



^{26}Mg excess in hibonites of the Rumuruti chondrite Hughes 030

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Abstract—The Rumuruti chondrites (R chondrites) constitute a new, well-established, chondrite group different from carbonaceous, ordinary, and enstatite chondrites. Most samples of this group are gas-rich regolith breccias showing the typical light/dark structure and consist of abundant fragments of various parent body lithologies embedded in a fine-grained, olivine-rich matrix. Most R chondrites contain the typical components of primitive chondrites including chondrules, chondrule and mineral fragments, sulfides, and rare calcium-aluminum-rich inclusions (CAIs). In Hughes 030, an interesting CAI consisting of abundant hibonite and spinel was found. Mg isotopic analyses revealed excess ^{26}Mg in components of R chondrites for the first time. The hibonite grains with high Al/Mg values (~1500 to 2600) show resolved ^{26}Mg excess. The slope of the correlation line yields an initial $^{26}\text{Al}/^{27}\text{Al} = (1.4 \pm 0.3) \times 10^{-6}$, which is ~40 times lower than the initial value measured in CAIs from primitive meteorites. The inferred difference in ^{26}Al abundance implies a time difference of ~4 million years for the closure of the Al-Mg system between CAIs from primitive chondrites and the Hughes 030 CAI. Based on mineralogy and the petrographic setting of the hibonite-rich CAI, it is suggested that 4 million years reflect the time interval between the formation of the CAI and the end of its secondary alteration. It is also suggested that most of this alteration may have occurred in the nebula (e.g. Zn- and Fe-incorporation in spinels). However, the CAI could not have survived in the nebula as a free floating object for a long period of time. Therefore, the possibility of storage in a precursor planetesimal for a few million years, resetting the magnesium-aluminum isotopic system, prior to impact brecciation, excavation, and accretion of the final R chondrite parent body cannot be ruled out.

INTRODUCTION

The R chondrites were established nine years ago as a new chondrite group, different from carbonaceous, ordinary, and enstatite chondrites (e.g. Schulze et al. 1994; Bischoff et al. 1994; Rubin and Kallemeyn 1994; Kallemeyn et al. 1996; Bischoff 2000). This group is named after the Rumuruti meteorite, the first, and so far the only, R chondrite fall (Schulze and Otto 1993; Schulze et al. 1994). The first R chondrite, Carlisle Lakes, was found in Australia in 1977 (Binns and Pooley 1979). Based on successful meteorite searches in hot and cold deserts in recent years, the number of R chondrites has been increased to about 20.

Generally, R chondrite samples are regolith breccias showing the typical light/dark structure and having solar-wind-implanted noble gases (Weber and Schultz 1995). These meteorites contain unequilibrated, type 3 fragments and clasts metamorphosed to various degrees and should be considered

as R3-5 or R3-6 breccias (e.g. Bischoff et al. 1994, 1998; Schulze et al. 1994; Kallemeyn, Rubin, and Wasson 1996). One of these regolith breccias is Hughes 030, which has recently been studied mineralogically and chemically (Bischoff et al. 1998). This chondrite contains abundant primitive type 3 fragments, which have been described in detail by Bischoff (2000).

During routine optical study of R chondrites, a calcium-aluminum inclusion was found in the Hughes 030 meteorite. Here, we report mineralogical and isotopic data on this inclusion. Calcium-aluminum-rich inclusions (CAIs) (and chondrules) are some of the earliest formed components of primitive meteorites: these components were formed in the nebula before their incorporation into meteorite parent bodies. A systematic study of the petrographic properties and chemical and isotopic composition of CAIs from different groups of primitive meteorites can enhance our understanding of the solar nebula and regions from which distinct meteorite

Table 1. Representative analyses of the main phases of the hibonite-bearing CAI in the R chondrite Hughes 30 and of some olivines from the surroundings; all data in wt%; all Fe as FeO.

| Mineral | Hibonite | Hibonite | Spinel* | Spinel* | Matrix olivine | |
|--------------------------------|----------|----------|---------|---------|----------------|-------|
| Na ₂ O | – | – | 0.22 | 0.29 | – | <0.03 |
| MgO | – | <0.01 | 10.4 | 9.3 | 29.1 | 28.6 |
| Al ₂ O ₃ | 92.7 | 92.2 | 65.2 | 58.5 | – | – |
| SiO ₂ | <0.03 | 0.06 | 1.05 | 5.8 | 35.5 | 35.1 |
| K ₂ O | <0.01 | <0.01 | 0.06 | 0.08 | <0.02 | <0.01 |
| CaO | 8.5 | 8.4 | 0.29 | 1.00 | 0.06 | 0.11 |
| TiO ₂ | 0.14 | 0.19 | 0.21 | 1.34 | <0.03 | <0.02 |
| Cr ₂ O ₃ | <0.02 | – | 0.05 | – | 0.05 | <0.02 |
| MnO | – | <0.03 | 0.17 | 0.23 | 0.43 | 0.48 |
| FeO | 0.31 | 0.44 | 17.8 | 14.6 | 33.7 | 35.1 |
| NiO | – | <0.05 | 0.08 | 0.05 | 0.14 | 0.15 |
| ZnO | <0.01 | – | 4.5 | 5.9 | <0.03 | <0.03 |
| Total | 101.72 | 101.30 | 100.03 | 97.09 | 99.06 | 99.54 |
| Fa | | | | | 39.4 | 40.8 |

*Spinel appears to be contaminated by different, unknown phase(s).

parent bodies sampled their constituents. Preliminary mineralogical and isotopic data on this inclusion were published by Bischoff and Srinivasan (2000).

ANALYTICAL PROCEDURES

A polished thin section from Hughes 030 (PL98015) was studied by optical microscopy in transmitted and reflected light. A field-emission scanning electron microscope (JEOL 6300F-SEM) was used to resolve the fine-grained texture of both the CAI and its surroundings. Mineral analyses were obtained with a JEOL JXA-8600 S electron microprobe operating at 15 kV and a probe current of 15 nA and with a JEOL 840A SEM equipped with a Pentafet-detector (Oxford Instruments) for energy dispersive analysis (EDS, LINK AN10000). Using the SEM for quantitative analysis, samples and appropriate mineral standards were measured at an excitation voltage of 20 kV and the beam current constancy was controlled by a Faraday cup. ZAF corrections were applied. Repeated analyses of the same areas and comparison with data obtained with the electron microprobe demonstrated the reproducibility of the system. Data from the electron microprobe were corrected according to Bence and Albee (1968).

The Al-Mg composition of the hibonite crystals were measured using the Cameca ims 4f ion microprobe at the Physical Research Laboratory, Ahmedabad, using standard techniques (Huneke, Armstrong, and Wasserburg 1983; Fahey et al. 1987a,b; Srinivasan, Huss, and Wasserburg 2000). The gold-coated, thin section was bombarded with a 17 keV ¹⁶O⁻ beam. A focused primary ion beam of ~0.5 nA resulted in a primary beam spot of about 5 microns. The primary beam current was adjusted to keep the ²⁴Mg⁺ signal below 2 × 10⁵ to minimize corrections due to deadtime. A mass resolving power of nearly 4,000 was sufficient to separate the masses of interest from neighboring hydride interferences. The reference value used for ²⁵Mg/²⁴Mg was

0.12663 and 0.13932 for ²⁶Mg/²⁴Mg (Catanzarro et al. 1966). The shifts in ²⁶Mg/²⁴Mg were calculated using a linear mass fractionation law and reported as:

$$\delta^{26}\text{Mg} = \Delta^{26}\text{Mg} - (2 \times \Delta^{25}\text{Mg}) \text{‰/amu}$$

where $\Delta^i\text{Mg} = ([^i\text{Mg}/^{24}\text{Mg}]_{\text{measured}} / [^i\text{Mg}/^{24}\text{Mg}]_{\text{standard}} - 1) \times 1000$. The Al/Mg ratios of different minerals were corrected for ionization efficiency using sensitivity factors obtained from measurements of suitable mineral standards.

RESULTS

Mineralogy: The Hibonite-Bearing CAI and Its Surroundings

The CAI is 170 × 130 μm in apparent size (Fig. 1). The most abundant mineral is hibonite. The grain size is relatively small (up to 50 μm) and some grains show cleavage plates. The second most common phase is anhedral spinel, which generally occurs intergrown with hibonite. The whole inclusion is extremely porous and surrounded by Ca-bearing phases (Fig. 1). These phases might result from alteration of former Ca-pyroxene. The observed porosity is most likely a result of alteration and leaching out of phases such as melilite. The inclusion is embedded in a fine-grained, olivine-rich matrix. Although the fine-grained matrix surrounding the CAI looks unrecrystallized and very primitive (Fig. 2), it is not of petrologic type 3. Based on the texture and composition of olivine, a petrologic type 4 is suggested for the surrounding. R chondrite type 3 clasts have matrix olivines with compositions different to those analyzed here (Bischoff 2000; see below). Olivine is the most abundant phase within the matrix. Most grains are elongated, others are blocky. The grain size is highly variable, but typically <5 μm. Pore space exists between most individual minerals (Fig. 2). In close vicinity of the CAI, zoning of olivine has not been observed, indicating a considerable degree of chemical equilibration.

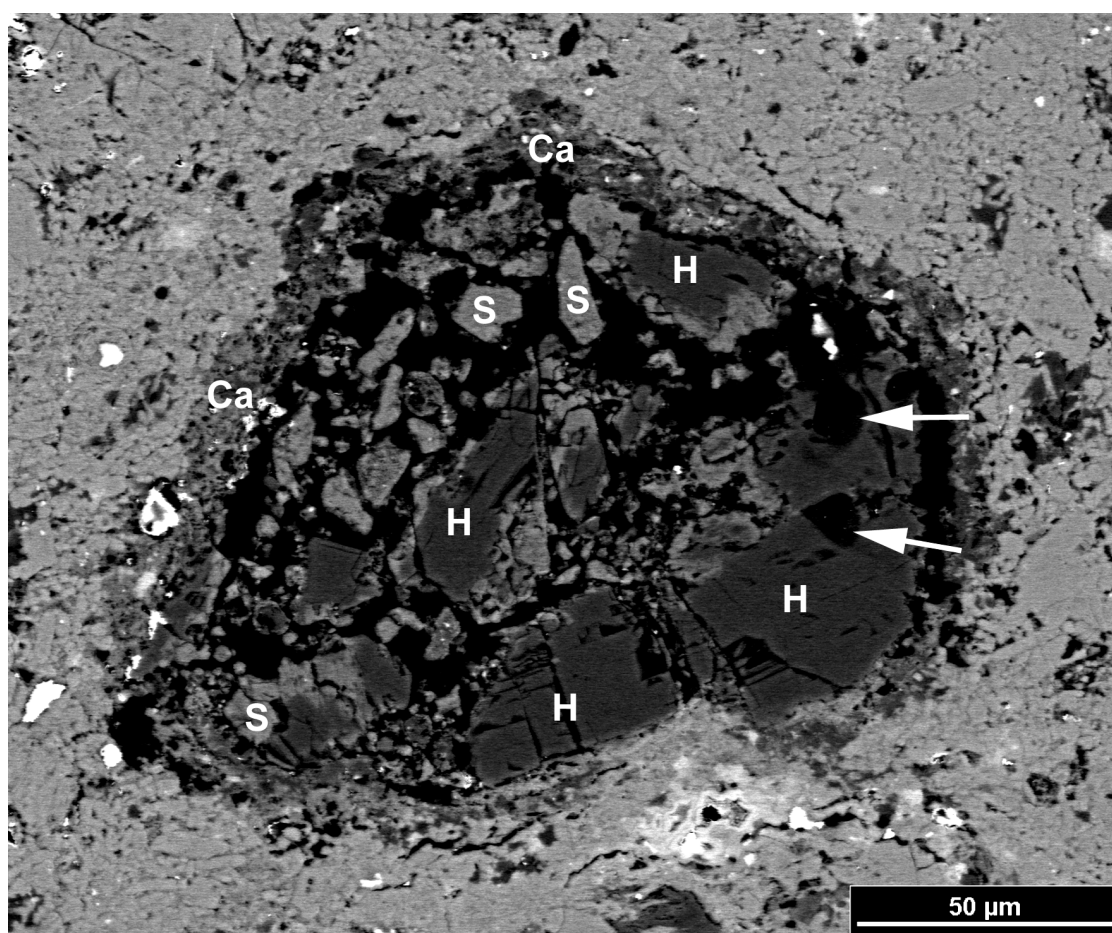


Fig. 1. Backscattered electron image of the porous CAI in the R chondrite Hughes 030. The dominant phases are hibonite (H) and Fe- and Zn-bearing spinel (S). The hibonites on the lower right hand side contain two holes due to ion-probe analyses (arrows). The whole inclusion is surrounded by an irregularly-shaped, Ca-bearing intergrowth of different unidentified phases (Ca). The bright white spots are relicts of Au from coating. The CAI is enclosed in a fine-grained, olivine-rich matrix. An enlargement of the upper right hand side is given in Fig. 2.

The matrix olivines in this fragment have the same Fa content (40.7 ± 0.9 mol%; Fig. 3) as matrix olivines in the bulk rock (40.6 ± 1.9 ; Bischoff et al. 1998; Bischoff 2000) and olivines in other equilibrated lithologies. Some representative analyses of matrix olivines are given in Table 1. Although the matrix mineralogy is strongly dominated by olivines, small grains of sulfides and Cr-rich spinels were also detected. According to the shock classification scheme for ordinary chondrites from Stöffler, Keil, and Scott (1991), the bulk rock has not been significantly shocked (Bischoff 2000, S2).

Major Element and Mg Isotopic Study of the Hibonites

Major element analyses of several hibonites revealed low concentrations of elements other than Al and Ca (Table 1). Magnesium, often incorporated in hibonites from other chondrite groups, is below the detection limit. The same holds for Cr and Mn (Table 1), and TiO_2 is very low. Considerable amounts of FeO were found (0.3–0.5 wt%). Relatively large FeO concentrations were also detected within the associated

spinel (Table 1). In addition, these spinels contain high concentrations of the volatile element Zn (Table 1). Because of the small grain size of spinel, analysis of clean, uncontaminated grains was impossible (Fig. 1, Table 1).

Hibonite crystals were analyzed for their Al-Mg composition using the ion microprobe. Three hibonite analyses with high Al/Mg values (~1500 to 2600) show clearly resolved ^{26}Mg excess (Table 2, Fig. 4). One of the hibonite analyses with a lower Al/Mg value (~200) does not show clearly resolved ^{26}Mg excess. Our attempts to measure spinels, the phase with a low Al/Mg ratio within the CAI, were not successful because of their small size. Instead, olivines in the matrix with low Al/Mg values were analyzed showing normal Mg isotopic composition. Therefore, we have used the Al-Mg data of the matrix olivine together with the hibonites in the Hughes 030 CAI to determine the initial $^{26}\text{Al}/^{27}\text{Al}$ value. This is reasonable because spinel grains within CAIs from other primitive meteorites with their low Al/Mg ratios do not show the presence of radiogenic ^{26}Mg . The slope of the correlation line yields an initial $^{26}\text{Al}/^{27}\text{Al} =$

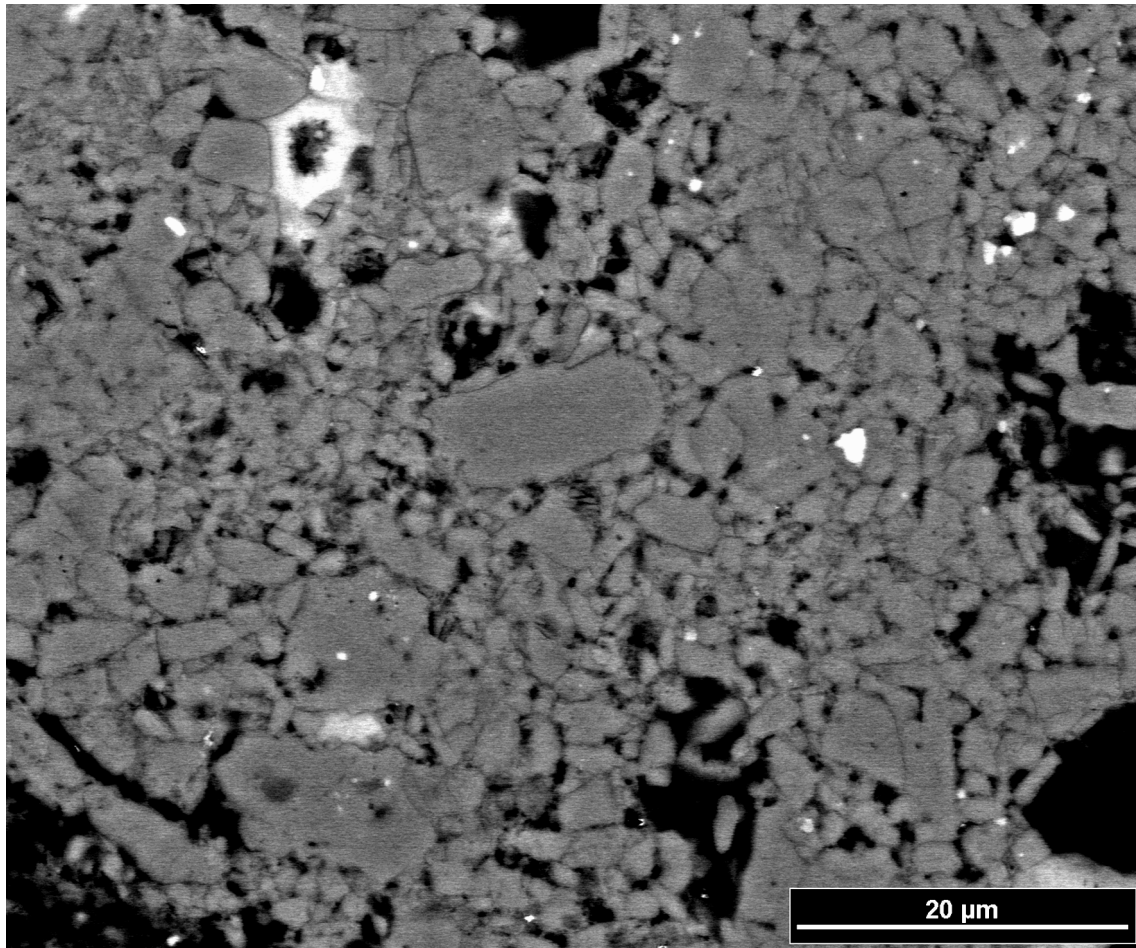


Fig. 2. Olivine is the most abundant phase within the matrix. Most grains are elongated, some are blocky. The grain size of the unzoned minerals is highly variable, but typically $<5 \mu\text{m}$. Pore space exists between most of the individual grains. The bright white spots are relicts from former Au coating. Image in backscattered electrons.

$(1.4 \pm 0.3) \times 10^{-6}$. This value is ~ 40 times lower than the initial value of $^{26}\text{Al}/^{27}\text{Al} \sim 5 \times 10^{-5}$ measured in CAIs from primitive meteorites.

DISCUSSION

Refractory CAIs from several different types of primitive meteorites; CV, CO, CM, CR, and CH meteorites; unequilibrated ordinary chondrites (UOCs); and E chondrites have been identified and studied for their mineral, chemical, and isotopic composition. The CAIs from the CV meteorites are rich in silicate-bearing phases like melilite, fassaite, plagioclase with rare olivine and oxide phases like hibonite and perovskite. The CAIs from CM meteorites, on the other hand, are often enriched in hibonites associated with spinel and perovskite. The CV CAIs are larger and more abundant, while CAIs in CM meteorites, UOCs, and E chondrites progressively decrease in size and abundance. In comparison, the Rumuruti chondrites are less endowed with CAIs (Russell 1998), which are both smaller and rarer compared to those

from CV meteorites. The task of identifying and analyzing CAIs from this class of meteorites for their Al-Mg composition is therefore extremely difficult. The spinel-hibonite-bearing CAI in Hughes 030 is unusual in its morphology and does not bear any resemblance to the spinel-hibonite-rich CAIs from CM meteorites.

The presence of the hibonite-rich CAI within the Hughes 030 meteorite may suggest that this meteorite sampled CAIs from the general population of CAIs. However, the ^{26}Al abundance of this CAI is nearly 40 times lower than those found in CAIs from primitive meteorites belonging to the carbonaceous chondrites, e.g., CV, CM meteorites, (see review by MacPherson, Davis, and Zinner 1995), unequilibrated ordinary chondrites (Russell et al. 1996; Huss et al. 2001), and enstatite chondrites (Guan et al. 2000). A large number of hibonite grains from CM meteorites have no evidence for ^{26}Al (e.g., Fahey et al. 1987a; Ireland, Fahey, and Zinner 1988; Ireland 1990; Sahijpal, Goswami, and Davis 2000). However, in the hibonite grains from CM meteorites with initial $^{26}\text{Al}/^{27}\text{Al} < 1 \times 10^{-6}$, the low $^{27}\text{Al}/^{24}\text{Mg}$ values make it difficult to

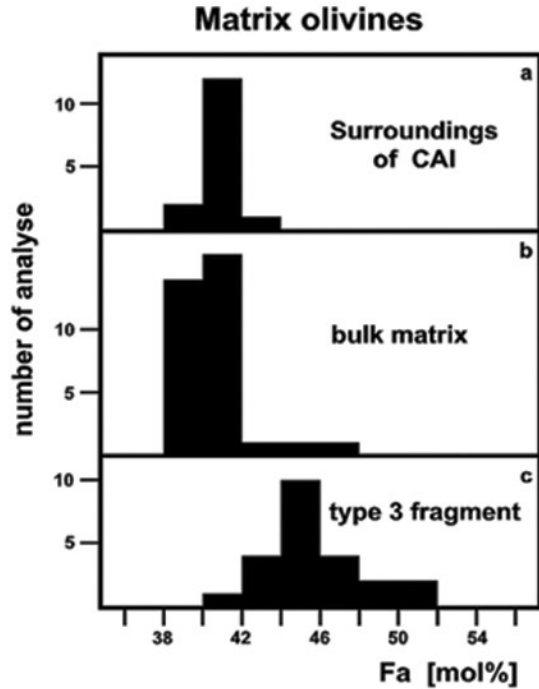


Fig. 3. Composition of matrix olivines close to the hibonite-bearing CAI: a) compared with that of matrix olivines of the bulk rock, and b) of a close unequilibrated, type 3 fragment, c) Bischoff 2000.

Table 2. Al-Mg data for Hughes 030 CAI. Hib = hibonite; M. Hib. = Madagascar hibonite (terrestrial standard); Olv = low Al/Mg-phase (perhaps matrix olivine). All errors are $2\sigma_m$.

| | $\Delta^{25}\text{Mg}$ | $\delta^{26}\text{Mg}$ | $^{27}\text{Al}/^{24}\text{Mg}$ |
|----------------|------------------------|------------------------|---------------------------------|
| M. Hib. | -8.8 ± 1.4 | 0.5 ± 2.6 | |
| Hughes 030 CAI | | | |
| Olv-1 | -10.1 ± 2.6 | 0.5 ± 2.3 | <0.2 |
| Olv-2 | -9.8 ± 1.6 | 0.6 ± 1.7 | <0.2 |
| Hib-1 | -10.3 ± 1.1 | 1.3 ± 2.7 | 20.3 ± 3.4 |
| Hib-2 | -9.9 ± 7.2 | 8.2 ± 9.4 | 199 ± 11 |
| Hib-3 | -9.3 ± 5.0 | 23 ± 10.8 | 1570 ± 294 |
| Hib-4 | -10.2 ± 5.7 | 23.7 ± 6.8 | 2561 ± 65 |
| Hib-5 | -10.6 ± 7.1 | 33.6 ± 17.2 | 2537 ± 552 |

measure resolved ^{26}Mg excess values. Therefore, in most CM hibonites with ^{26}Al abundance lower than the canonical value, only upper limits for $^{26}\text{Al}/^{27}\text{Al}$ are estimated. Furthermore, two hibonite grains with lower than canonical ^{26}Al abundance and resolved ^{26}Mg excess are FUN inclusions: HAL hibonite (Fahey et al. 1987a) and the hibonite-rich spherule A5 (Sahijpal, Goswami, and Davis 2000). Both have high $^{27}\text{Al}/^{24}\text{Mg}$ values. In contrast, the Hughes 030 hibonite-bearing CAI has high Al/Mg values. The Mg isotopic mass fractionation is normal, indicating that it is not a FUN inclusion. In addition, it shows clearly resolved ^{26}Mg excesses. This is a rare example of a hibonite-bearing object that shows a lower than canonical value of ^{26}Al abundance with resolved ^{26}Mg excesses. A similarly low ^{26}Al abundance was reported in the case of the

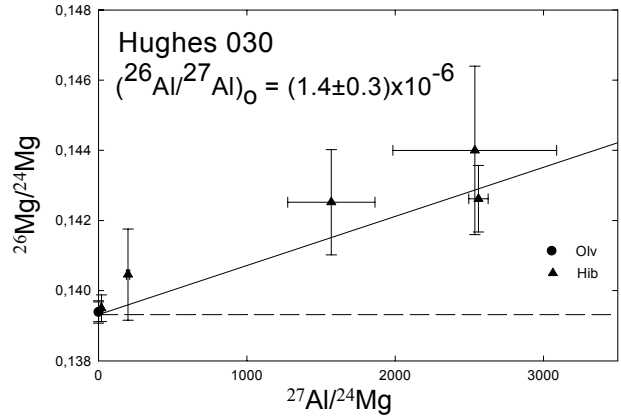


Fig. 4. The hibonite grains with high Al/Mg values (~ 1500 to 2600) show resolved ^{26}Mg excess. The slope of the correlation line yields an initial $^{26}\text{Al}/^{27}\text{Al} = (1.4 \pm 0.3) \times 10^{-6}$, which is ~ 40 times lower than the initial value measured in CAIs from other primitive meteorites. The dashed horizontal line represents the normal Mg isotopic composition measured in matrix olivines and terrestrial standards (not shown for clarity); hib = hibonite; olv = olivine.

Dhajala hibonite (Hinton and Bischoff 1984) with resolved ^{26}Mg excess. However, it was later established that the Dhajala hibonite is a FUN inclusion (Ireland et al. 1992). There are several possible explanations for the difference in ^{26}Al abundance between the Hughes CAI and CAIs with canonical ^{26}Al abundance in other primitive meteorites, and they are: 1) a time difference between the formation of the CAI in the Hughes R chondrite and CAIs from other primitive meteorites; 2) later metamorphism or low temperature alteration; and 3) heterogeneous distribution of ^{26}Al in the solar nebula.

If the general population of CAIs formed within regions with homogeneous distribution of ^{26}Al abundance, then a chronological interpretation of the data is reasonable. The simple interpretation is that the CAI in Hughes 030 has a lower ^{26}Al abundance than CAIs from other primitive meteorites because it formed much later. From the measured initial $^{26}\text{Al}/^{27}\text{Al}$ ratios in the Hughes CAI and CAIs from primitive meteorites, the estimated time difference is nearly 4 million years. However, it is difficult to reconcile how such a refractory phase like hibonite could form much later than CAIs and other less refractory objects and well within the chondrule forming epoch. It appears rather unlikely that high temperature and suitable chemical environment were available for the formation of hibonites late in the nebula, although it cannot be ruled out. If chondrules indeed formed later than CAIs as interpreted by some workers based on Al-Mg systematics, then high temperature conditions existed in the nebula for their formation. However, in addition to the high temperature conditions, it is an open question if the right chemical reservoirs existed for hibonite formation. Alternatively, if during the chondrule forming epoch, the Hughes 030 CAI was remelted and crystallized without altering its bulk chemical composition, then it could have

formed late. Therefore, the Al-Mg system would date a second event, which formed the present CAI, and a chronological significance can be attached to the ^{26}Al abundance.

The second possible interpretation is that this CAI formed at the same time as CAIs from other primitive meteorites and its Al-Mg systematic was reset later, either in the nebula and/or on precursor planetesimals. If alteration was responsible for the lower ^{26}Al abundance in this object, then this alteration event was completed nearly 4 million years after its initial formation. To distinguish nebular from parent body alteration, it is necessary to consider the petrologic context for the CAI and the chemical compositions of the constituent minerals. The surroundings of the CAI mainly consist of elongated olivines (Fig. 2) with pore space between individual grains. Texturally, there is no indication of significant matrix recrystallization. However, the matrix olivines are well equilibrated and unzoned. This may indicate that during slight annealing, elemental equilibration occurred, while observable recrystallization of the matrix phases did not take place. The texture of the matrix is relatively primitive (Fig. 2). On the other hand, the spinel grains in the CAI are enriched in Fe and Zn ($\text{ZnO} \geq 4.5 \text{ wt}\%$; Table 1). Similar observations were made in CAIs from ordinary chondrites (e.g., Bischoff and Keil 1983, 1984). The Cr-rich spinel grains in the matrix are, however, not enriched in Zn to the same extent. It is unlikely that the alteration event which introduced Zn into CAI spinels did not affect the Cr-rich spinels in the matrix. Therefore, our preferred interpretation is that this alteration process took place while the CAI was not in contact with the present matrix, but in the nebula or on a small precursor planetesimal. A slightly later thermal metamorphism, which affected the matrix olivines, may not have affected the hibonite in the CAI, which is a high temperature phase.

The hibonite-bearing CAI is enclosed within a lithology of petrologic type 4. It has been observed in CO chondrites that hibonites in all petrologic subtypes (3.0–3.7; Russell et al. 1998) and in the UOC Moorabie (type 3.8; Huss et al. 2001) retain a radiogenic ^{26}Mg signature. Some of these hibonites (from higher petrologic sub-types) may have experienced temperatures of up to 600°C or even higher for extended periods of time (Sears et al. 1991; McSween, Sears, and Dodd 1988). However, a critical evaluation of the effect of temperature on Al-Mg systematics in hibonite is not possible, because of lack of experimental data on diffusion rates of Mg in this mineral. We cannot, however, rule out the scenario that the Hughes CAI experienced alteration in an earlier generation parent body (precursor planetesimal), not necessarily related to the R chondrite parent body, before it was disrupted. The early accretion and impact-related destruction of precursor planetesimals has been discussed before (e.g., Metzler, Bischoff, and Stöffler 1992; Russell et al. 1996; Bischoff 1998; LaTourrette and Wasserburg 1998).

Russell et al. (1996) stated that if CAIs and Al-rich chondrules from unequilibrated ordinary chondrites formed from an isotopically homogeneous reservoir, then the chondrules having ^{26}Al must have formed or have been altered about two million years after the formation of CAIs. On the other hand, if both types of objects formed at the same time, the chondrules must have been affected by a later resetting of the Al-Mg-isotopic system. It cannot be expected that chondrules and CAIs survived for millions of years as free-floating objects in the nebula (Weidenschilling 1977). Therefore, Russell et al. (1996) suggested that the Al-Mg clock for some chondrules was reset prior to accretion of the final parent body in earlier-formed small bodies that were impact-fragmented. Investigation of aqueous alteration of primitive meteorites also led Metzler, Bischoff, and Stöffler (1992) and Bischoff (1998) to suggest the possibility of formation and destruction of small precursor planetesimals. They suggested that the disequilibrium mineral paragenesis in accretionary rims of primitive chondrites could be best explained assuming alteration of anhydrous minerals in relatively small and uncompacted precursor planetesimals that were later destroyed by collisions or explosion (Wilson et al. 1998) prior to accretion of the dust mantles and the final meteorite parent bodies.

All this has major consequences toward the time scale of accretion of the Hughes 030 parent body. The analyzed ^{26}Mg excess places a lower limit of nearly 4 million years from the time of formation of CAIs in other primitive meteorites with canonical ^{26}Al abundance and the formation of the Hughes parent body. Furthermore, it also implies that the formation of the parent body of brecciated meteorites such as Hughes 030 and Rumuruti, which involved collisions of several different meteorite parent bodies, occurred at least 4 million years after the CAI forming event. The Hughes 030 R chondrite regolith breccia was not significantly reheated subsequent to brecciation or lithification, as is indicated by the lack of equilibration between matrix components and Mg-rich olivines and pyroxenes in primitive type 3 fragments (Bischoff 2000).

The last possible interpretation is that ^{26}Al was heterogeneously distributed in CAI forming region(s). This could happen if the ^{26}Al carrier dust grains were not thoroughly mixed in the nebula or if the ^{26}Al was locally synthesized. In either case, the abundance of ^{26}Al will have no chronological significance (Huss et al. 2001). For example, CAIs from CH chondrites, which are considered as some of the most pristine CAIs based on petrographic and oxygen isotopic data, usually lack ^{26}Al (Weber, Zinner, and Bischoff 1995). Only one out of 18 CAIs has canonical ^{26}Al abundance. Therefore, Weber, Zinner, and Bischoff (1995) preferred heterogeneity in the ^{26}Al distribution compared to an extended duration of CAI formation over several million years. The latter scenario demands that CAIs with highly refractory phases such as grossite and hibonite formed after

^{26}Al had decayed below detectable limits. In recent years, several workers have investigated the possibility of production of ^{26}Al in the solar nebula by energetic particle reactions (e.g., Gounelle et al. 2001; Leya, Wieler, and Halliday 2002). There are two prevalent views regarding the source of ^{26}Al in the early solar system: 1) local production of ^{26}Al by energetic particle reactions, and 2) injection of ^{26}Al into the solar nebula by a stellar source in the terminal stages of its evolution. The presence of ^{10}Be in early solar system objects (McKeegan, Chaussidon, and Robert 2000; Srinivasan 2001; Sugiura, Shuzou, and Ulyanov 2001) supports the hypothesis that local production in the nebula played an important role. However, at this stage, it is not clear if one can consistently explain the abundance of several short-lived radionuclides (e.g., ^{26}Al , ^{41}Ca) by the local irradiation model (Goswami, Marhas, and Sahijpal 2001). For example, this model predicts that irradiation of average solar system material with energetic particles will underproduce ^{26}Al compared to ^{41}Ca as measured in CAIs. An ad hoc solution to this difficulty was proposed by using chemically and mineralogically layered proto-CAIs as the target material for the production of short-lived radionuclides (Gounelle et al. 2001). However, it is debatable whether such specialized target material was indeed responsible for the presence of short-lived radionuclides observed in the early solar system.

SUMMARY AND CONCLUSIONS

We have identified and analyzed a hibonite-bearing CAI from Hughes 030 Rumuruti chondrite. This CAI consists of hibonite and Fe- and Zn-bearing spinels and does not bear any morphological similarities with CAIs from CM meteorites. It has resolved ^{26}Mg excess due to the decay of ^{26}Al and its abundance is significantly lower than those measured in most pristine CAIs from primitive meteorites. The initial $^{26}\text{Al}/^{27}\text{Al}$ inferred from the Al-Mg data is $(1.4 \pm 0.3) \times 10^{-6}$, which is nearly 40 times lower than the canonical value. The magnesium isotopes in the hibonite from the Hughes CAI are not mass fractionated, thus suggesting that it is a normal and not a FUN-type CAI. This is a rare case of a non-FUN hibonite-bearing CAI having resolved ^{26}Mg excess and lower than canonical ^{26}Al abundance. Therefore, we believe that the Al-Mg systematics of this CAI was reset by a secondary event, which took place in a different environment and not in the current meteorite parent body. Processes involving formation and disruption of planetesimals continued for several million years after the initial formation of CAIs with canonical ^{26}Al abundance.

Although the Hughes CAI contains the high temperature phase hibonite, from this data alone we cannot conclude if the Hughes meteorite in particular and R chondrites in general sampled the population of CAIs that formed with initial $^{26}\text{Al}/^{27}\text{Al}$ values close to the canonical value. The mineral and chemical composition of the CAI and the surrounding matrix suggests that the alteration experienced by the CAI did not

take place in the present parent body of the Rumuruti chondrite. Furthermore, the low temperature process that equilibrated the matrix olivines probably did not affect the Al-Mg systematics in the CAI. The lower initial ^{26}Al abundance of the hibonite CAI most likely reflects a time interval between the formation of CAIs and the alteration event that affected the Hughes 030 CAI. This alteration presumably occurred both in the nebula and in a small precursor planetesimal.

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REFERENCES

- Bence A. E. and Albee A. L. 1968. Empirical correction factors for the electron microanalysis of silicates and oxides. *The Journal of Geology* 76:382–403.
- Binns R. A. and Pooley G. D. 1979. Carlisle Lakes: A unique oxidized chondrite (abstract). *Meteoritics* 14:349–350.
- Bischoff A. 1998. Aqueous alteration of carbonaceous chondrites: Evidence for preaccretionary alteration—A review. *Meteoritics & Planetary Science* 33:1113–1122.
- Bischoff A. 2000. Mineralogical characterization of primitive, type 3 lithologies in Rumuruti chondrites. *Meteoritics & Planetary Science* 35:699–706.
- Bischoff A. and Srinivasan G. 2000. Mg-26 excess in hibonites of the Rumuruti chondrite Hughes 030 (abstract). *Meteoritics & Planetary Science* 35:A26–A27.
- Bischoff A. and Keil K. 1983. *Catalog of Al-rich chondrules, inclusions, and fragments in ordinary chondrites*. Special Publication No. 22. Albuquerque: University of New Mexico. p. 33.
- Bischoff A. and Keil K. 1984. Al-rich objects in ordinary chondrites: Related origin of carbonaceous and ordinary chondrites and their constituents. *Geochimica et Cosmochimica Acta* 48:693–709.
- Bischoff A., Geiger T., Palme H., Spettel B., Schultz L., Scherer P., Loeken T., Bland P., Clayton R. N., Mayeda T. K., Herpers U., Meltzow B., Michel R., and Dittrich-Hannen B. 1994. Acfer 217—A new member of the Rumuruti chondrite group (R). *Meteoritics* 29:264–274.
- Bischoff A., Weber D., Bartoschewitz R., Clayton R. N., Mayeda T.K., Schultz L., Spettel B., and Weber H. W. 1998. Characterization of the Rumuruti chondrite regolith breccia Hughes 030 (R3-6) and implications for the occurrence of unequilibrated lithologies on the R-chondrite parent body (abstract). *Meteoritics & Planetary Science* 33:A15–A16.
- Catanzarro E. J., Murphy T. J., Garner E. L., and Shields W. R. 1966. Absolute isotopic abundance ratios and atomic weight of magnesium. *Journal of Research of the National Institute of Standards and Technology* 70A:453–458.
- Fahey A. J., Goswami J. N., McKeegan K. D., and Zinner E. 1987a. ^{26}Al , ^{244}Pu , ^{50}Ti , REE and trace elemental abundances in hibonite grains from CM and CV meteorites. *Geochimica et Cosmochimica Acta* 51:329–350.
- Fahey A. J., Zinner E. K., Crozaz G., and Kornacki A. S. 1987b.

- Microdistributions of Mg isotopes and REE abundances in type A calcium-aluminum-inclusions from Efremovka. *Geochimica et Cosmochimica Acta* 51:3215–3229.
- Goswami J. N., Marhas K. K., and Sahijpal S. 2001. Did solar energetic particles produce the short-lived nuclides present in the early solar system? *The Astrophysical Journal* 549:1151–1159.
- Gounelle M., Shu F. H., Shang H., Glassgold A. E., Rehm K. E., and Lee T. 2001. Extinct radioactivities and protosolar cosmic rays. *The Astrophysical Journal* 548:1051–1070.
- Guan Y., Huss G. R., MacPherson G. J., and Wasserburg G. J. 2000. Calcium-aluminum-inclusions from enstatite chondrites: Indigenous or foreign? *Science* 289:1330–1333.
- Hinton R. W. and Bischoff A. 1984. Ion microprobe magnesium isotope analysis of plagioclase and hibonite from ordinary chondrites. *Nature* 595:169–172.
- Huneke J. C., Armstrong J. T., and Wasserburg G. J. 1983. FUN with PANURGE: High mass resolution ion microprobe measurements of magnesium in Allende inclusions. *Geochimica et Cosmochimica Acta* 47:1635–1650.
- Huss G., MacPherson G. J., Wasserburg G. J., Russell S. S., and Srinivasan G. 2001. Aluminum-26 in calcium-aluminum-rich inclusions and chondrules from unequilibrated ordinary chondrites. *Meteoritics & Planetary Science* 36:975–997.
- Ireland T. R. 1990. Presolar isotopic and chemical signatures in hibonite bearing refractory inclusions from Murchison carbonaceous chondrite. *Geochimica et Cosmochimica Acta* 54:3219–3237.
- Ireland T. R., Fahey A. J., and Zinner E. K. 1988. Trace element abundances in hibonites from Murchison carbonaceous chondrite: Constraints on high temperature processes in the solar nebula. *Geochimica et Cosmochimica Acta* 52:2841–2854.
- Ireland T. R., Zinner E. K., Fahey A. J., and Esat T. M. 1992. Evidence for distillation in the formation of HAL and related hibonite inclusions. *Geochimica et Cosmochimica Acta* 56:2503–2520.
- Kallemeyn G. W., Rubin A. E., and Wasson J. T. 1996. The compositional classification of chondrites: VII. The R chondrite group. *Geochimica et Cosmochimica Acta* 60:2243–2256.
- LaTourrette T. and Wasserburg G. J. 1998. Mg diffusion in anorthite: implications for the formation of early solar system planetesimals. *Earth and Planetary Science Letters* 158:91–108.
- Leya I., Wieler R., and Halliday A. N. 2002. Nucleosynthesis by spallation reactions in the early solar system (abstract). *Meteoritics & Planetary Science* 37:A86.
- MacPherson G. J., Davis A. M., and Zinner E. K. 1995. The distribution of aluminum-26 in early solar system—A reappraisal. *Meteoritics* 30:365–386.
- McKeegan K. D., Chaussidon M., and Robert F. 2000. Incorporation of short-lived ^{10}Be in a calcium-aluminum-rich inclusion from the Allende meteorite. *Science* 289:1334–1337.
- McSween H. Y., Sears D. W. G., and Dodd R. T. 1988. Thermal Metamorphism. In *Meteorites and the early solar system*, edited by Kerridge J. F. and Matthews M. S. Tucson: University of Arizona Press. pp. 102–113.
- Metzler K., Bischoff A., and Stöffler D. 1992. Accretionary dusty mantles in CM chondrites: Evidence for solar nebula processes. *Geochimica et Cosmochimica Acta* 56:2873–2897.
- Rubin A. E. and Kallemeyn G. W. 1994 Pecora Escarpment 91002: A member of the new Rumuruti (R) chondrite group. *Meteoritics* 29:255–264.
- Russell S. S. 1998. A survey of calcium-aluminum-rich inclusions from Rumuruti chondrites: Implications for relationship between meteorite groups (abstract). *Meteoritics & Planetary Science* 33:A131–A132.
- Russell S. S., Srinivasan G., Huss G. R., MacPherson G. J., and Wasserburg G. J. 1996. Evidence for widespread ^{26}Al in the solar nebula and new constraints for nebula time scales. *Science* 273:757–762.
- Russell S. S., Huss G. R., Fahey A. J., Greenwood R. C., Hutchison R., and Wasserburg G. J. 1998. An isotopic and petrologic study of calcium-aluminum-rich inclusions from CO3 meteorites. *Geochimica et Cosmochimica Acta* 62:689–714.
- Sahijpal S., Goswami J. N., and Davis A. M. 2000. K, Mg, Ti and Ca isotopic compositions and refractory trace element abundances in hibonites from CM and CV meteorites: Implications for early solar system processes. *Geochimica et Cosmochimica Acta* 64:1989–2005.
- Schulze H. and Otto J. 1993 Rumuruti: a new Carlisle Lakes-type chondrite (abstract). *Meteoritics* 28:433.
- Schulze H., Bischoff A., Palme H., Spettel B., Dreibus G., and Otto J. 1994. Mineralogy and chemistry of Rumuruti: The first meteorite fall of the new R chondrite group. *Meteoritics* 29:275–286.
- Sears D. W. G., Hasan F. A., Batchelor J. D., and Lu J. 1991. Chemical and physical studies of type 3 chondrites-XI: Metamorphism, pairing and brecciation of ordinary chondrites. Proceedings, 21st Lunar and Planetary Science Conference. pp. 493–512.
- Srinivasan G. 2001. Be-B isotope systematics in CAI E65 from Efremovka CV3 chondrite (abstract). *Meteoritics & Planetary Science* 36:A195–A196.
- Srinivasan G., Huss G. R., and Wasserburg G. J. 2000. A petrographic, chemical and isotopic study of calcium-aluminum-rich inclusions and aluminum-rich chondrules from Axtell (CV3) chondrite. *Meteoritics & Planetary Science* 35:1333–1354.
- Stöffler D., Keil K., and Scott E. R. D. 1991. Shock metamorphism of ordinary chondrites. *Geochimica et Cosmochimica Acta* 55:3845–3867.
- Sugiura N., Shuzou Y., and Ulyanov A. 2001. Beryllium-boron and aluminum-magnesium chronology of calcium-aluminum-rich inclusions in CV chondrites. *Meteoritics & Planetary Science* 36:1397–1408.
- Weber D., Zinner E. K., and Bischoff A. 1995. Trace element abundances of magnesium, calcium, and titanium isotopic compositions of grossite-containing inclusions from the carbonaceous chondrite Acfer 182. *Geochimica et Cosmochimica Acta* 59:803–823.
- Weber H. W. and Schultz L. 1995. Noble gases in Rumuruti-group chondrites (abstract). *Meteoritics* 30:596.
- Weidenschilling S. J. 1977. Aerodynamics of solid bodies in the solar nebula. *Monthly Notices of the Royal Astronomical Society* 180:7–70.
- Wilson L., Keil K., Browning L. B., Krot A. N., and Bourcier W. 1999 Early aqueous alteration, explosive disruption, and reprocessing of asteroids. *Meteoritics & Planetary Science* 34:541–557.