VOLATILE AND MODERATELY VOLATILE TRACE ELEMENT COMPOSITION OF CHONDRULES AND MATRIX FROM CM CHONDRITES: IMPLICATIONS FOR CHONDRULE FORMATION.

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Introduction: In this study we compare trace element volatile data from Mighei chondrules to matrix in CM chondrites and other CCs, as part of ongoing work to contribute to the discussion on possible chondrule/matrix complimentarity, and the thermal environment of the early Solar System. Our results suggest that both volatile-enriched matrix and volatile-depleted chondrules have experienced a process of incomplete condensation, but to differing degrees.

Previously [1], we described laser ablation and solution ICP-MS analysis of the trace element chemistry of chondrite matrix in 18 carbonaceous chondrite falls, spanning the range of compositional types. The data showed that matrix is variable in composition on the micrometer scale, with the degree of variability increasing from CO/CV to CI. In the CI chondrites, our analyses revealed an order of magnitude variation in the abundance of volatile and moderately volatile trace elements over distances of a few hundred micrometers. Importantly, although their overall abundance varied, the ratio of volatiles with differing chemical affinities remained approximately constant, suggesting that the heterogeneity did not arise through secondary processing. Matrix was also found to be enriched in volatile and moderately volatile elements compared to the bulk meteorite, with the degree of enrichment tending to increase with volatility. The overall depletion in matrix volatile contents from CI followed a similar sequence to that observed in the bulk meteorite, with CV the most depleted, and CM the least. We found that average matrix composition is significantly different between different groups, and in several cases, we also saw differences in matrix composition between meteorites within the same group.

Earlier analyses of the trace element composition in bulk meteorites gave rise to two competing models. The Anders 2-component model [2], proposed that a volatile-rich component (matrix, of CI composition) accreted with volatile-depleted chondrules. A meteorites bulk composition was therefore dependent on the relevant amounts of chondrules and matrix that it accreted. Wasson and Chou [3], observing a monotonic decrease in volatile abundance with decreasing condensation temperature, proposed the incomplete condensation model, in which a solar gas is dissipated during condensation. Subsequent studies (e.g. [4],[5]) have tended to support the incomplete condensation model, and it is now broadly favoured.

More recently, the x-wind model [6] has also made predictions about matrix composition, suggesting that chondrules and matrix were separated by several AU at formation, and should therefore not be compositionally related. In the x-wind model, high-temperature processing of CAIs and chondrules occurs close to the Sun, and these components are then carried out to fall onto a 'cold' accretion disk, composed of essentially unaltered fine-grained interstellar material i.e. non-fragmental matrix should not be compositionally related to chondrules in a given meteorite.

Volatile element fractionation was one of the earliest and most fundamental chemical processes affecting meteoritic materials. Given the extreme compositional heterogeneity of primitive chondrites, it is therefore a priority to not only acquire trace element volatile data for bulk samples, but for individual components within these meteorites. Unfortunately, technical difficulties have meant that trace element volatile data for separated chondrules or matrix are extremely limited. Previous workers have used a range of techniques [7-12], typically applied to individual meteorites or small groups of samples. We have shown that a combination of laser ablation ICP-MS and solution ICP-MS analysis appears to be an effective means of investigating matrix trace element abundance in chondrites [1]. Here we extend that work to look at the volatile trace element composition of chondrules in the CM chondrite Mighei.

Experimental methodology: Laser ablation ICP-MS analysis were performed with a UP213 laser (Quintupled Nd:YAG delivering a 213 nm UV beam) coupled to a HP7500a ICP-MS (Open University). Ablations were performed in He atmosphere and the ICP-MS was operated in shield torch mode. Analyses were normalised to both an external standard, NIST612 and Ca content, respectively, in order to correct for drift and fractionation effects. Approximately 30 chondrules were analysed. Major element composition for was determined using element maps acquired on a JEOL 5900 LV SEM (Natural History Museum). The system allows both mineral modes and element abundance to be calculated from the map dataset, for areas ablated during laser ICP-MS analysis. To guard against local variation of major element content in the volume excavated by the laser, and allow comparison with matrix data, we also processed chondrule data ratioed relative to Yb and normalised to CI.

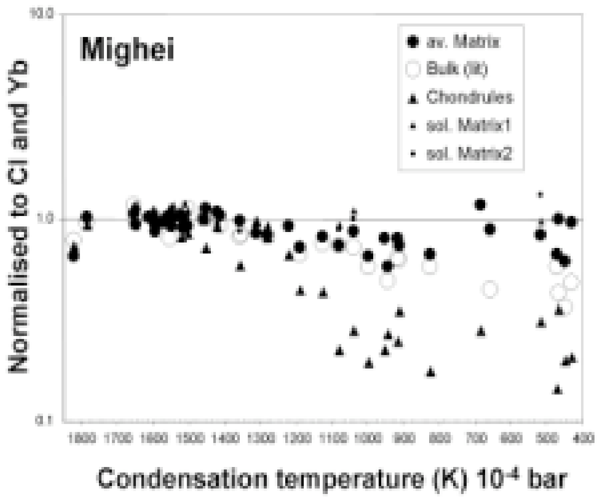

Figure 1. A comparison of trace element data from laser ablation and solution ICP-MS for Mighei, with literature data for the bulk meteorite. Elements are ordered based on condensation temperature.

Results: In the case of Mighei, chondrule and matrix compositions diverge in elements with condensation temperatures <1500K. That divergence appears to increase with increasing volatility, suggesting that a form of incomplete condensation occurred to produce volatile fractionation in both chondrules and matrix. The data for Mighei matrix, in which we observe a good correspondence between averaged LA-ICP-MS analyses, and solution ICP-MS on separated matrix, show that this material has a virtually flat trace element volatile pattern, only slighted depleted from CI in moderately volatile elements. A similar pattern is observed in matrix from other CM chondrites [1].

Discussion: If we were to consider chondrule formation as a local process, occurring close to the matrix with which chondrules would eventually accrete, then taking the Wasson and Chou [3] model as a starting point, it would be tempting to propose a 2-stage process of volatile fractionation. A large scale thermal event (such as a hot inner disk) imposes a uniform bulk composition on all material at a given heliocentric distance by a process of incomplete condensation. That event was clearly an open system, as volatiles were lost during condensation. Following this, local thermal events (chondrule formation) occurred in a closed system - volatiles are retained, but they are fractionated between chondrules and matrix. However, there is a large body of evidence arguing against evaporation as a means of producing fractionated volatile element patterns in meteoritic materials (e.g. [4,5,13,14]). That being the case, this scenario would then require that the material which went on to form chondrules underwent an additional cycle of complete volatilisation, followed by incomplete condensation, prior to chondrule formation – a rather complicated sequence of events.

If chondrule formation occurred in an x-wind setting, then we might again envisage a hot inner disk and incomplete condensation accounting for matrix compositions, and repeated cycling of volatilisation and incomplete condensation of chondrule materials accounting for the additional fractionation of volatiles that we observe in chondrules. In this scenario, we could anticipate that chondrules from different groups might have similar trace element volatile compositions, even though matrix varies. We are in the process of acquiring additional chondrule data from a broad suite of meteorites to discriminate between these scenarios.

Conclusions: Mighei is composed of volatile enriched matrix and depleted chondrules, the fractionation pattern in both cases consistent with a process of incomplete condensation. In a sense, elements of both the Anders and Wasson models could be said to apply.

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