# Scanning electron microscopy characterization of iron, nickel and sulfur in chondrules from the Allende meteorite – further evidence for between-chondrules major compositional differences

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**ABSTRACT**

*We analyze the relative contents and internal spatial elemental distribution of Fe, Ni and S in minerals within selected individual chondrules of a fragment of the Allende chondrite, as derived from scanning electron microscopy (SEM) - energy dispersive X-ray spectroscopy (EDS) analyses. Chondrules were selected to cover the range of micromagnetic properties in terms of hysteresis coercivity and magnetization ratios. Variation in micromagnetic properties appear correlated to the external and internal morphologies and mineralogical assemblages. In order to identify the distribution of mineral assemblages characterized by Fe, Ni and S, a mathematical technique for image analysis was applied to the SEM-EDS images. The resulting compositional images display the complexity in composition and microstructural morphologies of individual chondrules. Chondrule c27b is characterized by Fe-rich minerals and is Ni and S poor, although Ni and S appear concentrated within a Fe-rich rim. Chondrule c40b, formed by barred olivine, is Fe poor and has low contents of Ni and S; Fe is homogeneously distributed within the olivine crystals. Chondrule c53b has a spherical shape, except for a partly preserved Fe-rich rim that forms a bulge; minerals with higher contents of Fe, Ni and S are observed in the chondrule interior. Chondrule c55b, of porphyritic olivine type, has a more complex morphology, characterized by variable Fe, Ni and S compositional distribution and characteristic mineral assemblages. Results confirm that closely spaced chondrules within given sectors of Allende meteorite have major differences in elemental content and distribution, in addition to differences in shape, size, texture and mineralogy, which support the idea that chondrules underwent distinct thermal, shock, alteration and evolutionary histories, related to chondrule formation and alteration processes, in the early stages of evolution of the planetary system.*

*Key words: chondrules, chemistry, elemental distribution, mineralogy, Allende meteorite.*

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**RESUMEN**

*En este trabajo se analiza la distribución espacial y los contenidos relativos de hierro (Fe), níquel (Ni) y azufre (S) en condros individuales separados de un fragmento del meteorito Allende, por medio de observaciones y análisis con microscopía electrónica de barrido (SEM) – espectroscopía de rayos X de dispersión de energía (EDS). Los condros seleccionados presentan un rango amplio en sus propiedades micromagnéticas en términos de cocientes de coercitividad y magnetización, las cuales han sido correlacionadas con variaciones morfológicas y texturales. A fin de identificar la distribución de ensambles minerales caracterizados por su contenido de Fe, Ni y S, se aplicó una técnica matemática de análisis a las imágenes obtenidas por SEM-EDS. Las imágenes composicionales resultantes muestran la complejidad en la composición y la morfología microestructural de condros individuales. El condro c27b se caracteriza por minerales ricos en Fe y pobres en Ni y S, aunque presenta una capa externa rica en Fe que concentra Ni y S. El condro c40b, formado por olivino barrado, es pobre en Fe y tiene contenidos bajos de Ni y S; el Fe se encuentra distribuido de manera homogénea dentro de los cristales de olivino. El condro c53b tiene forma esférica con una capa parcial externa rica en Fe y arreglos internos de minerales ricos en Fe, Ni y S. El condro c55b, del tipo porfírico con olivino, tiene una morfología más compleja, caracterizada por una distribución variable de Fe, Ni y S. Los resultados confirman que condros espacialmente cercanos del meteorito Allende presentan marcadas variaciones en la distribución de Fe, Ni y S, además de diferencias en su forma, tamaño, textura y mineralogía, las cuales se asocian a una evolución compleja que involucra varios eventos de calentamiento y alteración durante los procesos de formación en las etapas tempranas de evolución del sistema planetario.*

*Palabras clave: condros, química, distribución elemental, mineralogía, meteorito Allende.*

## INTRODUCTION

Chondritic meteorites are formed by abundant chondrules and calcium-aluminum inclusions (CAIs) in an igneous-textured matrix. Chondrules are millimetric round-shaped silicate spherules, which formed by melting of solid dust precursors and subsequent rapid cooling in a dominantly reducing environment in the solar nebula (Hewins, 1997; Wood, 1988; Connolly and Love, 1998; Scott, 2007). Two distinct types of chondrules have been found: (a) the reduced type I chondrules, which are FeO and volatile poor and metal rich, and (b) the oxidized type II chondrules, which are FeO and volatile rich and metal poor (McSween, 1979; Wood, 1988). The chondrules and CAIs formed at the early stages of evolution of the solar system, and therefore the chronology and processes involved in their formation are key elements that have been long investigated. Here, we concentrate on a detailed study of the content and distribution of Fe, Ni and S in chondrules of the Allende meteorite, as derived from results of scanning electron microscopy (SEM) - energy dispersive spectroscopy (EDS) analyses. Results were analyzed for the spatial compositional and textural distribution, and their implications for chondrule formation and subsequent alteration processes in the early stages of evolution of the planetary system.

In this paper, we report new results from petrographic and geochemical studies of a suite of individual chondrules isolated from a fragment of the Allende meteorite. Allende meteorite is a member of the group of carbonaceous chondritic meteorites, which has been intensively studied since its fall on February 8, 1969 in Chihuahua, northern Mexico (Clarke *et al.*, 1970). Carbonaceous chondrites are composed of primitive undifferentiated material and represent the oldest preserved matter in the solar system (*e.g.*, Wood, 1988; Cameron, 1988; Hewins *et al.*, 1996; Scott, 2007).

## ALLENDE CHONDRULES

The Allende meteorite is an oxidized CV3 carbonaceous chondrite. CV3 chondrites are relatively rare as compared to other types of chondrites. Allende fall in 1969 was well documented, and a large amount of fragments (up to 2 tons) was recovered (Clarke *et al.*, 1970). As a result, considerable attention has been devoted to the Allende chondrite and numerous groups and laboratories have been able to analyze it, making Allende one of the most intensively investigated meteorites.

Allende is composed mainly of chondrules (*ca.* 43 % vol.), matrix (*ca.* 38.4 % vol.), and CAIs (*ca.* 9.4 % vol.); it contains olivine inclusions (*ca.* 3.2 % vol.), opaque minerals (*ca.* 3.1 % vol.), and lithic and mineral fragments (*ca.* 2.9 % vol.) (McSween, 1977). Allende displays a macroscopic texture that reflects abundance of chondrules of sub-millimeter size within the aphanitic black silicate matrix (Figure 1). Allende belongs to the oxidized chondrites with an anhydrous mineralogy, with hydrous phases restricted to chondrules and CAIs (Blander and Fuch, 1975). Oxidized chondrites contain olivines rich in FeO and no iron metal blebs, in contrast to the reduced type chondrites. Allende appears to have been partly altered and metamorphosed, with a metamorphic grade of 3.7. Studies indicate secondary alteration processes affecting Allende mineralogy and composition in various ways (*e.g.*, McSween, 1979, 1987; Krot *et al.*, 1995; Kavner and Jeanloz, 1998; Scott, 2007).

For this study, we prepared thin slabs of four selected chondrules identified as c27b, c40b, c53b and c55b from a larger chondrule set that has been studied in terms of size, morphology, geochemistry and magnetic mineral properties (Flores-Gutierrez and Urrutia-Fucugauchi, 2002; Flores-Gutiérrez *et al.*, 2010). The selected chondrules cover the range of micromagnetic properties from low to high coercivities and magnetizations, and in the previous study have been also shown to present distinct morphologies and internal mineralogical assemblages. Magnetic properties of chondritic meteorites have been long studied to determine the characteristics of magnetic fields in the protoplanetary nebula. Determination of the strength of paleofields from chondrites has been problematic, mainly because of methodological limitations and nature of the paleomagnetic record in meteorites. Paleointensity determinations based on laboratory acquisition of thermoremanent magnetizations are affected by alteration of magnetic carriers (*e.g.*, Suigura *et al.*, 1979; Urrutia-Fucugauchi, 1979, 1981; Wasilewski, 1981). Rock magnetic analyses using magnetic hysteresis, acquisition of laboratory remanences, coercivity and unblocking temperature spectra, temperature variation of susceptibility, remanent magnetizations and hysteresis may provide useful indications on the magnetic carriers (*e.g.*, Urrutia-Fucugauchi *et al.*, 1984). Magnetite formation in oxidized CV chondrites has been investigated and related to aqueous alteration processes (*e.g.*, Choi *et al.*, 1997). In Allende, magnetite has been shown to constitute a major magnetic phase. The highly energetic conditions and multiple heating events in the solar nebula may have contributed to complex mineral assemblages and paleomagnetic record. The paleomagnetic record was later modified by impacts, thermal and chemical alterations, weathering, and alterations in the terrestrial environment. Micromagnetic analyses of chondrules offer alternative high resolution tools to investigate on the nature of the paleomagnetic record and recording minerals.

The diameters of the studied chondrule vary from about 0.4 mm to 1.2 mm, with morphologies from almost spherical to irregular shapes. For slicing, individual chondrules were fixed with resin in 2.5 cm cylindrical containers and sliced with non-magnetic, thin (0.03 mm) cutting disks. Three or more thin slabs were prepared from each chondrule for the experimental analyses.

Allende chondrules are characterized by distinct mineralogical and compositional assemblages, ranging from simple equilibrated 2-3 main silicate mineral assemblages to complex arrangements with accessory minerals, including Fe, Ni and S minerals and alloys. Allende chondrules contain abundant Fe-Mg silicate minerals, mainly olivine $[Mg,Fe]_2SiO_4]$ and Ca-poor pyroxenes $[(Mg,Fe)_2Si_2O_6]$. Chondrule c40b represents a barred type, with olivine barred patterns, and c53b is a chondrule of the porphyritic olivine type. Other equilibrated chondrules are characterized by radial pyroxene barred patterns. Complex chondrules are characterized by distinct mineral associations with fayalite, spinels, cromites, magnetite and trolite, and Fe-Ni alloys. Complex chondrules suggest a range of fusion temperatures, which are indicated by the distinct constituent minerals. The presence of inclusions is evidence of further complexities in the medium for chondrule formation and in the mechanisms and temperature-pressure-fugacity conditions. For instance, the occurrence of Cr-rich spinels suggests the presence of fine dust in high relative proportion. Comparison with present conditions suggests concentrations several orders of magnitude larger, which is being interpreted in terms of primordial condensates from the pre-solar gas and dust nebula.

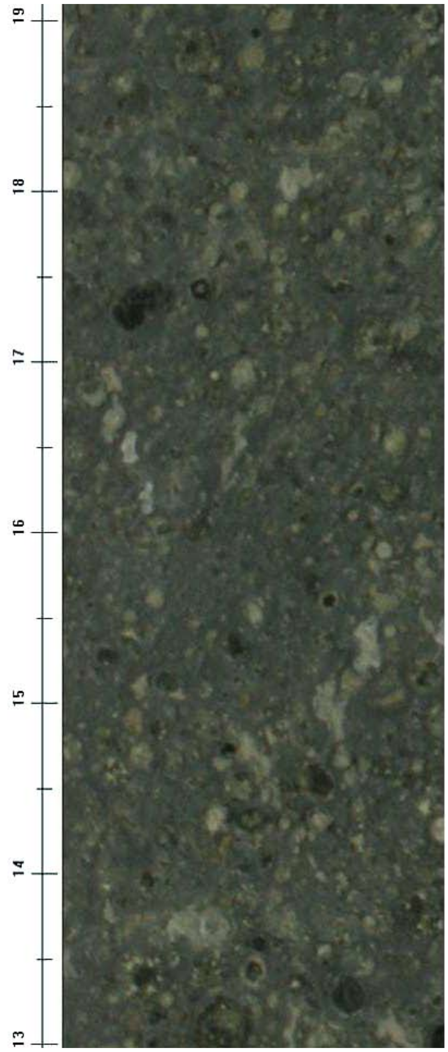


Figure 1. Fragment of the Allende carbonaceous chondritic meteorite (6 cm slab cut from Allende showing distribution of chondrules and refractory inclusions in the fine grained silicate matrix).

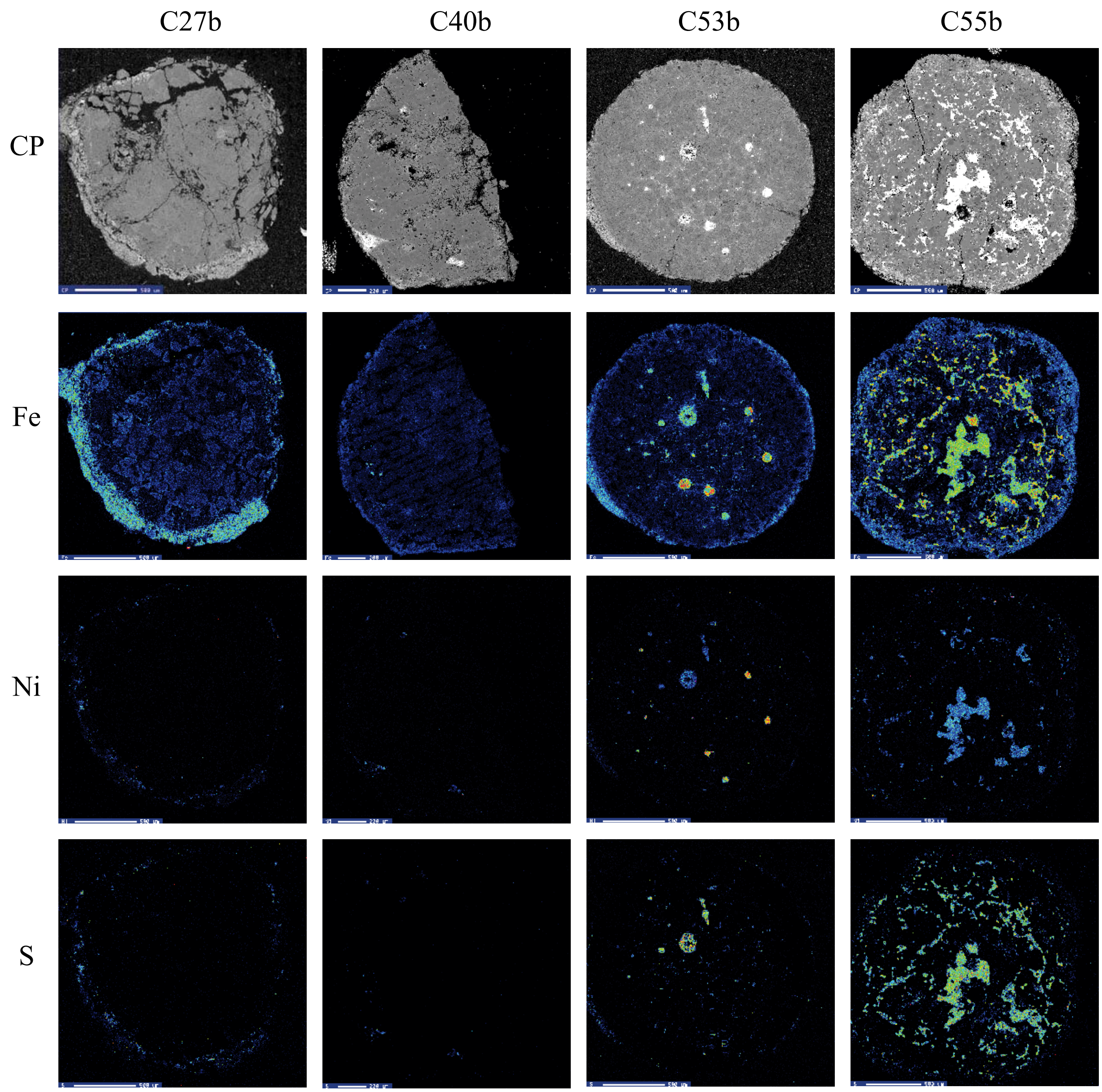


Figure 2. Scanning electron microscopy (SEM) and SEM-Energy dispersive spectroscopy (EDS) images for individual chondrules from Allende meteorite. SEM composite pictures (CP) and false color compositional images for Fe, Ni and S are shown for chondrules c27b, c40b, c53b and c55b (see text for description).

The chondrules analyzed have been described in a previous study, where additional compositional data are reported (Flores-Gutiérrez *et al.*, 2010). Chondrule c27b has an irregular shape with a thick incomplete rim that is Fe rich and with distinct Si and Mg composition. c27b is a composite chondrule with a Mg-rich central part surrounded by additional chondrule material remelted and altered by element diffusion; it is Ca and Al poor, which is also a characteristic of the igneous Fe-rich rim. Chondrule c40b displays an irregular shape, which on the basis of the internal microstructure and elemental compositional maps is related to fragmentation. c40b has a barred olivine texture marked by Mg-rich pyroxene and olivine barred patterns, with Ca-Al rich bands, low sulfur and low FeO contents. Chondrule c53b shows a nearly spherical shape, with a thin rim and a small bulge, which shows, in the Si, Mg and Fe compositional images, different elemental content and distribution (*e.g.*, lower Mg content and higher Fe content). c53b is a porphyritic olivine chondrule, S poor, and contains a few Fe-rich rounded particles. Chondrule c55b presents an irregular rounded shape with a thin rim, which can be distinguished more clearly with respect to its iron content. Its internal morphology is more complex, with larger crystals than those in c53b and a central zone of iron sulfides that can be distinguished in the texture of the Ca- and Al-rich minerals and by its Mg content.

## SCANNING ELECTRON MICROSCOPY AND MICROPROBE ANALYSES

The chondrule slabs were analyzed using a JEOL microprobe at the Laboratorio de Petrología, UNAM. Elemental compositional mapping was obtained with energy dispersive X-ray spectroscopy (EDS) analyses. Results for chondrules c27b, c40b, c53b and c55b are summarized in Figure 2, which also includes a SEM composite picture (CP) for each sample; the CP images (total X-ray emission) display the morphologies and internal structures of the chondrules, with c27b showing bimodal distribution and c40b, c53b and c55b showing unimodal distributions.

Distribution of Fe, Ni and S given in the false color images document the complexity in composition and microstructural morphologies of individual chondrules within a single fragment of the Allende meteorite. The diversity of these compositional distributions correlate with previous observations on wide variation in chondrule sizes, types, density, and magnetic hysteresis properties (Flores-Gutiérrez *et al.*, 2010). Chondrule c27b is characterized by Fe-rich minerals and is Ni and S poor. Ni and S are concentrated in the chondrule rim, which is also Fe rich; the rim can be clearly recognized in the CP image and is well delineated by the spatial distribution of Fe). Chondrule c40b is Fe poor, and has low contents of Ni and S; it is formed by barred olivines with Fe distributed more homogeneously within the olivine crystals. Chondrule c53b has a spherical shape, except for a partly preserved Fe-rich rim. Minerals with higher contents of Fe, Ni and S are present in the chondrule interior. Chondrule c55b has a more complex morphology and is characterized by more irregular distribution of Fe, Ni and that define characteristic mineralogical assemblages.

In order to identify the mineral assemblages characterized by Fe, Ni and S, we have applied a mathematical technique for image analysis, which is described in the following section. The analysis permits an accurate identification of the mineralogical diversity and its spatial distribution within the chondrules. Intersection zones isolated in the image analyses characterize minerals in the chondrules: troilite (FeS), magnetite ($Fe_2O_3$), awarite ($Ni_3Fe$), tetranite (FeNi), ilmenite ($FeTiO_3$), haezlewoodite ($Ni_3S_2$), millerite (NiS), polydymite ($Ni_3S_4$) and vaesite ($NiS_2$).

## SEM-EDS IMAGE ANALYSIS

We analyzed the mineral boundaries in the chondrules, focusing on the elements Fe, Ni and S. The mathematical tools employed are part of a commercial integrated development environment (IDE) for machine vision.

For the analyses, we first read the original images, which were transformed from RGB colour space to grey scales. Then we applied filters in order to achieve a best signal to noise ratio. A shock filter was applied to the input image to sharpen the edges the features contained in it. The principle of the shock filter is based on the consideration of a continuous image $f : R^2 \rightarrow R$. Then a class of filtered images of $f(x, y)$ may be created by evolving $f$ under the process

$$u_t = -sign(\Delta u)|\nabla u| , \tag{1}$$

$$u(x, y, 0) = f(x, y). \tag{2}$$

where subscripts denote partial derivatives, and $\nabla u=(u_x, u_y)^{\perp}$ is the (spatial) gradient of $u$. The initial condition (2) ensures that the process starts at time $t = 0$ with the original image $f(x, y)$ (Weickert, 2003).

Then the algorithm segments the image into regions of the same intensity (rastered into rectangles of size 5×5). In order to decide whether two adjacent rectangles belong to the same region, only the grey value of their centre points is used. If the grey value difference is less then or equal to 20 the rectangles are merged into one region, which means: If $g_1$ and $g_2$ are two grey values of the centre points to be examined, they are merged into the same region if:

$$|g_1 - g_2| < \text{Tolerance}$$

where *Tolerance* is set to 20 in our case.

Next, the regions are connected. The algorithm determines which regions are connected, from the set of input regions generated in the previous step, analysing their neighbourhood. We used an 8 degree neighbourhood, which is useful for determining the connected components of the foreground.

Next, the algorithm selects regions with the aid of shape features. For each input region a set of shape features is calculated. If each calculated feature is within a selected range, the region is added to the end result. In our case we have used the area and size features for each region.

The last step of our algorithm is to calculate additional features that help us to classify the regions. Those features are region number, area, mean, minimum and maximum intensity, standard deviation and rank. Final result of the algorithm is integrated into a file containing all information calculated for each selected region. In Figures 3 to 6, results in terms of the spatial assemblages of Fe, Ni and S for chondrules c27b, c40b, c53b and c55b are showed.

## INTEGRATED MINERAL ANALYSES

The mineralogical compositional differences and wide variation ranges in the chondrules are documented in the SEM-EDS image analyses (Figures 3 to 6). Minerals and alloys are identified by different colours, which display the spatial distribution and relative contents.

Chondrule c27b (Figure 3), which shows a complex assemblage of Fe minerals with some 10 distinct associations, is characterized in the intersection image analyses in terms of compositional distribution by a well delineated rim that extends to cover almost the entire chondrule (in contrast to the partial rim recognized in CP and Fe images), and characteristic patterns in the chondrule interior. Ni is mainly concentrated within the rim, whereas S is present in the rim minerals and in the mineral assemblages of the interior.

Chondrule c40b (Figure 4) is characterized by a well developed barred olivine pattern, which dominates the internal structure, although a mineral assemblage is also identified. The minerals identified are characterized by sizes in the order of a few microns and are distributed in the interstitial zones of the chondrule interior and form a partial rim. Some of the minerals that stand out in white color in the CP image apparently correspond to metallic inclusions rich in Fe, Ni and S.

Chondrule c53b (Figure 5), which shows a nearly spherical morphology and an apparent homogeneous distribution of Fe, is characterized by a complex mineral assemblage. Fe is distributed through the chondrule and is concentrated in granular assemblages with apparent polygonal shapes. Fe-rich minerals and Fe-Ni and Fe-Ni-S alloys are observed, which can be distinguished by the white structures in the CP image. Ni is enriched in minerals in the interior, which are marked by the grey inclusions in the CP image. S is more abundant in the larger inclusions and is also distributed in the interstitial spaces.

Chondrule c55b (Figure 6) shows a complex assemblage of minerals with high relative concentrations of Fe, Ni and S, which is distinct from the other chondrules analyzed. The characteristic mineral patterns are given by the irregular zones of elongated and clustered mineral assemblages of metallic inclusions around the olivines, pyroxenes and other Mg silicates. Fe is enriched in two large inclusions that also show high contents of Ni and S, and which can be distinguished as white zones of the CP image.

The Fe-, Ni- and S-rich mineral assemblages have been identified in Raman spectra (Flores-Gutiérrez *et al.*, in preparation). The Raman spectra for c53b indicate the presence of Ni minerals and alloys, with NiO or $Ni(OH)_2$, $NiS_2$ and $Ni_3S_4$.

The small partial rim in c53b appears to have a similar mineralogical assemblage as the thicker and more complete rim observed in c27b. These mineral assemblages are also present, albeit in less concentration, in the partial rim of chondrule c40b. Chondrule rims are thought to be formed at later times by processes affecting the chondrules. The analyses show that rims in c27b and c40b are enriched in Ni and S.

## DISCUSSION

Chondrules and CAIs formed at the early stages of the solar system evolution, and thus the chronology and processes involved in their formation are key elements to unravel the origin of the solar system (Wood, 1988; Cameron, 1988; Hewins *et al.*, 1996; Scott, 2007). Both chondrules and CAIs formed early by short-lived heating events that affected the dust and gas nebula. Studies indicate that temperatures may have reached some 1400 °C to 1800 °C for short periods of heating/cooling. Different mechanisms have been proposed for the melting of fine-grained solid matter. Chondrules appear to have formed at a later time than CAIs, as suggested from isotopic data and petrographic and microstructural observations. Isotopic analyses of the Al and Mg systematics have long been carried out in Allende samples, and provided constraints for the chronology of events forming CAIs and chondrules, and for solar nebula conditions (*e.g.*, Lee *et al.*, 1976; Zinner, 2002; Scott, 2007). Analyses of $^{26}Al$ isotopic differences in CAIs and chondrules have been discussed in terms of orderly or overlapping sequence of events (*e.g.*, Prinz *et al.*, 1986; Wood, 1988; Itoh and Yurimoto, 2003; Bizarro *et al.*, 2004; Krot *et al.*, 2005). Additional detailed studies of CAIs and chondrules are required to constrain the chronology of early events, processes and their spatial relationships (Itoh and Yurimoto, 2003; Bizarro *et al.*, 2004; Krot *et al.*, 2005). Experimental evidence on an early origin of CAIs includes the findings of relict CAIs inside chondrules. Studies have also reported findings of a chondrule inside a CAI, which may suggest contemporaneous formation of CAIs and chondrules, and an extended period of chondrule formation (Itoh and Yurimoto, 2003; Krot *et al.*, 2005). Studies favor that CAIs formed some 1 to 4 million years earlier (*e.g.*, Scott, 2007), though chondrules may have started to form together with CAIs, but chondrule formation lasted longer.

Several studies have focused on the mineralogy of chondrules, CAIs and matrix, in search of constraints for the formation mechanisms, conditions, spatial-temporal zoning and scale ranges within the solar nebula. In this study we have concentrated in studying the contents and spatial distribution of Fe, Ni and S within individual chondrules. Fe minerals are major constituents in chondrules, where they might occur in oxides, sulfides and metal alloys. Troilite (FeS), for instance, occurs frequently in chondrules, and its distribution and relative content provides constraints for formation conditions and subsequent alteration processes. Sulfur is volatile, condensing as troilite at about 983 °C through reactions between Fe-Ni alloys and hydrogen sulfide ($H_2S$). Sulfur may be easily lost at chondrule forming temperature ranges. Additionally, troilite may have formed at lower temperatures during cooling, associated with sulfur mobility. Distinction of primary high temperature and secondary low temperature troilite gives indications for the formation and alteration of chondrules (Yu and Hewins, 1998; Rubin, 2000; Jones *et al.*, 2005).

Chondrule c40b represents an olivine barred type, which was fragmented before incorporation into the matrix. This provides evidence on collisions in the chondrule forming region occurring before incorporation into the matrix and perhaps contemporaneously with the chondrule formation.

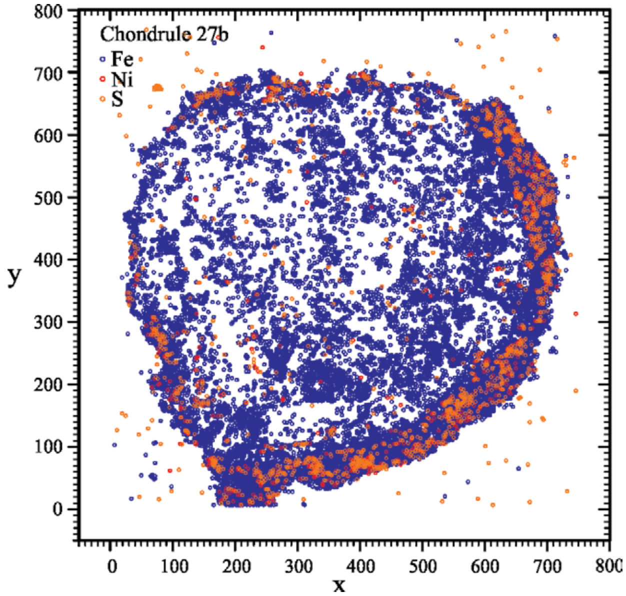


Figure 3. Metal boundaries inside c27b chondrule, determined using an image processing technique, focusing in the nickel, iron and sulphur elements. C27b is an example of an iron-rich chondrule with iron- and nickel-rich rim.

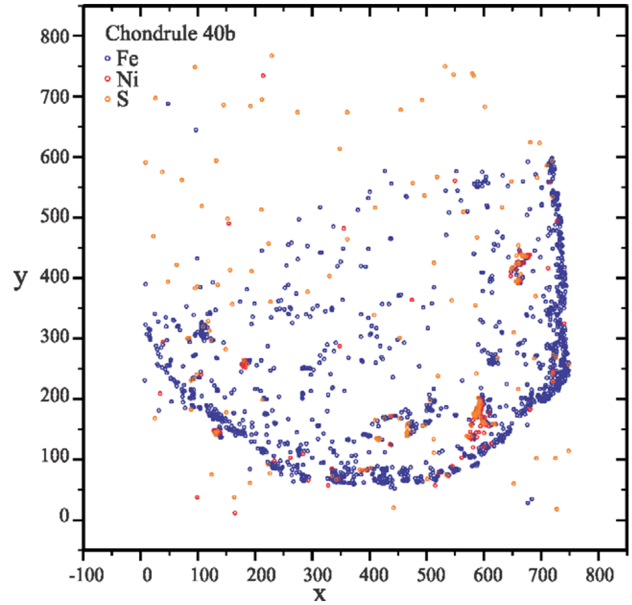


Figure 4. Metal boundaries inside c40b chondrule, determined using an image processing technique, focusing in the nickel, iron and sulphur elements. C40b is an example of iron-, nickel- and sulphur-poor chondrules.

Fragmented chondrules and refractory inclusions have been taken as indications for collisions and turbulent conditions in the solar nebula. Occurrence of compound chondrules and igneous rims has been considered in terms of multiple heating events in regions of the nebula. The chondrules examined in these studies of the Allende chondrite illustrate a range of chondrule morphologies, including compound chondrules, igneous-rimmed chondrules, fragmented chondrules and relatively homogeneous nearly spherical chondrules with olivine barred and olivine porphyritic types.

Chondrules have been found to separate into two different types: (a) the reduced type I chondrules characterized by the occurrence of iron metal blebs and FeO-poor olivine, and (b) the oxidized type II chondrules with no metal blebs

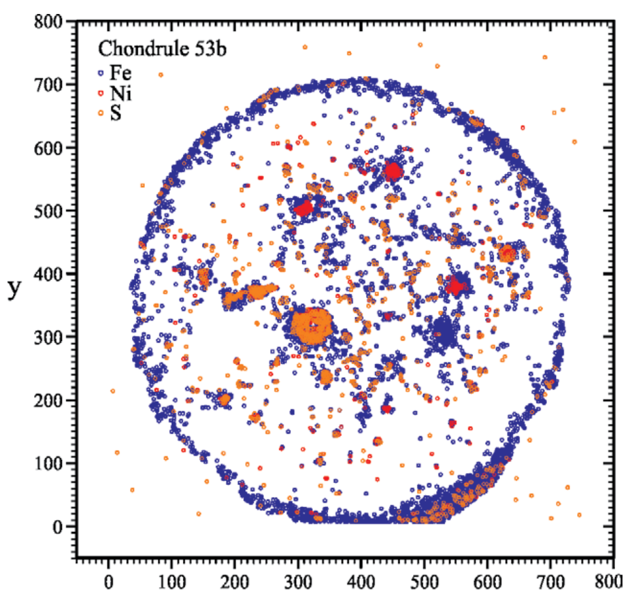


Figure 5. Metal boundaries inside c53b chondrule, determined using an image processing technique, focusing in the nickel, iron and sulphur elements. C53b is an example of iron- and nickel-poor chondrules with iron-rich rims. Observe the nickel and sulphur rich metallic inclusions.

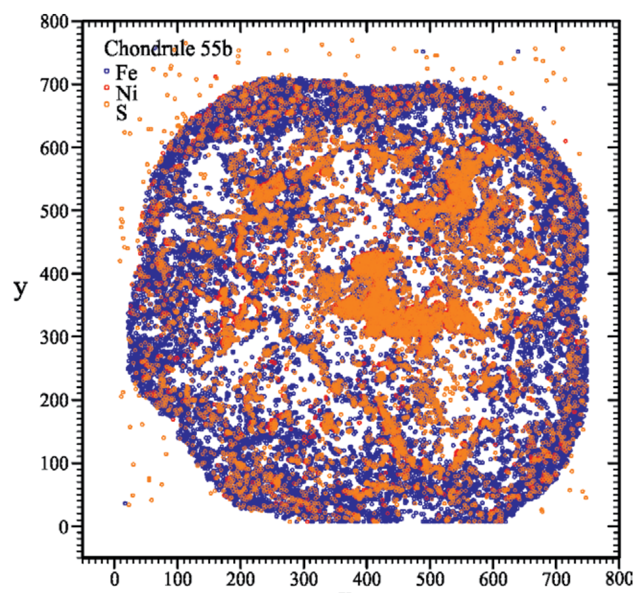


Figure 6. Metal boundaries inside c55b chondrule, determined using an image processing technique, focusing in the nickel, iron and sulphur elements. C55b is an example of iro-, nickel- and sulphur-rich chondrules. Note the internal mineralogical assemblage and spatial arrangement, with sulphur-rich minerals.

and FeO-rich olivine (McSween, 1979, 1985, 1987). SEM-EDS analyses show that chondrules in Allende correspond to type I, characterized by FeO-poor and metal-rich low volatile material. The sub-groups in the CV chondrites mainly depend on the relative contents of magnetite, which reflects on the modal ratios of magnetite to metal.

Fe minerals and in particular magnetite in the Allende chondrite have been intensively studied, as well as in other oxidized and reduced chondrites. Studies have proposed different scenarios for magnetite formation, including magnetite crystallization from cooling oxidized chondrule melts, oxidation of metallic nodules in the solar nebula, and later oxidation of metallic chondrule nodules in asteroids. Magnetite formation and timing are important in terms of chondrite origins and evolution, with processes separating into the solar nebula and, at later times, in protoplanets or asteroidal settings (Krot *et al.*, 1995). In the Allende, magnetite appears mainly in porphyritic olivine chondrules as spherical nodules, in association with Ni-rich alloys and sulfides. In our analyses, Fe appears with Si and Mg (fosterite to fayalite), with higher concentrations in chondrule rims (*e.g.*, c27b, c53b). In those cases, Fe occurs with Ni and S, forming Fe-Ni alloys and trolite. Silica is a major element in chondrule composition; in low concentrations it tends to be uniformly distributed and in higher concentrations it is distributed in wide regions and in rims. In c55b, it shows higher relative contents in the interstitial zones (Flores-Gutierrez *et al.*, 2010 and in preparation). Nickel distribution and Ni-rich minerals and alloys may also constitute an important indicator of alteration processes in the solar nebula and at later times. Metamorphic processes affecting chondrites allow Ni to migrate; this mechanism has been used to estimate metamorphic temperatures in pentlandite-bearing chondrites. These assemblages and their distribution suggest later secondary processes after initial chondrule formation, but can still take place in the solar nebula. Kring (1991) has interpreted the high temperature chondrule rims in terms of fluctuating conditions occurring in the solar nebula. Accretion of dust rims has been shown to occur under turbulent conditions, particularly in particle-rich regions of the solar nebula, which can be several hundred of kilometers in size (Cuzzi and Alexander, 2006). In this respect, Scott (2007) has recently concluded that most chondrites, including the Allende, were affected by aqueous metamorphic processes in the asteroid belt. This emphasizes the need for further detailed studies of additional CV3 primitive chondrites and further analyses of alteration and metamorphic processes that could occur in the solar nebula and/or the asteroidal belt.

Our results confirm that closely spaced chondrules within given sectors of Allende can show variable distinct elemental Fe, Ni and S contents and distributions. Chondrules examined display major differences in rock magnetic properties, in addition to variable complex size, textural and mineralogical differences. These results and the spatial and textural compositional distribution and mineralogy support chondrules underwent distinct thermal, shock, alteration and evolutionary histories during chondrule formation in the early stages of evolution of the planetary system.

## ACKNOWLDEGMENTS

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