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REFRACTORY INCLUSIONS IN THE ORNANS C30 CHONDRITE; Andrew M. Davis, James Franck Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637.

## INTRODUCTION

Several types of meteorites contain unusual objects 10 micrometers to 2 centimeters across that are enriched in refractory elements such as calcium, aluminum and titanium. These objects, commonly known as refractory inclusions, are most abundant in the meteorites known as carbonaceous chondrites. This abstract describes the refractory inclusions that have been found in the Ornans meteorite, a member of a little-studied group of carbonaceous chondrites. Some refractory inclusions in Ornans resemble those found in other meteorites, while others are unlike any seen before. The unusual inclusions in Ornans contain minerals with extraordinary enrichment in highly refractory elements.

First, a background section will describe carbonaceous chondrite types, the refractory inclusions found in them and the techniques used for finding and studying refractory inclusions. Then, the inclusions in Ornans will be described and compared with those found in other carbonaceous chondrites. The implications of the new work will be given at the end.

## BACKGROUND

### *Carbonaceous Chondrite Types*

Carbonaceous chondrites contain objects set in a fine-grained matrix. These objects include chondrules (spherical objects consisting of the common minerals olivine  $[(\text{Mg},\text{Fe})_2\text{SiO}_4]$  and pyroxene  $[(\text{Mg},\text{Fe})\text{SiO}_3]$  and glass, which have textures indicating rapid cooling); chondrule fragments; aggregates of olivine or pyroxene or both; grains of iron-nickel and iron and iron-nickel sulfides; and refractory inclusions. Three classes of carbonaceous chondrites are discussed in this abstract. C2 chondrites have an abundant black, fine-grained matrix (50 to 80% by volume) made of water-bearing minerals related to those found in clay. The chondrules and inclusions are small (up to 0.5 millimeters across). C30 chondrites have a fine-grained gray matrix of olivine (15 to 40% by volume) and small chondrules and inclusions up to 0.5 millimeter across. C3V chondrites have a fine-grained gray olivine matrix (20 to 50% by volume) but have larger chondrules, up to 2 millimeters across. Refractory inclusions up to 2 centimeters across have been found.

### *Refractory Inclusions in C3V Chondrites*

Refractory inclusions have been studied in C3V chondrites for over 15 years. Most of those studied are from the Allende meteorite, which is the largest and best known C3V chondrite (over 2 tons of it fell in Mexico in 1969). The inclusions are composed of minerals rich in highly refractory elements. These minerals are rare on earth and only found in refractory inclusions in meteorites. They include melilite  $[\text{Ca}_2(\text{Mg},\text{Al})\text{SiO}_7]$ , spinel  $[\text{MgAl}_2\text{O}_4]$ , fassaite  $[\text{Ca}(\text{Mg},\text{Al},\text{Ti})(\text{Si},\text{Al})_2\text{O}_6]$ , perovskite  $[\text{CaTiO}_3]$  and hibonite  $[\text{CaAl}_{12}\text{O}_{19}]$ . These minerals are the first ores predicted by thermodynamic calculations to condense from a cooling gas of solar composition. Since equilibrium thermodynamic calculations cannot predict the direction of temperature change, the mineralogy of the inclusions is also consistent with their being residues left from extensive evaporation of normal solar system material (e.g., bulk carbonaceous chondrites). Allende inclusions can be divided into

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two major types, fine-grained and coarse-grained, based on whether or not mineral grains can be seen in a normal optical microscope. Both types of inclusions have been altered before they were incorporated into the Allende parent body. During alteration, refractory minerals are replaced by minerals stable at lower temperature. The high temperature minerals are more extensively altered in fine-grained than in coarse-grained inclusions. Fine-grained inclusions are only now being studied in detail, because the grains in them are so small that they can only be seen in an electron microscope. There are two major types of coarse-grained inclusions in C3V chondrites: Type A and Type B. Type A inclusions consist of melilite and spinel with minor hibonite and perovskite and Type B inclusions consist of fassaite, melilite and spinel with minor perovskite.

Allende coarse-grained inclusions are enriched in all refractory elements by about 20 times relative to normal solar system condensible material. Thus, they are thought to represent the first 5% of condensible material to have condensed as the primitive solar nebula cooled. Conversely, they could represent the final 5% left after evaporation of normal solar system condensible material. Allende inclusions are the oldest objects known. Radiometric dating by the uranium-lead method shows that they formed 4.56 billion years ago when the solar system is believed to have formed. About 10 years ago, it was discovered that the Allende inclusions contain excess magnesium-26 from the decay of aluminum-26. Nucleosynthesis of aluminum-26 must have taken place before the collapse of the presolar cloud to form the solar system. Since half of the aluminum-26 decays every 720,000 years, the inclusions must have formed within only a few million years of formation of the solar system. It is in Allende inclusions that isotopic anomalies in many elements have been found. These anomalies provide information on the mechanism of nucleosynthesis of the elements.

#### *Refractory Inclusions in C2 Chondrites*

Most of the refractory inclusions studied in C2 chondrites have come from the Murchison meteorite, which, like the Allende meteorite, is large and widely available. The inclusions are much smaller, usually 200 micrometers across or less. The major types found are: Spinel-diopside, consisting of spinel rimmed by diopside [ $\text{CaMgSi}_2\text{O}_6$ ]; spinel-hibonite, consisting of spinel, hibonite and minor perovskite; melilite-rich, containing melilite, spinel and minor hibonite and perovskite; monomineralic grains of hibonite and spinel; and ultrarefractory, containing hibonite and corundum [ $\text{Al}_2\text{O}_3$ ]. The Murchison inclusions are generally more highly enriched in refractory elements than are inclusions in C3V chondrites and are thought to form at higher temperatures than the C3V chondrite refractory inclusions.

#### *How Refractory Inclusions are Found*

Inclusions in Allende are large and abundant. A stone of Allende, typically 10 centimeters in diameter, is sliced like a loaf of bread, with each slice 0.5 to 1 centimeter thick. The inclusions are easy to find, because they are white and the matrix and other objects are a medium gray. Inclusions can be sampled with dental tools for bulk methods of analysis or they can be impregnated with epoxy and made into a 30 micrometer thick section with a polished surface. Such a polished thin section can be studied with optical and electron microscopes and analyzed for its major and minor element chemical composition with an electron microprobe and its trace element chemical and major element isotopic composition with an ion microprobe. The sampling method used for Allende inclusions favors large inclusions.

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More recently, refractory inclusions have been studied in the Murchison C2 chondrite. The inclusions are small and less abundant, so it is difficult to find them on the surfaces of slices. The most successful method of separating refractory inclusions from Murchison is as follows. A stone of Murchison is disaggregated by soaking it in water and repeatedly freezing and thawing it. Since ice expands as it cools (which is why pop bottles burst when frozen), the meteorite is broken into tiny pieces. Hard objects like chondrules and inclusions are separated from the porous and weak matrix. The resulting powder is placed in a dense liquid, where the very dense inclusions and mineral fragments sink and the less dense matrix minerals float. The dense fraction is dried and examined under a low power optical microscope. Many refractory inclusions can be distinguished by their shape and color. Hibonite is especially easy to find because it is bright blue. The separated inclusions can be analyzed by bulk methods such as neutron activation analysis and mass spectrometry or they can be mounted in epoxy, polished and studied with microscopes and microbeam analytical methods. Since weak inclusions are destroyed by the disaggregation process and many inclusions do not contain colorful, attractive minerals, the samples obtained by this method are probably not representative of the population of refractory inclusions in C2 chondrites.

The only way to obtain a representative sample of inclusions is to look at a large sample of a carbonaceous chondrite and examine all objects in it. This has been done by examining polished thin sections of the C3V chondrites Allende and Mokoia and the C2 chondrite Mighei with optical and electron microscopes. These studies have only included those objects that are larger than 100 to 200 micrometers across. As we will see below, many of the most interesting inclusions are smaller than this.

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##### *Experimental Methods*

In the work done here, a polished thin section of the Ornans meteorite was examined under a scanning electron microscope which was equipped with an X-ray detector. When the 15 kilovolt electron beam strikes an atom in a sample, the atom gives off X-rays. Atoms of each element give off X-rays of different energies. The X-ray detector detects a wide variety of energies of X-rays at once and displays the X-ray energy spectrum on a computer monitor. The approximate chemical composition of the area under the beam can be determined by a glance at the computer monitor. An accurate chemical analysis can be made by collecting X-rays from a spot for a couple of minutes and using the computer to calculate the composition from the collected X-ray data. Spots as small as 1 micrometer across can be analyzed.

The area of the thin section of Ornans studied was about 75 square millimeters. This entire surface was examined at 500 times magnification, where an area 130 by 170 micrometers is viewed at once. In each area, the computer monitor was watched to see when there was a high concentration of calcium or aluminum, since these elements are strongly enriched in refractory inclusions. All inclusions greater than 20 micrometers across were photographed and analyzed.

##### *Results*

Using the method above 44 inclusions ranging in size from 30 micrometers across to 350 by 500 micrometers, were found. 26 of these inclusions were

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melilite-rich. They contain melilite, spinel and minor perovskite and hibonite. Their mineral chemistry and textures resemble those found in some Allende Type A coarse-grained inclusions, but they are smaller and more refractory than Allende inclusions. The melilite in them is lower in magnesium and silicon and higher in aluminum than melilite in Allende inclusions. This indicates that they formed at higher temperatures. No inclusions like Allende Type B inclusions were found, since no fassaite was found in any inclusion. 15 spinel-rich inclusions were found. Some convoluted inclusions have spinel cores and diopside rims like inclusions in Murchison, while others are compact inclusions consisting almost entirely of spinel with occasional perovskite grains.

The most interesting inclusions found are the 3 ultrarefractory inclusions. One is a 150 micrometer diameter inclusion composed almost entirely of 10 by 100 micrometer hibonite blades. It has many voids, so it is unlikely to have crystallized from a molten droplet. Thus it is probably not an evaporation residue. The second ultrarefractory inclusion is a single crystal of hibonite which encloses two grains of perovskite. The perovskites contain about 2% yttrium oxide. Yttrium is an extremely rare and refractory element and is normally present in perovskites from refractory inclusions at levels below 0.5%. The most exotic inclusion has been given the name OSCAR. It consists of an unusual mineral rich in calcium, aluminum, silicon, scandium, titanium and zirconium, which seems to be related to fassaite. This mineral contains 11 to 18% scandium oxide and 1.5 to 7% zirconium oxide. The other major mineral in this inclusion is perovskite which contains 6% yttrium oxide and 1% levels of some of the most refractory of the rare earth elements. This extraordinary inclusion is enriched in some refractory elements by a factor 10000 relative to normal solar system condensible material. It is difficult to believe that it could be extreme evaporation residue. OSCAR was described at the Meteoritical Society Meeting last summer in Albuquerque, New Mexico. An abstract about it is in press (A. M. Davis, 1984, A scandalously refractory inclusion in Ornans, *Meteoritics* 19).

Recall that most Allende inclusions have had some of their refractory minerals altered to lower temperature minerals prior to emplacement of the inclusions into the Allende parent body. The inclusions in Ornans have also been altered in a similar manner, but the alteration is less extensive than in the Allende inclusions. The Ornans refractory inclusions, as well as chondrules and mineral fragments, have experienced a second alteration step in the parent body. In this second step, there has been chemical exchange and reaction with the iron-rich olivine matrix.

## CONCLUSIONS

The highest temperature history of the early solar system can only be deciphered by examining inclusions from a variety of meteorites, since different meteorites seem to have different populations of refractory inclusion types. It is important to characterize inclusions down to very small sizes, certainly much less than 100 micrometers. The three most unusual inclusions in Ornans are all quite small. If exotic inclusions like OSCAR were much larger, they would significantly affect bulk analyses of the meteorite. As it is, the amount of scandium that would normally be found on a 25 square millimeter area of Ornans is concentrated into an area only 60 micrometers across. It is hoped that further study of the chemical and isotopic compositions of the Ornans refractory inclusions will broaden our knowledge of conditions in the early solar system.