

Micromagnetic and microstructural analyses in chondrules of the Allende meteorite

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ABSTRACT

Results of micromagnetic and microstructural studies of individual chondrules from the Allende carbonaceous meteorite are presented. Allende is a member of the CV3 carbonaceous chondrites, and part of the oxidized meteorites with iron in silicates and oxides. Magnetic hysteresis data in terms of plots of parameter ratios give relationships with chondrule size and shape, in particular with magnetization ratio (M_r/M_s) and coercivity (H_c). Morphology, internal structure and elemental composition are investigated by scanning electron microscopy and spectrometric analyses. Chondrules show low ranges of magnetization ratios (M_r/M_s from 0 to 0.22) and coercivity (H_c from 3 to 24 mT). Low values suggest that chondrules are susceptible to alteration and re-magnetization, which affects paleointensity determinations for the early planetary magnetic fields. A linear relation of M_r/M_s as a function of H_c is found up to values of 0.17 and 17 mT, respectively. This relation correlates with internal microstructure and composition, with compound chondrules showing higher hysteresis ratio and parameter values. Chondrules with hysteresis parameters falling outside the major trend show internal structures, composition and textures indicative of compound chondrules, and fragmentation and alteration processes. Microprobe analyses show distinct mineralogical assemblages with spatial compositional variation related to chondrule size, shape and microstructure.

Key words: chondrules, magnetism, structure, chemical composition, Allende meteorite.

RESUMEN

En este trabajo se presentan los resultados de estudios micromagnéticos y microestructurales en condros individuales separados del meteorito Allende. Allende es una condrita carbonácea CV3, oxidada y con hierro en los silicatos y óxidos. Los datos de histéresis magnética analizados en términos de graficas de cocientes de los parámetros de histéresis revelan relaciones con la forma y tamaño de los condros, en particular con los cocientes de magnetización y de coercitividad. La morfología, estructura interna y composición elemental se investigan con análisis de microscopía electrónica de transmisión y espectrometría. Los condros muestran valores bajos de cocientes de magnetización, entre 0 y 0.22,

y de coercitividad, entre 3 y 24 mT. Los valores bajos sugieren que los condros fueron afectados por alteración y remagnetización, lo cual limita los estudios de paleointensidad para la determinación de campos magnéticos en la nebulosa. Una relación lineal es observada entre los cocientes de magnetización y la coercitividad, para el rango entre 0.17 y 17 mT. Esta relación muestra correlación con los datos microestructurales y la composición, con condros compuestos mostrando valores altos de histéresis. Los condros cuyos parámetros salen fuera de la tendencia encontrada presentan estructuras y texturas que indican condros compuestos, fragmentación y alteración. Los análisis de microscopía electrónica y espectrométricos muestran arreglos mineralógicos relacionados al tamaño de condro, forma y microestructura.

Palabras clave: condros, magnetismo, estructura, composición química, meteorito Allende.

INTRODUCTION

Studies on the origin of the solar system have long been based on theoretical models and experimental investigations of chondritic meteorites, which represent the most primitive material available from the early stages of the solar nebula (Anders and Ebahara, 1982; Cameron, 1988; Hewins *et al.*, 1996; Connolly and Love 1998; Scott, 2007). Recently, high resolution astronomical observations of protoplanetary disks and apparently similar planetary systems have provided valuable insights on the initial conditions, characteristics and early evolution of planetary systems. Among the primitive meteorites, carbonaceous chondritic meteorites have proved particularly important (Wood, 1988). They are formed by chondrules and calcium-aluminum inclusions (CAIs) in a fine-grained aphanitic matrix. Chondrules are millimeter-scale melt droplets of igneous composition and together with CAIs have been intensively studied for their chemical and mineralogical composition, presence of radioactive isotopes, alteration features, etc. (*e.g.*, Blander and Fuchs, 1975; Chen and Wasserburg, 1981; Fegley and Palme, 1985; McSween, 1985, 1987; Hewins *et al.*, 1996; Scott, 2007). All this in efforts to understand the source(s) of the initial matter, matter source distribution, conditions, processes and mechanisms of chondrule formation, early and late alteration processes, and planetesimal formation and timing.

Studies on individual chondrules and CAIs and their internal structures, composition and textures provide evidence for more complex scenarios for the early solar system, with heterogeneous conditions and gradients in the solar nebula, suggesting fluctuating conditions, various heating mechanisms, complex matter distributions, varying oxidizing conditions, alteration effects and extended overlapping chronologies for chondrule, CAI and chondrule formation (*e.g.*, Fegley and Palme, 1985; Prinz *et al.*, 1986; Kring, 1991; Hood and Kring, 1996; Hong and Fegley, 1998; Scott, 2007). Our interest in the Allende meteorite aroused from studies of magnetic properties and quantitative paleointensity determinations of the early magnetic fields in the solar nebula (Flores-Gutiérrez and Urrutia-Fucugauchi, 2000, 2002). Analyses of magnetic mineralogy and magnetic

properties in individual Allende chondrules, while evidencing the internal complexity, also indicated first-order relationships of magnetic hysteresis properties with chondrule size and shape. Interpretation of the linear and higher order relations requires additional detailed studies of chondrule microstructures and morphologies. In this note we present results of morphological and microstructural analyses in chondrules of the Allende carbonaceous chondrite (Figure 1) and discuss their implications for the iron oxides and opaque minerals and chondrule formation.

THE ALLENDE METEORITE

The Allende meteorite has been critical in meteoritic and solar system origin studies since the initial investigations following its fall in Chihuahua, northern Mexico, on February 8, 1969. Allende belongs to the group of carbonaceous chondrites, which are relatively rare on Earth as compared to ordinary chondrites. The Allende meteorite fall was well documented and large quantities were recovered and rapidly distributed and analyzed in many laboratories around the world (Clarke *et al.*, 1970).

Allende has been classified as a CV3 carbonaceous chondrite that consists mainly of chondrules (*ca.* 43 % vol) and matrix (*ca.* 38.4 % vol), with the additions of CAIs (*ca.* 9.4 % vol), olivine inclusions (*ca.* 3.2 % vol), opaque minerals (*ca.* 3.1 % vol), and lithic and mineral fragments (*ca.* 2.9 % vol) (McSween, 1977). The macroscopic texture of Allende reflects the abundance of chondrules of sub-millimeter size within the aphanitic black matrix (Figure 1). Allende is part of the oxidized chondrites with an anhydrous mineralogy, with hydrous phases restricted to chondrules and CAIs. Oxidized chondrites show olivine rich in FeO and no iron metal blebs, in contrast to the reduced chondrites. Studies have also indicated secondary alteration processes affecting Allende mineralogy and composition in various ways (McSween, 1979, 1987; Krot *et al.*, 1995; Scott, 2007).

Studies on the Allende have resulted in significant advances in understanding the early conditions and formation of the solar system (Blander and Fuchs, 1975; Chen and



Figure 1. Fragment of the Allende chondritic meteorite, showing its texture with the characteristic chondrules and aluminum-calcium CAI inclusions incorporated into a black aphanitic matrix.

Tilton, 1976; Lee *et al.*, 1976; Sugiura *et al.*, 1979; Chen and Wasserburg, 1981; Anders and Ebahara, 1982; Hewins *et al.*, 1996; Kavner and Jeanloz, 1998). For instance, studies in Allende have provided the data on elemental abundance in the sun and planetary system, documentation of short-lived isotopes, notably aluminum with implications for a nearby supernova explosion, and presence of strong magnetic fields in the protoplanetary disk.

MORPHOLOGIES AND MICROSTRUCTURES IN CHONDRULES OF ALLENDE

Our initial study of magnetic mineralogy and magnetic properties of chondrules revealed apparent simple relationships between chondrule size and morphology and magnetic hysteresis parameters, pointing to first-order property relations. In particular, analyses quantified relationships between the magnetization ratio (M_r/M_s) and coercivity (H_c) (Flores-Gutiérrez and Urrutia-Fucugauchi, 2002). Chondrules with non-round shapes were outliers in the diagrams, suggesting that their external shapes had an effect on the hysteresis parameters, possibly associated with the presence of extraneous material or secondary process alterations. Magnetic domain states determined from the hysteresis parameter ratio plots (Day *et al.*, 1977; Dunlop, 2002) are pseudo-single domain (PSD) and multidomain (MD). The Day plots do not show any apparent trends and several chondrules display high coercivity ratios (H_{cr}/H_c) but slightly higher magnetization ratios (falling above the MD field).

For the study, about one-hundred individual chondrules were separated from the matrix, cleaned and mac-

roscopically analyzed. Basic characterization parameters determined include roundness, weight, diameter, and volume. Chondrule diameters range from about 0.04 to 0.32 mm. Chondrule weight ranges from about 0.001 milligrams to 0.12 milligrams. Hysteresis parameters were measured with the MicroMag system using maximum direct fields of 1 Tesla (T). The results display similar trends to those found in the initial study. From the diagrams of magnetization ratios plotted as a function of magnetic coercivity (Figure 2) we selected five chondrules for detailed study of internal structure. These chondrules (identified as M23, M27, M40, M53 and M55) show hysteresis parameter properties from low to high coercivity and low to high remanent and saturation magnetizations. Analyses of the density as a function of chondrule size show no significant variation, with densities ranging from about 2 to 3.5 g/cm³. Some chondrules show lower densities, particularly the larger ones with radius larger than 0.07 mm and up to 0.16 mm. The parameter ranges and relationships of the magnetization ratio as a function of chondrule size and mass are illustrated in Figures 3 and 4. The chondrules selected for study of the internal structure are also identified in the diagrams. In general, these chondrules span the ranges observed in the different bulk and hysteresis properties, as well as shapes and sizes.

The chondrules were sliced to investigate the internal structure and composition using a portable saw with non-magnetic thin disks. The internal morphology and microstructures in the chondrules have been examined using the JEOL JXA-8900R microprobe in the Laboratorio Universitario de Petrología, UNAM. The scanning electron microprobe is equipped with four wavelength dispersive spectrometers (WDS) and an energy dispersive spectrometer (EDS) system for semi-quantitative and quantitative elemental analyses. Scanning electron microscope (SEM) observa-

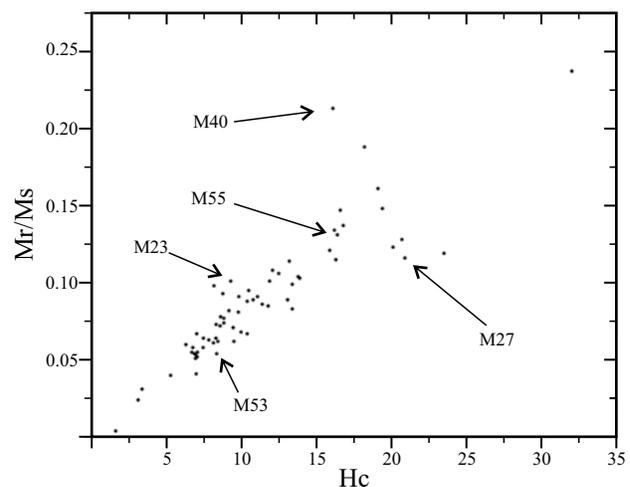


Figure 2. Plot of the magnetization ratio (M_r/M_s) as a function of coercivity (H_c) for individual chondrules from Allende. Note the linear trend for H_c less than 17 mT with M_r/M_s up to 0.17. Chondrules analyzed for internal microstructure are marked, covering the range of coercivity and magnetization characteristics.

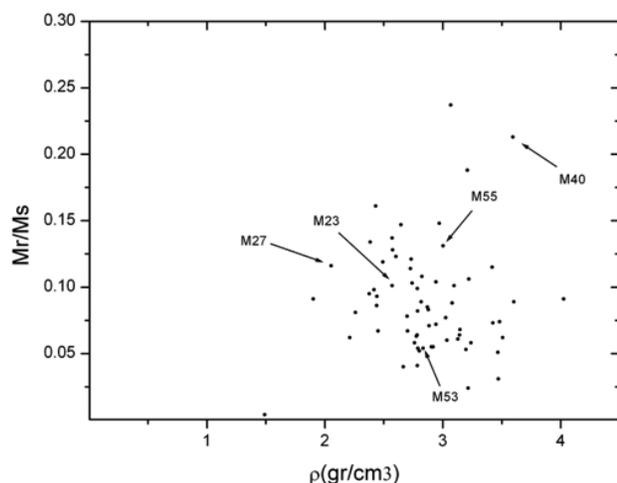


Figure 3. Plot of magnetization ratio Mr/Ms as a function of density. Chondrules analyzed by scanning electron microscopy are identified by the numbers.

tions and scan elemental data are summarized in Figures 5 to 9, showing the variation in sizes, shapes, internal structures and elemental composition in the chondrules.

Elemental analyses of the chondrule interior permit to investigate in detail the microstructures and compositional variations. Results in terms of scan images are summarized for each chondrule, with semi-quantitative data for Si, Ca, Al, Fe, Mg, Cr and S compositional spatial variations.

The Allende silicate chondrite has high contents of magnesium and iron. Major minerals are olivine (MgO 47–49 %, FeO 7–9 %, SiO_2 42–44 %), awaruite (FeO 28–32 %, NiO 68%), and enstatite (MgO 35–36 %, FeO 0.8 %, Al_2O_3 1.2 %, SiO_2 60 %), with kamacite, taenite, troilite, mackinawite, antigorite, majorite and pentlandite. Magnetite, chromite, Ni-Fe alloys, sulfides and sulfates and anorthite occurring as accessory minerals. Chondrules in the Allende present different textures and compositions, including anhedral, euhedral and recrystallized olivine chondrules,

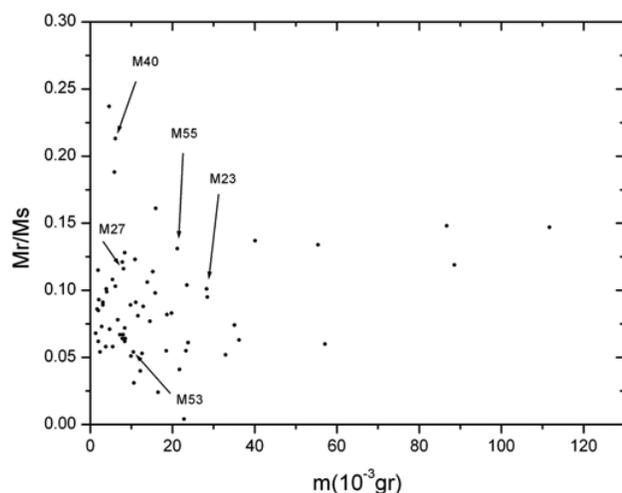


Figure 4. Plot of magnetization ratio Mr/Ms as a function of mass

barred olivine chondrules, pyroxene olivine chondrules and pyroxene chondrules. Magnetite, taenite and iron sulfides are the main magnetic minerals.

Most chondrules analyzed present nearly spherical shapes, as shown for chondrules M53 and M55 (Figures 5a and 6a). These chondrules show increasing magnetization ratios as a function of coercivity (Figure 2). M53 shows low H_c and Mr/Ms , whereas M55 shows higher H_c and higher Mr/Ms . Chondrule M53 has a nearly spherical shape, with a thin rim and a small bulge (Figures 5a–5e), which shows different elemental content and distribution in the Ca, Si, Al and S compositional images (e.g., higher Mg content and lower Fe content; Figures 5g, 5h). M53 is a porphyritic olivine chondrule, S-poor, that contains a few Fe-rich rounded particles. Chondrule M55 presents an irregular rounded shape with a thin rim (Figure 6a), which can be distinguished more clearly with respect to its iron content (Figure 6h). Its internal morphology is more complex, with larger crystals than those in M53 and a central zone of iron sulfides (Figures 6e, 6h), which can be observed in the texture of the Ca- and Al-rich minerals (Figures 6b, 6d) and Mg content (Figure 6g). It presents a low Cr content (Figure 6f).

Chondrules with higher magnetization ratios and coercivities (Figure 2) show more complex morphologies and internal structures. Chondrule M27 has an irregular shape with a thick incomplete rim (Figure 7a), which is Fe-rich and with distinct Ca, Si and Al composition (Figures 7b–7d). M27 is a composite chondrule with a central Mg-rich part surrounded by additional chondrule material re-melted and altered with element diffusion. It is Ca and Al poor (Figures 7b, 7d), which is also a characteristic of the igneous Fe-rich rim (Figure 7h). Chondrule M40 shows an irregular shape (Figure 8a), which from the internal microstructure and elemental compositional maps can be related to fragmentation. M40 has a barred olivine texture marked by Mg-rich pyroxene olivine barred patterns (Figure 8g), with Ca-Al rich bands (Figures 8b, 8d). M40 has no sulfur (Figure 8e) and a low homogenous content of FeO. Chondrule M23 has an irregular shape (Figure 9a), which is associated with a smaller rounded silicate Fe-poor chondrule precursor with homogeneous texture (Figures 9a, 9h). Its rim is marked by the Ca, Si and Al rich igneous material (Figures 9b–9d). The compound material is Fe-rich and of igneous texture (Figure 9h). This chondrule presents a higher Cr and Mg abundance in its central part (Figures 8e, 8g).

DISCUSSION

The conspicuous widespread abundance of chondrules in the primitive material represented in chondritic meteorites suggested, since the early studies, that chondrule formation was a key mechanism for accretion of the interplanetary dust material. The proto-chondrules were then heated to melting point and acquired their characteristic rounded droplet shapes with igneous composition. Formation

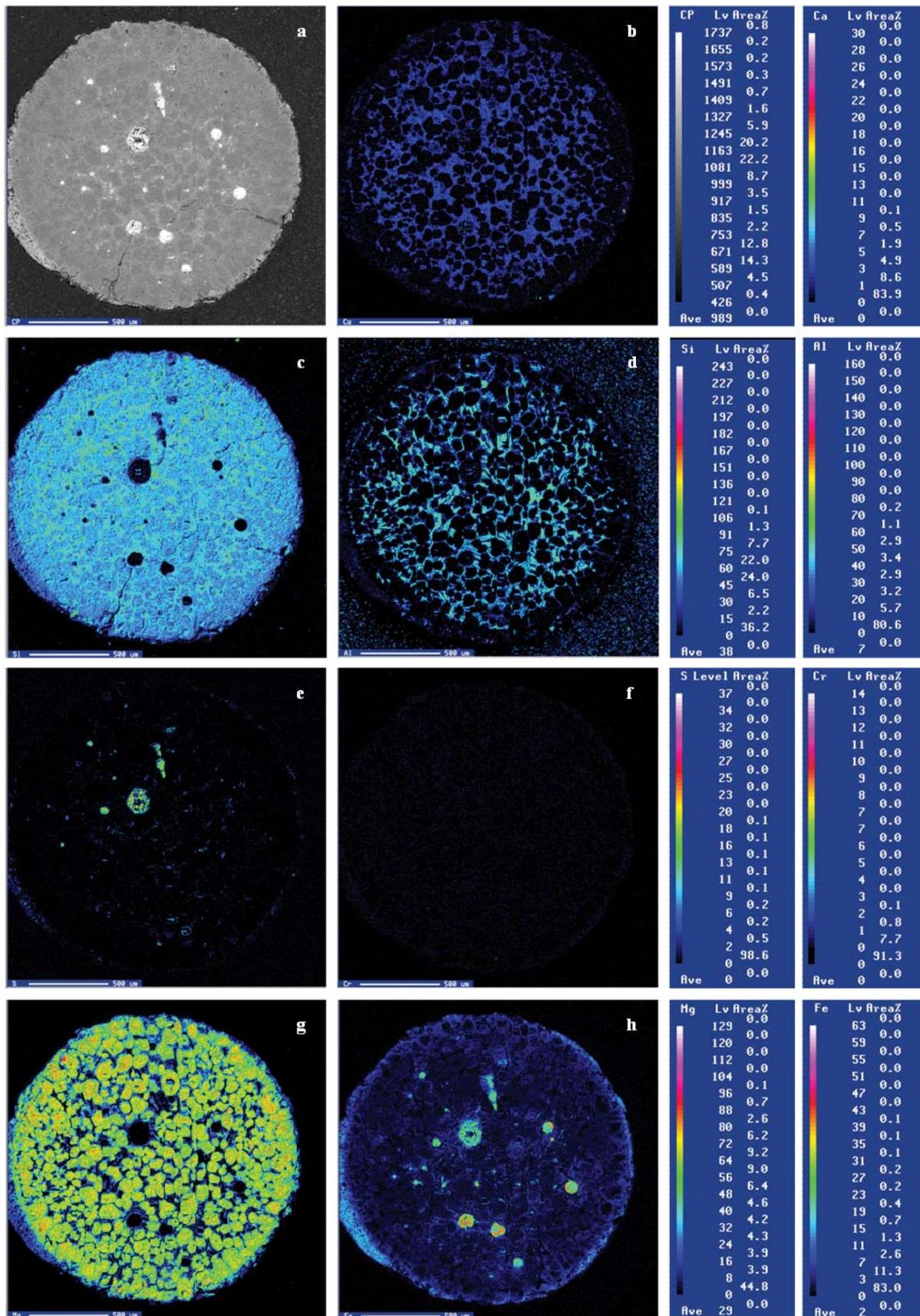


Figure 5. a: Scanning electron microscope images for chondrule M53 with scan elemental data for b: Si, c: Ca, d: Al, e: S, f: Mg, g: Cr, and h: Fe.

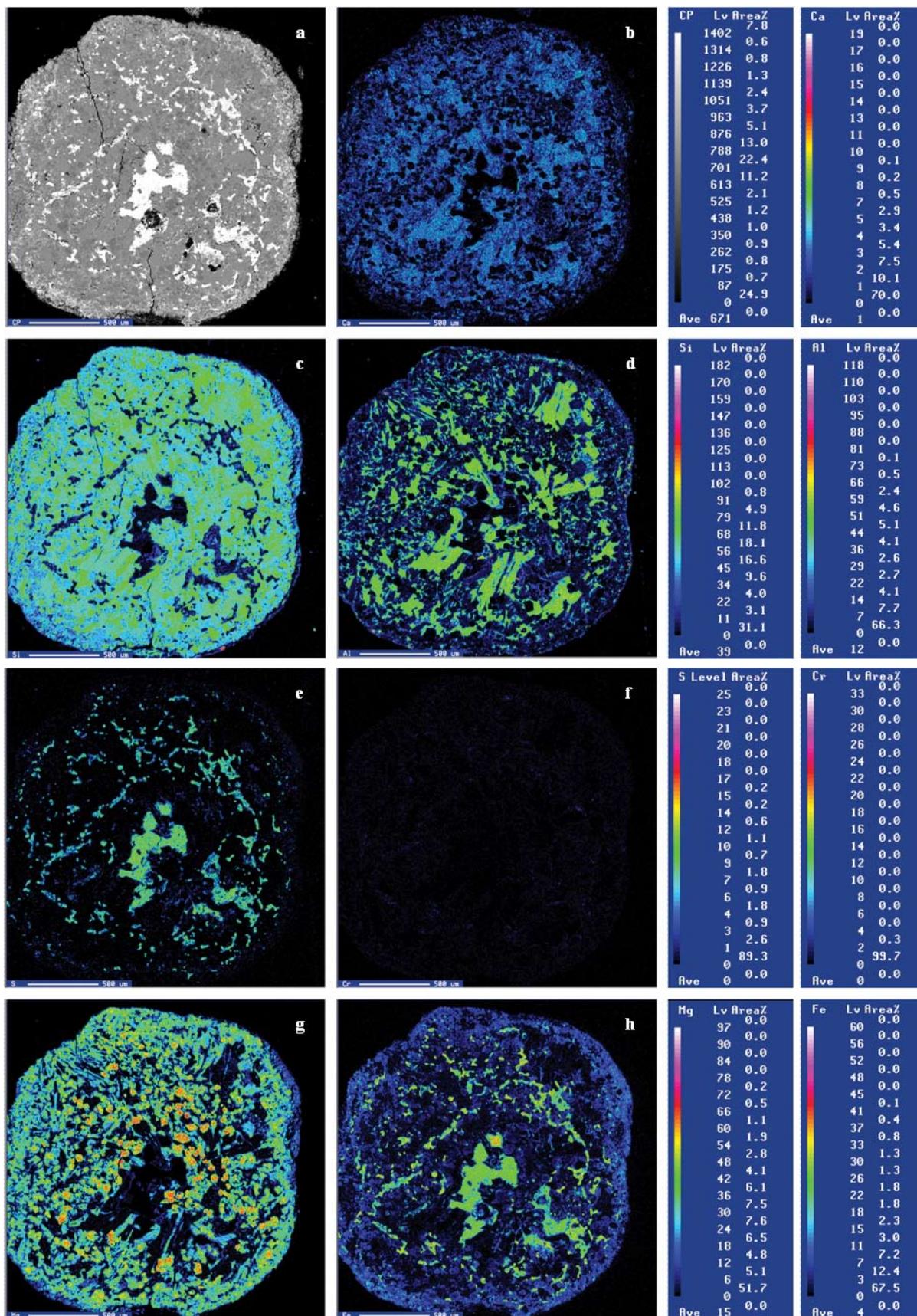


Figure 6. a: Scanning electron microscope images for chondrule M55 with scan elemental data for b: Ca, c: Si, d: Al, f: Cr, g: Mg, and h: Fe.

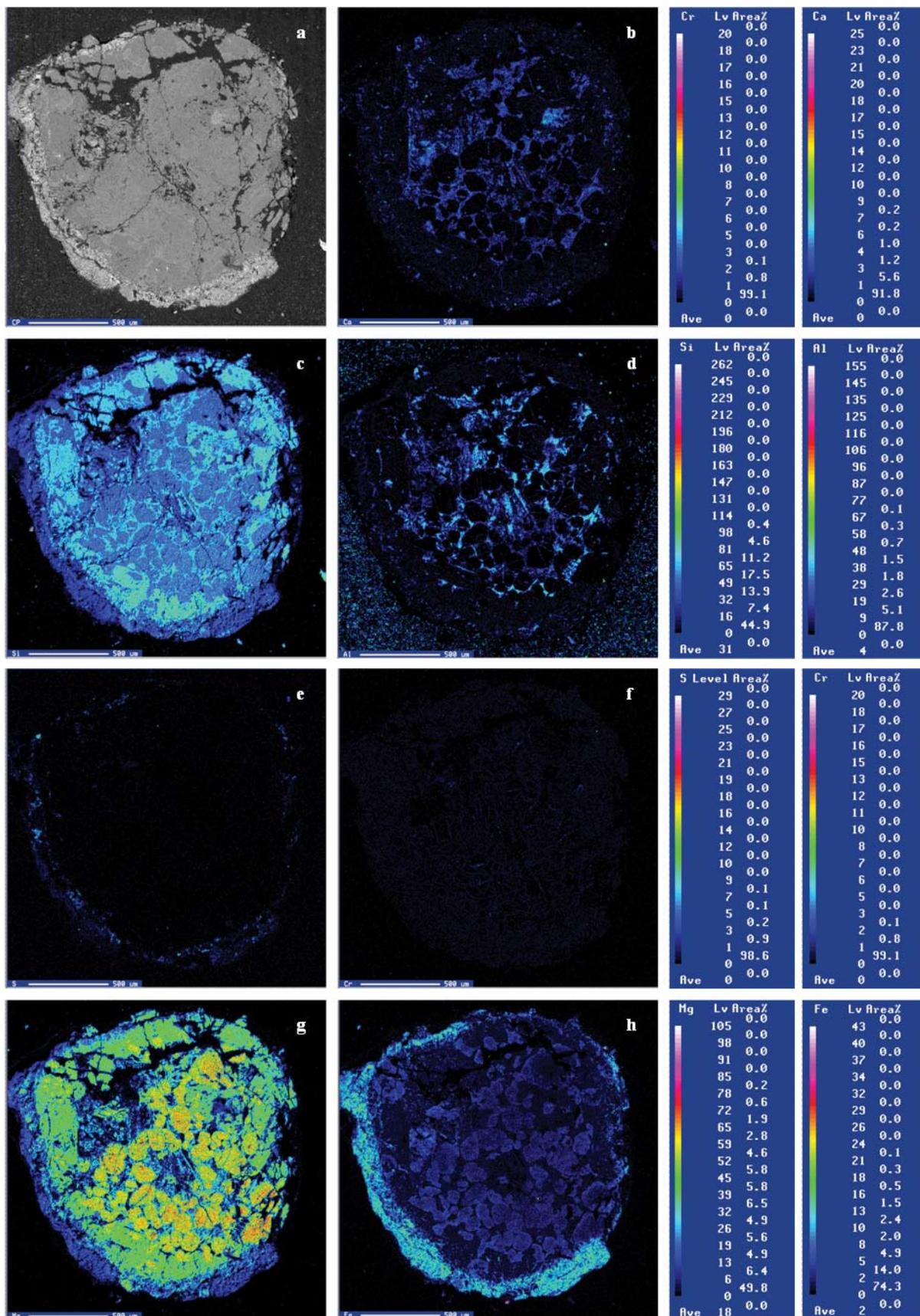


Figure 7. a: Scanning electron microscope images for chondrule M27 with scan elemental data for b: Ca, c: Si, d: Al, f: Cr, g: Mg, and h: Fe.

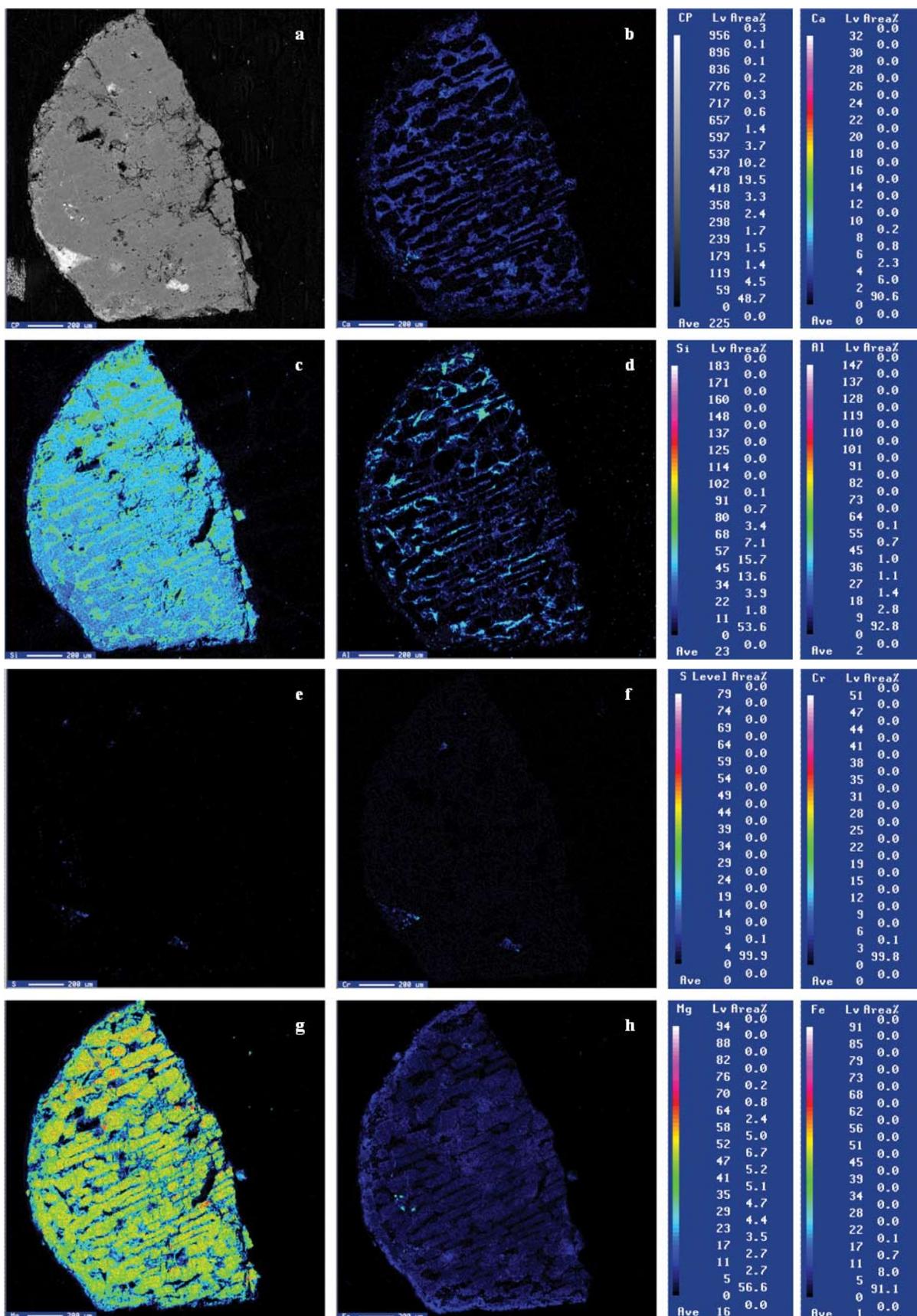


Figure 8. a: Scanning electron microscope images for chondrule M40 with scan elemental data for b: Ca, c: Si, d: Al, f: Cr, g: Mg, and h: Fe.

models of the solar system predict formation of chondritic bodies within a matrix incorporating the chondrules and CAIs. Proto-planetesimals were formed by accretion of chondritic bodies of various sizes in a long-term process of collisions and fragmentation/growth. Recently, studies on individual chondrules and CAIs and their internal structures, composition and textures provide additional evidence for more complex scenarios with heterogeneous conditions and gradients in the solar nebula, suggesting fluctuating conditions, various heating mechanisms, complex matter distributions, varying oxidizing conditions, alteration effects and extended overlapping chronologies for chondrule, CAI and chondrule formation (*e.g.*, Fegley and Palme, 1985; Prinz *et al.*, 1986; Kring, 1991; Hood and Kring, 1996; Hong and Fegley, 1998; Scott, 2007).

The opaque and magnetic mineralogy in meteorites has been long studied, with attention to the reducing/oxidizing conditions in the solar nebula. Chondritic meteorites form a continuous broad trend from 'reduced' with Fe in metallic form to 'oxidized' with Fe in silicates and oxides. Magnetic minerals are dominant phases in CV3 chondrites, including FeNi, iron oxides and silicates. Studies link the magnetite to aqueous alteration in proto-planetary bodies; our observations show that magnetite is a dominant phase responsible for the high field magnetic properties with PSD and MD domain states, along with taenite and iron sulfides and occurrence of iron in the silicates (Figures 5 to 9).

Analyses of magnetic hysteresis parameters show a simple linear relationship between the magnetization ratio and coercivity (Figure 2). Magnetization ratios are low, lower than 0.225, with the linear relationship present up to 0.17. Coercivity is low, lower than 24 mT. The linear relationship covers the range from about 2 mT to 17 mT. These low values suggest that chondrules are susceptible to alteration and re-magnetization, which has implications for retrieval of paleointensity estimates for the early planetary magnetic fields. Analysis of chondrules within the linear relation field and outliers may show some further indications for understanding the magnetic mineralogy and magnetic history. The indications from the microstructural observations suggest that magnetic properties may relate to chondrule internal structure and composition. Chondrules falling outside the relation are compound, with aggregation rims, and fractured (M40, M27 and M23), in contrast to those characterized by low H_c and M_r/M_s that appear homogeneous (M53 and M55). Figures 5a, 6a, 7a, 8a and 9a show the silica maps for four of the chondrules; their internal structure can be observed, which is also reflected in their external morphology and shape.

Samples from Allende have been long used to investigate the early magnetic fields in the protoplanetary nebula (Sugiura *et al.*, 1979). However, paleointensity determinations using different methods including magnetization ratios and the double heating Thellier technique give contrasting results. Paleointensity methods requiring

laboratory heating to high temperatures are limited by alteration processes affecting the magnetic minerals (*e.g.*, Banerjee and Hargraves, 1972; Urrutia-Fucugauchi, 1979). Methods using laboratory induced magnetizations such as isothermal remanent magnetization (IRM) and anisothermal remanent magnetization (ARM) have been developed (*e.g.*, Wasilewski, 1981; Gattacceca and Rochette, 2004). Effects of remagnetization, with acquisition of remanent components associated with chemical, thermal and magnetic viscosity processes, are major limitations in retrieving the early nebula magnetic fields (*e.g.*, Lanoix *et al.*, 1978; Sugiura *et al.*, 1979; Urrutia-Fucugauchi, 1981; Urrutia-Fucugauchi *et al.*, 1984). Studies have used whole samples, as well as individual chondrules. For instance, Banerjee and Hargraves (1972) reported estimates of 110 T from Thellier experiments. Lanoix *et al.* (1978) reported values from 100 to 700 T, and Wasilewski (1981) reported estimates of 1.2 to 15 T. The coercivity distribution in chondritic meteorites suggest that these materials are susceptible of magnetic overprinting, resulting from different processes during collisions, alteration within planetesimal bodies, exposition to high magnetic fields, lightning strikes, etc. This has suggested that reliable paleointensity estimates are more likely to be obtained from the high coercivity spectra in chondrules. Sugiura *et al.* (1979) reported data, obtained by applying a form of paleomagnetic conglomerate test, which suggest that chondrules retain a remanent magnetization acquired prior to their incorporation into the chondritic meteorite. The relationship uncovered for the magnetization ratio and coercivity (Figure 2) may permit to better understand the coercivity distribution. The connection to the internal chondrule structure, with compound chondrules, alteration rims, fracturing can be used for sample selection for paleointensity experiments.

Analyses of magnetic mineralogy, origin and alteration processes suggest a long chronology extending from interstellar dust accretion, chondrule formation with repeated melting events, formation of planetesimals, metamorphic and heating events of planetesimals and secondary alteration afterwards before and after arrival to Earth as meteorites. This extended chronology is illustrated in Figure 10, where thermal processes processed amorphous interstellar silicate dusts in the nebular disk that were accreted into chondrules and CAIs. Repeated melting events produced the chondrules that were later incorporated with CAIs, silicate fragments into chondrites and cometary bodies in different parts of the nebula. Planetesimals formed during a long period, involving metamorphic and thermal processes and these bodies also added debris from the collisions between the planetesimals (Scott, 2007). The complexity of chondrule formation processes, which are reflected in their internal structures, is illustrated in Figure 11. Chondrules with different morphologies and internal structures include compound chondrules, igneous rimmed chondrules, chondrules with metallic and foreign fragments and Al-rich chondrules with CAI inclusions.

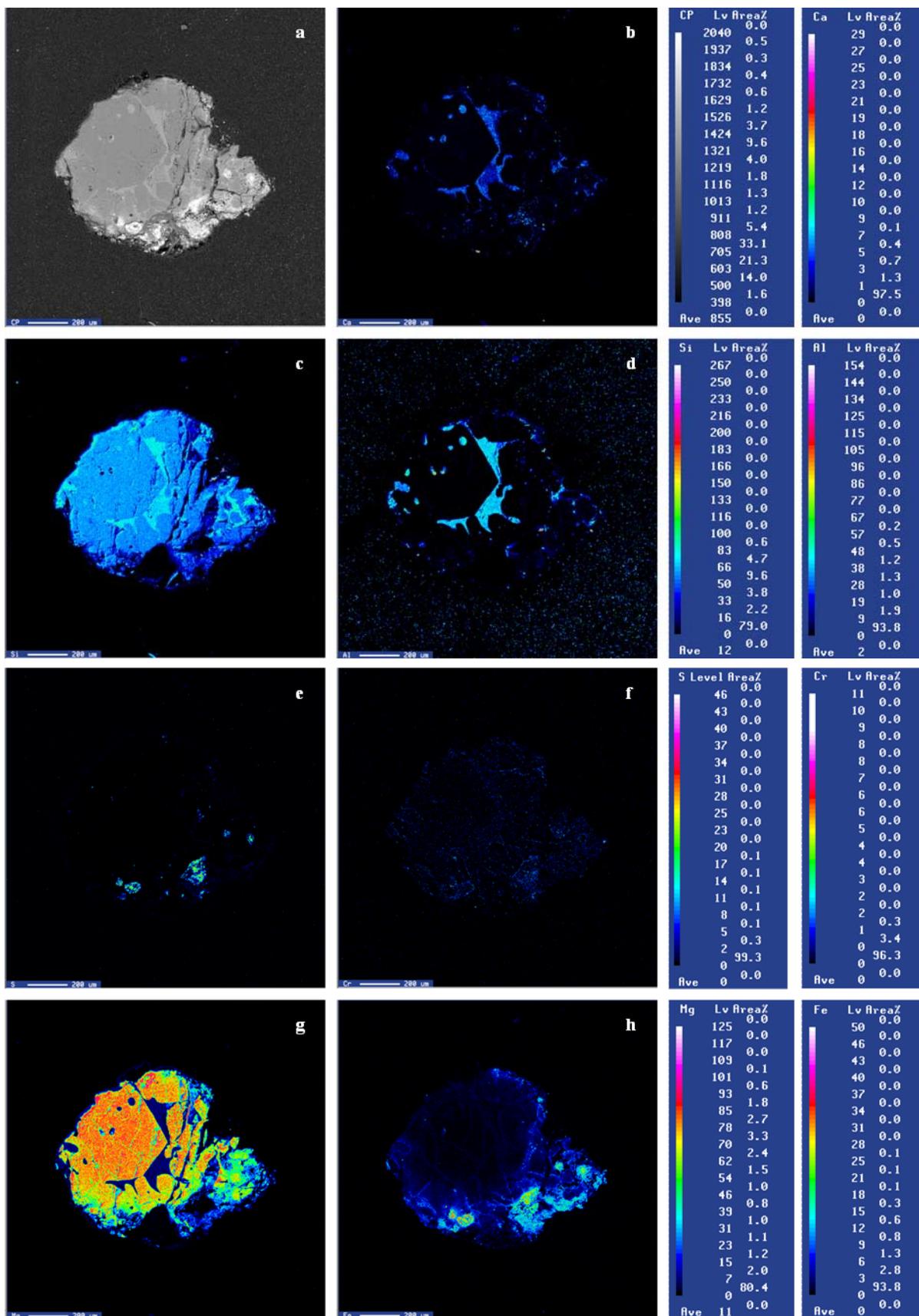


Figure 9. a: Scanning electron microscope images for chondrule M23 with scan elemental data for b: Ca, c: Si, d: Al, f: Cr, g: Mg, and h: Fe.

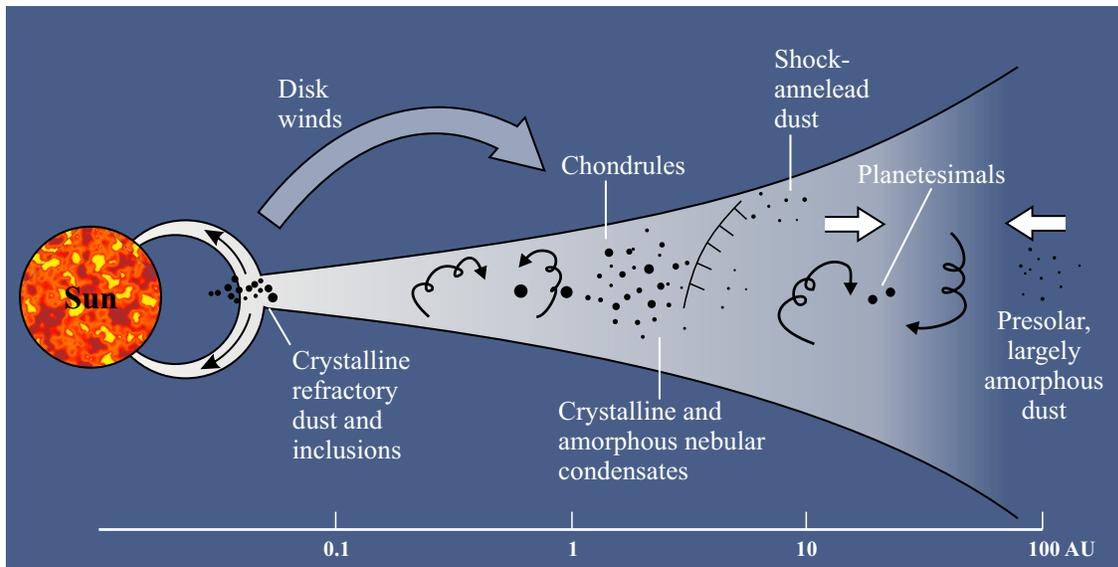
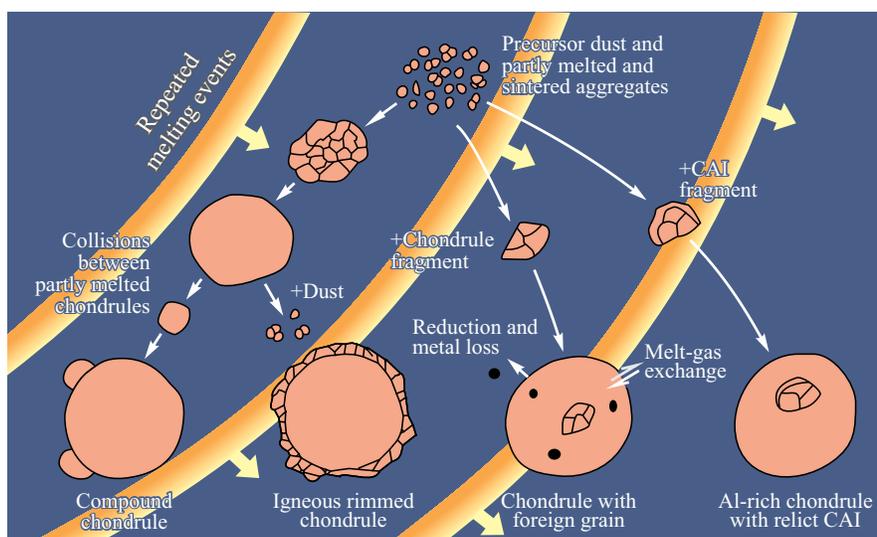


Figure 10. Schematic representation of protoplanetary nebula with relative position of chondrule formation region plotted as a function of relative distance, in astronomical units (AU), away from the proto-sun (adopted from Scott, 2007).

Models for chondrule formation show that early conditions in the planetary nebula included a wide range of interacting mechanisms, resulting in complex formation of chondrules from the initial crystalline refractory dust and inclusions (Figures 10 and 11). If these processes apply widely in the protoplanetary disk, it is hard to define a controlling mechanism for chondrule size and growth. Chondrule size ranges are different for the different chondritic meteorites, but show relatively narrow ranges for given types. The apparent restricted range in chondrule sizes has been little

discussed in models of chondrule formation, and it requires further investigation. The different meteorite types show distinct chondrule size ranges. Microanalyses of individual chondrules reveal the effects of accretion processes with several phases of addition of material and also indicate effects of secondary alteration processes. The relatively narrow ranges and the characteristic ranges in chondrite types support the presence of controlling/limiting processes involved in chondrule formation and subsequent accretion in chondritic bodies



Protoplanetary disk zone of crystalline and amorphous condensates

Figure 11. Schematic representation of chondrule forming processes from precursor dust and partly melted and sintered aggregate material. Diagram illustrates formation of compound chondrules, chondrules with igneous rims, chondrules with foreign particles and chondrules with relict calcium-aluminum inclusions, CAIs (adopted from Scott, 2007).

CONCLUSIONS

Results of our micromagnetic and microstructural study of individual chondrules from the Allende carbonaceous meteorite provide new data for analyses of internal chondrule structure and high field magnetic properties. Chondrules show wide ranges of magnetization ratios (Mr/Ms from 0 to 0.22) and coercivity (Hc from 3 to 24 mT), characterized by a linear relation of Mr/Ms as a function of Hc (Figure 2). This relation correlates with internal microstructure and composition, with compound chondrules showing higher hysteresis ratio and parameter values. Chondrules that present hysteresis parameters falling outside the major trend show internal structures, composition and textures indicative of compound chondrules, and fragmentation and alteration processes (Figures 5 to 9). Results have implications for oxidizing/reducing conditions and formation mechanisms of magnetic mineralogy in the early solar nebula. Allende is a member of the CV3 carbonaceous chondrites, and part of the oxidized meteorites with FeO-rich olivines and iron contained in silicates and oxides. Micromagnetic analyses in the chondrules identify magnetite as a main magnetic phase with pseudo-single domain and multidomain states. Magnetic hysteresis data in terms of plots of parameter ratios show distinct relationships with chondrule size, density, mass and shape. The relationships correlate with the internal microstructures and elemental compositional variation. Morphology, internal structure and elemental composition characterize distinct mineralogical assemblages with spatial compositional variation related to chondrule size and shape and magnetic properties.

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REFERENCES

- Anders, E., Ebahara, M., 1982, Solar-system abundances of the elements: *Geochimica et Cosmochimica Acta*, 46, 2363-2380.
- Banerjee, S.K., Hargraves, R.B., 1972, Natural remanent magnetizations of carbonaceous chondrites and the magnetic field in the early solar system: *Earth and Planetary Science Letters*, 17, 110-119.
- Blander, M., Fuchs, L.H., 1975, Calcium-aluminum-rich inclusions in the Allende meteorite: evidence for a liquid origin: *Geochimica et Cosmochimica Acta*, 39, 1605-1619.
- Cameron, A.G.W., 1988, Origin of the solar system: *Annual Review of Astronomy and Astrophysics*, 26, 441-472.
- Chen, J.H., Wasserburg, G.J., 1981, The isotopic composition of uranium and lead in Allende inclusions and meteoritic phosphates: *Earth and Planetary Science Letters*, 52, 1-15.
- Chen, J.H., Tilton, G.R., 1976, Isotopic lead investigations on the Allende carbonaceous chondrite: *Geochimica et Cosmochimica Acta*, 40, 635-644.
- Clarke, R.S., Jarosewich, E., Mason, B., Nelen, J., Gomez, M., Hyde, J.R., 1970, The Allende, Mexico, meteorite shower: *Smithsonian Contributions to the Earth Sciences*, 5, 1-53.
- Connolly, H.C., Love, S.G., 1998, The formation of chondrules: Petrologic tests of the shock wave model: *Science*, 280, 62-67.
- Day, R., Fuller, M.D., Schmidt, V.A., 1977, Hysteresis properties of titanomagnetites: grain size and composition dependence: *Physics of the Earth and Planetary Interiors*, 13, 260-266.
- Dunlop, J., 2002, Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc). 1. Theoretical curves and tests using titanomagnetite data: *Journal of Geophysical Research*, 107, B3, 10.1029/2001JB000486. EPM 4.1-4.22.
- Fegley, B., Jr., Palme, H., 1985, Evidence for oxidizing conditions in the solar nebula from Mo and W depletions in refractory inclusions in carbonaceous chondrites: *Earth and Planetary Science Letters*, 72, 311-326.
- Flores-Gutiérrez, D., Urrutia-Fucugauchi, J., 2000, Magnetic hysteresis properties and chondrule sizes in the Allende meteorite: Implications for heating/cooling conditions in the protoplanetary nebula: *EOS Transactions*, 81(48), abstract P21A-23.
- Flores-Gutiérrez, D., Urrutia-Fucugauchi, J., 2002, Hysteresis properties of chondritic meteorites: New results for chondrules from the Allende meteorite: *Geofísica Internacional*, 41, 179-188.
- Gattacceca, J., Rochette, P., 2004, Toward a robust normalized magnetic paleointensity method applied to meteorites: *Earth and Planetary Science Letters*, 227, 377-393.
- Hewins, R.H., Jones, R.H., Scott, E.D.R. (eds), 1996, *Chondrules and the Protoplanetary Disk*: Cambridge, U.K., Cambridge University Press, 360 pp.
- Hong, Y., Fegley Jr., B., 1998, Experimental studies of magnetite formation in the solar nebula: *Meteoritics and Planetary Science*, 33, 1101-1112.
- Hood, J.L., Kring, D., 1996, Models for multiple heating mechanisms, *in* Hewins, R.H., Jones, R.H., Scott, E.D.R. (eds), *Chondrules and the Protoplanetary Disk*: Cambridge U.K., Cambridge University Press, 12-13.
- Kavner, A., Jeanloz, R., 1998, The high-pressure melting curve of Allende meteorite: *Geophysical Research Letters*, 25, 4161-4164.
- Kring, D., 1991, High temperature rims around chondrules in primitive chondrites: evidence for fluctuating conditions in the solar nebula: *Earth and Planetary Science Letters*, 105, 65-80.
- Krot A. N., Yurimoto, H., Hutcheon, I.D., MacPherson, G. J., 2005, Chronology of the early Solar System from chondrule-bearing calcium-aluminum-rich inclusions: *Nature*, 434, 998-1001.
- Lanoix, M., Strangway, D.W., Pearce, G.W., 1978, The primordial magnetic field preserved in chondrules of the Allende meteorite: *Geophysical Research Letters*, 5, 73-76.
- Lee, T., Papanastassiou, D.A., Wasserburg, G.J., 1976, Demonstration of Mg excess in Allende and evidence for Al: *Geophysical Research Letters*, 3, 109-112.
- McSween, 1977, Carbonaceous chondrites of the Ornans type: a metamorphic sequence: *Geochimica et Cosmochimica Acta*, 41, 477-481.
- McSween, H.Y., 1979, Are carbonaceous chondrites primitive or processed? A review: *Reviews of Geophysics and Space Physics*, 17, 1059-1078.
- McSween, H.Y., 1985, Constraints on chondrule origin from petrology of isotopically characterized chondrules in the Allende meteorite: *Meteoritics*, 20, 523-539.
- McSween, H.Y., 1987, Aqueous alteration in carbonaceous chondrites: Mass balance constraints on matrix mineralogy: *Geochimica et Cosmochimica Acta*, 51, 2469-2477.
- Prinz, M., Weisberg, M.K., Nehru, C.E., Delaney, J.S., 1986, Layered chondrules in carbonaceous chondrites: *Meteoritics*, 21, 485-486.

- Scott, E.R.D., 2007, Chondrites and the protoplanetary disk: Annual Review of Earth and Planetary Sciences, 35, 577-620.
- Sugiura, N., Lanoix, M., Strangway, D.W., 1979, Magnetic fields of the solar nebula as recorded in chondrules from the Allende meteorite: Physics of the Earth and Planetary Interiors, 20, 342-349.
- Urrutia-Fucugauchi, J., 1979, Further reliability tests for determination of palaeointensities of the Earth's magnetic field: Geophysical Journal of the Royal Astronomical Society, 61, 243-251
- Urrutia-Fucugauchi, J., 1981, Some observations on short-term magnetic viscosity behaviour at room temperature: Physics of the Earth and Planetary Interiors, 26, P1-P5.
- Urrutia-Fucugauchi, J., Radhakrishnamurthy, C., Negendak, J.F.W., 1984, Magnetic properties of a columnar basalt from central Mexico: Geophysical Research Letters, 11, 832-835.
- Wasilewski, P., 1981, New magnetic results from Allende C3(V): Physics of the Earth and Planetary Interiors, 26, 134-148.
- Wood, J.A., 1988, Chondritic meteorites and the solar nebula: Annual Review of Earth and Planetary Sciences, 16, 53-72.

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