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

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Abstract

The ^{146}Sm - ^{142}Nd extinct decay scheme (^{146}Sm half-life of 103 My) is a powerful tool to trace early Earth silicate differentiation. Differences in ^{142}Nd abundance measured between different chondrite meteorite groups and the modern Earth challenges the interpretation of the ^{142}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 ~ 10 ppm in ^{142}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}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

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}Sm - ^{142}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}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}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}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}Sm is a pure *p-process* nuclide so any variation in the *p* production would affect the abundance of its daughter isotope ^{142}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}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 7th 2008. Its trajectory was back-tracked to a small asteroid called 2008 TC₃ (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 ¹⁴²Nd 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 ¹⁴²Nd/¹⁴⁴Nd 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-HNO₃ 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-HNO₃ (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 HNO₃, 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 HNO₃ 0.5M- HF 0.05 M and HNO₃ 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}Sm - ^{150}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 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 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 Eu/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 (μ -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 ± 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 (μNd), 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}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}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 ± 20 (2SD) ppm, ordinary chondrites (OC) of -16 ± 9 (2SD) ppm and EC of -12 ± 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 = 1.5×10^{-8} ; p-value CC-EC = 8.9×10^{-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:

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 ± 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 ± 16 (2SD) ppm, OC of -16
 304 ± 9 (2SD) ppm and EC of -11 ± 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 ± 0.0046 (2SD) for CC, 0.1946 ± 0.0033 (2SD) for OC and 0.1950 ± 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}Nd comes from two distinct contributions: its
 318 initial abundance and the quantity produced with time by the decay of ^{146}Sm . Since
 319 ^{146}Sm was alive only during the first 500 Ma of Solar System history, we can write
 320 the following equations:

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

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

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}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}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}Sm - ^{142}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}Sm - ^{143}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 ± 13 (2SD), -15 ± 9 (2SD), -8 ± 15 (2SD) for the method A and -32 ± 13 (2SD), -16 ± 9 (2SD), and -10 ± 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 ± 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 ± 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}Sm and ^{147}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}Nd which is mainly produced by *s-process* and ^{150}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}Nd and deficits in ^{143}Nd , ^{145}Nd , ^{148}Nd and ^{150}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}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 (FeCr₂S₄) 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}Nd with an average of -12.7 ± 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 ± 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}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 ± 4.4 ppm and $\mu^{142}\text{Nd}$ EL6 = -12.7 ± 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}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 ± 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}Sm - ^{142}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}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 ± 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}Nd with an average of -12.7 ± 6.0 (2SD) ppm. EL3 samples have a $\mu^{142}\text{Nd}$ value similar to the terrestrial standard within the error bars: -0.8 ± 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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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., Andrault, 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}Nd abundance. *Nature*, 537, 399-402.

635 Boyet, M., Carlson, R.W. (2005) ^{142}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}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 Tieloff, 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}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}Sm – ^{142}Nd systematics
681 measured in enstatite chondrites reveals a heterogeneous distribution of ^{142}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}Ar -
695 ^{40}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}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.

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

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)_N 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 ± 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}Sm - ^{143}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 ± 13 ($\mu^{142}\text{Nd}$), 4 ± 19 ($\mu^{145}\text{Nd}$), 16 ± 27 ($\mu^{148}\text{Nd}$) and 17 ± 68 ($\mu^{150}\text{Nd}$). For OC: -15 ± 9 ($\mu^{142}\text{Nd}$), 3 ± 15 ($\mu^{145}\text{Nd}$), 7 ± 15 ($\mu^{148}\text{Nd}$) and 14 ± 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 ± 6 ($\mu^{142}\text{Nd}$), 6 ± 9 ($\mu^{145}\text{Nd}$), 7 ± 8 ($\mu^{148}\text{Nd}$) and 17 ± 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.

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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 ± 6 for $^{142}\text{Nd}/^{144}\text{Nd}$, 0.512111 ± 4 for $^{143}\text{Nd}/^{144}\text{Nd}$, 0.348403 ± 2 for $^{145}\text{Nd}/^{144}\text{Nd}$, 0.241578 ± 2 $^{148}\text{Nd}/^{144}\text{Nd}$, and 0.236446 ± 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.

^a 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 ^a	0.11	0.05	0.12	0.10	0.10	0.05 ^a	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 ¹⁴⁵ Nd (V)	0.7 - 1.5	0.64
μ ¹⁴² Nd	0.0 ± 5.6	-10.9 ± 5.7
μ ¹⁴³ Nd	0.0 ± 7.4	640 ± 4.9
μ ¹⁴⁵ Nd	0.0 ± 4.4	5.7 ± 4.1
μ ¹⁴⁸ Nd	0.0 ± 8.2	9.9 ± 7.4
μ ¹⁵⁰ Nd	0.0 ± 10.9	11.5 ± 11.5
¹⁴² Ce ppm	0.4	1.2
¹⁴⁴ Sm ppm	0.4	0.3
n	6	1
¹⁴⁷ Sm/ ¹⁴⁴ Nd		0.1896
μ ¹⁴² Nd A		-1.4
μ ¹⁴² Nd B		-1.1
ε ¹⁴³ Nd, 4.568 Ga		0.06

Figure 1

Figure 2.

Figure 3.

Figure 4

Figure 5

Figure 6.

Figure 7

Table S1.

Compilation from:
Boyet and Carlson 2005 Rankenburg et al., 2006
Carlson et al., 2007 Gannoun et al., 2011
Bouvier and Boyet 2016 Burkhardt et al., 2016
Fukui and Yokoyama 2017

Name	Type	$\mu^{142}\text{Nd}$	$\mu^{143}\text{Nd}$	$\mu^{144}\text{Nd}$	$\mu^{145}\text{Nd}$	$\mu^{146}\text{Nd}$	$\mu^{147}\text{Nd}$	$\mu^{148}\text{Nd}$	$\mu^{149}\text{Nd}$	$\mu^{150}\text{Nd}$	$\mu^{151}\text{Nd}$	$\mu^{152}\text{Nd}$	$\mu^{153}\text{Nd}$	$\mu^{154}\text{Nd}$	corr A	corr B	$^{155}\text{Sm}/^{149}\text{Sm}$	Reference
Carbonaceous chondrites																		
Orgueil	CI-Fall	-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	
Cold Bokveld	CM2-Fall	-61.1	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-Fall	-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	
Murray	CM2-Fall	-38.2	997.2	4.9	28.6	29.2	8.0	5.0	8.0	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	26.2	4.0	5.0	5.0	8.0	11.0	-38.1	-36.9		0.1947		Carlson et al., Science 2007	
Gronow	CV3-Fall	-6.8	1356.1	-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	
Mokoia	CV3-Fall	-34.4	1001.3	1.7	21.9	39.8	5.0	5.0	5.0	8.0	11.0	-34.9	-34.9		0.1963		Carlson et al., Science 2007	
Allende	CV3-Fall	-21.8	1101.2	-1.8	8.7	14.1	1.5	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	891.4	4.4	-2.3	-20.7	7.5	6.3	5.4	9.6	13.3	-30.6	-30.3		0.1938		Boyet and Carlson 2005	
Allende Bomb	CV3-Fall	-29.7	924.4	0.3	6.3	-27.9	6.5	5.4	4.5	8.2	10.9	-25.3	-27.0		0.1929		Boyet and Carlson 2005	
Allende	CV3-Fall	-32.0	904.2	1.6	1.0	-12.5	7.1	5.6	5.4	9.8	13.2	-27.4	-28.7		0.1935		Boyet and Carlson 2005	
Allende	CV3-Fall	-41.0	966.6	3.0	6.0	118.0	5.0					-38.2	-39.3		0.1941		Rankenburg et al., 2006	
Allende (2)	CV3-Fall	-30.0	1076.2	2.0	9.0	8.0	5.0	1.4	9.0	4.0	24.0	-30.0	-31.0				Burkhardt et al. (2016)	
Allende (3)	CV3-Fall	-30.0	1088.4	5.0	4.0	-6.0	6.0	3.1	6.0	7.0	24.0	-31.0	-32.0				Burkhardt et al. (2016)	
Allende (4)	CV3-Fall	-33.0	1000.6	8.0	16.0	11.0	8.0	2.6	13.0	15.0	31.0	-31.0	-33.0				Burkhardt et al. (2016)	
Dho 1432	CR2-Found	-28.0		16.0	18.0	26.0	3.8		15.0	5.4	9.5	-26.0	-30.0	0.195			Fukui and Yokoyama 2017	
Murchison	CR2-Fall	-31.0		2.1	21.0	24.0	7.4		16.0	13.0	24.0	-32.0	-31.0	0.197			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	0.195			Fukui and Yokoyama 2017	
Dae 190	CO3-Found	-34.0		19.0	22.0	27.0	4.0		27.0	4.6	7.4	-35.0	-34.0	0.197			Fukui and Yokoyama 2017	
Tagish Lake	CR2 ungrouped-fall	-18.0		4.9	8.2	8.7	1.1		16.0	5.9	11.0			0.148			Fukui and Yokoyama 2017	
NWA 2000	CO3-Fall	-5.6		-6.7	0.8	4.3	5.1		48.0	5.9	11.0			0.174			Fukui and Yokoyama 2017	

Ordinary chondrites

Gladstone	H6-Find	-19.2	982.6	2.9	3.3	9.3	5.0		6.0	11.0	14.0	-11.9	-19.2	0.1911	Carlson et al., Science 2007
Howehead	L6-Fall	-19.8	974.4	2.0	8.7	12.1	3.0	8.0	3.0	6.0	8.0	-18.5	-19.6	0.1951	Carlson et al., Science 2007
Ucera	H5-Fall	-22.0	1013.0	-2.6	21.1	122.6	5.0		6.0	10.0	13.0	-22.4	-22.7	0.1963	Carlson et al., Science 2007
Peace River	L6-Fall	-17.3	1004.4	22.1	0.4	26.2	8.0		9.0	14.0	19.0	-8.8	-17.8	0.1903	Carlson et al., Science 2007
Sharps	H5-Fall	-16.2	974.9	8.5	1.6	-13.3	4.1	3.3	3.1	5.0	7.7	-15.4	-15.9	0.1959	Boyet and Carlson 2005
Sharps	H3-Fall	-13.9	1033.7	7.2	-2.4	-13.2	6.1	5.2	4.5	8.1	11.5	-13.2	-13.9	0.1951	Boyet and Carlson 2005
Richardson (Bomb)	H5-Fall	-19.5	1020.9	3.6	8.7	-29.7	8.0	6.5	6.1	11.3	14.8	-16.9	-19.2	0.1942	Boyet and Carlson 2005
Richardson	H5-Fall	-24.0	1009.9	3.1	22.9	-19.1	11.6	9.3	9.2	16.7	21.6	-21.4	-23.7	0.1942	Boyet and Carlson 2005
Dhjala	H3-Fall	-19.2	1021.5	3.9	-3.8	-0.5	6.9	5.6	4.8	8.2	12.1	-18.3	-18.9	0.1954	Boyet and Carlson 2005
Bruderheim	L6-Fall	-8.5	1020.2	2.8	-16.3	-27.3	7.7	6.3	5.8	10.6	13.9	-7.7	-8.1	0.1955	Boyet and Carlson 2005
Ilsegen	H5-Fall	-16.1	1005.9	5.2	11.3	25.5	4.5	3.9	4.9	6.2	11.8	-15.0	-15.4	0.1952	Burkhardt et al., 2016
Forest City	H5-Fall	-18.6	974.9	5.2	3.6	7.3	4.1	9.4	7.3	14.6	37.1	-16.2	-17.0	0.1944	Burkhardt et al., 2016
Queens Mercy	H6-Fall	-19.8	971.3	1.9	6.1	16.0	2.7	2.5	2.8	15.8	46.1	-17.7	-18.2	0.1948	Burkhardt et al., 2016
Bruderheim	H5-Fall	-19.4	904.6	2.4	0.9	11.8	0.9	2.2	0.0	15.2	49.7	-15.7	-16.3	0.1935	Burkhardt et al., 2016
Cheyabinsk	LL5-Fall	-18.3	1068.6	2.4	2.6	7.6	5.0	7.7	0.8	9.4	1.8	-18.8	-19.2	0.1963	Burkhardt et al., 2016
Dharmask	LL6-Fall	-14.3	1048.8	0.2	9.2	21.9	11.6	7.5	8.5	4.7	25.7	-15.1	-14.6	0.1905	Burkhardt et al., 2016
Farmington	H5-Fall	-15.9	945.2	9.6	9.8	23.8	1.5	4.4	8.1	6.4	4.2	-12.5	-14.0	0.1944	Burkhardt et al., 2016
St. Marguerite	H4-Fall	-16.3	1031.8	9.6	11.1	21.2	3.9	0.5	4.2	2.7	13.4	-15.6	-16.6	0.1955	Burkhardt et al., 2016
Pultusk	H5-Fall	-20.1	975.2	12.9	10.7	18.2	2.6	7.5	7.3	5.3	19.1	-16.2	-19.0	0.1934	Burkhardt et al., 2016
St. Marguerite (2)	H4-Fall	-24.4	1025.2	10.1	6.4	17.5	4.2	14.9	15.0	17.6	0.6	-23.5	-24.7	0.1954	Burkhardt et al., 2016
Kesen	H4-Fall	-12.0		-4.4	15.0	27.0	4.9		14.0	4.9	12.0				Fukui and Yokoyama 2017
Forest City	H5-Fall	-12.0		17.0	11.0	17.0	7.4		27.0	7.6	19.0	-12.0	-12.0	0.196	Fukui and Yokoyama 2017
Sanctov	L6-Fall	-14.0		6.8	13.0	20.0	5.1		16.0	5.9	11.0	-14.0	-13.0	0.196	Fukui and Yokoyama 2017
Etter	L5-Fall	-16.0		-12.0	8.9	19.0	4.0		27.0	4.6	7.4	-15.0	-15.0	0.195	Fukui and Yokoyama 2017
Modoc (1905)	L6-Fall	-19.0		-6.1	8.1	6.0	5.1		16.0	5.9	11.0	-17.0	-13.0	0.195	Fukui and Yokoyama 2017
Huamlet	LL4-Fall	-7.5		2.4	10.0	35.0	4.9		15.0	5.1	12.0	-5.1	-7.2		Fukui and Yokoyama 2017
Tuxtuac	LL5-Fall	-11.0		-7.3	6.4	13.0	5.1		16.0	5.9	11.0	-4.3	-12.0	0.192	Fukui and Yokoyama 2017
Saint-Séverin	LL6-Fall	-12.0		-5.7	10.0	23.0	7.8		14.0	12.0	12.0	-11.0	-8.9	0.192	Fukui and Yokoyama 2017
Adrian	H4-Found	-8.9		-7.5	-1.0	-1.7	5.1		16.0	5.9	11.0			0.1370	Fukui and Yokoyama 2017

Enstatite chondrites

Indarch	EH4-Fall	-14.6	969.7	0.3	3.7	10.2	5.0		6.0	8.0	11.0	-10.8	-14.3	0.1934	Carlson et al., Science 2007
SAHARA 97072	EH3-Found	-16.1	808.7	13.5	14.7	6.4	4.3	3.5	8.4	8.4	3.1	-3.4	-10.6	0.1875	Gannoun et al., PNAS 2011
SAHARA 97072	EH3-Found	-14.0	872.6	6.1	8.8	12.2	7.3	2.2	2.5	5.8	29.4	-10.3	-10.3	0.1875	Gannoun et al., PNAS 2011
SAHARA 97096	EH3-Found	-24.0	957.3	-4.2	19.5	28.5	4.3	6.3	7.2	14.3	31.5	-24.1	-22.2	0.1861	Gannoun et al., PNAS 2011
SAHARA 97158	EH3-Found	-7.4	895.1	2.5	-2.0	47.5	14.4	17.7	19.9	10.7	17.0	1.7	-4.1	0.1899	Gannoun et al., PNAS 2011
ALHA 77295	EH3-Found	-2.3	982.0	4.3	16.1	4.4	16.4	4.3	14.7	14.7	14.7	1.1	-1.970	Gannoun et al., PNAS 2011	
MAC 02837	EH3-Found	-4.4	1071.7	-5.3	-25.8	-14.1	4.1	0.7	4.8	29.0	51.8	-8.4	-5.5	0.1987	Gannoun et al., PNAS 2011
Indarch	EH4-Fall	-17.7	1014.9	2.0	0.7	4.3	7.4	12.5	6.4	0.0	36.6	-25.0	-17.4	0.2009	Gannoun et al., PNAS 2011
St. Mark's	EH3-Fall	-17.0	974.3	6.6	20.3	11.3	9.9	5.8	6.5	10.2	14.7	-15.7	-19.51	Gannoun et al., PNAS 2011	
MAC 02839	EH3-Found	-4.2	1049.3	-0.9	-12.2	-4.3	2.1	4.8	9.9	29.0	30.4	-6.6	-4.8	0.1976	Gannoun et al., PNAS 2011
MAC 88180	EL3-Found	3.1	1224.7	5.5	-8.8	-10.8	4.8	4.1	1.7	6.2	6.9	1.0	-1.9	0.1974	Gannoun et al., PNAS 2011
Kharpur	EL6-Fall	-13.2	1034.1	-10.3	-18.5	-25.4	5.1	4.4	4.1	7.2	9.5	-14.0	-14.4	0.1965	Gannoun et al., PNAS 2011
Eagle	EL6-Fall	-10.9	1156.1	1.9	1.5	0.1	6.0	5.0	4.7	8.3	11.2	-17.0	-14.2	0.2001	Gannoun et al., PNAS 2011
Hvittis	EL6-Fall	-1.8	1261.7	16.1	17.3	119.8	5.5	4.9	4.9	8.1	10.2	-8.8	-7.7	0.2007	Gannoun et al., PNAS 2011
MAC 02837	EL3-Found	-5.0	999.4	-1.9	-4.7	115.0	6.8	2.7	6.4	19.0	8.6	-8.8	-1.8	0.1948	Bouvier and Boyet 2016
MAC 02339	EL3-Found	-11.4	960.5	0.8	5.4	56.9	3.2	3.9	3.3	5.2	7.6	-8.2	-9.6	0.1939	Bouvier and Boyet 2016
ALHA 77295	EH3-Found	-10.4	963.7	0.0	-7.9	19.0	5.6	6.5	5.9	9.0	11.8	-9.1	-8.7	0.1951	Bouvier and Boyet 2016
MAC 02827	EL3-Found	-6.2	1285.4	4.7	1.7	-10.1	2.7	3.2	5.4	8.5		-12.1	-12.6	0.1999	Burkhardt et al., 2016
Hvittis (2)	EL6-Fall	-3.5	1262.7	3.2	3.6	25.6	2.6	3.1	5.6	7.7	21.4	-7.4	-9.5	0.1986	Burkhardt et al., 2016
Atlanta	EL6-Fall	-4.6	1332.1	2.1	2.5	-2.9	5.5	7.3	2.4	4.6	35.7	2.9	-12.4	0.1909	Burkhardt et al., 2016
Abee (1)	EH4-Fall	-18.9	1019.3	3.3	2.6	7.6	4.0	3.1	4.0	5.0	9.7	-1.4	-1.4	0.1874	Burkhardt et al., 2016
Indarch	EH4-Fall	-13.5	1006.2	-1.3	3.4	0.0	3.4	2.9	3.4	4.6	9.3	-11.8	-13.1	0.1948	Burkhardt et al., 2016
Saint-Sauveur	EH4-Fall	-10.0	1023.7	5.0	5.5	-4.9	3.2	2.5	3.2	5.0	8.5	-9.4	-9.7	0.1956	Burkhardt et al., 2016
Abee (2)	EH4-Fall	-5.5	745.3	7.7	0.6	22.4	4.5	3.1	4.0	6.6	9.7	3.0	1.4	0.1903	Burkhardt et al., 2016
Indarch (2)	EH4-Fall	-16.3	981.2	7.0	2.0	12.0	20.8	6.6	2.0	1				0.1948	Burkhardt et al., 2016
Atlanta (2)	EH4-Fall	-8.4	1345.4	1.7	-2.1	35.4	4.8	8.6	12.2	6.4	10.0	-14.2	-16.3	0.1999	Burkhardt et al., 2016
Atlanta (3)	EL6-Fall	-10.5	1075.4	4.7	0.7	10.7	0.9	0.0	0.0	0.0	15.0	-14.5	-16.3	0.1993	Burkhardt et al., 2016
Hvittis (3)	EL6-Fall	-9.6	1284.6	6.8	-0.5	1.5	9.9	0.6	0.0	0.0	15.0	-14.5	-16.3	0.1993	Burkhardt et al., 2016
Albion	EH4-Fall	-10.9	1156.1	1.9	1.5	0.1	6.0	5.0	4.7	8.3	11.2	-17.0	-14.2	0.2001	Bouvier and Carlson 2005
Abee	EH4-Fall	-43.6	950.5	-17.0	-31.4	-32.9	17.1	15.3	17.4	28.4	32.7	35.1	-41.5	0.1903	Bouvier and Carlson 2005
Rosa Kots	EH4-Fall	2.4	689.4	2.2	-24.7	-40.9	5.4	4.1	2.9	21.5	49.9	44.7	19.9	0.1675	Gannoun et al., PNAS 2011
Indarch	EH4-Fall	22.0	2053.3	4.9	10.8	5.9	11.6	11.6	11.6	11.6	11.6	11.6	11.6	0.1934	Gannoun et al., PNAS 2011

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

	Nd (ng)	I145 (V)	¹⁴² Nd/ ¹⁴⁴ Nd	2SE	¹⁴³ Nd/ ¹⁴⁴ Nd	2SE	¹⁴⁵ Nd/ ¹⁴⁴ Nd	2SE	¹⁴⁸ Nd/ ¹⁴⁴ Nd	2SE	¹⁵⁰ Nd/ ¹⁴⁴ Nd	2SE	¹⁴² Ce/ ¹⁴² Nd (ppm)	¹⁴⁴ Sm/ ¹⁴⁴ 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