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Old formation ages of igneous clasts on the L chondrite parent body reflect an early generation of planetesimals or chondrule formation

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ABSTRACT

The Barwell meteorite contains large, abundant clasts that are igneous in nature. We report iodine–xenon ages of five clasts and one sample of host chondrite material. The fragment of host chondrite material yielded the oldest age determined: 4567.8 ± 1.2 Ma. Two clasts produced old, well defined ages of 4564.96 ± 0.33 Ma and 4565.60 ± 0.33 Ma. These, and a third clast having a less precise old age of 4566.0 ± 3.2 Ma, are interpreted as recording the timing of crystallisation of the samples. They were incorporated into the Barwell parent body before it underwent thermal metamorphism, but the I–Xe ages survived secondary processing on the parent body and were not reset by metamorphism, metasomatism or shock. Two further clasts record younger ages of 4560.96 ± 0.45 Ma and 4554.22 ± 0.38 Ma. These samples contain a high abundance of albitic mesostasis, and the most likely explanation of the ages is that they record the timing of metasomatism on the parent body. We also analysed four host chondrite samples that do not give I–Xe ages: in these samples, the system appears to have been disturbed by shock.

It has been suggested previously that the igneous clasts are derived from an early generation of partially melted asteroids. We do not have direct evidence that the clasts we examined were necessarily derived from a partially differentiated body, only that they were derived from cooling of a silicate melt; the clasts could thus be the products of any one of several proposed models for chondrule formation. Our results indicate that processes akin to chondrule formation, in that they involve rapid cooling of a silicate melt, were ongoing at the same time as CAI formation, lending support to the suggestion that Al–Mg chondrule ages indicate either heterogeneous distribution of ^{26}Al or resetting of the Al–Mg system after chondrule formation.

1. Introduction

We have only limited understanding of the processes that occurred during the formation of planetary bodies in the early Solar System. The record of this period has long since been overwritten on Earth and the terrestrial planets by subsequent geological processing. It is, however, accessible through asteroidal meteorite samples, which preserve records of the chemical and physical processes that occurred in the earliest stages of Solar System evolution. This record shows that planetesimals that formed within the protoplanetary disk were heated by decay of the short-lived isotope, ^{26}Al (e.g. McCoy et al., 2006). This heating caused the earliest-formed planetesimals to melt and differentiate; those that formed later incorporated lower concentrations of ^{26}Al that were insufficient to cause melting but did lead to thermal metamorphism. These less-processed planetesimals preserve evidence of the individual components from which they formed, such as calcium- aluminium-rich inclusions (CAIs) and chondrules. They are the source of chondritic meteorites. Two linked questions remain within this broad picture. Was ^{26}Al homogeneously distributed across the region of the Solar System sampled by primitive meteorites? How long elapsed between the formation of CAIs and the formation of the parent bodies of chondritic meteorites? One way to resolve these linked questions is to test the consistency of chronologies of the early Solar System based on different radioisotope decays.

CAIs were the first solids to form in our Solar System, at an age derived from the Pb–Pb system of 4567.30 ± 0.16 Ma (Connelly et al., 2012). Al–Mg data suggest that the period over which CAIs formed could have been less than 50,000 years (Bizzarro et al., 2004; Jacobsen et al., 2008). According to Pb–Pb chronometry, chondrule formation began contemporaneously with that of CAIs (Bollard et al., 2017; Connelly et al., 2017). There may have been several distinct chondrule forming events during the first

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∼4 Ma (Villeneuve et al., 2009). Various different mechanisms have been proposed for chondrule formation, as recently reviewed by Connolly and Jones (2016) and Desch et al. (2012). The details of those mechanisms are beyond the scope of this work, but there is debate over how long the period of formation or recycling continued because, in contrast to Pb–Pb, the Al–Mg system indicates a gap of 1–2 Myr between CAI formation and the earliest chondrule ages (e.g. Kita et al., 2013; Krot et al., 2009; Luu et al., 2015; Villeneuve et al., 2009). Low initial $^{26}Al/^{27}Al$ ratios may indicate post-processing of chondrules rather than formation; for instance, it has been suggested that the majority of chondrules formed within the first million years of the protoplanetary disk, and that later chondrule ages reflect re-melting and recycling of chondrules that originally formed earlier (Bollard et al., 2017). Alternatively, they may reflect that CAIs formed at the same time as the earliest chondrules but in an environment where the $^{26}Al/^{27}Al$ ratio was higher – an example of ^{26}Al heterogeneity (Larsen et al., 2016; Larsen et al., 2011). In either case, the low chondrule $^{26}Al/^{27}Al$ ratios also account for the observation that the chondrite parent bodies into which they were subsequently incorporated did not acquire sufficient ^{26}Al to cause melting and differentiation (chondrules are considered more representative of the bulk material from which planetesimals formed than CAIs).

Further insights into the timing of early Solar System processes can be gained from planetesimals that formed earlier than the chondrite parent bodies. A picture is emerging of rapid accretion beginning contemporaneously with the condensation of CAIs (e.g. Nyquist et al., 2009; Wadhwa, 2014). These early-formed planetesimals were heated by ^{26}Al decay, differentiated and ultimately formed the parent bodies of iron and achondrite meteorites. Ages of eucrites, mesosiderites and angrites indicate that melting of silicates and differentiation of rocky bodies were widespread within a few million years of Solar System formation (Bizzarro et al., 2005). Models based on a homogeneous distribution of ^{26}Al require parent bodies that subsequently differentiated to have largely accreted within ∼1.7 Ma of Solar System formation, whereas if ^{26}Al was heterogeneously distributed throughout the Solar System this timing is reduced to within 0.25 Ma of CAI formation (Schiller et al., 2015). Pb–Pb ages of angrites, a group of meteorites considered to be among the oldest differentiated material in the Solar System, indicate crystallisation within ∼3 Ma of CAIs (Amelin, 2008; Connelly et al., 2008; Schiller et al., 2015). Iron meteorites also record early differentiation: Hf–W data from magmatic iron meteorites imply the iron meteorite parent bodies probably accreted within ∼0.3 Ma of CAI formation (Kruijer et al., 2014), and that differentiation and core formation in the oldest iron meteorites occurred within ∼2 Ma of CAI formation (Burkhardt et al., 2012; Davis and McKeegan, 2014; Kleine et al., 2005; Markowski et al., 2006; Scherstén et al., 2006). Inconsistencies between these Pb–Pb ages and Al–Mg data from differentiated bodies also support the theory that ^{26}Al was heterogeneously distributed (e.g. Connelly et al., 2008; Schiller et al., 2015).

The I–Xe chronometer provides another high resolution means of studying this sequence of events (as well as the subsequent ∼70 Ma of Solar System history) (Gilmour et al., 2006). It has been shown to be concordant with the Pb–Pb system across a range of samples (Gilmour and Crowther, 2017). I–Xe ages of individual chondrules span 10 Ma in many meteorites (Swindle et al., 1996 and references therein), with some, such as chondrules from Chainpur (LL3.4), spanning 50 Ma (Holland et al., 2005; Swindle et al., 1991). There has been debate about what this range of ages represents: formation ages (Holland et al., 2005) and aqueous alteration (Swindle et al., 1991) have been suggested. More recently, Gilmour and Crowther (2017) suggested the younger ages were set as the regolith of an asteroid was compacted under the impacts from a dissipating debris disk. However, it remains the case that, as Gilmour et al. (2000) observed, the earliest chondrule ages determined using the I–Xe, Mn–Cr and Al–Mg chronometers are in reasonable agreement, and they concluded that at least the earliest I–Xe chondrule ages represent formation ages (Gilmour and Crowther, 2017; Gilmour et al., 2000).

Around 4% of ordinary chondrite meteorites contain macrochondrules or large clasts, with L and LL chondrites containing more than H chondrites (Bridges and Hutchison, 1997; Ruzicka et al., 2000). Many of these clasts are igneous in nature, and it has been suggested that they originated on early formed, differentiated, parent bodies (e.g. Bridges and Hutchison, 1997; Corrigan and Lunning, 2016; Corrigan et al., 2015; Ruzicka et al., 2012, 2000). Two such clasts from the L5 chondrite Barwell yielded early I–Xe ages, around 4567 Ma (discussed in more detail in Section 2). These early ages indicate that the I–Xe system was not reset by metamorphism on the L chondrite parent body (Gilmour et al., 2000; Hutchison et al., 1988) and so preserves another record of the formation period of CAIs, chondrules, and the first planetesimals.

2. The Barwell meteorite

The Barwell meteorite, with total mass of 44 kg, was seen to fall over Leicestershire, UK on 24th December 1965 (Jobbins et al., 1966). It was originally classified as an L6 ordinary chondrite, but the currently recommended classification is L5 chondrite (Meteoritical Bulletin Database). Relict chondrules in Barwell are typically 1–2 mm in diameter, with some as large as 7 mm. Chondrules are well defined but are equilibrated with surrounding matrix, consistent with petrologic type 5. Barwell also contains large and abundant clasts, with individual clasts as large as 15 mm (Bridges and Hutchison, 1997). In a survey of clasts and large chondrules in ordinary chondrite meteorites, Bridges and Hutchison (1997) note that the majority of clasts are igneous in nature, and objects designated as clasts tend to exhibit broken surfaces and angular outlines, features indicative of them having originally belonged to larger objects.

One particular Barwell clast, or "pebble", identified by Hutchison et al. (1988) has attracted significant interest. This clast (from sample BM1966,59) has an oxygen isotopic composition within the range of equilibrated H chondrites, but has the mineralogy and texture of an igneous rock and fractionated rare earth element abundances. The oxygen isotopic composition of Barwell itself is typical of an equilibrated L-chondrite. The clast is primarily composed of olivine (∼70%) and plagioclase (∼28%) with minor spinel, metal, troilite and apatite, and no pyroxene. The composition of olivine in the clast is identical to that of the host L chondrite. However, plagioclase and spinel in the clast are only partially equilibrated with the host meteorite, exhibiting variations in compositions across the clast. Iodine concentrations in the inclusion and bulk rock were very different, 37 ppb and 5.2 ppb respectively (Hutchison et al., 1988), indicating that iodine was probably not equilibrated between the inclusion and host.

Bridges and Hutchison (1997) identified another 7 clasts and macrochondrules in Barwell samples. The largest of these is a 10 mm clast of indeterminate type, which also has an oxygen isotopic composition that lies close to the mean value of H-chondrites. A more recent study using X-ray micro-computed tomography (μCT) has identified a further 7 clasts, which are similar to the previously identified clasts in both morphology and density (Almeida et al., 2014). Recent analyses of the chemistry, oxygen isotopic composition and Hf–W ages of some of these inclusions indicate that they have many similarities to chondrules in ordinary chondrite meteorites (Almeida et al., 2017). Hf–W model ages ∼2–3 Ma after CAI formation suggest they formed contempora-