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The Formation History Of Layered Chondrules In Acfer-139 (CR2)

Matt Downen

Western Kentucky University, matthew.downen325@topper.wku.edu

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THE FORMATION HISTORY OF LAYERED CHONDRULES IN ACFER-139 (CR2)

A Capstone Experience/ Thesis Project
Presented in Partial Fulfillment of the Requirements for
the Degree Bachelor of Science with
Honors Program Graduate Distinction at Western Kentucky University

By
Matthew R. Downen

*****

Western Kentucky University
2011

CE/T Committee
Dr. Andrew Wulff
Dr. Louis-Gregory Strolger
Professor Nathan Phelps

Approved by
Advisor
Department of Geography and Geology
Chondrules are spherical grains made of silicates and metal that represent some of the oldest materials our solar system. Acfer-139 (CR) is a carbonaceous chondrite with large multilayered chondrules. The multilayered chondrules are composed of a silicate core surrounded by alternating layers of silicates and metals. Serial sectioning was used to analyze the sample in three dimensions. EMPA and LA-ICP-MS were used to create elemental maps of Acfer-139 (CR2) and determine the geochemistry of different layers in each thick section cut. XRCMT was used to construct a 3-D model of a large multilayered chondrule named Ch-1 with concentric layers of silicate and metal. A core to rim analysis of Ch-1 revealed increasing silica existing as olivine in the core and pyroxene at the edge. An increase in more volatile elements occurred from core to rim as well as a decrease in refractory elements. While the formation of layered chondrules is still being examined, core to rim analyses of Ch-1 support a formation consisting of silicate and metal layers being accreted onto the forsteritic core in a cooling protoplanetary disc.

Keywords: Meteorites, Chondrules, Chondrite, Geochemistry, Protoplanetary Disc
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VITA

May 22, 1989........................................Born- Vincennes, IN

2007..............................................Adair County High School, Columbia, KY

2010..............................................REU at American Museum of Natural History, NYC

2011 ...........................................Outstanding Senior in Geology, WKU

PUBLICATIONS


FIELDS OF STUDY

Major Field: Geology
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CHAPTER I

INTRODUCTION

Out of the 4.65 billion years our solar system has been around, humans have only been around to witness a very small part of it. We can look back millions and even billions of years into the history of our Earth by studying fossils and rocks, however, this has a limit; the fossil and rock record only extends so far, and it cannot tell us about the solar system before our Earth was present. The history of our solar system and its formation can be determined by studying materials that predate the Earth from our own solar system as well as by looking into space at different solar systems currently being formed. Meteorites are pieces of asteroids that have survived passing through Earth’s atmosphere and are some of the oldest rocks in the solar system (~4.65 billion years old). They contain valuable relics that can be used to tell the story of the generation of planets and other bodies in our solar system. Detailed mineralogical and petrological studies using various analytical techniques are used to determine the history of formation of meteorites and thus infer the evolution of our solar system. Acfer-139 is a stony meteorite with large grains called chondrules, some of which are multi-layered. The
chondrules provide an excellent record of different events that occurred during the solar system’s first several million years. Three dimensional analyses were used to determine changes in mineralogy and chemistry in crystals and metal grains in distinct layers of the chondrules. A combination of qualitative and quantitative analyses were used to support a theory explaining the formation of chondrules based on condensation and accretion of different minerals and metals in an overall cooling protoplanetary disk. Each successive layer of material accretes at a lower temperature to create a multi-layered chondrule and is of different composition.

Current theories for the formation of the solar system are based on principles of condensation and accretion of planetary material. Stars may explode leaving behind gases which collapse due to gravity to form the solar nebula. This nebula is the predominant setting for condensation of solar material. From this time in our solar system’s history, the only existing particles are presolar grains which are nanometer-sized grains created from the explosion of stars at the end of their life cycle. Over time (a few million years) the nebula changes into a rotating disk of dust and mostly hydrogen gas swirling about a central protostar. Material falls into the protostar adding more mass and increasing temperature. As this is happening, materials within the disk materials begin to condense from the gas in the form of CAIs (Calcium Aluminum-rich Inclusions), the first minerals to actually form in our solar system. CAIs are small in size (microns) and are found primarily in the matrix of meteorites. As the overall temperature of the protoplanetary disk decreases, new mineral phases like olivine, pyroxene, and metal alloys begins to condense out of the solar gas. These minerals are the primary constituents of chondrules which are millimeter-sized spherical grains composed of silicates and metal alloys. Table
1.1 shows the most common minerals found in meteorites and their compositions. Through accretion, these grains came together to form larger bodies like planetesimals and ultimately planets and asteroids.

Generally meteorites can be classified as chondrites or achondrites. Chondrites are more primitive meteorites that come from parent bodies that haven’t experienced differentiation. In other words, the asteroids from which chondrites come have not been differentiated into a core, mantle and crust, like the Earth. Achondrites are meteorites that come from parent bodies that have experienced planetary differentiation. The most distinctive characteristic of chondrites are chondrules. Chondrules predate the age of their meteorite parent bodies (asteroids), and are thus some of the oldest materials in the solar system. Because chondrules were formed in the earlier part of the solar system’s history, they exist as a record of the environmental conditions of the protoplanetary disk such as temperature, pressure, and composition.

A rigorous classification scheme exists for meteorites based on mineralogy, petrography, and isotopic composition. Weisberg et al. outlines the current classification scheme for meteorites in *Systematics and Evaluation of Meteorite Classification* which is based on classes, clans, and groups. Figure 1.1 shows a “family tree” of the different types of meteorites and their classification. Meteorite groups can also be given names based on a particular meteorite whose characteristics define the properties of that group. Acfer-139 is a carbonaceous chondrite. Carbonaceous chondrites are well known for containing a wide range of chondrule sizes as well as water and organic molecules. They also have a composition that is close to that of the sun which means they represent the chemistry of the early solar system (Figure 1.2). The carbonaceous chondrites are
divided into several groups called clans. Acfer-139 belongs to the Carbonaceous Penazzo-type (CR) clan. CR chondrites are characterized by their large chondrules which are metal-rich, porphyritic, olivine-rich, and some with multiple layers and rims of silicates and metal. They range from 40% to 70% matrix by volume composed of phyllosilicates, metals, and sulfides (Figure 1.3) (Weisberg et. al, 2006).

Chondrules, the defining component of chondrites, can be studied much in the same ways as crystals in terrestrial igneous rocks, and both tell a story about the conditions of their formation. Chondrules exhibit textures similar to terrestrial igneous rocks which crystallized from a melt. These textures include euhedral grains, porphyritic textures, parallel alignment of crystals, and others. The difference between chondrules and terrestrial igneous crystals is that the materials that formed the melt condensed from a gas rather than a magma chamber. The various mineral phases that crystallize to form chondrules may be compared to Bowen’s Reaction Series (Figure 1.4), a description of the order of mineral phases that crystallize from a melt in a magma chamber. Mg-rich olivine and Ca-plagioclase feldspar are the first phases to crystallize at high temperatures followed by pyroxenites in both Bowen’s Reaction Series and chondrules. In a gas of solar composition the first elements to form these minerals are predominantly Ca and Mg. Solid solution exists within olivine between two endmember phases: forsterite and fayalite (Figure 1.5). This solid solution is the result of the progressive substitution of similar ions within a specific structural site in a chemical structure as conditions change. Mg and Fe are similar in size and charge and therefore can both fit into the olivine structure, but Mg is slightly smaller and is preferred at higher temperatures forming the olivine forsterite. Fayalite is more Fe-rich and forms at a lower temperature than
forsterite. Solid solution also exists within the plagioclase feldspars between anorthite and albite (Figure 1.6). Anorthite is more Ca-rich and forms at higher temperatures than albite which is more Na-rich.

The first phases to form at high temperatures in our solar system are the calcium aluminum-rich inclusions (CAIs). These are primarily composed of the minerals corundum, hibonite, perovskite, grossite, and melilite. Though they are the first to form, most of the volume of chondrites is composed of chondrules (silicates and metal) rather than CAIs (Figure 1.7 and Figure 1.8). The chondrules formed when material was melted and allowed to cool so that silicate minerals like olivine, pyroxene, and feldspar could crystallize along with metal alloys of Fe and Ni.

Several explanations exist for the formations of chondrules. It is difficult to establish one idea of formation that can explain all of the properties visible in chondrules. Scientists know that chondrules were formed when condensed material was melted and then allowed to cool and crystallize. To melt this material, temperatures of around 1800°C must have been reached. The heating must have also been very rapid in order to keep the chondrule from completely evaporating. A cooling rate of a few hundred degrees per hour is required for the formation of the textures observed in chondrules (Ciesla, 2005). Volcanic igneous rocks on the surface of the Earth cool much faster and are characterized by tiny (not visible to the naked eye) grains. The cooling rate of chondrules would be much closer to that of intrusive igneous rocks, where there is enough time for crystals to develop. The most prominent problem associated with chondrule formation is the mechanism for rapid heating. The most notable theories are nebular lightning, FU Orionis-type outbursts, and shock waves. The generation of nebular lightning can be
compared to lightning on Earth, only with materials of different composition. Tiny dust particles bumping into each other within the protoplanetary disk created charged particles due to the transfer of electrons. The balancing of this difference in charge is released as lightning within the nebula. However it is believed that the nebular lightning may not provide sufficient energy to melt large volumes of material to produce the great abundance of chondrules we see.

FU Orionis-type outbursts occur when the amount of material accreting to the central star of a protoplanetary disk causes an increase in the star’s magnitude and essentially creates an explosion that releases massive amounts of energy. An event like this would generate enough heat to create chondrules, but the cooling time associated with this phenomenon is on the order of tens to hundreds of thousands of years. This is too slow to generate the kinds of igneous textures visible in chondrules (Ceisla et al., 2003).

The most accepted method of chondrule formation is by shock waves. Shock waves can provide rapid heating and the necessary cooling time for chondrules to form. The only problem with shock waves is the mechanism that produces them. It is believed that the shock waves are cause by planetesimals, small bodies of accumulated rock that existed in the protoplanetary disk. As the planetesimals traveled through the protoplanetary, the gas and dust would be pushed out of the way and heated to very high temperatures. It seems conflicting that planetesimals created the heating events to produce chondrules when they themselves are the parent bodies for chondrules. Amelin et al. in 2002 used Pb-Pb dating to show that chondrules formed about 2.5 million years after the CAIs. This is plenty of time needed to create large bodies through accretion in
the solar nebula (Ceisla et al., 2004). Heating events are just one aspect of chondrule formation. The formation history of multi-layered chondrules is another debated topic in meteoritics.

Multi-layered chondrules are chondrules with distinct concentric layers of silicates and metal alloys (Fe, Ni) surrounding an olivine-rich core. The multi-layered chondrule is enveloped in a dusty rim of silicates and metals. The formation of each of these layers requires more than just a heating event to produce the initial molten droplet the chondrule crystallizes from. Two explanations exist for the formations of multi-layered chondrules: the evaporation/recondensation model and the accretion model (Ebel et al., 2006). In the evaporation/recondensation model, a molten droplet of chondrule precursor material is heated to the point where elements evaporate from the chondrule interior and are immediately condensed back onto its surface. The accretion approach supports a formation of an olivine-rich core, with subsequent accretion of alternating metal alloys and silicate layers (with each layer increasing in silica content) in an environment with decreasing temperature. The environment of formation of chondrules would be localized clouds of chondrule precursor material that experience multiple heating events. SAHARA 00182 is a CR chondrite that may represent chondrules that have undergone multiple heating events and accretion to produce the multi-layered texture. Like Acfer-139, it contains large multi-layered chondrules composed of silicate and metal shells surrounding an olivine-rich core (Weisberg et al., 2001).

Acfer-139 is a CR chondrite found in the Algerian desert. It is characterized by large multi-layered chondrules (some almost 2mm in size), a low abundance of refractory inclusions, and chemical weathering (rusting of Fe) of metal blebs in chondrules and
matrix. The metal alloys in Acfer-139 exist as grains within the chondrules, “blebs” within the matrix, or as metal layers or “shells” within a multi-layered chondrule. Analyses were obtained on various chondrules to determine chemistry and mineralogy to support an accretion mechanism of formation.
CHAPTER II

METHODS AND TECHNIQUES

A variety of analytical techniques were used to study the multi-layered chondrules of Acfer 139 both qualitatively and quantitatively. The qualitative analyses were primarily from electron microprobe analysis (EMPA) and X-Ray computed microtomography (XRCMT) with a CT-scanner. Quantitative data was collected by EMPA and laser ablation- inductively coupled plasma- mass spectrometry (LA-ICP-MS). All equipment was used at the American Museum of Natural History in New York City and the Lamont- Doherty Earth Observatory of Columbia University.

The primary method used to study Acfer- 139 was analysis in three dimensions by serial sectioning. In serial sectioning, the sample was sliced with a tungsten carbide wire to produce three thick sections approximately 150µm thick (Acfer139-t2-ps1, Acfer139-t2-ps2, and Acfer139-t2-ps3). Figure 2.1 shows the set up for serial sectioning and naming of each section and slice. Each thick section was fixed in epoxy that was shaped to fit in the electron microprobe. Each thick section was polished with a diamond paste of varying size (1µm, 3µm, 6µm) from coarsest to finest. The thick sections were labeled and stored in desiccators to prevent further exposure to the atmosphere which could result
in weathering. Each thick section was also carbon coated to ensure a charge build up did not during EMPA resulting in errors during data collection. The piece of Acfer-139 from which the thick sections were cut was fixed in a brass ring with double sided tape and was also carbon coated.

Serial sectioning allows for the analysis of multiple faces of each section so that a three dimensional analysis can be obtained through the multi-layered chondrules of Acfer-139. Each section was analyzed with EMPA and LA-ICP-MS to determine the chemistry in three dimensions of crystals and metal blebs. XRCMT was used on the initial sample reconstruct a three dimensional model of chondrules in Acfer-139.

The first step in analyzing chondrules in Acfer-139 was to make elemental x-ray maps of each surface of each section. The maps served two purposes: to provide qualitative data by showing different mineral phases within the sample and act as a guide for the use of other techniques like LA-ICP-MS. The maps of each thick section could be used to keep track of sites for laser ablation analysis.

Many maps were made of different elements to show areas of high concentration of ions in the sample. Each surface was mapped for Mg, Ni, Ti, Al, Ca (WDS) and Mn, Fe, S, Si (EDS). These different x-ray maps were then taken and combined through a program and code created by Dr. Denton Ebel. A RGB (Red-Green-Blue) color scheme was used to depict different element concentrations (Figure 2.2). The result was elemental maps showing multiple element concentration in just one map. Combinations of different elements into one map allowed identification of different mineral phases in the sample. Figure 2.3 shows a backscattered electron image and various elemental x-ray
Maps from EMPA. Maps of the entire Acfer-139 sample were made as well as maps of specific chondrules of interest. Each chondrule was given its own name in the format of ch-1, ch-2, ch-3… etc (Figure 2.4). Each elemental map of thick section slices made by serial sectioning produced a three dimensional view of the mineralogy of the chondrules. The composite x-ray maps also allowed for the identification of different features within Acfer-139 (Figure 2.5).

EMPA and LA-ICP-MS were also used to collect quantitative data. These techniques were utilized to probe crystals and metal blebs from the core to the rim of several chondrules to get an idea of how the chemistry changes from core to rim. LA-ICP-MS was used to quantify Fe, Ni, Co, the platinum group elements, Au, Cr, Ga, Ge, W, and Mn in metal grains and to measure Na, Al, Si, P, Ca, Ti, Cr, Mn, Fe, Ni, and Co in olivine grains all with 20- 50 µm spot sizes. The purpose of using these specific elements was to determine the changes in volatile elements and refractory elements. Volatile elements like Au should be the last to crystallize from a melt or condense from a solar gas, while refractory elements like Mg will crystallize or condense sooner. All of the elements analyzed with EMPA and LA-ICP-MS act as indicators if the conditions of the environment in which they formed.

For EMPA the samples were set in a shuttle that could hold six samples. The location of each sample in the shuttle was recorded for later use in analysis. Parameters were also set for each analysis. Each sample was mapped at various resolutions (1- 4µm). Each EMPA analysis was composed of point and line scans that were set up on the machine and left to be executed overnight. The set up of these scans was done by recording coordinates of the edges of the sample to be scanned in the probe’s computer.
In Acfer-139, the largest chondrule (approximately 2mm) was designated ch-1. Ch-1 was mapped individually at high resolutions (1-4µm). Point and line scans were executed on each of the layers of the chondrule on crystals and metal blebs. In LA-ICP-MS, the carbon coat of the sample was removed. Maps from EMPA were used as a guide for pin pointing and recording crystals and metal blebs that had been laser ablated. Five multi-layered chondrules were analyzed. Ch-1 was the most studied chondrule because of its large size and many layers.

A new Phoenix v/tome/x CT scanner at the AMNH was used to collect 1700 X-ray images of ch-1 at 1 µm/voxel (volume element) edge that were reconstructed into a 3-D model. A region growing tool in Volume Graphics software was used to isolate metal layers and grains from silicate layers, determine volumes of selected layers, show metal grain distribution, and provide volume ratios of silicates to metal in each paired metal+silicate layer (Figure 2.6). Acfer-139 was mounted using clay and scotch tape, both acting as a stabilizer as the sample was rotated 360°. An initial scan of Acfer-139 using only clay was flawed because the clay was heated by the x-rays and caused the sample to move. Once clay and tape were combined, a detailed initial scan of ch-1 of Acfer-139 was obtained and a reconstruction was created (Figure 2.7).
CHAPTER III

RESULTS

The elemental x-ray maps generated from data collected by EMPA showed the mineralogy of various layers in three dimensions (Figure 3.1). Most chondrules in Acfer-139 consisted of a porphyritic olivine core dominated by forsterite, the Mg-rich variety of olivine (Figures 3.11 – 3.15). In ch-1 (Figures 3.2 and 3.3), the core was composed of euhedral forsterite crystals surrounded by a feldspathic glass. These grains of olivine were elongated in a sub-parallel manner, suggesting that they originally crystallized as a barred olivine chondrule. Barred olivine chondrules are chondrules with olivine crystals aligned parallel in distinct plates. There are three distinct layers of silicate minerals surrounding the core (Layer 1) to total four; labeled layers 1, 2, 3 and 4. From core to rim there is an increase in the amount of silica present. The layer of silicates just outside the core (Layer 2) is composed of olivine as well as orthopyroxenes (enstatite Mg$_2$Si$_2$O$_6$) and small amounts of clinopyroxene (diopside CaMgSi$_2$O$_6$). The next layer (Layer 3) contains approximately a half and half mixture of olivine and orthopyroxenes. The outer layer of silicate (Layer 4) is dominated by orthopyroxenes. Between each layer of silicate there are distinct layers of metal totaling 4. The metal in each of these layers is composed
predominantly of Fe and Ni and exists as grains and blebs. Metal layer 1 appeared to be composed of tiny metal grains dotting the surface of the core. Metal layer 2 was the largest layer of metal and contained several large grains of metal. Metal layer 3 was very thin and Layer 4 constituted the outer rim of ch-1.

LA-ICP-MS and EMPA revealed important information regarding the chemistry of different metal layers in the chondrules. In ch-1 metal grains were analyzed for volatile and refractory elements. The overall trend, from core to rim, was a decrease in refractory elements (PGE) and an increase in volatile elements (Ga and Au). A metal grain from Layer 1 (the inner layer of metal) and grains from Layer 2 showed a decrease from core to rim of Ru$^{101}$, Rh$^{103}$, Pd$^{105}$, W$^{182}$, W$^{183}$, Os$^{188}$, Os$^{189}$, Os$^{190}$, Ir$^{191}$, Ir$^{193}$, Pt$^{194}$, and Pt$^{195}$, and of which are refractory elements (Figure 3.4). In ch-1 there was also an increase in the volatile elements from core to rim of Au$^{197}$, Ga$^{69}$, and Ga$^{71}$ (Figure 3.5). Metal grains were also analyzed for Ni and Fe. Ni is more refractory than Fe, and should have greater concentrations in the core. This trend was seen in ch-1 (Figure 3.6 and Figure 3.7). Another chondrule, ch-3, was also analyzed. Ch-3 is a compound chondrule, an aggregate of multiple chondrules stuck together and enveloped in layers of silicate and metal. Ch-3 shows a decrease in Ni from core to rim (Figure 3.8) as well as in ch-6 (Figure 3.9). Ch-6 was also analyzed and showed a decrease in Ni and an increase in Fe from core to rim. Not all chondrules were able to be analyzed due to time constraints. Some chondrules did not have significant enough amounts of elements analyzed to be detected.

A three dimensional model was constructed of ch-1 using XRCMT and Volume Graphics software (Figure 3.10). The 3-D revealed each of the concentric layers of
silicate and metal as well as the overall shape of the chondrule. Within this model, layers of metal were isolated and volumes of metal layers were determined. The volume of the entire chondrule, ch-1, was 22mm$^3$. The volume of the inner metal ring, Layer 1, was approximately .12mm$^3$ and consisted entirely of tiny grains. Layer 2 of metal was the largest and was 1.70mm$^2$. It consisted of larger metal grains loosely connect with thin shells of metal. Layer 3 was determined to be about .2mm$^3$. The outer rim of the chondrule, Layer 4, could not be determined because its grains appeared too light for the region growing tool to pick up. This made the volume of metal in ch-1 approximately 2.02mm$^3$. With this information the total volume of silicates was determined to be 19.98mm$^3$. Not all grains were able to be assimilated with the region growing tool due to low resolution of tiny grains or low contrast. Silicates were not able to be distinguished between olivines and pyroxenes though that is a hope for future studies.
CHAPTER IV

DISCUSSION

Qualitative and quantitative analysis in three dimensions of multi-layered chondrules in Acfer-139 has revealed important mineralogical and chemical information regarding the formation of this meteorite and multi-layered chondrules. Ch-1 was the primary multi-layered chondrule studied chemically and physically. This chondrule was shown by XRCMT and EMPA combined with serial sectioning to have concentric layers of silicates and metal surrounding a forsteritic core composed of semi-parallel olivine crystals. Core to rim analysis by LA-ICP-MS and EMPA of metal grains in ch-1 show an increase in refractory elements (PGE and W) and a decrease in volatile elements (Au and Ga). Most of the metal grains are composed of Ni and Fe. Ni is more refractory than Fe and was shown to decrease from core to rim, while Fe increased. X-ray maps from EMPA displayed that most of the chondrules in Acfer-139 had multiple layers. From these maps the forsteritic core is visible surrounded by a thin grainy layer of metal. Each of the layers of silicate from core to rim becomes more and more silica-rich, changing from olivine to more pyroxene dominated. Ideally more metal grains in different layers of
the multi-layered chondrules would be analyzed to give a stronger and more thorough evaluation of the change in chemistry of the layers of metals.

Refractory elements will be the first to condense from a solar gas at high temperatures and volatile elements will condense at lower temperatures. Olivine, particularly forsterite, will crystallize from a melt at higher temperatures and orthopyroxenes (more silica-rich) will crystallize at a lower temperature than olivine. Because of difference in condensation and crystallization, ch-1 and the other chondrules of Acfer-139 must have started out at higher temperatures. The sub-parallel elongation of forsterite grains in the core suggest an initial formation of a barred olivine chondrule that was later melted again. After the initial formation of a forsterite core, metal grains rich in refractory elements and low in volatiles must have accreted to the surface; all of which took place in a high temperature environment. Multiple heating events must have occurred to bring in more melted material, but at a lower temperature to produce layers of metals with more volatile elements and silicates with more silica. Multiple accreting events occurred on the surface of the chondrule until a dusty rim of pyroxene and more volatile-rich metal was left. Figure 4.1 illustrates this phenomenon. Though the study does support a model of accretion for creating the multi-layered chondrules, the actual mechanism to produce the heating events cannot be proven by this study. Because chondrule formation is a localized process in the protoplanetary disk, it can be speculated that more than one type of heating even could produce the temperatures needed for chondrule formation. Planetesimals moving through the protoplanetary disk could move material around and expose it to different conditions creating different layers in
chondrules. Further studies need to be done to further constrain the conditions of formation including parameters like temperature, pressure, and distance from the sun.
Table 1.1 A list of common minerals found in meteorites with their chemical compositions. Most of the minerals composing chondrules are the silicates and metal alloys. The CAIs are composed of Ca, Al-rich phases. Phyllosilicates are a group of minerals (most commonly serpentine) that are found in the matrix and sometimes chondrules. Phyllosilicates indicate the presence of aqueous alteration.
Figure 1.1 Diagram showing the abundance of various elements in CR chondrites compared to the sun. The strong fit of the line indicates that CR chondrites are compositionally similar to the sun and represent the composition of the early solar system. Renazzo is the most well known CR chondrite. CR chondrites are also called Renazzo-type chondrites.
Figure 1.2 Diagram showing the classification of meteorites
(Weisberg et al., 2006).
Figure 1.3 A comparison of the different types of Carbonaceous chondrites (Weisberg et al., 2006).
Figure 1.4 Bowen’s Reaction Series for terrestrial igneous rocks. This is similar to the crystallization of minerals in chondrules; Olivine and anorthite form at the highest temperatures while pyroxene and albite form at cooler temperatures.
Figure 1.5 Phase diagrams of solid solution between forsterite and fayalite (top) and anorthite and albite (bottom). Both show that at higher temperatures forsterite and anorthite crystallize. As the temperature decreases olivine becomes more Fe-rich (fayalite) and plagioclase feldspar becomes more Na-rich (albite).
Figure 1.6 Feldspar triangle showing plagioclase series. Anorthite is the most Ca-rich while albite is the most Na-rich. Between these two extremes lies a continuum of compositions based on how much Ca or Na is present.
Figure 1.7 Diagram showing the order of phases that condense out of a gas of solar composition from high to low temperature. At high temperatures Ca, Al-rich phases condense first (corundum, hibonite, grossite, perovskite) followed by Mg-rich silicates (olivine, orthopyroxene, clinopyroxene) and metal alloys (Fe, Ni). This is similar to Bowen’s Reaction Series in that olivine (red line) forms at higher temperatures pyroxene (gray line).
Figure 1.8 Diagram showing the relative abundances of phases formed out of a gas of solar composition. Though Ca, Al-rich phases were the first to condense at higher temperatures, they do not contain much volume compared to olivine, pyroxene, and metal alloys. This is why CAIs are so small compared to chondrules which are made of mostly Mg-rich silicates and metal alloys. Refer to Table 1.1 for mineral names.
Figure 2.1 Naming scheme and set up for serial sectioning.
Figure 2.2 Triangle diagram depicting RGB (red-green-blue) color scheme for high concentrations of elements with mineral phases included.
Figure 2.3 (From top to bottom) Backscattered electron (BSE) map, Fe-Ni-S map, Mg-Ca-Al map. The BSE map shows the locations of metal grains (bright white spots) within Acfer139-t2-ps2B. The Mg-Ca-Al map shows that most of the meteorite is made of Mg-rich silicates (olivine and pyroxene).
Figure 2.4 BSE image with names of chondrules of interest. Some chondrules like ch-1 were not in this scan
Figure 2.5 Different objects within Acfer-139.
Figure 2.6 Image of the Volume Graphic software showing ch-1 slices in three dimensions (x, y, z) and the reconstructed 3-D model in the lower right hand corner. Highlighted areas (blue) are the areas being selected with the region growing tool.
Figure 2.7 Reconstructed model of ch-1 in Acfer-139 in Volume Graphics. The front flat face is the side that had been previously serially sectioned. The circular ring on the front face is a metal layer.
Figure 3.1 Images of ch-1 showing the results of serial sectioning. From top to bottom: Acfer139-t2-ps2B, Acfer139-t2-ps3A, and Acfer139-t2-ps4a. Each section cuts deeper into ch-1. In ps3a, the beginning of the metal layer surrounding the core can be seen. In ps4a the metal layer is distinct around the core (silicate Layer 1).
Figure 3.2 ch-1 displayed in a Mg-Ca-Al map of Acfer139-t2-ps3a defining features.

A) Orthopyroxene (Mainly enstatite)

B) Olivine

C) Feldspathic Glass

D) Rim

E) Metal Alloy Grains

F) Clinopyroxene (Mainly diopside)
Figure 3.3 Up close image of ch-1 displayed in a Mg-Ca-Al map defining the layers of silicate of Acfer139-t2-ps4a. The dark shading in the bottom of the image is the result of a flaw in EMPA data collection.
Figure 3.4 Refractory elements in ch-1 metal grains. A represents the inner layer of metal and B represents an outer layer of metal. Two metal grains in B were analyzed. All of the refractory elements show a decrease in concentration from core to rim.
Figure 3.5 An increase in volatile elements in ch-1 metal grains from core to rim of three distinct layers.
Figure 3.6 Graphs depicting an increase in Fe and a decrease in Ni and Co from core (1) to rim (3) of ch-1. Both Ni and Co are more refractory than Fe.
Figure 3.7 Graph depicting the change in Fe concentration across several layers in ch-1. A represents the innermost layer of metal grains and E represents the outer most layer of metal grains.
Figure 3.8 Ni in ch-3. The circles represent an inner layer of metal grains of ch-3 and the triangles represent an outer layer of metal grains in ch-3.
Figure 3.9 this diagram shows abundance of Fe, Ni, and Cr in metal layers of ch-6.

Though the change is gradual, there is a decrease in the abundance of Ni (more refractory) and an increase in the abundance of Fe (more volatile than Ni). Cr remains about the same.
Figure 3.10 3-D model of three distinct metal layers in ch-1 (inner-green, middle-red, outer-blue) and original 3-D reconstruction of sample.
Figure 3.11 Close up of ch-1 showing the well define olivine grains in the core as well as the multiple layers surround it.

Afer 139 (CR2) (polished thick section) mapped 7-Sep-2010 (color auto leveled) bulkl:3 micron/pixel (x25%) detail: 1 micron/pix (x32%) Mg-Ni-Ti-Al-Ca (Si, S, Fe, Mn EDS) + BSE
Figure 3.12

Ch-3 from top to bottom:

Acfer139-ts-ps2B
Acfer139-t2-ps2A
Acfer139-t2-ps4A
Each section cuts deeper in this compound chondrule. The middle image clearly shows 1 main chondrule with two smaller chondrules attached. The two smaller chondrules are enveloped by a layer of silicate and a metal rim.
Figure 3.13 Core of ch-6 consisting of olivine grains in feldspathic glass surrounded by metal grain layer and outer pyroxene-rich layer.
Figure 3.14 Ch-8 consisting of olivine core surrounded by clinopyroxene (yellow-green) and metal grains. A thick mantle of orthopyroxene (dark red) exists surrounded by another layer of metal grains and a possibly an aluminum-rich pyroxene (blue).
Figure 3.15 Ch-2 with a very large olivine core surrounded by a layer of metal grains, pyroxene, and outer dusty rim of metal.
Figure 4.1 Proposed model for the formation of multi-layered chondrules. The process if focused on accretion of different minerals and metals as temperature decreases.


