EVIDENCE AGAINST CHONDRULE-MATRIX COMPLEMENTARITY AS SEEN IN CO, CM and CR CHONDRITES.

A. Patzer[1,2], E. S. Bullock[2] and C. M. O'D. Alexander[2], [1] Geosciences Center, University of Goettingen, Germany, apatzer@uni-muenster,de [2] Earth and Planets Laboratory, Carnegie Institution for Science, Washington D.C. 20015, USA.

Introduction: We have undertaken a comprehensive study of carbonaceous chondrites (CCs) to determine the abundances and average compositions of their main components, and to examine the possible genetic relationship between the two major components, chondrules and matrix [1]. Two scenarios for the origins of chondrules and matrix have been much debated: (a) chondrule-matrix complementarity, which is based on the observation that absolute element ratios like Si/Mg, Fe/Mg, Ti/Al and Ca/Al exhibit opposite trends in CC chondrules and matrices, proposes a common origin and co-genetic evolution of both components [2 and ref. therein]; (b) chondrules and matrix are not genetically related [e.g., 3-7], with matrix having a ~CI-like composition and chondrules being largely responsible for the moderately volatile element fractionations in bulk CCs.

Method: Combining point-counting with electron microprobe analyses, we have investigated 12 CO, CM and CR chondrites (23,000 data points). We determined the bulk compositions of thin sections, as well as the average abundances and compositions of chondrules, matrix, refractory inclusions (RIs) and isolated grains in matrix. To minimize the potential for element exchange between components during parent body processing, only the most primitive samples were selected. To verify our method, we also examined one section of the well-studied CO3.2 Kainsaz, a fall that is free of weathering. We were able to reproduce all major and many minor elemental concentrations reported in the literature for average bulk COs [7] and Kainsaz [8] to better than 10 %. The elements most commonly cited as displaying evidence for complementarity are Mg, Si, Al, Ca, Fe and Ti. Iron, however, can be easily affected by chondrule metal-silicate fractionation, redistribution in the parent body and weathering, and our Ti data for matrix are likely compromised by an analytical artifact. Hence, we focused on Mg, Al, Si and Ca – four elements that we can determine very accurately in all three CC groups (we re-verified our method using ICP-MS data for bulk Paris from [8]).

Results: For some samples, our Al and Ca data reveal alteration (ALH 77307, Paris, Renazzo) and weathering (Acfer 094) effects. Consequently, these samples are ill suited to test models addressing the evolution of chondrules and matrix. For all other samples, the Si- and CI-normalized abundances of Al, Mg and Ca (Fig. 1) in the bulk meteorites are similar to the literature data [7]. All matrices are somewhat depleted in Mg. The CM matrices also display clear Ca deficits. Concomitantly, the CO and CM matrices are enriched in Al (and Ca: DOM 08006). Unlike their matrices, the CO and CR chondrules exhibit CI-like compositions. The Mg/Si/CI ratios in the CM chondrules are slightly elevated but the relative abundances of Al and Ca are lowered.

Discussion: The complementarity hypothesis assumes closed system conditions and implies that the relative distances of the chondrules and matrix compositions from CI are inversely proportional to their relative mass fractions (the lever rule). Our Mg, Si, Al and Ca data, however, are inconsistent with this correlation. In addition, the CO and CR chondrule compositions are CI-like. Furthermore, the bulk CC compositions are not only governed by those of their chondrules and matrices but also by their RIs – an observation not accounted for by the complementarity hypothesis.

As an alternative to complementarity, the RIs, chondrules and matrix could have formed in different places and/or at different times, and subsequently accreted together into the CC parent bodies. Recently, [7] proposed a model that, to first order, explains the bulk compositions of the CC groups as variable mixes of the same four components (RIs, chondrules, matrix and water). [7] assumed that: (1) the original matrix was dominated by compositionally CI-like material, except that it was anhydrous and contained no oxidized Fe, S, etc., (2) variable abundances of RIs are responsible for the elemental fractionations amongst the refractory and common lithophiles (e.g., Mg, Al and Si), and (3) on average, the chondrules have CI-like Mg/Si and (Al,Ca)/Si ratios, unless their precursors included RI material, but have moderately and highly volatile element compositions that are fractionated and, as such, are largely responsible for the bulk meteorite volatile element fractionations.

The signatures of Mg, Al and Ca – normalized to Si and CI – in CC chondrules and matrices observed in this study can be explained on the basis of the four-component model of [7] and factoring in the loss or addition of forsterite and refractory material (except the Ca deficit in CM matrix).

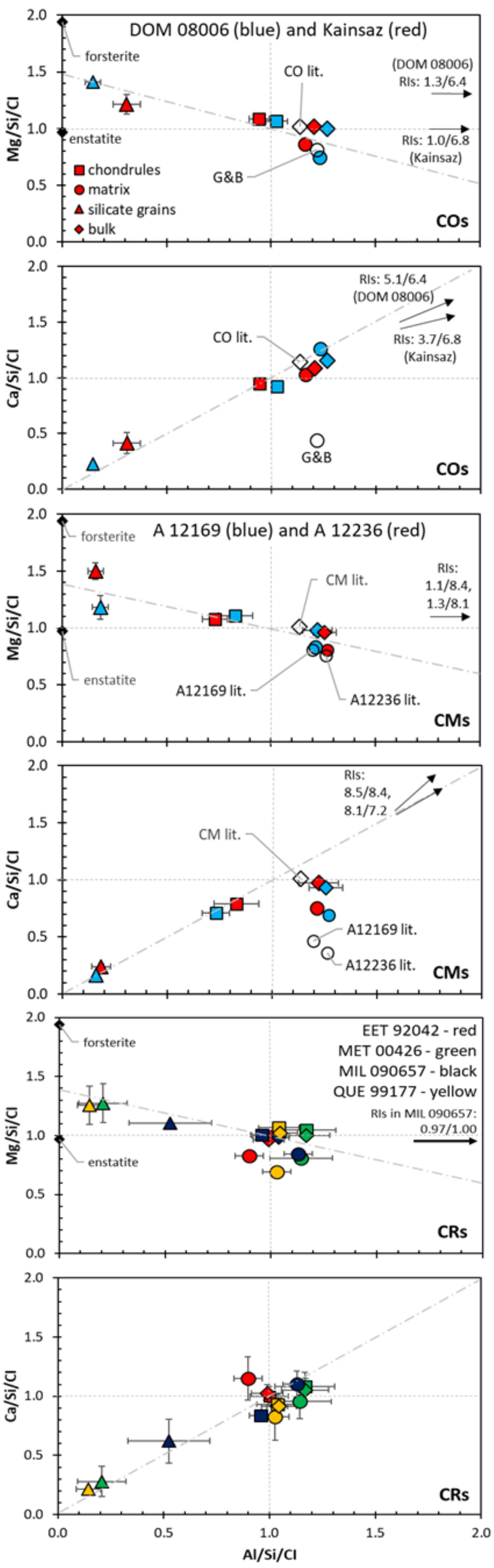

Fig. 1. The selected Si- and CI-normalized abundances of bulk CCs and their chondritic components ("silicate grains": isolated silicate grains >10 µm in matrix). The literature data are from [7] ("CO lit.", "CM lit."), [9] (Kainsaz matrix: "G&B") and [10] (A 12169 and A 12236 matrix, A = Asuka).

Chondrules: For Mg/Si and Al/Si, CO and CR chondrules are CI-like. The deviation from CI of the CM chondrule compositions can plausibly be explained if their precursors had a slightly sub-CI content of refractory material and, concomitantly, 9-12 wt.% of forsterite were added.

Matrix: Assuming an originally CI-like composition, matrix lost 10-15 wt.% of forsterite (>10 µm) prior to or during accretion. Relatively large forsterite and enstatite grains are seen, for instance, in cluster IDPs, and are required to give them their CI-like bulk compositions [11]. Aerodynamic sorting and preferential sticking of smaller grains during chondrule accretionary rim formation are two possible mechanisms for achieving this fractionation.

The Ca deficit in CM matrix could be due to Ca mobilization (on the thin section scale) in the CM parent body or during weathering. How this transport can be reconciled with signs of only incipient aqueous alteration and modest weathering, and why it effected the CMs but not the COs or CRs remains to be explored. Alternatively, the CM matrix might have been already Ca-deficient upon accretion. This scenario would require the pre-accretionary fractionation of Al and Ca – two refractory elements that otherwise behave in very similar geochemical ways. Clearly, additional studies exploring the exact circumstances of the relatively low Ca abundance in CM matrix are needed.

RIs: Based on their average compositions, the RIs in CO and CM chondrites contain 29-32 wt.% more CAI material than the RI component of [7].

References [1] Patzer A. et al. (2020) *LPS* 51 #2537. [2] Hezel D. et al. (2018) in *Chondrules: Records of Protoplanetary Disk Processes*. Cambridge Univ. Press, pp. 91-121. [3] Anders E. (1964) *Space Sci. Rev.* 3, 583-714. [4] Alexander C. M. O'D. (2005) *Meteoritics & Planet. Sci.* 40, 943-965. [5] Zanda B. et al. (2018) in *Chondrules: Records of Protoplanetary Disk Processes*. Cambridge Univ. Press, pp. 122-150. [6] van Kooten et al. (2019) *Proc. Natl. Acad. Sci.* 116, 18860-18866. [7] Alexander C. M. O'D. (2019) *GCA* 254, 277-309. [8] Braukmüller N. (2018) *GCA* 239, 17-48. [9] Grossman J. N. & Brearley A. J. (2005) *Meteoritics & Planet. Sci.* 40, 87-122. [10] Kimura M. et al. (2020) *Polar Sci.* 26, 100565. [11] Flynn, G. J. et al. (2009) *LPS* 40 #1166.