**DID EUCRITES AND ANGRITES EXPERIENCE SULFIDE SATURATION?** W. van Westrenen[1], E.S. Steenstra[1-3], J. Berndt[3], S. Klemme[3], A. Rohrbach[3] [1] [1]VU Amsterdam, the Netherlands, [2]The Geophysical Laboratory, Washington D.C., USA, [3]Institute of Mineralogy, Münster University, Germany (w.van.westrenen@vu.nl)

**Introduction:** Asteroidal basalts provide fundamental clues to the earliest volcanic and initial differentiation processes in our solar system [1-4] and the occurrence and/or extent of subsequent meteoritic veneers [5]. Siderophile and/or chalcophile element depletions in eucrites and angrites have been used to model core formation in their parent bodies as well as meteoritic late veneers [5-9]. In these models it is assumed that eucrites and angrites did not experience sulfide saturation in their source regions or during later magmatic differentiation. This is an important assumption as (highly) siderophile and/or chalcophile elements will be strongly concentrated in sulfides. Steenstra et al. [8] briefly assessed the extent of sulfide saturation of pristine non-cumulate eucrites using measured concentrations of S in eucrites in conjunction with a new thermodynamic model for predicting the S concentration at sulfide saturation (SCSS) [11]. These results in conjunction with qualitative interpretations of eucrite chalcophile element systematics did not provide evidence for sulfide saturation of eucritic source regions. However, [8] did not consider the possible effects on SCSS of sulfide and silicate compositions. To our knowledge, the possibility of sulfide saturation of angrites and their source regions has not been assessed previously, despite the importance of angrites for our understanding of the early solar system. As part of an extensive study focused on S systematics and elemental sulfide-silicate partition coefficients ($D_{sul/sil}$) [12-15], we performed high *P-T* experiments to assess the SCSS for eucritic and angritic melts and to simultaneously quantify $D_{sul/sil}$ of trace elements for these melts.

**Methods:** Synthetic equivalents of typical volcanic angrites (LEW 87051, D'Orbigny), a pristine non-cumulate eucrite [16] and a putative eucrite parent magma composition [17] were equilibrated with sulfides at high *P-T* using Bristol-type end loaded piston cylinder presses at VU and Münster University. Sulfide powders consisted of FeS doped with 1000 ppm of P, V, Co, Ni, Cu, Zn, Ga, Ge, Se, Nb, Mo, Cd, Sn, Sb, Te, Ta, W, Pb, Bi. All experiments were performed at 1 GPa and 1583-1883 K in C capsules using talc-pyrex assemblies. As in our previous work, experimental *T* was measured using a type B or D thermocouple [12-15]. After the experiments run products were embedded in epoxy, polished and analysed for major elements using EPMA and trace elements using LA-ICP-MS at Münster.

**Results:** Run products consisted of well segregated quenched sulfide melts in quenched silicate glasses [see 12]. Coloured symbols in Fig. 1 show the SCSS values measured for the various compositions as a function of FeO concentration of the silicate melt. It is clear that besides *T* silicate composition also affects the SCSS as previously established [11,18,19].

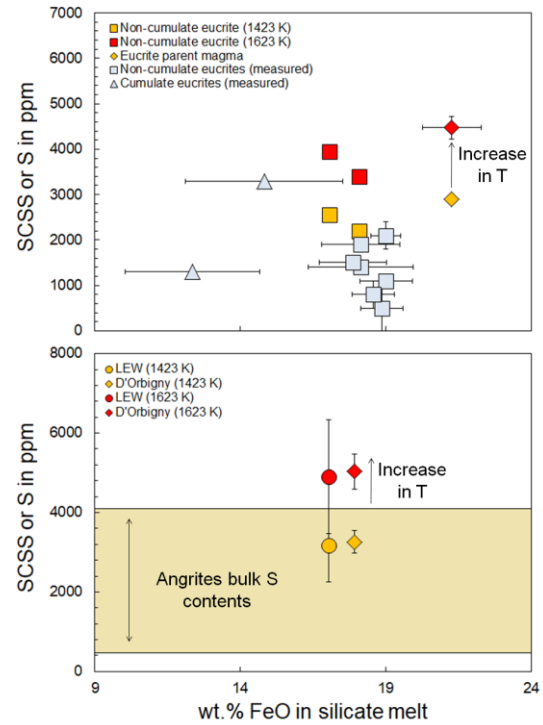


***Fig. 1:*** *The SCSS for eucrites* ***(a)*** *and angrites* ***(b)****, obtained at 1 GPa and 1583-1883 K as a function of silicate melt FeO contents. The SCSS data for eucrites and volcanic angrites were normalized to 1 atm and 1423 or 1623 K, using the thermodynamic model of [11]. Bulk S contents measured in predominantly monomict non-cumulate and cumulate eucrites [8 and references therein, 21] are plotted for comparison in plot* ***(a)****. In plot* ***(b)*** *horizontal bar represents bulk S concentration range in angrites [22].*

*Eucrites:* We now assess whether experimental SCSS values for eucrites are in the range of reported S concentrations. Eucrites are believed to have been formed at 1423-1523 K and 1 atm [20]. First, we compare our experimental SCSS values for non-cumulate eucrites with measured bulk S contents of eucrites [21]. We observe that SCSS values for FeS liquids are generally higher than measured bulk S concentrations (Fig. 1a). Only at the lowest *T* inferred for non-cumulate eucrite formation (1423 K) SCSS values are in the range of measured values for similar compositions. To further explore the possibility of FeS saturation in Vesta, we also modeled the SCSS using a revised model [12] as a function of crystallization of the Vestan

magma ocean [23] and compare these values with the bulk S contents of eucrites [21].

Figure 2 shows the results for FeS liquids and FeS + 30 wt.% Cu or Ni. As observed in Fig. 1, high *T* (>1600 K) during generation of eucritic melts makes sulfide saturation at these conditions unlikely. However, as *T* approaches the range inferred for eucrites [20] sulfide saturation becomes more likely, especially if sulfide liquids contain significant amounts of Ni and/or Cu. Similarly, at the MgO concentrations appropiate for non-cumulate eucrites the SCSS becomes sufficiently low to result in sulfide saturation of eucritic liquids (Fig. 2).

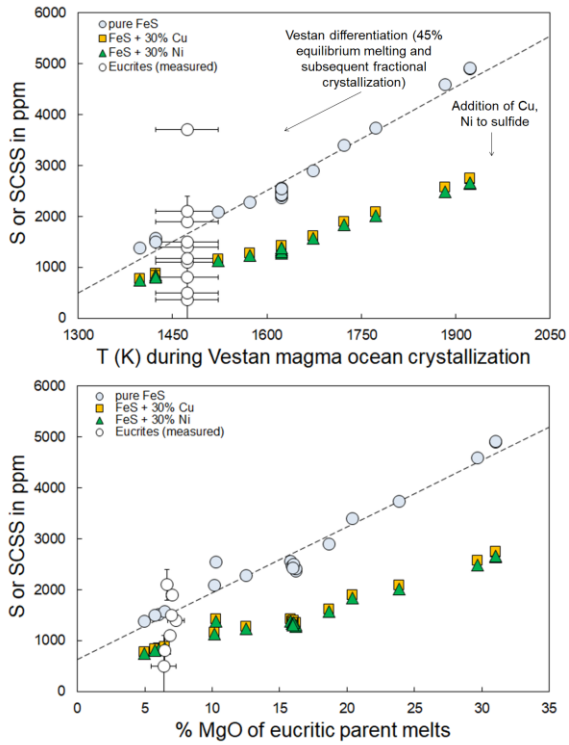


***Fig. 2:*** *The modeled SCSS during differentiation of the Vestan magma ocean / eucritic parent melts. The SCSS was calculated using the model of [12], while assuming three sulfide compositions (FeS, FeS + 30% Cu or Ni) and the experimentally determined silicate melt compositions inferred for Vestan differentiation at a given T and 1 atm [22].*

*Angrites*

Only two experiments with angrites have as of yet been analyzed for their S contents. Both values are within the range of bulk S contents measured for angrites [22], especially when lower temperatures for angrite formation are considered (Fig. 1b). Additional results presented at the meeting will provide more constraints on the possibility of sulfide saturation of angrites.

**Discussion:** Our preliminary results show that the most evolved eucritic melts could have been sulfide saturated, especially if sulfide liquids are non-stoichiometric FeS and/or if significant degassing of S occurred during and/or following emplacement of eucritic melts. Heavy $\delta^{34}S$ isotopic signatures of non-cumulate eucrites have been used to argue for degassing of S [21]. However, the implications of degassing of S for sulfide saturation critically depends on the timing of S loss from Vesta, which could have occurred during accretion and/or following crystallization of the magma ocean [21]. Metals and sulfides have also been found as a common accessory phase in several eucrites and diogenites. Alard and Gounelle [24] suggested that these phases were formed from a Fe-Ni-S magmatic liquid, with sequential crystallization of Fe-Ni metal followed by crystallization of an immiscible sulfide melt. However, other authors attribute the occurrence of such metal and sulfide phases to secondary metamorphic or metasomatic processes [e.g. 25]. Although the segregation of sulfide liquids during eucritic differentiation would be consistent with the compatibility of Ni and Co and incompatibility of Ga and P in eucrites [7], such trends have been proposed to be more consistent with olivine fractionation [e.g. 26], as observed for lunar low- and high-Ti basalts [11,26].

**Outlook:** More experiments and chemical analyses are currently being performed and will be used to additionally assess the extent of sulfide saturation in asteroidal mantles.

**References:** [1] Kleine et al (2004) *GCA* 13, 2935 [2] Greenwood et al (2005) *Nature* 435, 916 [3] Keil (2012) *Chem Erde* 72, 191 [4] Kleine et al (2012) *GCA* 84, 186 [5] Dale et al (2012) *Science* 336, 72 [6] Righter & Drake (1997) *MAPS* 32, 929 [7] Steenstra et al (2016) *GCA* 177, 48 [8] Steenstra et al (2019) *Icarus* 317, 669 [9] Day et al (2016) *Rev Min Geochem* 81, 161 [10] Steenstra et al (2017) *GCA* 212, 62 [11] Steenstra et al (2018) *GCA* 231, 130 [12] Steenstra et al (2019) *This meeting* [13] Van Haaster et al (2019) *This meeting* [14] Kelderman et al (2019) *This meeting* [15] Trautner et al (2019) *This meeting* [16] Warren et al (2009) *GCA* 73, 5918 [17] Grove & Bartels (1992) *LPSC* 22, 437 [18] Ding et al (2017) *GCA* 222, 319 [19] Smythe et al (2017) *AM* 102, 795 [20] Stolper et al (1977) *GCA* 41, 587 [21] Wu et al (2018) *GCA* 233, 1 [22] Wu et al (2017) *LPSC* 48, 2380 [23] Ashcroft & Wood (2015) *MAPS* 50, 1912 [24] Alard & Gounelle (2009) *MetSoc* 72, 5051 [25] Zhang et al (2018) *GCA* 220, 125 [26] Ruzicka et al (2001) *GCA* 65, 979