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# Mineralogical characterization of primitive, type-3 lithologies in Rumuruti chondrites

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**Abstract**–Rumuruti (R) chondrites constitute a new, well-established chondrite group different from the carbonaceous, ordinary, and enstatite chondrites. Many of these samples 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. Unequilibrated type-3 lithologies among these fragments have frequently been mentioned in various publications. In this study, detailed mineralogical data on seven primitive fragments from the R-chondrites Dar al Gani 013 and Hughes 030 are presented. The fragments range from ~300 $\mu$m in size up to several millimeters. Generally, the main characteristics can be summarized as follows: (1) Unequilibrated type-3 fragments have a well-preserved chondritic texture with a chondrule-to-matrix ratio of ~1:1. Chondrules and chondrule fragments are embedded in a fine-grained olivine-rich matrix. Thus, the texture is quite similar to that of type-3 carbonaceous chondrites. (2) In all cases, matrix olivines in type-3 fragments have a significantly higher Fa content (44–57 mol%) than olivines in other (equilibrated) lithologies (38–40 mol% Fa). (3) Olivines and pyroxenes occurring within chondrules or as fragments are highly variable in composition ($Fa_{0-65}$ and $Fs_{0-33}$, respectively) and, generally, more magnesian than those found in equilibrated R chondrites.

Agglomerated material of the R-chondrite parent body (or bodies) was highly unequilibrated. It is suggested that the material that accreted to form the parent body consisted of chondrules and chondrule fragments, mainly having Mg-rich silicate constituents, and Fe-rich highly oxidized fine-grained materials. The dominating phase of this fine-grained material may have been Fa-rich olivine from the beginning. The brecciated whole rocks, the R-chondrite regolith breccias, were not significantly reheated subsequent to brecciation or during lithification, as indicated by negligible degree of equilibration between matrix components and Mg-rich olivines and pyroxenes in primitive type-3 fragments.

## INTRODUCTION

Since 1994, the Rumuruti (R) chondrites have been recognized as a new well-established chondrite group different from the carbonaceous, ordinary, and enstatite chondrites (*e.g.*, Schulze *et al.*, 1994; Bischoff *et al.*, 1994; Rubin and Kallemeyn, 1994; Kallemeyn *et al.*, 1996). 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); meanwhile, the number of R chondrites has been increased to ~15.

Most R chondrite samples are regolith breccias showing the typical light–dark structure and having solar-wind-implanted rare 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; Schulze *et al.*, 1994; Kallemeyn *et al.*, 1996). Carlisle Lakes is an unbrecciated meteorite of petrologic subtype 3.8. Also, in Hammadah al Hamra 119 (Weber *et al.*, 1997) and in the small sample of Sahara 98248, no obvious brecciation could be identified (R4; Grossman, 1999).

Unequilibrated chondritic clasts or individual chondrules have been reported from many R chondrites in the past (*e.g.*, Weisberg *et al.*, 1991, their Fig. 1; Schulze *et al.*, 1994, their Fig. 5; Bischoff *et al.*, 1994, their Fig. 5; Rubin and Kallemeyn, 1994, their Fig. 4a). Jäckel *et al.* (1996) reported that several type-3 clasts were encountered in Dar al Gani (DaG) 013 having a perfect chondritic texture. They also found that these fragments consist of chondrules and chondrule fragments with highly unequilibrated olivines embedded in a fine-grained, olivine-rich matrix and that the composition of matrix olivines would "indicate a higher Fa content (~$Fa_{40-50}$) than typically found in other R chondrites and in the matrix of the equilibrated clasts (~$Fa_{39}$)." Abundant primitive, type-3 fragments were found in the Hughes 030 (R3–6) chondrite (Bischoff *et al.*, 1998). Texturally different unequilibrated fragments were described and, on the basis of the composition of matrix olivines within these fragments (up to $Fa_{\sim 60}$), Bischoff *et al.* (1998) concluded that "primitive unbrecciated R chondrites, which still have to be found, should have high Fa contents in matrix olivines (>>40 mol%)."

In this work, the mineralogy of various primitive, type-3 fragments from DaG 013 and Hughes 030 were studied for the first time in more detail and the results are presented here. The main aim of this study is to demonstrate the mineralogical and mineral-chemical characteristics of primitive clasts from R chondrites. Considering the chemical data and petrographic observations, some indications concerning metamorphism, brecciation, and late-stage lithification and breccia formation can be given.

## ANALYTICAL PROCEDURES

Polished thin and thick sections from DaG 013 (PL95141, PL96218) and Hughes 030 (PL98092, PL98016) were studied by optical microscopy in transmitted and reflected light. A JEOL 840A scanning electron microscope (SEM) was used to resolve the fine-grained texture of the type-3 clasts. 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 the JEOL 840A SEM

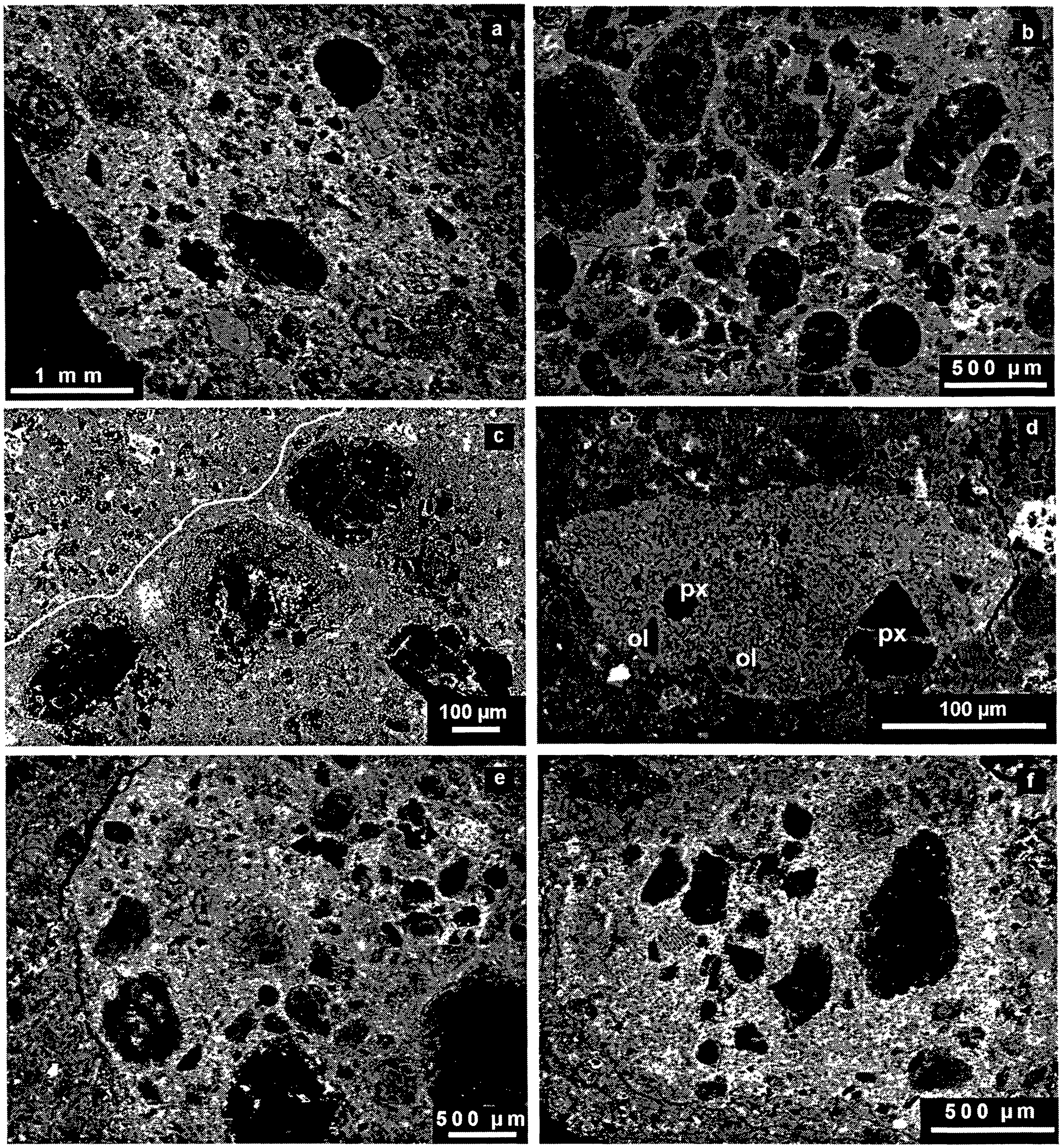


FIG. 1. Backscattered electron images of primitive type-3 fragments from the R-chondrites DaG 013 and Hughes 030. In all clasts, abundant chondrules or chondrule fragments with mainly FeO-poor constituents (*e.g.*, Fo-rich olivines, En-rich pyroxenes) occur. These have a dark grey appearance in backscattered electron images. (a) Dar al Gani 013, fragment No. 1: the boundary between the type-3 fragment and the bulk meteorite is clearly visible because of the lighter appearance (higher Fa contents) of matrix olivines in the primitive clast. (b) Dar al Gani 013, fragment X: chondritic textured area of a large unequilibrated fragment. (c) Hughes 030, fragment No. 1: several chondrules with mainly FeO-poor constituents at the (marked) boundary between the type-3 fragment and the bulk meteorite matrix. (d) Hughes 030, fragment No. 2: the smallest unequilibrated fragment analyzed having no complete chondrules and only some zoned olivines (ol) and pyroxenes (px) as coarse-grained constituents embedded in a fine-grained, olivine-rich ($Fa_{\sim 56}$) matrix. (e) Hughes 030, fragment No. 3: large chondritic textured, primitive fragment with a clearly visible boundary to the bulk meteorite. (f) Hughes 030, fragment 2-1: abundant chondrule fragments and some chondrules occur within this unequilibrated fragment. Most of the abundant mafic silicates, olivine and pyroxene, within the chondrules, and chondrule fragments are Fo- and En-rich, respectively (dark grey or black in the backscattered electron image). Compare Figs. 2–6 concerning the matrix textures and the chemical compositions of the main constituents of the fragments.

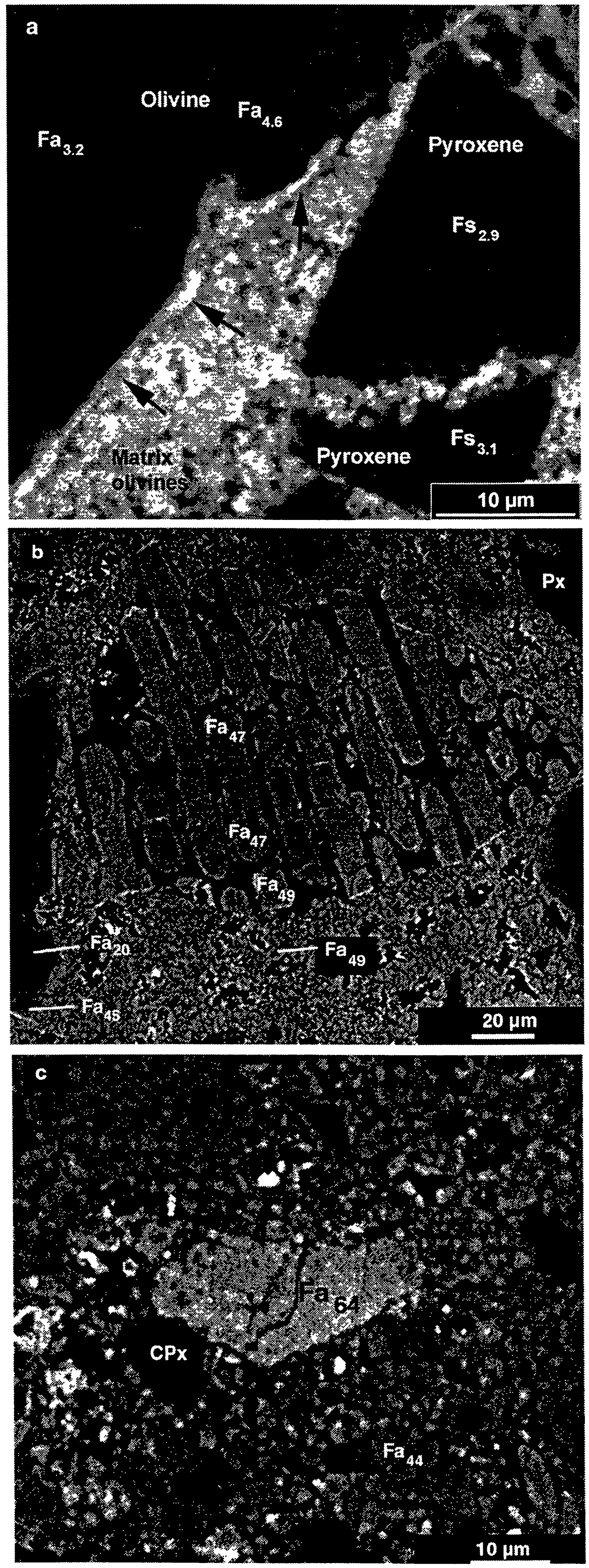


FIG. 2. (right) (a) A thin rim of Fa-rich olivine (arrows) surrounding Fo-rich olivine within fragment X from DaG 013. In addition, two completely unzoned, Mg-rich low-Ca pyroxenes are visible. (b) A chondrule fragment in clast 2-1 from Hughes 030. The olivine bars have a similar composition compared with the fine-grained matrix olivines. In the upper right corner, an unzoned, low-Ca pyroxene is visible (Px). The olivine fragment on the left hand side is significantly zoned. (c) A Fa-rich olivine fragment (~$Fa_{64}$) was found in the matrix of fragment 2-1. Note the sharp optical contrast between this clast (light grey) and the olivines within the matrix (medium grey). The degree of equilibration between matrix olivines and the Fe-rich olivine fragment is negligible (CPx: Ca-pyroxene). Backscattered electron images.

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 the 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).

## PETROGRAPHY

Many Rumuruti chondrites contain fragments of unequilibrated, type-3 lithologies (*e.g.*, Weisberg *et al.*, 1991; Schulze *et al.*, 1994; Bischoff *et al.*, 1994, 1998; Rubin and Kallemeyn, 1994; Jäckel *et al.*, 1996). In Hughes 030 and DaG 013, which both have not been significantly shocked (S2 and S1, respectively; using the shock classification scheme for ordinary chondrites from Stöffler *et al.*, 1991), these lithic fragments have textures resembling type-3 carbonaceous chondrites: chondrules and chondrule fragments having olivines and pyroxenes of various compositions are embedded in a fine-grained, olivine-rich matrix (Figs. 1–4). The chondrule-to-matrix ratio within primitive unequilibrated clasts is roughly 1:1 (Fig. 1) and much lower than that in ordinary chondrites (~6:1; Grossman *et al.*, 1988). Some examples of type-3 fragments from DaG 013 and Hughes 030 are shown in Fig. 1. The size of these fragments is highly variable ranging from <300 $\mu$m (Fig. 1d) up to many millimeters in largest dimension. In fact, one thin section of DaG 013 (PL96218; ~1 $cm^2$) consists almost completely of unequilibrated lithologies. The boundaries of these type-3 clasts can clearly be recognized in backscattered electron images (Fig. 1a,d,f) based on the higher Fa contents of the matrix olivines ($Fa_{>44}$) compared to the Fa contents of olivines from the host meteorite matrix (~$Fa_{40}$), which is basically equilibrated and recrystallized. Typically, the type-3 clasts contain abundant chondrules and chondrule fragments of variable sizes, but chondrules >500 $\mu$m in apparent diameter are rare. This is consistent with previous measurements that the average apparent chondrule diameter of R chondrites is on the order of 400 $\mu$m (*e.g.*, Bischoff *et al.*, 1994; Kallemeyn *et al.*, 1996). All typical chondrule types have been observed. Although matrix olivines within the clasts are very rich in FeO, the mafic silicates within the chondrules and chondrule fragments are mostly Fe-poor (see below), which is apparent in the backscattered electron images (Fig. 1).

As shown in Fig. 1, olivines in chondrules or chondrule fragments are often zoned. Also, forsteritic olivines have frequently been observed (Fig. 2a) sharply surrounded by thin rims of Fa-rich olivine. In other cases, chondrules or chondrule fragments with more or less unzoned Fa-rich olivines occur. Figure 2b shows such an object that contains olivine bars similar in composition to olivine grains within the fine-grained matrix (~$Fa_{48}$). In addition, a Fa-rich olivine fragment was encountered within the fine-grained matrix. Between this fragment and the matrix olivines, a distinct compositional difference was found (Fig. 2c).

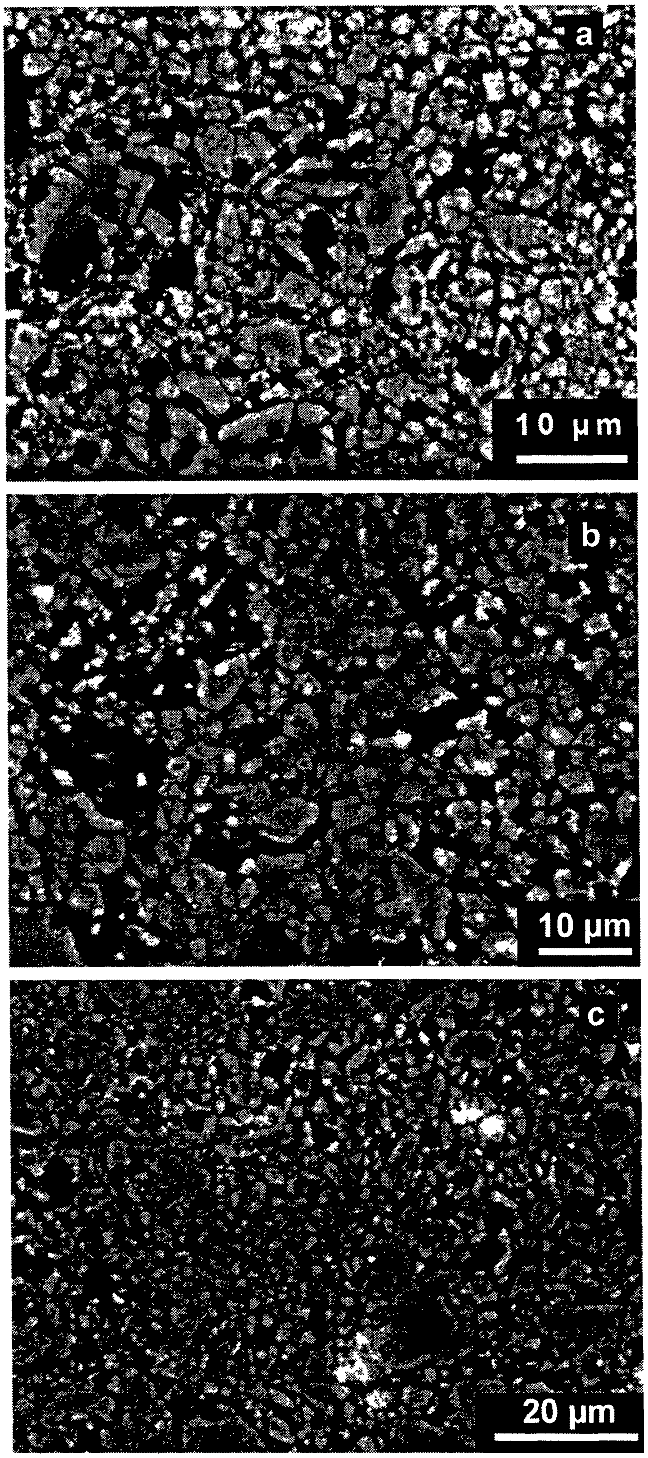


FIG. 3. Backscattered electron images of the matrix of unequilibrated, type-3 fragments from the R-chondrite Hughes 030: (a) fragment No. 1, (b) fragment 2-1, and (c) fragment No. 3. The matrix texture within all three fragments is quite similar. Lath-shaped (c) or blocky olivines (a and b) are by far the dominant constituents of a very porous groundmass. Zoning of some small matrix olivines is visible in (a). Sulfides, chromites, or both are rare (tiny white grains).

Some typical matrix textures from unequilibrated R-clasts are shown in Figs. 3 and 4. Matrix olivines from the unequilibrated clasts in Hughes 030 mostly occur as isolated, anhedral grains, typically <5 $\mu$m in size (Fig. 3). In some clasts, these grains are somewhat elongated (Fig. 3c) and slightly zoned. Matrix textures in two of the type-3 clasts from DaG 013 are shown in Fig. 4. Although some lath-shaped olivines occur in the matrix of fragment No. 2, the whole matrix appears to be slightly recrystallized, leading to larger grain sizes of the mineral constituents and larger pores (Fig. 4a). The matrix of fragment X is extremely fine grained, and mineral identification of most constituents is impossible by SEM and electron micoprobe (Fig. 4b). Analyses of olivines >3 $\mu$m revealed high Fa contents (~$Fa_{57}$; Fig. 5). A significant porosity within the unequilibrated, type-3 clasts from R chondrites is obvious (Figs. 3 and 4). Although the matrix mineralogy is strongly dominated by olivines, small grains of sulfides and Cr-rich spinels were also detected.

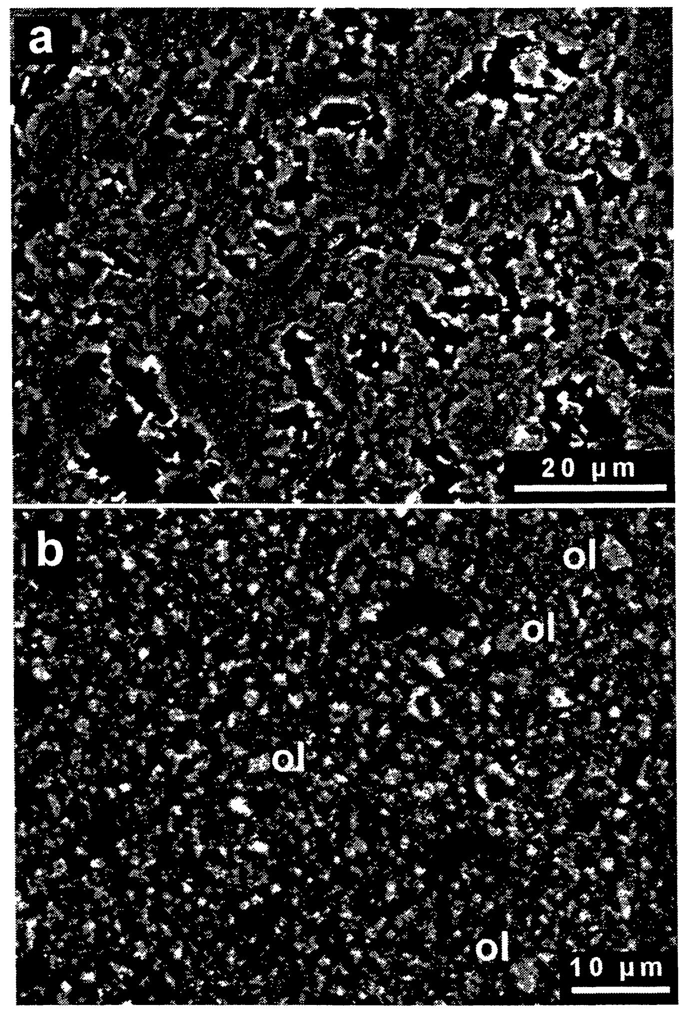


FIG. 4. Backscattered electron images of the matrix of unequilibrated, type-3 fragments from the R-chondrite DaG 013. (a) The matrix of fragment No. 2 consists predominantly of some lath-shaped and mainly anhedral olivines. The porosity (black areas) is quite high and sulfides and chromites are rare (tiny white grains). (b) The matrix of fragment X is extremely fine grained. Mineral identification of most constituents is impossible because of the small grain size; however, some olivine grains (>3 $\mu$m; ol) could be analyzed and have very high Fa contents (~$Fa_{57}$; Fig. 5).

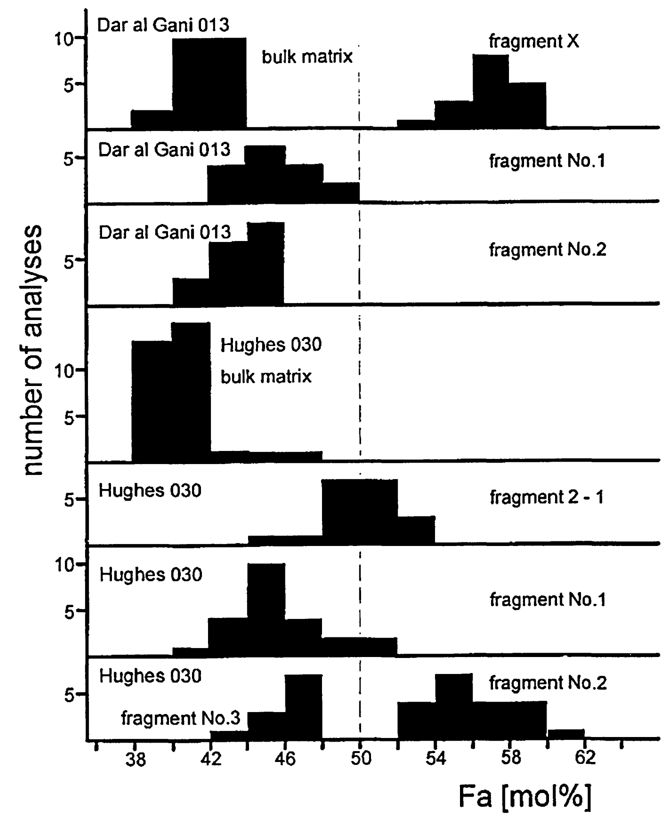


FIG. 5. Compositions of matrix olivines in unequilibrated, type-3 fragments from the R-chondrites DaG 013 and Hughes 030. For comparison, the olivine compositions of the host meteorite matrix are given. Note the high Fa contents of matrix olivines within the fragments DaG 014-X and Hughes 030-No. 2 (compare Table 1).

## CHEMISTRY OF MAIN MINERALS

Matrix areas of unbrecciated R chondrites (*e.g.*, Carlisle Lakes) are well recrystallized and mainly consist of equilibrated olivines ($Fa_{38-40}$), plagioclase, and relatively coarse-grained Ti-bearing, Cr-rich spinels. Olivines within the bulk-rock matrix of DaG 013 (mean: $Fa_{41.8}$) and Hughes 030 ($Fa_{40.6}$) have slightly higher Fa contents than olivine in most other R chondrites because of a lower degree of bulk-rock equilibration and recrystallization (Table 1; Fig. 5). The matrix olivines of equilibrated fragments in these twó chondrites, however, have a similar composition to matrix olivines in most R chondrites ($Fa_{38-40}$).

Within the unequilibrated, type-3 clasts, olivine is also by far the dominating mineral, but its composition differs significantly from olivine within the bulk rock. The average composition of matrix olivines of individual unequilibrated fragments varies between 44 and 57 mol% Fa (Fig. 5; Table 1). Within individual fragments, the composition of matrix olivines is quite homogeneous. Fragment X in DaG 013 and fragment No. 2 in Hughes 030 have the most Fa-rich matrix olivines, $Fa_{56.9\pm1.8}$ (range: 53.5–59.2 mol% Fa) and $Fa_{56.0\pm2.2}$ (range: 52.1–60.1 mol% Fa), respectively. It has to be noted that matrix in fragment X is very fine grained (Fig. 4b) and that only the largest grains were analyzed.

Olivine within chondrules and chondrule fragments is highly variable in composition and mostly more magnesian than matrix olivine (Fig. 6; Table 2). Generally, the olivine compositions vary between 0 and 45 mol% Fa without a distinct peak (Fig. 6). An olivine fragment in clast 2-1 from Hughes 030 has a Fa content of 64 mol%. In some Fo-rich olivines, tiny Fe,Ni metal grains were detected. Zoning of olivine within chondrules or chondrule fragments is common (Fig. 1). Frequently, a sharp boundary between Fo-rich olivine and Fa-rich matrix olivine has been observed. The example shown in Fig. 2a illustrates a Fo-rich olivine (96 mol% Fo) surrounded by Fa-rich olivine having about 50–55 mol% Fa. Low-Ca pyroxenes are highly variable in composition (mostly $Fs_{0-25}$; Table 2 and Fig. 7). In fragment X from DaG 013, Fs contents as high as 32.6 mol% were measured.

TABLE 1. Apparent size of primitive type-3 fragments (in mm).*

| Sample | Size | *n* | Fa (mean) | Fa (range) |
|---|---|---|---|---|
| DaG 013 | | | | |
| bulk matrix | – | 22 | 41.8 ± 1.0 | 39.8–43.7 |
| fragment No. 1 | 2.5 × 3.5 | 16 | 45.6 ± 2.1 | 42.2–49.9 |
| fragment No. 2 | 2.0 × 2.5 | 19 | 43.6 ± 1.4 | 41.2–45.6 |
| fragment X | 5.2 × 7.5 | 17 | 56.9 ± 1.8 | 53.5–59.2 |
| Hughes 030 | | | | |
| bulk matrix | – | 31 | 40.6 ± 1.9 | 38.6–47.2 |
| fragment No. 1 | 2.2 × 2.7 | 23 | 45.5 ± 2.5 | 41.3–50.3 |
| fragment No. 2 | 0.13 × 0.30 | 20 | 56.0 ± 2.2 | 52.1–60.1 |
| fragment No. 3 | 3.4 × 4.8 | 11 | 45.9 ± 1.2 | 43.7–47.4 |
| fragment 2-1 | 1.4 × 1.9 | 19 | 50.2 ± 2.2 | 44.2–52.3 |

*Compositions of olivine within these fragments and within the bulk matrix of the R-chondrites DaG 013 and Hughes 030; chemical data in mol% Fa. *n* = number of analyses; compare Fig. 5.

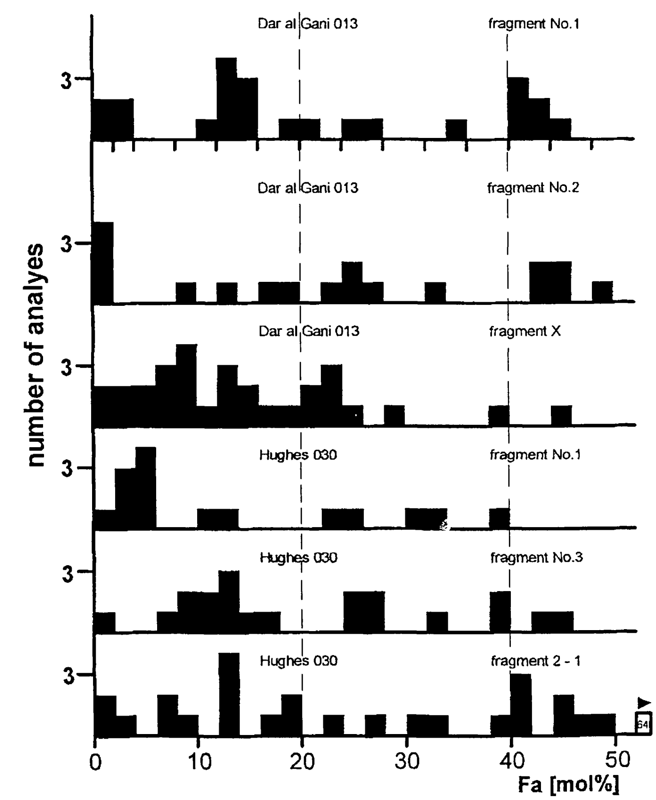


FIG. 6. Compositions of olivines within chondrules and chondrule fragments of unequilibrated, type-3 fragments from the R-chondrites DaG 013 and Hughes 030. Olivines in chondrules from all investigated type-3 fragments are highly variable in composition (compare Table 2).

TABLE 2. Compositions of olivine and low-Ca pyroxene within chondrules and chondrule fragments of primitive type-3 fragments from the R-chondrites DaG 013 and Hughes 030.*

| Sample | Olivine | | | | Pyroxene | | |
|---|---|---|---|---|---|---|---|
| | *n* | Fa (mean) | CV (%) | Fa (range) | *n* | Fs (mean) | Fs (range) |
| DaG 013 | | | | | | | |
| fragment No. 1 | 23 | 21.4 ± 14.9 | 70 | 0.7–44.6 | 20 | 9.2 ± 6.9 | 0.8–23.1 |
| fragment No. 2 | 17 | 20.9 ± 15.6 | 75 | 0.8–44.1 | 16 | 12.2 ± 7.9 | 1.1–25.0 |
| fragment X | 30 | 14.8 ± 10.8 | 73 | 1.6–45.3 | 30 | 10.0 ± 8.3 | 1.0–32.6 |
| Hughes 030 | | | | | | | |
| fragment No. 1 | 15 | 13.8 ± 12.9 | 93 | 1.6–40.0 | 2 | – | 4.7/16.0 |
| fragment No. 2 | | small number of olivines/pyroxenes | | | 3 | 12.6 ± 10.3 | 6.0–24.4 |
| fragment No. 3 | 20 | 21.0 ± 13.0 | 62 | 1.3–44.8 | 21 | 9.7 ± 7.5 | 1.3–23.7 |
| fragment 2-1 | 26 | 25.3 ± 17.6 | 70 | 1.9–63.7 | 14 | 12.7 ± 6.3 | 4.3–22.1 |

*Data in mol% Fa and Fs; CV = coefficient of variation of olivine compositions.
*n* = number of analyses; compare Figs. 6 and 7.

Other phases within type-3 fragments from R chondrites are quite rare. Chromium-rich spinels, plagioclase, sulfides, and Ca-pyroxene were occasionally encountered. The Cr-rich spinels appear to be much more abundant and larger in size within the equilibrated bulk chondrite matrix than within the primitive type-3 fragments. In some fragments, these grains are very rare. The compositions are highly variable as revealed from the analyses of ~40 grains: $TiO_2$ (0.1–8.3 wt%), $Cr_2O_3$ (12.5–67.6 wt%), $Al_2O_3$ (0.1–21.0 wt%), FeO (29.9–79.0 wt%).

Plagioclase analyzed in this study has an An component of 10.7 ± 2.5 mol% (range: 6.4–15.5 mol% An). Thus, rare plagioclase in type-3 fragments is similar in composition to feldspars from other bulk R chondrites (*e.g.*, Bischoff *et al.*, 1994; Schulze *et al.*, 1994; Rubin and Kallemeyn, 1994; Kallemeyn *et al.*, 1996).

Small sulfides, mostly heavily altered by terrestrial weathering, were frequently encountered within the primitive fragments. Only a small number of grains could be analyzed, and these have up to 31.3 wt% Ni.

Calcium-rich pyroxenes were mainly found in chondrules and chondrule fragments and are variable in composition. On the basis of the analyses of ~20 grains, the following compositional range can be given: $Fs_{3-21}$, $Wo_{20-46}$.

## DISCUSSION

### How Primitive Are the Unequilibrated Clasts in the Hughes 030 and Dar al Gani 013 Rumuruti Chondrites?

Carlisle Lakes has been classified as the only unbrecciated type-3 R chondrite. On the basis of a moderate degree of recrystallization, the sample is described as a subtype 3.8 chondrite (Rubin and Kallemeyn, 1989). Olivine more magnesian than $Fa_{37-41}$ is very rare in Carlisle Lakes. Some olivines having 83 mol% Fo were found enclosed in pyroxene of a large, 2.5 mm sized chondrule (Weisberg *et al.*, 1991). The situation is completely different for the type-3 clasts studied here. Olivines more magnesian than $Fa_{38}$ are the rule and not the exception. Representative olivines from chondrules and chondrule fragments were analyzed (randomly selected), and the data are summarized in Table 2 and Fig. 6. These olivines have been chosen in order to determine how primitive these fragments are. First of all, the coefficient of variation (CV) of olivine compositions was calculated revealing values between 62 and 93% (Table 2). Considering the subtype classification for ordinary chondrites, the subtypes for these clasts are certainly well below 3.5, because CV values between 40 and 50% characterize type-3.5 ordinary chondrites (Scott, 1984). Using Fig. 66 from Scott (1984), in this attempt the CV values for the olivine compositions in chondrules and chondrule fragments from unequilibrated R-chondrite clasts were plotted (Fig. 8). The data show that the studied clasts are highly primitive and that their petrologic subtype is significantly below 3.5. Here, it is suggested that the studied clasts are of subtype 3.2 (±0.1).

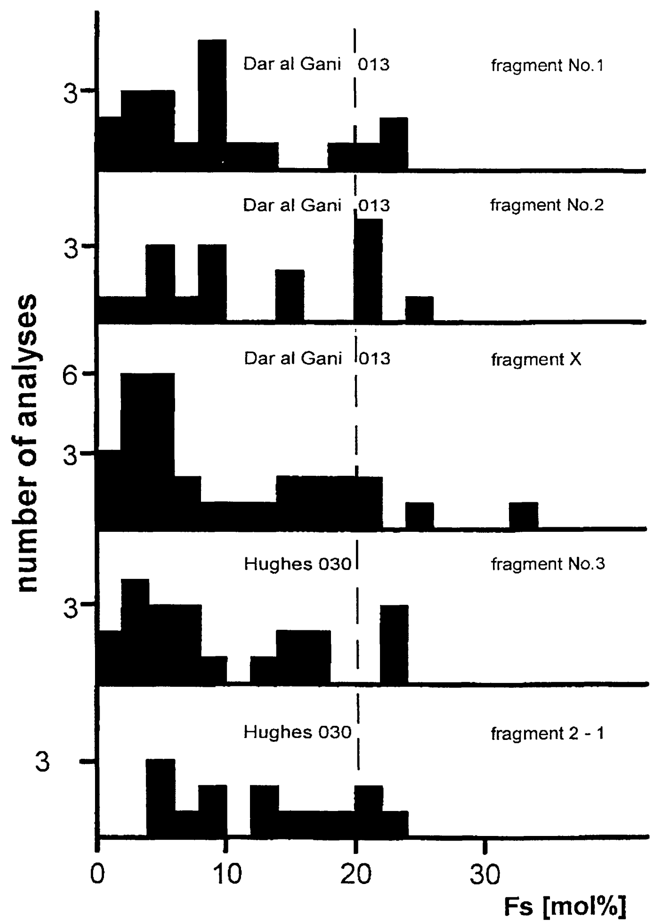


FIG. 7. Compositions of pyroxenes within chondrules and chondrule fragments of unequilibrated, type-3 fragments from the R-chondrites DaG 013 and Hughes 030. Pyroxenes in chondrules from all investigated type-3 fragments are highly variable in composition (compare Table 2).

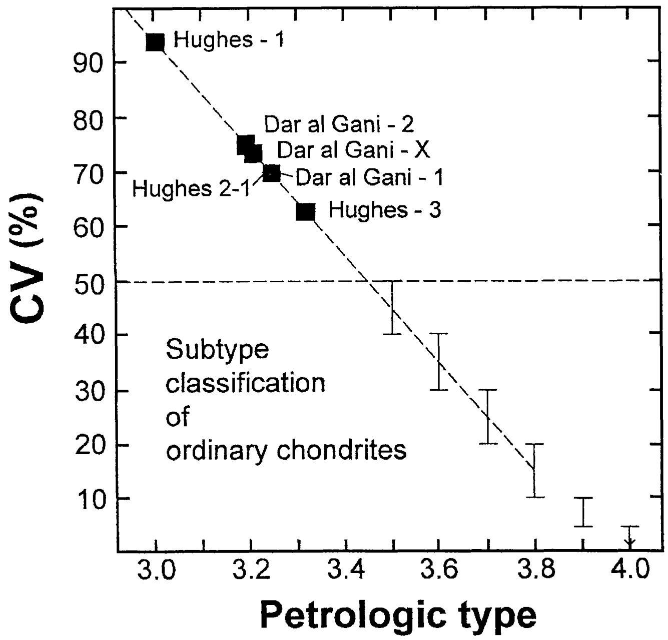


FIG. 8. Plot of coefficient of variation of olivine compositions (CV) against the petrologic subtypes (see Sears *et al.*, 1982, and Scott, 1984, for details). The lower part of the diagram includes the subtype classification of ordinary chondrites. The CV values for olivines in chondrules and chondrule fragments within type-3 clasts from R-chondrites are well above 50%.

In many groups of carbonaceous chondrites, olivine and pyroxene compositions tend to have pronounced peaks below 10 mol% Fa and Fs, respectively (*e.g.*, McSween, 1977; Scott and Jones, 1990; Bischoff *et al.*, 1993a,b). For the type-3 clasts from R chondrites, different characteristics have been found. Here, no obvious peak exists and chondrule olivines and pyroxenes vary from 0–64 mol% Fa and 0–33 mol% Fs (Figs. 6 and 7), respectively. The Fa- and Fs-distributions shown in these figures reflect the actual abundances. These distributions are more similar to those found in ordinary than in carbonaceous chondrites.

In all studied fragments, chondrules exist containing olivines with a Fa content in excess of 39 mol%, a value typically found for olivines in equilibrated clasts of R chondrites. Thus, a huge range of olivine compositions can be found. In Fig. 2, it is shown that chondrules exist with olivines of $Fa_{45-50}$, as well as that $Fa_{<4}$ olivines have sharp boundaries with olivines having >40 mol% Fa. In the latter case, zoning of the forsteritic olivine is negligible. The occurrence of chondrules and fragments with olivines of variable composition within individual type-3 clasts from R chondrites has to be a primitive feature. This statement is convincingly proved by another observation shown in Fig. 2c, where no chemical gradient was found between a $Fa_{64}$ fragment and the coexisting matrix olivines having ~45 mol% Fa. In no cases were any indications for considerable *in situ* equilibration found. In other words, these fragments studied here represent accreted materials (fragments, chondrules with variable composition of mafic silicates, matrix minerals) that have not been significantly altered by *in situ* thermal annealing. This result is consistent with suggestions by Weisberg *et al.* (1991). These authors stated that the occurrence of $Fa_{45}$ grains in a host that is mainly equilibrated with olivines of $Fa_{38}$ suggests that distinct R-chondrite lithologies equilibrated prior to final lithification.

**Formation of the R-chondrite Parent Body: Agglomeration of Chondrules with Variable Iron–Magnesium Ratios and Highly Oxidized Matrix Components**

Based on the mineralogy of primitive, type-3 fragments in R chondrites, it is suggested that the material that accreted to form the parent body (or bodies) primarily consisted of chondrules and chondrule fragments, mainly having reduced silicate constituents (reduced means more magnesian than typically found in the equilibrated host R chondrite), which occasionally contained Fe,Ni metals and highly oxidized, Fe-rich, fine-grained materials. Thus, the agglomerated material of the R-chondrite parent body(ies) was highly unequilibrated. The dominating phase of the fine-grained matrix may have been Fa-rich olivine from the beginning. If this assumption is correct, primitive R chondrites, which still have to be found as individual rocks, are mineralogically (*e.g.*, mostly MgO-rich mafic silicate phases in chondrules, Fa-rich matrix olivine) and texturally (*e.g.*, chondrule–matrix ratio close to 1.0) very similar to type-3 carbonaceous chondrites.

The paucity of Fe,Ni metal in the matrix of primitive, type-3 fragments from R chondrites indicates that the accreted matrix components were highly oxidized. It has been suggested previously that these materials were already oxidized prior to parent-body agglomeration. Several good reasons were given by Rubin and Kallemeyn (1994) ruling out the possibility that R chondrites agglomerated as reduced material (*e.g.*, material rich in coexisting metallic Fe,Ni and Mg-rich olivine and pyroxene). In their most convincing argument, these authors state that if the R chondrites had agglomerated ~6 vol% Fe,Ni metal, then because the molar volume of magnetite is twice that of kamacite, ~12 vol% magnetite should have been produced during parent-body oxidation. However, magnetite is only a rare phase in R chondrites (Kallemeyn *et al.*, 1996). In addition, Schulze *et al.* (1994) described some metals in Rumuruti. The existence of these metals indicates that some highly reduced phases accreted together with abundant oxidized matrix components. These metals would have been destroyed if oxidation had happened subsequent to accretion *in situ* on the R-chondrite parent body.

**Thermal Processes on the R-chondrite Parent Body**

Rubin and Kallemeyn (1994) and Kallemeyn *et al.* (1996) discussed several aspects of thermal processing on the R-chondrite parent body. On the basis of their limited sampling (the samples of DaG 013 and Hughes 030 were not studied), these authors did not recognize the extent of primitive, type-3 fragments in R chondrites, and their model concerning the parent-body history does not include this aspect in detail.

All models concerning the evolution and processing of a parent body require knowledge about the starting material. Therefore, the recognition of the primitive starting materials is of fundamental importance when considering aspects such as metamorphism, recrystallization, and phase equilibration. On the basis of the mineralogy of primitive, unequilibrated type-3 fragments, the "accreted starting material" must have consisted of coarse-grained components (chondrules, chondrule fragments) basically containing olivine and pyroxene with highly variable compositions (Figs. 6 and 7) and fine-grained material consisting (probably from the beginning; Fig. 5) of Fe-rich olivine ($Fa_{>50}$).

Dodd (1981) suggested metamorphic temperatures of about 1000–1100 K to produce type-5 and type-6 ordinary chondrites. Assuming similar temperatures for the R chondrites, within interior regions of the R-chondrite parent body, material was heated to form

R5 and R6 lithologies: Fo-rich olivines (~$Fo_{70-100}$) and En-rich pyroxene as well as Fa-rich matrix olivines (~$Fa_{>50}$) equilibrated to form chemically homogenous olivine with 38–40 mol% Fa and less abundant equilibrated Ca-poor pyroxene (~$Fs_{29}$ in Acfer 217; Bischoff *et al.*, 1994). In less strongly metamorphosed regions of the parent body, equilibration of olivine took place, whereas Ca-poor pyroxene greatly survived as unequilibrated grains. Similar observations are known from ordinary chondrites of type 4 and of high petrologic type 3 (*e.g.*, 3.8, 3.9). A typical R chondrite of this type is the unbrecciated meteorite Carlisle Lakes.

Assuming that metamorphism is a function of depth, the type-3 fragments studied here must derive from parent-body regions close to the surface, where thermal annealing was not strong enough to lead to significant equilibration and recrystallization.

### Brecciation and Late Parent-body Processes

Impact processes caused fragmentation on the R-chondrite parent body. Equilibrated and recrystallized lithologies (type 5 and 6) from greater depth were mixed as fragments together with clasts from near-surface lithologies. These include not only aberrant mineral clasts and chondrules (Kallemeyn *et al.*, 1996), but also a considerable abundance of type-3 fragments.

During impact processes, some material was highly heated resulting in the formation of impact-melt rocks (Jäckel *et al.*, 1996) and the cellular martensite–troilite melt mixture as found within Allan Hills (ALH) 85151 (Rubin and Kallemeyn, 1989). These impact-related lithologies cooled rapidly and were incorporated into the surface breccias. The real number of shock events responsible for producing the various constituents of a loose regolith is unknown. Considering these surface materials, interactions with the solar wind occurred, and these regolith materials became enriched in solar-wind gases (Weber and Schultz, 1995). During further impact activity, these loose regolith materials were consolidated (lithified) to form tough breccias. Tough breccias can be produced even under low-shock pressures (5–10(20) GPa: Kieffer, 1975; Gibbons *et al.*, 1975; Schaal *et al.*, 1979; Schaal and Hörz, 1980; Bischoff and Lange, 1984; Stöffler *et al.*, 1988; Bischoff and Stöffler, 1992). Both samples, DaG 013 (S1) and Hughes 030 (S2), were not shocked above 10 GPa during lithification or a later event as indicated by the presence of very weakly shocked minerals within the bulk rock.

Although highly heated fragments, like impact-melt rocks, occur within these R-chondritic breccias, it is very clear that the brecciated whole rock was not significantly reheated subsequent to brecciation or during lithification. The abundant unequilibrated clasts are good indicators as well as the occurrence of martensite in ALH 85151 (Rubin and Kallemeyn, 1989). Because Fe-Mg exchange in olivine is a rapid process, observations in type-3 clasts do not allow a significant heating process (Fig. 2).

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## REFERENCES


BENCE A. E. AND ALBEE A. L. (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.* **76,** 382–403.

BINNS R. A. AND POOLEY G. D. (1979) Carlisle Lakes (a): A unique oxidized chondrite (abstract). *Meteoritics* **14,** 349–350.

BISCHOFF A. AND LANGE M. A. (1984) Experimental shock-lithification of chondritic powder: Implications for ordinary chondrite regolith breccias (abstract). *Lunar Planet. Sci.* **15,** 60–61.

BISCHOFF A. AND STÖFFLER D. (1992) Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. *Eur. J. Min.* **4,** 707–755.

BISCHOFF A. *ET AL.* (1993a) Paired Renazzo-type (CR) carbonaceous chondrites from the Sahara. *Geochim. Cosmochim. Acta* **57,** 1587–1603.

BISCHOFF A., PALME H., SCHULTZ L., WEBER D., WEBER H. W. AND SPETTEL B. (1993b) Acfer 182 and paired samples, an iron-rich carbonaceous chondrite: Similarities with ALH 85085 and relationship to CR chondrites. *Geochim. Cosmochim. Acta* **57,** 2631–2648.

BISCHOFF A. *ET AL.* (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., 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). *Meteorit. Planet. Sci.* **33 (Suppl.),** A15–A16.

DODD R. T. (1981) *Meteorites—A Petrologic–Chemical Synthesis.* Cambridge Univ. Press, New York, New York, USA. 368 pp.

GIBBONS R. V., MORRIS R. V., HÖRZ F. AND THOMPSON T. H. (1975) Petrographic and ferromagnetic resonance studies of experimentally shocked regolith analogs. *Proc. Lunar Planet. Sci. Conf.* **6th,** 3143–3171.

GROSSMAN J. N. (1999) The Meteoritical Bulletin, No. 83. *Meteorit. Planet. Sci.* **34 (Suppl.),** A169–A186.

GROSSMAN J. N., RUBIN A. E., NAGAHARA H. AND KING E. A. (1988) Properties of chondrules. In *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), pp. 619–659. Univ. Arizona Press, Tucson, Arizona, USA.

JÄCKEL A., BISCHOFF A., CLAYTON R. N. AND MAYEDA T. K. (1996) Dar al Gani 013—A new Saharan Rumuruti-chondrite (R3–6) with highly unequilibrated (type 3) fragments (abstract). *Lunar Planet. Sci.* **27,** 595–596.

KALLEMEYN G. W., RUBIN A. E. AND WASSON J. T. (1996) The compositional classification of chondrites: VII. The R chondrite group. *Geochim. Cosmochim. Acta* **60,** 2243–2256.

KIEFFER S. W. (1975) From regolith to rock by shock. *The Moon* **13,** 301–320.

MCSWEEN H. Y., JR. (1977) Petrographic variations among carbonaceous chondrites of the Vigarano type. *Geochim. Cosmochim. Acta* **41,** 1777–1790.

RUBIN A. E. AND KALLEMEYN G. W. (1989) Carlisle Lakes and Allan Hills 85151: Members of a new chondrite grouplet. *Geochim. Cosmochim. Acta* **53,** 3035–3044.

RUBIN A. E. AND KALLEMEYN G. W. (1994) Pecora Escarpment 91002: A member of the new Rumuruti (R) chondrite group. *Meteoritics* **29,** 255–264.

SCHAAL R. B. AND HÖRZ F. (1980) Experimental shock metamorphism of lunar soils. *Proc. Lunar Planet. Sci. Conf.* **11th,** 1679–1695.

SCHAAL R. B., HÖRZ F., THOMPSON T. D. AND BAUER J. F. (1979) Shock metamorphism of granulated lunar basalts. *Proc. Lunar Planet. Sci. Conf.* **10th,** 2547–2571.

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

SCOTT E. R. D. (1984) Classification, metamorphism, and brecciation of type 3 chondrites from Antarctica. *Smiths. Contr. Earth Sci.* **26,** 73–94.

SCOTT E. R. D. AND JONES R. H. (1990) Disentangling nebular and asteroidal features of CO3 carbonaceous chondrite meteorites. *Geochim. Cosmochim. Acta* **54,** 2485–2502.

SEARS D. W., GROSSMAN J. N. AND MELCHER C. L. (1982) Chemical and physical studies of type 3 chondrites–I: Metamorphism related studies of Antarctic and other type 3 ordinary chondrites. *Geochim. Cosmochim. Acta* **46,** 2471–2481.

STÖFFLER D., BISCHOFF A., BUCHWALD V. AND RUBIN A. E. (1988) Shock effects in meteorites. In *Meteorites and the Early Solar System* (eds. J. F. Kerridge and M. S. Matthews), pp. 165–202. Univ. Arizona Press, Tucson, Arizona, USA.

STÖFFLER D., KEIL K. AND SCOTT E. R. D. (1991) Shock metamorphism of ordinary chondrites. *Geochim. Cosmochim. Acta* **55,** 3845–3867.

WEBER H. W. AND SCHULTZ L. (1995) Noble gases in Rumuruti-group chondrites (abstract). *Meteoritics* **30,** 596.

WEBER D., SCHULTZ L., WEBER H. W., CLAYTON R. N., MAYEDA T. K. AND BISCHOFF A. (1997) Hammadah al Hamra 119—A new, unbrecciated Saharan Rumuruti chondrite (abstract). *Lunar Planet. Sci.* **28,** 1511–1512.

WEISBERG M. K., PRINZ M., KOJIMA H., YANAI K., CLAYTON R. N. AND MAYEDA T. K. (1991) The Carlisle Lakes-type chondrites: A new grouplet with high $\Delta^{17}O$ and evidence for nebular oxidation. *Geochim. Cosmochim. Acta* **55,** 2657–2669.