DIFFERENCES IN CHEMICAL, PHYSICAL AND COLLECTIVE PROPERTIES BETWEEN CARBONACEOUS AND NON-CARBONACEOUS MAGMATIC IRON METEORITES.

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Introduction: The major groups of chondritic meteorites differ in the intrinsic properties they acquired in the solar nebula. These include bulk chemical composition, bulk O-, Ti-, Cr- and Mo-isotopic compositions, oxidation state, mineralogy, mineral chemistry, chondrule and CAI size, proportions of different types of chondrules and CAIs, proportions of rimmed and compound chondrules, thicknesses of chondrule rims, and modal abundances of chondrules, CAIs, opaque phases, fine-grained silicate matrix material, organic material and presolar grains.

It is plausible that the different chondrite groups agglomerated at different distances from the Sun. Rubin [1] listed the inferred formation locations of chondrite groups in order of increasing heliocentric distance: EH-EL, H-L-LL, R, CR, CV-CK, CM-CO, CI. Wasson [2] suggested that the large differences between carbonaceous (C) and non-carbonaceous (NC) chondrites in refractory-lithophile abundances and O-isotopic compositions indicate that these two classes formed far from each other. He proposed that CM chondrites agglomerated beyond 3 AU (where C asteroids predominate). Warren [3,4] proposed that C chondrites formed beyond Jupiter, in line with the suggestion of Wood [5] that CI, CM, CR, CO and CV chondrites formed beyond the snow line.

Some C and NC chondritic asteroids experienced large-scale melting, underwent differentiation and produced iron cores. Iron meteorites derived from these cores can be dubbed C and NC irons, respectively. It is useful to focus on the so-called "magmatic" iron groups, i.e., those that formed by fractional crystallization in molten cores. This ascribed origin is based on the substantial fractionation of refractory siderophiles (e.g., Ir, Os, Re, Ru, Pt) from common (e.g., Ni, Co) and volatile (e.g., Au, Ga, Ge, As) siderophiles in some of these groups. For example, the concentration ranges of Ir, Re and Os in group IIAB (~130 members) are ~4000, ~6000 and ~10,000, respectively [6,7]. Fractionations arise because the solid/liquid distribution coefficient D is >1 for refractory siderophiles and <1 for many common and volatile siderophiles under the conditions of core crystallization.

It seems plausible that the C irons formed in the cores of differentiated asteroids residing in the outer solar system beyond Jupiter while the NC irons formed in the cores of differentiated asteroids in the inner solar system. Based on Mo- and W-isotopic compositions, Kruijer et al. [8-10] determined that the C magmatic irons include groups IIC, IID, IIF, IIIF and IVB while the NC magmatic irons include groups IC, IIAB, IIIAB, IIIE and IVA. Both major groups of non-magmatic irons (IAB and IIE) are also non-carbonaceous.

Kruijer et al. suggested that proto-Jupiter accreted rapidly between the C and NC zones, exceeding 20 Earth masses (M_E) within ~1 Ma after CAI formation. This giant planet acted as a barrier between the C and NC reservoirs by hindering the radial drift of small particles toward the inner solar system. These small particles could include CAIs, which appear to have concentrated in dust-rich nebular regions [1]. Proto-Jupiter continued to grow by accreting gas onto its core; by 3-4 Ma after CAI formation it had grown to ~50 M_E, opening a gap in the nebular disk [11]. During this epoch, proto-Jupiter may have migrated [12], causing small C bodies beyond its orbit to scatter. Many reached the inner solar system.

Refractory siderophiles: Because the CI- and Ni-normalized refractory siderophile abundances in C chondrites exceed those in NC chondrites [13], it is worthwhile to determine if C and NC irons inherited these differences. To test this possibility, I used the extensive data set of J. T. Wasson (pers. comm., 2017) on iron-meteorite compositions determined by INAA.

Among the four NC-iron groups, only Group IIAB has high refractory siderophiles; the other NC-iron groups possess the four lowest median Ir/Ni and median Ir/Au values among all magmatic iron groups.

C irons have higher average median Ir/Ni ratios (0.122±0.032 vs. 0.040±0.064) and much higher average median Ir/Au ratios (84.2±153 vs. 3.71±6.09) than NC irons. The high median Ir/Au value among C irons is due largely to the low mean concentration of Au in Group IVB (0.105±0.04 µg/g). But even if Group IVB is excluded, the C irons still have appreciably higher average median Ir/Au ratios than NC irons: 16.0±6.74 (n=4) vs. 3.71±6.09 (n=5). In summary, C irons are richer than NC irons in refractory siderophiles.

Inheritance of refractory siderophiles: CAIs occur in all chondrite groups, albeit in significantly different proportions. The modal abundance of CAIs is much higher in C chondrites (excluding CI) than NC chondrites: 0.6 – 4 vs. 0.01 – 0.04 vol.% [1]. If CI chondrites are excluded, the mean CAI modal abundance (vol.%) in C chondrites (1.96±1.47, n=5) greatly exceeds that in NC chondrites (0.02±0.01, n=6).

Typical CAIs are enriched by factors of 20-30 in W, Re, Os, Ru, Ir, Pt and Mo relative to CI chondrites [14]. A large fraction of the refractory siderophiles in CAIs is present in metal-rich assemblages dubbed "Fremdlinge" [15]. There are two varieties: 10-1000-

µm-size aggregates of metallic Fe-Ni, magnetite and sulfide [16] and 0.05-5-µm-size refractory metal nuggets consisting of pure metals or metal alloys [17].

Because a substantial fraction of the refractory-element inventory in C chondrites is present in CAIs [1], C chondrites should have higher concentrations of refractory siderophiles than NC chondrites. This is indeed the case. The CI- and Ni-normalized abundance ratios of refractory siderophiles show marginally non-overlapping distributions between C (1.00 – 1.37) and NC (0.785 – 0.998) chondrite groups. The differences in the means are significant – C chondrites: 1.18±0.14 (n=6); NC chondrites: 0.943±0.12 (n=6).

Iron meteorites derived from melted carbonaceous chondritic materials should inherit the metallic elements from the initial allotment of Fremdlinge more-or-less quantitatively. On average, these magmatic C irons should contain higher bulk concentrations of refractory siderophiles than magmatic NC irons derived from NC chondrites. Good indicators of the differences between C and NC irons are the bulk Ir/Ni and Ir/Au ratios. For small sample sizes, the median Ir/Ni and Ir/Au ratios are the most useful parameters for distinguishing C from NC irons. As shown above, the C irons have higher average median Ir/Ni ratios (0.122±0.032 vs. 0.040±0.064) and median Ir/Au ratios (84.2±153 vs. 3.71±6.09) than NC irons. It therefore seems likely that the C irons inherited their high refractory siderophile concentrations from their carbonaceous-chondrite precursors.

CRE ages: If C irons formed in the outer solar system, it might be expected that it would take longer for individual meteorites to enter the inner solar system and reach the Earth. This expectation can be tested by examining the cosmic-ray exposure (CRE) ages of C and NC irons. The record of exposure to cosmic rays (mainly protons with energies >5 MeV) begins when bodies are reduced to roughly meter size through collisional fragmentation. I used the data set of G. F. Herzog (pers. comm., 2017) for the ^{38}Ar (T_{38}) CRE ages of C and NC irons, excluding all anomalous irons.

The C-iron groups contain the group with the longest mean CRE age – Group IIC (where the sole analyzed meteorite has a CRE age of 1242 Ma). The mean CRE age of the analyzed C-iron groups (787±356 Ma; n=4) is much greater than the mean of the NC-iron groups (275±148 Ma; n=5). Even if group IIC is excluded, the C irons still have much higher CRE ages than the NC irons: 635±229 Ma (n=3) vs. 275±148 Ma (n=5). Of the five NC-iron groups, four have lower CRE ages than that of any C iron group.

Number of members of iron groups: The average number of individual meteorites among the magmatic C-iron groups (12±7) is much lower than the average number of individual meteorites among the magmatic NC-iron groups (110±122). As of this writing, the Meteoritical Bulletin Database (MBD) shows that C irons contain the three groups with the lowest number of members (IIC - 8, IIF - 6, IIIF - 9) and the NC irons contain the three groups with the greatest number of members (IIAB - 129, IIIAB - 309, IVA - 83).

The higher CRE ages of C irons are consistent with these bodies having formed in the outer solar system and having spent more time in interplanetary space before encountering a resonance. During their long sojourn, multi-meter-size C-iron fragments were apt to collide with similarly sized bodies and undergo fragmentation. Bodies originating in the outer solar system and spending hundreds of millions of years longer in interplanetary space would be more likely than bodies originating in the inner solar system to fragment to small sizes and be destroyed before reaching Earth. This is consistent with the lower average number of specimens among C-iron groups in our collections.

Conclusions: The inference from isotopic data that some magmatic iron-meteorite groups (IIC, IID, IIIF, IVB) (a.k.a. C irons) formed from melted carbonaceous-chondrite precursors is supported by the generally higher concentrations of refractory siderophiles in these groups relative to magmatic NC iron groups (IC, IIAB, IIIAB, IIIE, IVA). The longer average CRE ages of C-iron groups are consistent with formation in the outer solar system and a long residence time in interplanetary space before reaching Earth. Another consequence of C irons having spent a long time as small bodies in interplanetary space (where there was an increased probability of collisional fragmentation) is the lower number of members of the C-iron groups.

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