured*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio but instead the *integrated*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio calculated from the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  long-lived radiogenic systematics. Since recent changes of Sm/Nd ratios, for example

due to weathering, are not recorded in the evolution of  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio is deduced from the measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios considering that all samples evolved from the same initial  $^{143}\text{Nd}/^{144}\text{Nd}$  value of 0.506686 which corresponds to the composition of the CHUR at 4.568 Ga (Bouvier et al., 2008). Then, the normalized-CHUR  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio is calculated following the steps described in Method A using the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of the CHUR from 4.568 Ga to present-day.

To evaluate the influence of the chosen method on the CHUR-normalized  $\mu^{142}\text{Nd}$  values, we re-corrected all published  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios with the two methods and compared the results in Figure 3B and C. Note that the Sm/Nd ratios of OC and CC from Fukai and Yokoyama (2017) were measured by quadrupole ICPMS and are thus reported with a much lower precision (1-1.5%) than that typically obtained (about 0.2%) by isotope dilution with MC-ICPMS measurements of the spiked Sm and Nd isotopic compositions. Such a large uncertainty on Sm/Nd ratios propagates to errors of about 10 ppm on the CHUR-normalized  $\mu^{142}\text{Nd}$  values. Fukai and Yokoyama (2017) did not need to determine the precise  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of their samples because they used the method B to calculate their normalized  $\mu^{142}\text{Nd}$  values. However, we encourage future studies to systematically measure both the Nd isotope composition and the corresponding Sm/Nd ratio at high precision using the isotope dilution method.

Weighted averages for CC, OC and EC are  $-32 \pm 13$  (2SD),  $-15 \pm 9$  (2SD),  $-8 \pm 15$  (2SD) for the method A and  $-32 \pm 13$  (2SD),  $-16 \pm 9$  (2SD), and  $-10 \pm 12$  (2SD) for the method B. Mean values are identical within errors but when looking at the data



373 in further details, significant differences are identified within the EC group. This is  
374 illustrated in Figure 4C where both methods of correction are compared. For CC and  
375 OC, all  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios plot along the 1:1 line whereas the EC show a larger  
376 scatter. This scatter indicates that changes in the Sm/Nd ratios of EC have occurred at  
377 different times, probably early in the Solar System history and recently by  
378 weathering. The larger dispersion of the Sm/Nd ratios observed in EC may be  
379 explained by their unique mineralogy as they formed under extreme reducing  
380 conditions. Larimer and Bartholomay (1979) suggested that EC formed within a  
381 region in the solar nebula with a high C/O ratio ( $>1$ ). Although rare earth elements are  
382 mainly carried by silicate minerals in other chondrite groups, about half of the Sm and  
383 Nd elemental budget of EC is hosted in oldhamite, which is a Ca-sulfide (CaS). In-  
384 situ measurements indicate that CaS are very rich in REE relative to CI chondrites (10  
385 to 100 times the CI values; Crozaz and Lundberg, 1995; Gannoun et al., 2011b). In  
386 EH3, the CaS have fractionated REE patterns with an enrichment in LREE relative to  
387 HREE ( $(\text{La}/\text{Yb})_{\text{N}} = 1\text{-}15$ ) and positive anomalies in Eu and Yb (Crozaz and Lundberg,  
388 1995; Gannoun et al., 2011b). Although in-situ REE measurements of CaS were  
389 conducted only in EH3 samples, the measurements carried out in other groups of EC  
390 and in aubrites (reduced enstatite achondrites) show diverse REE patterns which may  
391 be associated with the weathering of CaS (Floss et al., 1990; Floss and Crozaz, 1993;  
392 Crozaz and Lundberg, 1995). Petrological observations have shown that CaS are not  
393 uniformly distributed in enstatite chondrites from EH and EL subgroups. In EH, CaS  
394 is mainly included in metal-sulfide nodules even if it can be present in the matrix or in  
395 chondrules dominated by silicate phases (El Goresy et al., 1988; Gannoun et al.,  
396 2011b; Piani et al., 2016). Our observations of EL3 samples suggest that CaS is  
397 mostly found in chondrules where it is intimately intergrown with enstatite and

occasionally with diopside (El Goresy et al., 2017). Its occurrence in metal-dominated nodules is less common. Although metal-sulfide nodules are more subject to oxidation/weathering than silicate assemblages, CaS enclosed in metal should be better preserved because metal has no fracture veins like silicates. No clear relationship has been found between REE fractionation and the type of samples (group, fall vs. found, etc). To minimize the amplitude of the correction on  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios and reduce the errors caused by a potential Sm/Nd fractionation during weathering, we selected a subset of EC samples (11 samples, 16 measurements) with measured  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios very close to the CHUR value i.e. between 0.1926 and 0.1994 ( $\pm 1.7\%$ ). Within this range, the correction reaches a maximum of  $\pm 5$  ppm on the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios, i.e. equivalent to the average external reproducibility. Taking only this subset of EC samples yields an average  $\mu^{142}\text{Nd}$  of  $10 \pm 12$  (2SD) for the two methods A and B, hence does not change the mean nor improve the standard deviation obtained for the whole EC group.

## 4.2. Stable Nd isotope signature of EC relative to other groups

Neodymium has 7 isotopes from mass 142 to 150. Nucleosynthetic anomalies, which are mass-independent variations, can be identified by measuring 3 stable isotope ratios:  $^{145}\text{Nd}/^{144}\text{Nd}$ ,  $^{148}\text{Nd}/^{144}\text{Nd}$  and  $^{150}\text{Nd}/^{144}\text{Nd}$ . Both  $^{142}\text{Nd}/^{144}\text{Nd}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  are modified by radiogenic productions from  $^{146}\text{Sm}$  and  $^{147}\text{Sm}$  respectively, and  $^{146}\text{Nd}/^{144}\text{Nd}$  is used for internal mass bias correction and normalization to a common ratio value of 0.7219. Except  $^{142}\text{Nd}$  which is mainly produced by *s-process* and  $^{150}\text{Nd}$  which is a pure *r-process* nuclide, all other isotopes

are formed by a combination of *s*- and *r*-processes in different stellar environments (Arlandini et al., 1999; Bisterzo et al., 2011). A change in the *s*/*r* proportions thus modifies the Nd isotope patterns. Excess in *s*-process produces excess in  $^{142}\text{Nd}$  and deficits in  $^{143}\text{Nd}$ ,  $^{145}\text{Nd}$ ,  $^{148}\text{Nd}$  and  $^{150}\text{Nd}$  with the deficits increasing from mass 143 to mass 150. Measurements obtained on individual EC are presented in Figure 6. The average values for both CC and OC groups are shown for comparison. For clarity, errors bars (2SD) are not shown in the figure but are instead provided in the figure caption. The large errors calculated for CC reflect the variability of *s*-process nuclides among this group owing to the contribution of CAIs. In a  $\mu^{150}\text{Nd}$  vs  $\mu^{148}\text{Nd}$  binary plot, bulk CC and separated CAIs plot on the mixing line calculated from isotope production in stellar models (see Fig. 3 in Bouvier and Boyet, 2016). CAIs can be the carrier of large *s*-process excess signature with deficits in  $\mu^{148}\text{Nd}$  and  $\mu^{150}\text{Nd}$  of several tens of ppm (Brennecka et al., 2013; Marks et al., 2014; Bouvier and Boyet, 2016).

The compositions of EC are scattered in the 3 binary plots without any clear correlation (Figure 6). Results of mixing of the *s*-model prediction with the terrestrial composition are indicated by the dashed lines depending on the model used: 1) stellar model by Arlandini et al. (1999) or 2) using the composition of SiC as representative of a pure *s*-process component (Hopp and Ott, 1997). Deficits in  $^{142}\text{Nd}$  measured in enstatite chondrites from the EH group and the EL6 subgroup are small and equal to -11 ppm in average. For such small deficit, the expected deviations in 145, 148 and 150-Nd are equal to +5, +11 and +17 ppm, respectively. These variations remain very small in comparison to the measurement precision (external reproducibility) obtained with the last generation of multi-collector thermal ionization mass spectrometers

(TIMS). In the recent study of Burkhardt et al. (2016), both  $^{142}\text{Nd}/^{144}\text{Nd}$  and  $^{148}\text{Nd}/^{144}\text{Nd}$  ratios were measured using a dynamic procedure leading to better external reproducibilities than static measurements. The relative deterioration of the Faraday collectors and their change of efficiency through time are important sources of imprecision and inaccuracy for the determination of isotope ratios using static multicollection (Makishima and Nakamura, 1991; Thirlwall, 1991). However, even with dynamic procedures on TIMS, the external reproducibilities for  $^{148}\text{Nd}/^{144}\text{Nd}$  reach 11 and 15 ppm on repeated measurements of the BHVO-2 rock standard and JNdi-1 standard, respectively. Better precisions have been recently reported by Saji et al. (2016) using multi-collector inductively coupled plasma mass spectrometry and a sample-standard bracketing technique. Five measurements of the carbonaceous chondrite Allende (CV3) give an external reproducibility of 1 ppm on the  $^{148}\text{Nd}/^{144}\text{Nd}$  ratio with intensity of 14 V at mass 142. Because enstatite chondrites are about 2 times more depleted in Nd than CV3 carbonaceous chondrites, this technique would require large quantities of EC samples (i.e. 2 g). A new 4-mass-step acquisition scheme developed by Garçon et al. (2018) by thermal ionization mass spectrometry is very promising because this routine is able to return all Nd isotope ratios dynamically and provide a robust evaluation of the data to assess the quality of the data (e.g., mixing effects on the filament, fractionation between acquisition steps).

### **4.3. The isotope similarity between EL3 samples and the Earth**

Amongst all the classified meteorites, enstatite chondrites represent only 2% of the chondrites with 189 and 160 samples for the EH and the EL subgroups,

473 respectively. They have been distinguished on the basis of their Fe/Si bulk ratios as  
474 high-Fe (EH) or low-Fe (EL) (Sears et al., 1982; Kallemeyn and Wasson, 1986). The  
475 two EC subgroups also differ in their sulfide mineralogy. In addition to troilite (FeS),  
476 daubréelite (FeCr<sub>2</sub>S<sub>4</sub>) and oldhamite, which are common to both EH and EL  
477 subgroups, niningerite (MgS) is the diagnostic sulfide of EH, whereas alabandite  
478 (MnS) is specific to EL. Most of enstatite chondrites are found objects that may have  
479 been affected by weathering during their long residence time at the Earth surface. Fall  
480 objects are extremely rare with only 7 samples for EH (2 EH3: Parsa and Qingzhen; 3  
481 EH4: Abee, Adhi Kot, Indarch; 2 EH5: St. Mark's and Saint-Sauveur; Itqiy and  
482 Galim (b) are classified as EH but present highly fractionated trace element patterns),  
483 whereas 8 fall samples for EL are all from the EL6 group, except small fragments  
484 from the newly discovered Almahata Sitta meteorite. This meteorite was classified as  
485 a polymict ureilite and contains EC fragments of a few grams amongst a variety of  
486 lithologies. Fragment MS-177 was originally assigned an equilibration grade as EL3/4  
487 with claimed impact-melt metal pockets (Bischoff et al., 2010). In contrast, El Goresy  
488 et al. (2017) argued for an origin by condensation based on the study of textures and  
489 sulfide mineral chemistries. REE patterns reported for EL6 samples are fractionated  
490 (Figure 1). Rubin et al. (2009) claims this depletion observed in many EL6 and some  
491 more primitive EL as a result of impact processes. EL6 samples would then represent  
492 a residuum largely depleted in LREE and Ca. No evidence for claimed impact melting  
493 was reported by El Goresy et al. (2017) in any EH or EL investigated. The good  
494 agreement observed between  $\mu^{142}\text{Nd}$  values corrected using Methods A and B for EL6  
495 samples supports a fractionation event early in the history of the parent body. Ar-Ar  
496 isochron ages suggest closure of the K-Ar system at 4.45-4.49 Ga for EL5 and EL6  
497 chondrites (Hopp et al., 2014).

498

499       When the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios are classified by metamorphic types (Figure 7),  
500 there is no difference for samples from the EH group. In contrast, two different  
501 populations are distinguished for the EL samples. EL6 samples have a larger deficit in  
502  $^{142}\text{Nd}$  with an average of  $-12.7 \pm 6.0$  (2SD) ppm when corrected with method B. EL3  
503 samples have a  $\mu^{142}\text{Nd}$  value similar to the terrestrial standard within the error bars: -  
504  $0.8 \pm 7.0$  (2SD) ppm. The p-value from two sample t-test yields 0.001, meaning that  
505 the EL3 and EL6 populations likely do not share the same  $^{142}\text{Nd}$  means when  
506 corrected with method B. Samples from EL3 and EL6 subgroups are also statistically  
507 different when considering the two-sided Student's *t*-values 95% confidence intervals  
508 :  $\mu^{142}\text{Nd}$  EL3 =  $-0.8 \pm 4.4$  ppm and  $\mu^{142}\text{Nd}$  EL6 =  $-12.7 \pm 2.3$  ppm (see Table S1). This  
509 difference suggests either that EL3 and EL6 samples come from different parent  
510 bodies or that the correction for the  $^{142}\text{Nd}$  radiogenic production is not correct for EL6  
511 samples. The correction assumes an evolution over 4.568 Ga while Ar-Ar isochron on  
512 EL6 samples (Hopp et al., 2014) suggests a fractionation event 70 Ma after the  
513 beginning of the solar system history. Considering a two-stage evolution (chondritic  
514  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of 0.196 from  $T_0$  to  $T_1$  with  $T_0 - T_1 = 70$  Ma, the EL6 average  
515  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of 0.2005 from  $T_1$  to present time shifts the correction by -2 ppm  
516 only. This average value  $\mu^{142}\text{Nd}$  for EL6 remains statistically different from the EL3  
517 subgroup. Another compelling result for the difference amongst EC compositions  
518 comes from the measurement of Ru isotopes (Fischer-Gödde and Kleine, 2017).  
519 Although the average of all EH and EL chondrites has a small deficit in  $\epsilon^{100}\text{Ru}$  ( $-0.08$   
520  $\pm 0.04$ , 95% confidence interval of the mean), the sample suite includes only one EL3  
521 PCA 91020. This EL3 gave  $\epsilon^{100}\text{Ru} = +0.02$  which is outside the 95% confidence  
522 interval of the average of the combined EL and EH data and similar to the Earth's

composition. A difference between Earth and EC has been reported for Mo isotopes but no EL3 samples have been analyzed in this dataset meaning that the reported average Mo isotopic composition of EC is based on EL6 samples only (Burkhardt et al., 2011; Dauphas et al., 2002; Dauphas 2017). The Zn isotopic compositions of the two EL3 chondrites measured by Moynier et al. (2011) are also identical to the terrestrial values, whereas the analyzed EL6 chondrites are all enriched in heavy isotopes and highly depleted in Zn. The origin of the volatile element depletion between EL3 and EL6 chondrites can be explained by volatilization, probably during thermal metamorphism. All these measurements suggest that EL samples do not come from a single parent body. Similar conclusions were reached from petrographic and geochemical observations for EH3 samples. Both normal and reverse MgS–FeS zoning profiles in niningerite grains adjacent to troilite reveal an origin on different parental asteroids with different MnS-contents in the niningerites (Lin and El Goresy, 2002; Gannoun et al., 2011b). At least 8 different parent bodies have been recently proposed for the entire EC group based on chemical variations measured in sulfide and metal phases (Weyrauch et al., 2017). However all these samples share very close isotope signatures suggesting they condensed within the same region of the solar nebula. Although our conclusion supports a genetic relationship between EL3 samples and the Earth, this statement is based on the analysis of cosmochemical materials present in our meteorite collection that represent a very small record of materials present in the Solar System. Recent high-precision Mo and Ru isotope measurements have highlighted a terrestrial signature in IAB iron meteorites indicating that their parent bodies could be the building blocks of the Earth (Worsham et al., 2017). Unfortunately the lithophile behavior of REE makes it impossible to study these meteorites for  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics.

## 5. Conclusion

Among all groups of chondrites, EC have measured  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios the closest to the modern terrestrial signature ( $\mu^{142}\text{Nd} = -11 \pm 12$  (2SD) ppm). In order to compare initial  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios, data must be corrected from the  $^{142}\text{Nd}$  radiogenic production since the formation of the Solar System. Two methods of corrections are compared (*measured*  $^{147}\text{Sm}/^{144}\text{Nd}$  vs. *integrated*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios). The two methods yield results that are identical within the errors bars. Enstatite chondrites show a larger scatter of Sm/Nd ratios in comparison to other chondrite groups that can be attributed to early fractionation processes (e.g. samples from the EL6 subgroup) and/or recent changes caused by weathering. In these chondrites, REE are mainly concentrated in the calcium-sulfide phase (oldhamite), which is very sensitive to weathering. For this latter reason we conclude that corrections based on *integrated*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios are more accurate for enstatite chondrites. The average of these corrected values  $\mu^{142}\text{Nd}$  give  $-10 \pm 12$  (2SD) ppm. We report no significant variation in the 3 stable Nd isotope ratios ( $^{145}\text{Nd}/^{144}\text{Nd}$ ,  $^{148}\text{Nd}/^{144}\text{Nd}$  and  $^{150}\text{Nd}/^{144}\text{Nd}$ ) in EC relative to terrestrial Nd standard.

When the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios are ordered by enstatite chondrite sub-groups, there is no difference for samples from the EH sub-group. In contrast, two different populations are distinguished for the EL sub-group. EL6 samples have a larger deficit in  $^{142}\text{Nd}$  with an average of  $-12.7 \pm 6.0$  (2SD) ppm. EL3 samples have a  $\mu^{142}\text{Nd}$  value similar to the terrestrial standard within the error bars:  $-0.8 \pm 7.0$  (2SD) ppm. These



two populations are statistically different (p-values and 95% confidence interval uncertainties). These results are in agreement with those obtained for other elements (e.g. Zn and Ru) and suggest that 1) EL3 and EL6 samples do not come from the same parent body, and 2) EL3 samples are isotopically similar to the Earth. Because these enstatite chondrites are relatively small in size and number, they are usually not available for destructive isotopic measurements. Average values based on both the geochemical and isotopic compositions of EL6 samples should not be considered as representative of the whole EL group. The enstatite chondrite model (Javoy, 1995; Javoy et al., 2010, Kaminski and Javoy, 2013) considers instead that the Earth is built from essentially pure EH material for explaining the Mg/Si ratio of the Earth's upper mantle. A better knowledge on the mineralogy of the lower mantle and the proportion of silicon in the Earth's core could help in resolving this discrepancy.

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## **List of Figures**

**Figure 1.** Rare earth element (REE) patterns measured in enstatite chondrites from both EH and EL subgroups normalized to CI chondrites (Anders and Grevesse, 1989). New data are represented in black and Grey fields/line are data from Barrat et al. (2014) A) EH3 and impact melts (IM). LAP 02225 is an impact melt (Antarctic meteorite newsletter, Izawa et al., 2010). Galim is an unusual LL/EH polymict breccia with two lithologies: Galim (a) is a heavily-shocked LL6 chondrite and Galim (b) an impact melt breccia. Kota Kota (EH3) displays a strong enrichment in LREE. B) EH4 and EH5. Abee (EH4) is enriched in REE compared to other samples from the EH4 and EH5 groups. C) EL3 and one meteorite from the EL5 subgroup (Adrar Bous). MAC 88180 (two dissolutions) has two patterns that are both strongly enriched. Almahata Sitta MS-177 has the lowest REE contents. D) EL6 meteorites. All EL6 samples present very similar REE patterns, except EET 92063 described as highly weathered and classified in an anomalous EL6 by Barrat et al. (2014).

**Figure. 2.** (La/Sm)<sub>N</sub> normalized to CI chondrites using the values of Anders and Grevesse, (1989) compared with Yb contents (in ppm) for EC samples. Data are from this study and literature data from Gannoun et al. (2011b), Barrat et al. (2014) and Kalleyman and Wasson (1986). IM: impact melt.

814

815 **Figure. 3.** Compilation of  $\mu^{142}\text{Nd}$  values (in ppm) in carbonaceous, ordinary and  
816 enstatite chondrites. For each individual data point, errors bars show internal errors  
817 (i.e. in-run errors, 2SE) or 2SD when several replicates of the same sample were  
818 measured. Vertical pale yellow bands represent the mean of each chondrite groups  
819  $\pm 2\text{SD}$  and vertical green bands represent 95% confidence intervals. A) Measured  
820  $\mu^{142}\text{Nd}$  expressed in part per million (ppm) deviations relative to the measured  
821 standard values. B)  $\mu^{142}\text{Nd}$  normalized to the CHUR  $^{147}\text{Sm}/^{144}\text{Nd}$  following the  
822 correction method A. C)  $\mu^{142}\text{Nd}$  normalized to the CHUR  $^{147}\text{Sm}/^{144}\text{Nd}$  value  
823 following the correction method B. See Figure 5 and text for further details. Literature  
824 data are from: Boyet and Carlson (2005); Andreasen and Sharma (2006); Carlson et  
825 al. (2007); Gannoun et al. (2011a); Bouvier and Boyet (2016); Burkhardt et al.  
826 (2016); Fukai and Yokohama (2017); and this study for Almahata Sitta MS-177. All  
827 values are shown but six samples were removed from calculated weighted averages  
828 reported in the figure caption for their respective groups because they have either  
829 highly fractionated Sm/Nd ratios (Tagish Lake, NWA 2090, Adrian, Kota Kota and  
830 Blithfield) or correspond to a single run with a large internal uncertainty meaning that  
831 the measurement is not reliable (Abee). Weighted mean values for CC are:  $-33 (\pm 16,$   
832  $\pm 4$  for 2SD and 95% confidence interval, respectively);  $-32 (\pm 13; \pm 3), -32 (\pm 13; \pm$   
833  $3)$  in graphs A, B and C. Weighted mean values for OC are:  $-16 (\pm 9, \pm 2); -15 (\pm 9;$   
834  $\pm 2), -16 (\pm 9; \pm 2)$  in graphs A, B and C. Weighted mean values for EC are:  $-11 (\pm$   
835  $12, \pm 2); -9 (\pm 15; \pm 3), -10 (\pm 12; \pm 2)$  in graphs A, B and C. Number of  
836 measurements is 20 (10 samples) for CC, 28 (24 samples) for OC and 29 (17 samples)  
837 for EC. Individual values and calculations (averages, errors) are reported in Table S1.  
838

**Figure 4.** A. Compilation of measured  $\mu^{142}\text{Nd}$  vs.  $^{147}\text{Sm}/^{144}\text{Nd}$  for the different chondrite samples. The line corresponds to a slope for a 4.568 Ga isochron. Here the line is forced through the mean value of the ordinary chondrites group. B. Histogram showing the distribution of measured  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios in the different groups of chondrites. C. Comparison of the  $\mu^{142}\text{Nd}$  normalized to the chondritic evolution following the two calculation methods (A vs B) explained in the main text and shown schematically in Figure 5. D. Same diagram as C for EC samples only.

**Figure 5.** Schematic illustration of the correction method for the normalization of  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios to a common chondritic evolution. A. Method A using the measured  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of the sample. B. Method B using the calculated Sm/Nd ratio from the long-lived  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  systematics.  $T_0$  is the age of the Solar System formation, i.e. 4.568 Ga (Bouvier and Wadhwa, 2010). More details can be found in the text. The CHUR parameters are those defined by Bouvier et al. (2008).

**Figure 6.** A. Mass independent stable Nd isotope composition of enstatite chondrites  $\mu^{142}\text{Nd}$  corr. B vs  $\mu^{148}\text{Nd}$ ; B.  $\mu^{145}\text{Nd}$  vs  $\mu^{148}\text{Nd}$ ; C.  $\mu^{145}\text{Nd}$  vs  $\mu^{150}\text{Nd}$ . Average values  $\pm 2\text{SD}$  (all in ppm) for CC are  $-32 \pm 13$  ( $\mu^{142}\text{Nd}$ ),  $4 \pm 19$  ( $\mu^{145}\text{Nd}$ ),  $16 \pm 27$  ( $\mu^{148}\text{Nd}$ ) and  $17 \pm 68$  ( $\mu^{150}\text{Nd}$ ). For OC:  $-15 \pm 9$  ( $\mu^{142}\text{Nd}$ ),  $3 \pm 15$  ( $\mu^{145}\text{Nd}$ ),  $7 \pm 15$  ( $\mu^{148}\text{Nd}$ ) and  $14 \pm 54$  ( $\mu^{150}\text{Nd}$ ). CC data include 20 measurements on 10 samples. For OC, a total of 29 measurements carried out on 25 different samples are considered. For comparison, the average values obtained from OC data published in Burkhardt et al. (2016) are  $-18 \pm 6$  ( $\mu^{142}\text{Nd}$ ),  $6 \pm 9$  ( $\mu^{145}\text{Nd}$ ),  $7 \pm 8$  ( $\mu^{148}\text{Nd}$ ) and  $17 \pm 13$  ( $\mu^{150}\text{Nd}$ ) (all in ppm). Dashed lines (long and short respectively) represent mixing of the s-model prediction with the

terrestrial composition following: 1) stellar model by Arlandini et al. (1999), and 2) using the composition of SiC as representative of a pure s-process component (Hopp and Ott, 1997). External reproducibilities are not provided because this compilation includes data obtained by different authors and using different techniques.

**Figure 7.** Corrected  $\mu^{142}\text{Nd}$  (normalized to the chondritic evolution using method B) in enstatite chondrites. Samples are ordered by groups. Fall meteorite samples are shown in bold.

## **List of Tables**

**Table 1.** Rare Earth element contents of enstatite chondrites measured by ICP-MS. Two methods of acid digestion were used: (A) in PFA Savillex® beakers on hot plate at atmospheric pressure, (b) into individual pressurized Parr® bombs.

**Table 2.** Measured Nd isotope composition of the JNdi-1 standard and MS-177 (EL3). Errors correspond to the external reproducibility for the JNdi-1 standard runs (2SD) and internal error for MS-177.  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio has been measured by isotope dilution. The initial  $\epsilon^{143}\text{Nd}$  is calculated at 4.568 Ga using the CHUR parameters defined by Bouvier et al. (2008). The average values measured for the terrestrial standard (n=7) are  $1.141850 \pm 6$  for  $^{142}\text{Nd}/^{144}\text{Nd}$ ,  $0.512111 \pm 4$  for  $^{143}\text{Nd}/^{144}\text{Nd}$ ,  $0.348403 \pm 2$  for  $^{145}\text{Nd}/^{144}\text{Nd}$ ,  $0.241578 \pm 2$   $^{148}\text{Nd}/^{144}\text{Nd}$ , and  $0.236446 \pm 3$  for  $^{150}\text{Nd}/^{144}\text{Nd}$  (see details in Table S2).

Table 1.

Rare Earth Elements measured in enstatite chondrites by ICP-MS

\* Results already published in Gannoun et al. (2011b)

# Dissolution A) in PFA Savillex® beakers on hot plate at atmospheric pressure, B) into individual pressurized Parr® bombs.

<sup>a</sup> mass of the aliquot uptaken for measuring REE that corresponds to 5% of the total dissolution

sample name	ALHA 77295*	Sahara 97072*	Sahara 97096*	Sahara 97158*	Kota Kota EH3	Abee EH4 X	Indarch EH4 X	St Mark's EH5 X	MAC 02837 EL3	MAC 02839 EL3	MAC 88180 EL3	MAC 88180 EL3	MS-177 EL3 X	Adrar Bous EL5	Eagle EL6 X	Hvittis EL6 X	Hvittis EL6 X	Hvittis EL6 X	Hvittis EL6 X	Khairpur EL6 X
type	EH3	EH3	EH3	EH3	EH3	EH4 X	EH4 X	EH5 X	EL3	EL3	EL3	EL3	EL3 X	EL5	EL6 X	EL6 X	EL6 X	EL6 X	EL6 X	EL6 X
Fall																				
weight (g)	0.05	0.05	0.05	0.05	0.05	0.16	0.05	0.05	0.05	0.05	0.12	0.13	0.08 <sup>a</sup>	0.11	0.05	0.12	0.10	0.10	0.05 <sup>a</sup>	0.05
dissolution #	A	A	A	A	A	B	A	A	A	A	A	B	B	B	A	A	A	A	B	A
La	0.247	0.233	0.237	0.231	0.506	0.274	0.222	0.215	0.247	0.265	0.449	0.432	0.156	0.192	0.189	0.141	0.136	0.181	0.250	0.175
Ce	0.556	0.545	0.590	0.542	1.235	0.721	0.555	0.542	0.616	0.663	1.174	1.113	0.379	0.488	0.509	0.392	0.350	0.487	0.677	0.457
Pr	0.087	0.086	0.093	0.087	0.162	0.110	0.089	0.086	0.097	0.103	0.176	0.169	0.056	0.075	0.084	0.062	0.063	0.077	0.107	0.074
Nd	0.423	0.438	0.455	0.435	0.749	0.557	0.433	0.416	0.480	0.530	0.895	0.847	0.290	0.381	0.442	0.326	0.326	0.401	0.571	0.374
Sm	0.144	0.123	0.146	0.132	0.207	0.183	0.144	0.134	0.158	0.168	0.307	0.278	0.096	0.121	0.136	0.112	0.111	0.137	0.193	0.124
Eu	0.053	0.049	0.054	0.049	0.071	0.059	0.053	0.052	0.058	0.062	0.080	0.076	0.054	0.060	0.047	0.045	0.044	0.048	0.058	0.050
Gd	0.205	0.188	0.209	0.191	0.269	0.256	0.204	0.196	0.226	0.243	0.390	0.374	0.133	0.177	0.212	0.160	0.165	0.196	0.264	0.179
Tb	0.035	0.034	0.037	0.033	0.044	0.045	0.035	0.035	0.038	0.041	0.073	0.069	0.025	0.030	0.036	0.029	0.028	0.035	0.049	0.031
Dy	0.244	0.250	0.257	0.232	0.301	0.317	0.245	0.236	0.268	0.295	0.474	0.449	0.174	0.208	0.254	0.201	0.207	0.243	0.337	0.221
Ho	0.054	0.053	0.057	0.051	0.063	0.069	0.054	0.051	0.059	0.064	0.103	0.097	0.039	0.047	0.058	0.044	0.045	0.052	0.073	0.050
Er	0.161	0.160	0.172	0.156	0.189	0.201	0.160	0.154	0.174	0.194	0.306	0.294	0.120	0.142	0.174	0.139	0.142	0.160	0.218	0.147
Tm	0.023	0.022	0.027	0.023	0.028	0.030	0.025	0.023	0.026	0.029	0.047	0.045	0.018	0.021	0.027	0.022	0.023	0.025	0.032	0.023
Yb	0.155	0.150	0.174	0.144	0.183	0.196	0.162	0.155	0.182	0.194	0.323	0.307	0.117	0.150	0.187	0.152	0.155	0.177	0.202	0.157
Lu	0.024	0.022	0.026	0.024	0.028	0.030	0.025	0.023	0.026	0.028	0.048	0.045	0.021	0.024	0.029	0.023	0.023	0.028	0.033	0.024

Table 2

	JNdi-1	MS-177
I <sup>145</sup> Nd (V)	0.7 - 1.5	0.64
μ <sup>142</sup> Nd	0.0 ± 5.6	-10.9 ± 5.7
μ <sup>143</sup> Nd	0.0 ± 7.4	640 ± 4.9
μ <sup>145</sup> Nd	0.0 ± 4.4	5.7 ± 4.1
μ <sup>148</sup> Nd	0.0 ± 8.2	9.9 ± 7.4
μ <sup>150</sup> Nd	0.0 ± 10.9	11.5 ± 11.5
<sup>142</sup> Ce ppm	0.4	1.2
<sup>144</sup> Sm ppm	0.4	0.3
n	6	1
<sup>147</sup> Sm/ <sup>144</sup> Nd		0.1896
μ <sup>142</sup> Nd A		-1.4
μ <sup>142</sup> Nd B		-1.1
ε <sup>143</sup> Nd, 4.568 Ga		0.06

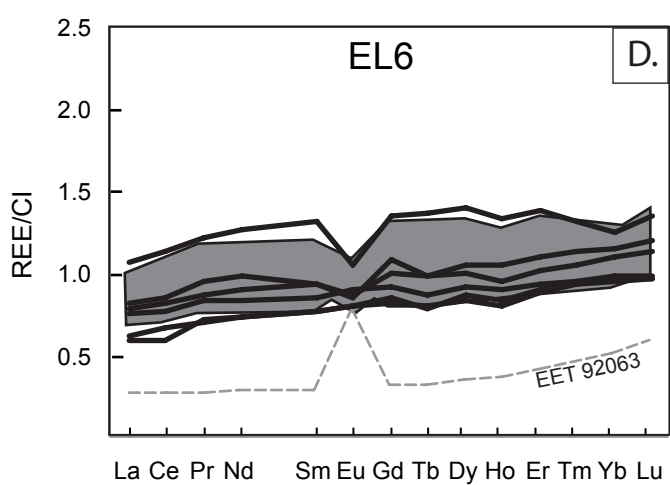
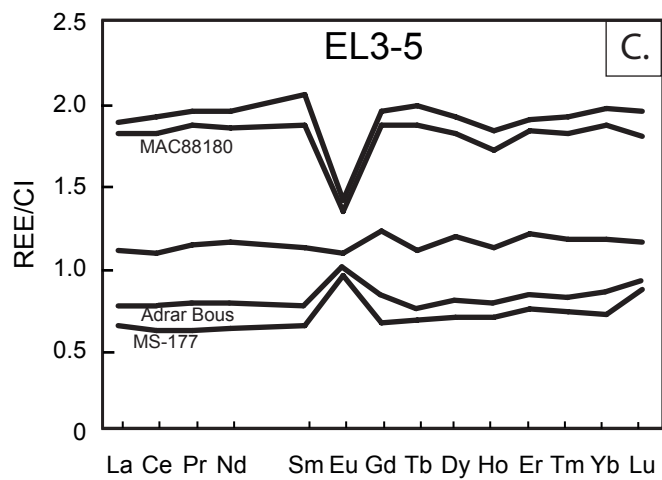
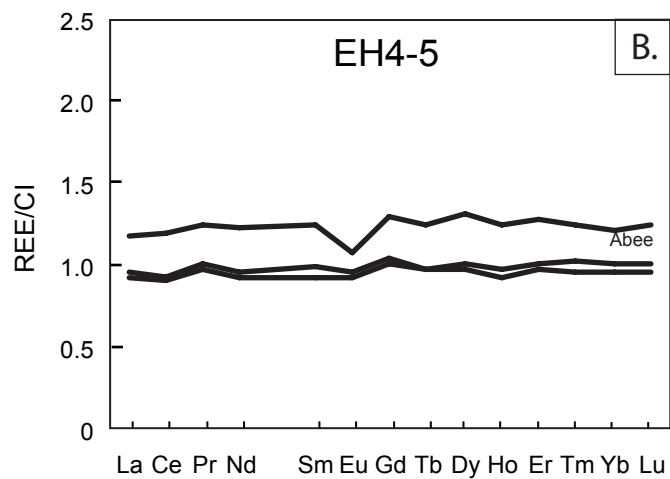
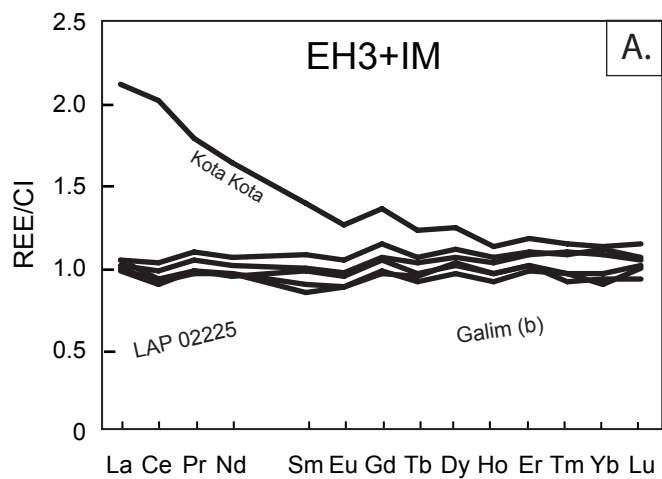


Figure 1



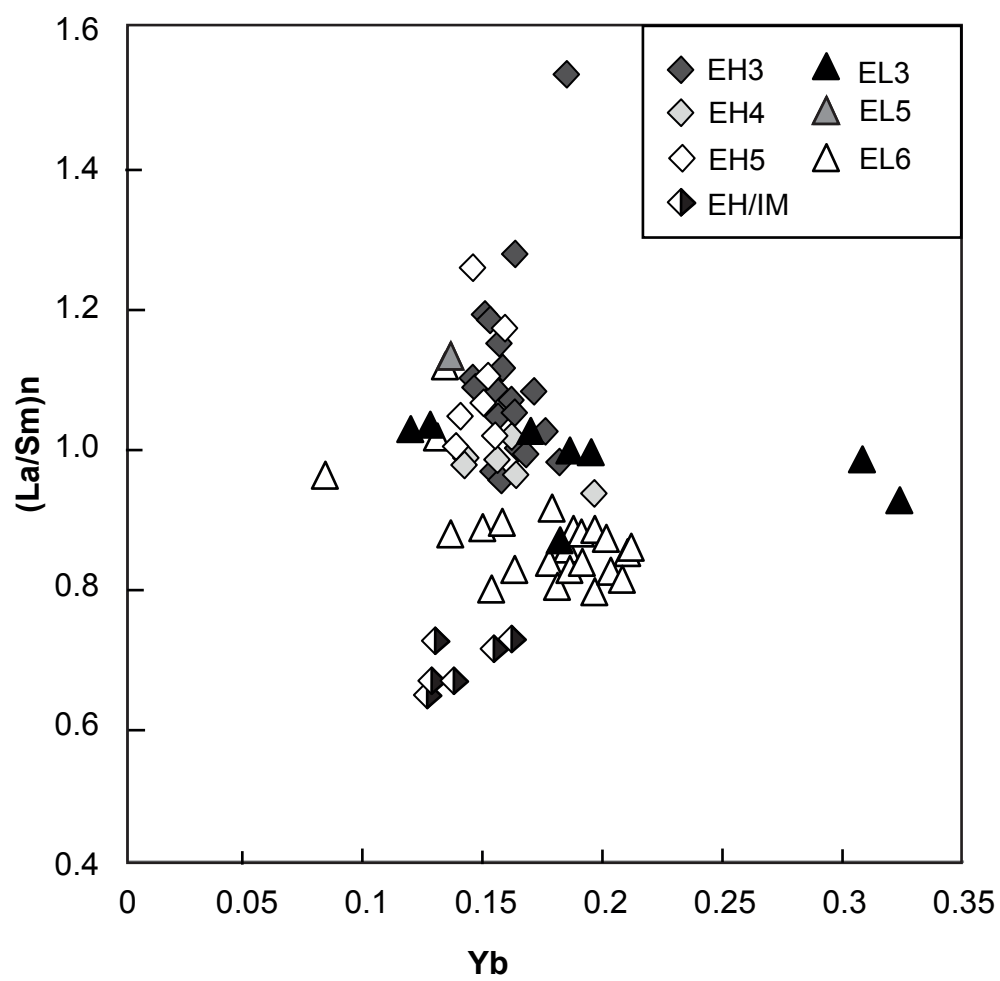


Figure 2.

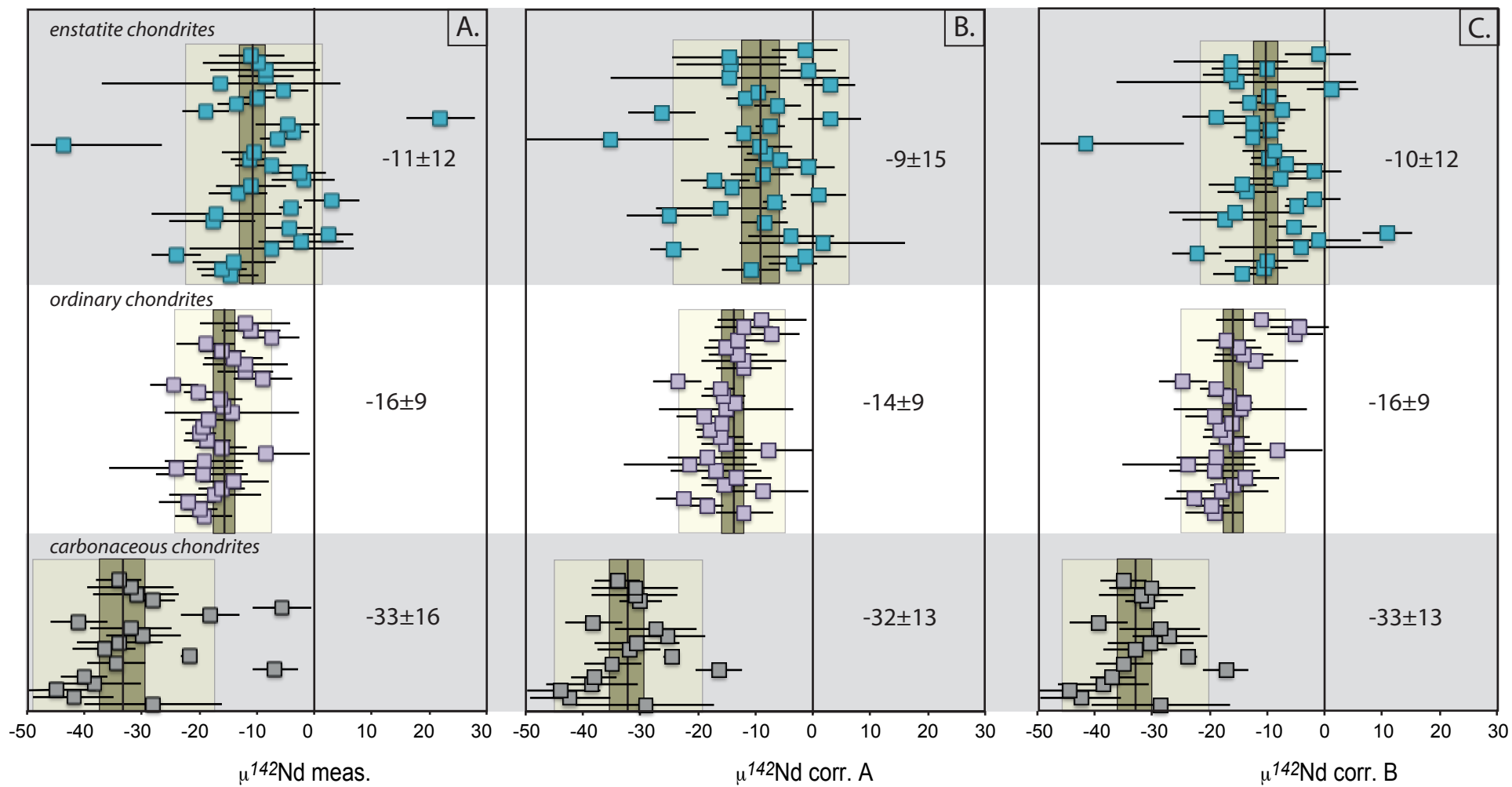


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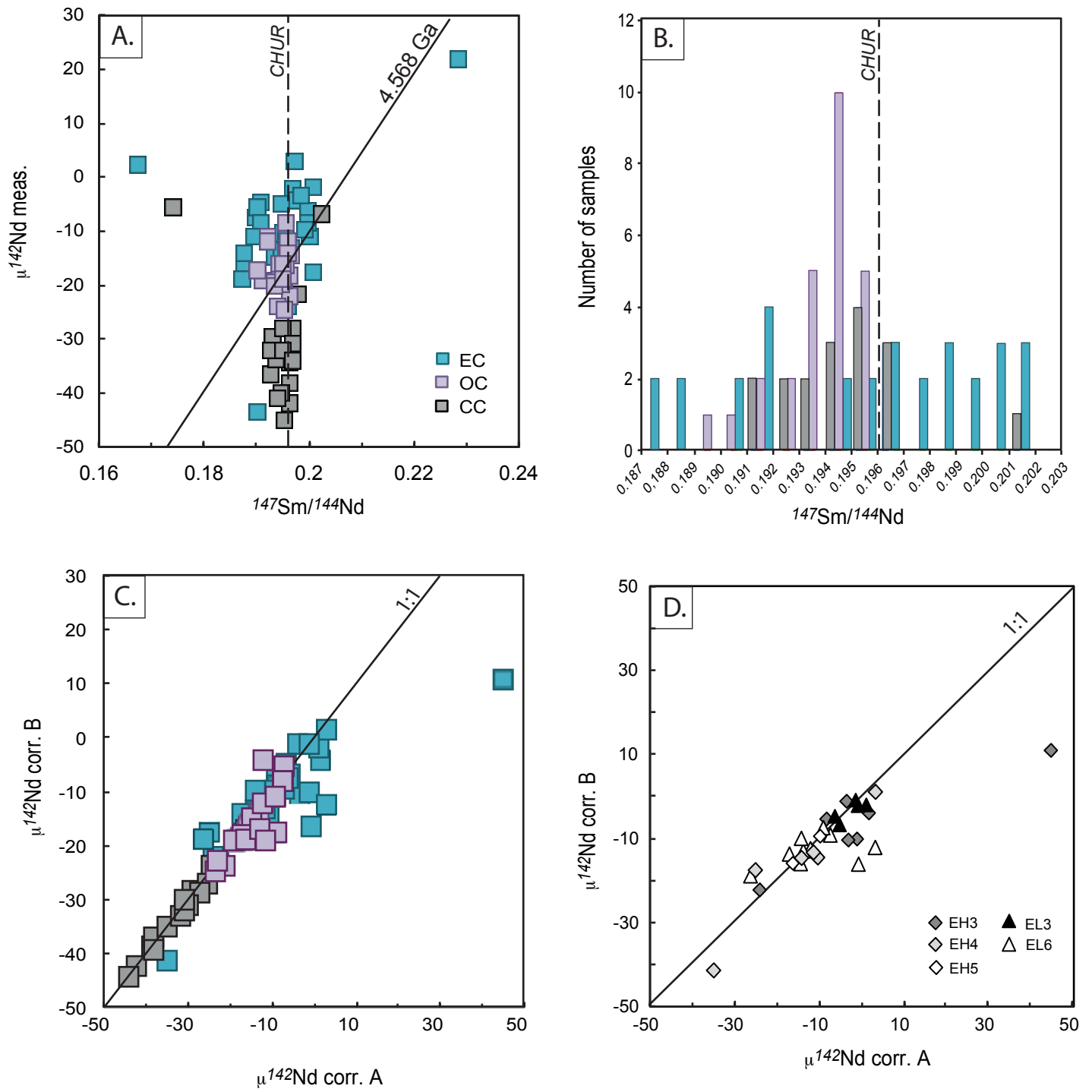


Figure 4

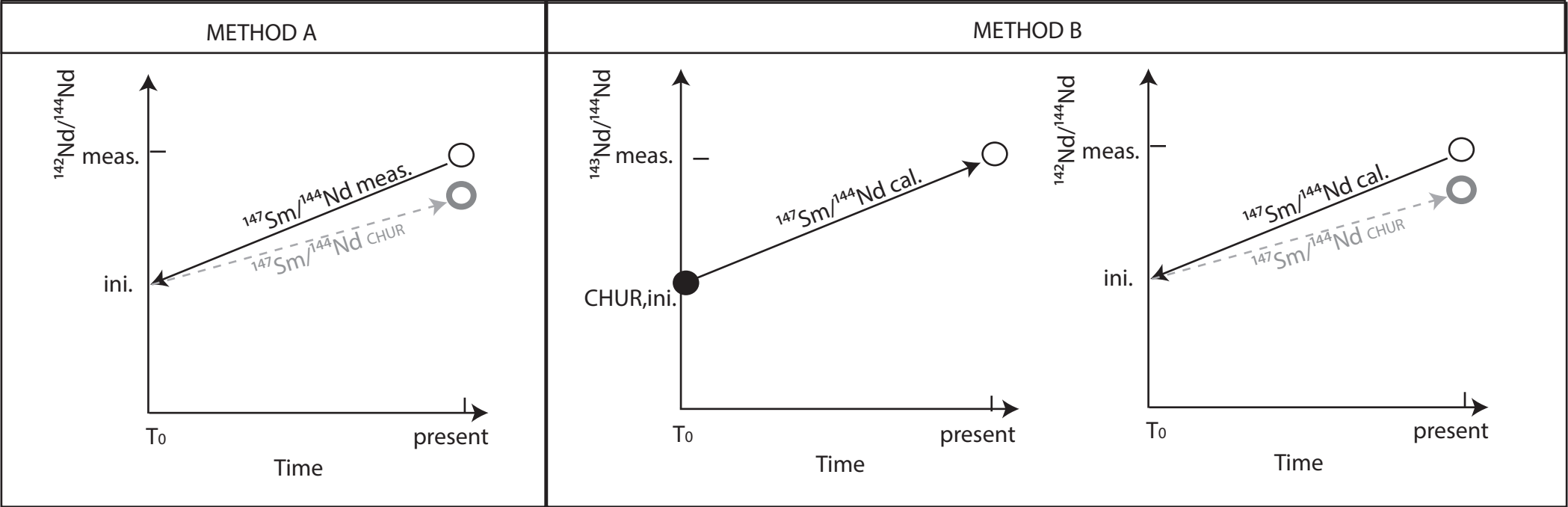


Figure 5

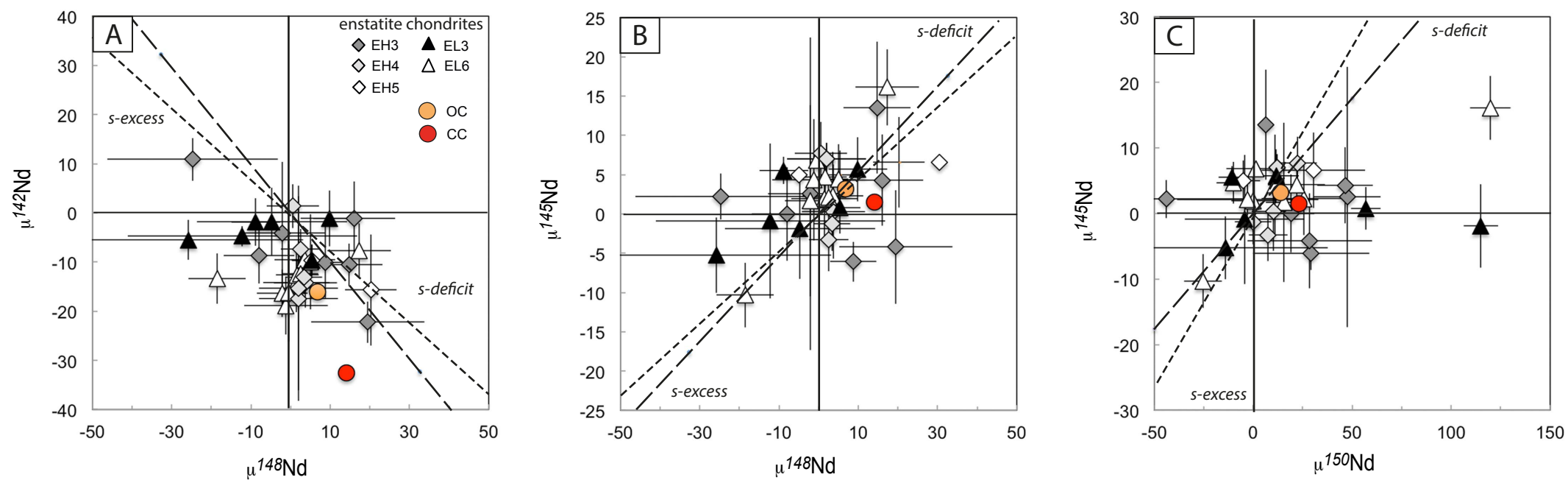


Figure 6.

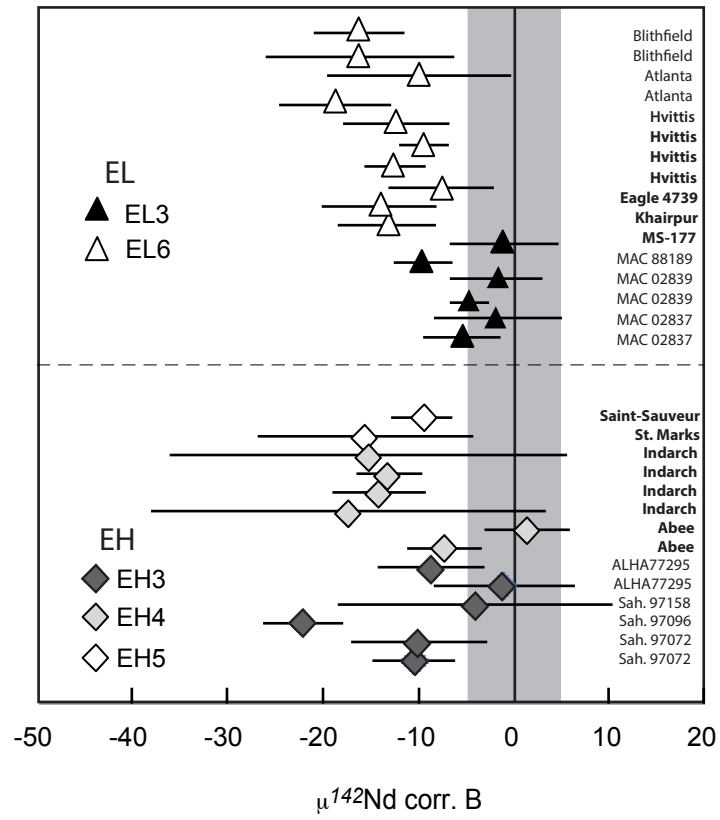


Figure 7

Name	Type	$\mu^{14}\text{Nd}$	$\sigma^{14}\text{Nd}$	$\mu^{15}\text{Nd}$	$\sigma^{15}\text{Nd}$	$\mu^{25}\text{Nd}$	$\sigma^{25}\text{Nd}$	$\mu^{26}\text{Nd}$	$\sigma^{26}\text{Nd}$	$\mu^{27}\text{Nd}$	$\sigma^{27}\text{Nd}$	$\mu^{14}\text{Nd}$	$\sigma^{14}\text{Nd}$	$\mu^{15}\text{Nd}$	$\sigma^{15}\text{Nd}$	$\mu^{25}\text{Nd}$	$\sigma^{25}\text{Nd}$	$\mu^{26}\text{Nd}$	$\sigma^{26}\text{Nd}$	$\mu^{27}\text{Nd}$	$\sigma^{27}\text{Nd}$	$\mu^{14}\text{Nd}$	$\sigma^{14}\text{Nd}$	$\mu^{15}\text{Nd}$	$\sigma^{15}\text{Nd}$	$\mu^{25}\text{Nd}$	$\sigma^{25}\text{Nd}$	$\mu^{26}\text{Nd}$	$\sigma^{26}\text{Nd}$	$\mu^{27}\text{Nd}$	$\sigma^{27}\text{Nd}$	Reference
<b>Carboxonaceous chondrites</b>																																
Oregani	C-I all	-28.0	1000.7	-25.3	4.1	1.3	12.0	5.0	13.0	20.0	28.0	-29.2	-28.5	0.1968	Carlson et al., Science 2007																	
Kid Bokkeld	CM2 falc	-41.9	1001.7	2.6	25.7	42.3	7.0	5.0	7.0	12.0	17.0	-42.2	-42.4	0.1962	Carlson et al., Science 2007																	
Mighei	CM2 falc	-45.0	960.5	8.0	50.5	88.8	7.0	5.0	7.0	13.0	18.0	-44.0	-44.4	0.1953	Carlson et al., Science 2007																	
Allende	Cv3-fall	-38.2	997.2	4.9	28.6	45.0	8.0	5.0	5.0	15.0	19.0	-38.5	-38.5	0.1962	Carlson et al., Science 2007																	
Allende	Cv3-fall	-40.0	858.8	13.2	30.2	40.2	5.0	5.0	5.0	8.0	11.0	-38.1	-36.9	0.1947	Carlson et al., Science 2007																	
Gronspira	Cv3-fall	-46.8	1196.1	-12.1	7.9	18.2	4.0	5.0	4.0	6.0	10.0	-16.3	-17.2	0.2024	Carlson et al., Science 2007																	
Allende	Cv3-fall	-34.4	1.7	21.9	18.8	5.0	5.0	5.0	5.0	11.0	14.0	-34.9	-34.9	0.1949	Carlson et al., Science 2007																	
Allende	Cv3-fall	-21.8	1136.2	-1.8	8.7	14.1	15.1	6.7	15.4	19.9	32.5	-24.6	-23.6	0.1979	Gannoun et al., PNAS 2011																	
Allende	Cv3-fall	-36.6	889.3	4.0	7.3	4.8	5.5	4.5	3.8	7.2	10.3	-32.0	-32.9	0.1930	Boyet and Carlson 2005																	
Allende	Cv3-fall	-33.9	891.8	4.4	-2.3	-20.2	7.5	6.3	5.4	9.8	13.3	-30.6	-30.3	0.1938	Boyet and Carlson 2005																	
Allende + Bomb	Cv3-fall	-29.7	724.4	0.4	22.4	35.5	8.0	5.0	5.0	10.0	13.0	-30.2	-30.2	0.1929	Boyet and Carlson 2005																	
Allende	Cv3-fall	-32.0	90.4	1.6	1.0	-12.5	7.1	5.6	5.4	9.8	13.2	-27.4	-27.8	0.1947	Rankenberry et al., 2006																	
Allende	Cv3-fall	-41.0	966.6	3.0	6.0	118.0	5.0	5.0	5.0	24.0	28.0	-38.2	-39.3	0.1943	Rankenberry et al., 2006																	
Allende (2)	Cv3-fall	-30.0	1005.2	5.0	4.0	6.0	1.0	9.0	4.0	9.0	11.0	-31.0	-31.0	0.1947	Burkhart et al. (2016)																	
Allende (3)	Cv3-fall	-30.0	1008.4	5.0	4.0	-6.0	6.0	3.1	6.0	7.0	24.0	-31.0	-32.0	0.1940	Burkhart et al. (2016)																	
Allende (4)	Cv3-fall	-33.0	1000.0	8.0	16.0	11.0	8.0	2.6	13.0	15.0	31.0	-31.0	-31.0	0.1930	Burkhart et al. (2016)																	
Dale Gribbin	CM2 falc	-28.0	1000.0	5.0	4.0	26.0	18.0	15.0	5.4	1.5	26.0	-30.0	-31.0	0.195	Fukui and Yokoyama 2017																	
Murchison	CM2 falc	-31.0	2.1	23.0	24.0	7.4	16.0	13.0	2.0	32.0	-31.0	-31.0	-31.0	0.1957	Fukui and Yokoyama 2017																	
Allende	Cv3-fall	-32.0	1.1	19.0	27.0	7.5	16.0	16.0	26.0	-30.0	-31.0	-31.0	-31.0	0.195	Fukui and Yokoyama 2017																	
Dale 190	CDI-formed	-34.0	19.0	22.0	27.0	4.0	27.0	4.6	7.4	-35.0	-34.0	-34.0	-34.0	0.1957	Fukui and Yokoyama 2017																	
CAI-grained fall	Cv3-fall	-18.0	4.9	3.1	8.7	8.1	8.7	8.1	8.7	8.1	8.7	-18.0	-18.0	0.146	Fukui and Yokoyama 2017																	
WVA-2000	CO3-fall	-5.6	-6.7	0.8																												

Individuals	EH4-Fall	-14.6	96.9	3	3.7	10.2	5.0	6.0	8.0	11.0	-10.8	14.3	0.1393	Carlson et al., Science 2007		
Indach	EH4-Fall	-16.1	98.0	13.5	14.7	6.4	4.3	3.5	8.4	8.4	3.4	1.0	0.1875	Gammou et al., PNAS 2011		
SAHARA 9702	EH4-Fall	-14.0	87.26	6.1	4.8	29.2	7.3	2.2	2.5	5.8	29.4	-1.3	0.1875	Gammou et al., PNAS 2011		
SAHARA 9706	EH4-Fall	-24.0	95.3	4.2	19.5	28.5	43.3	6.3	7.2	14.3	31.5	-2.2	0.1875	Gammou et al., PNAS 2011		
SAHARA 9709	EH4-Fall	-7.4	95.5	2.5	2.0	1.5	2.0	1.5	1.5	1.5	1.5	1.5	0.1393	Gammou et al., PNAS 2011		
ALH47295	EH4-Fall	-23	98.02	4.3	16.5	46.4	74.4	6.3	5.8	10.4	14.1	-3.7	0.1393	Gammou et al., PNAS 2011		
Indach	EH4-Fall	-4.4	107.1	5.3	-25.8	-14.1	7.4	4.7	29.0	51.8	3.5	5.1	0.1875	Gammou et al., PNAS 2011		
Indach	EH4-Fall	-17.7	114.3	2.0	0.7	7.4	12.5	6.4	17.4	-25.0	17.4	29.0	0.1875	Gammou et al., PNAS 2011		
St. Mark's	EH5-Fall	-17.0	97.3	5.6	20.3	30.4	11.3	9.9	5.8	6.5	26.2	-16.0	0.157	Gammou et al., PNAS 2011		
Indach	EH5-Fall	-14.2	99.0	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.1875	Gammou et al., PNAS 2011		
MSK 88180	EH5-Fall	31	122.4	5.5	-48	-10.8	-4.8	4.1	1.7	6.2	6.9	1.0	0.1934	Gammou et al., PNAS 2011		
Khairpur	EL6-Fall	-13.2	104.1	-10.3	-18.5	-25.4	5.1	4.4	4.1	7.2	9.5	-14.0	0.1394	Gammou et al., PNAS 2011		
EL6-Fall	-10.9	115.6	1.9	1.5	0.1	6.0	5.0	4.7	8.3	11.2	17.0	-14.2	0.2001	Gammou et al., PNAS 2011		
EL6-Fall	-1.8	161.3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	0.1875	Gammou et al., PNAS 2011		
ALH47295	EL3-Fall	-5.0	99.94	-1.9	4.7	115.0	6.8	2.7	6.4	19.0	8.6	-0.8	0.1848	Bouvier and Boyet 2016		
MSK 88239	EL3-Fall	-11.4	96.05	0.8	5.4	56.6	19.0	3.3	5.2	7.6	8.2	-1.6	0.1935	Bouvier and Boyet 2016		
ALH47295	EL3-Fall	-10.4	103.7	9.7	9.0	10.0	16.6	1.5	1.5	1.5	1.5	1.5	0.1875	Bouvier and Boyet 2016		
Hertis (1)	EL6-Fall	-6.5	128.5	4.7	1.7	-10.0	3.2	2.7	3.2	5.4	8.5	-12.1	0.1989	Burkhardt et al., 2016		
Hertis (2)	EL6-Fall	-3.5	23.2	3.3	3.6	25.6	2.9	3.1	5.6	7.4	21.4	-7.4	0.1989	Burkhardt et al., 2016		
Hertis (3)	EL6-Fall	-4.6	131.2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	0.1989	Burkhardt et al., 2016		
Abee (1)	EH4-Fall	-18.9	56.25	3.3	2.6	7.6	4.0	3.1	4.0	5.0	9.7	6.1	0.1874	Burkhardt et al., 2016		
Abee (2)	EH4-Fall	-13.5	96.05	0.8	5.4	56.6	19.0	3.3	5.2	7.6	8.2	-1.6	0.1935	Burkhardt et al., 2016		
St. James	EH5-Fall	-10.0	102.7	5.0	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	0.1875	Burkhardt et al., 2016		
St. James	EH5-Fall	-5.5	74.5	2.7	0.6	22.4	4.5	4.1	6.0	6.6	9.7	3.0	0.14	0.1903	Burkhardt et al., 2016	
St. James	EH5-Fall	-5.3	101.2	7.0	2.6	20.0	2.0	2.0	2.0	2.0	2.0	2.0	0.1875	Burkhardt et al., 2016		
Atlanta (2)	EH4-Fall	-4.8	133.45	1.7	-2.1	1.5	4.8	8.6	12.2	6.4	9.0	-0.8	0.163	0.1909	Burkhardt et al., 2016	
Burkhardt (1)	EH5-Fall	-8.5	107.93	4.4	5.1	22.0	9.7	0.9	4.5	2.3	14.4	-14.2	0.100	0.1998	Burkhardt et al., 2016	
Burkhardt (2)	EH5-Fall	-9.6	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	6.8	0.1875	Burkhardt et al., 2016		
MS-177	EL3-Fall	-10.9	64.00	5.0	4.5	11.5	5.7	4.9	4.1	7.4	11.5	1.4	-1.1	0.1896	This study	
Abee	EH4-Fall	-43.6	99.05	17.0	-31.4	-32.9	17.1	15.3	17.4	28.4	32.7	-35.1	0.1901	0.1901	Boyet and Carlson 2005	
Atlanta (2)	EH4-Fall	-2.4	149.4	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.1875	Burkhardt et al., PNAS 2011		
St. James	EH5-Fall	22.0	265.1	4.3	-1.1	10.9	5.9	1.9	7.7	10.5	3.6	-26.2	1.8	0.2285	0.1888	Burkhardt et al., 2016

Carbonaceous Chondrites										
ALL										
n = 12	mean	-30.5	2.0	13.6	20.5			-31.8	-32.3	0.1920
	weighted mean	-31.4	1.4	15.1	16.1			-33.4	-33.7	
	ZSD	20.1	18.4	26.6	65.3			11.0	12.5	0.0246
	95% conf.	4.4	4.1	5.9	14.5			3.0	2.9	0.0061
	ZSE	4.3	3.9	5.7	13.9			2.9	2.8	
	n	22	22	22	22			20	20	18
Carbonaceous Chondrites										
Tagish Lake and NWA2090										
n = 10	mean	-32.4	2.8	14.7	21.9			-31.8	-32.3	0.1959
	weighted mean	-33.1	4.1	15.9	16.7			-32.3	-32.8	
	ZSD	16.3	18.7	26.9	68.0			13.0	12.5	0.0046
	95% conf.	3.8	4.1	5.9	14.5			3.0	2.9	0.0012
	ZSE	3.7	4.2	6.0	15.2			2.9	2.8	0.0011
	n	20	20	20	20			20	20	16
Ordinary Chondrites										
ALL										
n = 25	mean	-16.4	3.2	6.8	13.7			-14.8	-16.0	0.1924
	weighted mean	-16.2	2.1	6.9	13.1			-13.7	-15.4	
	ZSD	8.8	15.1	15.2	53.4			9.3	8.7	0.0224
	95% conf.	1.7	2.9	2.9	10.1			1.8	1.7	0.0044
	ZSE	1.6	2.8	2.8	9.9			1.8	1.7	0.0043
	n	29	29	29	29			27	28	27
Ordinary Chondrites										
Adrian										
n = 24	mean	-16.7	3.6	7.1	14.2			-14.8	-16.0	0.1946
	weighted mean	-16.4	2.7	6.6	13.5			-14.2	-15.9	
	ZSD	8.5	14.8	15.2	54.0			9.3	8.7	0.0033
	95% conf.	1.6	2.9	2.9	10.5			1.8	1.7	0.0007
	ZSE	1.6	2.8	2.9	10.2			1.8	1.7	0.0006
	n	28	28	28	28			27	28	26
Enstatite Chondrites										
ALL										
n = 19	mean	-9.6	1.8	0.2	15.4			-8.0	-10.5	0.1950
	weighted mean	-12.1	0.5	-5.6	8.0			-10.4	-12.7	
	ZSD	20.7	12.6	24.9	69.3			26.4	17.7	0.0084
	95% conf.	3.7	2.3	4.5	12.5			4.8	3.2	0.0016
	ZSE	3.7	2.2	4.4	12.2			4.7	3.1	0.0016
	n	32	32	32	32			32	32	29
Enstatite Chondrites										
-Abee B&C 2005, Kota Kota, Bishfield (1)										
n = 17	mean	-9.9	2.3	2.1	19.3			-8.3	-9.8	0.1950
	weighted mean	-10.6	2.2	-1.2	15.4			-8.9	-10.3	
	ZSD	12.1	11.1	21.0	66.4			14.8	11.5	0.0084
	95% conf.	2.3	2.1	4.0	12.6			2.8	2.2	0.0016
	ZSE	2.2	2.1	3.9	12.3			2.8	2.1	0.0016
	n	29	29	29	29			29	29	29
Enstatite Chondrites EL3										
n=4										
	mean	-5.7	1.8	-2.1	33.7			-3.2	-3.8	0.1947
	weighted mean	-1.3	-0.3	-7.2	4.6			-0.7	-0.8	0.0045
	ZSD	11.8	12.5	23.7	75.0			7.9	7.0	0.0065
	95% conf.	7.3								

**Table S2.**  
**Nd compositions of MS-177 and terrestrial samples**

	Nd (ng)	I145 (V)	<sup>142</sup> Nd/ <sup>144</sup> Nd	2SE	<sup>143</sup> Nd/ <sup>144</sup> Nd	2SE	<sup>145</sup> Nd/ <sup>144</sup> Nd	2SE	<sup>148</sup> Nd/ <sup>144</sup> Nd	2SE	<sup>150</sup> Nd/ <sup>144</sup> Nd	2SE	<sup>142</sup> Ce/ <sup>142</sup> Nd (ppm)	<sup>144</sup> Sm/ <sup>144</sup> Nd (ppm)	N
JNdi-1_F1R1	500	0.97	1.141852	0.000006	0.512110	0.000002	0.348403	0.000001	0.241576	0.000002	0.236445	0.000002	0.7	0.4	540
JNdi-1_F1R2	500	0.97	1.141850	0.000005	0.512112	0.000002	0.348403	0.000001	0.241578	0.000001	0.236445	0.000002	0.2	0.3	900
JNdi-1_F2R1	500	1.28	1.141847	0.000004	0.512110	0.000001	0.348403	0.000001	0.241579	0.000001	0.236446	0.000001	0.3	0.4	900
JNdi-1_F3R1	500	1.68	1.141853	0.000003	0.512111	0.000001	0.348403	0.000001	0.241579	0.000001	0.236448	0.000001	0.3	0.5	900
JNdi-1_F4R1	250	0.70	1.141844	0.000006	0.512108	0.000002	0.348402	0.000001	0.241579	0.000002	0.236448	0.000002	0.4	0.3	900
JNdi-1_F5R1	250	1.48	1.141851	0.000004	0.512114	0.000002	0.348404	0.000001	0.241579	0.000001	0.236448	0.000002	0.3	0.5	720
JNdi-1_F6R1	250	0.97	1.141852	0.000004	0.512112	0.000002	0.348403	0.000001	0.241579	0.000001	0.236446	0.000002	0.34	0.42	900
Mean JNdi-1			1.141850		0.512111		0.348403		0.241578		0.236446		0.4	0.4	
2s			0.000006		0.000004		0.000002		0.000002		0.000003				
2s (ppm)			5.6		7.4		4.4		8.2		10.9				
n			7		7		7		7		7				
MS177_F9R1	300	0.64	1.141838	0.000007	0.512439	0.000002	0.348405	0.000001	0.241581	0.000002	0.236448	0.000002	1.2	0.3	640