SESSION 7

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Carbonaceous chondrite meteorites as a record of protoplanetary disk conditions

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Abstract. Chondritic meteorites, and especially the most volatile-rich chondrites, the carbonaceous chondrites, preserve a record of the solar protoplanetary disk dust component and how it has been changed both in the disk environment itself and in its asteroidal parent body. Here we review some of the key features of carbonaceous chondrites and report some new data on their organics component. These show that the nebula reached temperature of >1000°C, but only very locally, to produce chondrules. Most meteoritic material underwent thermal and/or aqueous processing, but some retain delicate nebular components such as complex organic molecules and amorphous silicates.

Keywords. Chondrites, Meteorites, Protoplanetary Disk, Asteroids

1. Introduction

Chondrite meteorites can be used as tools to investigate the conditions and timescales of the evolution of the solar protoplanetary disk 4.6 Byr ago (e.g. Russell (2018)). Chondrites are asteroidal fragments that have not experienced sufficient heating to completely melt. They are aggregates of early solar system products and so can be used as probes of protoplanetary disk composition and environment. Carbonaceous chondrites are of particular interest because their high volatile abundances suggest a formation location in the outer solar system, beyond the snow line (e.g. Weisberg *et al.* (2006)). Furthermore the composition of some carbonaceous chondrites, the CI meteorites, are a good match for the composition of the Sun (minus H and He), demonstrating a lack of geochemical or cosmochemical processing of this material (Lodders (2003)).

Chondrites provide a direct record of protoplanetary materials; however processes that occurred both in the asteroid and later on Earth have changed the mineral compositions and blurred the original signatures. Here we summarise the composition of carbonaceous chondrites that are petrographic type 3, that are samples that have experienced only minimal aqueous and thermal events in the asteroidal parent body. We also describe some of our recent work on the mineralogy of carbonaceous chondrites using scanning electron microscopy (SEM), transmission electron microscopy (TEM) and carbon K-edge X-ray absorption near edge structure (C-XANES).

2. Primordial protoplanetary disk material

Most carbonaceous chondrites are dominated by rounded spherules of once-molten silicates called chondrules, which range in size from tens of microns to millimetres (Fig. 1). Minor components of carbonaceous chondrites include calcium aluminium rich inclusions (CAIs) and metal and sulfide fragments. The chondrules and other components are surrounded by a fine grained micron to sub-micron material called matrix (Fig. 1). These are

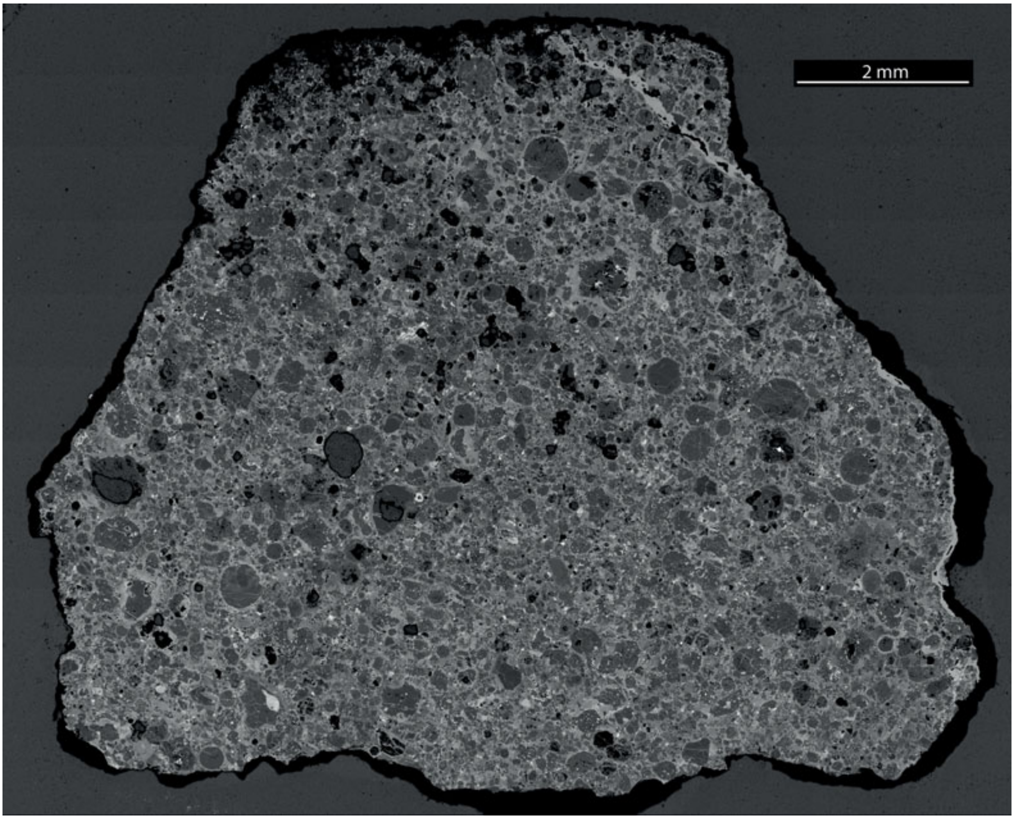

Figure 1. SEM Back Scattered Electrons (BSE) image of the Colony meteorite (CO3.0). The sample is about 10 mm across and it clearly shows the main components of a carbonaceous chondrite meteorite. Chondrules are the dark grey and well rounded inclusions, while the matrix is the light grey material that is holding everything together.

the basic building blocks that accreted from disk material to form early planetesimals. Most chondrules formed at temperatures between around 1400°C and 2000°C and cooled very quickly, at rates between 10 and 3000°C/hour (Jones et al., 2018). The formation of chondrules requires very extensive, transient heating events to have occurred within the protoplanetary disk. The cause of this flash heating is unknown, although shock events and impacts are the most popular theories (Connolly & Jones (2017)).

Matrix material in the least altered meteorites is a complex mixture of amorphous and crystalline silicates, oxides, sulphides and metals that has remained largely unchanged since the time it was accreted into the asteroid parent body. Also present are organic materials, which may be interstellar or solar in origin, and unprocessed isotopically anomalous circumstellar grains formed around stars ancestral to the Sun e.g. Zinner (2003). The matrix in the least altered carbonaceous chondrites are a good match for unprocessed protoplanetary dust (Scott & Krot (2005)).

A key observation of carbonaceous chondrites is the dichotomy between materials such as chondrules and CAIs that have clearly experienced high temperatures (>1000°C), finely intermixed with matrix material that experienced only minimal (<200°C) thermal processing. Furthermore, the bulk chemical and isotopic compositions of chondrules and matrix require that they formed from a single chondritic reservoir that was unmixed during the chondrule forming process (e.g. Palme *et al.* (2015); Budde, *et al.* (2016)).

Thus, the same reservoir of material underwent an unknown process that enabled heating to liquidus temperatures for a fraction of the dust, while other parts of the dust were unaffected.

3. Asteroidal processing

The degree of processing that has been experienced by a meteorite is indicated by its petrographic type, which is a number between 1 and 6. Only Type 3 chondritic meteorites have experienced minimal asteroidal alteration, and more specifically Type 3.00 show almost no changes since the dust material accreted to form a planetesimal. Once part of an asteroid, most protoplanetary material experienced extensive processing that caused chemical equilibration and the formation of new minerals. Meteorites of Types 1 and 2 have undergone extensive aqueous alteration, resulting in the formation of phyllosilicates, carbonates and iron oxides. Meteorites of Type 4 and above have experienced significant heating, resulting in coarsening of mineral grains, and homogenisation of their compositions. Almost all meteorites show some evidence of the shock events in their history, which act heterogeneously depending on the chemical and physical properties of the material.

While the heating and aqueous alteration has been traditionally most studied within chondrules and CAIs, we have an ongoing programme to investigate these processes within meteorite matrix, using the CO3.0 - 3.8 meteorite group that shows a particularly clear metamorphic sequence. Matrix is especially susceptible to alteration because of its low temperature components and small grain size. A TEM study showed that in the most pristine samples the matrix consists of an amorphous groundmass in which there are embedded submicron crystals of silicates, metal and sulphides. In samples that have been even gently heated (to $\sim$ 300°C; Huss *et al.* 2006), the amorphous component crystallises (Bonato *et al.* (2018)).

The CO3 meteorites contain up to 1% organic material as a complex mixture of soluble organic species and a kerogen-like insoluble organic matter (IOM) component. Our C-XANES measurements show very clear changes in the organics inventory of CO meteorites, even in only mildly altered samples. The highly primitive CO3.00 Dominion Range 08006 meteorite contains clear spatial variations in the organics inventory, with some areas richer than others in ketone (C=O), aromatic (C=C) or carboxyl (-COOH) groups. However, meteorites that show any evidence at all of heating (e.g. CO3.1 Miller Range 090010) have a much more homogeneous distribution of organic species with all groups having a strong aromatic absorption peak (Bonato *et al.* (2019)).

4. Conclusions

Characterising the nature and spatial relationships of the mineralogy and geochemistry of carbonaceous chondrites enables a better understanding of the origins and environmental conditions of the dust component of the solar protoplanetary disk and how it may have changed over their 4.56 Byr asteroidal history. Nebular processes acting on interstellar dust have extensively changed it, with temperatures high enough to cause silicate melting reached in some regions of the protoplanetary disk. Furthermore, even gentle heating in an asteroid alters the primordial protoplanetary dust, making it more crystalline and destroying and changing the organic component, which is particularly delicate and easily changed by warming.

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