

**THE VESTAN CORE AS A MAJOR RESERVOIR FOR VOLATILE ELEMENTS.** W. van Westrenen<sup>1</sup>, E.S. Steenstra<sup>1,2</sup>, D. Dankers<sup>1</sup>, J. Berndt<sup>3</sup>, S. Matveev<sup>4</sup>, S. Klemme<sup>3</sup>. <sup>1</sup>Vrije Universiteit Amsterdam, the Netherlands, <sup>2</sup>The Geophysical Laboratory, Washington D.C., United States, <sup>3</sup>Institute of Mineralogy, Münster University, Germany <sup>4</sup> Faculty of Geosciences, Utrecht University, the Netherlands ([w.van.westrenen@vu.nl](mailto:w.van.westrenen@vu.nl))

**Introduction:** Vesta, the 2<sup>nd</sup>-largest body in the asteroid belt, is believed to be a prime example of a rocky protoplanet. Studies of the HED meteorite suite, considered to be sourced from Vesta, provide insight into protoplanet differentiation processes. Euclrites and diogenites are considered to be depleted in many volatile elements [1,2], but the depletions of many volatile siderophile elements (VSE) are not well constrained. Although previous work indicated that the Vestan core equilibrated with its mantle in a global melting event [3,4], the possible contribution of core formation to the volatile budget of HED meteorites has not been assessed to date. This prohibits an assessment of the overall volatile depletion systematics of Vesta. Here, we compile published VSE abundances in diogenites and euclrites to constrain their depletions in the Vestan mantle and assess to what extent these depletions could be explained by volatility-related depletion, partitioning into sulfides in the mantle, and/or their partitioning into the Vestan core.

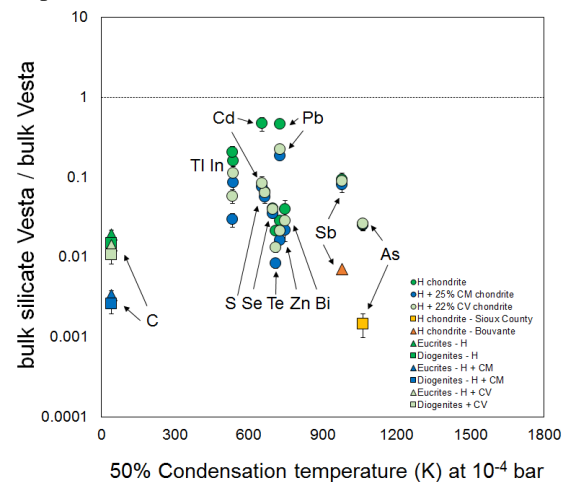
**Methods:** Vestan mantle abundances of the VSE were estimated by assuming indigenous abundances of these elements in diogenites to be lower limits and their abundances in non-cumulate euclrites to be upper limits, given the incompatible nature of these elements. Estimates of VSE are based on euclrites - diogenites found in non-glacial environments [5]. A major part of euclrite data was based on the compilation of [6]. Diogenite abundances were taken from [7,8]. Diogenites and/or euclrites with anomalous O isotopic signatures were excluded. Tl and Ir contents were used to monitor possible FeS and meteoritic contributions to VSE measurements, respectively. We explore a bulk Vesta H-chondritic bulk composition and addition of a 22% CV or 25% CM component [9-11].

Metal-silicate partition coefficients ( $D$ 's) that are required to explain VSE depletions in the Vestan mantle were calculated by using Eq. (1):

$$D_m^c(i) = ((C_{bv(i)} - xC_{bsv(i)}) / (C_{bsv(i)} (1 - x))) \quad (1)$$

where  $C_{bv(i)}$  is the concentration by weight of element  $i$  in bulk Vesta. The  $C_{bsv(i)}$  term represents the estimated abundance of element  $i$  in bulk silicate Vesta and  $x$  is the assumed Vestan core mass fraction. We assume a Vestan core mass of  $25 \pm 2$  %, which is an average based on bulk compositional calculations and refractory siderophile element modelling [4]. Previously reported metal- or sulfide-silicate  $D$ 's [12-14], obtained between 1–2.5 GPa and 1673–2023 K, were

corrected to a common  $fO_2$  value of  $\Delta IW - 2$  according to their proposed valence states [3,4,13,15]. The  $T$  range is directly relevant for Vestan differentiation, whereas the  $P$  range is higher than that for the Vestan core mantle boundary (0.1 GPa). However, there are no clear pressure effects within the 1–2.5 GPa range for the elements considered here, so this is unlikely to significantly affect our results [12]. S-Se-Te are an exception as their siderophile behavior strongly increases with  $P$  [12,16]. Their  $D$  values were corrected with the  $P$  dependencies from [12].



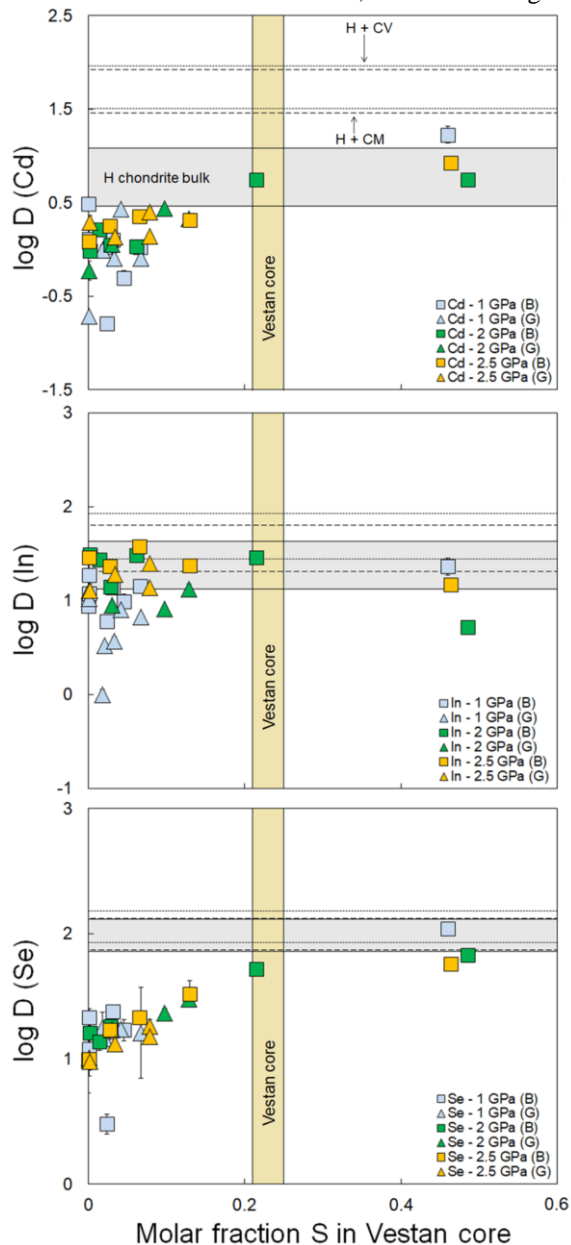
**Fig. 1.** VSE depletions in the Vestan mantle, assuming a H chondritic, H + CV or H + CM Vestan bulk composition [9,10], versus their 50% condensation  $T$ .

**Results:** The compiled estimates for VSE Vestan mantle depletions are poorly correlated with condensation  $T$  (Fig. 1), suggesting their depletions cannot be reconciled with volatility only. Fig. 1 suggests other processes (i.e. sulfide saturation and/or partitioning into the core) affected their abundance in the Vestan mantle.

**Partitioning of VSE into sulfides:** Although S abundances in euclrites and diogenites can be up to 4000 ppm, the vast majority of diogenites and euclrites have S abundances <2500 ppm [e.g. 6]. A recent predictive model for the sulfur concentration at sulfide saturation (SCSS) suggests that at 1 atm and 1423 – 1523 K ~5000 ppm S can be dissolved in euclritic compositions [17]. Significant degassing of S seems to be ruled out from S isotope compositions reported for HED's [18]. The source regions of the euclrites are therefore unlikely to be sulfide saturated.

**Partitioning of VSE into Vesta's core:** Indigenous refractory siderophile element abundances in HED's

have been used to argue for core-mantle equilibrium in Vesta's early history [3,4], consistent with a magma ocean stage on Vesta [19]. Consideration of the VSE partitioning behavior shows that most of these elements are sufficiently siderophile to explain their depletions in the Vestan mantle by their partitioning into a S-rich Vestan core. This is shown for Cd, In and Se in Fig. 2.



**Fig. 2**  $D$ 's of Cd, In, Se versus S in the Vestan core (data from ref. [12]). Horizontal bars represent the different required  $D$ 's for different bulk Vesta compositions (solid = H chondrite, dashed = H + 22% CV, finely dashed = H + 25% CM). Vertical bars represents estimated S content of the Vestan core [4,10]. Letters in parentheses denote the type of silicate composition used in the partitioning experiments (G= granite, B = basalt).

Similar results are found for Pb, Te, S, Tl, C, showing that core formation in Vesta is a highly effective process that can deplete these (highly) volatile elements in HEDs. Note that a S-rich Vestan core is also compatible with the depletions of moderately siderophile elements [3,4], the abundance of S in HED's and with the proposed building blocks for Vesta [3,4,10].

As and Sb are both far more abundant in the Vestan mantle than expected from their highly siderophile behavior – this is most likely related to the analytical challenges to measure their indigenous abundances in meteoritic samples. Zn is significantly more depleted than expected from metal-silicate partitioning alone. However, depletion through volatile loss from Vesta is difficult to reconcile with Zn isotopic compositions of eucrites, which could suggest a Zn-poor Vestan bulk composition or preferential partitioning of Zn into spinel [20].

**Implications for volatile depletion in Vesta:** Our results indicate that the global event of metal halide degassing inferred from halogen and/or alkali abundances in eucrites [21] did not significantly affect the depletions of many VSE in the Vestan mantle, consistent with the Cd and S isotopic compositions measured in eucrites [18,22]. Our results underline the feasibility of planetary cores being a major reservoir for many volatile elements that are depleted in planetary mantles and that are currently assumed to have suffered incomplete condensation during accretion or (partial) degassing after accretion.

**References:** [1] Mittlefehldt (1987) *GCA* 51, 267 [2] Sarafian et al (2017) *EPSL* 459, 311 [3] Righter & Drake (1997) *MAPS* 32, 929 [4] Steenstra et al (2016) *GCA* 177, 48 [5] Mittlefehldt & Lindstrom (1991) *GCA* 55, 77 [6] Kitts & Lodders (1998) *MAPS* 33, A197 [7] Wolf et al (1983) *GCA* 47, 2257 [8] Mittlefehldt (1994) *GCA* 58, 1537 [9] Lodders (2000) *SCR* 92, 341 [10] Toplis et al (2013) *MAPS* 48, 2300 [11] Newsom (1995) *Global Earth Phys*, AGU [12] Steenstra et al (2017) *Sci Rep* 7, 14552 [13] Wood et al (2014) *GCA* 145, 248 [14] Wood et al (2008) *RSAMPES* 366, 4339 [15] Steenstra et al (2017) *GCA* 212, 62 [16] Rose-Weston et al (2009) *GCA* 73, 4598 [17] Smythe et al (2017) *AM* 102, 795 [18] Wu et al (2016) *LPSC* #2344 [19] Greenwood et al (2005) *Nature* 435, 916 [20] Paniello et al (2012) *GCA* 86, 76 [21] Sarafian et al (2017) *EPSL* 459, 311 [22] Schönbächler et al (2008) *Met Soc* #5268