

**A MODEL FOR SIDEROPHILE ELEMENT DISTRIBUTION IN PLANETARY DIFFERENTIATION.** M. Humayun<sup>1</sup>, T. Rushmer<sup>2</sup>, K. Rankenburg<sup>3</sup>, and A. D. Brandon<sup>3</sup>, <sup>1</sup>National High Magnetic Field Laboratory and Dept. of Geological Sciences, Florida State University, Tallahassee, FL 32310, USA ([humayun@magnet.fsu.edu](mailto:humayun@magnet.fsu.edu)), <sup>2</sup>Dept. of Geology, University of Vermont, Burlington, VT 05405, USA, <sup>3</sup>NASA JSC, Mail Stop KR, Houston, TX 77058, USA.

**Introduction:** Planetary differentiation begins with partial melting of small planetesimals. At low degrees of partial melting, a sulfur-rich liquid segregates by physical mechanisms including deformation-assisted porous flow [1]. Experimental studies of the physical mechanisms by which Fe-S melts segregate from the silicate matrix of a molten H chondrite are part of a companion paper [1]. Geochemical studies of these experimental products revealed that metallic liquids were in equilibrium with residual metal in the H chondrite matrix [2]. This contribution explores the geochemical signatures produced by early stages of core formation. Particularly, low-degree partial melt segregation of Fe-S liquids leaves residual metal in the silicate matrix. Some achondrites appear to be residues of partial melting, e.g., ureilites, which are known to contain metal [3]. The metal in these achondrites may show a distinct elemental signature. To quantify the effect of sulfur on siderophile element contents of residual metal we have developed a model based on recent parametrizations [4] of equilibrium solid metal-liquid metal partitioning experiments [5].

**Methodology:** Two types of chondritic precursor were considered: a CI chondrite composition body, and an H chondrite composition body.

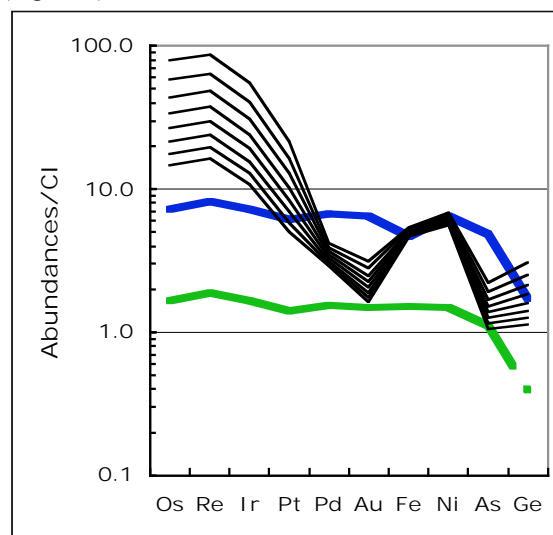
For the **CI chondrite composition**, we assumed that reduced C reacted with oxidized iron to form FeO and Fe-Ni metal. The carbon and Fe contents of Jarosewich's Orgueil analysis [6] were used to calculate pre-melting abundances of FeO, Fe-Ni metal and FeS. The results were used to calculate the metal-silicate partition coefficient of Fe ( $D^{m/s} \sim 13$ ). For the model results shown, it should be noted that abundances of CO<sub>2</sub> and SO<sub>3</sub> were excluded from equilibrium calculations as such species may be outgassed prior to equilibration. The inclusion of these species would decrease the metal-silicate partition coefficient for Fe. Other elements that may be affected include Co, Ga and W. For highly siderophile elements, the metal-silicate partition coefficients were taken to be 10<sup>5</sup>, while those of Ni and Ge were set at 10<sup>3</sup>. These metal-silicate partition coefficients were used to calculate the composition of the metallic liquid formed by partial melting of a CI composition body. The liquid metal composition is a

function of the degree of partial melting, being more sulfur-rich at low degrees of partial melting. In the present model, this effect has not been included. Total melting of the metal in a CI chondrite body produces a melt with about 19 wt % S.

For the **H chondrite composition**, the amount of reduced C was too small to make a substantial difference to the abundance of reduced Fe. Thus, the abundances of FeO, Fe metal and FeS of an average H composition [6] were used directly. A total metallic melt of such a composition has about 8.5 wt % S. Higher S contents may be expected for lower degree partial melts, but this has not yet been included in the present model.

Siderophile element abundances for CI and H compositions were obtained from Wasson & Kallemeyn [7]. Residual metal in equilibrium with H chondrite liquid metal was calculated for cases where the amount of residual metal was very small.

**Results:** Results of siderophile element signatures for an H chondrite composition were calculated for varying sulfur contents (0-14 wt %) in the liquid (Figure 1).

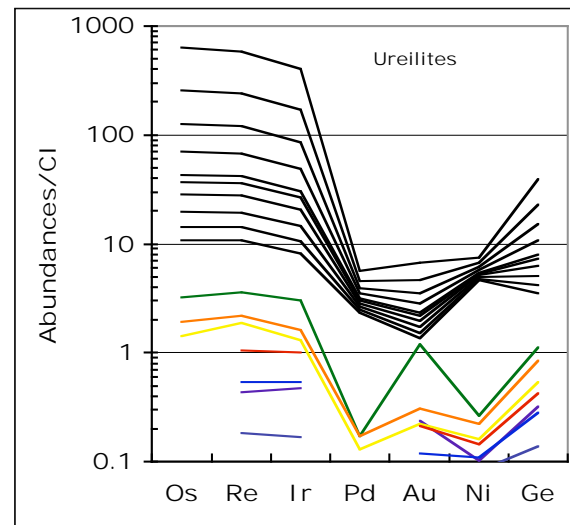


**Figure 1.** Siderophile element patterns for residual metals formed by partial melt removal from an H6 chondrite, as a function of S content from S=0-14 wt % in 2% increments (dark lines). The siderophile element patterns for average H chondrite (green line), and for the inferred liquid metal (blue line) are also shown.

As expected, the abundances of Os, Re and Ir in residual metal increase with increasing S content of the liquid. The model liquid composition is shown. Since the abundances were normalized by convention to a CI chondrite composition [7], the H chondrite composition is also shown. Some elemental fractionations (e.g. Re/Os) are inherited from the precursor H chondrite composition, including the volatile element depletions in As and Ge. We have found no natural data against which to compare the model for an H chondrite composition. Note the low abundances of incompatible Pd, Au and As in the metal.

**Applications to ureilites.** We applied the CI chondrite model to the compositions of ureilites (Figure 2). Ureilites are olivine-orthopyroxene rocks with carbonaceous veins rich in siderophiles. The  $\Delta^{17}\text{O}$  of ureilites indicates that their silicate minerals were derived from a CV chondrite-like source [8]. The origin of the carbonaceous veins has been controversial including both local and exotic origins [9]. Notably, the siderophile element pattern for Re, Os, Ir and W is approximately chondritic, and only slightly lower than for bulk chondrite compositions [9]. In Figure 2, we show siderophile element data on 6 ureilites, including a vein separate from Haverö [10]. The siderophile element pattern in the ureilites, particularly the Haverö vein, resembles the model very well. The fit for Au is not good, but the steep drop off for Pd, and the Ge/Ni fractionation are all consistent with residual metal formed from a sulfur-rich metallic liquid. Since Ge is more volatile than Ni, the positive  $(\text{Ge}/\text{Ni})_{\text{CI}}$  is evidence against a volatility-related pattern. Further, both Ge and Ni occur at ppm-levels, are not perturbed by residual liquid metal (unlike Pd/Ir), and their ratio is sensitive to the melt S content. Using the  $(\text{Ge}/\text{Ni})_{\text{CI}}$  values of ureilites we infer sulfur contents to be mainly  $>20$  wt %. It should be noted that the model is based on the sulfur (and Ge) content of a CI composition. The lower S contents of CV chondrite compositions ( $0.4\times\text{CI}$ ) implies that such high inferred S contents are compatible only with very low degree partial melts. Thus, the siderophile element pattern of ureilites is consistent with an origin as residues of low-degree partial melting of CV chondrite-like compositions. It is conceivable that ureilites were formed on the CV chondrite parent body, by localized heating. The low-degree partial melts inferred for the ureilite siderophile element pattern is consistent with their retaining unequilibrated  $\Delta^{17}\text{O}$  [8]. Probably, not all ureilites formed in a single

place, but may represent localized heating events (impacts?). The liquid composition removed from ureilites has not been identified as of yet.



**Figure 2.** Siderophile element patterns for residual metal from a metallic liquid with S=0-24 wt %, in 3% intervals (dark lines) compared with data for ureilites [10]: Haverö vein (green), Kenna vein (orange), Kenna (yellow), Novo Urei (red), Haverö (blue), Dyalpur (violet), Goalpara (indigo).

**Conclusions:** The siderophile element pattern in residual metal is easily recognized by its high, chondritic-relative abundances of Re, Os and Ir, and by low Pd, Au and As, relative to Fe and Ni. The presence of small amounts of residual metal provides a good match to the siderophile patterns of ureilites. Ureilites likely originate as residues from low-degree partial melts of CV chondrite-like compositions.

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