Fe-Ni mobilization in primitive CO chondrites: Implications for progressive aqueous alteration in the parent body.
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Introduction: Chondrites that escaped significant secondary alteration are essential for investigating isotopic signatures of the protosolar nebula and constraining early solar system chronology. Telus et al. [1] showed that fluid-induced Fe and Ni mobilization occurred even in the most unequilibrated ordinary chondrites (UOCs), both falls and finds. CO3.0s are more pristine than ordinary chondrites of the same petrologic type, based on presolar silicate grain abundances [2]. Here, we extend the study of [1] by analyzing the Fe and Ni distributions in CO3.0s, ALHA 77307, DOM 08006, DOM 10104, and MIL 090038, and Acfer 094 (ungrouped C3.0) to better characterize the alteration history of these primitive chondrites. We are especially interested in whether these chondrites are good candidates for studying the ^{60}Fe-^{60}Ni systematics of chondrules.

Samples: ALHA 77307 has a weathering grade of A, DOM 08006 and DOM 10104 have weathering grades of A/B, and MIL 090038 has a weathering grade of B [3]. Acfer 094 has a weathering grade of W2 [3]. We analyzed one thin section of each chondrite, except for ALHA 77307 (two).

Methods: We used the X-ray fluorescence microscopy beamline at the Australian Synchrotron to collect high-resolution maps of these chondrites. The Maia detector at this beamline provides high spatial resolution and high-sensitivity mapping of Ni and other minor elements. We first collected low-resolution maps of each thin section, and then mapped several chondrules in each section. See [1] for more details of the synchrotron technique.

Results: Low-temperature, fluid-assisted Fe-Ni mobilization is indicated by Fe and/or Ni enrichment along factures within chondrules. We also report on Cr exsolution in olivines as this is a strong indicator of mild thermal metamorphism in primitive chondrites [4]. Examples of Ni and Cr maps are shown in Fig. 1 and Fig. 2, respectively.

DOM 08006 experienced minimal aqueous alteration and thermal metamorphism. We observed negligible Fe or Ni mobilization along chondrule fractures. Chromium exsolution in olivine was not observed in DOM 08006. This is the least altered of the chondrites we have analyzed thus far, consistent with its high presolar silicate abundances [2].

ALHA 77307 has experienced significant aqueous alteration, but minimal thermal metamorphism. Both sections show Ni-rich and Ni-poor matrix regions, the latter are 1–2 mm^2 in size. The difference in bulk Ni content between Ni-poor and Ni-rich regions is ~0.5 wt.%. Chondrules that show the most Fe-Ni mobilization are associated with the Ni-poor regions of the matrix. Chondrule olivines in both thin sections exhibit no Cr exsolution. One section, listed below as ALHA 77307 (TS2) has Ca-enriched fractures (1-3 mm in length) that occur in only one half of the thin section. Chondrules in this region show Ca-enrichment within fractures and along grain boundaries.

For DOM 10104, the Ni map of the thin section shows numerous Ni-poor regions, (1–3 mm^2 in size). The difference in Ni content between Ni-poor and Ni-rich regions is ~1 wt.%. Chondrules show some Fe-Ni mobilization, but it is mostly minimal. Many, but not all, of the chondrule olivines exhibit Cr exsolution.

In MIL 090038, we observed minimal Fe-Ni mobilization. There is one region of the thin section (~5×1 mm^2 in size) that is enriched in Ni by ~0.5 wt.% compared to the Ni-poor region right beside it (Fig. 1A). Chondrules in the Ni-poor regions (Fig. 1B) show evidence for more extensive alteration than those in Ni-rich regions (Fig 1C). All the chondrules show significant Cr exsolution (Fig. 2). This chondrite is the only chondrite that shows significant Zn enrichment along the boundaries of the chondrules, CAIs, and matrix fragments that is easily observed from the low-resolution thin section maps.

For Acfer 094, we could easily see Fe-enriched fractures across the entire thin section from the low-res thin section map. All the chondrules show evidence of Fe-Ni mobilization, but none show Cr exsolution. The chondrules in Acfer 094 exhibit the most extensive Fe-Ni mobilization, but it is moderate compared to many of the unequilibrated ordinary chondrites (UOCs) of similar petrologic type. Fe-enrichments in CAIs observed by [5], may be a result of this alteration.

Discussion: Previous work shows that Fe-Ni mobilization can be quite extensive in UOCs [1]. This is a late-stage alteration, as it mostly occurs along fractures. Since all UOC falls show evidence for this alteration, this may be a signature of parent body alteration, but a terrestrial weathering origin cannot be ruled out.

Fe-Ni mobilization in CO3s and Acfer 094 is similar to or less extensive than the alteration in Semarkona. With proper characterization, extraneous Fe and Ni could be avoided for *in situ* analyses of type II chondrules. The chondrites of this study listed in order of increasing late-stage aqueous alteration are:

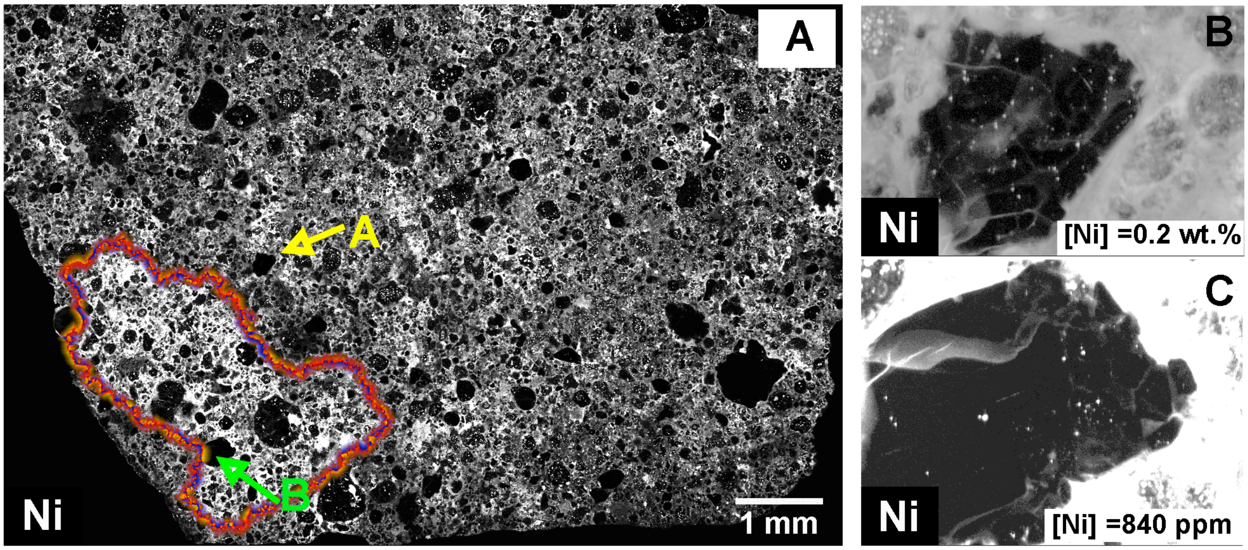

Figure 1. Ni map of MIL 090038 (A) shows Ni variation in the matrix. The largest Ni-rich region (5×2.5 mm) is highlighted in red. Two chondrules are marked on the thin section map, one in the Ni-poor area (B) and one in the Ni-rich area (C). Both are type II (Fe-rich) chondrules with Ni-rich blebs. Chondrules in the Ni-poor regions show more extensive Fe and Ni mobilization and have higher bulk Ni concentrations than those in the Ni-rich regions.

DOM 08006 < ALHA 77307 (TS1) ≈ DOM 10104 < MIL 090038 < ALHA 77307 (TS2) < Acfer 094. All, except Acfer 094, have weathering grades of A and/or B, but the degree of alteration does not correlate with weathering grade, supporting the concept that this alteration has a parent body origin that could potentially be overprinted by terrestrial weathering.

For UOCs, the degree of Fe-Ni mobilization correlate with the degree of thermal metamorphism [1], but there is no such correlation for CO3.0s. DOM 08006, ALHA 77307, and Acfer 094 exhibit no Cr exsolution, indicating they experienced little thermal metamorphism [4]. The chondrites listed in order of increasing amounts of Cr exsolution in olivine are: Acfer 094 ≈ DOM 08006 ≈ ALHA 77307 < DOM 10104 < MIL 090038.

Conclusions: Overall, CO3.0s show varying degrees of late-stage Fe-Ni mobilization that are likely a signature of parent body alteration and can potentially be used to further constrain the petrologic types of primitive carbonaceous chondrites. This alteration in UOCs complicated efforts to constrain the initial abundance of ^{60}Fe in the Solar System [1, 6], whereas CO3.0s show significantly less aqueous alteration than UOCs, making them better candidates for constraining the ^{60}Fe-^{60}Ni systematics of chondrules. Analyzing CO3 falls may help better distinguish whether our observations are signatures of terrestrial or parent body alteration.

References: [1] Telus M. et al. (2016) *Geochim. Cosmochim. Acta.* 178, 87-105. [2] Floss C and Haenecour P. (2016) *Geochem. J.* 50, 3-25. [3] Meteoritical Bulletin. [4] Grossman J. N. and Brearley A. J. (2005) *Meteorit. Planet. Sci.* 40, 87-122. [5] Simon SB and Grossman L. (2011) *Meteorit. Planet. Sci.* 8, 1197-1216. [6] Telus M. et al. (2017) *Geochim. Cosmochim. Acta.* 221, 342-357.

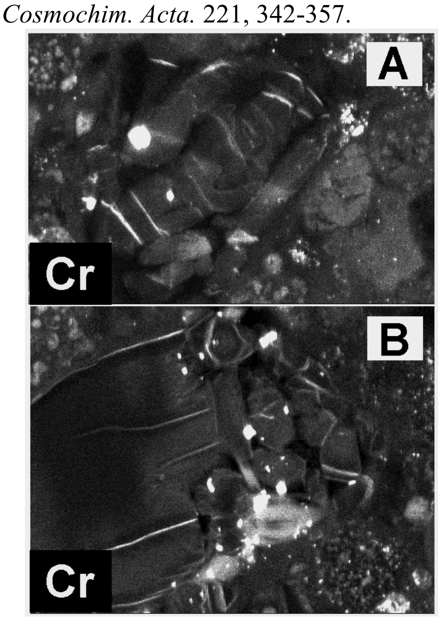

Figure 2. Cr maps of the chondrules from Fig. 1.

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