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

3  
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13 Keywords:  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics, enstatite chondrites, Earth's evolution, Earth's  
14 building blocks

15

16 **Abstract**

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

26 Sitta containing pristine fragments of an unmetamorphosed enstatite chondrite  
27 belonging to the EL3 subgroup. Once  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios are normalized to a common  
28 chondritic evolution, samples from the EC group (both EL and EH) have a deficit in  
29  $^{142}\text{Nd}$  but the dispersion is important ( $\mu^{142}\text{Nd} = -10 \pm 12$  (2SD) ppm). This scatter  
30 reflects their unique mineralogy associated to their formation in reduced conditions  
31 (low  $f\text{O}_2$  or high C/O). Rare-earth elements are mainly carried by the sulfide phase  
32 oldhamite (CaS) that is more easily altered than silicates by weathering since most of  
33 the EC meteorites are desert finds. The EL6 have fractionated rare-earth element  
34 patterns with depletion in the most incompatible elements. Deviations in Nd mass  
35 independent stable isotope ratios in enstatite chondrites relative to terrestrial standard  
36 are not resolved with the level of analytical precision achieved by modern mass  
37 spectrometry techniques. Here we show that enstatite chondrites from the EL3 and  
38 EL6 subgroups may come from different parent bodies. Samples from the EL3  
39 subgroup have Nd ( $\mu^{142}\text{Nd} = -0.8 \pm 7.0$ , 2SD) and Ru isotope ratios undistinguishable  
40 from that of the Bulk Silicate Earth. EL3 samples have never been analyzed for Mo  
41 isotopes. Because these enstatite chondrites are relatively small in size and number,  
42 they are usually not available for destructive isotopic measurements. Average values  
43 based on the measurement of EL6 samples should not be considered as representative  
44 of the whole EL group because of melting and thermal metamorphism events  
45 affecting the Sm/Nd ratios and prolonged open-system history. The EL3 chondrites  
46 are the best candidates as the Earth's building blocks. These new results remove the  
47 need to change the composition of refractory incompatible elements early in Earth's  
48 history.

49

## 50 **1. Introduction**

51

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

76 lithophile elements under terrestrial redox conditions (Bouhifd et al., 2015), a  
77 differentiation event of the silicate Earth in the first 30 Ma of Solar System history  
78 has been proposed to explain this offset. One type of model considers that the bulk  
79 Silicate Earth (BSE) preserves a relative chondritic abundance of refractory lithophile  
80 elements. The early-depleted mantle reservoir (high Sm/Nd) served as the source for  
81 magmatism since its formation whereas the enriched reservoir remains isolated from  
82 mantle convection and is still untapped (Boyet and Carlson, 2005). Other scenarios  
83 proposed that the complementary enriched reservoir (low Sm/Nd) has been lost to  
84 space by collisional erosion of planetesimals (Caro et al., 2008; O'Neill and Palme,  
85 2008) leaving the Bulk Earth depleted in incompatible elements and with a higher  
86 Sm/Nd ratio relative to the well-constrained average composition of whole-rock  
87 chondrites from the carbonaceous (CC), ordinary (OC) and enstatite (EC) chondrite  
88 groups (Bouvier et al., 2008).

89  
90       These models have been challenged by the discovery of variations in mass  
91 independent stable Sm and Nd isotope ratios in whole-rock chondrites and their  
92 components (Andreasen and Sharma, 2006; Carlson et al., 2007; Gannoun et al.,  
93 2011; Brennecka et al., 2013, Bouvier and Boyet, 2016; Burkhardt et al., 2016). The  
94 isotope  $^{142}\text{Nd}$  is mainly produced by *s-process* but has a small contribution of *p-*  
95 *process*, estimated to be lower than a few percent (Arlandini et al., 1999; Bisterzo et  
96 al., 2011). The parent isotope,  $^{146}\text{Sm}$  is a pure *p-process* nuclide so any variation in  
97 the *p* production would affect the abundance of its daughter isotope  $^{142}\text{Nd}$  as well.  
98 Although we have undisputable evidences for different contribution of *s-process*  
99 isotopes in Solar System materials and measurable variations in the  $^{142}\text{Nd}/^{144}\text{Nd}$   
100 ratios, the origin of the terrestrial  $^{142}\text{Nd}$  signature compared to the chondrite

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

109

110 We have compiled all the Nd isotope data published on EC so far. We also  
111 present the first measurements on an observed fall Almahata Sitta containing  
112 fragments of the EL3 subgroup, such as the fragment MS-177. The fireball of  
113 Almahata Sitta fall was captured on camera in northern Sudan on October 7<sup>th</sup> 2008.  
114 Its trajectory was back-tracked to a small asteroid called 2008 TC<sub>3</sub> (Bischoff et al.,  
115 2010). Additionally, REE concentration measurements are presented for samples  
116 belonging to the two subgroups of enstatite chondrites (EH and EL). Since the  
117 identification of <sup>142</sup>Nd variations attributed to nucleosynthetic anomalies requires a  
118 comparison at the same Sm/Nd evolution, we present in detail two methods of  
119 calculations used for normalization of all chondrites to a common Sm/Nd and the  
120 difficulties inherent to the enstatite chondrite sub-groups. The <sup>142</sup>Nd/<sup>144</sup>Nd ratios are  
121 then compared to the corresponding mass independent stable Nd isotope ratios for  
122 each meteorite to establish their significance with respect to the distribution of  
123 nucleosynthetic anomalies amongst the chondrite groups. Finally, their potential  
124 contributions as Earth's building blocks are discussed.

125

126

## 127 **2. Samples and Methods**

### 128 **2.1. Trace element contents in EC**

129

130 Rare earth element concentrations have been measured for 12 EC from EH (4)  
131 and EL (8) sub-groups. The meteorite names and sample subgroups are reported in  
132 Table 1. Two techniques of dissolution have been used: 1) samples were digested in  
133 PFA Savillex® beakers using a mixture of concentrated HF-HNO<sub>3</sub> acids in 3:1  
134 proportion at 120°C on hot plate during 48h; 2) samples were digested in individual  
135 Parr® pressure vessels in concentrated HF-HNO<sub>3</sub> (10:1) for 5 days at 155°C. In both  
136 cases, after drying down the samples, perchloric acid was added and evaporated on a  
137 hot plate to break down the fluorides. After successive dissolution/evaporation cycles  
138 in concentrated HNO<sub>3</sub>, samples were taken back into solution in PFA Savillex®  
139 beakers or in Parr® pressure vessels in 6M HCl. All measurements were performed  
140 using the Agilent 7500 quadrupole ICP-MS at the Laboratoire Magmas et Volcans  
141 (LMV) in Clermont-Ferrand, with the exception of Almahata Sitta MS-177 and  
142 Hvittis that were measured at the University Western Ontario using a Thermo iCAP  
143 Qc quadrupole ICP-MS. Both ICP-MS are equipped with He collision cells. Samples  
144 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  
145 laboratories, respectively. Counts per second were calibrated using rock standards  
146 BCR-2, BHVO-2 or BIR 1a. The rock standards and a synthetic standard solution  
147 (CMS) were routinely analyzed to validate the efficiency of the digestion procedures  
148 and the accuracy and precision of the acquired data. Blank and standard solutions  
149 were measured every 4 samples. Both the external reproducibility estimated from

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

152

153

## 154 **2.2. $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ systematics and mass independent stable Nd isotopes**

155

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

167

168 The separation procedure for the Nd isotopic composition required 3 steps as  
169 described in Garçon et al. (2018). The Ce was separated from other trivalent REE  
170 using the oxidation of Ce to  $\text{Ce}^{4+}$  on Ln-Spec resin (Tazoe et al., 2007; Li et al.,  
171 2015). Then the separation between Nd and Sm was achieved on Ln-Spec resin using  
172 0.20N to 0.25N HCl. Total procedural blanks are generally lower than a few tens of pg  
173 for Nd. The Nd isotopic compositions were measured as  $\text{Nd}^+$  using the LMV Triton  
174 Plus™ Multicollector Thermal Ionization Mass Spectrometer. For MS-177, Nd

175 isotope ratios were obtained in static mode following the method described in  
176 Gannoun et al. (2011a). Static measurements were preferred because the amount of  
177 Nd was small (~300 ng for MS-177) and dynamic routines require large sample size  
178 (e.g. 750 ng for the 4-line acquisition scheme developed by Garçon et al., 2018). In  
179 addition, we used a mass spectrometer equipped with new faraday collectors (6  
180 month-old). No sign of deterioration of the faraday collectors was identified during  
181 the measurements. Ce and Sm contributions, monitored at masses 140 and 147  
182 respectively, were lower than 3 ppm on masses 142 and 144 for both standard and  
183 sample measurements. Nd isotope ratios were corrected for mass fractionation to  
184  $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$  using the exponential mass-fractionation law. The external  
185 reproducibility (2SD) calculated from 6 repeated measurements of the JNdi-1  
186 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  $^{145}\text{Nd}/^{144}\text{Nd}$ ,  
187 8.2 ppm on  $^{148}\text{Nd}/^{144}\text{Nd}$ , and 10.9 ppm on  $^{150}\text{Nd}/^{144}\text{Nd}$  (Table 2).

188

### 189 **3. Results**

190

191 The new REE data are reported in Table 1 and compared to published values  
192 from Gannoun et al. (2011b) and Barrat et al. (2014) in Figure 1. Data from  
193 Kalleyman and Wasson (1986) is not shown in Figure 1 because they reported the  
194 concentrations of only 5 REEs (La, Sm, Eu, Yb, and Lu), which is insufficient to  
195 define proper REE patterns. All EH samples have flat REE patterns with  
196 concentrations very similar to those reported in CI, except Kota Kota (EH3) that is  
197 enriched in LREE (Figure 1A). This split is the most visibly weathered in color and  
198 texture of our collection, and the meteorite was described as a strongly weathered EC  
199 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.

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

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

245

246

## 247 **4. Discussion**

### 248 **4.1. $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$ systematics in enstatite chondrites**

249

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

275 significantly affected by neutron fluence effects and that the correction on  $^{142}\text{Nd}/^{144}\text{Nd}$   
276 ratios is negligible or within the measurement precision (e.g. Boyet and Carlson,  
277 2005; Bouvier and Boyet, 2016). McCoy-West et al. (2017) have determined the  
278 mass-dependent stable Nd isotope composition using a double spike technique.  
279 Chondrites and terrestrial samples have identical isotopic compositions with  
280  $\delta^{146}\text{Nd}/^{144}\text{Nd} = -0.025 \pm 0.025\%$  (2SD; n=39) and  $\delta^{146}\text{Nd}/^{144}\text{Nd} = -0.022 \pm 0.034\%$   
281 (2SD; n=30) respectively. These results imply that no bias is produced by the  
282 correction of instrumental mass fractionation effects when processing the raw data.

283

284 The first high-precision  $^{142}\text{Nd}$  measurements on chondrites have shown that  
285 differences in  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios existed among chondrite groups and that these  
286 variations were not correlated with changes of Sm/Nd ratios (Boyet and Carlson  
287 2005). The new compilation combining all data measured on chondrites since 2005  
288 leads to the same conclusion. The different groups of chondrites have different  
289 measured  $^{142}\text{Nd}/^{144}\text{Nd}$  values (Figure 3A). We note that results obtained from  
290 different chondrite fragments which were processed in different labs using different  
291 analytical techniques are in good agreement. On average carbonaceous chondrites  
292 (CC) have a  $\mu^{142}\text{Nd}$  of  $-31 \pm 20$  (2SD) ppm, ordinary chondrites (OC) of  $-16 \pm 9$   
293 (2SD) ppm and EC of  $-12 \pm 21$  (2SD) ppm. Although standard deviations overlap,  
294 two sample t-tests strongly suggest that the three populations of chondrites are distinct  
295 from each other with p-values lower than 0.05 (p-value CC-OC =  $1.5 \times 10^{-8}$ ; p-value  
296 CC-EC =  $8.9 \times 10^{-10}$ ; p-value OC-EC = 0.004). Five samples have  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios  
297 far from the CHUR value of 0.1960 (dashed line in Figure 4A and 4B; Bouvier et al.,  
298 2008): NWA 2090 (CO3) and Tagish Lake (C2-ungrouped, not represented in the  
299 figure:  $^{147}\text{Sm}/^{144}\text{Nd}=0.148$ ) for CC, Adrian (H4) for OC (not represented in the figure:

300  $^{147}\text{Sm}/^{144}\text{Nd}=0.137$ ), and Kota Kota and Blithfield for EC. Moreover one EC sample  
 301 displays an extreme  $\mu^{142}\text{Nd}$  value and this measurement has a large error bar (Abee: -  
 302  $44 \pm 17$  (2SE) ppm (Boyet and Carlson 2005). When all these samples are excluded  
 303 from the averaging calculation, CC have a  $\mu^{142}\text{Nd}$  of  $-33 \pm 16$  (2SD) ppm, OC of  $-16$   
 304  $\pm 9$  (2SD) ppm and EC of  $-11 \pm 12$  (2SD) ppm. All these groups have similar  
 305 measured Sm/Nd ratios even if a larger range is observed for EC (Figure 4A, B).  
 306 When the same samples are selected, the mean  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of each group is  
 307  $0.1959 \pm 0.0046$  (2SD) for CC,  $0.1946 \pm 0.0033$  (2SD) for OC and  $0.1950 \pm 0.0084$   
 308 (2SD) for EC. The median values are equal to 0.1953, 0.1951 and 0.1952 for these 3  
 309 groups, respectively. CC and OC have normal distributions whereas EC present a  
 310 larger scatter. These values are slightly lower than the CHUR value of  $0.1960 \pm$   
 311  $0.0004$  (2SD) defined from the average of unequilibrated chondrites (Bouvier et al.,  
 312 2008) but are similar within uncertainties. Two sample t-tests further confirm that the  
 313 mean  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios of the three populations are undistinguishable from each  
 314 other since p-values are much higher than 0.05 (p-value CC-OC = 0.9; p-value CC-  
 315 EC = 0.3; p-value OC-EC = 0.3).

316

317 The measured abundance of  $^{142}\text{Nd}$  comes from two distinct contributions: its  
 318 initial abundance and the quantity produced with time by the decay of  $^{146}\text{Sm}$ . Since  
 319  $^{146}\text{Sm}$  was alive only during the first 500 Ma of Solar System history, we can write  
 320 the following equations:

$$321 \quad ^{142}\text{Nd}_{meas} = ^{142}\text{Nd}_{T0} + ^{146}\text{Sm}_{T0} \quad (1)$$

$$322 \quad (^{142}\text{Nd}/^{144}\text{Nd})_{meas} = (^{142}\text{Nd}/^{144}\text{Nd})_{T0} + (^{146}\text{Sm}/^{144}\text{Nd})_{T0} \quad (2)$$

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

326 These equations show that any fractionation of the Sm/Nd ratio during the  $^{146}\text{Sm}$   
327 lifetime will significantly affect the measured  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios. In order to compare  
328 initial  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios between chondrites, the data are thus corrected from the  
329  $^{142}\text{Nd}$  radiogenic production since the formation of the Solar System and normalized  
330 to a common chondritic evolution following the CHUR parameters defined by  
331 Bouvier et al. (2008). Two different methods of calculation can be used assuming a  
332 modification of the Sm/Nd ratio either early in the Solar system history or once the  
333  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics is extinct.

334

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

336 This correction is illustrated in Figure 5A. The  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio of the sample is  
337 calculated back in time to the age of the Solar System formation, *i.e.* 4.568 Ga  
338 (Bouvier and Wadhwa, 2010) using the *measured*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio. From this initial  
339  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio, a modern value is recalculated using the CHUR  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio  
340 of 0.1960 (Bouvier et al., 2008). Such a correction assumes that the modification of  
341 the Sm/Nd ratio occurred at the beginning of Solar System history *i.e.* when the  
342 chondrites form.

343

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

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

348 due to weathering, are not recorded in the evolution of  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, the  
349  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio is deduced from the measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios considering that all  
350 samples evolved from the same initial  $^{143}\text{Nd}/^{144}\text{Nd}$  value of 0.506686 which  
351 corresponds to the composition of the CHUR at 4.568 Ga (Bouvier et al., 2008).  
352 Then, the normalized-CHUR  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio is calculated following the steps  
353 described in Method A using the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of the CHUR from 4.568 Ga to  
354 present-day.

355

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

369

370 Weighted averages for CC, OC and EC are  $-32 \pm 13$  (2SD),  $-15 \pm 9$  (2SD),  $-8$   
371  $\pm 15$  (2SD) for the method A and  $-32 \pm 13$  (2SD),  $-16 \pm 9$  (2SD), and  $-10 \pm 12$  (2SD)  
372 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 ( $(\text{La}/\text{Yb})_{\text{N}} = 1-15$ ) 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

398 occasionally with diopside (El Goresy et al., 2017). Its occurrence in metal-dominated  
399 nodules is less common. Although metal-sulfide nodules are more subject to  
400 oxidation/weathering than silicate assemblages, CaS enclosed in metal should be  
401 better preserved because metal has no fracture veins like silicates. No clear  
402 relationship has been found between REE fractionation and the type of samples  
403 (group, fall vs. found, etc). To minimize the amplitude of the correction on  
404  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios and reduce the errors caused by a potential Sm/Nd fractionation  
405 during weathering, we selected a subset of EC samples (11 samples, 16  
406 measurements) with measured  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios very close to the CHUR value i.e.  
407 between 0.1926 and 0.1994 ( $\pm 1.7\%$ ). Within this range, the correction reaches a  
408 maximum of  $\pm 5$  ppm on the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios, i.e. equivalent to the average external  
409 reproducibility. Taking only this subset of EC samples yields an average  $\mu^{142}\text{Nd}$  of -  
410  $10 \pm 12$  (2SD) for the two methods A and B, hence does not change the mean nor  
411 improve the standard deviation obtained for the whole EC group.

412

413

#### 414 **4.2. Stable Nd isotope signature of EC relative to other groups**

415

416 Neodymium has 7 isotopes from mass 142 to 150. Nucleosynthetic anomalies,  
417 which are mass-independent variations, can be identified by measuring 3 stable  
418 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  
419  $^{143}\text{Nd}/^{144}\text{Nd}$  are modified by radiogenic productions from  $^{146}\text{Sm}$  and  $^{147}\text{Sm}$   
420 respectively, and  $^{146}\text{Nd}/^{144}\text{Nd}$  is used for internal mass bias correction and  
421 normalization to a common ratio value of 0.7219. Except  $^{142}\text{Nd}$  which is mainly  
422 produced by *s-process* and  $^{150}\text{Nd}$  which is a pure *r-process* nuclide, all other isotopes

423 are formed by a combination of *s*- and *r*-processes in different stellar environments  
424 (Arlandini et al., 1999; Bisterzo et al., 2011). A change in the *s*/*r* proportions thus  
425 modifies the Nd isotope patterns. Excess in *s*-process produces excess in  $^{142}\text{Nd}$  and  
426 deficits in  $^{143}\text{Nd}$ ,  $^{145}\text{Nd}$ ,  $^{148}\text{Nd}$  and  $^{150}\text{Nd}$  with the deficits increasing from mass 143 to  
427 mass 150. Measurements obtained on individual EC are presented in Figure 6. The  
428 average values for both CC and OC groups are shown for comparison. For clarity,  
429 errors bars (2SD) are not shown in the figure but are instead provided in the figure  
430 caption. The large errors calculated for CC reflect the variability of *s*-process nuclides  
431 among this group owing to the contribution of CAIs. In a  $\mu^{150}\text{Nd}$  vs  $\mu^{148}\text{Nd}$  binary  
432 plot, bulk CC and separated CAIs plot on the mixing line calculated from isotope  
433 production in stellar models (see Fig. 3 in Bouvier and Boyet, 2016). CAIs can be the  
434 carrier of large *s*-process excess signature with deficits in  $\mu^{148}\text{Nd}$  and  $\mu^{150}\text{Nd}$  of  
435 several tens of ppm (Brennecka et al., 2013; Marks et al., 2014; Bouvier and Boyet,  
436 2016).

437

438 The compositions of EC are scattered in the 3 binary plots without any clear  
439 correlation (Figure 6). Results of mixing of the *s*-model prediction with the terrestrial  
440 composition are indicated by the dashed lines depending on the model used: 1) stellar  
441 model by Arlandini et al. (1999) or 2) using the composition of SiC as representative  
442 of a pure *s*-process component (Hopp and Ott, 1997). Deficits in  $^{142}\text{Nd}$  measured in  
443 enstatite chondrites from the EH group and the EL6 subgroup are small and equal to -  
444 11 ppm in average. For such small deficit, the expected deviations in 145, 148 and  
445 150-Nd are equal to +5, +11 and +17 ppm, respectively. These variations remain very  
446 small in comparison to the measurement precision (external reproducibility) obtained  
447 with the last generation of multi-collector thermal ionization mass spectrometers

448 (TIMS). In the recent study of Burkhardt et al. (2016), both  $^{142}\text{Nd}/^{144}\text{Nd}$  and  
449  $^{148}\text{Nd}/^{144}\text{Nd}$  ratios were measured using a dynamic procedure leading to better  
450 external reproducibilities than static measurements. The relative deterioration of the  
451 Faraday collectors and their change of efficiency through time are important sources  
452 of imprecision and inaccuracy for the determination of isotope ratios using static  
453 multicollection (Makishima and Nakamura, 1991; Thirlwall, 1991). However, even  
454 with dynamic procedures on TIMS, the external reproducibilities for  $^{148}\text{Nd}/^{144}\text{Nd}$   
455 reach 11 and 15 ppm on repeated measurements of the BHVO-2 rock standard and  
456 JNdi-1 standard, respectively. Better precisions have been recently reported by Saji et  
457 al. (2016) using multi-collector inductively coupled plasma mass spectrometry and a  
458 sample-standard bracketing technique. Five measurements of the carbonaceous  
459 chondrite Allende (CV3) give an external reproducibility of 1 ppm on the  $^{148}\text{Nd}/^{144}\text{Nd}$   
460 ratio with intensity of 14 V at mass 142. Because enstatite chondrites are about 2  
461 times more depleted in Nd than CV3 carbonaceous chondrites, this technique would  
462 require large quantities of EC samples (i.e. 2 g). A new 4-mass-step acquisition  
463 scheme developed by Garçon et al. (2018) by thermal ionization mass spectrometry is  
464 very promising because this routine is able to return all Nd isotope ratios dynamically  
465 and provide a robust evaluation of the data to assess the quality of the data (e.g.,  
466 mixing effects on the filament, fractionation between acquisition steps).

467

468

### 469 **4.3. The isotope similarity between EL3 samples and the Earth**

470

471 Amongst all the classified meteorites, enstatite chondrites represent only 2%  
472 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

523 composition. A difference between Earth and EC has been reported for Mo isotopes  
524 but no EL3 samples have been analyzed in this dataset meaning that the reported  
525 average Mo isotopic composition of EC is based on EL6 samples only (Burkhardt et  
526 al., 2011; Dauphas et al., 2002; Dauphas 2017). The Zn isotopic compositions of the  
527 two EL3 chondrites measured by Moynier et al. (2011) are also identical to the  
528 terrestrial values, whereas the analyzed EL6 chondrites are all enriched in heavy  
529 isotopes and highly depleted in Zn. The origin of the volatile element depletion  
530 between EL3 and EL6 chondrites can be explained by volatilization, probably during  
531 thermal metamorphism. All these measurements suggest that EL samples do not come  
532 from a single parent body. Similar conclusions were reached from petrographic and  
533 geochemical observations for EH3 samples. Both normal and reverse MgS–FeS  
534 zoning profiles in niningerite grains adjacent to troilite reveal an origin on different  
535 parental asteroids with different MnS-contents in the niningerites (Lin and El Goresy,  
536 2002; Gannoun et al., 2011b). At least 8 different parent bodies have been recently  
537 proposed for the entire EC group based on chemical variations measured in sulfide  
538 and metal phases (Weyrauch et al., 2017). However all these samples share very close  
539 isotope signatures suggesting they condensed within the same region of the solar  
540 nebula. Although our conclusion supports a genetic relationship between EL3 samples  
541 and the Earth, this statement is based on the analysis of cosmochemical materials  
542 present in our meteorite collection that represent a very small record of materials  
543 present in the Solar System. Recent high-precision Mo and Ru isotope measurements  
544 have highlighted a terrestrial signature in IAB iron meteorites indicating that their  
545 parent bodies could be the building blocks of the Earth (Worsham et al., 2017).  
546 Unfortunately the lithophile behavior of REE makes it impossible to study these  
547 meteorites for  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics.

548

549

## 550 **5. Conclusion**

551

552 Among all groups of chondrites, EC have measured  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios the  
553 closest to the modern terrestrial signature ( $\mu^{142}\text{Nd} = -11 \pm 12$  (2SD) ppm). In order to  
554 compare initial  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios, data must be corrected from the  $^{142}\text{Nd}$  radiogenic  
555 production since the formation of the Solar System. Two methods of corrections are  
556 compared (*measured*  $^{147}\text{Sm}/^{144}\text{Nd}$  vs. *integrated*  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios). The two methods  
557 yield results that are identical within the errors bars. Enstatite chondrites show a  
558 larger scatter of Sm/Nd ratios in comparison to other chondrite groups that can be  
559 attributed to early fractionation processes (e.g. samples from the EL6 subgroup)  
560 and/or recent changes caused by weathering. In these chondrites, REE are mainly  
561 concentrated in the calcium-sulfide phase (oldhamite), which is very sensitive to  
562 weathering. For this latter reason we conclude that corrections based on *integrated*  
563  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios are more accurate for enstatite chondrites. The average of these  
564 corrected values  $\mu^{142}\text{Nd}$  give  $-10 \pm 12$  (2SD) ppm. We report no significant variation  
565 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  
566 relative to terrestrial Nd standard.

567

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

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

585

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587

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598

599

600 **References**

- 601 Anders, E., & Grevesse, N. (1989). Abundances of the elements: Meteoritic and solar.  
602 *Geochimica et Cosmochimica acta*, 53(1), 197-214.
- 603 Andreasen, R., Sharma, M. (2006). Solar nebula heterogeneity in p-process samarium  
604 and neodymium isotopes. *Science*, 314(5800), 806-809.
- 605 Arlandini, C., Käppeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., &  
606 Straniero, O. (1999). Neutron capture in low-mass asymptotic giant branch stars:  
607 cross sections and abundance signatures. *The Astrophysical Journal*, 525(2), 886-  
608 900.
- 609 Barrat, J. A., Zanda, B., Jambon, A., & Bollinger, C. (2014). The lithophile trace  
610 elements in enstatite chondrites. *Geochimica et Cosmochimica Acta*, 128, 71-94.
- 611 Bermingham, K. R., Mezger, K., Scherer, E. E., Horan, M. F., Carlson, R. W.,  
612 Upadhyay, D., ... & Pack, A. (2016). Barium isotope abundances in meteorites and  
613 their implications for early Solar System evolution. *Geochimica et cosmochimica*  
614 *acta*, 175, 282-298.
- 615 Bischoff, A., Horstmann, M., Pack, A., Laubenstein, M., & Haberer, S. (2010).  
616 Asteroid 2008 TC3—Almahata Sitta: A spectacular breccia containing many  
617 different ureilitic and chondritic lithologies. *Meteoritics & Planetary Science*,  
618 45(10 - 11), 1638-1656.
- 619 Bisterzo, S., Gallino, R., Staniero, O., Cristallo, S., Käppeler, F., 2011. The s-process  
620 in lowmetallicity stars -II. Interpretation of high-resolution spectroscopic ob-  
621 servations with asymptotic giant branch models. *Mon. Not. R. Astron. Soc.*418,  
622 284–319.

623 Bouhifd, M. A., Boyet, M., Cartier, C., Hammouda, T., Bolfan-Casanova, N.,  
624 Devidal, J. L., Andraut, D. (2015). Superchondritic Sm/Nd ratio of the Earth:  
625 Impact of Earth's core formation. *Earth and Planetary Science Letters*, 413, 158-  
626 166.

627 Bouvier, A., Vervoort, J. D., & Patchett, P. J. (2008). The Lu–Hf and Sm–Nd isotopic  
628 composition of CHUR: constraints from unequilibrated chondrites and  
629 implications for the bulk composition of terrestrial planets. *Earth and Planetary  
630 Science Letters*, 273(1), 48-57.

631 Bouvier, A., & Wadhwa, M. (2010). The age of the Solar System redefined by the  
632 oldest Pb-Pb age of a meteoritic inclusion. *Nature Geoscience*, 3(9), 637-641.

633 Bouvier, A., Boyet, M. (2016). Primitive Solar System materials and Earth share a  
634 common initial  $^{142}\text{Nd}$  abundance. *Nature*, 537, 399-402.

635 Boyet, M., Carlson, R.W. (2005)  $^{142}\text{Nd}$  Evidence for Early (>4.53 Ga) Global  
636 Differentiation of the Silicate Earth. *Science*, 309, 576-581.

637 Brennecka, G. A., Borg, L. E., & Wadhwa, M. (2013). Evidence for supernova  
638 injection into the solar nebula and the decoupling of r-process nucleosynthesis.  
639 *Proceedings of the National Academy of Sciences*, 110, 17241-17246.

640 Burkhardt, C., Kleine, T., Oberli, F., Pack, A., Bourdon, B., Wieler, R. (2011).  
641 Molybdenum isotope anomalies in meteorites: constraints on solar nebula  
642 evolution and origin of the Earth. *Earth and Planetary Science Letters*, 312, 390-  
643 400.

644 Burkhardt, C., Borg, L. E., Brennecka, G. A., Shollenberger, Q. R., Dauphas, N.,  
645 Kleine, T. (2016). A nucleosynthetic origin for the Earth's anomalous  $^{142}\text{Nd}$   
646 composition. *Nature*, 537, 394-398.

647 Carlson, R.W., Boyet, M., Horan, M. (2007) Chondrite barium, neodymium, and  
648 samarium isotopic heterogeneity and Early Earth Differentiation, *Science*, 316,  
649 1175-1178.

650 Caro, G., Bourdon, B., Halliday, A. N., & Quitté, G. (2008). Super-chondritic Sm/Nd  
651 ratios in Mars, the Earth and the Moon. *Nature*, 452, 336-339.

652 Crozaz, G., & Lundberg, L. L. (1995). The origin of oldhamite in unequilibrated  
653 enstatite chondrites. *Geochimica et Cosmochimica Acta*, 59, 3817-3831.

654 Dauphas, N. (2017). The isotopic nature of the Earth's accreting material through  
655 time. *Nature*, 541, 521-524.

656 Dauphas, N., Marty, B., & Reisberg, L. (2002). Inference on terrestrial genesis from  
657 molybdenum isotope systematics. *Geophysical Research Letters*, 29(6). 8.1-8.3

658 Dauphas, N., Poitrasson, F., Burkhardt, C., Kobayashi, H., & Kurosawa, K. (2015).  
659 Planetary and meteoritic Mg/Si and  $\delta^{30}\text{Si}$  variations inherited from solar nebula  
660 chemistry. *Earth and Planetary Science Letters*, 427, 236-248.

661 El Goresy, A., Yabuki, H., Ehlers, K., Woolum, D., & Pernicka, E. (1988). Qingzhen  
662 and Yamato-691: A tentative alphabet for the EH chondrites. In *Proceedings of the*  
663 *NIPR Symposium on Antarctic Meteorites* (Vol. 1, pp. 65-101).

664 El Goresy, A., Lin, Y., Miyahara M., Gannoun A., Boyet M., Ohtani, E., Gillet, P.,  
665 Trieloff, M., Simionovici, A., Feng, L., Lemelle, L. (2017). Origin of EL3  
666 chondrites: evidences for variable C/O ratios during their course of formation – A  
667 state of the art scrutiny. *Meteoritics & Planetary Science*, 52, 781–806.

668 Fitoussi, C., Bourdon, B. (2012) Silicon isotope evidence against an enstatite  
669 chondrite Earth. *Science*, 335, 1477-1480.

670 Fischer-Gödde, M., Kleine T. (2017) Ruthenium isotopic evidence for an inner Solar  
671 System origin of the late veneer. *Nature*, 541, 525-527. doi:10.1038/nature21045.

672 Floss, C., & Crozaz, G. (1993). Heterogeneous REE patterns in oldhamite from  
673 aubrites: Their nature and origin. *Geochimica et Cosmochimica Acta*, 57, 4039-  
674 4057.

675 Floss, C., Strait, M. M., & Crozaz, G. (1990). Rare earth elements and the  
676 petrogenesis of aubrites. *Geochimica et Cosmochimica Acta*, 54, 3553-3558.

677 Fukai, R., & Yokoyama, T. (2017). Neodymium isotope heterogeneity of ordinary  
678 and carbonaceous chondrites and the origin of non-chondritic  $^{142}\text{Nd}$  compositions  
679 in the Earth. *Earth and Planetary Science Letters*, 474, 206-214.

680 Gannoun, A., Boyet, M., Rizo, H., El Goresy, A. (2011a).  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics  
681 measured in enstatite chondrites reveals a heterogeneous distribution of  $^{142}\text{Nd}$  in  
682 the solar nebula. *Proceedings of the National Academy of Sciences*, 108, 7693-  
683 7697.

684 Gannoun, A., Boyet, M., El Goresy, A., Devouard, B. (2011b). REE and actinide  
685 microdistribution in Sahara 97072 and ALHA77295 EH3 chondrites. *Geochimica  
686 et Cosmochimica Acta*, 75, 3269-3289.

687 Gautam, I., Ray, J. S., Bhutani, R., Balakrishnan, S., & Dash, J. K. (2017). Role of  
688 fractionation correction in accurate determination of  $^{142}\text{Nd}/^{144}\text{Nd}$  by TIMS: A  
689 case study of 1.48 Ga alkaline rocks from Khariar, India. *Chemical Geology*, 466,  
690 479-490.

691 Garçon M., Boyet M., Carlson R.W., Horan M.F., Auclair D., Mock T.D. (2018)  
692 Factors influencing the precision and accuracy of Nd isotope measurements by  
693 thermal ionization mass spectrometry. *Chemical Geology*, 476, 493-514.

694 Hopp, J., Trieloff, M., Ott, U., Korochantseva, E. V., & Buykin, A. I. (2014).  $^{39}\text{Ar}$  -  
695  $^{40}\text{Ar}$  chronology of the enstatite chondrite parent bodies. *Meteoritics & Planetary  
696 Science*, 49, 358-372.

697 Hoppe, P., & Ott, U. (1997). Mainstream silicon carbide grains from meteorites. In  
698 *AIP Conference Proceedings*, 402, No. 1, pp. 27-58.

699 Izawa, M. R. M., King, P. L., Flemming, R. L., Peterson, R. C., & McCausland, P. J.  
700 A. (2010). Mineralogical and spectroscopic investigation of enstatite chondrites by  
701 X - ray diffraction and infrared reflectance spectroscopy. *Journal of Geophysical*  
702 *Research: Planets*, 115(E7). E07008, doi:10.1029/2009JE003452

703 Jackson, M. G., Carlson, R. W., Kurz, M. D., Kempton, P. D., Francis, D., &  
704 Blusztajn, J. (2010). Evidence for the survival of the oldest terrestrial mantle  
705 reservoir. *Nature*, 466, 853-858.

706 Javoy, M. (1995). The integral enstatite chondrite model of the Earth. *Geophysical*  
707 *Research Letters*, 22(16), 2219-2222.

708 Javoy, M., Kaminski, E., Guyot, F., Andrault, D., Sanloup, C., Moreira, M., ... &  
709 Jaupart, C. (2010). The chemical composition of the Earth: Enstatite chondrite  
710 models. *Earth and Planetary Science Letters*, 293(3), 259-268.

711 Kallemeyn, G. W., & Wasson, J. T. (1986). Compositions of enstatite (EH3, EH4, 5  
712 and EL6) chondrites: Implications regarding their formation. *Geochimica et*  
713 *Cosmochimica Acta*, 50, 2153-2164.

714 Kaminski, E., & Javoy, M. (2013). A two-stage scenario for the formation of the  
715 Earth's mantle and core. *Earth and Planetary Science Letters*, 365, 97-107.

716 Larimer, J. W., & Bartholomay, M. (1979). The role of carbon and oxygen in cosmic  
717 gases: Some applications to the chemistry and mineralogy of enstatite chondrites.  
718 *Geochimica et Cosmochimica Acta*, 43, 1455-1466.

719 Leitch, C. A., & Smith, J. V. (1982). Petrography, mineral chemistry and origin of  
720 Type I enstatite chondrites. *Geochimica et Cosmochimica Acta*, 46(11), 2083-  
721 2097.

722 Li, C. F., Li, X. H., Li, Q. L., Guo, J. H., Li, X. H., Feng, L. J., & Chu, Z. Y. (2012).  
723 Simultaneous determination of  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{147}\text{Sm}/^{144}\text{Nd}$  ratios and Sm–Nd  
724 contents from the same filament loaded with purified Sm–Nd aliquot from  
725 geological samples by isotope dilution thermal ionization mass spectrometry.  
726 *Analytical chemistry*, 84(14), 6040-6047.

727 Li, C.-F., Wang, X.-C., Li, Y.-L., Chu, Z.-Y., Guo, J.-H., Li, X.-H., 2015. Ce–Nd  
728 separation by solid-phase micro-extraction and its application to high-precision  
729  $^{142}\text{Nd}/^{144}\text{Nd}$  measurements using TIMS in geological materials. *J. Anal. At.*  
730 *Spectrom.* 30, 895–902. <http://dx.doi.org/10.1039/C4JA00328D>.

731 Lin, Y., & El Goresy, A. (2002). A comparative study of opaque phases in Qingzhen  
732 (EH3) and MacAlpine Hills 88136 (EL3): Representatives of EH and EL parent  
733 bodies. *Meteoritics & Planetary Science*, 37(4), 577-599.

734 Makishima, A., & Nakamura, E. (1991). Calibration of Faraday cup efficiency in a  
735 multicollector mass spectrometer. *Chemical Geology: Isotope Geoscience section*,  
736 94(2), 105-110.

737 Marks, N. E., Borg, L. E., Hutcheon, I. D., Jacobsen, B., & Clayton, R. N. (2014).  
738 Samarium–neodymium chronology and rubidium–strontium systematics of an  
739 Allende calcium–aluminum-rich inclusion with implications for  $^{146}\text{Sm}$  half-life.  
740 *Earth and Planetary Science Letters*, 405, 15-24.

741 McCoy-West, A. J., Millet, M. A., & Burton, K. W. (2017). The neodymium stable  
742 isotope composition of the silicate Earth and chondrites. *Earth and Planetary*  
743 *Science Letters*, 480, 121-132.

744 Michel-Lévy, M. C., & Bourot-Denise, M. (1988). A new look at the Galim (a) and  
745 Galim (b) meteorites. *Mineral. Mag*, 52, 519-525.

746 Moynier, F., Paniello, R. C., Gounelle, M., Albarède, F., Beck, P., Podosek, F., &  
747 Zanda, B. (2011). Nature of volatile depletion and genetic relationships in enstatite  
748 chondrites and aubrites inferred from Zn isotopes. *Geochimica et Cosmochimica*  
749 *Acta*, 75(1), 297-307.

750 O'Neil, J., Carlson, R. W., Francis, D., & Stevenson, R. K. (2008). Neodymium-142  
751 evidence for Hadean mafic crust. *Science*, 321(5897), 1828-1831.

752 O'Neill, H. S. C., & Palme, H. (2008). Collisional erosion and the non-chondritic  
753 composition of the terrestrial planets. *Philosophical Transactions of the Royal*  
754 *Society of London A: Mathematical, Physical and Engineering Sciences*,  
755 366(1883), 4205-4238.

756 Piani, L., Marrocchi, Y., Libourel, G., & Tissandier, L. (2016). Magmatic sulfides in  
757 the porphyritic chondrules of EH enstatite chondrites. *Geochimica et*  
758 *Cosmochimica Acta*, 195, 84-99.

759 Rankenburg, K., Brandon, A. D., & Neal, C. R. (2006). Neodymium isotope evidence  
760 for a chondritic composition of the Moon. *Science*, 312(5778), 1369-1372.

761 Rubin, A. E., Huber, H., & Wasson, J. T. (2009). Possible impact-induced refractory-  
762 lithophile fractionations in EL chondrites. *Geochimica et Cosmochimica Acta*,  
763 73(5), 1523-1537.

764 Russell, S. S., Folco, L., Grady, M. M., Zolensky, M. E., Jones, R., Righter, K., ... &  
765 Grossman, J. N. (2004). The meteoritical bulletin, no. 88, 2004 July. *Meteoritics &*  
766 *Planetary Science*, 39(S8).

767 Saji, N. S., Wielandt, D., Paton, C., & Bizzarro, M. (2016). Ultra-high-precision Nd-  
768 isotope measurements of geological materials by MC-ICPMS. *Journal of*  
769 *analytical atomic spectrometry*, 31(7), 1490-1504.

770 Savage, P. S., Moynier, F. (2013). Silicon isotopic variation in enstatite meteorites:  
771 clues to their origin and Earth-forming material. *Earth and Planetary Science*  
772 *Letters*, 361, 487-496.

773 Sears, D. W., Kallemeyn, G. W., & Wasson, J. T. (1982). The compositional  
774 classification of chondrites: II The enstatite chondrite groups. *Geochimica et*  
775 *Cosmochimica Acta*, 46(4), 597-608.

776 Tazoe, H., Obata, H., & Gamo, T. (2007). Determination of cerium isotope ratios in  
777 geochemical samples using oxidative extraction technique with chelating resin.  
778 *Journal of Analytical Atomic Spectrometry*, 22(6), 616-622.

779 Thirlwall, M. F. (1991). Long-term reproducibility of multicollector Sr and Nd  
780 isotope ratio analysis. *Chemical Geology: Isotope Geoscience section*, 94(2), 85-  
781 104.

782 Warren, P. H. (2011). Stable-isotopic anomalies and the accretionary assemblage of  
783 the Earth and Mars: A subordinate role for carbonaceous chondrites. *Earth and*  
784 *Planetary Science Letters*, 311(1), 93-100.

Weyrauch, M., Horstmann, M., & Bischoff, A. (2017). Chemical variations of sulfides  
and metal in enstatite chondrites—Introduction of a new classification scheme.  
*Meteoritics & Planetary Science*, 1-22.

Worsham, E. A., Walker, R. J., & Bermingham, K. R. (2016). High-precision  
molybdenum isotope analysis by negative thermal ionization mass spectrometry.  
*International Journal of Mass Spectrometry*, 407, 51-61.

785 Worsham, E. A., Bermingham, K. R., & Walker, R. J. (2017). Characterizing  
786 cosmochemical materials with genetic affinities to the Earth: Genetic and  
787 chronological diversity within the IAB iron meteorite complex. *Earth and*  
788 *Planetary Science Letters*, 467, 157-166.

789 Zambardi, T., Poitrasson, F., Corgne, A., Méheut, M., Quitté, G., & Anand, M.  
790 (2013). Silicon isotope variations in the inner solar system: Implications for  
791 planetary formation, differentiation and composition. *Geochimica et*  
792 *Cosmochimica Acta*, 121, 67-83.

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794

795 **List of Figures**

796 **Figure 1.** Rare earth element (REE) patterns measured in enstatite chondrites from  
797 both EH and EL subgroups normalized to CI chondrites (Anders and Grevesse, 1989).  
798 New data are represented in black and Grey fields/line are data from Barrat et al.  
799 (2014) A) EH3 and impact melts (IM). LAP 02225 is an impact melt (Antarctic  
800 meteorite newsletter, Izawa et al., 2010). Galim is an unusual LL/EH polymict breccia  
801 with two lithologies: Galim (a) is a heavily-shocked LL6 chondrite and Galim (b) an  
802 impact melt breccia. Kota Kota (EH3) displays a strong enrichment in LREE. B) EH4  
803 and EH5. Abee (EH4) is enriched in REE compared to other samples from the EH4  
804 and EH5 groups. C) EL3 and one meteorite from the EL5 subgroup (Adrar Bous).  
805 MAC 88180 (two dissolutions) has two patterns that are both strongly enriched.  
806 Almahata Sitta MS-177 has the lowest REE contents. D) EL6 meteorites. All EL6  
807 samples present very similar REE patterns, except EET 92063 described as highly  
808 weathered and classified in an anomalous EL6 by Barrat et al. (2014).

809

810 **Figure. 2.**  $(La/Sm)_N$  normalized to CI chondrites using the values of Anders and  
811 Grevesse, (1989) compared with Yb contents (in ppm) for EC samples. Data are from  
812 this study and literature data from Gannoun et al. (2011b), Barrat et al. (2014) and  
813 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 Blithfiled) 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

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

846

847

848 **Figure 5.** Schematic illustration of the correction method for the normalization of  
849  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios to a common chondritic evolution. A. Method A using the  
850 measured  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of the sample. B. Method B using the calculated Sm/Nd  
851 ratio from the long-lived  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  systematics.  $T_0$  is the age of the Solar System  
852 formation, i.e. 4.568 Ga (Bouvier and Wadhwa, 2010). More details can be found in  
853 the text. The CHUR parameters are those defined by Bouvier et al. (2008).

854

855 **Figure 6.** A. Mass independent stable Nd isotope composition of enstatite chondrites  
856  $\mu^{142}\text{Nd}$  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  
857  $\pm 2\text{SD}$  (all in ppm) for CC are  $-32 \pm 13$  ( $\mu^{142}\text{Nd}$ ),  $4 \pm 19$  ( $\mu^{145}\text{Nd}$ ),  $16 \pm 27$  ( $\mu^{148}\text{Nd}$ )  
858 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  
859  $14 \pm 54$  ( $\mu^{150}\text{Nd}$ ). CC data include 20 measurements on 10 samples. For OC, a total of  
860 29 measurements carried out on 25 different samples are considered. For comparison,  
861 the average values obtained from OC data published in Burkhardt et al. (2016) are -  
862  $18 \pm 6$  ( $\mu^{142}\text{Nd}$ ),  $6 \pm 9$  ( $\mu^{145}\text{Nd}$ ),  $7 \pm 8$  ( $\mu^{148}\text{Nd}$ ) and  $17 \pm 13$  ( $\mu^{150}\text{Nd}$ ) (all in ppm). Dashed  
863 lines (long and short respectively) represent mixing of the s-model prediction with the

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

868

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

872

873

#### 874 **List of Tables**

875

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

879

880 **Table 2.** Measured Nd isotope composition of the JNdi-1 standard and MS-177  
881 (EL3). Errors correspond to the external reproducibility for the JNdi-1 standard runs  
882 (2SD) and internal error for MS-177.  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio has been measured by isotope  
883 dilution. The initial  $\epsilon^{143}\text{Nd}$  is calculated at 4.568 Ga using the CHUR parameters  
884 defined by Bouvier et al. (2008). The average values measured for the terrestrial  
885 standard (n=7) are  $1.141850 \pm 6$  for  $^{142}\text{Nd}/^{144}\text{Nd}$ ,  $0.512111 \pm 4$  for  $^{143}\text{Nd}/^{144}\text{Nd}$ ,  
886  $0.348403 \pm 2$  for  $^{145}\text{Nd}/^{144}\text{Nd}$ ,  $0.241578 \pm 2$   $^{148}\text{Nd}/^{144}\text{Nd}$ , and  $0.236446 \pm 3$  for  
887  $^{150}\text{Nd}/^{144}\text{Nd}$  (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	Indarch EH4	St Mark's EH5	MAC 02837 EL3	MAC 02839 EL3	MAC 88180 EL3	MAC 88180 EL3	MS-177 EL3	Adrar Bous EL5	Eagle EL6	Hvittis EL6	Hvittis EL6	Hvittis EL6	Hvittis EL6	Khairpur EL6
type	EH3	EH3	EH3	EH3	EH3	X	X	X	EL3	EL3	EL3	EL3	X	EL5	EL6	EL6	EL6	EL6	EL6	EL6
Fall						X	X	X					X		X	X	X	X	X	X
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

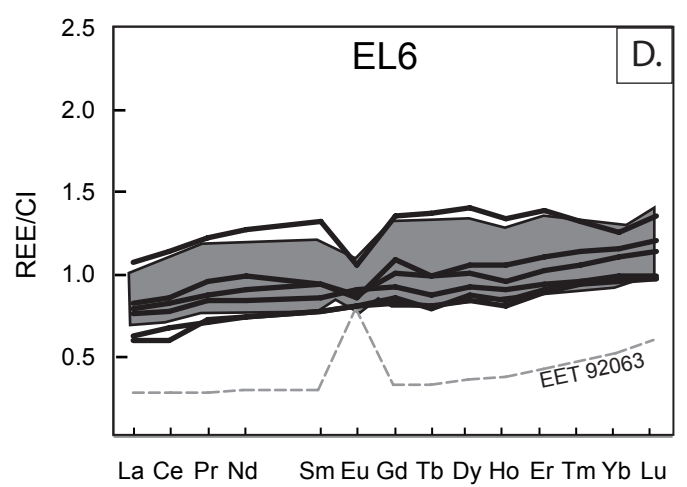
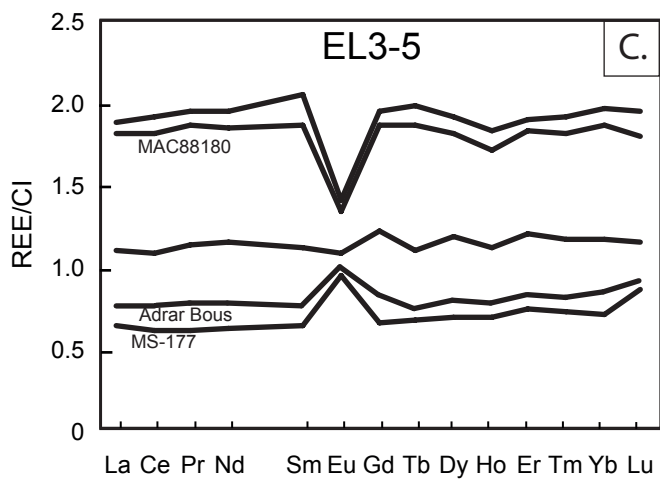
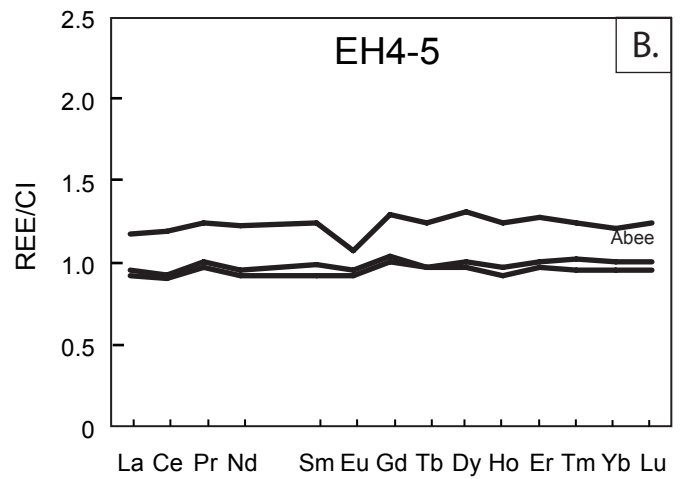
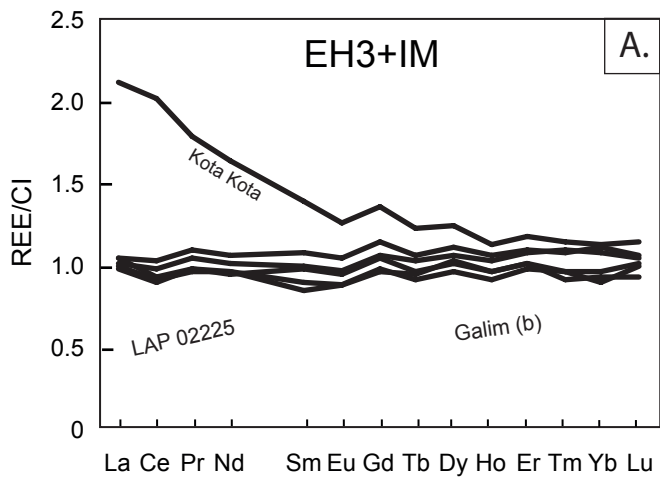


Figure 1

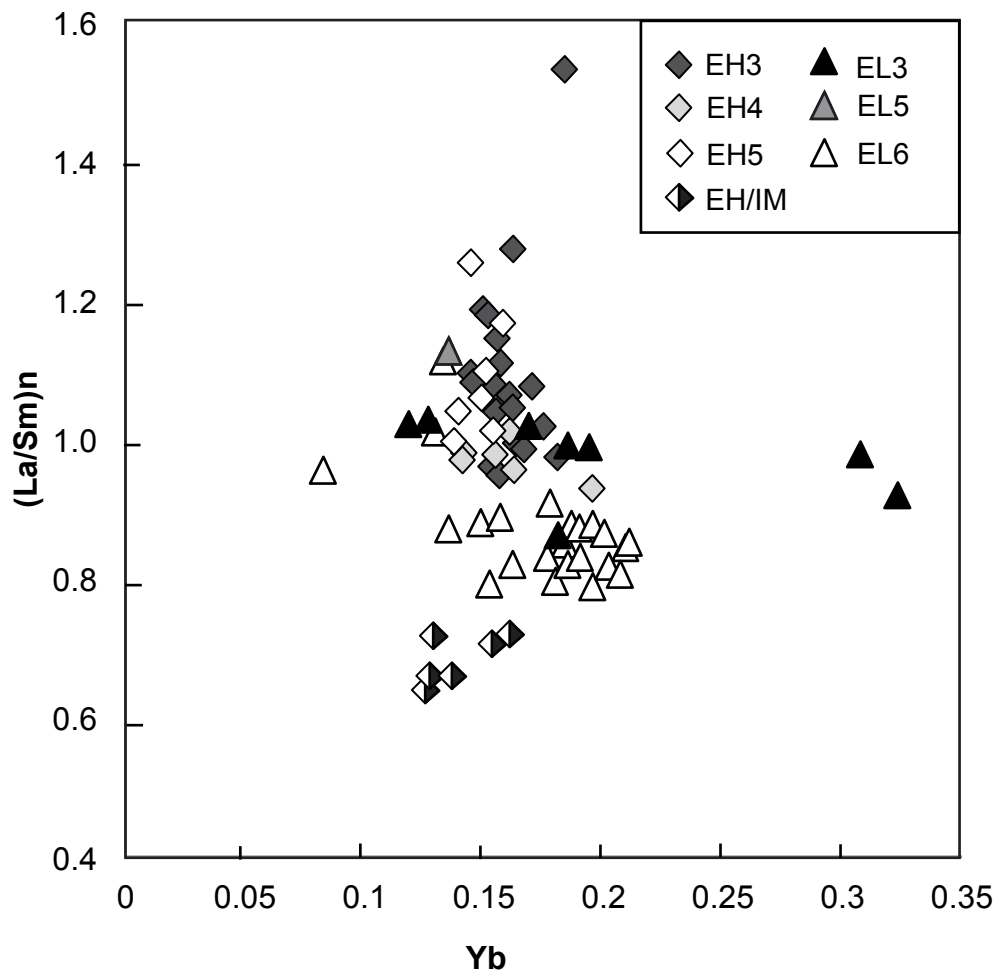


Figure 2.

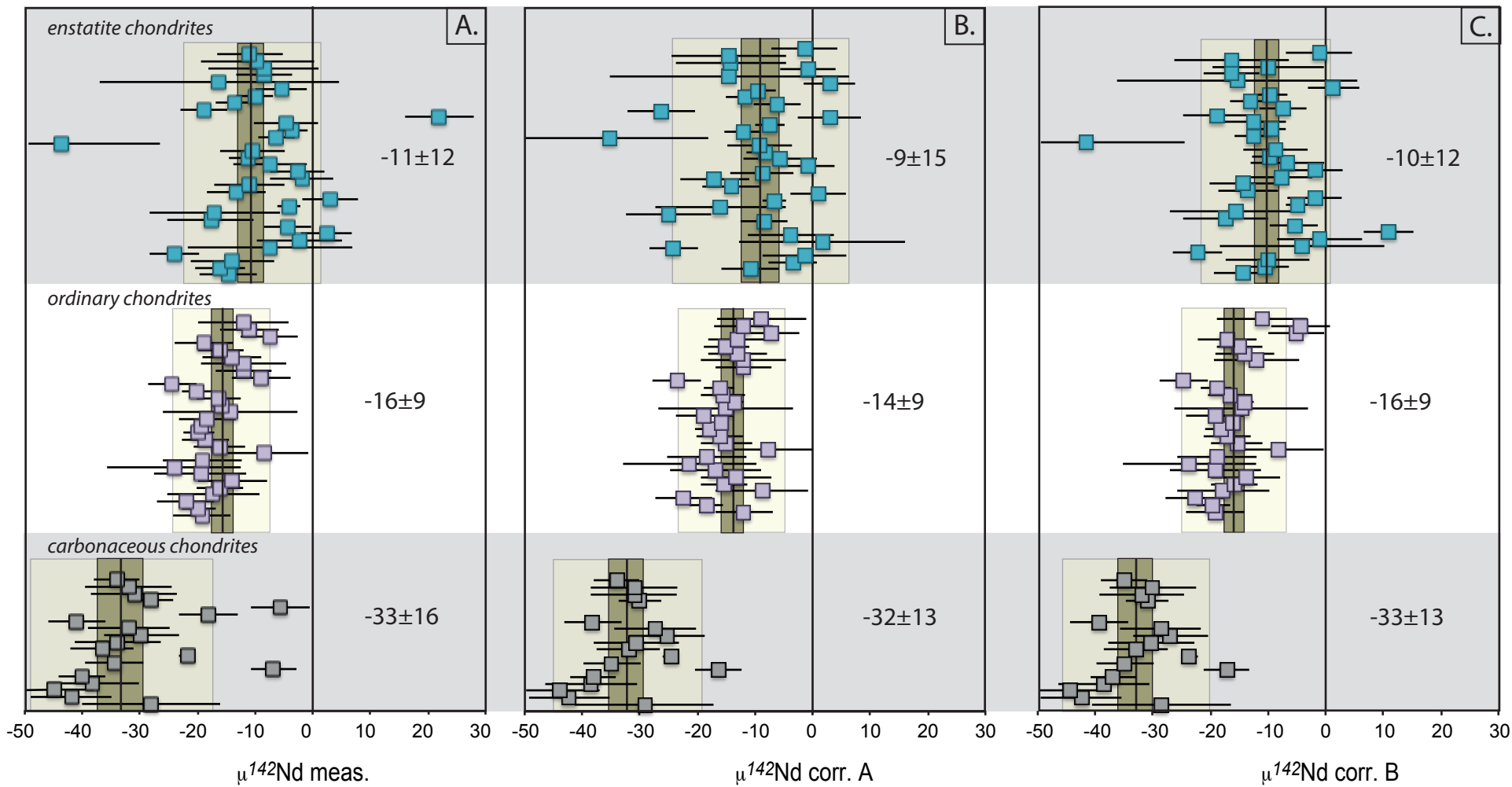


Figure 3.

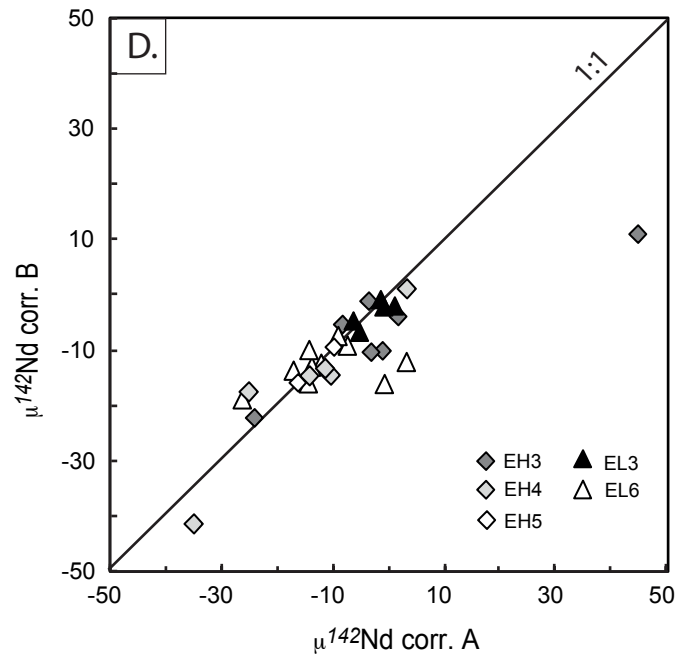
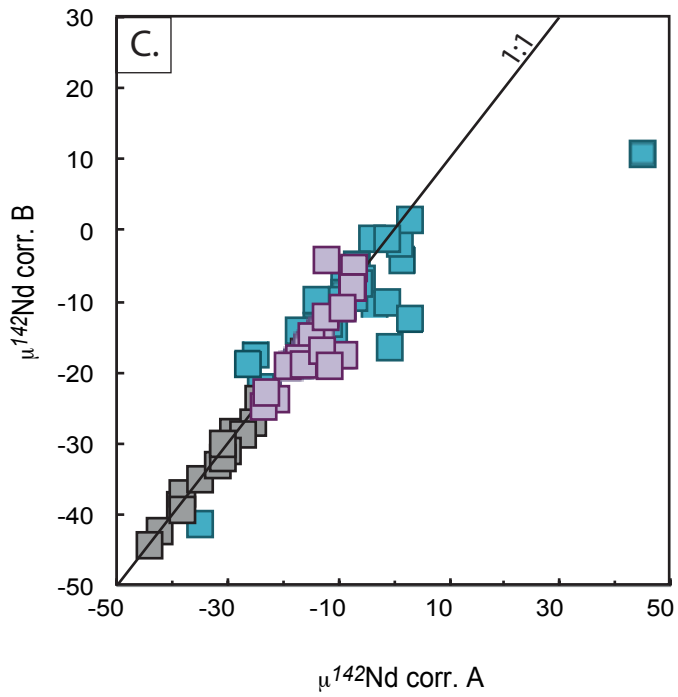
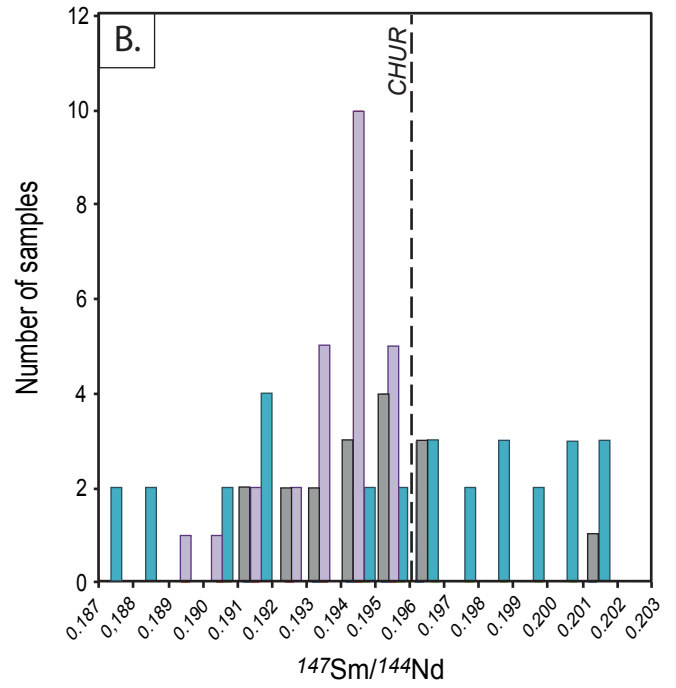
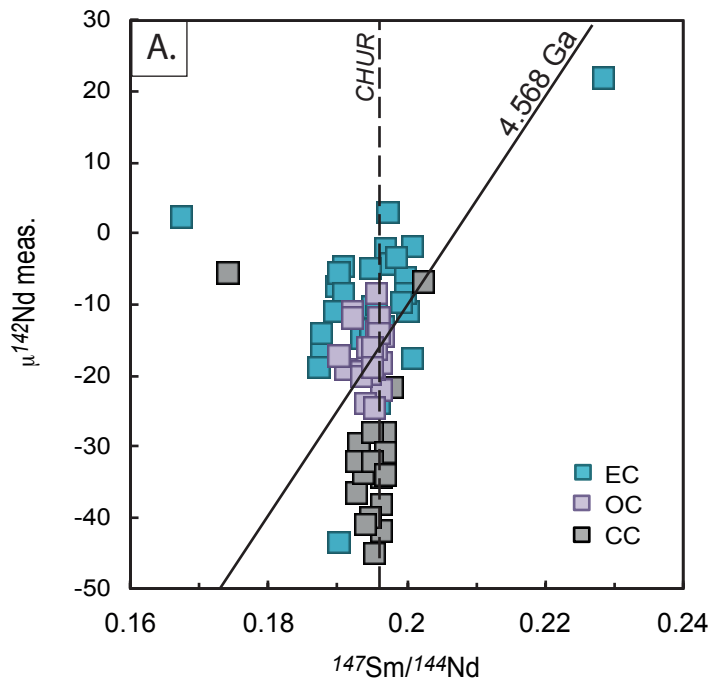


Figure 4

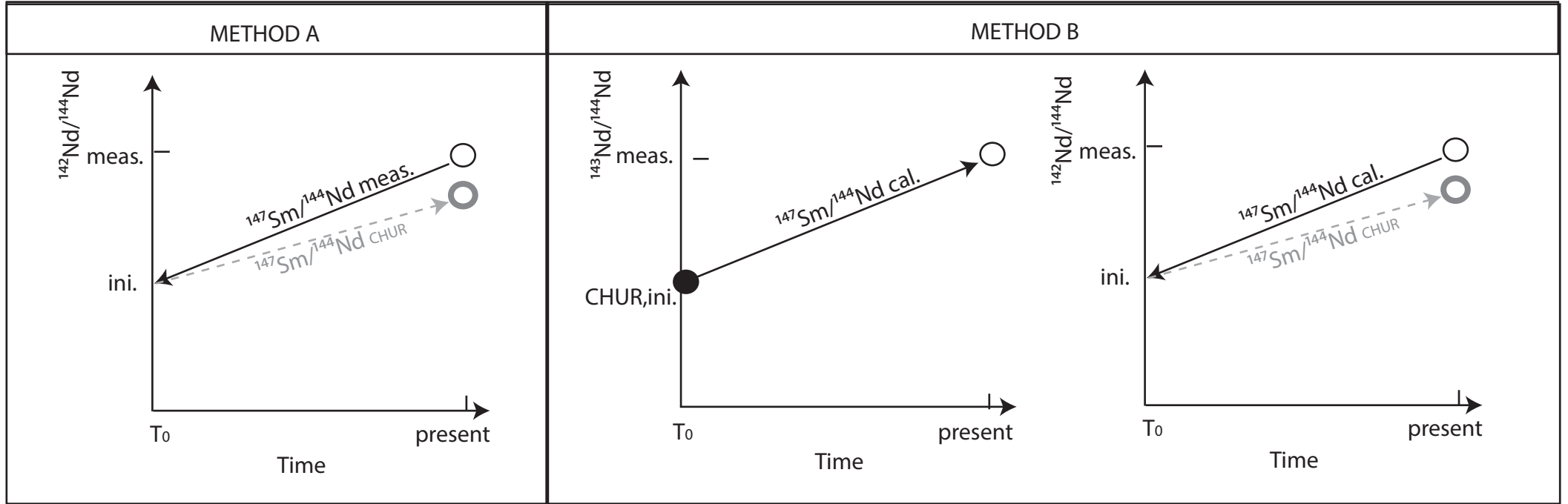


Figure 5

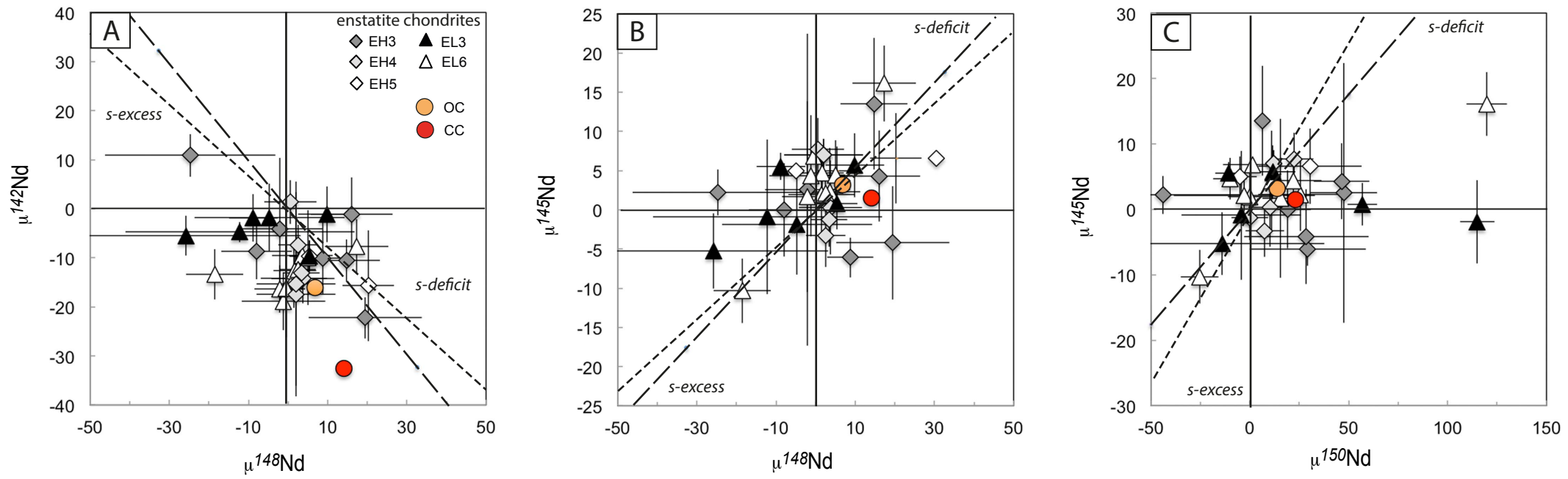


Figure 6.

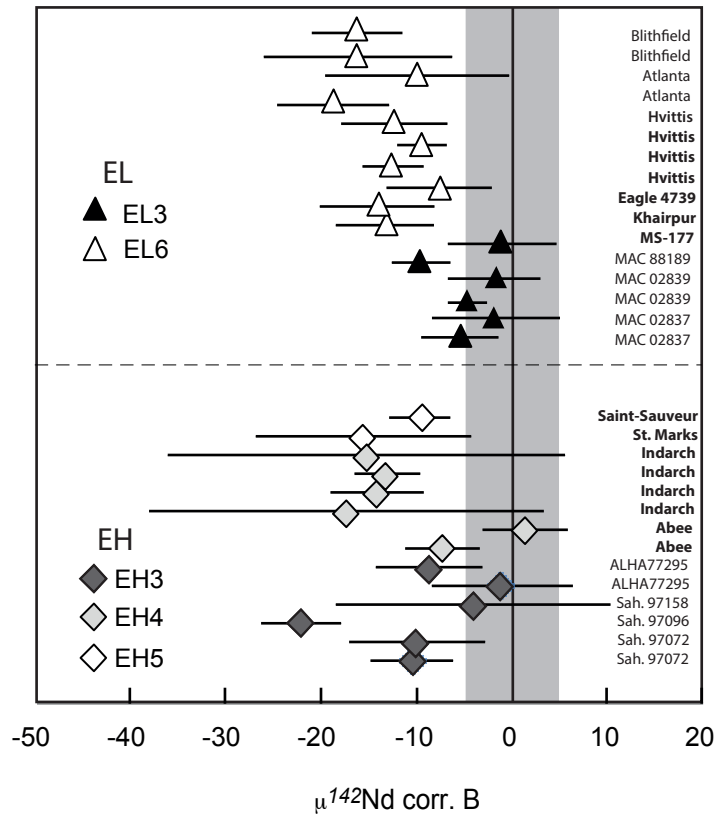


Figure 7



**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