

**Chromium stable isotopic insights into the origin of the volatile element depletion of Vesta.** K. Zhu<sup>1</sup>, P. A. Sossi<sup>1</sup>, J. Siebert<sup>1</sup> and F. Moynier<sup>1</sup> <sup>1</sup>Institut de Physique du Globe de Paris, Université Sorbonne Paris Cité, CNRS, 1 rue Jussieu, Paris 75005, France (zhu@ipgp.fr)

**Introduction:** The howardite-eucrite-diogenite (HED) suite is a family of differentiated meteorites that likely originated from the 4-Vesta asteroid. The HED parent body accreted and differentiated a core and a crust within 5 Myrs after the formation of the Solar System [1]. A striking peculiarity of the HED parent body is its strong depletion in volatile elements compared to undifferentiated meteorites and the Earth [2]. The origin and condition of this depletion is presently debated.

Stable isotope ratio of moderately volatile elements can be used to trace the mechanisms of volatile depletion in planetary bodies (e.g. [2]). Chromium is one such element, with a 50% nebular-condensation temperature of 1296 K [3]. However, it behaves differently from other volatile elements (e.g. Zn, K, Ga, Cl) because it has several stable oxidized gas species. Since Cr could be more oxidized in the vapor than in the melt, during equilibrium evaporation, the reduced residue may be enriched in the lighter isotopes compared to the vapor [4]. On the other hand, kinetic isotopic fractionation would always leave the residue enriched in the heavier isotopes. Hence, Cr isotopes can distinguish between evaporation at kinetic (the residue is heavier) or equilibrium (the residue is lighter) conditions. If the evaporation happens at equilibrium, then isotopic fractionation scales with  $1/T^2$ , and the isotopic fractionation can be used to quantify the evaporation temperature and to test whether evaporation occurred during a giant impact (higher T) or degassing of a magma ocean (lower T).

**Sample and analytical methods:** Eleven eucrites (including 8 non-cumulate and 3 cumulate eucrites), 4 diogenites and 3 terrestrial basalts were studied. A  $^{50}\text{Cr}$ - $^{54}\text{Cr}$  double spike were mixed with the samples after complete dissolution following [4]. The Cr stable isotope composition of purified samples were analyzed on the Neptune Plus MC-ICP-MS housed at the Institut de Physique du Globe de Paris. The data are reported as the permil deviation of the  $^{53}\text{Cr}/^{52}\text{Cr}$  ratio from the NIST SRM 979 ( $\delta^{53}\text{Cr}$ ), and another standard, NIST SRM 3112a, is used to monitor the stability of the machine. A correction for Cr isotope anomalies (data are from [1,5]) was applied in order to properly perform the double spike reduction.

**Results:** The  $\delta^{53}\text{Cr}$  values for eucrite samples range from -0.13 to -0.25‰, with an average of -0.20 ‰. Most eucrites are characterized by lower Cr content, lower Mg# and lighter  $\delta^{53}\text{Cr}$  than diogenites. The 5

diogenites samples display higher  $\delta^{53}\text{Cr}$  (mean -0.10 ‰), reaching up to -0.07‰. For comparison, chondrites (and the Earth) have  $\delta^{53}\text{Cr}$  of  $\sim$ -0.10 ‰, which is heavier than eucrites but overlapping with diogenites [4,6].

When  $\delta^{53}\text{Cr}$  values are reported as a function of Cr concentration (and Mg#), diogenites and eucrites are clustered in two discrete groups, with eucrites isotopically light and depleted in Cr (1750 ~ 5673 ppm) compared to the isotopically heavier and Cr-richer diogenites (4404 ~ 6780 ppm) (Figure 1a,b). Chromium contents are positively correlated with the  $\delta^{53}\text{Cr}$  of diogenite meteorites whereas they are not in eucrites (Figure 1a).

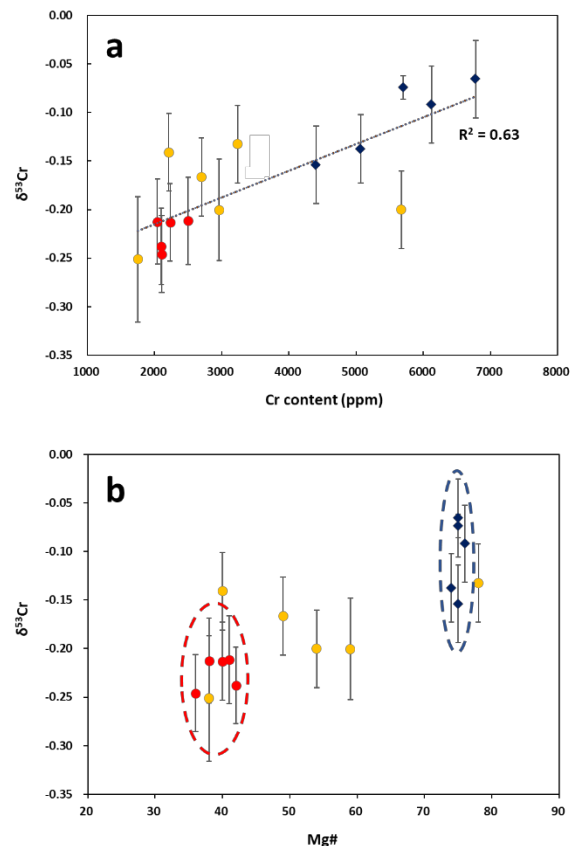


Figure 1 a. Cr isotope composition, expressed as  $\delta^{53}\text{Cr}$  vs. Cr content in the HED samples. b. Cr isotope composition vs. Mg# in the HED samples. Red circles: non-cumulate eucrites, orange circles: cumulate eucrites and blue diamonds: diogenites.

**Discussion:** Isotopic variations among eucrites and diogenites reflect the fractionation of Cr between the

melt and crystallising mineral phases that incorporate different proportions of  $\text{Cr}^{2+}$  and  $\text{Cr}^{3+}$  during differentiation. On Vesta, basaltic eucrites have assemblages that reflect equilibration at lower  $f\text{O}_2$  relative to terrestrial magmas,  $\approx 1$  log unit below the Iron-Wüstite buffer yielding  $\text{Cr}^{2+}/\Sigma\text{Cr} \approx 0.9$  in the melt using the calibration of [7]. Diogenites are orthopyroxenites (OPX)  $\pm$  spinel cumulates and  $\text{Cr}^{3+}$  is more compatible in OPX and spinel than is  $\text{Cr}^{2+}$ . Therefore, the diogenites concentrate isotopically heavy,  $\text{Cr}^{3+}$ -rich orthopyroxene and spinel resulting in their Cr heavy isotope enrichment relative to eucrites.

Since main-trend non-cumulate eucrites, Juvinas, Jonzac and Camel Donga represent primary melts of the Vestan mantle [8], their composition is inferred to reflect that of Vesta. Their average  $\delta^{53}\text{Cr}$ ,  $-0.22 \pm 0.03\%$  (2SD, N=3), is lighter than chondrites and also Earth [4,6].

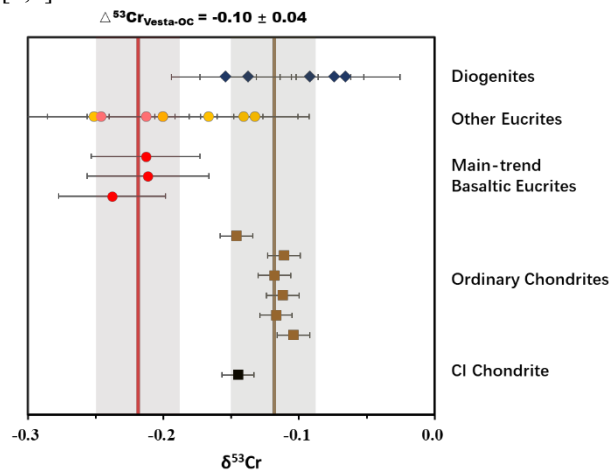


Figure 2 The Cr isotope compositions of Diogenites (blue diamonds), Eucrites (circles). The red is for main-trend basaltic eucrites, and the pink is for Stannern-trend basaltic eucrites and orange for other eucrites). Both ordinary (brown squares) and carbonaceous (black square) chondrites are plotted. The light red shade indicates the 2SD of  $\delta^{53}\text{Cr}$  for 3 basaltic eucrites which may represent Vesta. The  $\delta^{53}\text{Cr}$  deficit between Vesta and ordinary chondrites is  $\Delta^{53}\text{Cr}_{\text{Vesta-OC}} = -0.10 \pm 0.04$ , which is attributed to equilibrium fractionation during Cr loss at a magma ocean stage.

The enrichment in the lighter Cr isotope of Vesta compared to chondrites cannot be caused by Vestan core formation. This is because only 1~3% Cr would enter the core. Therefore, the most likely origin for the light isotope enrichment is evaporation under equilibrium conditions, which can further constrain the volatile temperatures between isotope fractionation between  $\text{CrO}_{(l)}$  and  $\text{CrO}_{2(g)}$  [4] (see figure 3).

$$\Delta^{53}\text{Cr}_{\text{CrO}_{(l)}-\text{CrO}_{2(g)}} = (-0.31 \pm 0.16) \times \frac{10^6}{T^2} (\%).$$

If Vesta originates from ordinary chondrite-like material ( $\delta^{53}\text{Cr} = -0.12 \pm 0.03 \%$ , similar nucleosynthetic anomalies), their deficit,  $\Delta^{53}\text{Cr}_{\text{Vesta-OC}} = -0.10 \pm 0.04$ , corresponds to  $< 1800$  K. For a CI chondrite precursor ( $\delta^{53}\text{Cr} = -0.15 \pm 0.01 \%$ ), an extreme scenario, temperatures must have been lower than 2300 K.

These relatively low temperatures ( $< 2300$  K) for Vesta's volatile loss can be reconciled with degassing during a Vestan magma ocean stage, as recently suggested for the Moon [4].

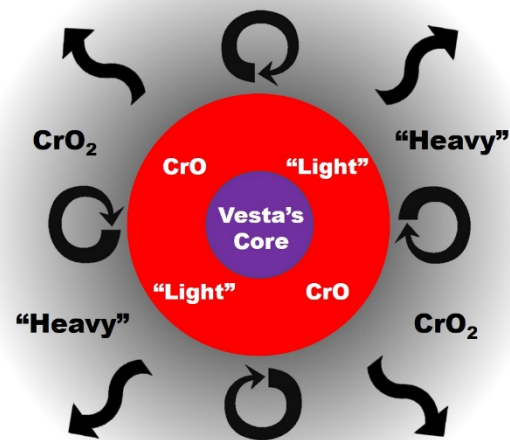


Figure 3 Schematic diagram illustrating the effect of volatile loss on the Cr stable isotope composition of Vesta. The core only contains 1~3% of Vesta's Cr budget, and core formation did not likely induce Cr isotope fractionation.

**References:** [1] Trinquier A. et al. (2008) *GCA*, 72, 5146–5163. [2] Day J. and Moynier F. (2014) *Phil. Trans. R. Soc. A*, 372, 20130259. [3] Lodders K. (2003) *ApJ*, 591, 1220–1247. [4] Sossi P. et al. (2018) *PNAS*, 115, 10920–10925. [5] Trinquier A. et al. (2007) *ApJ*, 655, 1179–1185. [6] Bonnard P. et al. (2016) *EPSL* 435, 14–21. [7] Berry A. et al. (2006) *AM* 91, 1901–1908. [8] Stolper E. M. (1977), *GCA*, 41, 587–611

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