1

Introduction

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Abstract

In this chapter, we review the history of chondrule research and introduce some of the basic concepts in the study of chondrules, including the classification of chondrites and the nomenclature of chondrule types.

1.1 Introduction

Chondrules are igneous-textured ferromagnesian silicate ± Fe,Ni-metal ± sulfides droplets that are ubiquitous in the majority of chondritic meteorites (chondrites). As survivors of the time when the early Sun was surrounded by a protoplanetary disk, their characteristics can provide clues to disk processes and planet formation. They formed from molten droplets, so their shape tends to be spherical, although they are also present as fragments in meteorites. A first-order observation of chondrules is that they have been melted and largely avoided evaporation, and therefore require conditions in which melts were stable.

In this book, we present the latest mineralogical, petrologic, chemical, and isotopic observations of chondrules that may place constraints on the environment in their formation regions in the protoplanetary disk. At the end of the book are chapters presenting models for chondrule formation. This book follows a workshop on the topic of *Chondrules and the Protoplanetary Disk* that was held on 27−28 February 2017 at the Natural History Museum in London, UK. We are grateful to the Natural History Museum, the Meteoritical Society, and the Royal Astronomical Society for their support of this workshop.

1.2 A Brief History of Chondrule Research

These rounded inclusions were described in even the earliest recognized meteorite falls: in his description of the Benares meteorite fall in 1798, the English chemist Edward Howard remarked "Internally they consisted of a small number of spherical bodies, of a slate colour, embedded in a whitish gritty substance" (Howard, 1802). The word "chondrule" derives from the Ancient Greek χόνδρος or *chondros*, meaning grain. Gustav Rose (1798–1873) coined the word "chondrite" in 1863, and soon after Tschermak began to call the rounded spherules within them "chondren," which eventually became "chondrules" (see Connolly and Jones, 2017). An understanding that they were once molten droplets also came early; they were described by

Henry Clifton Sorby as “drops of fiery rain” in 1877 during a talk at the then-new Natural History Museum in South Kensington, London.

Chondrules have been the subject of research ever since. Merrill (1920) produced the first review of possible chondrule-forming mechanisms. Chondrules were the subject of a workshop in Houston in 1983, at which the chondrule was definitively defined and a book produced (King, 1983). At a later workshop in Albuquerque, New Mexico in 1993, definitive evidence was presented that chondrules formed in a flash heating event. This workshop resulted in a book on chondrules (Hewins, Jones, and Scott, *Chondrules and the Protoplanetary Disk*: Cambridge University Press, 1996).

In this chapter, we cover some relevant basic concepts in meteoritics that may be useful for the nonexpert readers to make sense of succeeding chapters. An additional review of chondrule properties and some current chondrule-forming mechanisms can be found in Connolly and Jones (2017).

1.3 Primary Classification of Meteorites

Meteorites are broadly divided into those that have been melted, and those which have remained unmelted since their accretion. Melted meteorites include irons, stony irons, and achondrites, or igneous-textured rocks. Specific chondrites have been identified as coming from asteroids, the Moon, and Mars. Some meteorites (called primitive achondrites) have been partly melted, and these may contain rare chondrules (e.g., Krot et al., 2014).

The unmelted meteorites are called chondrites. Chondrites retain some of their primordial early solar system bulk chemical composition; within a factor of two they have a bulk composition similar to that of the Sun’s photosphere, excluding volatile gases (Palme et al., 2014). These meteorites are the hosts of most chondrules.

Chondritic meteorites make up around 92 percent of our meteorite collections (Meteoritical Society, 2018). These are broadly divided into Ordinary + Rumuruti-like, Carbonaceous and Enstatite classes (Figure 1.1), based on differences in bulk chemical and oxygen isotopic compositions, along with the minor K and G grouplets (Weisberg et al., 2006, 2015). These meteorite classes are further subdivided into 13 groups that are classically presumed to have come from separate parent bodies. Recent work has suggested that may not always be the case, although the genetic relationship between groups is often controversial. For example, bulk chemical and oxygen isotopic compositions suggest the CVs and CKs may come from the same parent body (Greenwood et al., 2010), although bulk Cr isotopic compositions of CVs and CKs indicate that this may not be the case (Yin et al., 2017).

Chondrites are composed of chondrules, refractory inclusions along with isolated metal and sulfide grains, all surrounded by a fine-grained matrix. The proportions of these components show very clear differences between classes (Weisberg et al., 2006). The size distribution of chondrules in each group is also very distinctive, to the extent that this characteristic can be used to assist classification. Chondrule sizes vary by almost an order of magnitude among chondrite classes and groups, from an average of 0.15 mm in COs to 1 mm in CVs (Jones, 2012).

The classification of meteorites is described in more detail in Weisberg et al. (2006) and Krot et al. (2014).

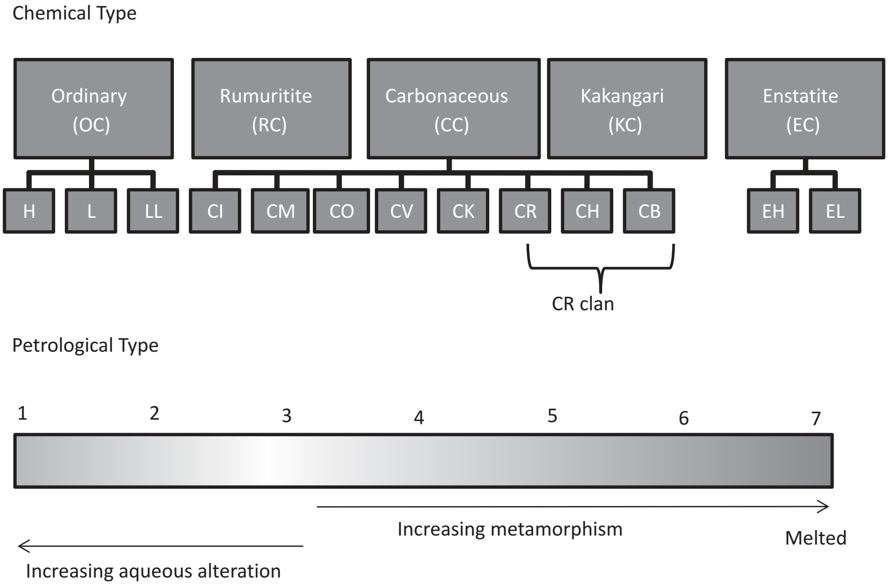

Figure 1.1 A simplified classification scheme for chondrites. Kakangari chondrites (KC) define a grouplet; Rumuritite chondrites (RC) define a group.

1.4 Secondary Classification

The primary classification of meteorites attempts to define groups that are clearly chemically and isotopically distinct and perhaps originate from separate parent bodies. In addition, meteorites have experienced geological processing while on their parent bodies. These include thermal and shock metamorphism, and aqueous alteration. Chondrites are designated a number (1–7) to describe this secondary processing (Van Schmus and Wood, 1967; Weisberg et al., 2006). Type 7s have been completely melted and, therefore, strictly speaking, are no longer chondrites. Types 2 and 1 have experienced increasing amounts of aqueous alteration, and types 3–6 have experienced increasing amounts of heating. Type 3 chondrites are, therefore, the meteorites that best retain their original petrographic features, mineralogy, mineral chemistry, and chemical compositions. Type 3s are further subdivided into types 3.0–3.9, indicating increasing amounts of parent body heating.

Many chondrites have also experienced shock from asteroidal impacts. The extent of shock is highly variable, with some chondrites not displaying any evidence at all and some being melted or brecciated from the impact events. A shock classification scheme is best developed for the ordinary chondrites (Stöffler et al., 1991).

1.5 Tertiary Classification

Some meteorites, especially those that are found (finds) rather than observed to fall (falls), experienced a further episode of changes while on the surface of the Earth. These processes have produced weathering effects, most notably oxidation of iron to form a series of iron oxides and hydroxides (Bland et al., 2006) which has led to weathering schemes (e.g., Wlotzka, 1993). Additionally, some new minerals such as sulfates may form. For those interested in early solar system processes, it is important to recognize these effects so they can be disentangled from primordial early solar system processes.

1.6 Types of Chondrules

1.6.1 Textural Types

Chondrules exhibit a variety of textures that are a function of their initial composition and thermal histories. The most common textural type of chondrules is porphyritic. These are composed of euhedral to subhedral crystals embedded in a fine-grained or glassy mesostasis. The crystals can be olivine only (Porphyritic olivine (PO) chondrule), olivine plus pyroxene (POP) or, more rarely, except in enstatite chondrites, pyroxene only (PP). Another common texture for chondrules is barred olivine (BO). These chondrules are comprised of skeletal olivine crystals surrounded by mesostasis. The morphology of olivine is typically in the form of subparallel plates that are part of the same crystal (see Figure 3.1 for examples of different textures). Less common textures of chondrules include radial pyroxene (RP), cryptocrystalline (CC), and glassy (GC).

Metal and sulfide grains are commonly found as blebs in chondrules, and tend to be concentrated around the outermost parts. In all cases, the mesostasis is composed of glass (in the lowest petrological type chondrites only) or a fine-grained mixture of crystals, most commonly high-Ca pyroxenes ($(Ca,Mg,Fe)SiO_3$) and feldspar ($(Na,Ca)(Si,Al)_4O_8$). Chondrules, especially porphyritic ones, often contain relict grains (see Chapter 2).

1.6.2 Chemical Types

Most chondrules from unaltered (type 3) chondrites are predominantly composed of olivine $(Mg, Fe)_2SiO_4$ and low-Ca pyroxene $(Mg, Fe)SiO_3$. Of these, the majority tend towards the magnesium end-member compositions (forsterite and enstatite) and are poor in volatile elements compared to solar compositions. These are called type I chondrules; they have a reduced mineralogy, and any iron within them is commonly in the form of metal blebs rather than combined in silicates. Some chondrules are more oxidized and contain ferromagnesian olivine and pyroxene (Fo $>$ 10 mol% and En $>$ 10 mol%, where Fo (at.%) = $Mg/(Mg + Fe) \times 100$ and En (at.%) = $Mg/(Mg + Fe + Ca) \times 100$); these are termed type II chondrules. Type I and type II chondrules coexist in most chondrite groups (with type I being always more abundant), but their proportions vary, with ordinary chondrites containing more type II chondrules than carbonaceous or enstatite chondrites (Jones, 2012). These types are subdivided into type IA (silica-poor, olivine rich) and type IB (silica-rich, pyroxene-rich).

Porphyritic chondrules are the predominant texture in most chondrites. However the exact proportions of textural types differs between meteorite groups, and, as discussed in Section 1.3, the size distribution also varies enormously between chondrite groups. Therefore, each group has sampled a unique reservoir, and models of the early solar system must account for this ability to separate reservoirs in space and/or time (Jones, 2012).

A minority of chondrules are Al-rich ($>$10 wt% Al_2O_3; Bischoff and Keil, 1983). Al-rich chondrules can contain anorthite, spinel, and/or glassy Al-rich mesostasis. They are found in all chondrite groups, but are most abundant in CVs. Anorthite-rich chondrules (ARCs) are a subset of Al-rich chondrules (Kring and Holmen, 1988). ARCs may provide a genetic link between refractory inclusions and ferromagnesian chondrules (Krot and Keil, 2002). The related Na-rich chondrules, containing between 4 and 15 wt% Na_2O, may have formed by melting together of Na-rich material and refractory-rich material (Ebert and Bischoff, 2016).

1.7 Refractory Inclusions

Refractory inclusions are a rare component in most chondrite groups. There are two types of refractory inclusions: amoeboid olivine aggregates (AOAs) and calcium-aluminum-rich inclusions (CAIs). Amoeboid olivine aggregates are composed of Ca, Al-rich material enclosed by forsterite (Krot et al., 2004; note that olivine in AOAs is Ca-poor, see Sugiura et al., 2009). Calcium-aluminum-rich inclusions make up between 0 and 3 percent of chondrite groups (Hezel et al., 2008) and are composed of Ca, Al-rich oxides and silicates such as spinel ($MgAl_2O_4$), melilite ($(Ca,Na)_2(Al,Mg)(Si,Al)_2O_7$), anorthite ($CaAl_2Si_2O_8$), fassaite ($Ca(Mg,Fe,Al)(Si,Al)_2O_6$), and perovskite ($CaTiO_3$) (MacPherson, 2014). CAIs can be either fluffy or compact in texture. Compact CAIs are igneous and formed by melting of solid precursors; they often show evidence for evaporation, suggesting that melts were not stable. Fluffy CAIs are aggregates of condensates from a hot gas. CAIs are very ancient and provide the time marker for the beginning of the solar system at 4567.3$\pm$0.16 Myr (Connelly et al., 2012).

1.8 Where Do Chondrites Come From?

The texture of chondrites suggests they have never been melted, which points to their origin in a small minor body as a parent that has not had enough heat to melt. Asteroidal-sized bodies, therefore, are the likely parent of chondrites. In most cases, the exact body from which each meteorite comes from is unknown. In some instances, the orbital source of the meteorite can be determined from triangulating observations of fireballs (e.g., Brown et al., 2011), but this has only been successfully undertaken for a handful of meteorite falls. These orbital analyses typically indicate an origin from the main asteroid belt. The CI carbonaceous chondrite Orgueil has been suggested as coming from a comet from historical records of its fall (Gounelle et al., 2006).

The Japanese Aerospace Exploration Agency (JAXA) Hayabusa mission provided the first proof that some chondrites originate in specific asteroids. This mission visited the 25143 Itokawa “S-type” asteroid in 2005 and brought fragments of this asteroid back to Earth in 2010. The returned material closely resembles LL5 ordinary chondrites, therefore providing a definitive link between S-type asteroids and the ordinary chondrites (Yurimoto et al., 2011).

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Cambridge University Press
978-1-108-41801-0 — Chondrules: Records of Protoplanetary Disk Processes
Edited by S. S. Russell , H. C. Connolly Jr. , A. N. Krot
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Part I

Observations of Chondrules

2

Multiple Mechanisms of Transient Heating Events in the Protoplanetary Disk

Evidence from Precursors of Chondrules and Igneous Ca, Al-Rich Inclusions

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Abstract

In this chapter, we summarize our current knowledge of the mineralogy, petrography, oxygen-isotope compositions, and trace element abundances of precursors of chondrules and igneous Ca,Al-rich inclusions (CAIs), which provide important constraints on the mechanisms of transient heating events in the protoplanetary disk. We infer that porphyritic chondrules, the dominant textural type of chondrules in most chondrite groups, largely formed by incomplete melting of isotopically diverse solid precursors, including refractory inclusions (CAIs and amoeboid olivine aggregates (AOAs)), fragments of chondrules from earlier generations, and fine-grained matrix-like material during highly-localized transient heating events in dust-rich disk regions characterized by ^{16}O-poor average compositions of dust (Δ^{17}O ~ –5‰ to +3‰). These observations preclude formation of the majority of porphyritic chondrules by splashing of differentiated planetesimals; instead, they are consistent with melting of dustballs during localized transient heating events, such as bow shocks and magnetized turbulence in the protoplanetary disk, and, possibly, by collisions between chondritic planetesimals. Like porphyritic chondrules, igneous CAIs formed by incomplete melting of isotopically diverse solid precursors during localized transient heating events. These precursors, however, consisted exclusively of refractory inclusions, and the melting occurred in an ^{16}O-rich gas (Δ^{17}O ~ –24‰) of approximately solar composition, most likely near the protosun. The U-corrected Pb–Pb absolute and Al–Mg relative chronologies of igneous CAIs in CV chondrites indicate that these melting events started contemporaneously with condensation of CAI precursors (4567.3 ± 0.16 Ma) and lasted up to 0.3 Ma, providing evidence for the earliest transient heating events capable of melting refractory dustballs in the innermost part of the disk. There is no evidence that chondrules were among the precursors of igneous CAIs, which is consistent with an age gap between CAIs and chondrules. In contrast to typical (non–metal-rich) chondrites, the CB metal-rich carbonaceous chondrites contain exclusively magnesian nonporphyritic chondrules formed during a single-stage event ~5 Ma after CV CAIs, most likely in an impact-generated gas–melt plume. Bulk chemical compositions of CB chondrules and equilibrium thermodynamic calculations suggest that at least one of the colliding bodies was differentiated. The uniformly ^{16}O-depleted igneous CAIs in CB chondrites most likely formed by complete melting of preexisting refractory inclusions that was accompanied by gas–melt interaction in the plume. CH metal-rich carbonaceous chondrites represent a mixture of the CB-like materials

(magnesian skeletal olivine and cryptocrystalline chondrules and uniformly ^{16}O-depleted igneous CAIs) formed in an impact plume and the typical chondritic materials (magnesian, ferroan, and Al-rich porphyritic chondrules, uniformly ^{16}O-rich CAIs, and chondritic lithic clasts) that appear to have largely predated the impact plume event. We conclude that there are multiple mechanisms of transient heating events that operated in the protoplanetary disk during its entire lifetime and resulted in formation of chondrules and igneous CAIs.

2.1 Introduction

Based on bulk chemical and oxygen isotopic compositions, mineralogy, and petrography, 14 chondrite groups comprising four major classes are currently recognized: (1) carbonaceous – CI, CM, CR, CO, CV, CK, CH, and CB; (2) ordinary – H, L, and LL; (3) enstatite – EH and EL; and (4) Rumuruti – R; and K chondrite grouplet (Krot et al., 2014). Chondrules and associated Fe,Ni-metal, refractory inclusions [Ca,Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)] and fine-grained matrix are the major components in most chondrites (Figure 2.1a–b; Scott and Krot, 2014). The important exceptions are CI chondrites, which virtually lack chondrules (Leshin et al., 1997), and metal-rich chondrites [CB, CH/CB, CH (Figure 2.1c–f), and two ungrouped meteorites – Grosvenor Mountains (GRO) 95551 and Northwest Africa (NWA) 5492] – which virtually lack fine-grained matrices (Krot et al., 2002; Weisberg et al., 2015).

Chondrules, which are commonly composed of silicates ± Fe,Ni-metal ± Fe,Ni-sulfides, formed from molten or partially molten droplets that were freely floating in space before being accreted to the chondrite parent bodies. We note that igneous CAIs, the oldest solar system solids dated (Connelly et al., 2012), also satisfy this definition (see the following text) and, therefore, provide important constraints on the earliest transient heating events in the protoplanetary disk. The O-isotope compositions of chondrules and refractory inclusions in unmetamorphosed chondrites (e.g., CR2–3) are distinctly different (Figure 2.2), indicating that these chondritic components originated in isotopically distinct disk regions: ^{16}O-poor planetary-like and ^{16}O-rich solar-like, respectively. CAIs formed in a disk region, most likely near the protosun, that was exposed to irradiation by solar energetic particles, had high ambient temperature (at or above the condensation temperature of forsterite, >1,300 K), and had a dust-to-gas ratio that was approximately solar (1/100) (e.g., McKeegan et al., 2000; Scott and Krot, 2014; Sossi et al., 2017). They were subsequently transported radially away to the accretion regions of the chondritic and cometary planetesimals (e.g., Brownlee et al., 2006; Ciesla, 2010). In contrast, chondrules are thought to have formed in relatively cold (<1,000 K), dust-rich [dust-to-gas ratio ~(10^2–10^5) × solar] regions of the protoplanetary disk (e.g., Cuzzi and Alexander, 2006; Alexander et al., 2008; Alexander and Ebel, 2012; Bischoff et al., 2017). Rubin (2010) pointed out many correlations among chondrule properties (textures, proportions of chondrules with igneous rims, average chondrule sizes, and so on) in different chondrite groups and used this as support for the idea that chondrules formed locally, at different heliocentric distances. It is not known, however, whether chondrule formation occurred only in the inner Solar System (i.e., inside Jupiter's orbit) or took place in the outer disk (i.e., outside Jupiter's orbit) as well (e.g., Walsh et al., 2011; Van Kooten et al., 2016; Budde et al., 2016a).

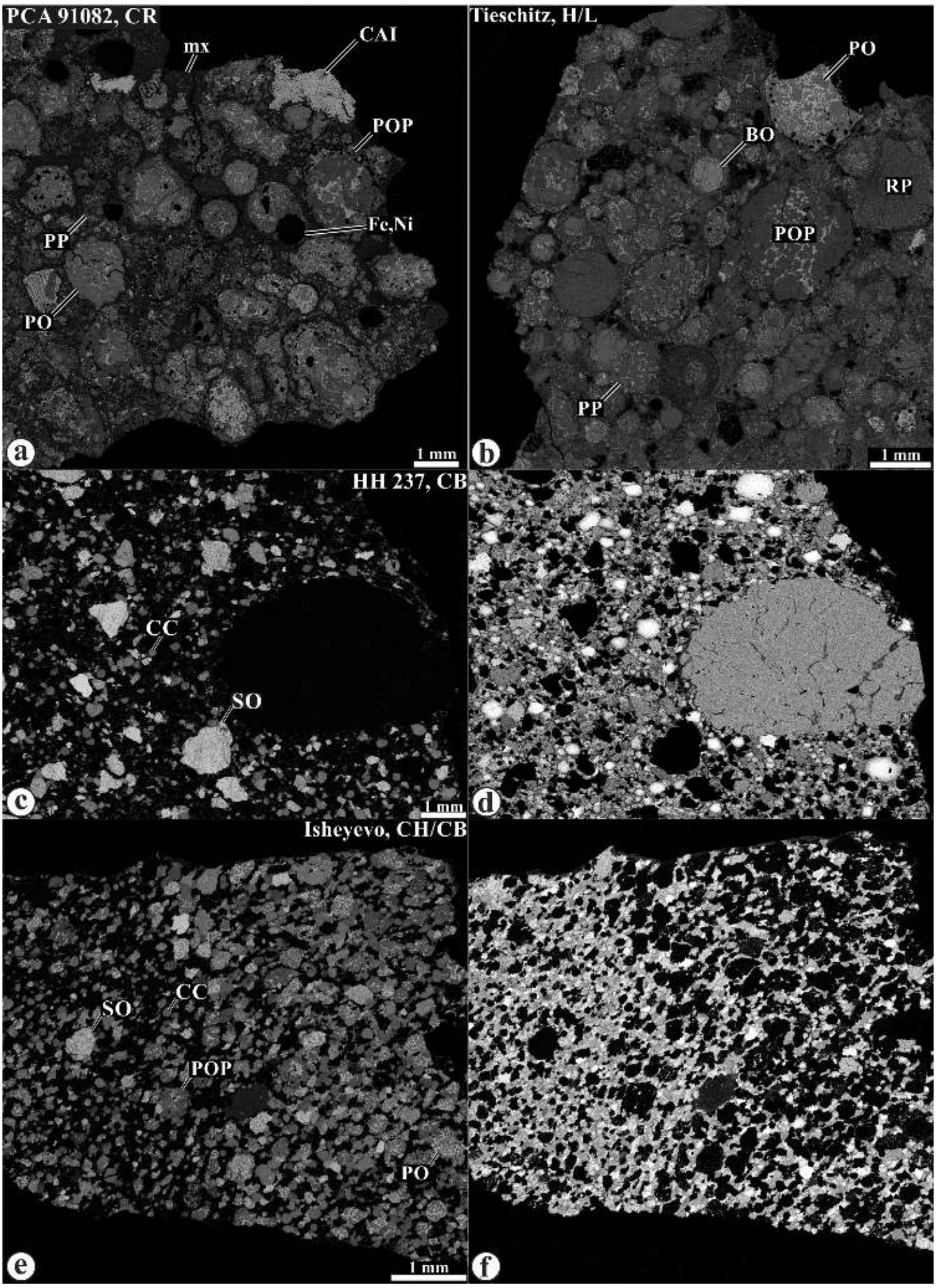

Figure 2.1 (a–c, e) Combined x-ray elemental maps in Mg (red), Ca (green) and Al (blue) and x-ray elemental maps in Ni (d, f) of PCA 91082 (CR2), Tieschitz (H/L3), Hammadah al Hamra (HH) 237 (CB), and Isheyevo (CH/CB) chondrites. Typical chondrites consist of three major components: (1) chondrules

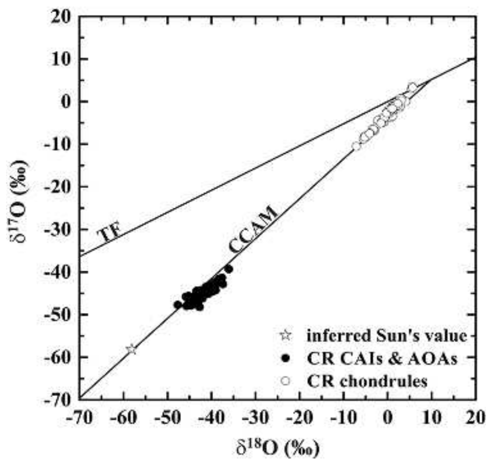

Figure 2.2 Oxygen–isotope compositions of refractory inclusions (CAIs and AOAs) and chondrules from CR carbonaceous chondrites. Individual refractory inclusions and chondrules are isotopically uniform. There are, however, significant differences in O-isotope compositions between these groups of objects, suggesting formation in isotopically distinct reservoirs. Refractory inclusions are ^{16}O-enriched relative to chondrules, but ^{16}O-depleted relative to the Sun. The inferred composition of the Sun is from McKeegan et al. (2011). The Terrestrial Fractionation (TF) and Carbonaceous Chondrite Anhydrous Mineral (CCAM) lines are shown for reference. Data from Krot et al. (2006a), Makide et al. (2009), Schrader et al. (2014), and Tenner et al. (2015).

Fine-grained matrices appear to be chemically and isotopically complementary to chondrules, suggesting their close genetic relationship – i.e., formation in the same disk region (e.g., Bland et al., 2005; Hezel and Palme, 2008, 2010; Palme et al., 2014, 2015; Ebel et al., 2016; Becker et al., 2015; Budde et al., 2016a, 2016b; Chapter 4). In contrast, Zanda et al. (2012; Chapter 5) advocate for the lack of chondrule-matrix complementarity and their origin in different disk regions. According to this hypothesis, chondrules formed near the protosun, were transported over large radial distances, and mixed with thermally unprocessed, primitive matrix in colder disk regions.

Caption for Figure 2.1 (*cont.*) + Fe,Ni-metal (Fe,Ni); (2) refractory inclusions (CAIs and AOAs); and (3) interstitial matrix (mx). The vast majority of chondrules have porphyritic olivine (PO), porphyritic pyroxene (PP) and porphyritic olivine-pyroxene (POP) textures; chondrules with radial pyroxene (RP) and barred olivine (BO) are less common. In contrast, the metal-rich CB, CH/CB, and CH carbonaceous chondrites lack matrix and contain abundant Fe,Ni-metal. CB chondrites contain exclusively magnesian nonporphyritic chondrules with skeletal olivine (SO) and cryptocrystalline (CC) textures, and rare refractory inclusions. CH chondrites contain chondrules with both porphyritic and nonporphyritic (SO and CC) textures. The CH/CB chondrite Isheyevo (Figures 2.1e and f) consists of the metal-rich, CB-like (left) and metal-poor, CH-like (right) lithologies with gradual boundaries between them. The origin of these lithologies is discussed by Morris, Garvie, and Knauth (2015). (A black-and-white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)