Formation of accretionary dust mantles in the solar nebula: Evidence from preirradiated olivines in CM chondrites

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Abstract—CM chondrites are regolith breccias consisting of lithic clasts embedded in a fine-grained clastic matrix. The majority of these lithic clasts belongs to a texturally well-defined rock type (primary rock) that can be described as an agglomerate of chondrules and other coarse-grained components, most of which are surrounded by fine-grained rims (dust mantles). Metzler et al. (1992) explain these textures as the result of accretionary processes in the solar nebula, while an alternative model explains them to be the result of regolith processes on the parent body (Sears et al. 1993).

The main intention of the present study is to discern between both models by investigating the occurrence, frequency, spatial distribution, and textural setting of preirradiated (track-rich) olivines in CM chondrites. Track-rich olivines were studied in situ in six polished thin sections from 4 different CM chondrites (Cold Bokkeveld, Mighei, Murchison, Nogoya) by optical and scanning electron microscopy (SEM). It was found that their occurrence is restricted to the clastic matrix of these meteorites. The primary rock seems to have formed in an environment shielded from cosmic radiation, since fragments of this rock are free of track-rich grains and solar noble gases. This finding supports the solar nebula model for the formation of dust mantles around chondrules and other coarse-grained components, and points against a regolith origin.

In Cold Bokkeveld, a small breccia-in-breccia clast was found, which has been irradiated as an entity within the uppermost millimeters to meters of its parent body for at least about 3 Ma. This clast seems to represent a compacted subsurface layer that was later excavated by impact and admixed to the host breccia.

Furthermore, the results of this study may affect the interpretation of compaction ages obtained by fission track methods, since these ages may be mixtures of different contact ages between fine-grained, U-rich dust and U-poor olivines. In some cases, they may date the formation of dust mantles in the solar nebula, while in other cases the lithification of the host breccias may be dated.

INTRODUCTION

CM chondrites are primitive meteorites originating from parent bodies that have been affected to various extent by impact brecciation and aqueous alteration, but seem to have escaped considerable thermal processing after their formation 4.56 Ga ago (e.g., Sears and Dodd 1988; Brearley and Jones 1998). Hence, these rocks contain information on the physical and chemical conditions in the protoplanetary nebula and during planetary accretion. CM chondrites are impact breccias composed of subangular mineral and lithic clasts set in a clastic matrix (e.g., Fuchs et al. 1973; Dodd 1981; Metzler et al. 1992; Metzler 1995). This texture is shown in Fig. 1 for the CM chondrite Nogoya, where a variety of lithic clasts, both lighter and darker than the surrounding clastic matrix, can be observed. The boundaries between clasts and matrix are usually sharp and can be identified macroscopically (e.g., Heymann and Mazor 1967) or using scanning electron microscopy (SEM) techniques (Fig. 2). Most lithic clasts belong to a texturally well-defined rock type (primary rock) that is internally unbrecciated, consists of chondrules, CAIs, and other coarse-grained components, most of which are surrounded by fine-grained rims or dust mantles (Metzler et al. 1992; see upper part of Fig. 2). The clastic matrix, in which the fragments of primary rock are embedded, consists of fine-grained debris (see lower part of Fig. 2). The mineralogical and chemical composition of clastic matrix and primary rock in a given meteorite is very
similar, leading to the assumption that both lithologies formed from coherent primary rock by comminution (Metzler et al. 1992).

Most CM chondrites are regolith breccias with enhanced concentrations of solar wind implanted noble gases (e.g., Heyman and Mazor 1967; Smith et al. 1978) and contain mineral grains that were targeted by heavy ions from solar and galactic cosmic radiation (e.g., Pellas et al. 1969; Caffee et al. 1988). These grains can be detected by optical microscopy after etching the samples with suitable chemical agents. These so-called track-rich grains show high densities of nuclear tracks (lattice defects) formed by the interaction with charged particles (e.g., Fleischer et al. 1975). Two olivine grains of this type from Cold Bokkeveld are shown in Fig. 3.
The main intention of the present study is to investigate the occurrence, frequency, spatial distribution, and textural setting of track-rich olivines using polished thin sections. Although there is a considerable data base (e.g., Price et al. 1975; MacDougall and Price 1974; Goswami and Lal 1979), most studies are based on olivines that were extracted from their host meteorites by crushing the samples and hand picking of suitable grains. Although generally appropriate for basic investigations and for obtaining statistical data, this method destroys the original textures and leaves no information on the textural settings. The use of this standard procedure makes it impossible to identify the host lithology of track-rich components, and important information gets lost. The work by Goswami and MacDougall (1983) seems to be the only exception. They present a sketch of a thin section from the CM chondrite Murray, which shows the locations of in situ etched olivines in track-rich inclusions. However, at the time, little was known about the internal texture of brecciated CM chondrites and no attempt was made to correlate the locations of these grains with distinct lithological units.

To address this shortcoming, large polished thin sections from Cold Bokkeveld, Mighei, Murchison, and Nogoya were mapped with SEM, subsequently etched to reveal the tracks, and investigated by optical microscopy. This method preserves the textural relationship between track-rich grains and their host lithologies.

The results of this study are relevant to the interpretation of the bulk texture and the formation history of CM chondrites, and help to answer the following questions (see the Discussion section):

1. Is there a distinct host lithology for track-rich grains in CM chondrites?
2. Is there a systematic correlation between the occurrence of preirradiated grains and solar wind implanted noble gases?
3. Did dust mantles around chondrules and other coarse-grained components form by solar nebula processes or by regolith activity on the parent body?

SAMPLES AND ANALYTICAL TECHNIQUES

Eight polished thin sections (surface 1.5–5.3 cm²; thickness about 40 microns) from four CM chondrites were studied by optical microscopy (transmitted and reflected light) and SEM (Table 1). Chemical analyses were obtained using an energy dispersive X-ray analyzing system (Link AN10000) attached to a JEOL 840A scanning electron microscope.

For each thin section, a mosaic of backscattered electron (BSE) images was prepared to map the texture and the distribution of the main lithologies. These mosaics store detailed information on the original state of the etched thin sections and help identify textural features on the µm scale. Six of the eight thin sections were etched in boiling WN solution (Krishnaswami et al. 1971) for about 4.5 hr to reveal the nuclear tracks in olivine. To protect the sensitive surfaces from erosion during etching, the thin sections were stored in a teflon container permeable to the etching solution. After etching, the sections were cleaned in hot distilled water and, subsequently, dried under red light.

After etching, each thin section was scanned by optical
microscopy with a magnification of 800× to identify and locate track-rich olivines. These show either a much higher density of nuclear tracks than the surrounding transit irradiation background and/or a steep track gradient due to irradiation by solar cosmic rays in the uppermost regolith layers. Track-rich olivine grains identified by this method were located and mapped on the BSE photomosaics. Additionally, the size and track density of each grain was determined to identify the track density distribution and possible correlations between grain size and track density.

RESULTS

Etching Effects on Polished Thin Sections

Due to chemical treatment, all thin sections changed their appearance from nearly opaque to translucent. After etching, many textural details, previously detectable only by scanning electron microscopy, are visible by the naked eye, as shown for Nogoya in Fig. 1. After etching, most fragments of primary rock strongly contrast with the clastic matrix because they appear lighter or darker than the surrounding material (Fig. 1). The observation that fragments of primary rock in Nogoya react differently to the etching solution can be explained by the fact that these clasts have been affected to various degrees by aqueous alteration on the parent body (e.g., Zolensky and McSween 1988; Metzler 1995).

Much of the fine-grained material, e.g., clastic matrix and fine-grained rims around chondrules, was removed during etching. Only a thin layer of these components, directly glued to the glass holder by the resin sheet, remains. On the other hand, coarser components like chondrules and large mineral grains are preserved showing their original thickness of about 40 microns. This observation implies that most olivine grains smaller than the original thickness of the sections (about 40 microns) have been removed during etching and are lost for track investigations. Due to the removal of fine-grained opaque components, the characteristic agglomeration texture of primary rock, previously visible only in backscattered electron images, is now easily visible in transmitted light (Fig. 4).

The most important finding is that the textural relationships between various components in all etched thin sections are preserved, i.e., all track-rich grains can be unambiguously assigned to their host lithologies.

Background Track Densities (Transit Irradiation)

Background track densities in meteoritic minerals are produced by galactic cosmic rays (GCR) during meteoroid transit to Earth (e.g., Caffee et al. 1988; Vogt et al. 1990). Background track densities observed in the investigated samples (Table 2) vary between $3.6 \times 10^4$ tracks/cm$^2$.
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(Nogoya) and $5.1 \times 10^5$ tracks/cm$^2$ (Mighei). These values, although depending on the shielding depth within the corresponding meteoroids, roughly correspond to the exposure ages of the host meteorites, which vary between 0.25 and 3 Ma (Metzler 1990). These exposure ages are based on $^{21}$Ne production rates of $0.243 \times 10^{-8}$ cc STP/g Ma (Nishiizumi et al. 1980).

Table 2. Nuclear track data for olivine grains from the investigated samples.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>PTS$^a$ surface (cm$^2$)</th>
<th>Number of analyzable olivines</th>
<th>Background track density (tracks/cm$^2$)$^b$</th>
<th>Percentage of preirradiated olivine grains</th>
<th>Percentage of preirradiated olivines with track gradient</th>
<th>Mean track density in preirradiated olivines (tracks/cm$^2$)$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Bokkeveld</td>
<td>4.6 (3PTS)</td>
<td>2400</td>
<td>$2.6 \times 10^7$</td>
<td>$2.2 (3.5)^d$</td>
<td>$17 (27)^d$</td>
<td>$1.8 \times 10^7$</td>
</tr>
<tr>
<td>Inclusion CoBo-ii-1</td>
<td>0.08</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mighei</td>
<td>2.6</td>
<td>810</td>
<td>$5.1 \times 10^5$</td>
<td></td>
<td></td>
<td>$1.5 \times 10^7$</td>
</tr>
<tr>
<td>Murchison</td>
<td>5.3</td>
<td>2700</td>
<td>$7.1 \times 10^4$</td>
<td>$2.1 (3.2)^e$</td>
<td>$29$</td>
<td>$2.5 \times 10^7$</td>
</tr>
<tr>
<td>Nogoya</td>
<td>1.8</td>
<td>310</td>
<td>$3.6 \times 10^4$</td>
<td></td>
<td></td>
<td>$1.1 \times 10^7$</td>
</tr>
</tbody>
</table>

$^a$Polished thin sections.
$^b$Transit irradiation
$^c$Track densities $>5 \times 10^7$ were taken as $5 \times 10^7$ for calculation.

Textural Setting of Track-Rich Olivines

I inspected 6220 olivine grains in 6 thin sections using optical microscopy (Table 2) and found that 115 grains have been irradiated before transit of the parent meteoroid to Earth. Olivines with track densities $>10^6$ tracks/cm$^2$ were classified as track-rich and were found in three of the four studied meteorites in a small but remarkably constant quantity of about 2.1–2.3%. These values are similar to the results by MacDougall and Phinney (1977) and Goswami and Lal (1979) who obtained values between 1.8 and 3.5%. The grains were mapped in the previously prepared BSE photomosaics and the results were transformed into sketch maps shown in Figs. 5a–5f. These sketch maps show the main CM lithologies, i.e., clastic matrix and embedded fragments of primary rock.

All track-rich grains are located in the clastic matrix of these meteorites (Fig. 5). The locations are indicated by black dots. No track-rich grain has been found within fragments of primary rock (hatched areas). The sketch map of the Mighei thin section (Fig. 5d) indicates that it is a large fragment of primary rock, free of any track-rich olivine. Track-rich grains have been found in the clastic matrix of Murchison, Cold Bokkeveld, and Nogoya. A common feature is their distinctly inhomogeneous spatial distribution. In Murchison and Nogoya, large areas of clastic matrix are free of them, while they are concentrated in others. This is most obvious in the case of Murchison (Fig. 5e) where the left part of the section shows a fairly homogeneous distribution, contrasted by the inhomogeneous distribution on the right hand side. This figure visualizes earlier findings by Price et al. (1975) and Goswami and Lal (1979), who describe large variations in the proportion of track-rich grains in bulk olivine separates obtained from different locations in a given CM specimen.

In addition to isolated track-rich olivines, two thin sections of Cold Bokkeveld, which had been sliced parallel to each other, contain a specific lithology full of track-rich olivines. This fragment differs from the surrounding clastic matrix by its distinct texture and mineralogical composition. It is named CoBo-ii-1, has a size of about 4 × 1 mm, and is characterized by its elongated shape (Fig. 6). This fragment can be observed in 4 parallel thin sections, two of which were not etched for track revelation (see Table 1; Fig. 7). The 3-dimensional information from Fig. 7 indicates that it represents a platy-shaped fragment that must have been admixed to the Cold Bokkeveld breccia before compaction. Petrographic investigations of the four parallel thin sections revealed that this fragment itself is a breccia (breccia-in-breccia-structure) consisting of fragments of primary rock, embedded in fine-grained clastic matrix. CoBo-ii-1 has a mineralogical composition that is distinctly different from its surrounding material and is characterized by the absence of tochilitine and the frequent occurrence of magnetite clusters. Its texture and mineralogy resembles the more heavily (aqueously) altered portions of other CM chondrites, e.g., Nogoya (e.g., Metzler 1995). Although it is beyond the scope of this paper to describe the composition of this fragment in detail, it seems clear that it represents a brecciated subsurface layer of the Cold Bokkeveld parent body, which has undergone a specific evolution (see below).

Track Densities in Preirradiated Olivines

The mean track density in preirradiated olivines is remarkably constant, ranging from $1.1–2.5 \times 10^7$ tracks/cm$^2$ (Table 2). The percentage of olivines with track gradients, irradiated by solar cosmic rays directly on the parent body surface, varies between 17 (Cold Bokkeveld) and 29
Fig. 5. Sketch maps indicating the spatial distribution of the main lithologies and preirradiated olivines (black dots) in thin sections of the investigated samples. The distribution of track-rich olivines is inhomogeneous and the occurrence of these grains is restricted to the clastic matrix. The hatched areas represent fragments of primary rock, areas without signature represent clastic matrix. Dashed lines in sketch maps from Cold Bokkeveld indicate the preirradiated breccia-in-breccia clast CoBo-ii-1 (compare Figs. 6 and 7): a, b, and c) Cold Bokkeveld; d) Mighei; e) Murchison; f) Nogoya.
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(Nogoya). These values are similar to literature data obtained from extracted olivines (MacDougall and Phinney 1977; Goswami and Lal 1979).

Fragments of Primary Rock

Although large areas of the studied thin sections consist of fragments of primary rock (Fig. 5), none of these fragments contain track-rich grains. The same holds for the thin section of Mighei, which consists entirely of a single fragment of primary rock. Olivines in this lithology show track density distributions typical for single stage irradiations of the corresponding meteoroids during transit from parent body to Earth (see above).

Inclusion CoBo-ii-1 (Breccia-in-Breccia Structure)

All olivines in this lithology that are suitable for track counting (25 grains) are track-rich. The track densities vary from grain to grain between 0.52 and $2.78 \times 10^7$ tracks/cm$^2$, with a mean track density of $1.48 \times 10^7$ tracks/cm$^2$ (Table 2; Fig. 8). The variation factor of 5.4 is close to the value of 4, which is the variation in track revelation due to different crystal orientations in thin sections (Pellas, personal communication).

Clastic Matrix

Data for preirradiated olivines in the clastic matrix from Cold Bokkeveld and Murchison are shown in Fig. 9. In both meteorites, the track densities vary between $1 \times 10^6$ tracks/cm$^2$ and $>5 \times 10^7$ tracks/cm$^2$. Grains with track gradients show similar distributions. Please note that the data for Cold Bokkeveld (Fig. 9a) include those from the breccia clast CoBo-ii-1, leading to the peak between 1 and $2 \times 10^7$ tracks/cm$^2$ (compare Fig. 8). The data for several track-rich grains included in the database of Table 2 are not shown in this figure because they were not suitable for track counting (due to inclusions, opacity, etc.).

To identify possible correlations between grain sizes and track densities, the data from Murchison are used and shown in Fig. 10. The grain sizes of track-rich grains vary between...
Grains with track gradients were observed exclusively in the size fraction between 110 and 700 microns, but this observation might result from the fact that track gradients in smaller grains are difficult to detect.

**DISCUSSION**

**Brecciation of CM Chondrites in a Planetary Environment**

Track-rich olivines were found throughout the clastic matrix of the investigated samples, while lithic clasts are free of these grains. This is the typical finding for extraterrestrial impact breccias, where the track-rich components were admixed to the fine-grained portion during impact activity on the parent body’s surface (e.g., Bunch and Rajan 1988; Caffee et al. 1988). During this process, solar and galactic particle irradiation penetrated the uppermost millimeters to meters of the parent body surfaces and produced freshly irradiated components for admixture. In the case of CM chondrites, fragments of primary rock probably represent fresh samples of unbrecciated bedrock excavated by impacts from the depths that were never reached by cosmic radiation. These fragments were admixed to the CM breccias together with track-rich grains that previously resided at the very surface of the parent body.
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On the other hand, it is remarkable that the amount of preirradiated grains is relatively low compared to other types of regolith breccias, e.g., those from the Moon (Macdougall 1982). The absence (or at least scarcity) of preirradiated lithic clasts also discerns CM chondrites from achondritic, lunar, and OC regolith breccias. These differences may be explained by the very old compaction ages of these meteorites, which give values in the order of 4.5 Ga (see below). These data imply that CM breccias are not the result of recent impact activity but formed during an epoch of planetary evolution that was dominated by rapid growth and burial of preexisting surfaces rather than by regolith reworking.

Inclusion CoBo-ii-1: A Preirradiated Breccia-in-Breccia Structure in Cold Bokkeveld

The clast CoBo-ii-1 seems to represent a preirradiated breccia-in-breccia structure, formed by impact processes on the parent body. It is important to note that this clast type has texturally nothing in common with fragments of primary rock with their typical accretionary texture.

The variation factor in track densities of only 5.4 within this clast of 4 mm in length indicates that it was irradiated as a single entity by a uniform dose of galactic cosmic particle irradiation, otherwise, the observed track densities should differ much more. Since no solar flare tracks (track gradients) can be observed, this clast was probably irradiated in a near-surface layer of the regolith. The clast must have been shielded from solar radiation while located within the GCR-track production zone, which means a depth between a few millimeters to a few meters. Assuming a location just below the solar flare track production zone, i.e., in the uppermost millimeters of the regolith layer, the clast must have been irradiated for about 3 Ma by GCR. This value was obtained using the observed mean track density and the nomogram by Bhattacharya et al. (1973). It is a minimum value since locations deeper within the regolith layer would increase the irradiation times significantly.

The clast CoBo-ii-1 seems to have undergone the following evolution: 1) formation as part of primary rock with its typical accretionary fabric (e.g., dust mantles around chondrules, CAIs, etc.); 2) aqueous alteration (e.g., formation of magnetite clusters); 3) impact brecciation and admixture of unaltered material (e.g., Fe-rich olivine without phyllosilicate reaction zones); 4) breccia compaction; 5) irradiation by galactic cosmic rays in close vicinity to the parent body surface, shielded from solar cosmic radiation; 6) second stage of impact brecciation, launch, and admixture to the present breccia in the shape of a lithic clast; and 7) breccia compaction. Although this scenario seems to be rather complicated, especially concerning the multiple impact brecciation and compaction, it is well-known from many other types of extraterrestrial breccias.


Models for the Formation of Accretionary Dust Mantles

The majority of lithic clasts in CM chondrites belongs to a texturally well-defined rock type (upper part of Fig. 2) that can be described as an agglomerate of chondrules and other coarse-grained components, most of which are surrounded...
by accretionary dust mantles. Due to its ubiquitous occurrence and accretionary texture, this rock type is called “primary (accretionary) rock” by Metzler et al. (1992). These authors explain the formation of dust mantles by sticking of fine-grained dust to chondrule surfaces in the solar nebula, a potential mechanism already proposed by Bunch and Chang (1984) and is now widely accepted (e.g., Hewins and Herzberg 1996; Pagne and Cuzzi 1997; Morfill et al. 1998; Cuzzi et al. 1998; Lauretta et al. 2000; Simon and Grossman 2001; Hua et al. 2002; Zega and Buseck 2003).

An alternative model explains the formation of dust mantles by regolith processes on the parent body (Sears et al. 1993). This model assumes that the formation of dust mantles and admixture of track-rich grains occurred simultaneously in a single process, namely regolith gardening due to impact activity on the parent body. These authors assume that dust mantles possibly formed by the “objects sloshing about in the mud” of the “apparently very wet regolith.” In the view of these authors, the entire texture of CM chondrites is the product of planetary processes.

Both models predict that CM chondrites contain track-rich grains, but there is a decisive difference concerning their textural setting. The model by Metzler et al. predicts their occurrence exclusively in the clastic matrix, since it assumes that, in the first step, dust mantles formed in the solar nebula, followed by a calm accretion of mantled objects to the parent body and suffering mild compaction and lithification. Up to this evolutionary state, the material was shielded from cosmic radiation. In the second step, brecciation and irradiation are the dominant processes in a more violent regolith environment, leading to the formation of clastic matrix with admixture of track-rich olivines. In contrast to this chronological sequence, the model by Sears et al. predicts the occurrence of track-rich components throughout the entire breccia, i.e., within clastic matrix portions, within fragments of primary rock, and even within dust mantles.

Shielding of Primary Rock During Accretion

The existence of primary rock as a major lithology seems to prove that the earliest rock generation from CM parent bodies mainly formed from dust-mantled components, followed by compaction. The observation that the investigated fragments of primary rock do not contain any preirradiated olivine implies that during this process, the material was shielded from cosmic radiation. This conclusion is confirmed by Nakamura et al. (1999a, b), who performed in situ noble gas analyses using a laser microprobe. It was found that fragments of primary rock from Murray, Murchison, Nogoya, and Yamato-791198 do not contain solar gases but are dominated by planetary noble gas components. These observations, together with the accretionary overall appearance of primary rock, clearly refute a regolith origin as proposed by Sears et al. (1993).

Shielding of Accretionary Dust Mantles During Their Formation in the Solar Nebula

The nuclear track data presented here clearly support the solar nebula model for dust mantle formation because the primary rock and its dust mantled components were shielded from radiation, possibly by nebular dust.

There is a positive correlation between the occurrence of track-rich olivines and solar noble gases. Nakamura et al. (1999a, b) have shown that solar noble gases are preferentially located in the clastic matrix, i.e., solar gases and track-rich olivines share the same host lithology. The formation of accretionary dust mantles apparently results from the sticking of dust to the surfaces of chondrules in a nebular environment, shielded from cosmic radiation.

Summary of Arguments for a Solar Nebula Origin of Accretionary Dust Mantles

The observations on track-rich olivines complete a long list of arguments for a nebular origin of dust mantles around chondrules and other coarse-grained components in CM chondrites (see Metzler et al. 1992; Metzler and Bischoff 1996). These data indicate that the formation of dust mantles, the agglomeration of dust mantled objects, and the lithification and brecciation/irradiation on the parent body seems to be the most plausible chronological sequence in CM chondrite formation. The main arguments for a solar nebula origin of accretionary dust mantles are:

1. No track-rich olivines exist in primary rock, but are present in the clastic matrix (this study).
2. No solar wind implanted noble gases exist in primary rock and dust mantles, but are present in the clastic matrix (Nakamura et al. 1999a, b).
3. High amounts of planetary noble gases exist in dust mantles (Nakamura et al. 1999a).
5. Dust mantles exist only around primary nebula products like chondrules, CAIs, etc., not around lithic clasts or other components that were formed on the parent body (Metzler et al. 1992).

Reevaluation of Compaction Ages for CM Chondrites

MacDougall and Kothari (1976) measured fission tracks in olivines from CM chondrites to calculate the so called compaction ages of CM chondrites. These age calculations are based on fission track densities produced by the spontaneous fission of Pu and U, and counted on contact faces between “U-poor” isolated olivine grains and “U-rich” fine-grained matrix. The authors conclude that their compaction ages, ranging from 4.22 to 4.42 Ga, represent the time when olivine grains and matrix came intimately in contact, followed by compaction and lithification. The data from each meteorite show a considerable spread and the compaction
ages, calculated from the mean fission track densities in a given sample leave a gap of 0.2–0.4 Ga between compaction and the formation of the solar system. Woolum and Hohenberg (1993) recalculated the data using a reestimated primordial Pu/U ratio and found that the ages obtained by MacDougall and Kothari (1976) now shift to values between 4.48–4.52 Ga, i.e., much closer to the 4.56 Ga of solar system formation. This means that both solar wind implanted noble gases and track-rich grains result from the irradiation by the ancient sun because both components were admixed to these breccias before compaction and lithification.

Nevertheless, the large variation of fission track densities between single grains in a given meteorite remains to be explained. MacDougall and Kothari (1976) discuss several possibilities, e.g., dislocations counted as tracks and Pu-variations in the fine-grained matrix. Another explanation arises when the petrographic observations in CM chondrites (Metzler et al. 1992) and the present data are taken into account. These data indicate a multi-stage evolution of CM chondrites, where U-rich matrix and U-poor olivines came into contact by two different processes. At first, fine-grained dust coated the surfaces of olivines in the solar nebula, forming thick layers of “matrix” and producing the earliest generation of fission tracks on olivine surfaces. After accretion of these dust mantled components, the resulting planetesimals were reworked by impact processes, leading to the break-up of preexisting olivine-bearing components like chondrules. A population of fresh olivine grains with pristine surfaces was produced and admixed to the clastic matrix of the resulting breccias, leading to a second onset of fission track production on fresh olivine surfaces.

Although difficult to quantify, this multi-stage evolution may contribute to the observed data spread. Since it is not known from which lithologies the olivine grains were separated by MacDougall and Kothari (1976), the meaning of mean fission track values and the corresponding mean compaction ages appears of limited value. These values may include data from grains that came into contact with the matrix in the solar nebula and those from a later period, when olivines came into contact with fine-grained material in a planetary environment due to impact activity. In my view, the highest fission track values from single grains date the time of dust mantle formation, while the lowest values date the real closure of the systems, i.e., the compaction of the host breccias.

SUMMARY AND CONCLUSIONS

Eight polished thin sections from four CM chondrites were studied by optical and scanning electron microscopy to investigate the occurrence, frequency, spatial distribution, and textural setting of preirradiated (track-rich) olivines in CM chondrites. The intention of this study was to correlate the occurrence of these grains with the main lithological units, i.e., clastic matrix and fragments of primary rock and to discern between two models for CM chondrite formation. The results of the present study are:

1. The background track density (Table 2) due to transit irradiation (3.6 × 10^4 to 5.1 × 10^5 tracks/cm^2) is clearly discernable from the track density in preirradiated olivines (>1 × 10^6 tracks/cm^2).

2. Three of the four samples (Cold Bokkeveld, Murchison, Nogoya) are brecciated and contain a remarkably constant quantity of track-rich olivines (2.1–2.3%; Table 2). The Mighei sample appears to be unbrecciated and is free of these grains.

3. The mean track densities in track-rich grains ranges between 1.1 and 2.5 × 10^7 tracks/cm (Table 2).

4. The percentage of preirradiated olivines with track gradients, typical of regolith irradiation, varies between 17 (Cold Bokkeveld) and 29 (Nogoya; Table 2). Extracting the data for clast CoBo-ii-1 from the Cold Bokkeveld data narrows the range to 25–31%, which is close to literature data.

5. There is no correlation between the track density in a given grain and the occurrence of a track gradient (Fig. 9).

6. The clastic matrix is the host lithology for all observed track-rich olivines. Fragments of primary rock are free of these grains.

7. A single lithic clast (CoBo-ii-1), rich in track-rich olivines, is found in Cold Bokkeveld, representing a breccia-in-breccia structure, typical for extraterrestrial impact breccias. This lithology seems to have been irradiated for at least 3 Ma as part of a brecciated and aqueously altered subsurface layer on its parent body.

8. Using recent data on in situ noble gas measurements (Nakamura et al. 1999a, b) based on the same petrologic classification scheme as used in the present work, it turns out that there is a clear positive correlation between the occurrence of solar type noble gases and track-rich olivines.

These results complete a long list of arguments for a regolith origin of clastic matrix and a nebular origin of dust mantles around chondrules and other coarse-grained components in CM chondrites (Metzler et al. 1992; Metzler and Bischoff 1996).

In interpreting calculated compaction ages, one should consider this multistage formational history of CM chondrites. According to the model described above, conventional compaction ages might be mixtures of different contact ages between fine-grained U-rich dust and U-poor olivines, each with a distinct meaning, i.e., formation of dust mantles in the solar nebula and the lithification of the host breccias, respectively.

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