Geochimica et Cosmochimica Acta Vol. 56, pp. 3791–3807

0016-7037/92/$5.00 + .00

Chemical and physical studies of chondrites: X. Cathodoluminescence and phase composition studies of metamorphism and nebular processes in chondrules of type 3 ordinary chondrites

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(*Received October 3, 1991; accepted in revised form April 29, 1992*)

Abstract—The cathodoluminescence (CL) properties of eight type 3 ordinary chondrites and one L5 chondrite have been determined, and phenocryst and mesostasis compositions have been analyzed in the chondrules of four of them (Semarkona, type 3.0; Krymka, 3.1; Allan Hills A77214, 3.5; and Dhajala, 3.8) in order to investigate their origins and metamorphic history. Two major classes of chondrule with eight subdivisions have been identified mainly on the basis of CL properties, and >95% of the chondrules can be assigned to these groups on the basis of phenocryst and mesostasis composition. Class A chondrules, consisting of those with plagioclase-normative mesostasis with bright CL, are subdivided into groups A1, A2, A3, A4, and A5. Class B chondrules, with little or no CL and having quartz-normative mesostases in the least metamorphosed chondrites which becomes feldspathic with metamorphism, are subdivided into groups B1, B2, and B3. Relationships between the eight chondrule groups can be deduced from their relative abundance in each of the nine chondrites. Groups A1, A2, B1, and A5 are present in Semarkona (15, 20, 60, 5% by number, respectively), group A5 chondrules in Semarkona being more heterogeneous than A5 chondrules in chondrites of higher petrologic type. Chondrule group A1 evolves into A3 then A4 and then A5 during metamorphism while A2 evolves into A4 and then A5. Chondrule group B1 evolves into B2, B3, and then A5 but higher levels of metamorphism are required to complete the series than for the A1–5 series. Conversion of a group to an adjacent group can be observed in Allan Hills A77214 (3.5), where several chondrules are group B3 in their central regions and group A5 in their outer regions. The present chondrule groups are essentially independent of texture. Since group A and group B chondrules differ in bulk composition, redox state, and possibly oxygen isotope systematics, their relative abundance might be a factor in the creation of the nine chondrite classes.

INTRODUCTION

THE PRESENT STUDY WAS originally undertaken to clarify the relationship between induced TL of type 3 chondrites and metamorphism (SEARS et al., 1980; SEARS et al., 1989); but it soon became apparent that CL provided a new means of exploring and characterizing early solar system material, particularly the diversity of chondrule properties (DEHART et al., 1987, 1988, 1989a,b; STEELE, 1986) and of the effects of metamorphism (DEHART and SEARS, 1985, 1986). Metamorphic equilibration of the type 3 chondrites results in homogenization of mineral compositions (particularly olivine and metal), decreases in carbon and inert gas abundance, the formation of feldspar in the place of chondrule glass, loss of Ni from the sulfides, and an increase in mean FeO of the olivine (DODD et al., 1967; DODD, 1969; SEARS et al., 1980; HUSS et al., 1981; AFIATTALAB and WASSON, 1980). Some of these changes reflect the destruction of discrete populations of chondrules, others reflect the destruction of the unusual fine-grained matrix and other unusual phases characteristic of the most primitive meteorites. Cathodoluminescence properties reflect many of these processes because they depend on mineral composition and are sometimes sensitive to very subtle changes.

The great variety in chondrule properties has often been noted. KIEFFER (1975) and DODD (1981) distinguished between "droplet" and "clast" or "lithic" chondrules, while GOODING and KEIL (1981) sorted chondrules into "porphyritic" and "non-porphyritic" textures with six subdivisions. MCSWEEN (1977) and SCOTT and TAYLOR (1983) used olivine compositions and texture to define types IA, IB, II, III, and IV. GROSSMAN (1988) reviewed a great variety of theories for chondrule origin, few of which could be eliminated with any certainty using the current database. This is partly because much of the existing database concerns chondrules from metamorphosed meteorites and even the most modest levels of metamorphism affect composition, and partly because existing schemes are not "comprehensive," i.e., they tend to concern homogeneous subsets of chondrules. There is possibly a consensus favoring processes acting on previously existing dust (TAYLOR et al., 1983) and the chondrule groups may reflect precursor composition. It is also possible that the groups reflect processes accompanying chondrule formation, or maybe both formation processes and precursor compositions were involved (HEWINS, 1988; LOFGREN, 1989). It is clear that not all chondrules were entirely melted during chondrule formation since many of them contain relic grains (RAMBALDI, 1981; NAGAHARA, 1981), and DODD (1981) suggests that "droplet" chondrules were entirely melted while "clast" chondrules are abraded fragments of igneous rocks.

The fine-grained matrix is more susceptible to metamorphic and other forms of alteration than the chondrules. Ordinary chondrite matrices generally have fairly low Mg numbers which increase with metamorphism, presumably as

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Table 1. Sections used in the present study with frequency (per cent by numbers) of chondrule groups as a function of petrologic type *

Meteorite	Section # source+	Pet. Type	No. of Chond.	A1	A2	A3	A4	A5	B1	B2	B3
Semarkona	USNM 1805	3.0	76	10.5	25.0	0.0	0.0	5.0	56.9	0.0	2.6
Bishunpur	BM 80399	3.1	98	7.1	0.0	12.2	12.8	12.8	0.0	51.0	1.0
Krymka	USNM L729-7	3.1	134	5.2	0.0	20.9	17.8	17.8	0.0	29.9	1.5
Chainpur	BM1915,86	3.4	90	0.0	0.0	10.0	11.7	27.2	0.0	38.8	6.7
ALHA77214	MWG PTS#8	3.5	124	1.6	0.0	2.4	15.5	36.1	1.6	0.0	41.9
Hedjaz	BM 1925,13	3.7	69	0.0	0.0	0.0	21.3	49.7	0.0	0.0	29.0
Dhajala	PRL	3.8	62	0.0	0.0	0.0	18.4	42.9	0.0	0.0	38.7
Bremorvorde	BM 33910	3.9	60	0.0	0.0	5.0	19.0	44.3	0.0	0.0	31.7
Barwell	BM 1966	5	63	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0

*Data obtained by assigning all the chondrules in these sections to the chondrule groups using their CL. Groups A4 and A5 cannot readily be distinquished by CL and the above statistics assume the following (based on the four analyzed chondrites underlined): Semarkona, 100%A5; Krymka, Bishunpur, 50%A5; Chainpur, ALHA77214, Hedjaz, Dhajala, 70%A5. We assume Barwell chondrules are entirely A5 because many studies show that the mesostases of equilibrated chondrites are sodic feldspar (Van Schmus and Ribbe, 1968).

+USNM, Roy Clark and Twyla Thomas, National Museum of Natural History, Smithsonian Institution (Semarkona polished thick section made at UCLA). BM, Robert Hutchison, British Museum (Natural History). MWG, Meteorite Working Group of the NSF/NASA. PRL, D. Lal, Physical Research Laboratory, Ahmedabad (polished thin section made at JSC).

metallic Fe forms and segregates from the fine-grained material. An exception is Semarkona which has a great many forsterite grains in the matrix (NAGAHARA, 1984; HUSS et al., 1981). The matrices of several type 3 ordinary chondrites of especially low type contain signs of aqueous alteration, including the presence of calcite and hydrated silicates (HUTCHISON et al., 1987; ALEXANDER et al., 1989).

In the present study, we discuss the CL properties of nine ordinary chondrites of a variety of petrologic types with particular emphasis on detailed studies of the compositions of the relevant phases in four of these: Semarkona (3.0), Krymka (3.1), Allan Hills A77214 (3.5), and Dhajala (3.8). We describe a means of classifying chondrules that is based on the composition of their two major components, the mesostasis and phenocrysts. The system is applicable to >90–95% of the chondrules in a given meteorite and it describes the range of material produced by nebular material and of the effect of metamorphism on the chondrules. We also discuss the relevance of the results for the origin of the nine chondrite classes.

EXPERIMENTAL

The thin sections we used in our study are listed in Table 1. Note that Krymka is better considered type 3.1 rather than 3.0 (SEARS et al., 1989). Photomosaics of the CL image for each section were prepared using a Nuclide Corporation (now MAAS) "Luminoscope" attached to a standard petrographic microscope, with the 14 ± 1 kev, 7 ± 1 μA beam being defocussed to a 1.0×0.7 cm ellipse. Typically 30–40 photographs were taken at $\times 50$ using Kodak VR400 35 mm film with 1.0–2.5 minute exposures. Prints were obtained using the C-40 development process with apparent CL intensity and color being determined from the prints. Although this is somewhat a subjective procedure, especially for low light levels, we are interested in only the most obvious differences in CL where there is little ambiguity. The color reproductions of SEARS et al. (1989) should clarify our terminology. With the help of transmitted and reflected light photographs, maps were made of chondrules, chondrule fragments, matrix clasts, and areas of matrix for microprobe analysis (DEHART, 1989).

Electron microprobe analyses were made with the Cameca Camebax microprobe at the Johnson Space Center, Houston, using natural mineral standards and the Cameca PAP data reduction routines (DEHART, 1989). The three sigma detection limits for each oxide were SiO_2, 0.03%; TiO_2, 0.03%; Al_2O_3, 0.02%; FeO, 0.04%; MnO, 0.04%; MgO, 0.02%; CaO, 0.02%; Na_2O, 0.02%; K_2O, 0.02%; Cr_2O_3, 0.04%; and P_2O_5, 0.02%. Mesostases and fine-grained matrices were analyzed by rastering the beam over a 3×3 micrometer area (15 keV accelerating voltage, 15 nA beam current) with each reported analysis representing the mean of 3 to 9 replicates. Backscattered electron images provided a record of the chondrule and mesostasis texture and of the regions analyzed.

RESULTS

Cathodoluminescence Petrography and a New Chondrule Classification Scheme

As a first step, we divided the chondrules into a number of CL groups, first into those with bright CL (group A) and those with weak or no CL (group B), and then into eight smaller groups according to the CL of the mesostasis and the phenocrysts (SEARS et al., 1989) and certain compositional

Table 2. Definitions of chondrule groups in terms of cathodoluminescence and mesostasis composition.

	Mesostasis*	Chondrule Grains
A1	yellow	red
A2	yellow	none/dull-red
A3	blue	red
A4	blue (An≥50)	none/dull-red
A5	blue (An≤50)	none
B1	none/dull-blue (Qtz≥50)	none/dull-red
B2	dull-blue (Qtz 30-50)	none/dull-red
B3	purple (Qtz 15-30)	none

* An and Qtz refer to normative anorthite and quartz (mole %) calculated from defocussed electron beam microprobe analysis.

criteria (Table 2). There does not appear to be a simple relationship between the present groups and the textural groups, but there is a relationship between present groups and the McSween-Scott-Taylor type (Table 3).

Table 1 lists the frequency of occurrence of the CL groups in each of the nine meteorites studied here. 90–99% of the chondrules can be assigned to the present groups, the remaining chondrules being rare or unique individuals (e.g., chondrules consisting of pyroxene grains in a glassy, pyroxene-normative mesostasis, both phases with red CL, and a chondrule consisting entirely of SiO_2 and having blue CL). The proportion of group A chondrules to group B chondrules in these chondrites varies with petrologic type, and there are systematic changes in the proportion of each chondrule group within the main A and B groups.

There are several examples of chondrules whose mesostases are "zoned" with respect to their CL and compositional properties, one of them being a compound chondrule (Fig. 1). This zoning is especially common in Allan Hills A77214 (3.4) where about 25% of the chondrules have group B3 interiors and outer portions of group A5. The interface between the two chondrules in Fig. 1 is also group A5, suggesting

Table 3. Distribution of CL groups over the structural groups and McSween-Scott-Taylor types*

	Structural Group+							Types@			
Group	PO	POP	PP	G	BO	C	RP	IA	IB	II	III
Semarkona											
A1	2	2	-	-	-	-	-	4	-	-	-
A2	-	3	3	-	-	-	-	1	5	-	-
A3	-	-	-	-	-	-	-	-	-	-	-
A4	-	-	-	-	-	-	-	-	-	-	-
A5	3	-	3	-	-	-	-	-	3	3	-
B1	3	2	-	1	1	-	-	-	-	4	1
B2	-	-	-	-	-	-	-	-	-	-	-
B3	-	-	-	-	-	-	-	-	-	-	-
Krymka											
A1	1	-	-	-	-	-	-	1	-	-	-
A2	-	-	-	-	-	-	-	-	-	-	-
A3	3	2	-	-	-	-	-	4	1	-	-
A4	1	5	-	-	-	-	-	1	1	2	-
A5	1	5	-	-	-	-	-	-	1	2	-
B1	-	-	-	-	-	-	-	-	-	-	-
B2	2	6	1	1	1	-	-	1	2	6	1
B3	-	-	-	-	-	-	-	-	-	-	-
ALHA77214											
A1	-	-	-	-	-	-	-	-	-	-	-
A2	-	-	-	-	-	-	-	-	-	-	-
A3	1	-	-	-	1	-	-	2	-	-	-
A4	2	1	-	-	1	-	-	2	1	1	-
A5	9	6	2	-	1	-	1	2	6	10	1
B1	2	-	-	-	-	-	-	-	-	2	-
B2	-	-	-	-	-	-	-	-	-	-	-
B3	8	6	1	-	1	-	-	-	4	10	-
Dhajala											
A1	-	-	-	-	-	-	-	-	-	-	-
A2	-	-	-	-	-	-	-	-	-	-	-
A3	1	-	-	-	-	-	-	-	-	-	-
A4	1	4	-	-	-	-	-	1	1	2	1
A5	2	6	3	-	-	-	1	4	2	5	1
B1	-	-	-	-	-	-	-	-	-	-	-
B2	-	-	-	-	-	-	-	-	-	-	-
B3	5	2	-	-	1	-	2	-	-	6	4
Barwell$											
A1	-	-	-	-	-	-	-	-	-	-	-
A2	-	-	-	-	-	-	-	-	-	-	-
A3	-	-	-	-	-	-	-	-	-	-	-
A4	-	-	-	-	-	-	-	-	-	-	-
A5	~20	~50	~10	~4	~4	~4	~8	-	-	-	-
B1	-	-	-	-	-	-	-	-	-	-	-
B2	-	-	-	-	-	-	-	-	-	-	-
B3	-	-	-	-	-	-	-	-	-	-	-

* Unlike those in Table 1, the above statistics apply only to chondrules which have been analyzed. Chondrules with zoned CL are treated as two chondrules in the above table, this is significant only for Allan Hills A77214.

+ Gooding and Keil (1981): PO, porphyritic olivine; POP porphyritic olivine-pyroxene; PP, porphyritic pyroxene; G, granular; BO, barred olivine; C, cryptocrystaline; RP, radiating pyroxene.

@ McSween (1977), Scott and Taylor (1983): IA, low-FeO, microporphyritic; IB, low-FeO, poikilitic pyroxene; high-FeO, porphyritic; III, non-porphyritic.

$ Statistics (percentages) from Gooding and Keil (1981).

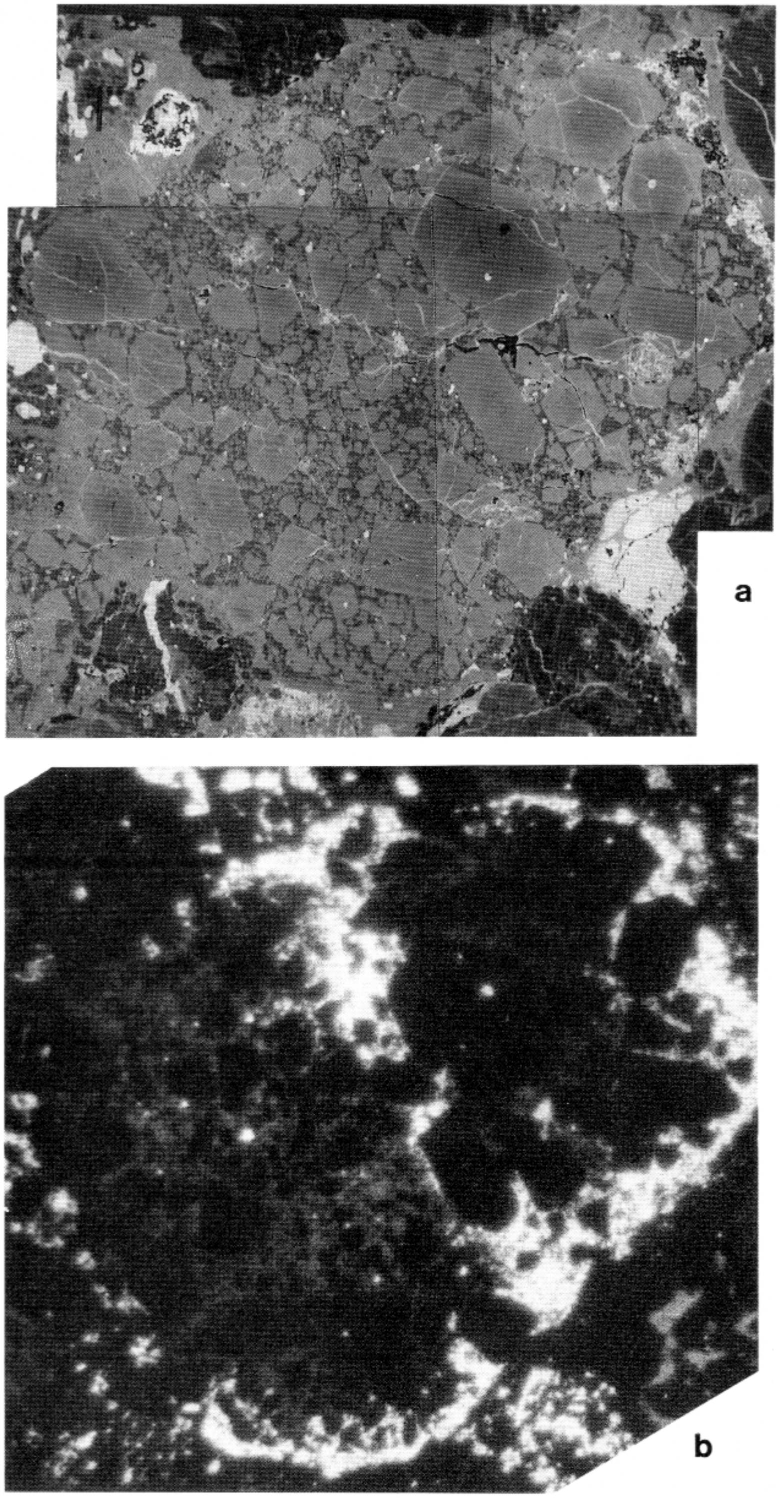

FIG. 1. (a) A backscattered electron image and (b) a CL photomicrograph of compound chondrule 46 in Allan Hills A77214. The outer regions of the mesostasis produced high levels of blue CL while the interior regions produce little or no CL. In terms of the CL groups defined in Table 2, the interior regions are B2 and the exterior regions are A4. There are major compositional differences between the two regions (see Fig. 3). The CL image clearly shows the compound nature of this chondrule, although this is not quite so clear in the BSE image. Significantly the interface between the two chondrules is also group A4, suggesting that the zoning pre-dates the accretion of the two chondrules or that the interface between the two chondrules acted as a conduit for diffusion. The figure is 1 mm in its horizontal dimension.

either that the CL zoning predated the union of the two chondrules or the interface acted as a conduit for the compositional changes causing the zoning. The phenomenon is rare in other chondrites, although it was briefly described in CO and CV chondrites by IKEDA and KIMURA (1985). We found one chondrule in Krymka with a B1 interior and A5 exterior, while another had an A1 interior and A3 exterior. In every case, the outer regions of zoned chondrules have properties we identify with greater levels of metamorphism.

The fine-grained matrix of the most primitive chondrites, which appears to act as a "cement" for the components and rims certain chondrules, has very bright red CL. It is a very conspicuous feature of the CL of Semarkona, and traces of it are present in Bishunpur and Krymka. Matrix with red CL is absent in the higher types, although the heavily brecciated Ngawi contains clasts of such material (SEARS et al., 1989).

Mesostasis

Our mesostasis data (see DEHART, 1989, for details) agree well with those of previous workers (JONES and SCOTT, 1989; JONES, 1990). Mesostases in type 3 ordinary chondrites have a wide variety of compositions which are reflected in their CL properties (DEHART et al., 1987). They are predominantly feldspar, quartz, and pyroxene normative, with ilmenite, chromite and apatite being ≤5% normative. For group A chondrules, mesostases are ~80% feldspar-normative, the remaining ~20% being primarily pyroxene, while group B mesostases are up to 50% quartz-normative (Fig. 2). The group A and B chondrules are well resolved in Semarkona but become less so as the petrologic type increases. Group A1 and A2 chondrules are also well resolved from A5 in Semarkona. Apparently the mesostasis is particularly sensitive to the lowest levels of metamorphism. The norms reflect several other trends which appear to be related to changes in the bulk composition during metamorphism. For example, the normative pyroxene is diopside in group A but hypersthene in group B.

Compositional profiles across the mesostases of zoned chondrules show the trends expected from their CL zoning (Fig. 3). MATSUNAMI et al. (1991) present detailed data for a Semarkona chondrule similar to that shown here in which thermoluminescence correlated with CL.

The texture of chondrule mesostases is quite variable and appears to be related to the present groups (Fig. 4, Table 4). "Simple" textures are the most common in group A, while in group B "simple" and "intermediate" textures are equally common. The proportion of these two textural types is fairly constant along the A1 to A5 series, but there is a notable increase in the proportion of "intermediate" textures in going from B1 to B3 and the textural complexity of chondrules also increases with the petrologic type of the host chondrite. "Complex" textures are rare in all meteorites. These observations are in agreement with earlier work (MCSWEEN, 1977; SCOTT and TAYLOR, 1983; JONES and SCOTT, 1989; JONES, 1990) and apparently reflect the crystallization of the

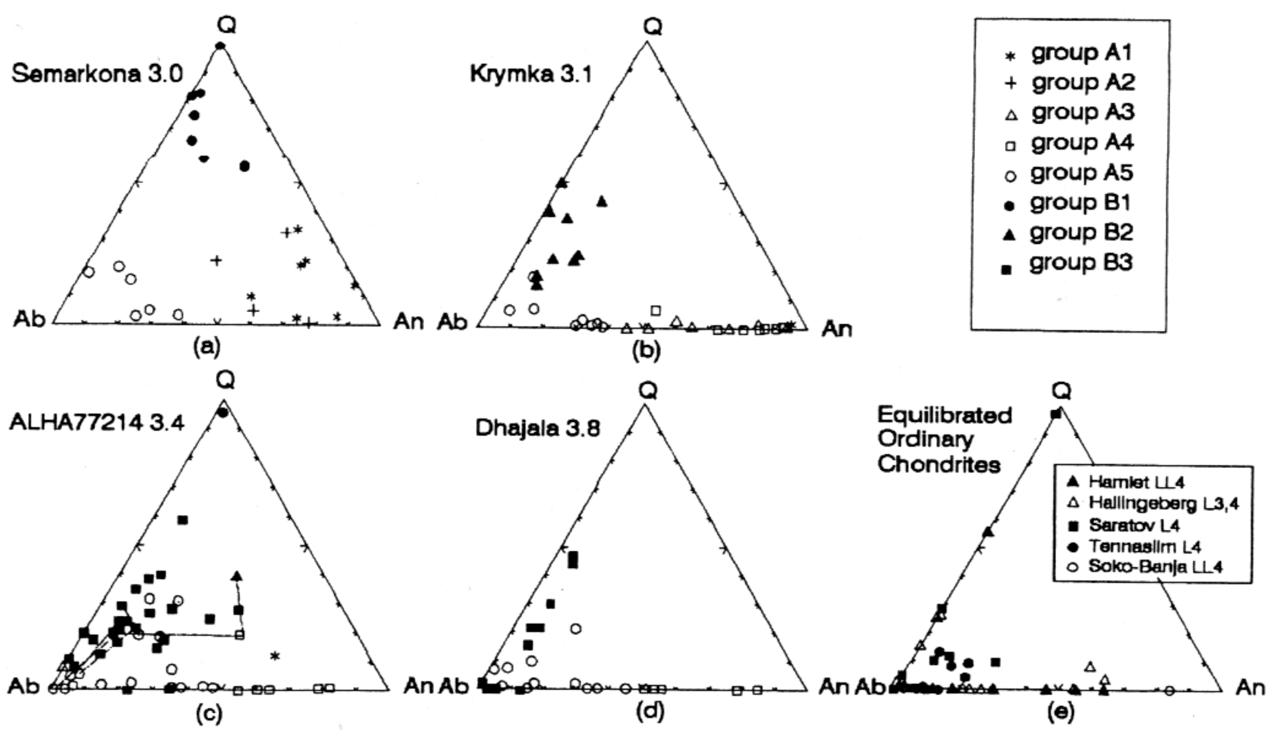

FIG. 2. Ternary plots for the major normative minerals in the chondrule mesostases analyzed in Semarkona (a), Krymka (b), ALHA77214 (c), and Dhajala (d). In most cases, the mesostases are >50% normative feldspar, but the nonluminescent mesostases in Semarkona are frequently quartz normative. Tie-lines connect data for chondrules in which the mesostases have outer zones and interiors with differing cathodoluminescence and compositional properties. Also shown (e) are data from GOODING (1979) for the mesostases of five type 4 ordinary chondrites.

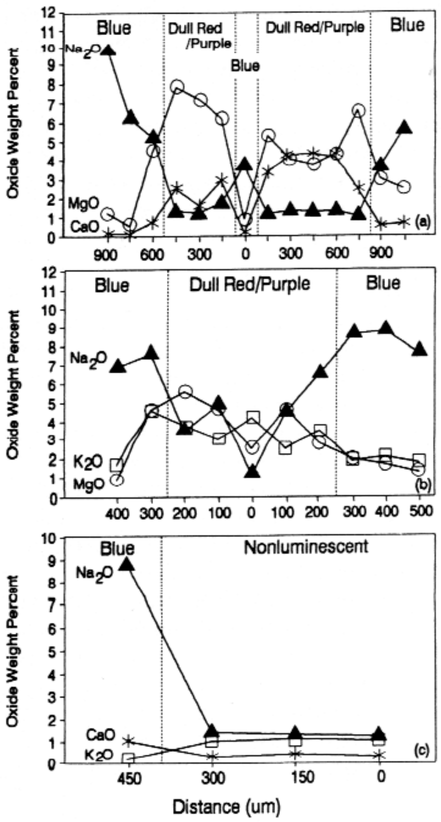

FIG. 3. Compositional profiles for the mesostases in chondrules 46 (a) and 50 (b) in Allan Hills, which is notable for the number of zoned chondrules, and chondrule 13 (c) in Semarkona. In each case, the region of lower CL is encircled by the region of higher CL. The CL colors of the different chondrule regions are indicated.

mesostasis during metamorphism (VAN SCHMUS and WOOD, 1967; DODD, 1969).

We were able to microprobe several microlites located in the mesostases, although with great difficulty. They appeared to be Fe-rich olivines and Ca-, Al-rich pyroxenes, in agreement with earlier observations (JONES and SCOTT, 1989).

Chondrule Olivine and Pyroxenes

Our data for chondrule olivines and pyroxenes are summarized in Figs. 5 and 6 and Table 5 (see DEHART, 1989, for details). The olivines in the various groups show reasonably well-defined differences in composition with the group A1 and A3 chondrules being rather similar. The FeO contents of the olivines in group A1 are <2% and in the same range as that of type IA chondrules, while olivines of group A3 extend to larger values, up to 4%. Group A2 olivines have somewhat higher FeO, similar to that of olivines in type IB chondrules. Groups A4, B1, and B2 have the most fayalitic olivine which resembles that of type II chondrules in the lower petrologic types (SCOTT and TAYLOR, 1983; JONES and SCOTT, 1989; JONES, 1990).

Our data for the refractory elements (Ca, Al, and Ti) in olivine agree well with those of previous workers (JONES and SCOTT, 1989; JONES, 1990), with STEELE's (1986) blue luminescing forsterite plotting at the upper limits of our A1 range. There is a negative correlation between the refractory elements and Fe, as observed for Ca and Al by DODD (1978). Calcium, Ti, and Al decrease along the A1, A2, A4, A5 series, with overlap between A1 and A3 and between A4 and A5. Group B olivines are generally lower in Ca, Ti, and Al than those of group A, and group B2 olivines are lower in Ca than those of group B1, but again there is much overlap. With increasing petrologic type, compositions move towards a restricted range of "equilibrium" values, so that in Dhajala the data are tightly clustered where the olivines are compositionally homogeneous except that group A5 chondrules contain higher concentrations of Ti than group B3 chondrules.

The relatively volatile elements, Mn and P, correlate reasonably well with Fe in the olivines of the least-metamorphosed chondrites. With increasing metamorphism, the Mn or P to Fe ratio decreases until eventually all chondrules reach a common value. This could reflect either condensation related processes (HEWINS, 1991) or reduction and volatile loss (LU et al., 1991). Of course, inter- and intragroup trends are unrelated and igneous zoning complicates matters further. The Cr content of the olivine shows somewhat different behavior, being high (~0.5 wt% Cr_2O_3) in all chondrule groups in Semarkona, except A1 and A3 (0.50–0.15%), but is much lower in Krymka olivine (~0.2 wt%). In Allan Hills A77214 and Dhajala, the Cr content of the olivine is below the detection limit. Apparently it "equilibrates" more rapidly during metamorphism than Mn and P, probably due to the formation of chromite (JOHNSON and PRINZ, 1991). Again these data are in good agreement with earlier results (JONES and SCOTT, 1989; JONES, 1990; STEELE, 1986).

It would be of value to see if olivine grains enclosed in the two zones of zoned chondrules showed differences in composition expected on the basis of unzoned chondrules. Unfortunately, the outer regions of the zoned chondrules are usually too narrow to totally enclose olivine grains (see Fig. 1). An exception was one chondrule in Semarkona (no. 13) in which the olivines did show the expected compositional

Table 4. Distribution of mesostasis textural types*

	Simple	Inter-mediate	Complex
CL group A	45	4	2
CL group B	19	21	2
A1	5	1	1
A2	2	1	1
A3	5	2	0
A4	33	17	6
A5			
B1	11	7	1
B2			
B3	8	16	1
Semarkona	13	8	1
Krymka	20	6	2
ALHA77214	18	18	4
Dhajala	13	12	3

* These are qualitative descriptive terms for the apparent complexity of the matrix, as observed in the SEM. The appearance of the mesostasis is governed mainly by the number of microlites. See Fig. 4.

a

b

c

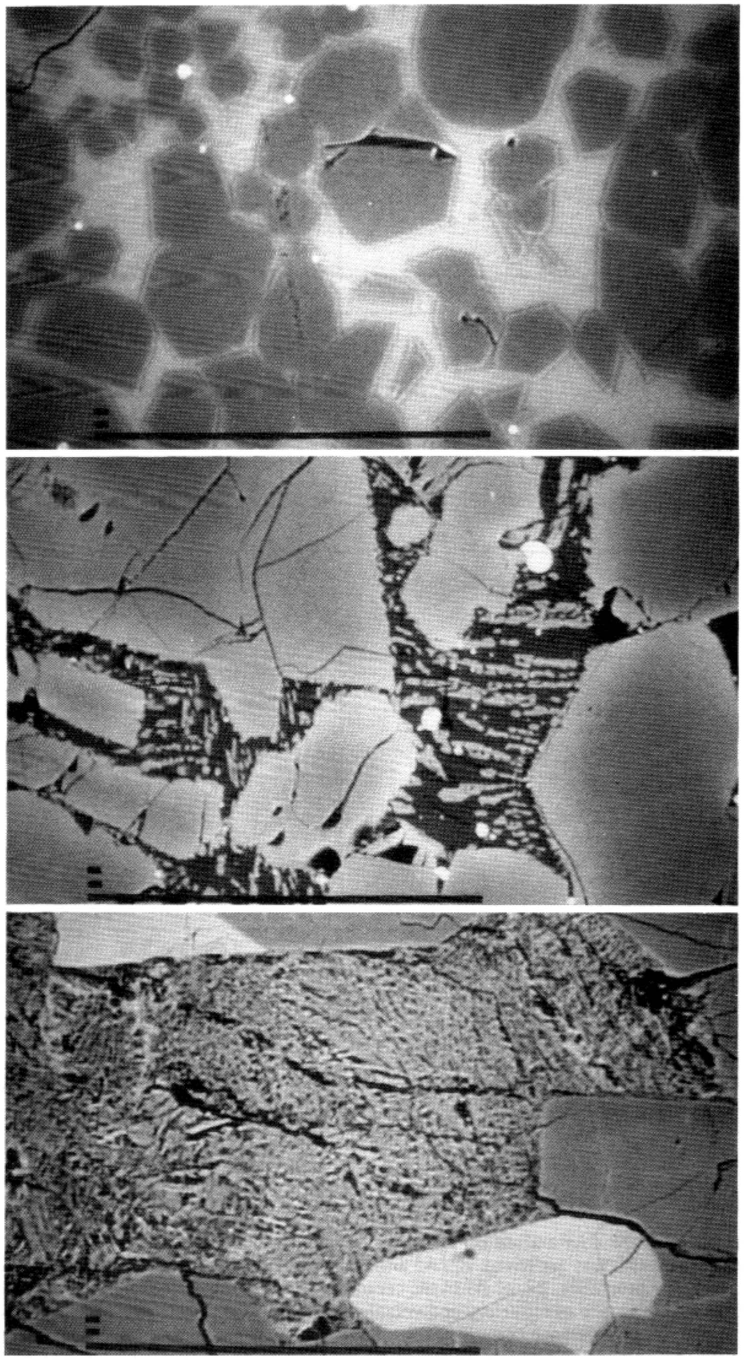

FIG. 4. Backscattered electron images showing the range of textures observed in the mesostasis of chondrules. The textures are classified as (a) "simple" with <20 modal percent (b), "intermediate" with 20–50 modal percent, or (c) "complex" with >50 modal percent microlytes embedded in glass (c). The examples are all from chondrules in Semarkona (numbered 10, 25, and 29, respectively). The microlytes vary from Fe-rich olivines and pyroxenes to Ca-Al rich pyroxenes. Horizontal fields of view are 150, 100, and 60 microns for Fig. 4(a),(b), and (c), respectively.

differences. Olivines were frequently found to be in contact with two types of compositionally distinct mesostasis, but we did not detect any compositional gradients across the grains. We have indicated the zoned chondrules in Fig. 5. Not surprisingly, they usually plot in the region expected for the group of the central region, perhaps with an indication of extending to higher FeO contents.

Figure 6 shows our analyses for the central regions of low-Ca pyroxenes. Many showed considerable compositional zoning. In A1–3 chondrules the FeO content of the pyroxenes

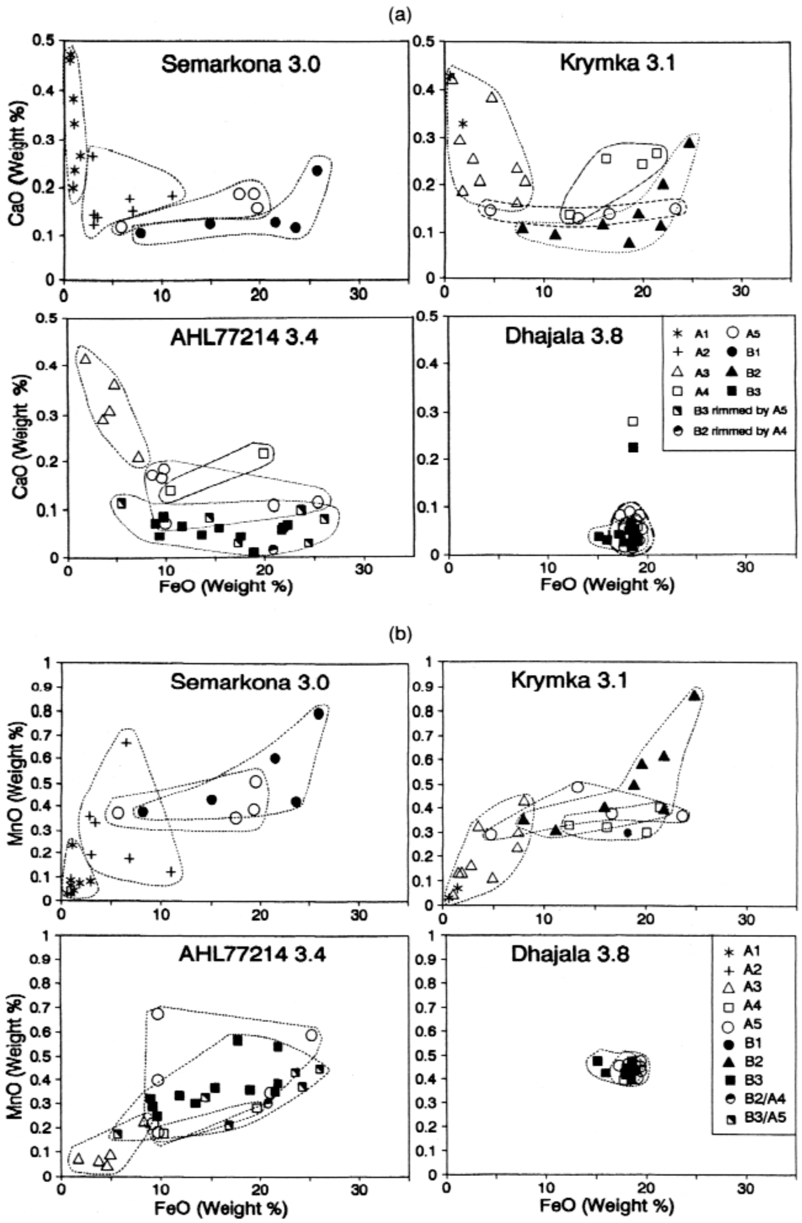

FIG. 5. Summary of the composition of chondrule olivines, coded according to the group of the chondrule (or chondrule region) in which they are found. B2/A5 and B3/A5 refer to chondrules whose mesostasis are zoned in their CL and compositional properties, B2, or B3 in the central regions and A5 in the outer regions. (a) CaO vs. FeO, (b) MnO vs. FeO as representative of refractory and volatile elements, respectively. Al and Ti show very similar patterns to Ca, the only significant difference being that the olivines in A4, A5 chondrules in Dhajala are significantly higher in Ti than the olivines in B3 chondrules in Dhajala. The volatile elements Mn, Cr, and P show very different behavior to the refractory elements and to each other but the chondrule groups are still resolvable, albeit with some overlap.

is low, unlike that of B1, B2, and A5 chondrules. There are weak suggestions that pyroxenes of group A5 chondrules are higher in Ca than groups A1–3 and group B1 are lower in Ca than in group A4. We found virtually no low-Ca pyroxene in B3 chondrules. The pyroxenes are always more heterogeneous than olivines and even in Dhajala show considerable heterogeneity. This is usually attributed to slower diffusion rates in pyroxene compared to olivine.

More than 80% of the high-Ca pyroxenes we located were in Dhajala A4 and A5 chondrules, usually rimming olivine or low-Ca pyroxene. They showed a broad range of compositions with the refractory elements, Ca, Al, and Ti, showing a negative correlation with FeO until FeO reaches about 8 wt%, above which the data level out or perhaps show a slight positive correlation (Fig. 7). Group A4 is noteworthy for the high TiO_2 and low FeO of its calcic-pyroxenes.

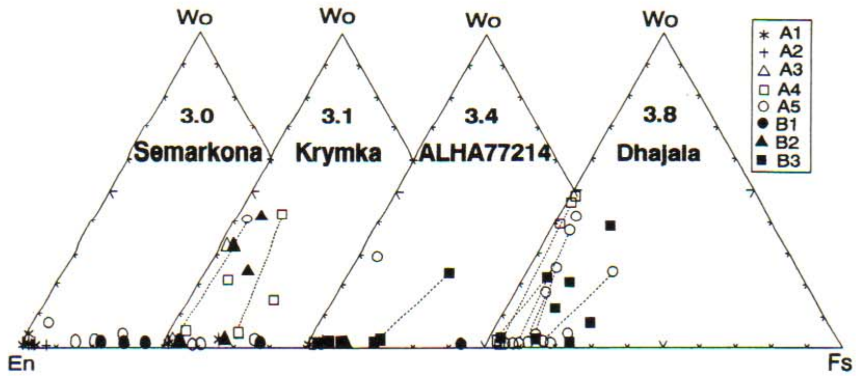

FIG. 6. Composition of chondrule pyroxenes, coded according to the CL group of the chondrule (or chondrule region) in which they are found. Data from zoned chondrules are connected with tie-lines.

Matrix Components

In addition to determining the compositions of isolated olivines and pyroxenes in the matrix, we determined the composition of the fine-grained opaque matrix in Semarkona and Krymka using a defocussed beam and measured the composition of glasses in the matrix of Allan Hills A77214 and Dhajala (Table 6; see DEHART, 1989, for details). Our data agree well with those of HUSS et al. (1981) and HUTCHISON et al. (1987), including the low sums due to porosity or unanalyzed components (NAGAHARA, 1984). The glass fragments have sodic feldspar compositions like the chondrule mesostases with blue CL. The FeO content of the isolated olivines and pyroxenes is very low in Semarkona but increases with petrologic type of the host meteorite. The Cr content appears to decrease.

One of the isolated olivine grains in Krymka was large enough to obtain a compositional profile (Fig. 8). The Fe and Ca zoning is like that of the type A zoning of MIYAMOTO et al. (1986) and the olivines in type I (JONES and SCOTT, 1989) and type II (JONES, 1990) chondrules, consistent with normal igneous zoning. However, Mn anticorrelates with Fe in this grain, unlike any other isolated olivine observed in primitive meteorites, including other Krymka grains (STEELE, 1989). Calcite and an unidentified Fe-rich silicate in the matrix were also analyzed. The analysis of the Fe-rich silicate has a low sum, and this phase may be a hydrated phyllosilicate.

DISCUSSION

The Chondrule Groups

Although these groups were originally established on the basis of CL properties, these properties reflect major differences in mineral composition; and group membership can reliably be established without CL data. The scheme is defined essentially by Fig. 9 and summarised in Tables 5 and 7. The advantages of this chondrule classification scheme are as follows.

1) It is based on properties (phenocryst and mesostasis compositions) known to be important in deciphering chondrule history and is easily applied. The value of the scheme is independent of the present interpretations of those trends. The fields in Fig. 9 incorporate ≥70% of the relevant data in Figs. 2 and 5 and may be used with little difficulty to assign chondrules to groups in the absence of CL data. In some cases, chondrules will straddle groups because the CL and compositional changes are gradational, but this information is also of value (namely, the zoned chondrules in ALHA77214). The distinction between group A1 and A3 chondrules in the CL properties of the mesostases is especially marked (distinctive bright yellow CL mesostasis vs. equally bright blue CL for A1 and A3, respectively). DEHART and LOFGREN (1991a,b) discuss the origin of the yellow CL and the cause of these differences.
2) It reflects both primary and secondary alteration processes so that chondrules with different secondary properties (e.g., degree of metamorphic alteration) are not clumped together on the basis of similar primary properties (e.g., texture). This is especially important since the chondrules from a given meteorite may show considerable differences in their response to metamorphic alteration.
3) The scheme is very sensitive, i.e., very small differences in metamorphism apparently cause major differences in phase composition; this is especially true of the mesostasis.
4) The scheme incorporates the strengths of existing schemes and yet includes ≥95% of the chondrules present in the meteorites. For instance, Semarkona types IA, IB, and II are included in groups A1, A2, and B, respectively. The comprehensiveness of the scheme is important, for instance, as possible trends could be missed because of concentration on subsets or "endmembers." In questions involving mass-balance, e.g., the relationship between chondrule composition and bulk composition (e.g., LARIMER and ANDERS, 1967; WAI and WASSON, 1977; WOOD, 1985, 1987), it is clearly important that the full range of chondrules is considered.

The Chondrule CL Groups—Metamorphic Effects

The relationship between chondrule group and metamorphism is summarized in Fig. 10. Group A1 and B1 chondrules

Table 5. Average compositions for minerals and the mesostasis of the six chondrule cathodoluminescence groups*

	No+	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr_2O_3	P_2O_5	Total	Norms	
Olivine														Fa	
A1	57	42.1	0.03	0.10	2.39	0.09	54.4	0.31	0.04	<.02	0.22	<.02	99.7	2.4	
A2	11	41.8	<0.03	0.08	3.27	0.22	53.5	0.18	0.03	<.02	0.46	<.02	99.6	3.3	
A3	24	42.0	0.04	0.11	2.41	0.07	54.9	0.30	<.02	<.03	0.15	<.02	100.1	2.4	
A4	86	39.8	0.03	0.07	14.0	0.27	45.5	0.21	0.02	<.02	0.11	<.02	99.9	15.1	
A5	101	39.6	<0.03	0.03	14.8	0.36	44.9	0.12	0.03	<.02	0.14	0.03	99.9	15.8	
B1	31	39.0	<0.03	0.05	17.3	0.50	42.3	0.15	0.03	<.02	0.49	0.02	98.8	19.0	
B2	48	39.6	<0.03	0.08	15.3	0.42	44.0	0.17	0.03	<.02	0.18	0.02	99.8	16.7	
B3	127	39.0	<0.03	0.02	18.0	0.40	42.5	0.06	0.03	<.02	0.04	0.04	100.1	19.4	
Low-Ca pyroxene														Wo	Fs
A1	17	57.1	0.30	2.51	1.2	0.14	34.7	3.41	0.05	<.02	0.46	0.06	99.9	7.4	1.8
A2	18	58.5	0.04	0.39	2.4	0.19	37.1	0.25	0.04	<.02	0.52	<.02	99.5	0.5	3.5
A3	7	58.7	0.21	0.98	0.7	0.11	38.3	0.60	0.02	<.02	0.40	<.02	100.1	1.1	1.1
A4	12	57.0	0.18	2.49	4.3	0.18	35.2	0.96	0.02	<.02	0.63	<.02	100.9	1.9	6.5
A5	77	57.3	0.05	0.41	6.9	0.43	33.4	0.80	0.07	<.02	0.64	<.02	100.0	1.8	11.2
B1	12	53.8	0.02	0.38	19.9	0.58	23.9	0.57	0.05	<.02	0.82	<.02	100.0	1.2	31.4
B2	22	57.7	0.03	0.25	5.9	0.40	34.5	0.54	0.03	<.02	0.63	<.02	100.1	1.1	8.9
B3	40	57.5	0.11	0.77	6.1	0.35	34.1	0.94	0.11	<.02	0.56	<.02	100.6	1.8	9.3
High-Ca pyroxene														Wo	Fs
A1	2	48.7	0.82	11.36	0.57	0.09	16.6	20.9	0.08	<.02	0.33	(0.32)	99.7	47.1	1.0
A3	2	50.7	0.77	6.60	1.28	0.65	22.6	15.5	0.12	<.02	(2.29)	0.03	100.5	32.4	2.1
A4	13	50.8	1.86	7.39	2.19	0.16	18.2	19.1	0.13	<.02	0.60	0.07	100.6	41.5	3.8
A5	19	52.8	0.46	3.22	7.26	1.13	18.9	14.0	0.44	<.02	1.68	0.07	99.9	30.9	12.1
B1	1	53.7	0.31	1.81	10.1	0.68	15.2	15.8	(1.11)	<.02	1.80	(0.49)	100.9	35.0	17.6
B2	3	54.4	0.53	3.90	3.64	1.13	21.0	13.6	0.33	0.08	1.77	<.02	100.4	29.9	6.3
B3	7	52.9	0.65	2.91	7.94	0.49	19.3	13.9	0.53	0.04	1.11	0.07	99.9	29.0	14.9
Mesostasis														Plag	Qtz
A1	10	53.3	0.45	21.1	1.67	0.13	5.15	14.6	1.67	0.05	0.28	0.17	98.6	50.2	9.1
A2	4	56.9	0.60	19.3	2.80	0.49	4.25	11.5	2.42	0.26	0.35	0.22	99.1	42.5	12.6
A3	6	52.0	0.49	26.2	1.97	0.16	2.95	11.1	4.07	0.60	0.24	0.08	99.9	45.4	1.4
A4	17	50.0	0.30	27.4	1.74	0.11	3.19	14.2	2.89	0.13	0.21	0.04	100.2	61.6	0.1
A5	41	62.5	0.38	19.6	2.78	0.16	2.62	4.98	7.12	0.30	0.12	0.31	100.9	19.9	5.7
B1	7	74.7	0.41	11.9	5.21	0.20	1.25	1.62	1.37	0.77	0.06	0.31	97.8	10.8	55.0
B2	12	65.5	0.50	14.7	6.53	0.18	3.98	1.82	4.78	1.34	0.16	0.13	99.6	14.8	18.6
B3	35	66.8	0.46	15.0	3.80	0.15	4.56	4.00	5.92	0.72	0.15	0.40	101.9	13.1	15.4

* Suspect values in parenthesis. These values are probably high because of beam overlap with the mesostasis during microprobe analysis.

\+ 'No' refers to the number of grains in the case of olivine and pyroxene analyses and the number of points analyzed in the case of mesostasis analyses.

differ in major respects, but the group A vs. B differences gradually disappear with increasing metamorphism until the two series converge on group A5. A small proportion of the chondrules in Semarkona are group A5. Apparently, the chondrule-forming process was capable of producing a few chondrules which resemble the chondrules in equilibrated chondrites; however, olivines in the A5 chondrules in Semarkona are considerably more heterogeneous than those in the higher petrologic types. Also present in the original pre-metamorphic chondrule suite are the A2 chondrules which are genetically related to the group A1 chondrules (LU et al., 1991). Homogenization of mineral and mesostasis compositions in the A1–4 series occurs at lower levels of metamorphism than in the B1–3 series. The following mineralogical trends, produced in response to increasing metamorphism, have been identified.

1) The mesostasis composition becomes less calcic and more sodic. This is most marked among group A but is present in both groups and is apparent in Fig. 2.
2) Also reflecting the bulk composition of the mesostasis, the normative diospide decreases and the normative hypersthene increases.
3) For group A chondrules, the FeO content of the olivines increases. For group B chondrules, the FeO content of the olivines homogenizes.
4) The heterogeneity of the chondrule olivines and pyroxenes decreases, especially at levels of metamorphism equivalent to petrologic types > 3.4 (Fig. 11). The most heterogeneous chondrules are members of group A4 with group A5 and the B groups usually being the most homogeneous. Groups A1 and A2 are also very homogeneous. Nevertheless, chondrules of all groups are considerably more

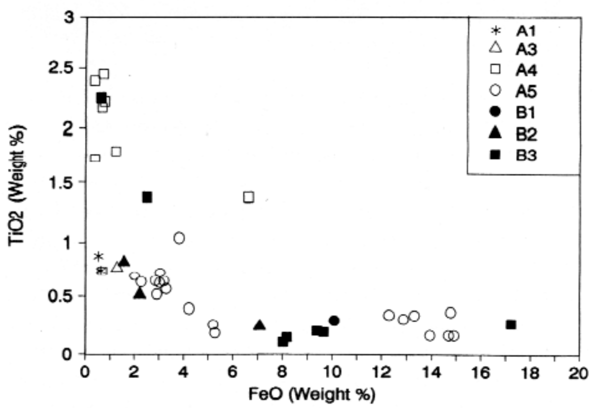

FIG. 7. Plot of TiO_2 against FeO for chondrule pyroxenes, coded according to the CL group of the chondrule (or chondrule region) in which they are found.

uniform in composition in Dhajala than the other chondrites.

5) The olivine becomes devoid of the trace and minor elements which characterize the olivines of the lowest petrologic types, most notably Ca, Cr, Al, and Ti (Fig. 5).
6) The clinopyroxenes become less calcic (Fig. 6). Especially noteworthy is the high TiO_2 and low FeO of group A4 clinopyroxenes compared to the other groups, principally group A5. Perhaps primary clinopyroxenes are Ti-poor, while those formed during metamorphism are initially high in Ti and lose Ti during subsequent metamorphism.
7) The mesostasis of group B chondrules, which was originally oversaturated in silica, becomes feldspathic. This process is very sluggish and does not become complete until petrologic type 4 levels of metamorphism or higher (Fig. 2).

There are several implications of these data. First, metamorphism has made extensive changes not only to the mineral chemistry but also to the bulk chemistries of meteoritic chondrules. There are even major differences between Semarkona (3.0) and its closest neighbor, Krymka (3.1). It clearly cannot be assumed that because a chondrite is type 3, the metamorphism experienced is too little for its chondrules to have had their composition affected. Second, because different chondrules respond differently and at different rates (Fig. 10), chondrule-to-chondrule differences in the degree of equilibration do not reflect different levels of parent-body metamorphism, i.e., they do not imply metamorphism prior to emplacement in the meteorite (DODD, 1978; SCOTT, 1984). SEARS et al. (1984) previously made this point on the basis of induced TL studies of Dhajala chondrules. Third, since chondrule groups A and B cut across textural groups (PO, POP, PP, etc.), the structures are only weak indicators of history. Presumably, the influence of secondary factors such as the number and type of nucleation centers and cooling rates affects structures more than precursor composition, for instance. Fourth, we suspect that the broader distinction into "droplet" and "clast" chondrules is related to the chondrule groups: group A are "droplet" chondrules and group B are "clast" chondrules. There is, of course, a relationship between chondrule group and McSween-Scott-Taylor chondrule types, at least for the low petrologic types, since both relate to the FeO content of the olivine. Similarly, the present classes reflect some of the trends observed by WLOTZKA (1983) in two type 3.4 chondrites, including a possibility for group B chon-

Table 6. Representative analyses of the matrix and isolated grains in the matrix.

Phase	No	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Cr_2O_3	P_2O_5	Total
Semarkona													
Red CL oliv.	11	42.31	0.02	0.16	1.38	0.15	55.25	0.22	0.04	0.01	0.31	0.01	99.85
Blue CL oliv.	1	41.65	0.08	0.51	1.16	0.02	54.60	0.46	0.03	0.00	0.11	0.02	98.63
Non-CL oliv.	1	41.42	0.01	0.06	4.28	0.05	52.65	0.20	0.12	0.00	0.48	0.00	99.29
Non-CL pyrox.	4	57.72	0.07	0.48	3.23	0.29	36.12	0.38	0.12	0.02	0.80	0.00	99.23
Calcite	4	0.14	0.01	0.00	1.36	0.14	0.39	62.27	0.30	0.02	0.01	0.05	63.70
Fe-rich phase	1	41.44	0.00	2.24	35.82	0.22	4.40	0.45	0.48	0.40	0.02	0.03	85.16
Opaque matrix	4	35.93	0.02	4.35	23.55	0.15	11.50	0.82	2.31	0.59	0.25	0.09	79.56
Krymka													
Red CL oliv.	2	42.95	0.04	0.20	0.65	0.01	55.99	0.51	0.01	0.01	0.14	0.00	100.52
Non-Cl oliv.	9	39.92	0.00	0.02	12.34	0.50	45.76	0.21	0.01	0.00	0.15	0.02	98.93
Red-CL pyrox.	8	58.85	0.09	0.68	1.24	0.07	37.82	0.48	0.02	0.42	0.01	0.00	99.69
Non-CL pyrox.	9	57.90	0.02	0.26	5.27	0.08	35.16	0.25	0.00	0.00	0.63	0.00	99.57
Blue glass	1	68.00	0.14	19.49	0.99	0.04	0.90	2.00	5.70	0.06	0.02	0.01	97.36
Opaque matrix	3	33.74	0.05	4.51	37.60	0.33	11.85	1.27	1.49	0.18	0.37	0.14	91.52
ALHA77214*													
Olivine cores	2	39.39	0.06	0.06	15.95	0.03	45.36	0.42	0.00	0.00	0.09	0.02	101.39
Olivine rims	2	35.50	0.04	0.04	33.05	0.35	31.17	0.31	0.00	0.01	0.06	0.01	100.54
Olivine Fa>45	5	33.86	0.01	0.00	40.49	0.64	23.32	0.29	0.04	0.01	0.94	0.06	99.66
Blue glass	2	66.77	0.51	15.23	4.04	0.10	3.89	4.60	2.80	1.59	0.01	0.87	100.40
Dhajala													
Olivine	8	39.22	0.01	0.01	18.26	0.42	42.83	0.04	0.01	0.01	0.03	0.01	100.83
Pyroxene	16	57.63	0.00	0.32	8.66	0.39	32.50	0.56	0.03	0.01	0.22	0.00	100.32
Blue glass	4	63.47	0.52	17.21	1.92	0.10	4.03	2.10	8.27	1.79	0.16	0.75	100.30
Opaque matrix - literature data+													
Ref. 1		37.40	0.06	3.27	25.90	0.21	11.50	0.73	2.53	0.60	0.29	----	82.59
Ref. 2		38.80	0.07	4.30	24.00	0.15	12.00	1.05	2.30	0.63	0.25	0.25	86.20
Ref. 2		34.80	0.07	2.77	39.84	0.36	12.00	1.11	0.84	0.35	0.28	0.19	92.25

* All the olivines and pyroxenes are non-cathodoluminescent.
+ Ref. 1, Hutchison et al., 1987; Ref. 2, Huss et al. (1981).

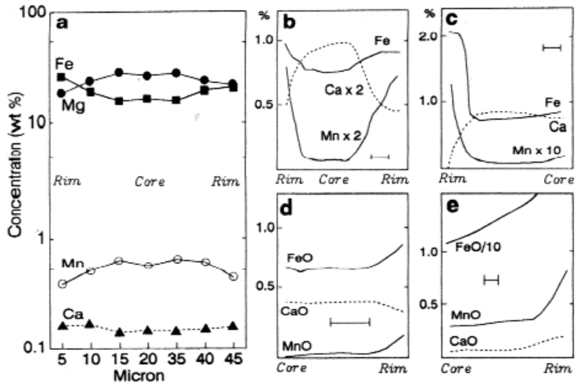

FIG. 8. Profile across an isolated olivine grain found in the fine-grain matrix in Krymka compared with sketches of profiles in olivine grains reported in the literature. (a) The Fe-rich olivine grain found in Krymka matrix during the present study. (b) An isolated Fe-poor grain found in the fine-grained matrix of Murchison (STEELE, 1986, based on his figure 8). (c) An isolated Fe-poor olivine grain found in the fine-grained matrix of Krymka (STEELE, 1986, based on his figure 9). (d) An Fe-poor olivine in a type Ia (group A1) chondrule in Semarkona (JONES and SCOTT, 1989, based on their figure 4). (e) An Fe-rich olivine found in type II (group B1) chondrule in Semarkona (JONES, 1990, based on her figure 3). The present grain resembles neither chondrule nor previously observed matrix grains and is highly unusual in showing an anti-correlation between Fe and Mn.

drules to be less circular in section than the smaller group A chondrules. Fifth, the present data provide further evidence that the TL sensitivity-metamorphism relationship is due to the formation of feldspar as chondrule glass crystallizes. Only 5% of the chondrules in Semarkona produce the blue luminescence used in the measurement of TL sensitivity, compared with 100% in equilibrated meteorites. Furthermore, the luminescence of the Semarkona chondrules is very weak. The present study and others show that the TL is produced by sodic feldspars which are scarce in the majority of chondrules in low petrologic types but are abundant in the equilibrated types. This topic was discussed in greater detail by SEARS et al. (1989).

The Chondrule CL Groups—Primary Effects

The chondrule groups present in Semarkona A1, A2, A5, and B1 represent pre-metamorphic material and provide an opportunity to explore the nature of processes which occurred before parent body metamorphism. Their primary differences are:

1) Group A1, A2 chondrules are very refractory, containing calcic feldspar normative mesostases and volatile-depleted elemental pattern. In contrast, group B1 chondrules contain sodic feldspar- and quartz-normative mesostases and normal CI-like elemental abundances (LU et al., 1990).
2) Group A1, A2 chondrules are highly reduced, containing FeO-poor olivine. SCOTT and TAYLOR (1983) type IA chondrules are in this group, and we find them to generally contain Ni-free metal. It is also our impression that type A1 chondrules are frequently surrounded by metal- and sulfide-rich rims, which is relatively rare in group B chondrules. In contrast, group B chondrules, which include type II chondrules, contain FeO-rich olivines and no metal.
3) Two Semarkona group B chondrules that have been analyzed to date contain oxygen isotope compositions in the "normal" range for equilibrated chondrite chondrules, but unfortunately there are no data for Semarkona group A chondrules. Chondrules hand-picked from Semarkona, on which the existing literature data are based, are probably entirely group B because group A chondrules are small and friable (SEARS and DEHART, 1989). Without oxygen isotope data for group A chondrules, an understanding of oxygen isotope data for chondrites is impossible since such chondrules are abundant. There are data for Allende chondrules which suggest a relationship between chondrule group and oxygen isotope data. The Allende group A chondrules have $\delta^{18}O < 3.5‰$ ($\delta^{17}O < -1‰$), while 5 out of 7 group B chondrules analyzed to date have heavier oxygen than this (CLAYTON et al., 1983; MCSWEEN, 1985).
4) A small fraction (5%) of the primary chondrules are group A5, i.e., they have mesostasis and phenocrysts whose compositions resemble those of the equilibrated chondrites. However, the coefficient of variation for the Fe in olivine decreases from 5–20% in Semarkona to <2% in Dhajala. This suggests that the "equilibrated" state of the A5 chondrules in Semarkona does not reflect metamorphism of the chondrules prior to emplacement in the meteorite, rather that the chondrule-forming process was

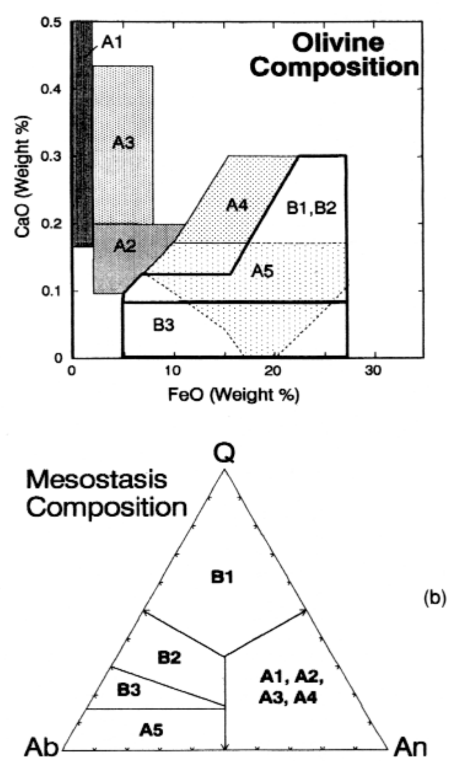

FIG. 9. Discrimination plots for the classification of chondrules using (a) olivine and (b) normative mesostasis compositions.

Table 7. Mineral, petrologic and chemical properties of the CL groups*.

	Mesostasis (normative)	Oliv %FeO	Oliv %CaO	Oliv CV(%)	Low-Ca Px (%FeO)	Bulk Lithophiles	Comments
A1	~80% plag (An>50%)	<2	>0.17	>8	<1.5	Vol depleted	Inc type IA
A2	~80% plag (An>50%)	2-10	0.1-0.2	<8	<3.5	Vol depleted	Inc PP
A3	~80% plag (An>50%)	<4	>0.2	10-40	<1.4	Vol depleted	
A4	~80% plag (An>50%)	>4	0.16-0.3	5-20	2-10	Flat	
A5	>80% plag (An<50%)	>10	<0.16	<5	2-10	Flat	
B1	>50% quartz	7-25	0.08-0.3	5-30	2-10	Flat	(Inc type II,
B2	30-50% quartz	10-25	0.08-0.3	5-30	2-10	Flat	(norm O isotopes
B3	30-15% quartz	15-20	<0.08	5-30	2-10	Flat	

* Some of the mineral and phase composition fields are not rectangular, see Fig. 9.

sometimes capable of producing objects without fractionating their compositions.

Origins and History of Chondrules

Most (95%) of the chondrules in Semarkona consist of components whose composition is unlike that expected from the composition of the whole rock and are, in this sense, "fractionated." For example, the A1–4 group chondrules have low FeO olivines and/or calcic mesostases and the group B chondrules have SiO_2-rich mesostases. There are arguably three plausible types of mechanisms which could account for the primary chondrule groups. They could reflect (i) the effects of aqueous or other secondary processes acting on the same original material, (ii) differences in the composition of the precursor material, or (iii) processes occurring during chondrule formation, e.g., loss of volatiles and reduction during chondrule formation.

The compositional differences are such that we can rule out process (i) as a means of explaining the differences between group A and group B chondrules. Certainly there is mineralogical evidence for aqueous alteration in Semarkona and Bishunpur (HUTCHISON et al., 1987; ALEXANDER et al.,

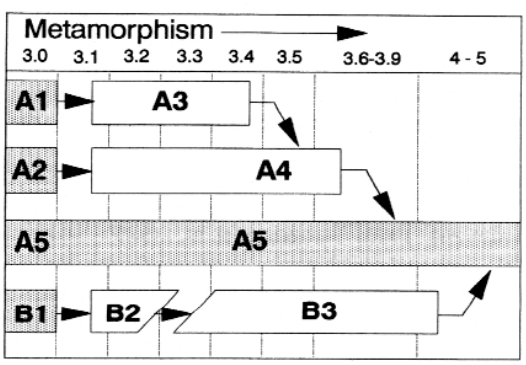

FIG. 10. Schematic representation of the proposed metamorphic relationship between the CL groups. Group A1, the genetically related group A2, the "equilibrated" group A5 and group B1 are "primary," i.e., pre-metamorphic, and compositionally distinct. Metamorphism causes the A and B series to homogenize and ultimately converge on group A5. However, the ease of homogenization is greater for group A, and considerable levels of parent body metamorphism are necessary to homogenize group B chondrules. An estimate of the level of parent body metamorphism, as reflected in the petrologic type, is indicated by the type alongside each step.

1989), and we have found chondrules in Semarkona with very strange CL properties which are reminiscent of textures in Murchison and which we think might reflect extensive aqueous alteration. However, such textures are very rare—less than one chondrule in fifty having such a texture. We agree with many previous researchers that differences among the chondrule groups reflect either differences in precursor properties or differences in the chondrule formation process and we have previously summarized the arguments for process (iii) (LU et al., 1990). In fact, both processes may have been operative to some extent. The separation of the entire chondrule population into groups in the manner we suggest here will almost certainly help in identifying which of processes (ii) or (iii) was most important, or at least clarify some of the details.

An example of how the present chondrule groups can help with deciphering chondrule history concerns the major issue of Na and other volatile element loss during chondrule formation. HEWINS (1991) recently argued that the lack of a negative correlation between Na and calculated liquidus temperature for chondrules as a whole was evidence against the idea that chondrules suffered Na-loss during their formation. In fact, there is a negative correlation between Na and calculated liquidus temperature for the genetically related Semarkona group A1 and A2 chondrules (SEARS et al., 1991b) which is not shared by the unrelated group B chondrules. Hewins did not show such a plot for Semarkona, reproducing McSween's data for CV chondrites instead, which show considerable scatter. We suggest that the A1–4 group chondrules did suffer volatile-loss. And since the amount of loss correlates with olivine FeO, that loss of Fe through reduction and evaporation accompanied Na-loss. We note in passing that many lithophile elements, including Si, were also probably lost during chondrule formation; so the matter is very complicated. The argument of SCOTT and TAYLOR's (1983) that the abundance of olivine in all chondrules is evidence against FeO reduction and Fe volatilization assumes constant Mg/Si; however, this ratio changes because of the differential volatility of Mg and Si.

The zoned chondrules may provide clues to the behavior of volatiles during and subsequent to chondrule formation. A few such chondrules exist in Semarkona (Fig. 3; MATSUNAMI et al., 1991), so apparently some Na transport was occurring before parent body metamorphism. Perhaps these chondrules were exposed to a Na-rich environment in the gas or parent body regolith, or maybe aqueous fluids carried

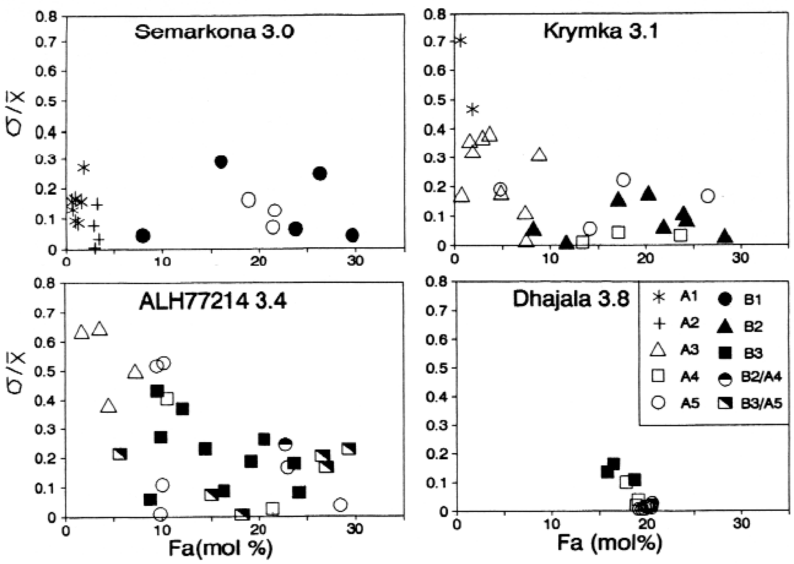

FIG. 11. Plots of the coefficient of variation (standard deviation divided by the mean) against FeO content of chondrule olivine, coded according to chondrule group.

in the Na during parent body processes. However, by far the greatest abundance of zoned chondrules is in the Allan Hills A77214 chondrite in which the chondrules are B3 in the centers and are A5 in the outer zones. It is especially important that this meteorite is petrologic type 3.5. ALHA 77214 represents a transition between the type 3.4 chondrite, Chainpur (in which B2,3 chondrules outnumber A5 chondrules), and Hedjaz (where A5 chondrules outnumber B3 chondrules). Apparently the mechanism by which Na was transported into the chondrules was by radial transport into the mesostasis and that the process mainly occurs at metamorphic levels equivalent to petrologic type 3.5 (500–700°C, SEARS et al., 1990a).

Another example of the value of a comprehensive chondrule classification is the study of JONES (1990) who suggested that lack of intermediate Fe values to those of type I and type II chondrules was evidence that one group was not formed from the other. In fact, although genetic relationships are complicated, A2 group does constitute such intermediate chondrules.

The Unique CL Properties of the Matrix of Primitive Meteorites: The Importance of Forsterite in Primitive Solar System Material

The fine-grained, inter-chondrule matrix is also very susceptible to alteration during metamorphism. In Semarkona, it also displays a characteristic, uniform bright-red CL and it is widespread, whereas in Krymka and Bishunpur it is sparse and irregularly distributed. It is entirely absent in higher petrologic types, except in low petrologic type clasts in the heavily brecciated Ngawi. A similar fine-grained, widespread, red CL phase is abundant in low petrologic type carbonaceous chondrites such as Colony (CO3.0), Allan Hills A77307 (CO3.1), and Murchison (CM2) (SEARS et al., 1991a). Whatever the mineralogical cause, this material is clearly a characteristic of the fine-grained component of the most primitive members of all chondrite classes.

The most plausible candidate for this red CL phase is submicron grains of forsterite. Forsterite normally has bright-red CL. It produces blue CL only when depleted in transition metals and enriched in refractory elements (STEELE, 1986, 1989), which is rare. We were able to analyse a few larger red CL grains in the fine-grained matrix and found them to be forsterite. NAGAHARA (1984) and HUSS et al. (1981) have shown that Semarkona is unusual among type 3 ordinary chondrites in that its fine-grained matrix contains abundant forsterite, while the matrix olivine in higher petrologic type chondrites is fairly fayalitic. It is possible, but doubtful, that this reflects differences in the Fe/Mg of the matrix of Semarkona and the higher types. However, this is doubtful because the bulk compositions of Krymka and Semarkona are very similar. Rather it probably reflects redistribution of Fe between the matrix, metal, and chondrules, all of which underwent major physical and chemical changes during the initial stages of metamorphism. Several authors have shown that forsterite is also present in the matrix of Colony, Allan Hills A77307, and CM chondrites (BREARLEY, 1990; BUNCH and CHANG, 1980; TOMEOKA et al., 1989). NAGAHARA (1984) discussed possible nebular origins for the forsterite in the matrix of Semarkona. We assume that the metamorphism-dependence of the red CL is caused by the fine-grained nature of the forsterite and its intimate association with Fe-rich materials. About 2% FeO is sufficient to quench the CL of olivine (STEELE, 1986; DEHART, 1989).

The relatively large isolated grains found in the matrix are also often forsterite (STEELE, 1988). Opinion differs as to the origin of these isolated olivines. STEELE (1986) and OLSEN and GROSSMAN (1974) suggest that they are primary nebula products, while MCSWEEN (1977), MCKINLEY et al. (1984), DESNOYERS (1980), NAGAHARA and KUSHIRO (1982), and ROEDDER (1981) suggest that they are fragments of chondrule olivines. In isolated olivine grains in the matrices of primitive chondrites and olivines in type IA chondrules, Fe and Mn are similarly zoned and inversely correlated with Ca. By contrast, Fe, Mn, and Ca are similarly zoned in the olivines of type II chondrules. In the grain in Fig. 8, Fe and Ca are similarly zoned and inversely correlate with Mn. In fact, the profiles for the present Krymka grain shown in Fig. 8 are unlike any previously observed in isolated or chondrule olivines and do not point unequivocally to an origin by nebular or igneous processes.

Origin of the Chondrite Groups

The role of chondrules in determining the bulk composition of the chondrites and, therefore, the nine chondrite groups (SEARS, 1988; SEARS and DODD, 1988) has often been discussed (e.g., LARIMER and ANDERS, 1967; SAFRONOV and VITJAZEV, 1986; WOOD, 1985, 1987). This idea has been criticized on the grounds that the chondrules do not show depletions in their volatile elements (e.g., WAI and WASSON, 1977). It now seems that this criticism was, at least to some extent, premature because most of the chondrule data in the literature were for metamorphosed chondrules. The extent of the compositional diversity of chondrules is also much greater than previously supposed. Chondrules with significant volatile depletions are now known to be present in the primitive ordinary chondrites and in relatively high abundance (LU et al., 1990, 1991).

Since chondrules constitute the largest volume fraction of the meteorites, it seems clear that their properties will have an influence on the bulk composition of the chondrites. In fact, the relative proportions of the various chondrule groups may play some role in defining the nine chondrite groups and in explaining the unusual reduced chondrites (GRAHAM et al., 1977; SCOTT et al., 1985; SEARS et al., 1990b; WASSON et al., 1991). Certainly the differences in the properties of the group A and group B chondrules are similar to those distinguishing the chondrite groups (lithophile element abundances and redox state; as yet there are no data for oxygen isotopes in group A chondrules). Within the type 3 ordinary chondrites, the ratio of group A to group B chondrules is reasonably constant showing only a systematic increase due to the formation of group A5 chondrites by metamorphism. There is ample evidence for systematic differences in the chondrule populations in each chondrite group (DODD, 1981), although the applicability of the present chondrule classification scheme to the other chondrite groups has yet to be evaluated.

CONCLUSIONS

The cathodoluminescence properties of the type 3 chondrites show considerable complexity and an increase in overall CL level as one proceeds to greater levels of metamorphism and great diversity in the CL displayed by the lower petrologic types (SEARS et al., 1989). By sorting the chondrules into eight groups (Table 2) and by determining the number of chondrules in these groups as a function of petrologic type (Table 1), it is possible to deduce genetic/evolutionary sequences of the chondrules (Fig. 10). Four of the chondrule groups are present in Semarkona (3.0) and are presumed to be primary, i.e., pre-accretionary. Of these four groups, two (groups A1 and A2) are genetically related since they are similar to each other in many ways, including similar bulk compositions and unusual rare-earth element patterns (LU et al., 1991). One (group A5) consists of chondrules whose mesostasis and phenocryst compositions resemble those of chondrules in equilibrated chondrites but with greater compositional heterogeneity. The remaining group (group B1) differs from the others in many ways, most notably in its quartz-normative mesostasis.

The remaining four groups represent chondrules formed from the others by metamorphism. Group A1 and A2 chondrules produce group A3, A4, and, finally, group A5 chondrules by open-system metamorphism, while group B1 chondrules evolve into group B2, B3, and then A5 chondrules during metamorphism. Evolution along the A1,2–A5 series occurs at much lower levels of metamorphism, being essentially completed within the petrologic type 3 chondrites, compared to the evolution along the B1–A5 series which requires petrologic type 5 levels of metamorphism. The range of chondrules observed in a given chondrite depends therefore on the range originally present and on the level of metamorphism experienced by the meteorite as a whole. There is no evidence in the chondrites that chondrules were metamorphosed prior to emplacement in the chondrite as argued by SCOTT (1984) and DODD (1978). The CL and compositional zoning of certain chondrules normally reflects metamorphic redistribution of volatiles, although other processes may be effective on occasion.

There are major compositional differences in chondrules which account for their CL properties and the chondrule groups. Group A chondrules have plagioclase-rich mesostases; and in group A1–3 chondrules, the phenocrysts are FeO-poor. Group B chondrules have mesostases which have considerable quartz in their norms with the amount decreasing along the B1 to B3 series. It is possible to use phenocryst and mesostasis composition to assign chondrules to groups (Fig. 9; Table 7), although in some instances the trends are gradational and there is overlap in composition. The present system of chondrule classification is superior to previous systems since it is based on the major element composition of the major chondrule components and it includes >90% of the chondrules present in the meteorites. Unlike previous systems it does not concentrate on a small homogeneous subset; neither is it based on secondary properties like texture. It does incorporate some of the features previously observed. For example, the "droplet" and "clast" distinction of KIEFFER (1975) and DODD (1981), the related observations of WLOTZKA (1983), and the McSween-Scott-Taylor types IA, IB and II are integrated into the scheme.

Since the group A and group B chondrules differ from each other in bulk composition, redox state, and possibly oxygen isotope properties, and also since the ratio of group A to group B chondrules differs from chondrite class to chondrite class, it is possible that the nine chondrite groups were created in part by the proportion of admixture of group A to Group B chondrules.

Forsterite is an important constituent of the fine-grained precursor dust for the chondrites. Primitive chondrites from all classes have a distinctive bright red cathodoluminescence which readily disappears at very low metamorphism levels, presumably by reaction with Fe-rich phases.

Acknowledgments—We are grateful to the individuals and institutions listed in Table 1 for the loan of thin sections, and to Walter Manger, Department of Geology, University of Arkansas, for the loan of the cathodoluminescence apparatus. We also thank Martin Prinz for discussions, and Rhian Jones and Ed Scott for the loan of the thin sections used in their work and Ian Steele, Karl Ramseyer and, especially, Roger Hewins for constructive reviews. This research is supported by grants from NASA (NAG9-81 to DWGS, and NGT-50064 to JMD) and from the Quintana Petroleum Corporation, Houston, (to W. Manger).

Editorial handling: C. Koeberl

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