

PERCOLATIVE SULFIDE CORE FORMATION IN OXIDIZED METEORITE PARENT BODIES. S.D. Crossley^{1,2,3}, J.B. Setera^{4,5}, W.P. Buckley⁵, S.A. Eckley⁵, E.W. O’Neal⁵, J.I. Simon², K. Righter², ¹Lunar & Planetary Lab, University of Arizona (crossley@arizona.edu) 1629 E. University Blvd. P.O. Box 210092 Tucson, AZ 85721, ²NASA Mailcode XI2 Johnson Space Center, ³Lunar and Planetary Institute, USRA – Houston, 3600 Bay Area Blvd, Houston, TX 77058, ⁴University of Texas at El Paso, Jacobs JETS II Contract, NASA JSC, ⁵Jacobs-JETS, ARES Division, NASA JSC.

Background: Most models of planetary differentiation involve the formation of metallic cores during or after extensive silicate melting, but some volatile-rich reservoirs in the protoplanetary disk did not accrete substantial amounts of Fe,Ni-metal. Instead, their potential core-forming assemblages were dominated by Fe,Ni-sulfides and oxides due to high f_{O_2} and f_{S_2} [e.g., 1]. Derivative melts from these assemblages may have been capable of percolative migration leading to core formation prior to silicate melting [2]. However, no direct evidence for this process has been reported in meteoritic literature.

Similarly, while many iron meteorites are thought to represent cores of their respective parent bodies, no direct evidence for Fe,Ni-sulfide/oxide cores have been reported to-date. The most promising potential for such evidence may be found in the anomalous noble metal trace element proportions of relict oxidized primitive achondrites (i.e., brachinites, $\log f_{O_2} \sim IW-1$ [1]), which are similar to those found in sulfides of Rumuruti-type chondrites (RCs) that contain only trace amounts of Fe,Ni-metal at $\log f_{O_2} \geq IW-1$ [1-3].

This work addresses the following outstanding questions: (1) Are molten sulfides in oxidized meteorite assemblages capable of percolative melt migration? (2) How is this process recorded in the noble metal (i.e., siderophile/chalcophile) trace element geochemistry of relevant meteorites? (3) Did O,S-rich meteorite parent bodies form sulfide cores?

Methods: *Melt percolation experiments.* To assess the potential for percolative melt migration in meteorite parent bodies with equilibrated mineralogy and textures, we conducted a set of partial melting experiments in evacuated SiO₂ glass tubes with a chip of R chondrite La Paz Icefield (LAP) 04840 at temperature steps of 900 and 1,020°C. Glass assemblies were placed vertically in a box furnace and heated for 48 hours at each temperature step. These temperatures isolate melting of sulfides (i.e., pentlandite and troilite) prior to silicate anatexis in RCs ($\sim 1,040^\circ\text{C}$) [4]. LAP 04840 was selected for its high petrologic type (R5/6) [5] that most closely approaches textural equilibrium during anatexis. Prior to heating and after each step, the meteorite chip and assembly were scanned in situ using μ -XCT (voxel resolution 4.8 μm) at ARES to observe the migration of sulfide liquids. A final high-resolution scan (voxel

resolution 0.7 μm) of an excised section of the 1,020°C experiment was collected at UTCT.

After the final scan, the sample was extracted and analyzed via EPMA using the JEOL 8530F at ARES and a Phenom XL SEM/EDS at the LPI SEM Facility.

Noble metal partitioning experiments. Our second consideration was the identification of diagnostic noble metal signatures consistent with the physical mechanism of sulfide melt fractionation observed in the melt percolation experiments. A complementary set of trace element partitioning experiments was conducted by partially melting synthetic RC sulfide mixtures of pentlandite-troilite and monosulfide solid solution (MSS, 8 wt% Ni) in evacuated SiO₂ tubes at the same temperatures as melt percolation experiments. Noble metal trace elements (Os, Ir, Ru, Pt, and Pd) were doped at 5 ppm. Trace element contents of melts and residual sulfides were measured via LA-ICP-MS at ARES.

Results/Discussion: *Sulfide Melt Percolation.* Lower-resolution XCT scans of melt percolation experiments with LAP 04840 show localized percolation of molten sulfides (bright phases in XCT data) up to 900°C. This process is evident through changes in sulfide morphologies, which include formation of vesicles within sulfide melt pools. By 1,020°C, some resolvable melt veins/sheets ($>5 \mu\text{m}$

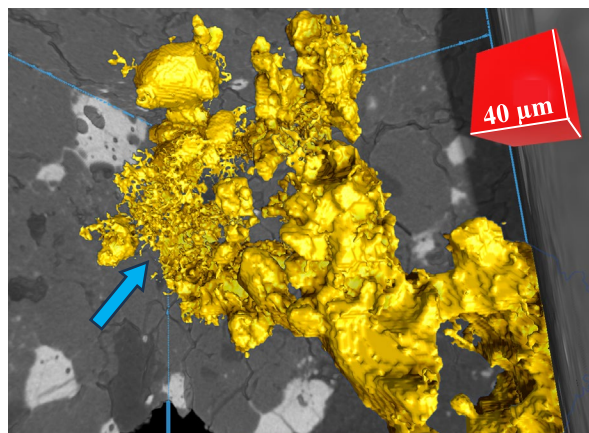


Fig. 1. Formation of dendritic sulfide melt veinlets (blue arrow) in our 1,020°C experiment facilitate interconnectivity via percolative melt migration. An interconnected melt network is rendered in situ (yellow) using our most conservative classification threshold. In the top-left of the cropped XCT data (greyscale), vesicles were formed within molten sulfide (bright phases) as liquids were displaced and percolated between nearby silicate grains.

diameter) were evident throughout the sample, and the ratio of surface area to volume of bright phases increased by ~20% across the experimental temperature range as sulfide nodules melted, drained from their origins, and displaced into surrounding pores. The total volume of sulfides decreased throughout experiments as interstitial melt veinlets fell below voxel resolution.

Higher-resolution scans of an excised subsection of the 1,020°C experiment (Fig.1) show the formation of dendritic melt veinlets (<1 μm diameter), which permeate the silicate matrix and connect neighboring sulfide melt pools. The observed interconnectivity of these melt networks is further supported by homogeneous EPMA measurements of quenched sulfide melts. Melt composition indicated that melting was primarily of pentlandite, which reacted with troilite to form peritectic Ni-rich MSS (~6 wt%).

Noble Metal Trace Element Geochemistry. Partial melting experiments with synthetic RC sulfides yielded noble metal partitioning behaviors with decreasing compatibility in the following order: Os~Ru>Ir>>Pd>Pt (Fig. 2). This order of compatibility is consistent with anomalous interelement ratios measured in restitic oxidized brachinite meteorites [1,6]. Notably, these interelement ratios are not reproduced through modeling solid-liquid metal fractionation even in relatively S-rich (25%) metal-dominated assemblages [6]. In contrast, the entire range of oxidized brachinite noble metal ratios can be reproduced through batch melting ~89-94% of RC-like sulfides. Alternatively, incorporation of trace amounts (i.e., <0.1%) of Ni-rich metal (i.e., awaruite), which is a trace phase in some RCs, can also reproduce brachinite interelement ratios. In either scenario, interelement ratios require that Fe,Ni-sulfides were the dominant carriers of noble metals.

Similar noble metal ratios observed in the basaltic melt fractions of oxidized asteroids (i.e., GRA 06128/9 [6]) suggest that their protolith(s) also fractionated noble metals through loss of a sulfide-dominated melt prior to silicate melting. If the initial sulfide liquids were otherwise entrained within subsequent silicate melts, then the derivative basalts would be correspondingly enriched in the incompatible noble metals.

Cumulatively, this work provides the first evidence for sulfide melt percolation in a meteorite parent body. Given the requisite sequence of melting events from these experiments and previously reported evidence for a magnetic dynamo within the RC parent body [7], this process likely led to formation of sulfide-dominated cores in volatile-rich regions of the early solar system.

Conclusions:

1) Melts produced by sulfide assemblages in RC chondrites are capable of forming interconnected melt networks by 1,020°C, prior to silicate melting. This

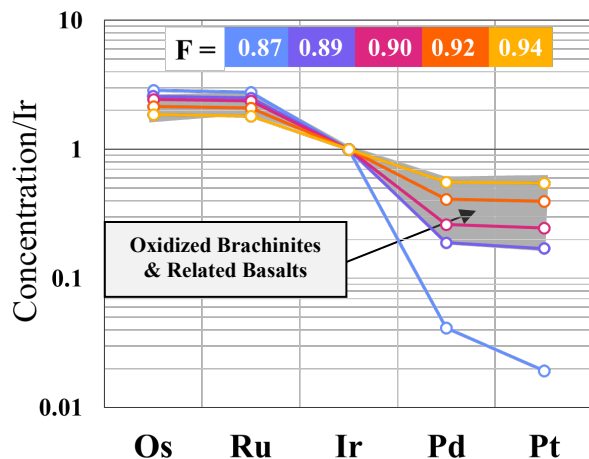


Fig. 2. Noble metal trace element partitioning experiments with troilite-pentlandite at 1,020°C (blue, $F_{\text{sulfides}}=0.87$) can reproduce the relative compatibilities of noble metals measured in oxidized brachinites and oligoclase-rich basalts (grey field) [5]. Interelement ratios across the entire range of oxidized brachinites and corresponding basalts can be modeled through continued batch melting ($F_{\text{sulfides}}=0.89-0.94$).

suggests that similarly oxidized and sulfur-rich parent bodies would have experienced widescale percolative migration of liquid sulfide.

2) Residual MSS in experiments reproduces the noble metal proportions of oxidized brachinites through partial melting of synthetic sulfide assemblages. These interelement proportions are not reproducible through partial melting in systems that contained any more than trace amounts of Fe,Ni-metal. Similar noble metal proportions in corresponding basaltic analogues of the brachinites are consistent with sulfide melt fractionation prior to extensive melting of silicates.

3) Agreement between our experimental results, noble metal analyses of oxidized primitive achondrites [1,6], and reported paleomagnetic evidence for a weak geodynamo in the RC parent body [7] provide the first evidence for the formation of sulfide cores through percolative melt migration in planetary bodies.

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