**Additional file**

**Title:** Redistribution of Sr and rare earth elements in the matrices of CV3 carbonaceous chondrites during aqueous alteration in their parent body

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**Article type**: Express letter

**Methods**

**1. Mineralogy and petrology**

Mineralogical and petrological characterization and X-ray mapping of the matrices were obtained with scanning electron microscopy (SEM) and field-emission electron probe microanalysis (FE-EPMA). A 25 nm-thick carbon film was applied to the sample surfaces prior to the SEM and FE-EPMA analyses in order to eliminate the electrostatic charge. The SEM (JSM-6610 at the Korea Polar Research Institute) was equipped with a backscattered electron imaging system and an energy dispersive X-ray spectrometer. The X-ray spectra were obtained at a 15 keV accelerating voltage and the beam current mode of ss50 that provided the finest probe diameter to identify minerals. X-ray chemical maps of the matrices were obtained with an FE-EPMA (JEOL JXA-8530F at Korea Polar Research Institute) equipped with a wavelength dispersive X-ray spectrometer under the conditions of 15 kV accelerating voltage and a 50 nA beam current. The magnetite modal abundances were counted by using backscattered electron or X-ray mapping images in order to check the correlations between REEs and Sr abundances of matrices with magnetite abundances (details are described in section 2.3 in the main text).

**2. Chemical compositions of matrices**

We analyzed the chemical components of the matrices (Na2O, MgO, SiO2, Al2O3, Cr2O3, MnO, FeO, NiO, K2O, CaO, TiO2, P2O5, SO3) by FE-EPMA (JEOL JXA-8530F at Korea Polar Research Institute) followed by analysis of REEs, Sr and Ca abundances by secondary ion mass spectrometry (SIMS; CAMECA ims-6f at the Kochi Institute for Core Sample Research, JAMSTEC). Same matrix areas of ~80 × 80 m2 were measured by FE-EPMA and SIMS in order to check for correlations between REEs and Sr abundances of matrices with their chemical compositions (details are described in section 2.3 in the main text). We obtained 14 data from the CV3OxB MET 00430 host matrix, 10 data from the CV3OxB MET 01070 host matrix, 11 data from the CV3OxA LAP 02206 host matrix, 5 data from the CV3Ox A 881317 matrix 5, 5 data from the CV3Red RBT 04143 matrix 5 and 3 data from the CV3Red RBT 04143 matrix 6). We carefully chose matrix areas without Ca-Al-rich inclusions or Fe-oxide weathering veins for the measurements.

For the FE-EPMA analysis, we operated at 15 kV accelerating voltage and 10 nA beam current, and the focused electron beam was rastered over ~80 × 80 m2. The ZAF correction method was applied.

For the SIMS measurements, a focused 16O- primary beam ~30 m in diameter with an intensity of ~14 nA was rastered over ~80 × 80 m2. The primary 16O- ions were accelerated with 13 keV to sputter the sample surface. Positive secondary ions with masses of 30 (30Si+), 44 (44Ca+), 88 (88Sr+) and 138-175 (138Ba+, 139La+, 140Ce+, 141Pr+, 142Nd+, 147Sm+, 151Eu+, 153Eu+, 158Gd+, 159Tb+, 163Dy+, 165Ho+, 166Er+, 169Tm+, 172Yb+ and 175Lu+) were accelerated with -4.4 KeV, energy filtered using a -60 or -100 V offset with a 30 eV energy window. One analysis consists of 10 cycles of the measurement, and the acquisition times of all secondary ions were 1 s for 30Si and 44Ca, 2 s for 88Sr and 10 s for REEs. Each run started after the stabilization of the secondary ion beam intensity following pre-sputtering. The measured REE abundances are corrected by the contributions of REE-monoxide and sensitivity factors for REEs relative to Si. Further details of the analytical procedure and data correction will be given elsewhere (Kobayashi and Ito, in preparation; Jogo et al., submitted). After the SIMS measurements, the size and depth of each spot were measured by a laser microscope at the Kochi Institute for Core Sample Research, JAMSTEC.

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| Table S1. Primary and secondary minerals in CV3 matrices |  |  |
| Sample | MET 00430 | MET 01074 | LAP 02206 | A 881317 | RBT 04143 | RBT 04143 |
| Subtype | OxB | OxB | OxA | Ox | Red | Red |
| Matrix# | Host matrix | Host matrix | Host matrix | Matrix 5 | Matrix 5 | Matrix 6 |
| Type | Type 1 | Type 1 | Type 2 | Type 2 | Type2 | Type 3 |
| **Ca-rich phase** |  |  |  |  |  |  |
|  | kirschsteinite |  |  |  |  | + | + |
|  | Ca-pyroxene | + | + | + | + | + | + |
|  | Ca-phosphate |  |  | + | + | + |
| **Fe-metal** |  |  |  |  |  |  |
|  | FeNi-metal\* |  |  |  | + | + | + |
|  | kamacite\* |  |  |  |  | + | + |
|  | awaruite |  |  | + |  |  |  |
| **Fe-sulfide** |  |  |  |  |  |  |
|  | Fe,Ni-sulfide | + | + | + |  | + | + |
|  | Fe-sulfide |  |  |  |  | + | + |
| **Others** |  |  |  |  |  |  |
|  | fayalite | + | + |  |  |  |  |
|  | ferrous olivine | + | + | + | + | + | + |
|  | magnetite | + | + |  | + | + | + |
|  | phyllosilicate | + | + |  |  |  |  |
|  | sodalite |  |  | + |  |  |  |
|  | nepheline |  |  | + |  |  |  |
|  | plagioclase |  |  | + |  |  |  |
| \*: primary mineral |  |  |  |  |  |

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| --- | --- | --- | --- | --- | --- |
| Table S2. REE, Sr and Ca contents of CV3 matrices  |  |  |  |  |  |
| Sample | MET 00430 | MET 01074 | LAP 02206 | A 881317 | RBT 04143 | RBT 04143 |
| Subtype | OxB |  | OxB |  | OxA |  | Ox |  | Red |  | Red |  |
| Matrix | Host matrix | Host matrix | Host matrix | Matrix 5 | Matrix 5 | Matrix 6 |
| Type | Type 1 |  | Type 1 |  | Type 2 |  | Type 2 |  | Type 2 |  | Type 3 |  |
| N | 14 |  | 10 |  | 11 |  | 5 |  | 5 |  | 3 |  |
| Data | average | 1 | average | 1 | average | 1 | average | 1 | average | 1 | average | 1 |
| **ppm** |  |  |  |  |  |  |  |  |  |  |  |  |
| La | 0.38 | 0.11 | 0.43 | 0.17 | 0.40 | 0.07 | 0.27 | 0.04 | 0.24 | 0.04 | 0.33 | 0.17 |
| Ce | 0.83 | 0.29 | 0.98 | 0.42 | 0.83 | 0.14 | 0.61 | 0.08 | 0.55 | 0.07 | 0.66 | 0.34 |
| Pr | 0.13 | 0.06 | 0.15 | 0.07 | 0.12 | 0.02 | 0.09 | 0.02 | 0.08 | 0.01 | 0.10 | 0.04 |
| Nd | 0.71 | 0.24 | 0.79 | 0.31 | 0.70 | 0.13 | 0.49 | 0.09 | 0.43 | 0.10 | 0.52 | 0.24 |
| Sm | 0.20 | 0.06 | 0.20 | 0.06 | 0.18 | 0.04 | 0.15 | 0.03 | 0.14 | 0.05 | 0.13 | 0.05 |
| Eu | 0.11 | 0.05 | 0.10 | 0.06 | 0.11 | 0.03 | 0.06 | 0.06 | 0.05 | 0.03 | 0.05 | 0.02 |
| Gd | 0.24 | 0.05 | 0.23 | 0.07 | 0.22 | 0.07 | 0.19 | 0.03 | 0.17 | 0.05 | 0.20 | 0.08 |
| Tb | 0.05 | 0.01 | 0.04 | 0.01 | 0.04 | 0.01 | 0.05 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 |
| Dy | 0.37 | 0.07 | 0.27 | 0.04 | 0.31 | 0.05 | 0.21 | 0.02 | 0.19 | 0.02 | 0.16 | 0.03 |
| Ho | 0.08 | 0.01 | 0.06 | 0.01 | 0.06 | 0.01 | 0.05 | 0.01 | 0.04 | 0.01 | 0.03 | 0.01 |
| Er | 0.20 | 0.06 | 0.19 | 0.04 | 0.21 | 0.05 | 0.17 | 0.03 | 0.17 | 0.03 | 0.12 | 0.01 |
| Tm | 0.04 | 0.01 | 0.03 | 0.01 | 0.04 | 0.01 | 0.02 | 0.00 | 0.03 | 0.01 | 0.02 | 0.01 |
| Yb | 0.26 | 0.06 | 0.27 | 0.05 | 0.25 | 0.05 | 0.20 | 0.03 | 0.22 | 0.08 | 0.12 | 0.00 |
| Lu | 0.04 | 0.01 | 0.04 | 0.01 | 0.03 | 0.01 | 0.03 | 0.00 | 0.02 | 0.01 | 0.03 | 0.01 |
| Sr | 24.73 | 10.53 | 17.52 | 7.70 | 7.81 | 2.75 | 14.92 | 3.22 | 7.26 | 2.29 | 10.37 | 6.43 |
| Ca (wt%) | 2.97 | 1.05 | 2.64 | 1.10 | 1.30 | 0.86 | 1.09 | 0.78 | 1.40 | 0.22 | 1.58 | 1.19 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| **REE/CI** |  |  |  |  |  |  |  |  |  |  |  |  |
| La | 1.61 | 0.49 | 1.82 | 0.72 | 1.72 | 0.29 | 1.17 | 0.17 | 1.02 | 0.16 | 1.40 | 0.73 |
| Ce | 1.37 | 0.48 | 1.62 | 0.69 | 1.38 | 0.23 | 1.00 | 0.14 | 0.92 | 0.12 | 1.09 | 0.56 |
| Pr | 1.49 | 0.64 | 1.68 | 0.75 | 1.39 | 0.27 | 0.99 | 0.17 | 0.89 | 0.06 | 1.12 | 0.49 |
| Nd | 1.58 | 0.53 | 1.74 | 0.67 | 1.56 | 0.28 | 1.08 | 0.21 | 0.94 | 0.22 | 1.16 | 0.52 |
| Sm | 1.38 | 0.41 | 1.39 | 0.41 | 1.19 | 0.27 | 1.01 | 0.21 | 0.92 | 0.32 | 0.89 | 0.36 |
| Eu | 1.93 | 0.87 | 1.84 | 1.01 | 1.99 | 0.59 | 1.15 | 1.13 | 0.97 | 0.55 | 0.89 | 0.31 |
| Gd | 1.21 | 0.27 | 1.16 | 0.36 | 1.14 | 0.36 | 0.95 | 0.18 | 0.88 | 0.25 | 1.03 | 0.43 |
| Tb | 1.40 | 0.31 | 1.00 | 0.26 | 1.10 | 0.29 | 1.34 | 0.27 | 0.66 | 0.15 | 0.66 | 0.16 |
| Dy | 1.51 | 0.30 | 1.12 | 0.16 | 1.26 | 0.19 | 0.85 | 0.09 | 0.77 | 0.07 | 0.66 | 0.11 |
| Ho | 1.45 | 0.25 | 1.00 | 0.16 | 1.17 | 0.15 | 0.88 | 0.10 | 0.80 | 0.18 | 0.62 | 0.15 |
| Er | 1.26 | 0.37 | 1.21 | 0.26 | 1.30 | 0.34 | 1.09 | 0.20 | 1.05 | 0.21 | 0.77 | 0.05 |
| Tm | 1.57 | 0.39 | 1.35 | 0.32 | 1.46 | 0.30 | 1.01 | 0.12 | 1.04 | 0.35 | 0.74 | 0.32 |
| **Yb** | 1.61 | 0.39 | 1.66 | 0.29 | 1.51 | 0.33 | 1.21 | 0.19 | 1.35 | 0.46 | 0.75 | 0.01 |
| Lu | 1.51 | 0.49 | 1.61 | 0.56 | 1.43 | 0.42 | 1.05 | 0.13 | 0.77 | 0.32 | 1.03 | 0.49 |
| Sr | 3.17 | 1.35 | 2.25 | 0.99 | 1.00 | 0.35 | 1.91 | 0.41 | 0.93 | 0.29 | 1.33 | 0.82 |
| Ca | 3.20 | 1.14 | 2.84 | 1.19 | 1.78 | 0.61 | 1.64 | 0.31 | 1.51 | 0.24 | 2.27 | 0.73 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| Sr/Yb/CI | 2.05 | 0.90 | 1.37 | 0.58 | 0.71 | 0.32 | 1.63 | 0.48 | 0.78 | 0.38 | 1.76 | 1.07 |
| Average and 1: average and standard deviation of individual SIMS measurement data; N: number of data  |

Fig. S1. A back scattered electron image of CV3Red RBT 04143. Fe-oxide weathering veins occur in fractures of the section. Clast boundaries between matrices 5 and 6 are described by dotted-lines.



Fig. S2. Ce anomaly (the value obtained from interpolation between La and Nd) vs Ca (wt%), Nd (ppm) and Sr (ppm) of CV3 matrices. Error bars are 1. R2: correlation coefficient.



Fig. S2. *Continued.*



Fig. S3-1. S (blue square), Ni (red triangle), P (green circle), Al (blue square) and Na (green circle), and magnetite abundance (green square) vs La/CI plots of CV3OxB MET 00430, CV3OxB MET 01074 and CV3OxA LAP 02206 host matrices. S, Ni, P, Al and Na contents are shown in wt% and magnetite abundance are shown in m2. Error bars are 1. The correlation coefficient (R2) for each correlation is shown by the same color of symbols.



Fig. S3-2. S, Ni, P, Al and Na (wt%) and magnetite abundance (m2) vs La/CI plots of CV3Ox A 881317 matrix 5 and CV3Red RBT 04143 matrices 5 and 6 . Error bars are 1. Symbols and notations are the same as Fig. S2-1.



Fig. S4. Partition coefficients of Sr and REEs in phosphate, Ca-pyroxene, plagioclase, magnetite and olivine from melt. Data source: Kuhner et al., 1989; Nielsen et al., 1992; Kennedy et al., 1993; Prowatke and Klemme, 2006; Sun et al., 2017.

