FORMATION OF RENAZZO CHONDRULE METAL INFERRED FROM SIDEROPHILE ELEMENTS.
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Introduction: Metallic Fe-Ni is the principal source of opacity in protoplanetary disks, and disk temperatures are proposed to be thermostatically regulated by evaporation and recondensation of Fe-Ni alloys [1]. It could be anticipated that most of the Fe-Ni metal in primitive chondrites comprise direct condensates from nebular processes, but few candidates for such condensates have been identified. Grossman and Olsen [2] proposed that such metal condensates could be recognized by chondritic Ni/Co, and by P, Cr, Co and Ni abundances consistent with calculated condensation trends from a gas of solar composition. Metal grains with chondritic Ni/Co ratios in CH, CR and CB chondrites have been proposed to be potential candidates for such metal condensates [3, 4]. The most compelling evidence for such condensates are the zoned metal grains in QUE94411 [5, 6], a CB chondrite. We continue our siderophile element investigations into the origin of chondrite metal by examining metal preserved in petrographic context in Renazzo, the only pristine CR fall [3], by laser ablation microanalysis. Proposed origins of CR metal have included condensation from a solar gas [3, 4], reduction during chondrule formation [7], and devolatilization of condensate sulfides [8, 9]. Metal in Renazzo is described in a companion paper [9], and comprises several types: metal in chondrule interiors, metal on chondrule rims, and large metal grains outside of chondrules. Ion probe determinations of Os, Ir, Pt and Au abundances led [7] to propose that Renazzo metal formed by reduction during chondrule formation, and that the metal rimming chondrules was formed by recondensation of evaporated Fe onto chondrule rims. Here, we provide new analyses of refractory and volatile siderophile elements to better constrain this process.

Experimental: Two polished thin sections, Renazzo #719 and Renazzo #45, from the MNHN collection were examined by optical microscopy and electron microprobe (EMP) analysis, some images of which are shown in [9]. BSE images and x-ray maps were prepared using a JEOL JSM 5800LV SEM (UC). Selected spots were analyzed for siderophile elements using a CETAC LSX-200 laser ablation system coupled to a Finnigan Element™ magnetic sector ICPMS [6, 10]. Spot sizes were 25-50 µm on rim metal, and 50-100 µm on large metal grains; ablated pit depths were about 15 µm. Siderophile elements were determined by monitoring the following isotopes ^{57}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{69}Ga, ^{74}Ge, ^{75}As, ^{95}Mo, ^{101}Ru, ^{105}Pd, ^{118}Sn, ^{121}Sb, ^{184}W, ^{185}Re, ^{192}Os, ^{193}Ir, ^{195}Pt and ^{197}Au. For Renazzo #719, Fe, Co, Ni, Cu, Mo, W, Re, PGEs and Au were determined on core and rim metal; for Renazzo #45, the volatile siderophile elements Ga, Ge, As, Sn and Sb were included, while Au was removed (section had been previously Au-coated). For small rim metal grains, elements determined were limited to Fe-Pd to improve precision. Further analytical details have been presented elsewhere [10, 11].

Results: Data on 70 metal grains from 11 Renazzo chondrules were obtained. Fig. 1a shows CI-chondrite normalized Pd/Fe *vs*. Ni/Fe for the three metal types in Renazzo; Fig. 1b shows Cu/Fe *vs*. Ni/Fe for the same grains. The elements Co and Ni were highly correlated in all analyzed metal, consistent with previous EMP analysis [3, 9, 12]. The refractory siderophile elements, Mo, Ru, W, Re, Os, Ir, and Pt, were mutually correlated, and so subsequent measurements on small grains determined only Mo and Ru. These elements, and Pd, also correlated with Ni and Co. Some rim metal grains exhibit $(Pd/Fe)_{CI}>1$. Chondrule interior metal grains exhibit systematic Cu depletions relative to Renazzo bulk metal [13], while chondrule rim metal grains exhibit enrichments of Cu. Isolated large metal grains are close to Renazzo bulk metal composition, $(Cu/Fe)_{CI}=$ 0.18 [13]. The CI-normalized average $(Ga/Fe)_{CI}=$ 0.028±0.014 (1σ) for both interior and exterior metal, is similar to bulk Renazzo metal, 0.032 [13]; and $(Ge/Fe)_{CI}=$ 0.01-0.02 for both types of metal. A single analysis of fine matrix revealed CI levels of Ga and Ge, consistent with the findings of [14].

Discussion: The relative order of condensation from a gas of solar composition is Re, Os, Ir, Ru, Mo, Pt>Ni>Co>Pd≈Fe>Au>Cu>Ga>Ge [2, 6]. In contrast, the relative order of oxidation is Ga>Fe≈W≈Mo>Co>Ni≈Ge>Cu>Os, Ir, Pt, Au>Pd. Note that Pd would correlate with Fe in condensation, but not during oxidation-reduction, processes. Further, evaporation of Fe from a metal-silicate droplet of CI composition proceeds by the loss of the more volatile FeO [15] which would decouple Fe and Pd evaporation rates. In Renazzo chondrules, where both metal and FeO-bearing silicates coexist, the abundances of the elements Fe and Ga in the metal are likely to be affected by both redox processes and volatility, while the abundances of Co, Ni, Cu, Ge, Pd, and Au are affected by evaporation-condensation reactions, alone. Ruthenium, Os, Ir, and Pt are expected to behave passively, as observed by mutual correlations between these elements.

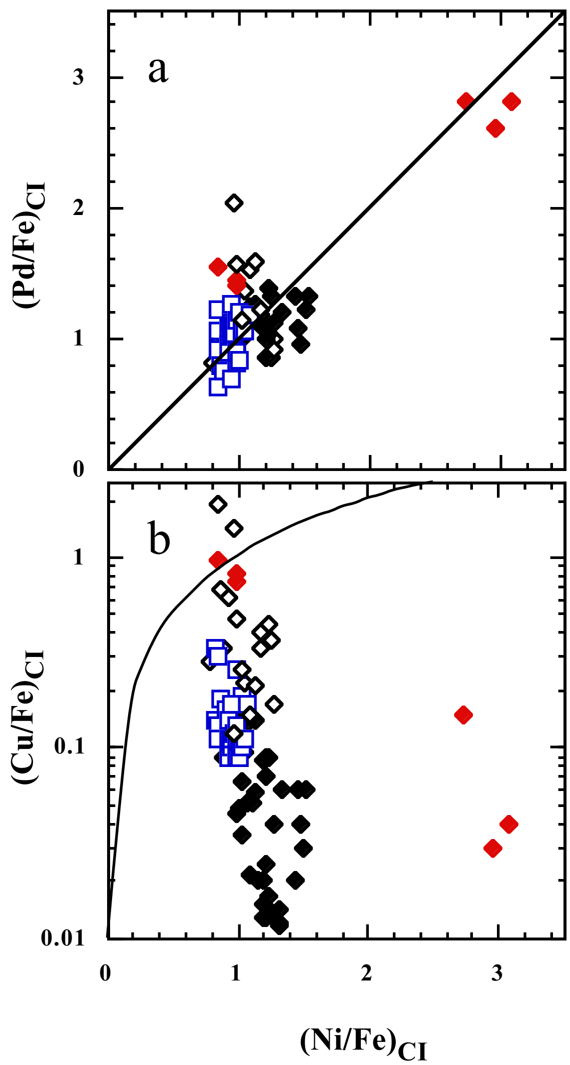

Figure 1. Fe, CI-chondrite normalized abundances [16] of a) Pd *vs*. Ni, and b) Cu *vs*. Ni. Solid diamonds: chondrule interior metal, open diamonds: chondrule exterior metal, blue squares: isolated large metal, red diamonds: Chondrule 719-4 metal. The curves show a 1:1 correlation of Pd or Cu *vs*. Ni expected from redox processes, passing through a CI composition.

Evidence against an origin of Renazzo chondrule metal by direct condensation from a gas of solar composition is provided by the correlation of Pd with Ni (Fig. 1a). This is particularly evident in Renazzo 719-4, the chondrule depicted in Fig. 1c of [9], where the core metal exhibits high Ni/Fe in Fig. 1. Some of the chondrule exterior metal grains exhibit suprachondritic Pd/Fe ratios, possibly indicating vapor phase FeO which would not recondense in metal, implying a low partial pressure of hydrogen in the vapor phase. In Fig. 1b, a clear separation by volatility can be seen in Cu/Fe *vs*. Ni/Fe, with chondrule exterior metal plotting on the volatile-rich side of the trend. Further, isolated large metal grains plot intermediate between the compositions of chondrule interior and chondrule exterior grains. Such grains probably originated as interior metal that accreted exterior metal droplets before being centrifuged out of the chondrule.

Renazzo chondrule interior metal shows evidence of volatilization of Pd, Fe, Cu, and Au, followed by recondensation of these elements on to the chondrule exterior metal. This effect is small in Pd (≈20%), but significant in Cu. The observed 40-60% higher Ni/Fe indicates that chondrule interior metal is enriched in Ni relative to CI (and bulk Renazzo) values, and is a measure of the maximum Fe loss by volatility. Kong et al. [14] interpreted their NAA abundance data on separated CR components as evidence for evaporation from chondrules followed by recondensation into matrix. The data presented here show that recondensation occurred onto chondrule rims in an important way, to the extent that bulk chondrules (estimated from isolated metal grains) are similar in their volatile element abundances to bulk Renazzo metal [13]. The net depletion of volatiles in Renazzo cannot be unambiguously related to volatilization from chondrules, but may have been inherited from chondrule precursors. This is supported by the abundances of the more volatile elements, Ga and Ge, which do not show systematic fractionations between exterior and interior metal, but are about equally depleted in both types of metal.

A condensation origin of Renazzo metal from a gas of solar composition is firmly excluded. Resolution of the other hypotheses [7, 9] remains to be completed.

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