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SCANNING ELECTRON MICROSCOPY OF CHONDRITIC METEORITES: EVIDENCE FOR CONDENSATION AND AGGREGATION PROCESSES DURING THE BIRTH OF THE SOLAR SYSTEM

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Abstract

Carbonaceous chondrite meteorites preserve evidence of how the solar system formed and evolved through its earliest stages. Extracting these clues from small and very fine grained (a few tens of μm and smaller in many cases) meteorite components has required extensive use of microbeam techniques—scanning electron microscopy (SEM), electron and ion microprobe. Correlated studies have allowed textural, major and trace element and isotopic data to be gathered on the same precious microsamples. The best method for examining textures in these meteorites is scanning electron microscopy of flat polished sections using compositional back-scattered electron imaging.

KEYWORDS:
Meteorite, solar system, solar nebula, carbonaceous chondrite, back-scattered electron imaging.

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Introduction

The solar system formed 4.55 billion years ago from a collapsing cloud of interstellar gas and dust. Our present understanding of this ancient event derives from a variety of sources, including direct observations and sampling of other solar system bodies (e.g., the Moon), dynamical properties of the solar system as a whole and astronomical observations of young stars now forming. Much information has been gained through the study of meteorites because they are samples of primitive solar system matter. Some, like iron meteorites and many "achondrites", are thought to be pieces of former small moons or asteroids that were destroyed by collisions with other bodies. Other meteorites, called chondrites (so named for their most distinctive constituents, chondrules: spheroidal millimeter-sized bodies that formed by solidification of molten silicate droplets), are aggregates of primitive material that is probably preplanetary and represents the stuff from which planets first accreted. Their formation ages (determined radiometrically) cluster tightly around 4.5 billion years. They are preserved because they were never buried deep within moon- and planet-sized bodies where melting and metamorphism would have destroyed the original properties of the primordial matter.

The most primitive samples of all include a subset of chondrites known as carbonaceous chondrites (named because they are carbon-rich, ~0.5-5.0 weight % carbon, relative to most other chondrites). Their bulk compositions (elemental abundances relative to silicon) approach the average composition of the sun exclusive of the gaseous elements, and they contain isotopic and chemical evidence not only for early solar system processes but also for events predating the solar system.

Studies of carbonaceous chondrites and their constituent inclusions over the past 15 years have provided important constraints on theories of solar system formation. Much of this work would have been impossible 30 years ago because the necessary technology was not available. This review will highlight some of the results that have been obtained through the use of scanning electron microscopy to study the very fine grained components of these meteorites.

Carbonaceous Chondrites: Clues to Ancient Processes

The Search for Nebular Condensates: Refractory Components

Many researchers believe that one operative process in the heterogeneous primitive solar nebula was condensation of solid grains out of locally hot gas. Later accretion of those grains led to the formation of larger bodies. Theoretical models of condensation indicate that the first solids to condense, at high temperatures, are refractory (having very high volatilization temperatures) oxides and silicates of Ca, Al, Ti and some trace elements such as the rare earths, Zr, and Sc. At lower temperatures, Mg-rich silicates, metallic iron-nickel alloy, sulfides and volatile-rich compounds can condense (Lord, 1965; L. Grossman, 1972; Wood, 1988). Because of low total gas pressures in the nebula (estimated to be $<10^{-3}$ atm), condensation probably proceeded directly from a vapor phase to crystalline solids without formation of an intermediate liquid (Grossman and Clark, 1973).

Although many of the minerals found in chondrites are indeed those predicted by the thermodynamic models, the texturally inferred relative sequence of mineral formation and the compositions of some minerals (especially, the oxidized iron contents) are commonly at variance with predictions (e.g., Kornacki and Wood, 1984). This observation, plus isotopic data (e.g., Clayton et al., 1985), are evidence that most original condensate material has been extensively melted, distilled and otherwise altered since its formation. The examples described below are some of the very few examples of grains in chondrites that are widely accepted as bona fide preserved solar nebula condensates. Most of the other cases that have been proposed are controversial.

L. Grossman et al. (1975) documented the first clear evidence of condensation, in an inclusion from the Allende carbonaceous chondrite. They examined broken pieces of the very fine-grained inclusion (most crystals in it are <20 μm in maximum dimension) with a scanning electron microscope and found cavities lined with elongate needles of nepheline ($NaAlSiO_4$) and equant crystals of grossular garnet ($Ca_3Al_2Si_3O_{12}$). Allen et al. (1978) found extraordinary needles of wollastonite ($CaSiO_3$) in another Allende inclusion; similar needles are illustrated here in Fig. 1. Many of these 1-2 μm-thick wollastonite needles have aspect ratios (L/W) of 50 or more. In each of the above cases, the facts that the crystals have fully developed shapes (unimpeded by neighboring crystals) and project into cavities suggest that they formed by crystallization from a fluid phase. Particularly in the case of the wollastonite needles, however, the crystals have the further attributes of "whiskers"—vapor-condensed crystals produced in the laboratory, known for strength and flexibility. Grossman et al. (1975) and Allen et al. (1978) concluded that the nepheline, grossular and wollastonite crystals condensed from a high temperature gas in the solar nebula.

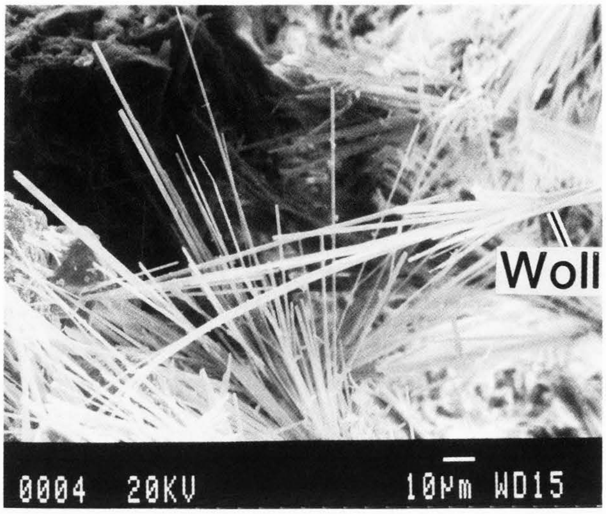

Figure 1. Secondary electron image of wollastonite (Woll) needles lining a cavity in an inclusion from the Allende carbonaceous chondrite (Smithsonian Specimen No. USNM 3658).

Armstrong et al. (1982) and MacPherson et al. (1984) described inclusions with cores consisting entirely of <10 μm-sized hibonite ($CaAl_{12}O_{19}$) crystals having well developed crystalline forms. Condensation calculations predict that hibonite is one of the first major-element-bearing phases to solidify during the cooling of a hot gas of solar composition, forming when the higher temperature phase corundum (Al_2O_3) becomes unstable and reacts with the nebular gas. Corundum is very rare in meteorites, but the compositionally similar mineral hibonite is common. MacPherson et al. (1984) showed SEM photomicrographs of an inclusion from the Murchison carbonaceous chondrite in which tiny perfectly shaped hibonite crystals sit loosely next to one another, with no mutual intergrowths that would suggest in situ growth together with their neighbors in a crowded environment; the spaces between these crystals are entirely void. Thus, although they are not whiskers, these tiny and well-formed hibonites probably formed by condensation of individual crystals from a vapor, and the inclusions containing them formed by later aggregation of those grains. Ion microprobe analyses of the trace element contents of similar crystals (e.g., Hashimoto et al., 1986; Hinton et al., 1988) reveal rare earth element abundance patterns in which the two most volatile rare earths—europium and ytterbium—are highly depleted relative to the other rare earths; such a pattern is consistent with (but not restricted to) formation by condensation. Fahey et al. (1987) also used an ion microprobe to analyze a group of hibonite crystals from Murchison whose textural setting is unknown (they were separated from the meteorite by mechanical disaggregation in the laboratory); some of them have fractionated abundances of the rare earth elements that can be explained easily only if the crystals are condensates (Boynton, 1975). Therefore, the morphology and chemistry of some of these hibonite crystals makes them strong candidates for preserved vapor-condensate crystals from the early solar nebula.

Two comments on experimental techniques are noteworthy. First, because of the necessity of analyzing the chemical and isotopic compositions of individual small crystals, correlated microbeam techniques are now routinely being applied to the same samples. This allows the extraction of a maximum amount of information from fine grained and precious material, and better constrains possible origins of these very complex samples. Sample examination and textural documentation (by SEM) is followed either by energy dispersive or (where grain size permits) wavelength dispersive quantitative analysis of major elements in the constituent phases; finally, trace elements and isotopes are measured using an ion microprobe. Examples of such correlated studies are those by Clayton et al. (1984) and Hinton et al. (1988). The second comment concerns the tremendous impact that compositional (as opposed to topographical) back-scattered electron (b.s.e.) imaging has had on meteorite studies, greater in fact than secondary electron imaging (s.e.i.). Indeed, many SEM studies now use b.s.e. imaging almost to the exclusion of s.e.i. In unravelling the complex chemical and physical histories of meteorites and their components, it is necessary to clearly understand the physical and chemical relationships between the phases. For this reason, most work is done on flat polished thin sections rather than on rough broken surfaces; these sections provide (a) representative cross sections of the rocks and (b) suitable and well documented samples for quantitative analysis by ion or electron microbeam techniques. Modern b.s.e. detectors can easily discern small differences (< 1) in mean atomic number and yet retain excellent spatial resolution, allowing for different phases in a given sample to be clearly distinguished and their interrelationships observed. Moreover, the usual s.e.i. problem of charging along cracks is eliminated. It is fair to say that b.s.e. examination of meteorite thin sections is no longer considered a luxury; it is now a necessary method of documentation which, considering the fine grain size of many meteorite samples, has become more important than light optical microscopy.

Accretion in the Nebula: Matrix and Dark Rims in CV3 Chondrites, and the Unique Meteorite ALH85085

The matrices of certain types of carbonaceous chondrites, including Allende, consist mostly of elongate olivine ($[Fe,Mg]_2SiO_4$) grains less than 10 μm in maximum size. Green et al. (1971) used high resolution TEM observations to show that the grains are well formed single crystals. MacPherson et al. (1985) used SEM observations and electron microprobe analytical data to argue that these matrix grains (and similar ones in rim structures surrounding inclusions in the same meteorite; see below) originated as nebular condensate grains that later aggregated together. Evidence for such an interpretation includes the tiny crystal sizes, crystal perfection, and the absence of intergrowths between neighboring crystals (thus demonstrating the independent formation of each separate grain followed by later aggregation). However, the case for these crystals being condensates is somewhat controversial because their high oxidized iron contents are difficult to explain by condensation theory; the crystals may have experienced chemical alteration after their formation.

Early descriptions of the Allende chondrite (e.g., Fruland et al., 1978; Grossman, 1975; King and King, 1981) noted that various kinds of clasts and inclusions within it have dark mantles surrounding them. MacPherson et al. (1985) examined such dark mantles around refractory inclusions in Allende and found that: (a) the mantles are layered; (b) the minerals within each layer are commonly not in chemical equilibrium with one another; (c) the constituent grains are well formed single crystals showing no intergrowths with neighboring grains; (d) overall mantle thickness and individual layer thicknesses are extremely variable and controlled by the topography of the underlying inclusion surfaces. In particular, thicknesses are greatest in depressions and pockets on the inclusion surfaces; (e) individual layers differ in bulk composition and grain size; (f) the meteorite matrix is similar in texture and mineralogy to the rim layers but somewhat different in bulk composition, being more iron rich.

The porous textures, well developed crystal shapes, lack of crystal intergrowths, disequilibrium mineral assemblages, and topography dependent thicknesses cumulatively suggest that the mantles are nebular accretionary structures, formed by the sticking together of condensate grains in the solar nebula. The lack of internal equilibrium implies accretion at sufficiently low temperatures to suppress diffusional exchange or chemical reactions. MacPherson et al. (1985) proposed that these rim structures represent some of the very earliest manifestations of accretion in the solar nebula, formed by very gentle collisions between dust grains and inclusions. The mantles preferentially accumulated in the surface depressions of the inclusions because, in such places, the grains were protected from being dislodged by subsequent collisions. The platy and needle-like shapes of the crystals tended to produce an interlocking meshwork of crystals, something like a lint ball. The meteorite matrix, with its similar textures, may represent in effect a "super-rim"; if so, the entire meteorite is a primary accretionary structure. Because the transition from micrometer-sized dust particles suspended in the solar nebula to accretion of planets is a poorly understood process, accretionary rims represent small but important clues to how planetary formation began.

J.N. Grossman et al. (1988), Scott (1988) and Weisberg et al. (1988) described a newly discovered meteorite—found in the Allan Hills region of Antarctica and dubbed ALH85085 (see Fig. 2)—whose properties are unlike those of any previously known chondrite. Col-

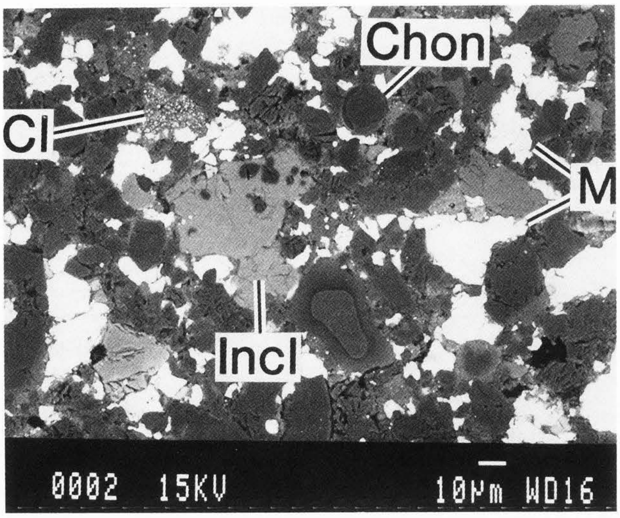

Figure 2. Back-scattered electron image of a polished thin section of the meteorite ALH85085. Most of the dark grey fragments are olivine ($[Mg,Fe]_2SiO_4$) and pyroxene ($[Mg,Fe]SiO_3$) grains. The bright grains are Fe-Ni metal (M), which in many places mold around the silicate grains. Also shown are a clast (Cl) of another meteorite (a carbonaceous chondrite), a spherical "chondrule" (Chon), and a fragment of a refractory inclusion (Incl) that consists mostly of oxides and silicates of Ca and Al. Refractory particles such as the one shown may represent the first solid particles to have formed in our solar system (see text).

lectively, the detailed electron microprobe/electron microscope studies of this unique object show that: (1) it is much finer grained than all chondrule-bearing chondrites; (2) it is exceptionally rich in Fe-Ni metal relative to all known chondrites; (3) it is depleted in many "volatile" elements (such as Na and S) relative to other chondrites; (4) it contains large numbers of small (most are smaller than 100 μm) refractory inclusions (Fig. 2) that approximate the mineralogy and composition of the theoretical high temperature solar nebula condensates discussed earlier; and, (5) unlike the case in other chondrites, the metal grains mold around many of the silicate constituents in the meteorite (Fig. 2), suggesting plastic deformation. J.N. Grossman et al. (1988) proposed that ALH85085 accreted under unusually high temperature conditions, such that the volatile elements had not fully condensed and the metal was sufficiently soft to deform around the silicate grains during accretion. The properties of this rare meteorite may thus extend greatly our knowledge of the accretionary processes in the early solar system that led to the formation of the planets.

Conclusions

Components within primitive chondritic meteorites contain important clues to events that occurred during the earliest history of our solar system, including condensation of solid matter from the primordial nebula and aggregation of that matter into progressively larger bodies. Many of these meteorite components are too fine grained (less than 10-20 μm) to effectively study by light microscopy and conventional chemical methods; their study has required the extensive use of microbeam techniques. Scanning electron microscopy has proven an ideal tool for studying these objects by virtue of combining moderately high resolution, X-ray microanalysis capabilities, and the ability (unlike transmission electron microscopy) to examine relatively large samples in the context of ordinary petrographic thin sections. Compositional backscattered electron imaging is the technique of choice for most textural studies. Recent consortium studies make use of correlated SEM, electron microprobe and ion microprobe techniques to achieve a level of detailed textural, chemical and isotopic analysis never before possible.

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Editor's Note: All of the reviewer's concerns were appropriately addressed by text changes, hence there is no Discussion with Reviewers.