PARENT BODY HISTORIES RECORDED IN OXIDIZED CHONDRITE SULFIDES: IMPLICATIONS FOR CORE FORMATION.

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Summary: Core formation within highly oxidized, sulfur-rich parent bodies that lack metal is poorly understood. Under some conditions, it may be possible to crystallize a metallic core from sulfide melts. These materials could be identified among iron meteorites if they retain the distinct siderophile trace element characteristics of their parent sulfide melts. We analyzed sulfides in an R chondrite across a range of metamorphic conditions to observe the distribution of siderophile elements up to the onset of differentiation. While some elements partition similarly into sulfides as they would into metals, several others show distinct affinities for pentlandite, pyrrhotite, oxides, and/or silicates. If FeNi metal were to crystallize from a pentlandite-rich melt, its composition could likely be distinguished by elevated Ni content and depleted W, Mo, and Pt trace element concentrations.

Introduction: In chondritic meteorites, oxidation state and sulfur content play a critical role in establishing the mineralogy of core forming components (metals and sulfides). This is evident when comparing the Rumuruti chondrites (RCs) and ordinary chondrites (OCs), which otherwise share many similar petrologic and isotopic characteristics [e.g., 1]. However, RCs formed under more oxidizing and more sulfur-rich conditions [2]. As a consequence, RCs do not contain FeNi metal above trace abundances [3], and their Fe-Ni-S systems are instead dominated by sulfides pentlandite and pyrrhotite. The observation that oxidized primitive materials, including RCs and many carbonaceous chondrites, lack appreciable metal content raises two questions: (a) Can core formation occur on highly oxidized, sulfur-rich parent bodies that initially lack metal? (b) How could core components of such parent bodies be identified among iron meteorites?

Sulfide phases are among the first to melt in chondritic mineralogies [4], and evidence for the segregation of pentlandite melt from silicate residue is preserved in oxidized primitive achondrites [5]. Once removed, liquid pentlandite (FeNiS) can subsequently precipitate Ni-rich metal [6], providing a pathway for metallic core formation despite an initial lack of metal.

Siderophile elements with high affinities for FeNi metal are the most common tools used in the classification of iron meteorites [e.g., 7]. Despite a lack of FeNi metal, RCs still contain chondritic abundances of siderophile elements [8], which are largely held by sulfides [5]. If the siderophile trace element systematics among sulfides can be characterized, then predictions can be made regarding diagnostic features for iron meteorites that crystallized from sulfide melts.

We have measured the distribution of siderophile elements among RC sulfides across multiple petrologic grades to assess their origins and distribution during metamorphism up to the point of incipient melting. This data may be used to estimate the trace element characteristics of sulfide melts, to provide diagnostic tools for identifying iron meteorites that crystallized from sulfide melts, and to establish a priori parameterization for modelling core formation on oxidized, sulfur-rich parent bodies.

Methods: R chondrite Northwest Africa (NWA) 11304 is a polymict breccia composed of petrologic types R3-6, providing an ideal opportunity to observe the sequence of metamorphic processes within a single sample. Sections of NWA 11304 were analyzed for major element chemistry of sulfides via EMPA. In situ trace element measurements for sulfides were collected using LA-ICP-MS. Metamorphic classifications of clasts within NWA 11304 are based on silicate major
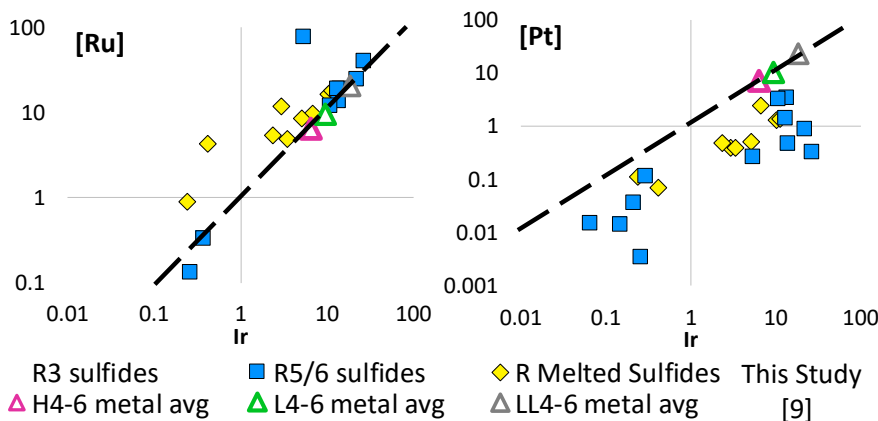

Fig. 1. CI-normalized Ru/Ir and Pt/Ir diagrams exemplify the variable behaviors of siderophile elements in sulfide systems that lack metal. Ru/Ir remains chondritic (dashed line) among both RC sulfides and OC metals. However, while Pt/Ir is chondritic in OC metals, it consistently subchondritic in RC sulfides. This is likely due to the presence of discrete Pt-rich grains that frequently occur in sulfides. This aberrant behavior is reflected across several other nominally siderophile elements, as well. CI normalization from [10].

element variation and petrographic textures after methods for other RCs and OCs [11].

Results/Discussion: *Pre-accretional History:* On average, sulfides from type 3 RC clasts typically contain chondritic siderophile interelement ratios (Fig. 1) similar to metals in ordinary chondrites. The similar interelement ratios between these phases could be attributed to nebular sulfidation of OC-like metals [12], although subsequent impact melting of R chondrite sulfides [13] obscures evidence of this mechanism. Subchondritic Pt/Ir ratios in RC sulfides are due to the presence of Pt-rich metals, arsenides, and sulfarsenides (1-10 µm). Whether these phases are formed during impact melting of sulfides [13] or through alteration of nebular condensates [14] is uncertain, but similar phases have been reproduced in melting experiments with As-rich pentlandite melts [15].

Metamorphic History: The distribution of siderophile elements between sulfides pentlandite and pyrrhotite remains largely unchanged between clasts of petrologic types 3 and 4. In RC clasts of petrologic type 5-6, pyrrhotite and pentlandite exsolve from monosulfide solid solution (MSS) and coarsen, as indicated by clustering of interelement ratios in Fig. 1. In R5-6 clasts, pentlandite highly siderophile element content is comparable to OC taenite, apart from Pt. Mo/Ni and W/Ni ratios (Fig. 2) decrease for metals and sulfides in the order H>L>LL>R, consistent with oxidation state [2], as Mo and W oxidize and partition into silicates and oxides. Oxidation likely takes place during metamorphic equilibration between matrix materials, lithic fragments, and chondrules, as Mo/Ni of RC sulfides decreases from type 3 to type 5/6 by an order of magnitude.

Prior to the onset of melting, the siderophile trace element characteristics of sulfide-dominated Fe-Ni-S mineralogies diverge from metal-dominated systems. In the absence of metal, siderophile elements partition largely into pentlandite in proportions similar to OC metals. There are, however, several critical distinctions. Platinum is roughly an order of magnitude less compatible with pentlandite than with taenite or kamacite. Redox-sensitive siderophile elements, W and Mo, are largely excluded from sulfides, and likely partition into silicates and oxides.

Future Experimental Work: Upon melting, the majority of siderophile elements remain in the pentlandite melt fraction, as indicated by impact melted sulfides in NWA 11304 (Fig. 1). However, no suitable distribution coefficients for siderophile elements among this mineral assemblage have been reported in literature. Further experimental work is needed to model trace element partitioning between sulfides and metals during
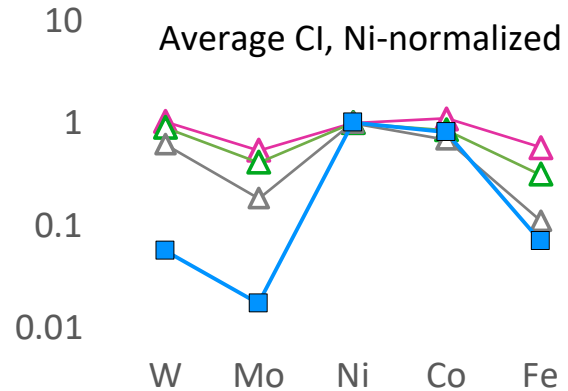

Fig. 2. Redox-sensitive W and Mo in RC pentlandite continue a trend from OC metals, where W/Ni and Mo/Ni decrease as the degree of oxidation increases. Co/Ni ratios for RCs are most similar to L or LL chondrite metals. Symbols are defined in Fig. 1. OC metal data are from [9].

melting and crystallization in order to model this core formation pathway and identify related iron meteorites.

Implications for Core Formation: Once FeNiS melts segregate from silicate residues, metals that crystallize in equilibrium with pentlandite liquid should contain ~60 wt% Ni [6]. This is within the compositional range of some anomalous iron meteorites, such as Oktibbeha County [16], which is comparatively depleted in W, Mo, and Pt, but has significantly lower concentrations of Os and Ir [17]. Devolatilization of S would also drive a pentlandite liquid toward a more metallic composition, which could result in crystallization of coexisting pyrrhotite, kamacite, and taenite [6], potentially providing an alternative formation mechanism for some "nonmagmatic" iron meteorites that may have crystallized from S-rich metallic liquids [e.g., 18]. In either scenario, iron meteorites crystallized from a pentlandite liquid should reflect the trace element concentrations of their parent melts: depleted W, Mo, and Pt concentrations and high Ni content.

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