MODAL MINERALOGY OF CI AND CI-LIKE CHONDRITES BY POSITION SENSITIVE DETECTOR X-RAY DIFFRACTION.

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Introduction: The CI chondrites have bulk elemental compositions nearly identical to the solar photosphere and are considered the most primitive samples in the meteorite collection. However, they contain ~20 wt% H_2O in a phyllosilicate-rich matrix, as well as magnetite, sulphides and carbonates, and are interpreted as having experienced extensive aqueous alteration [1]. In addition, the CI chondrites are also recognized as regolith breccias. Unravelling the effects of secondary processing on the mineralogy of the CI chondrites has important implications for understanding the formation and evolution of the CI parent body(ies) and the nature of water in the early solar system.

Detailed mineralogical studies of CI chondrites by optical and electron microscopy are hampered by the fine-grain size (<1 μm) and heterogeneous textures of the matrix. Transmission electron microscopy (TEM) has been useful in examining the minerals present within the matrix but these measurements sample only small volumes and modal abundances remain poorly constrained. Position sensitive detector X-ray diffraction (PSD-XRD) is capable of resolving the abundances of fine-grained (>50 nm) minerals within complex samples and has previously been successfully applied to studies of the altered CM meteorites [2, 3]. In this work we have used PSD-XRD to determine the modal mineralogy of the CI falls Alais, Orgueil (BM1985, M148) and Ivuna (BM1991, M5), plus the unusual "CI-like" Antarctic finds Y-980115 (sub. no. 93) and Y-82162 (sub. no. 50).

Experimental: XRD patterns were collected from the CI chondrites using an INEL X-ray diffractometer with a curved 120° PSD in a static geometry relative to the X-ray beam and sample. As the geometry is fixed and all angles (0 – 120°) are measured simultaneously, conditions remain identical between analyses of the meteorites and mineral standards. For XRD analysis the CI chondrites were powdered (<37 μm), immediately packed into Al-wells (volume of ~150 mm^3), and then measured for up to 16 hours in order to achieve good signal-to-noise ratios. Pure standards of every mineral identified within the meteorites were analysed under the same analytical conditions for 30 minutes. Phase quantification was achieved using a peak stripping method described fully by [2, 3]. Modal abundances were determined for each phase present in the CI chondrites at >1 wt% with uncertainties typically <5 %.

Results: *Alais, Orgueil and Ivuna.* Fig. 1 shows XRD patterns collected from Alais, Orgueil and Ivuna. The Alais sample contained phyllosilicate (serpentine/saponite, 86.7 vol.%), magnetite (5.6%), sulphides (2.8%) and dolomite (2.6%). Following subtraction of all crystalline phases, the remaining counts were fitted using a non-crystalline Fe-(oxy)hydroxide standard to bring the sample pattern to zero. This likely represents ferrihydrite (2.3%). To investigate heterogeneity, two separate samples of Orgueil and Ivuna were analysed. For Orgueil, the two samples had similar abundances of phyllosilicate (85.8 – 87.0 vol.%), magnetite (4.7 – 5.6), sulphides (3.1 – 5.6%) and ferrihydrite (2.7 – 3.2%). Olivine was present in Orgueil-1 (2.3%) but not Orgueil-2 (Fig. 2). The Ivuna samples were also similar to one another, containing phyllosilicate (85.1 – 88.0 vol.%), magnetite (6.3 – 7.8%), sulphides (4.4 – 5.6%) and dolomite (1.3 – 1.5%).

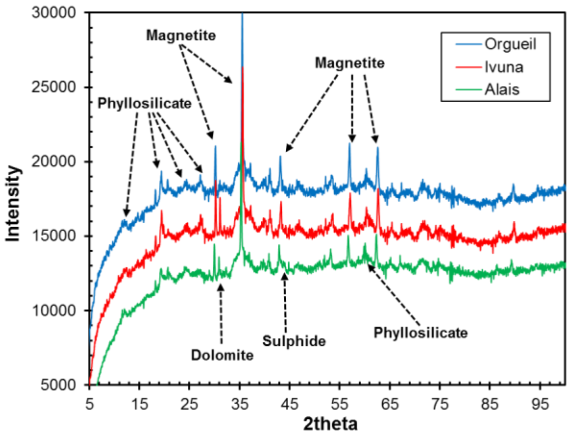

Figure 1. XRD patterns collected from CI chondrites Alais, Orgueil and Ivuna. Alais and Ivuna are offset on the Y-axis for clarity.

Y-980115 and Y-82162. Fig. 3 shows XRD patterns collected from Y-980115 and Y-82162. In contrast to the CI falls, the main diffraction peaks were from sulphides and olivine. The mineralogy of Y-980115 included phyllosilicate (74.9 vol.%), sulphides (16.5%), olivine (6.8%) and magnetite (1.8%). Y-82162 contained phyllosilicate (76.5 vol.%), sulphides (13.9%), olivine (7.9%) and magnetite (1.7%).

Discussion: The accuracy of the determined modal mineralogies for Alais, Orgueil and Ivuna are supported by calculated Fe abundances (17.8 wt%, 20.2 wt% and 21.1 wt% respectively) that are in good agreement with previous studies [e.g. 4]. Based on the abundance of magnetite and dolomite, and the alteration of sulphides, it has been suggested that Orgueil and Ivuna suffered a greater degree of aqueous alteration than Alais [5–7]. This does not appear to be reflected in the abundance of phyllosilicate, which shows a narrow range (85 – 88 vol.%) within these samples. Orgueil and Ivuna do contain a higher abundance of sulphides than Alais, whilst Ivuna also contains the most magnetite. However, the abundance of magnetite in Alais, which is slightly higher than previous estimates [5], is similar to Orgueil. The abundance of dolomite in Orgueil and Ivuna has been reported as ~5 vol.% [6], but we found <3 vol.% in Alais and Ivuna, and no dolomite in either of the Orgueil samples we analysed.

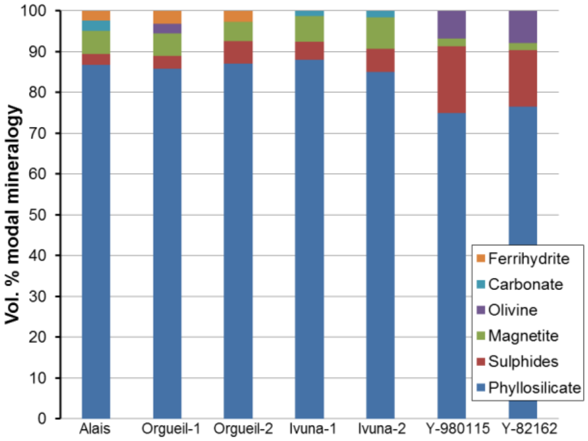

Figure 2. Modal mineralogy of CI and CI-like chondrites determined by PSD-XRD.

Variations in the abundances of minor phases are unsurprising considering that these meteorites are breccias. Orgueil and Ivuna are more brecciated than Alais and contain several lithological units with varying amounts of phyllosilicate, carbonate and olivine [6]. Despite this we observe only minor differences in the modal mineralogy of separate Orgueil and Ivuna samples, although some heterogeneity is suggested by the presence of 2.3 vol.% olivine in Orgueil-1 but undetectable levels in Orgueil-2. In comparison, [8] reported ~6 vol.% olivine in an earlier study of Orgueil by PSD-XRD. The absence of ferrihydrite in Ivuna is consistent with previous observations [4]. Ferrihydrite could be the result of terrestrial weathering, but as Alais, Orgueil and Ivuna are falls, if this were the case it should probably be present in all of them. Alternatively, the ferrihydrite formed during an oxidation event that affected some regions of the parent body more than others [4].

The petrology and bulk chemistry of Y-82162 are similar to the CI chondrites but its O-isotopic composition and H_2O content (8 wt%) differ from the non-Antarctic samples [9]. The modal mineralogy of Y-82162, with significantly higher abundances of sulphides and olivine, clearly marks it out as distinct from Alais, Orgueil and Ivuna. The high abundance of silicate, coupled with the relatively low amount of phyllosilicate, possibly indicate that Y-82162 represents precursor material that suffered less aqueous alteration than the other CIs. However, as olivine in the matrix is not primary and appears to have formed through partial dehydration of phyllosilicate at temperatures of 600 – 700°C, Y-82162 is probably a thermally metamorphosed “CI-like” meteorite [9].

The isotopic and petrological characteristics of Y-86029, another Antarctic “CI-like” meteorite, are similar to Y-82162 and [10] suggested that it was heated to 500 – 600°C. Based on its modal mineralogy Y-980115 also belongs to this group of thermally metamorphosed CI chondrites. The non-Antarctic CIs show no evidence for heating, suggesting that Y-82162, Y-980115 and Y-86029 either come from a separate region of the CI parent body, or more likely are derived from a different parent body(ies).

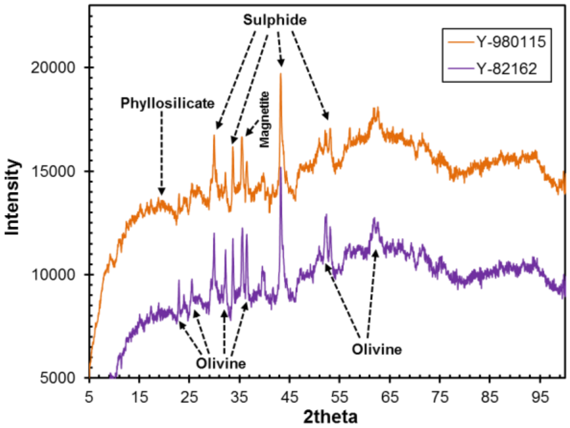

Figure 3. XRD patterns collected from "CI-like" chondrites Y-980115 and Y-82162 (offset on the Y-axis).

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