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Review

Meteorite paleomagnetism - From magnetic domains to planetary fields and core dynamos

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Resumen

Los meteoritos condríticos representan los registros más tempranos de la evolución del Sistema Solar, proveyendo información sobre las condiciones, procesos y cronología de la formación de los primeros materiales sólidos, planetesimales y cuerpos diferenciados. La evidencia sobre los campos magnéticos en las etapas tempranas de evolución del sistema solar se ha obtenido a partir de estudios en meteoritos condríticos. Estos meteoritos se caracterizan por la abundancia de cóndrulos, que constituyen pequeñas esferas de silicatos de tamaño milimétrico, formadas a partir del polvo en la nebulosa y que fueron calentadas y enfriadas rápidamente. Los condrulos retienen un registro de magnetización remanente, que data del tiempo de calentamiento y enfriamiento durante la formación de cóndrulos y su acreción en planetesimales. Los estudios sobre las diferentes clases de meteoritos, incluyendo a los meteoritos condríticos ordinarios y los meteoritos condriticos carbonáceos han documentado resultados contrastantes con una rango amplio de magnitudes de los campos magnéticos en el disco protoplanetario. Ello ha dificultado definir la naturaleza de los campos magnéticos en las etapas iniciales de evolución. Los desarrollos recientes en instrumentación y técnicas de análisis de magnetismo de rocas y paleointensidades permiten una mayor precisión. Los análisis de micromagnetismo, geoquímica, petrografía y microscopía electrónica proveen de una alta resolución, previamente no disponible, para caracterizar las propiedades magnéticas e interacciones a escalas de dominio magnético. En este trabajo revisamos los estudios en cóndrulos del meteorito condrítico Allende, que revelan relaciones entre los parámetros magnéticos de histéresis y propiedades físicas. Los parámetros y cocientes de coercitividad, magnetización remanente y magnetización de saturación muestran correlaciones con la densidad y tamaño de los cóndrulos, los cuales están relacionados a la estructura interna, mineralogía, composición y morfología. Los cóndrulos compuestos, fragmentados y con anillos de recubrimiento se caracterizan por propiedades de histéresis magnética distintas, asociadas a la composición y arreglos mineralógicos y microestructuras. Los registros de magnetización remanente y las estimaciones de paleointensidades derivadas en estudios del Allende y otras condrítas carbonáceas apoyan adquisición de la magnetización bajo la influencia de campos magnéticos internos dentro de planetesimales. Los resultados apoyan una rápida diferenciación, siguiendo la formación de las inclusiones de calcio y aluminio y condrulos para formar los planetesimales. Los planetesimales se caracterizarían por una estructura diferenciada con núcleos metálicos con capacidad de dinamo autosustentable por periodos de varios millones de años. El meteorito condrítico Allende se formó y derivó de un planetesimal parcialmente diferenciado, con un núcleo de hierro capaz de sostener un campo magnético interno.

Palabras clave: Paleomagnetismo, meteoritos, campos magnéticos, dínamos, Sistema Solar.

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Abstract

Meteorites represent the earliest records of the evolution of the solar system, providing information on the conditions, processes and chronology for formation of first solids, planetesimals and differentiated bodies. Evidence on the nature of magnetic fields in the early solar system has been derived from chondritic meteorites. Chondrules, which are millimeter sized silicate spherules formed by rapid melting and cooling, have been shown to retain remanent magnetization records dating from the time of chondrule formation and accretion of planetesimals. Studies on different meteorite classes, including ordinary and carbonaceous chondrites, have however provided contrasting results with wide ranges for protoplanetary disk magnetic fields. Developments on instrumentation and techniques for rock magnetic and paleointensity analyses are allowing increased precision. Micromagnetic and an array of geochemical, petrographic and electronic microscopy analyses provide unprecedented resolution, characterizing rock magnetic properties at magnetic domain scales. We review studies on chondrules from the Allende meteorite that reveal relationships among hysteresis parameters and physical properties. Coercivity, remanent and saturation remanence parameters correlate with chondrule size and density; in turn related to internal chondrule structure, mineralogy and morphology. Compound, fragmented and rimmed chondrules show distinct hysteresis properties, related to mineral composition and microstructures. The remanent magnetization record and paleointensity estimates derived from the Allende and other chondrites support remanent acquisition under influence of internal magnetic fields within parent planetesimals. Results support that rapid differentiation following formation of calcium-aluminum inclusions and chondrules gave rise to differentiated planetesimals with iron cores, capable of generating and sustaining dynamo action for million year periods. The Allende chondrite may have derived from a partly differentiated planetesimal which sustained an internal magnetic field.

Key words: Paleomagnetism, meteorites, magnetic fields, dynamos, Solar System.

Introduction

Studies of meteorites provide the earliest records concerning the conditions and evolution of the planetary system (Wood, 1988; Cameron, 1988; Lauretta and McSween, 2006). Meteorites constitute the oldest rocks preserved from the initial stages of planetary accretion. Information on the age of the solar system, conditions and chronology for formation of first solids, planetesimals and early differentiated bodies is based on studies of chondrites and other primitive meteorites (Wood, 1988; Hewins *et al*., 1996; Scott, 2007; Connelly *et al*., 2012). Chondrites are composed by millimeter sized silicate spherules named chondrules and calcium-aluminum rich inclusions (CAIs) embedded in a fine grained silicate matrix. In recent years research on the origin and evolution of the solar system has expanded, with developments from planetary missions, astronomical observations, discovery of exoplanets and theoretical and numerical simulation models. The multi-and interdisciplinary approaches and new data are providing fresh insights on the origin of planetary systems. Major questions on fundamental aspects still remain open, including conditions and chronology in the early phases.

Many studies on meteorites focused on the petrography and geochemistry, which permitted to distinguish and characterize distinct classes of meteorites. Meteorites are divided into primitive and differentiated classes, which include ordinary and carbonaceous chondrites and achondrites and iron meteorites, respectively (Weisberg *et al*., 2006). Chondrules represent molted droplets of aggregated fine silicate dust, recording transient heating events in the solar nebula (Hewins, 1997; Zanda, 2004; Scott, 2007). They show different textures and mineral assemblages, with some containing fragments of other chondrules and rare CAIs. Preservation of chondrules indicates that chondrites were not melted through their subsequent history after formation. In contrast, differentiated meteorites, which include iron and iron-silicate meteorites, were subject to various degrees of melting and metamorphism, and interpreted as derived from planetesimals later fragmented by collisions.

Understanding the early stages of planetary system evolution has remained a complex difficult task. Considerable effort is spent in characterizing the distinct classes of meteorites, which are investigated with a wide range of analytical techniques. Studies have documented new minerals and unraveled evidence on the formation and alteration histories of meteorites and parent planetesimals with increasing detail (Taylor *et al*., 1987; Nyquist *et al*., 2009; Weiss and Elkins-Tanton, 2013). The conditions and nature of processes involved in the formation of the proto-Sun, chondrules, CAIs, and early accreted planetesimals remain poorly constrained.

We review micromagnetic and microstructural studies on chondrites with particular emphasis on the Allende chondrite (Figure 1), focusing on the early magnetic fields in the solar system and how they relate to the evolution of meteorite parent planetesimals. Developments of analytical techniques and better understanding of rock magnetic properties and magnetization mechanisms are allowing improved resolution in characterizing the magnetic records of meteorites.

The nature and role of magnetic fields in the protoplanetary nebula, with formation of the proto-stars and accretionary disk had long been examined (Kulsrud, 1999; Ossendrijver, 2003; Vallée, 2011). Interest in magnetic fields and their role in the evolution of protoplanetary nebulas have been sparked by recent studies with detection of magnetic fields in accretion disks (Donati *et al*., 2005). Studies on meteorite records of the solar protoplanetary nebula have focused on characterizing magnetic properties and mineralogy and in paleointensity determinations. The magnetic field magnitude is estimated from remanent magnetization records in chondrites and individual chondrules (e.g., Butler, 1972; Nagata, 1979). Early estimates gave a wide range of field magnitudes with relatively large uncertainties, which prompted search of alternative paleointensity determination methods. In the past years, the field of meteoritics has significantly evolved and expanded. In this review we address recent developments in using micromagnetic analyses and studies on early differentiated bodies with potential for sustained internal magnetic field generation. Results from individual chondrules provide more consistent data with improved analytical resolution (Acton *et al*., 2007; Flores-Gutierrez *et al*., 2010a,b; Emmerton *et al*., 2011). Formation of differentiated bodies with iron cores and capacity for generating internal magnetic fields have added to the interest in documenting the characteristics and presence of magnetic fields in the protoplanetary nebula (Carporzen *et al*., 2010; Fu *et al*., 2012; Tarduno *et al*., 2012; Sterenborg and Crowley, 2013).

Chondritic meteorites

Chondrites are part of the primitive meteorites, characterized by the abundance of chondrules. Several classes have been distinguished in petrographic and geochemical studies. Chondrites are classified into ordinary (H, L and LL), carbonaceous (CB, CH, CI, CK, CM,

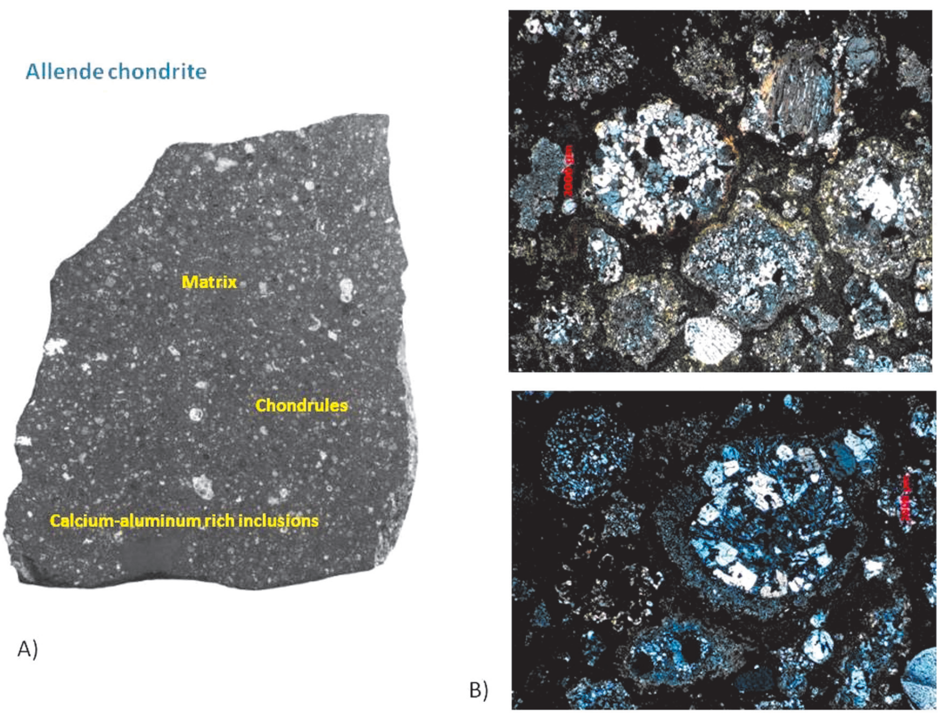


Figure 1. (A) Image of a slab fragment of the Allende CV3 chondritic meteorite showing the chondrules, refractory calcium-aluminum rich inclusions and fine grained silicate matrix. (B) Thin-section microphotographs of Allende chondrules, showing the diversity of textures, morphologies and mineral compositions.

CO, CR and CV), enstatites (EH and EL) and R and K chondrites. Ordinary chondrites represent the most abundant, making up to 80-85 % of falls. The three major groups H, L and LL are characterized by the distinct petrologic types 3 to 6, interpreted as derived from three separate parent planetesimals (Weisberg *et al*., 2006). Carbonaceous chondrites are relatively rare, representing a small percentage of falls. In general, the different groups have been interpreted as derived from distinct parent planetesimals (Weisberg *et al*., 2006). Genetic relationships are being investigated for different chondrite, iron and other meteorites, relating differentiated and undifferentiated types (Greenwood *et al*., 2010).

Other meteorites include the achondrites and the primitive achondrites (Weisberg *et al*., 2006; Rochette *et al*., 2009; Macke *et al*., 2011). The achondrites represent the group of differentiated meteorites, characterized by variable degrees of melting and metamorphism, divided into angrites, aubrites, howardites-diogenites-eucrites (HED meteorites), mesosiderites, pallasites and iron meteorites. These groups include several subgroups (e.g., iron meteorites and pallasites), with several ungrouped meteorites with distinct mineralogical and chemical assemblages. Primitive achondrites include acapulcoites, lodrinites, ureilites and winonaites. Silicate inclusions in IAB and IIICD iron meteorites are part of this group, probably derived from partial melting of chondrites in a parent planetesimal. H chondrites and iron IIE meteorites are probably coming from a partly differentiated parent planetesimal. Differentiated meteorites include those derived from known planetary sources such as the lunar and martian meteorites.

Meteorite classification schemes have evolved over time, reflecting development of new analytical techniques. Classification schemes are based on petrologic, mineralogic, geochemical and isotopic analyses. Van Shamus and Wood (1967) proposed a widely used classification system for chondrites based on compositional groups and six petrologic types. Petrologic types 1 and 2 correspond to unmetamorphosed chondrites affected by varying degrees of aqueous alteration and types 3–6 represent to distinct levels of thermal metamorphism (McSween, 1987, 1979). For several groups of carbonaceous chondrites, there have no petrologic type 4 (e.g., CI, CH, CM, CO, CR and CV). The classification has been modified over the years (Weisberg *et al*., 2006), including inclusion of type 7 chondrites (Hus *et al*., 2006). Differences in magnetic properties have been used to characterize and distinguish the different meteorite classes, where the wide ranges in magnetic susceptibility and other physical properties are used to characterize ordinary chondrites, enstatites and achondrites (Rochette *et al*., 2003, 2009; Macke *et al*., 2010, 2011).

Another aspect to consider in characterizing meteorites is the effects of hydrothermal and aqueous metamorphic alterations (Rubin, 2000). Studies have shown that most chondrites were affected by various degrees of metal/silicate and refractory/volatile fractionation. The fractionation has been associated with chondrule formation processes; although some studies have suggested fractionation mechanisms triggered by nebular condensation. Chondrule formation modified the composition of the nebula. CI chondrites, characterized by olivine and pyroxene minerals and rare to absent chondrules, preserve the chemical and isotopic composition of the solar nebula. CI chondrites, including the CV Allende carbonaceous chondrite, were affected by aqueous metamorphism, highlighting further study of alteration and metamorphic processes.

Chondrules are relatively abundant in the different chondrite classes, constituting volumetrically from 15 vol % up to 80 vol % (Zanda, 2004; Scott, 2007). The abundance of chondrules supports that chondrule formation was a major widespread process in the solar nebula. The rapid melting and cooling of the silicate droplets operated over an extended period, overlapping with CAI formation (Itoh and Yurimoto, 2003; Bizarro *et al*., 2004). Chondrule sizes are dominantly sub-millimeter and show characteristic ranges in the different chondrite classes. Chondrules show distinct internal structures, textures and mineralogical assemblages (e.g., Figure 1B). Rimmed, fragmented and composite chondrules indicate a dynamic complex formation history, involving several heating events and extended formation period in the nebula. Several contrasting mechanisms have been proposed to account for the transient heating and chondrule formation and for their later incorporation within fine-grained silicate matrix, and eventually into planetesimals (Hewins *et al*., 1996; Rubin, 2000; Connelly *et al*., 2012).

Magnetic studies of meteorites

Study of rock magnetic properties and remanent magnetization records are the field of paleomagnetism and rock magnetism (Dunlop and Ozdemir, 1997). Early recognition that magnetic minerals with domain states corresponding to single (SD) and pseudo-single

(PSD) domains are able to preserve records on time scales of the order of the solar system age provided a tool for studies of ancient fields (Weiss *et al*., 2010). Studies on chondritic meteorites suggested that magnetizations could have been acquired at their time of formation, opening the possibility of investigating the presence and nature of magnetic fields in the solar nebula. Measurements of magnetic properties on meteorites documented the presence of remanent magnetizations, with different coercivity and unblocking temperature characteristics (Butler, 1972; Lanoix *et al*., 1978; Nagata, 1979; Sugiura *et al*., 1979; Fuller and Cisowski, 1987).

Different paleointensity methods for estimating the magnitude of the magnetizing field have been applied. Occurrence of alterations induced by heating in the laboratory has limited application of thermal methods, in particular the double-heating Thellier method, in which the natural remanent magnetization (NRM) is assumed to be dominantly a thermoremanent magnetization (TRM). The Thellier double-heating method is widely applied in terrestrial igneous rocks, where it provides accurate estimates of the ancient paleofield magnitudes. Microcoercivity, thermomagnetic and microscopy techniques have been developed to investigate on the magnetic properties, mineralogy, domain state and magnetic interactions are available for igneous rocks (Davis and Evans, 1976; Day *et al*., 1977; Urrutia-Fucugauchi *et al*., 1984; Dunlop and Ozdemir, 1997), which are expanded by an array of high-resolution imaging techniques (Uehara and Nakamura, 2006; Uehara *et al*., 2011; Feinberg *et al*., 2006; Harrison *et al*., 2002). Analytical tests to detect heating-induced alterations and effects of anisotropy, cooling time and magnetic interactions have been developed (e.g., Dunlop and Yu, 2010; Lawrence *et al*., 2008; Yu, 2006; Urrutia-Fucugauchi, 1979; Coe, 1967). The alteration problems in meteorites have limited use of Thellier method (Butler, 1972; Nagata, 1979) and alternative non-heating methods using laboratory imparted remanences, like the isothermal remanent magnetization (IRM), have been developed using NRM/IRM ratio determinations (Gattacceca and Rochette, 2004; Yu, 2006; Muxworthy *et al*., 2011).

Paleointensity estimates reported in the early studies showed relatively high scatter. Studies focused on chondritic meteorites, where presence of CAIs and chondrules supports that they have not been affected by melting since they were first accreted, but have also been carried out on other meteorite classes. Banerjee and Hargraves (1972) reported estimates of 110 mT from Thellier experiments. Lenoix *et al*. (1978) reported values from 100 to 700 mT, and Wasilewski (1981) reported estimates of 1.2 to 15 mT. Complexities of paleomagnetic records and technique limitations hampered the studies resolution. Recent studies on individual chondrules using the non-heating REM, REMc and Preisach methods have provided new paleointensity estimates. Acton *et al*. (2006) summarized paleointensity estimates using the REM methods on bulk samples and chondrules from different meteorites with ranged between 3 and 147 mT (Figure 2A). Results using the REMc method yielded consistently lower values, between <1 and 11 mT. Emmerton *et al*. (2011) reported paleointensity determinations ranging between 13 and 60 mT and 3 to 56 mT, for Allende and Mokoia chondrules, respectively. The ranges are wide, and authors suggest that Mokoia is possible affected by remagnetization, while Allende might carry a primary remanence, partly affected by post accretionary remagnetization.

Magnetic property studies focused on characterizing the magnetic mineralogy with the iron-nickel minerals and iron-titanium oxides (Lanoix *et al*., 1978; Nagata, 1979). Studies on C1 and C2 carbonaceous chondrites documented grouped remanent magnetization directions, with AF coercivity spectra suggesting thermal or thermochemical remanences consistent with acquisition during accretion (Banerjee and Hargraves, 1972). CV3 chondrites, like the Allende meteorite, which were affected by secondary aqueous alteration also yielded stable magnetizations, interpreted as primary accretion or post-accretion magnetizations (Butler, 1972). Optical and scanning electron microprobe analyses indicated that taenite and possibly awaruite were the major iron minerals. Thermomagnetic analyses by Butler (1972) indicated 95 wt% taenite with 67% Ni and 5 wt% taenite with 36% Ni. The results were consistent with data for a range of chondrites (E, H, L, LL and C chondrites) and achondrites, with dominant iron-nickel minerals (Nagata, 1979).

The origin and acquisition age of remanent magnetization have been investigated using different experimental approaches, including stepwise demagnetization and application of conglomerate tests on chondrites (Sugiura *et al.*, 1979). The initial studies were made on whole-rock samples, as needed for measuring in spinner magnetometers, with cylindrical specimens cut from meteorite fragments, comprising mixtures of chondrules, CAIs and matrix. Results indicate that the remanence is probably ancient, and not significantly modified by terrestrial processes. Studies identified and isolated remanent magnetizations acquired during meteorite entry

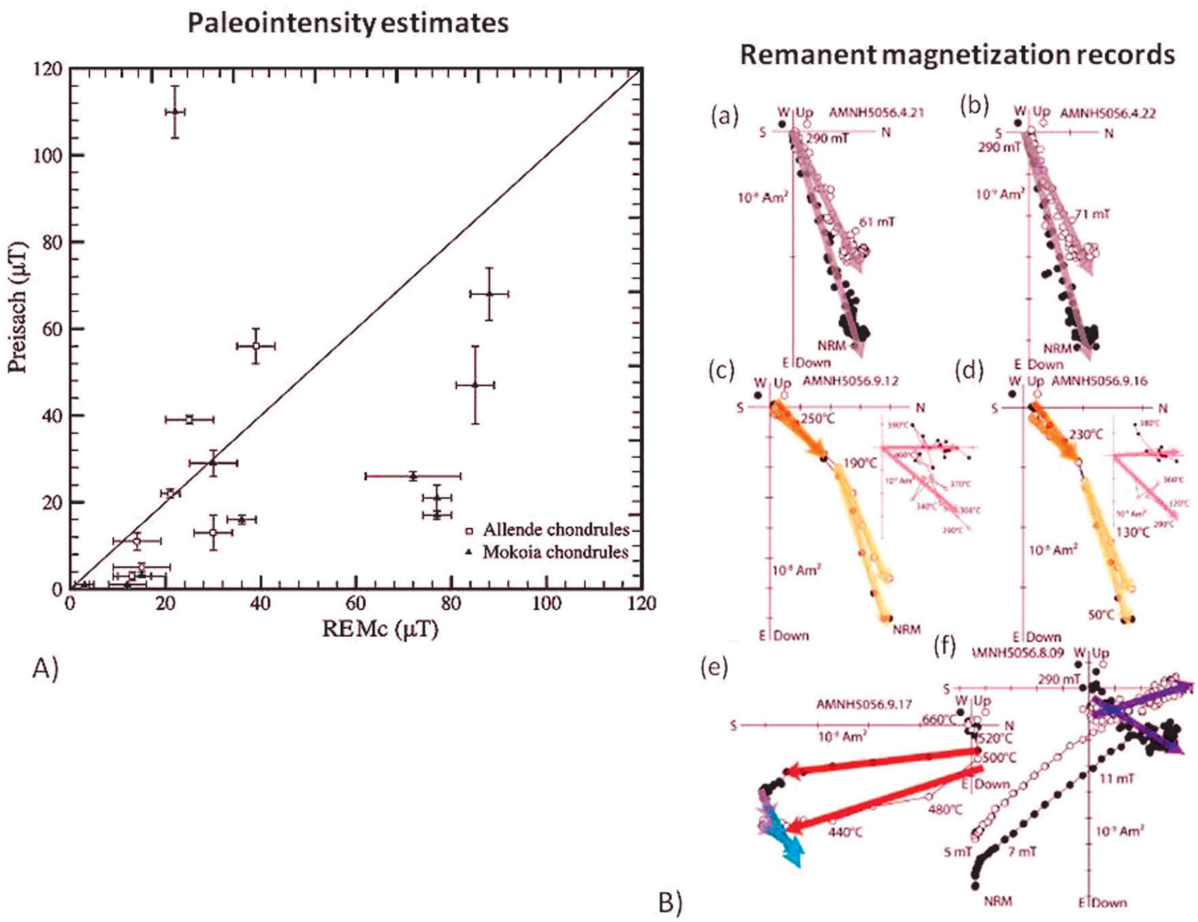


Figure 2. (A) Summary of paleointensity estimates on chondrules from the Allende and Mokoia meteorites. The graph shows the comparison of estimates obtained using the Preisach and REMc methods (after Emmerton et al., 2011). Mean and associated error bars are indicated; for Preisach method it is the weighted mean for individual demagnetization steps and for REMc method it is the arithmetic mean for selected AF demagnetization steps. (B) Vector plots for AF and thermal demagnetization of Allende samples, showing the characteristic univectorial and multi-component magnetizations, marked by the vector demagnetization trajectories in different colors. Plots (c) and (d) after thermal demagnetization reveal the dominant lower unblocking temperature component and the intermediate middle unblocking temperature component unblocked between 190° C and 290° C. In the insets, plots depict the high temperature components (taken from Carporzen *et al*., 2011).

into earth´s atmosphere, characterizing the fusion thin crusts. Stepwise demagnetization shows remanence is characterized by low, intermediate and high coercivity and unblocking temperature components (Figure 2B; Carporzen *et al*., 2011).

The contrasting paleomagnetic records, analytical problems and complex magnetic mineralogy have stimulated studying the magnetic properties of meteorites at increasingly finer resolution using micromagnetic techniques (Flores-Gutierrez and Urrutia-Fucugauchi, 2002; Acton *et al*., 2007; Emmerton *et al*., 2011). Studies focused on chondritic meteorites, where presence of CAIs and chondrules supports that they have not been affected by melting since they were first accreted, but have also been carried out on other meteorite classes.

Magnetic hysteresis measurements have been carried out in bulk samples and in individual chondrules. Data show occurrence of ferrimagnetic minerals with high saturation values and intermediate and low coercivities, indicating magnetite and low-Ti titanomagnetites. Hysteresis parameter ratio plots show chondrules are characterized by dominantly PSD and multidomain (MD) states (e.g., Weiss *et al*., 2010; Acton *et al*., 2007; Emmerton *et al*., 2011; Flores-Gutierrez and Urrutia-Fucugauchi, 2002). Emmerton *et al*. (2011)

presented magnetic data for 28 and 17 chondrules from the Mokoia and Allende chondrites, respectively. The dominant magnetic phase in the chondrites was interpreted as an FeNi phase (taenite, kamacite or awarite), contributing about 48 % in Mokoia and about 42 % in Allende. The Mokoia chondrules showed higher magnetic mineral concentrations, wide range of magnetic properties and dominant SD domain states. Allende chondrules showed low coercivity distributions and limited magnetic interactions. Alternating field (AF) and thermal demagnetization of chondrules and bulk samples reveal univectorial to multicomponent magnetizations. Some chondrules carry complex magnetizations, which are not resolved using AF or thermal demagnetization. Acton *et al*. (2006) report magnetic hysteresis ratio plots for chondrules and matrix for the Allende, Karoonda and Bjurbole chondrites showing wide variation ranges, with Mr/Ms ratios between 0.03 and 0.39 and Hcr/Hc ratios between 0.1 and 9. Mokoia chondrules plot in the PSD field showing a restricted trend, while Allende chondrules show more variability plotting in the PSD and MD fields, similar to other CV3 and C chondrites. Mokoia chondrules show variation trends suggesting mixtures of SD and MD particles, contrasting with the scattered pattern shown in the Allende chondrules and matrix (Figure 3).

Coercivity distribution in chondritic meteorites suggest they may be affected by overprinting, during metamorphism or collisions, alteration in planetesimal bodies, and also exposed to ambient conditions on Earth after atmospheric entry including high magnetic fields, lighting strikes, etc (Weiss *et al*., 2010). This has suggested that reliable paleointensity estimates are more likely to be obtained from the high coercivity spectra in chondrules. Sugiura *et al*. (1979) and Sugiura and Strangway (1983) reported data supporting that chondrules retain a remanent magnetization acquired prior to their incorporation into the chondritic meteorite using a form of conglomerate test (Weiss *et al*., 2010). The relationships uncovered for the magnetization ratio and coercivity in the Allende chondrite may permit to better understand the coercivity distribution (Flores-Gutierrez and Urrutia-Fucugauchi, 2002). The connections to internal chondrule structure and morphologies, with compound chondrules, alteration rims, fracturing can be used for sample selection for paleointensity experiments.

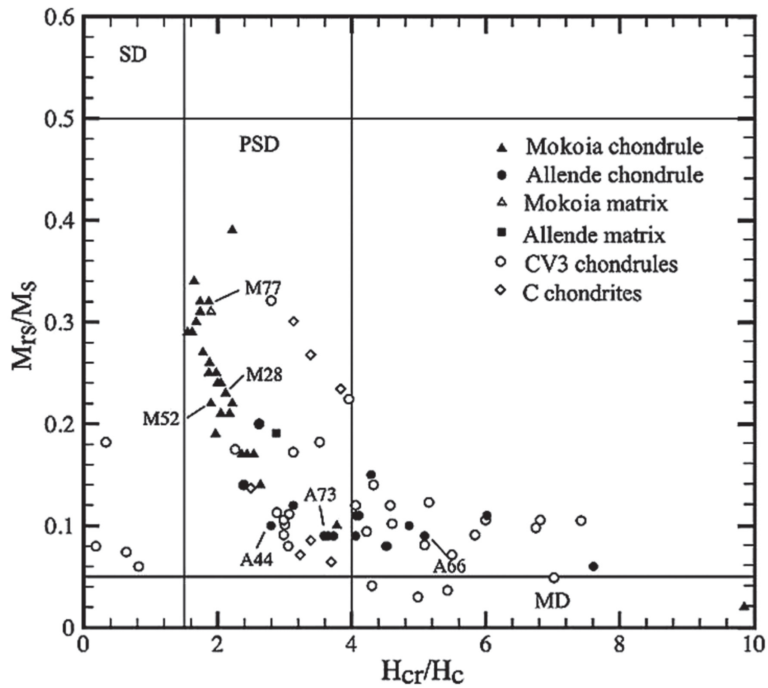


Fig. 3. Example of magnetic hysteresis data for chondrules and matrix samples from Allende and Mokoia meteorites, plotted in a hysteresis parameter ratio plot (from Emmerton *et al*., 2011). Domain state fields are indicated (Day *et al*., 1977); observe data points plot in pseudo-single domain (PSD) and multidomain (MD) fields. Mokoia chondrules show a mixture trend of single domain (SD) and MD behavior; in contrast to the scattered pattern for Allende chondrules (see text for discussion).

Allende Chondrite

The Allende meteorite is an oxidized CV3 carbonaceous chondrite (Figure 1). These chondrites are relatively rare as compared to other types such as the ordinary chondrites. Its fall in the area of Allende town, Chihuahua, northern Mexico on February 1969 was well documented, with a relatively large amount of fragments up to 2 tons recovered (Clarke *et al*., 1970). At the time, samples were distributed to numerous laboratories, making Allende one of the most intensively investigated meteorites. Several major findings have been first reported in Allende samples, including evidence for short lived Mg-Al isotope system supporting a supernova explosion at the early stage of nebula condensation (Lee *et al*., 1976).

Allende is characterized by high magnesium and iron contents, with 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%). Other minerals present are kamacite, taenite, troilite, mackinawite, antigorite, majorite and pentlandite, with magnetite, chromite, Ni-Fe alloys, sulfides and sulfates and anorthite as accessory minerals. Chondrules show different textures and mineral compositions (e.g., Figure 1B), characterized by anhedral, euhedral and recrystallized olivine chondrules, barred olivine chondrules, pyroxene olivine chondrules and pyroxene chondrules. Major magnetic minerals are magnetite, taenite and iron sulfides.

Two different chondrules types are observed: FeO-poor reduced type I chondrules with iron metal blebs and olivines and FeO-rich oxidized type II chondrules with no metal blebs and olivines (McSween, 1979, 1987). The Allende chondrite is characterized by FeO-poor chondrules and low-volatile rich. Divisions of CV chondrite sub-groups depend on relative contents of metal and magnetite, which is reflected on the modal ratios of metal to magnetite.

Magnetite formation in oxidized and reduced chondrites have been intensively studied, with different mechanisms proposed, including crystallization from oxidized melts, oxidation of metallic nodules in the solar nebula, and secondary oxidation of metallic chondrule nodules in planetesimals (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. Flores-Gutierrez *et al*. (2010a) study shows that Fe is associated with Si and Mg (fosterite to fayalite), with higher concentrations in chondrule rims. Fe forms FeNi alloys and trolite. Si 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 the rims. In one of the chondrules analyzed, Si shows higher relative contents in the interstitial zones. Nickel distribution in Ni-rich minerals and alloys seems an important indicator of alteration, with metamorphism allowing Ni to migrate, recording metamorphic temperatures in pentlandite-bearing chondrites. The mineralogy suggests secondary events following chondrule formation in the solar nebula. Kring (1991) considered the high-temperature chondrule rims as indicators of fluctuating conditions, with accretion of dust rims occurring under turbulence in particle rich regions up to several hundred of kilometers in scale (Cuzzi and Alexander, 2006).

Analysis of hysteresis ratio plots and compilation of hysteresis data show a relatively higher scatter for the Allende and other chondrites, in contrast to data for chondrites characterized by less variability and trends of SD and MD domain particles (Figure 3). Flores-Gutierrez and Urrutia-Fucugauchi (2002) and Flores-Gutierrez *et al*. (2010a) investigated the domain state pattern for Allende chondrules and found that Allende is characterized by a variation range in hysteresis parameter ratio plots related to chondrule size (Figure 4).

Hysteresis magnetization ratios (Mr/Ms) vary from 0 to 0.22, showing a linear relation as a function of coercivity (Hc), which varies from 3 to 24 mT. The variation trend 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 of compound, fragmented or altered chondrules. The relationships between chondrule size and hysteresis parameters were not expected from previous studies, suggesting possible deeper associations with chondrule composition. Flores-Gutierrez *et al*. (2010a) analyzed the internal chondrule structures and compositions using scanning electron microscope on individual chondrules. Separation of chondrules and CAIs from the fine-grained silicate matrix is time consuming, and studies use generally a few chondrule samples. Results from 100 individual chondrules permit to evaluate the relations of chondrule size, density and hysteresis parameters and parameter ratios (Figure 4). Chondrule densities vary from about 2 to 3.5 kg/m^3, showing a rough trend to decrease with increasing chondrule size.

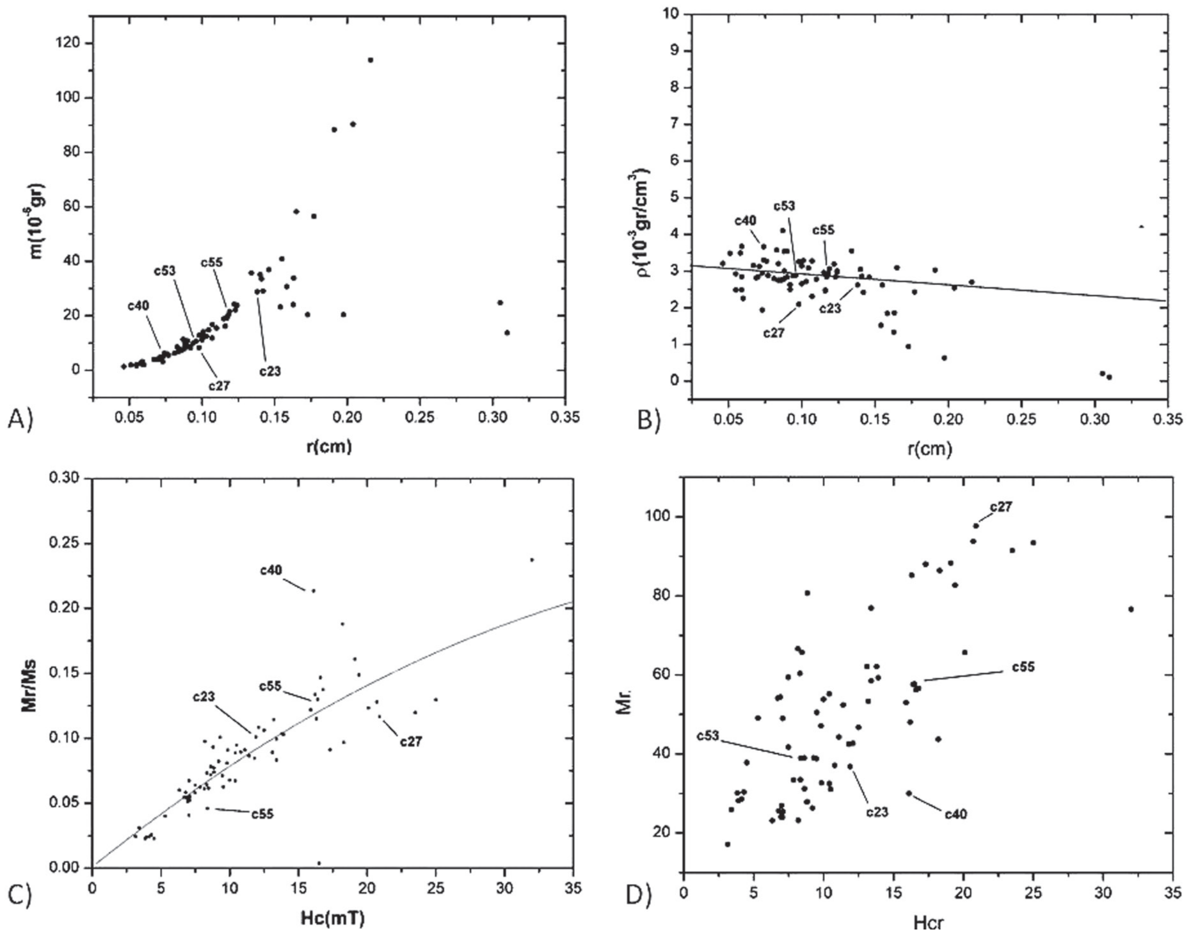


Figure 4. (A) Plot of mass as a function of chondrule radii (B) density as a function of chondrule radii (C) magnetization ratio as a function of coercivity (D) Remanent magnetization as a function of remanence coercivity (after Flores-Gutierrez *et al*., 2010a,b). Selected chondrules marked are also shown in the microprobe analyses in Figure 5 B (see text for discussion).

Plot as a function of chondrule radii show a wide scatter, with a decreasing trend. Some chondrules show lower densities, particularly the larger ones with radius larger than 0.07 mm and up to 0.16 mm. Magnetic hysteresis parameters were associated with chondrule structure, mineralogical composition and morphology. Analyses of chondrules within the scatter plot relations and outsiders documented that chondrules showed characteristic behaviors related to their internal structure and properties.

Magnetic hysteresis parameter ratios show simple linear relationships between the magnetization ratio and coercivity (Figure 4). 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 remagnetization, which has implications for retrieval of paleointensity estimates for the early planetary magnetic fields. Reliable paleointensity estimates might be better obtained from high coercivity spectra.

Analysis of chondrules within the linear relation field and outliers show that magnetic properties correlate with chondrule internal structure and mineral composition (Figure 5). Chondrules falling outside the relation are compound, with partial aggregation rims and/or fractured (chondrules c40, c27 and c23), in contrast to those chondrules with low coercivity Hc and magnetization Mr/Ms ratios, which appear homogeneous (chondrules c53 and c55). Silica maps characterize chondrule structures, which can be correlated with chondrule size, external morphology and shapes.

Results show that closely-spaced chondrules in given fragments of Allende are characterized by highly variable Fe, Ni and S composition.

Differences in magnetic properties relate to characteristic sizes, textures and mineralogy. Spatial distributions suggest chondrules record distinct shock and alteration processes during formation stages. Scanning electron microscope (SEM) analyses constrain the composite nature, with fragmented chondrules, different accretionary rims, mineralogic and elemental compositions and coalesced compound chondrules.

The relationship uncovered for the magnetization ratio and coercivity (Figure 5A) permit to better constrain the coercivity distribution and relations to internal structure, with compound chondrules, alteration rims, fracturing appear useful criteria for sample selection in paleointensity experiments. The combined hysteresis data and microscope observations permit to characterize populations of chondrules, with distinct magnetic mineralogy, morphology and internal structure.

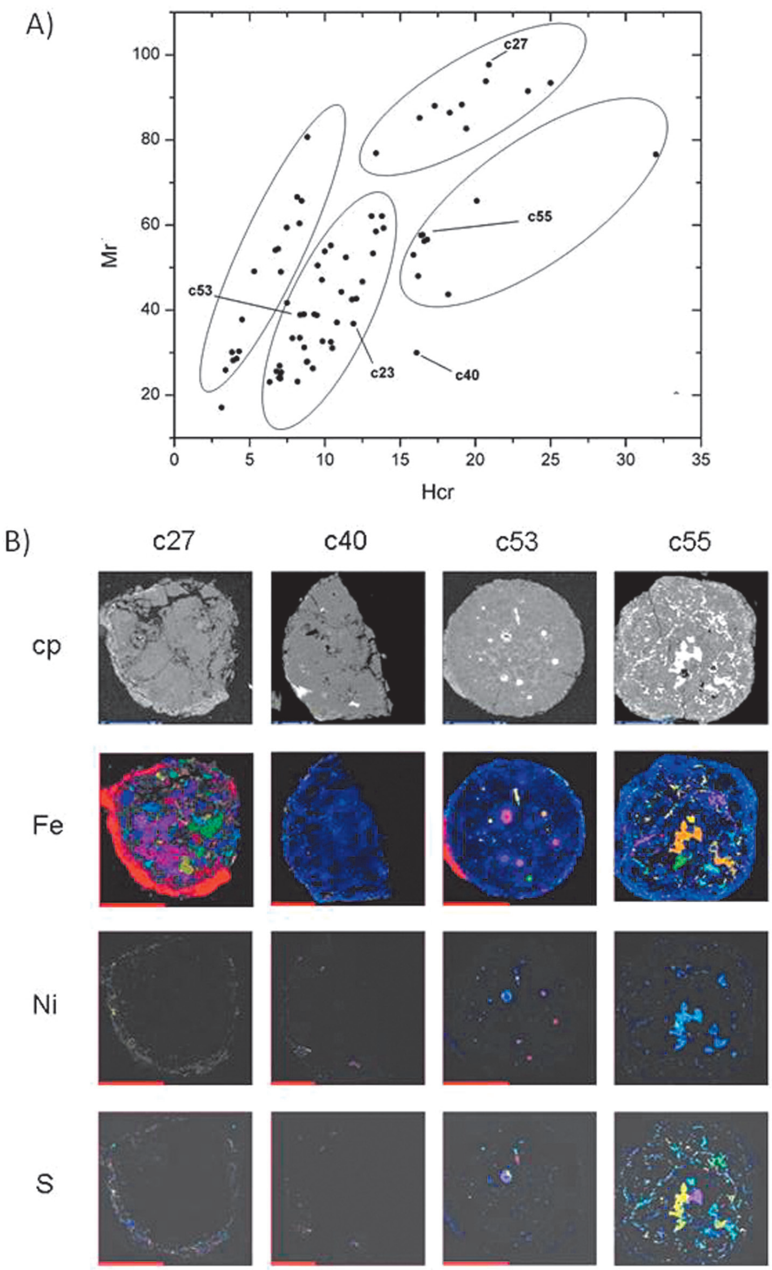


Figure 5. (A) Remanent magnetization-coercivity diagram, showing interpreted chondrule distributions. Compare with diagram in Figure 4 D. (B) scanning electron microscope and elemental analyses (Flores-Gutiérrez *et al*., 2010b).

Observations provide further evidence on multiple heating events and long time scales involved in chondrule formation (Scott, 2007). The wide range of internal structures and mineralogical compositions in a single fragment of the Allende indicate that Allende chondrite formed from a heterogeneous assemblage of chondrules, which underwent complex pre-accretionary histories (Figure 6). This is further examined below in relation to the chronological constrains on the early stages of evolution of the protoplanetary disk.

Chronology of solar system early evolution

The age of ~4,568 millions of years derived from radiometric studies of meteorites is obtained from dating CAIs and chondrules from chondrites and other primitive meteorites (Connelly *et al.*, 2012). Chondrules and refractory inclusions in carbonaceous chondrites give the oldest radiometric dates, providing a chronology of events in the accreting protoplanetary disk. Radiometric dating on primitive angrites, eucrites, and chondrules, refractory inclusions and olivine aggregates from chondrites provides a chronology for solar system early stages (Amelin *et al*., 2002; Bouvier and Wadhwa, 2010; Connelly *et al*., 2012).

Chondrules and CAIs formed from dust agglomerates by short-lived heating events that affected the gas nebula. Transient temperatures may have reached up to 1400° to 1800° C with rapid heating/cooling. Mechanisms proposed for melting of fine-grained solid matter include a wide range of processes. Chondrules appear to have been formed at a later time than refractory inclusions, as suggested from isotopic analyses and petrographic and microstructural observations (Figure 7). Isotopic analyses of the Al and Mg systematics completed in Allende chondrite provided constraints for the event chronology of CAIs and chondrules and solar nebula conditions (Lee *et al*., 1976; Scott, 2007). Analyses of ^{26}Al isotopic differences in CAIs and chondrules have been discussed in terms of orderly or overlapping sequence of events (Itoh and Yurimoto, 2003; Bizarro *et al*., 2004; Krot *et al*., 2005). Refractory inclusions appear having started to form 1 to 4 million years earlier (Scott, 2007). 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,

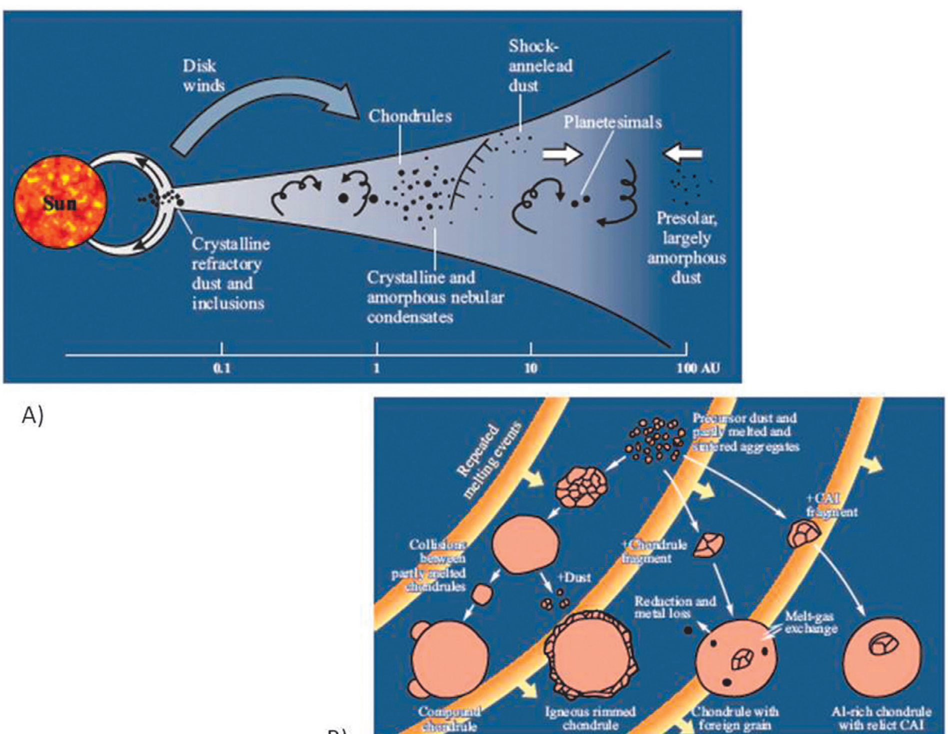


Figure 6. (A) Model for the accretion disk, showing the chondrule and refractory calcium-aluminum inclusions formation sectors. (B) protoplanetary disk zone of crystalline and amorphous condensates, showing the distinct chondrule morphologies (modified after Scott, 2007).

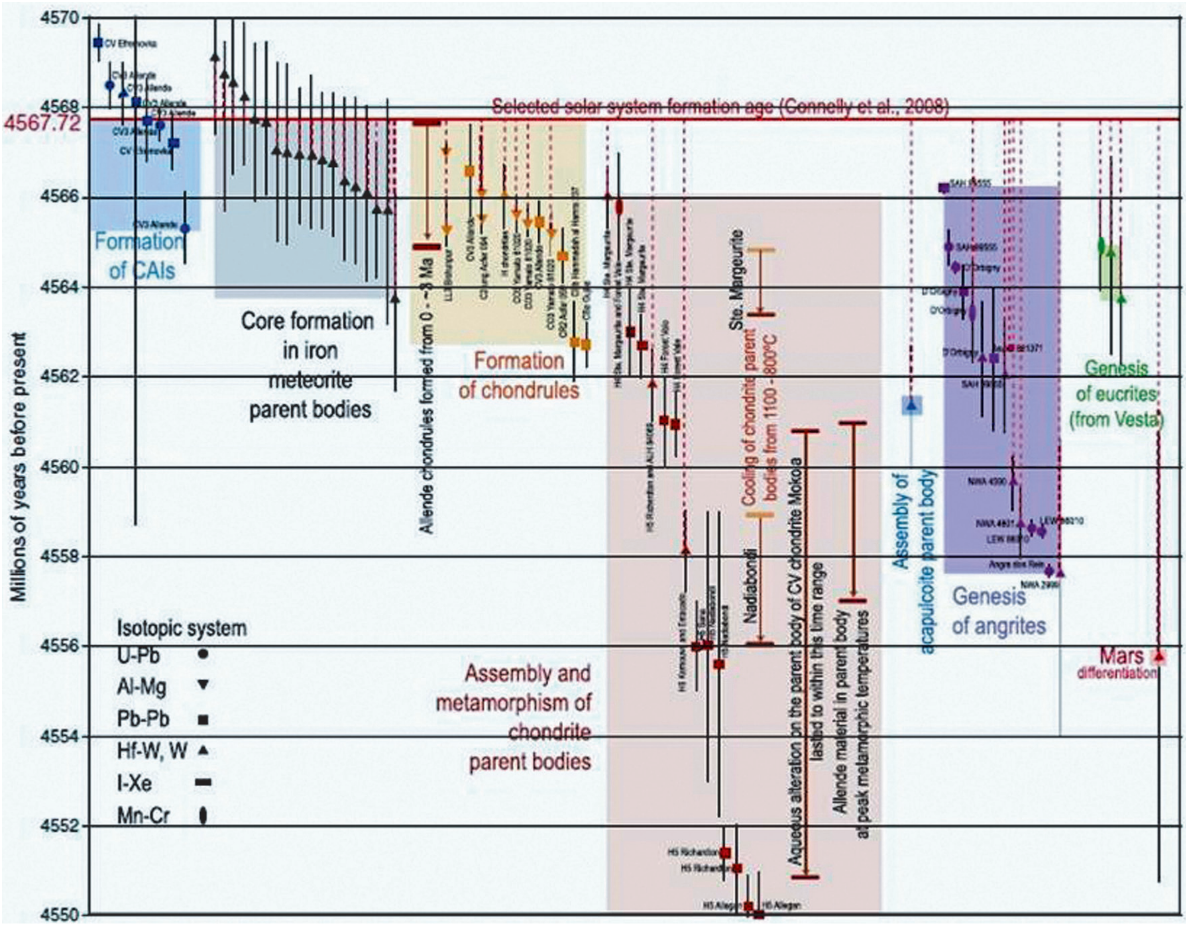
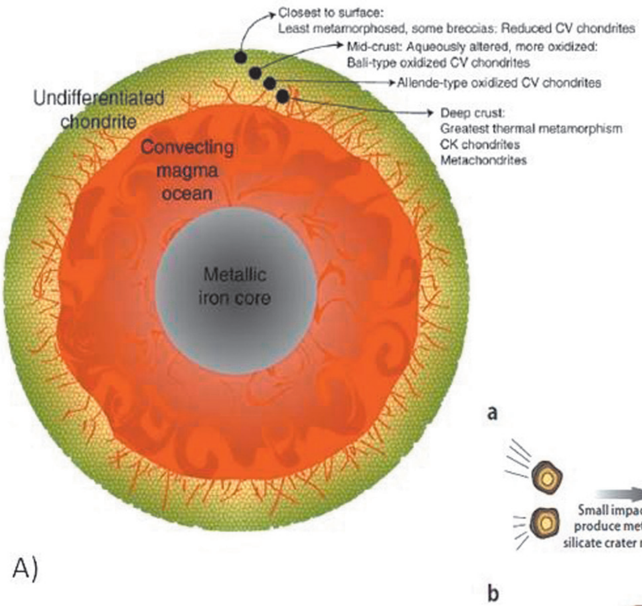


Figure 7. Age plot for the first millions of years, for formation of refractory inclusions, chondrules and iron, chondrite, angrite and eucrite parent planetesimals (after Elkins-Tanton *et al*., 2011).

which support contemporaneous formation of CAIs and chondrules, and an extended period of chondrule formation (Itoh and Yurimoto, 2003; Krot *et al*., 2005).

A chronology of events that incorporates the rapid accretion of differentiated palanetesimals within the first millon years, constrained by ages from different isotopic systems, is illustrated in Figure7 (Kleine *et al*., 2002; Weiss and Elkins-Tanton, 2013). In this model, accretion of chondrite parent planetesimals occurred shortly after chondrule formation with an extended period marked by hydrous alteration and thermal metamorphism. Carbonaceous chondrites developed in the crust of partly differentiated planetesimals, large enough to have metallic cores and internal magnetic fields (Figure 8; Elkins-Tanton *et al*., 2011; Carporzen *et al*., 2011; Sahijpal and Gupta, 2011). Dynamo action was sustained for several millions of years, consistent with thermal evolution and rapid differentiation processes. The early stage was marked by collisions, which fragmented the planetesimals, leading to the partial or complete disruption, producing the differentiated and undifferentiated meteorite types (Figure 8B). Depending on the crustal level, distinct chondrite types originate, marked by varying hydrous alteration and metamorphic degrees (Figure 8A). CK chondrites come from deep crustal levels, whereas Allende CV3 chondrite comes from an intermediate crustal level.

Use of short lived radioisotopes like the Al-Mg system provides temporal resolution for asteroid accretion, differentiation and secondary alterations (Nyquist *et al*., 2009). Isotope geochemical studies on the Allende carbonaceous chondrite and other chondrites documented presence of the radioactive isotope aluminium-26, which indicates that a supernova exploded in the vicinity of the solar nebula, initiating compression of the gas and dust molecular cloud.



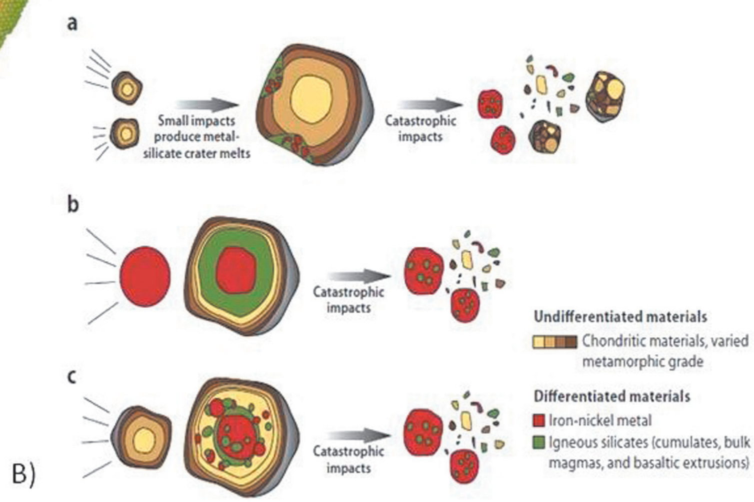


Figure 8. (A) Schematic model for a chondrite parent planetesimal, with a differentiated interior, convecting magma mantle and a metallic core capable of sustained dynamo action (Elkins-Tanton *et al*., 2011). Distinct chondritic meteorites showing variable aqueous alteration and metamorphic degrees originated from different crustal levels. The Allende CV3 chondrites come from an intermediate crustal level. (B) Schematic model for formation of different meteorite types from collision of the parent planetesimals with variable size impactors (Weiss and Elkins-Tanton, 2013). Note formation of undifferentiated and differentiated meteorites resulting from small to large impacts.

CAI fragments inside chondrules are consistent with the older ages for CAIs, also indicating that chondrule formation occurred in a nebula sector with CAIs present. There are different models for formation of chondrules and refractory inclusions, some involving distinct separate sectors in the nebula (Figure 6A). Radiometric dates constrain the period for CAI and chondrule formation. Chondrule size varies among different chondrite classes, which has been interpreted in terms of distinct regions for chondrite formation and/or chondrule sorting mechanisms. Chondrules showing fragmentation, coalesced composite chondrules, chondrule fragments inside chondrules and chondrules with rims (Figure 6B) support relatively large spans for the formation with multiple fast heating events.

The observations on individual chondrules from a fragment of the Allende meteorite show that highly diverse types coexist with fragmented, rimmed and composite chondrules characterized by distinct mineralogy (Figure 5B). Findings support a dynamic evolution of chondrule formation, fragmentation and partial metasomatism before and during chondrule aggregation (Scott, 2007). The recent reports of chondrule fragments inside CAIs add support for overlapping chondrule and refractory inclusion formation, within given sectors of the nebula (Itoh and Yurimoto, 2003; Bizarro *et al*., 2004).

Discussion

In recent years, improvements on instrumentation and analytical techniques provide increased resolution in studying and characterizing the various classes of meteorites. Use of microanalytical methods permits to investigate meteorite constituent minerals at increasing detail. In the case of chondrites studies focus on the CAIs, chondrules, metal grains and matrix, to investigate the early evolution stages of the solar system. Radiometric dating on CAIs and chondrites give the oldest dates, constraining the chronology of accretion. Chemical and isotopic analyses on CI and carbonaceous chondrites show they preserve the composition of the solar nebula.

Chondrites are characterized by a trend from 'reduced' with Fe in metallic form to 'oxidized' with Fe in silicates and oxides. Magnetic minerals in CV3 chondrites are FeNi, iron-titanium oxides and magnetite in olivines, with magnetite formed by aqueous alteration. The results from the hysteresis analyses of individual chondrules show magnetite as dominant phase with PSD and MD domain states, which along with taenite and iron sulfides make the magnetic signal of Allende.

Chondrules examined in a fragment of the Allende chondrite display relations between mass and size (Figure 4A). The relation is partly dependent on density (Figure 4B), with density decreasing with size. Examination of the apparent scatter in the size-density plot shows a dependency on internal structure and mineralogical assemblage. The composite and fragmented nature of some chondrules is related to outliers in the plots. The study also uncovered simple relationships among the magnetic hysteresis properties, which need further consideration using detailed petrographic and geochemical analyses on a larger group of chondrules. The magnetization ratio shows a dependency on the coercivity (Figure 4C). The plot of remanent magnetization as a function of remenent coercivity shows a trend of increasing intensity with increasing coercivity (Figure 4D). There is however significant scatter, in contrast to the pattern shown using the magnetization ratio. The examination of the internal structure and mineralogical assemblage uncovers correlations between the magnetic properties, variation patterns and chondrule characteristics (Figure 5A, B).

The wide range of variation in chondrule structures, composition and hysteresis properties has implications for the paleomagnetic and paleointensity studies (Flores-Gutierrez *et al*., 2010a, b), indicating that the differences in magnetization vector components and paleointensity record relate to chondrule structure and mineralogy. Magnetic hysteresis parameters and domain structure are related to chondrule morphology, size and density, which in turn reflect internal structure and mineralogic differences (Figure 5A, B). A next step is to obtain paleointensity estimates and expand the analyses and correlations between magnetic hysteresis properties and chndrule structure and mineralogical composition.

The studies, reviewed in the previous section on paleomagnetic records in chondrites, show that they are secondary with remanent magnetizations acquired in the planetesimals under ambient fields generated by active internal dynamo action (Carporzen *et al*., 2011; Elkins-Tanton *et al*., 2011). The paleomagnetic evidence for differentiated planetesimals with iron cores and sustained internal magnetic fields rests on the magnetization record and remanence acquisition mechanism. Carporzen *et al*. (2011) summarized the records for unidirectional magnetizations in the Allende, residing in middle unblocking temperature components, interpreted as up to ~290 C partial TRM (pTRM) or thermochemical (CTRM) magnetizations (e.g., Figure 2B). This secondary component is carried in magnetite, pyrrothite and awaruite, which formed as a result of hydrous alteration (which is further discussed below). The ambient magnetic field under which the magnetization was blocked is constrained from paleointensity estimates from both Thellier and laboratory imparted AF demagnetization methods, which Carporzen *et al*. (2011) set at minimum fields of 20 mT and up to about 60 mT. The high magnetic field magnitude is compatible with internal fields. The other requirement in this interpretation of the Allende paleomagnetic record is the timing and duration for remanence acquisition, which are constrained from the isotope chronometers. In the study, chondrules are considered to have formed over an interval of 1.2 to 3 Ma, starting at about 200 ka after formation of refractory inclusions. Carporzen *et al*. (2011) discussed the temporal constrains in further detail, concluding that an extended period of elevated temperatures and hydrous alteration was involved in the acquisition of the paleomagnetic record.

The scenario for magnetization acquisition in the crust of a differentiated parent planetesimal appears consistent with magnetite formation as an alteration product. CV chondrites have been divided into magnetite-rich and magnetite-poor subgroups, marked by the modal ratio of magnetite to metal (McSween, 1977; McMahon and Haggerty, 1980). Different mechanisms for magnetite formation have been proposed, with some occurring in the solar nebula and some in planetesimals (Krot *et al*., 1995). Choi *et al*. (1997) analyzed the oxygen isotope compositions of magnetites and olivines in the Allende, where they are closely related. Magnetite is present as spherical nodules in porphyritic-olivine chondrules, associated with Ni-rich metal and sulfides. The oxygen isotopes differ, implying that magnetite and olivine are in isotopic disequilibrium, with more negative magnetite δ-O than those expected for the solar nebula. Choi *et al*. (1997) interpreted that magnetite formed by aqueous oxidation of metal, which had already undergone oxygen isotope exchange with fine-grained silicate material in the parent planetesimal.

Modeling of the size and internal structure of differentiated bodies with iron cores and undifferentiated crusts has been used to further constrain the early thermal state evolution (e.g., Elkins-Tanton *et al*., 2011; Sahijpal and Gupta, 2011; Storenberg and Crowley, 2013). Models show that dynamo action might have been sustained for several million years. Further modeling incorporating stringent boundary conditions on thermal state and heat transport are needed to constrain the evolution of the planetesimal dynamos. The crustal structure and thickness and temperature-pressure profiles, fluids and layering in parent planetesimals remain to be incorporated in the modeling, including the magnetization acquisition mechanisms at different crustal levels.

Paleomagnetic data for meteorites inferred to originate at various levels marked by distinct hydrous alteration and metamorphic grades (Figure 8A) might allow testing and refining the differentiated planetesimal model. Paleomagnetic data for terrestrial lower crust, metamorphic lithologies and crustal and mantle xenoliths might provide some potentially useful analogies. Modeling of expected paleomagnetic records and rock magnetic property variations with depth within the crust might allow testing the remanent acquisition mechanisms. The effects of the large impacts involved in fragmenting the planetesimals (Figure 8B), including shock remagnetization, need also to be investigated in the paleomagnetic records of the different meteorites.

Forward modeling and inversion of crustal magnetic anomalies on the Moon and Mars have been used to estimate paleomagnetic poles and derive constraints on the internal dynamo generated magnetic fields (e.g., Cisowski *et al*., 1983; Scott and Fuller, 2004; Lillis *et al*., 2013). Occurrence of polarity reversals of the core dynamos has also been analyzed from modeling of crustal magnetic field anomalies (Arkani-Hamed, 2001). This cannot be accomplished for the fragmented chondrite parent planetesimals, but might be possible to be eventually investigated for the large differentiated asteroids Ceres and Pallas.

Paleomagnetic analyses of different meteorite types, including carbonaceous chondrites, eucrites and pallasites, suggest that their acquired remanent magnetizations under the influence of internal magnetic fields (Weiss *et al*., 2008; Carporzen *et al*., 2011; Tarduno *et al*., 2012; Weiss and Elkins-Tanton, 2013). This implies differentiated planetesimals with convecting cores capable of sustaining dynamo action for extended periods. To sustain dynamo action an energy source is required, plus a thermal state and evolution that allows the crust and upper mantle to cool enough for magnetization acquisition. Most of these differentiated bodies were later destroyed by collisions or other disturbances such as tide forces. Part of the differentiated bodies have been preserved forming the planets, satellites, dwarf planets and specially the large asteroids Ceres and Pallas in the asteroid belt (Elkins-Tanton *et al*., 2011).

The studies on eucrite meteorites support that their acquired remanent magnetizations in a magnetic field, consistent with an internal field with surface magnitude of around 2 microtesla (Fu *et al*.,2012). The asteroid Vesta in the asteroid belt is the smallest differentiated body known. The paleomagnetic record suggests that Vesta might had had a convecting metallic core in the early stages.

Stony-iron meteorites have been assumed to form in the interior of differentiated planetesimals, near the core-mantle boundary. Therefore, they come from differentiated bodies with developed cores that could sustain dynamo action. Paleomagnetic analysis of stony-iron meteorites such as the main group pallasites could provide information on planetesimals´ magnetic fields Paleomagnetic analyses of pallasites characterized soft coercivity highly anisotropic magnetizations, likely associated with the Fe-Ni metal (Nagata, 1979). Pallasites, characterized by metal-silicate assemblages composed of olivines and Fe-Ni are particularly interesting, since olivine and metal phases tend to separate, so a mechanism seems required to keep them without segregation.

The different types of iron meteorites and achondrites indicate different parent planetesimals, which supports widespread formation of differentiated bodies in the early stages. Burbine *et al*. (2002) estimated that more than 100 parent planetesimals are required to account for the diversity in achondrites and iron meteorites, including the early estimates by Wasson (1990) on the probable large numbers of iron meteorite parent planetesimals. Ungrouped iron meteorites have been related to some 50 parent planetesimals (Goldstein *et al*., 2009), as suggested by the differences in sulfur compositions. Goldstein *et al*. (2009) propose that iron meteorites were derived from relatively large parent bodies, with sizes up to 1000 km or more, which formed before chondrite accretion outside the asteroid belt zone.

The widespread early formation of differentiated planetesimals and apparent lack of such bodies in the asteroid belt has been discussed in several studies. Surface weathering and impact debris cover may have masked the spectroscopic observations (e.g., Nakamura *et al*., 2011). Other effects may include the preservation of primitive undifferentiated crusts (Weiss end Elkins-Tanton, 2013). The layered internal structures in planetesimals offers an explanation of the genetic relations uncovered for distinct meteorite classes, where they originate upon collision fragmentation from different levels from the iron cores, mantles and crusts. The paleomagnetic record for the Allende chondrite supports an origin from an intermediate crustal level in a partly differentiated parent planetesimal. Carporzen *et al*. (2011) showed that the magnetization in the Allende was likely acquired over an extended period under the influence of an internal magnetic field. The characteristic magnetization is univectorial acquired in a magnetic field of about 20 mT, likely corresponding to a partial TRM or a thermochemical C-TRM. The magnetic carriers, magnetite, pyrrothite and awaruite, are consistent with this interpretation, corresponding to secondary minerals formed from hydrous alteration and thermal metamorphism.

Fu and Elkins-Tanton (2013) examined the thermal evolution of planetesimals in which short lived radiogenic isotopes provided sufficient heat for differentiation with formation of layered structures. In those bodies, heat dissipation involved magmatic processes resulting in magmas ascending through the crust. Modeling by Fu and Elkins-Tanton (2013) supports that magmas were volatile-depleted, and likely emplaced through enstatite crusts but likely not through CV and CM crusts, as indicated by the paleomagnetic constraints.

Conclusions

In recent years, planetary missions, Earth-based astrophysical observations, use of a range of analytical techniques of microscopy, isotope geochemistry and magnetic properties, discovery of exoplanets, and development of evolutionary models for planetary nebula have opened new research multidisciplinary fields, with the potential of integrative approaches.

Meteorites represent the earliest rocks preserved from the initial stages of formation of the solar system, providing the record on the conditions, processes and chronology for formation of first solids, planetesimals and differentiated bodies. Refractory calcium-aluminum inclusions and chondrules give the oldest radiometric dates. New dating studies provide higher resolution on the chronology of events, constraining the formation of CAIs and chondrules and accretion of differentiated planetesimals.

Evidence on the nature of magnetic fields in the early solar system has been derived from chondritic meteorites. Chondrites and in particular chondrules, which are millimeter sized silicate spherules formed by rapid melting and cooling, have remanent magnetization records which in some cases date from the time of chondrule formation and accretion of planetesimals. Studies on different meteorite classes, including ordinary and carbonaceous chondrites, have provided contrasting results, with a range of estimates for proto-planetary magnetic fields.

Developments on instrumentation and techniques for rock magnetic and paleointensity analyses are allowing increasing precision. Micromagnetic measurements and a range of geochemical and electronic microscopy analyses are providing unprecedented resolution, characterizing rock magnetic properties at magnetic domain scales. Magnetic hysteresis analyses on individual chondrules from the Allende CV3 chondrite reveal relationships among hysteresis parameters and physical properties (Figure 4). Coercivity, remanent and saturation remanence parameters correlate with chondrule size and density; related to internal chondrule structure, mineralogy and morphology (Flores-Gutierrez *et al*., 2010a,b). Compound, fragmented and rimmed chondrules have distinct hysteresis properties, related to mineral composition (Figure 5).

The remanent magnetization record and paleointensity estimates derived from the Allende and other chondrites support remanent acquisition under influence of internal magnetic fields within parent planetesimals. Rapid differentiation in the first 10 Ma following formation of refractory inclusions and chondrules gave rise to planetesimals with metallic cores (Fig. 7), capable of generating and sustaining dynamo action for million year periods (Weiss and Elkins-Tanton, 2013). Observations on turbulent circumstellar disks also indicate rapid planetesimal formation (Johansen *et al*., 2007), providing a broad perspective for evolution of planetary systems. Paleomagnetic and thermal modeling constrain the evolution of early planetesimals, which might presently be represented by large sized asteroids such as Vesta (Fu *et al*., 2012). The Allende chondrite and other undifferentiated meteorites may have formed by fragmentation from collisions, representing different crustal levels in their parent planetesimals (Figure 8; Carporzen *et al*., 2011; Elkins-Tanton and Weiss, 2011). Constraining the crustal levels, temperature/pressure profiles, role of fluids and conditions for aqueous alteration and metamorphism are part of the major open questions remaining. Models of heat sources and transfer mechanisms and thermal state evolution are being used to better define accretion processes and possible boundary conditions (Elkins-Tanton *et al*., 2011; Sahijpal and Gupta, 2011). The crustal thickness and layering may have been different, depending on the internal structure, accretion history and size/timing of last major accretion event.

Recent studies of molecular clouds, discovery of exoplanets and detection of magnetic fields in protoplanetary accretion disks are opening new avenues. Integrative interdisciplinary approaches involving astronomical, astrophysical and planetary sciences provide a broad perspective, allowing a better understanding for formation of planetary systems.

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