Chromium stable isotopic insights into the origin of the volatile element depletion of Vesta. K. Zhu1, P. A. Sossi1, J. Siebert1 and F. Moynier1 1Institut 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}Cr-^{54}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}Cr/^^{52}Cr ratio from the NIST SRM 979 (δ^{53}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 δ^{53}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 δ^{53}Cr than diogenites. The 5 diogenites samples display higher δ^{53}Cr (mean -0.10 ‰), reaching up to -0.07‰. For comparison, chondrites (and the Earth) have δ^{53}Cr of ~0.10 ‰, which is heavier than eucrites but overlapping with diogenites [4,6].

When δ^{53}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 δ^{53}Cr of diogenite meteorites whereas they are not in eucrites (Figure 1a).

![Figure 1](image.png)

Figure 1 a. Cr isotope composition, expressed as δ^{53}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 Cr\textsuperscript{3+} and Cr\textsuperscript{4+} during differentiation. On Vesta, basaltic eucrites have assemblages that reflect equilibration at lower fO\textsubscript{2} relative to terrestrial magmas, \approx 1 \log unit below the Iron-Wüstite buffer yielding Cr\textsuperscript{3+}/Cr \approx 0.9 in the melt using the calibration of \cite{7}. Diogenites are orthopyroxenites (OPX) \pm spinel cumulates and Cr\textsuperscript{3+} is more compatible in OPX and spinel than is Cr\textsuperscript{4+}. Therefore, the diogenites concentrate isotopically heavy, Cr\textsuperscript{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 \cite{8}, their composition is inferred to reflect that of Vesta. Their average \delta\textsuperscript{53}Cr, -0.22 \pm 0.03\%\textsubscript{o} (2SD, N=3), is lighter than chondrites and also Earth \cite{4,6}.

If Vesta originates from ordinary chondrite-like material (\delta\textsuperscript{53}Cr = -0.12 \pm 0.03 \%, similar nucleosynthetic anomalies), their deficit, \Delta\delta\textsuperscript{53}Cr\textsubscript{Vesta-OC} = -0.10 \pm 0.04, corresponds to < 1800 K. For a CI chondrite precursor (\delta\textsuperscript{53}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 \cite{4}.

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{Figure3.png}
\caption{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.}
\end{figure}

**Acknowledgement:** We thank the ERC under the European Community’s H2020 framework program/ERC grant agreement (Pristine, no. 637503) and the French National Research Agency (ANR) for a Chaire d’Excellence Sorbonne Paris Cité (IDEX13C445) and for the UnivEarthS Labex program (no. ANR-10-LABX-0023 and ANR-11-IDEX-0005-02).

**References:**