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THE CR CHONDRITE CLAN

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Abstract: The (1) CR chondrites, (2) LEW 85332, (3) Acfer 182, (4) ALH 85085-like chondrites, and (5) Bencubbin-like chondritic breccias are five kinds of chondritic groups which have dramatically different petrographic characteristics, but have mineralogical, bulk chemical, and oxygen and nitrogen isotopic similarities that indicate they are closely related. They are all considered to be members of what we term the CR chondrite clan. Distinguishing characteristics of CR clan chondrites include: (a) reduced, Mg-rich mafic silicates, (b) hydrous matrix and/or dark inclusions (except for Bencubbin-like chondrites), (c) high modal abundances of FeNi metal, (d) FeNi metal having a solar Ni:Co ratio, (e) solar (CI) abundances of refractory and moderately volatile lithophiles, and highly depleted abundances of volatile lithophiles, (f) similar oxygen isotopic compositions of whole rocks, chondrules and matrices, which are on or near the CR mixing line, and (g) anomalously high ^{15}N abundances. CR clan chondrites must have formed in the same local region of the nebula, from closely related reservoirs of materials. The coexistence of anhydrous chondrules with hydrous matrix (and dark inclusions) in the LEW 85332, Acfer 182, and ALH 85085-like chondrites, as well as the widely differing degrees of hydration within and between chondritic samples, implies that hydration of the components was not variable in a single locality, but took place at a variety of locales prior to final lithification of the CR clan chondrites.

1. Introduction

In order to (1) constrain the physical and chemical conditions in the early solar nebula, (2) understand the nature of the primitive materials that accumulated to form the asteroids, comets, and larger bodies in our solar system, and (3) decipher the processes responsible for the formation of these bodies, it is important to document the range of chondrite groups and determine intergroup relationships. With the increasing number of new types of chondritic meteorites from hot and cold deserts (*i.e.*, Australia, Algeria and Antarctica), classification of chondrites and the relationships between chondrite groups becomes increasingly important. Clan as well as group relationships need to be established. The term "clan" is used here as a higher order of classification than "group" and is defined as chondrites that have chemical and isotopic similarities that suggest petrogenetic kinship, but have petrologic and/or bulk chemical characteristics that challenge a group relationship.

Currently, there are twelve chondrite groups (R, H, L, LL, EH, EL, CI, CM, CO, CV, CR, CK) whose characteristics are well-established. Additionally, there are a number of new kinds of chondrites which cannot be placed into any of the existing chondrite groups and represent new grouplets. Kakangari-like chondrites or K group (MASON and WIIK, 1966; GRAHAM and HUTCHISON, 1974; DAVIS et al., 1977; PRINZ et al., 1989, 1991; WEISBERG et al., 1993a; KALLEMEYN, 1994) and Coolidge-like chondrites (KALLEMEYN and RUBIN, 1994) are two examples.

In this current work, we review and examine the characteristics of five kinds of chondrites which are petrographically dissimilar, but have geochemical (bulk chemical and oxygen and nitrogen isotopic) and mineralogical similarities that strongly suggest that they are closely related and thus belong to the same clan. The five kinds of chondrites are: (1) CR chondrite group, (2) LEW 85332 chondrite, (3) Acfer 182 (and paired samples 207 and 214) chondrite, (4) ALH 85085-like chondrites, and (5) the Bencubbin and Weatherford (Bencubbin-like) chondritic breccias (Table 1).

Of the five kinds of chondrites, CR is a major well-established chondrite group, whereas the other four are new kinds of chondrites, some of which are represented by only one or two meteorites. (1) The CR chondrites are a group of eleven meteorites and their paired samples (BISCHOFF et al., 1993a; WEISBERG et al., 1993b; ICHIKAWA and IKEDA, 1994; KALLEMEYN et al., 1994; NOGUCHI, 1995). One of the CR chondrites, Kaidun, is a complex chondrite breccia that appears to be mainly CR chondrite, as suggested by petrologic and oxygen isotope data (IVANOV, 1989; CLAYTON et al., 1994). (2) LEW 85332 is a single meteorite (RUBIN and KALLEMEYN, 1990; PRINZ et al., 1993a). (3) Acfer 182 is a single meteorite that is paired with Acfer 207 and 214 (PRINZ and WEISBERG, 1992; BISCHOFF et al., 1993b). (4) The ALH 85085-like

Table 1. List of all of the meteorites in the five kinds of chondrites in the CR clan.

CR group	LEW 85332[4]	Acfer 182[4]	ALH 85085-like[5]	Bencubbin-like
Renazzo			ALH 85085	Bencubbin
Al Rais			PAT 91546	Weatherford
El Djouf 001[1]			PCA 91328	
Kaidun[2]			PCA 91452	
EET 87770[3]			PCA 91467	
MAC 87320			RKPA 92435	
PCA 91082				
Y-790112				
Y-791498				
Y-793495				
Y-8449				

[1]Paired with 9 Acfer meteorites (BISCHOFF et al., 1993b).
[2]A complex chondritic breccia which appears to be mainly CR (CLAYTON et al., 1994).
[3]Paired with 40 other EET meteorites (Antarct. Meteorite Newslett., 1989, 1994).
[4]Represented by only one meteorite, paired with Acfer 207 and 214.
[5]Pairing of some (or all) of these meteorites is uncertain.

chondrites (GROSSMAN *et al.*, 1988; SCOTT, 1988; WEISBERG *et al.*, 1988; WASSON and KALLEMEYN, 1990; BISCHOFF *et al.*, 1993b, 1994; PRINZ *et al.*, 1994) consist of six meteorites—ALH 85085, PAT 91546, PCA 91328, PCA 91452, PCA 91467, and RKPA 92435—some of which might be paired. (5) The Bencubbin-like chondrites (LOVERING, 1962; MASON and NELEN, 1968; KALLEMEYN *et al.*, 1978; NEWSOM and DRAKE, 1979; WEISBERG *et al.*, 1990; PRINZ *et al.*, 1993b) are two chondritic breccias, Bencubbin and Weatherford, with similar characteristics; they are petrographically most dissimilar to all other clan members, as well as to any other chondritic group.

Previous studies have suggested relationships between the five kinds of chondrites (*e.g.*, GROSSMAN *et al.*, 1988; WEISBERG *et al.*, 1988; WEISBERG *et al.*, 1990; PRINZ and WEISBERG, 1992; BISCHOFF *et al.*, 1993a,b; PRINZ *et al.*, 1992, 1993a, 1994; WEISBERG *et al.*, 1993b). Additionally, Acfer 182, and ALH 85085-like chondrites have been batched together as belonging to a new "CH" chondrite group (BISCHOFF *et al.*, 1993b), but we argue that their petrologic characteristics differ too much for a group-level relationship. It has also been suggested that ALH 85085 and Bencubbin are "subchondritic", impact-formed meteorites because of their unusual characteristics (KALLEMEYN *et al.*, 1978; WASSON and KALLEMEYN, 1990); however, GROSSMAN *et al.* (1988), SCOTT (1988), and WEISBERG *et al.* (1988) argued in favor of a nebular origin for ALH 85085 and WEISBERG *et al.* (1990) argued that the Bencubbin silicate clasts are chondrules and that Bencubbin is a chondrite formed in the nebula. We suggest that the five kinds of chondrites constitute what we call the CR clan.

2. Mineralogy and Petrology

The CR clan chondrites (listed in Table 1) exhibit a wide range of petrologic characteristics, as shown in Fig. 1a–e. Modal abundances (all modal data given in vol%) and chondrule sizes are the most obvious differences between the five kinds of chondrites in the CR clan (Table 2). CR chondrites are characterized by large (average diameter≈0.8 mm, maximum≈1 cm) multilayered, metal-rich chondrules and abundant (30–50 vol%) matrix+dark inclusions (DI). The matrix+DI component consists of hydrous phyllosilicates-mainly serpentine and saponite (ZOLENSKY, 1991; ZOLENSKY *et al.*, 1992), carbonates, sulfides, and magnetite framboids and platelets; anhydrous silicates are minor in the matrix. Chondrules range from being completely anhydrous, to having hydrated mesostases with anhydrous phenocrysts (olivine and pyroxene), to being completely hydrous with little or no trace of anhydrous silicates. Hydrous minerals in CR chondrules include serpentine and saponite, and some chondrules have a chlorite-rich mesostasis. FeNi metal averages ~7%, and is mostly within the chondrules and their rims. (See WEISBERG *et al.* (1993b) and BISCHOFF *et al.* (1993a) for details of CR chondrite petrologic characteristics.)

Petrographically, LEW 85332 (RUBIN and KALLEMEYN, 1990; PRINZ *et al.*, 1992, 1993a) is dramatically different from the CR chondrites in having much smaller chondrules (avg. diam.≈170 μm) and about 30% matrix+DI (Fig. 1, Table 2). The chondrules are nearly all anhydrous whereas the matrix is hydrous (serpentine-rich) with petrographic characteristics similar to those of CR matrix, including serpentine-

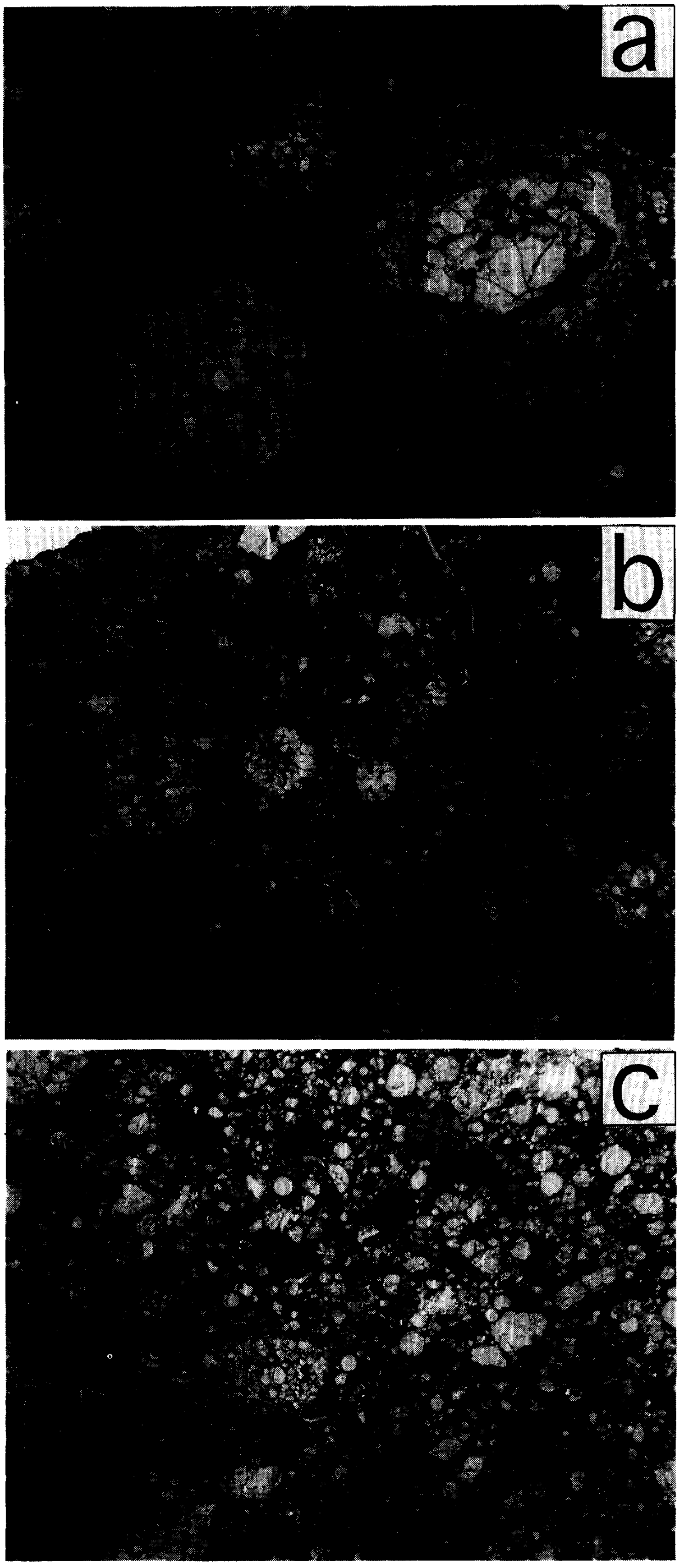

Fig. 1. Plane-polarized light photomicrographs (field of view=5 mm) of (a) the Al Rais CR chondrite, (b) LEW 85332, (c) Acfer 182, (d) the PAT 91546 ALH 85085-like chondrite, and (e) Bencubbin (silicate only), showing the marked petrographic differences between the meteorites in the CR chondrite clan. The most notable difference is in chondrule, fragment and inclusion sizes which range from an average of ~20 μm in the ALH 85085-like chondrites to the ~1 cm barred olivine clasts in Bencubbin.

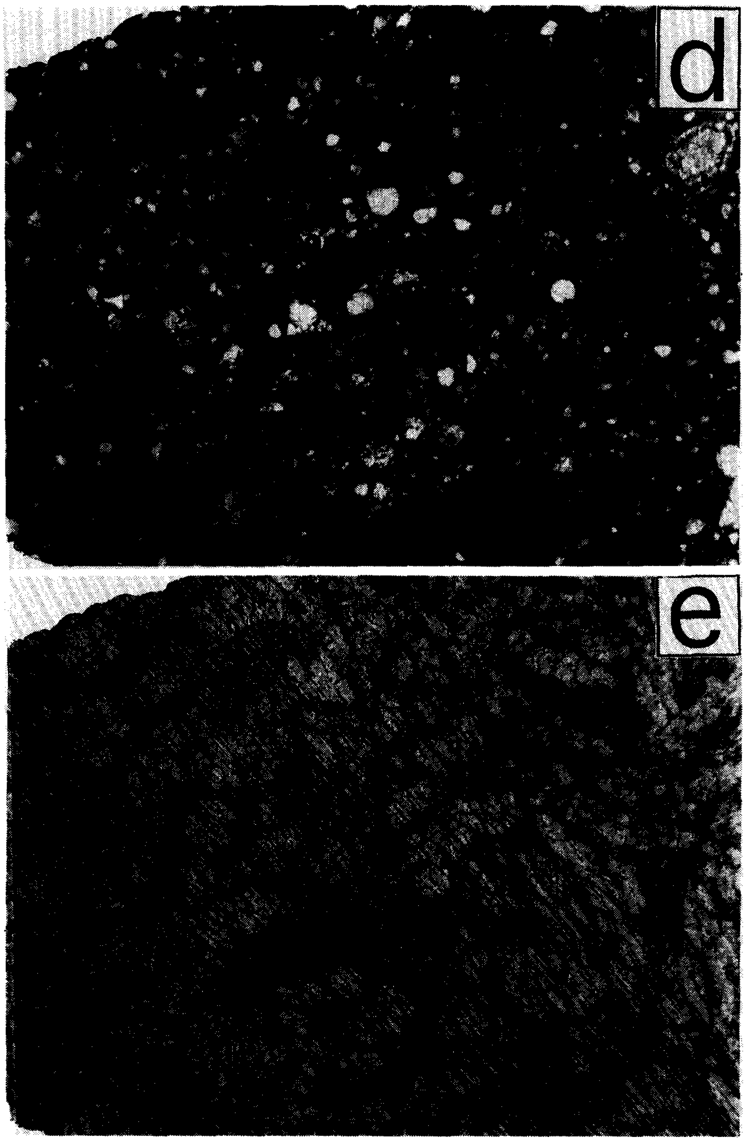

Fig. 1.

rich phyllosilicates, sulfides, and magnetite framboids and platelets. As in the CR chondrite group, metal makes up ~7%, but the metal abundance of LEW 85332 is difficult to determine due to extensive weathering.

Acfer 182 (PRINZ and WEISBERG, 1992; BISCHOFF *et al.*, 1993b) has even smaller chondrules than LEW 85332 (avg. diam.≈90 μm) and ~30% matrix+DI. As in LEW 85332, the chondrules are essentially anhydrous and the matrix and DI are hydrated, with similar petrographic characteristics to those of CR matrix and DI. Metal is mainly located in the matrix and constitutes ~9%.

ALH 85085-like chondrites (GROSSMAN *et al.*, 1988; SCOTT, 1988; WEISBERG *et al.*, 1988; WASSON and KALLEMEYN, 1990; BISCHOFF *et al.*, 1993b; PRINZ *et al.*, 1994) have the smallest chondrules in any chondrite (avg. diam.≈20 μm) and are also unusual in that the dominant chondrule type is cryptocrystalline, whereas the major chondrule textural type is porphyritic in the CR, LEW 85332, and Acfer 182 chondrites, as well as in most other chondrite groups. Matrix+DI make up only ~5% and, as in LEW

Table 2. Petrologic characteristics of the five kinds of CR clan chondrites.

	CR (Avg.)	LEW 85332	Acfer 182	ALH 85085-like	Bencubbin -like
Mode (vol%)					
Chondrules, Frag's & CAIs	49	62	55	73	40
Matrix & DIs^{+}	44	31	36	5	not found
Metal & Sulfide^{++}	7	7	9	22	60
Avg. chondrule diameter (μm)	800	170	90	20	10^4
Major chondrule textural type	POP	POP	POP-RP/C	RP/C	BO/C
Silicates (mol%)					
Olivine Fa range	<1–47	<1–37	<1–63	<1–36	2–3
Modal Fa	1–3	2	2–4	2	3
Pyroxene Fs range	<1–28	<1–30	<1–56	<1–33	2–3
Modal Fs	1–3	1–3	1–4	2	3
Metal (wt%)					
Ni range	3.4–14.3$^{\#}$	4.8–8.5	4.5–11.0	3.8–11.5$^{\#}$	5.3–7.5
Co range	0.1–0.5	0.2–0.3	0.1–0.4	0.2–0.5	0.2–0.3
References	1, 2, 3	4, 5	6, 7	6, 8, 9, 10	11

POP-porphyritc; RP/C-radial pyroxene or cryptocrystalline; BO-barred olivine. $^{+}$includes microchondrules ($\leq$200 μm). $^{++}$Sulfide is minor ($\leq$1%). $^{\#}$Rare metal grains with up to ~25% Ni are found. References: (1) BISCHOFF *et al.* (1993a), (2) KALLEMEYN *et al.* (1994), (3) WEISBERG *et al.* (1993b), (4) PRINZ *et al.* (1993a), (5) RUBIN and KALLEMEYN (1990), (6) BISCHOFF *et al.* (1993b), (7) PRINZ *et al.* (1993b), (8) GROSSMAN *et al.* (1988), (9) SCOTT (1988), (10) WEISBERG *et al.* (1988), (11) WEISBERG *et al.* (1990).

85332 and Acfer 182, all chondrules are essentially anhydrous and coexist with hydrous matrix and DI. Metal is interstitial to chondrules and fragments and constitutes ~22%, making it more metal-rich than any other chondrite, except for the Bencubbin-like chondritic breccias. One of the meteorites in this group, ALH 85085, contains minerals that are commonly associated with the highly reduced E chondrites, including Si-bearing metal, osbornite-TiN, and alabandite-(Mn,Fe)S (KIMURA and EL GORESY, 1989; WEBER *et al.*, 1994a).

The Bencubbin-like chondrites (LOVERING, 1962; MASON and NELEN, 1968; KALLEMEYN *et al.*, 1978; NEWSOM and DRAKE, 1979; WEISBERG *et al.*, 1990; PRINZ *et al.*, 1993b) are unlike any other chondrite. They are breccias consisting of cm-sized metal (~60%) and silicate clasts (~40%). The silicate clasts are texturally and/or compositionally barred olivine chondrules or chondrule fragments (Fig. 1e), with textures ranging from coarse-barred to cryptocrystalline (WEISBERG *et al.*, 1990). No hydrous matrix or DI are found in these chondrites, but they contain a variety of minor ordinary chondrite and R chondrite clasts and an anhydrous olivine-rich DI.

Olivine and pyroxene in most chondrules and fragments in CR clan chondrites

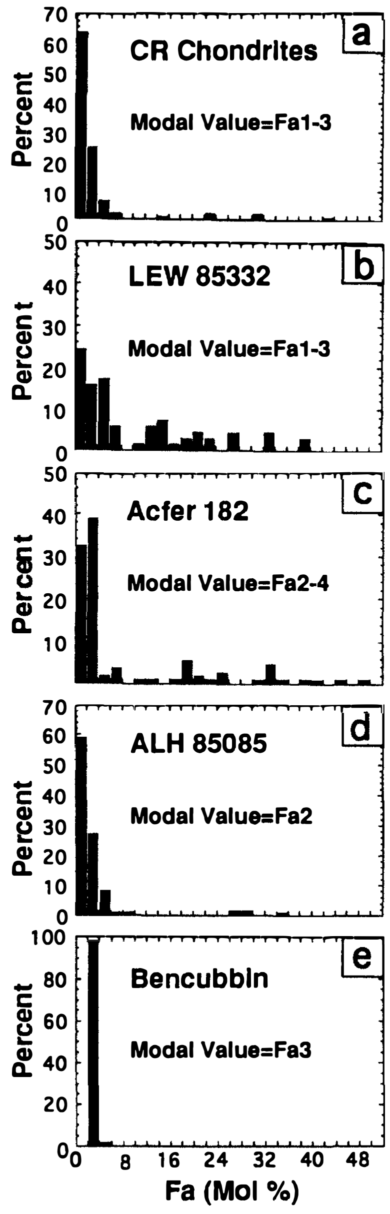

Fig. 2. Histograms of the Fa values (in mole%) of olivine in (a) CR chondrites, (b) LEW 85332, (c) Acfer 182, (d) ALH 85085, and (e) Bencubbin, showing that the majority of the anhydrous mafic silicates are similarly reduced in all of the chondrites in the CR clan. All of the histograms peak (modal values) at values of $Fa_{<4}$. Data from: BISCHOFF et al. (1993a, b), KALLEMEYN et al. (1994), RUBIN and KALLEMEYN (1990), WEISBERG et al. (1990, 1993b).

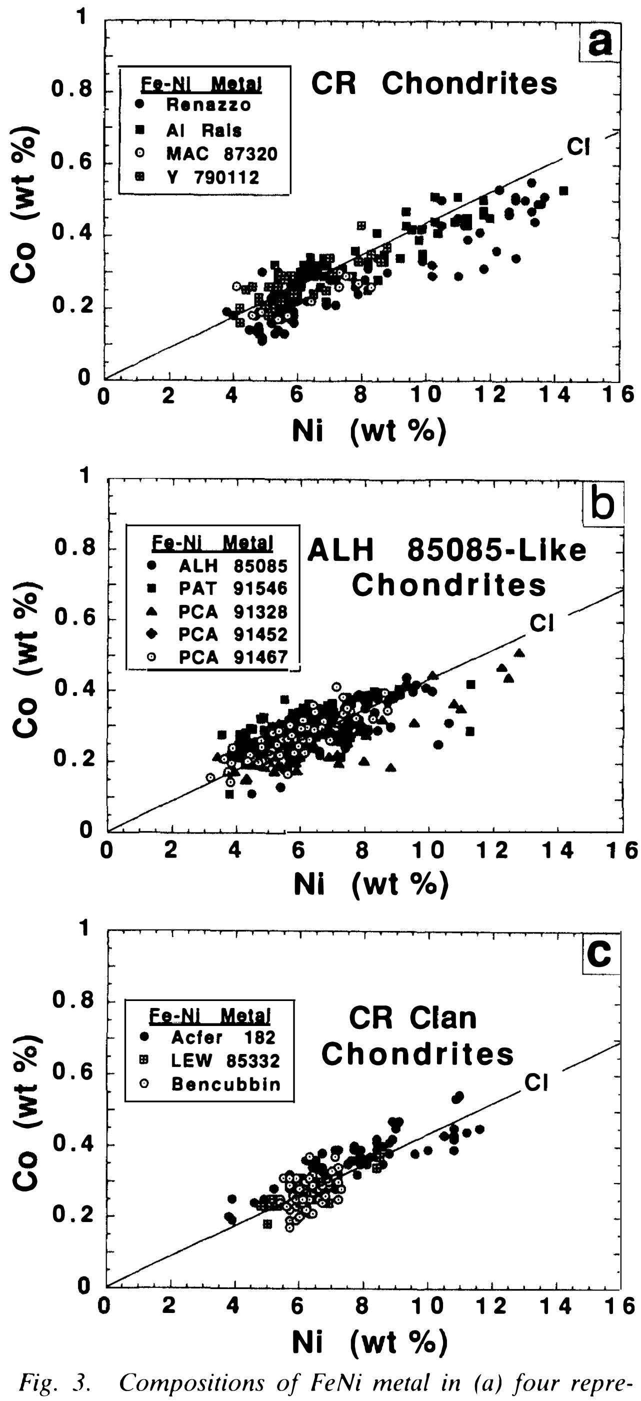

Fig. 3. Compositions of FeNi metal in (a) four representative CR chondrites, (b) ALH 85085-like chondrites, and (c) Acfer 182, LEW 85332, and Bencubbin chondrites, shown on a Ni vs. Co plot. The line labeled CI is the solar Ni:Co ratio from ANDERS and GREVESSE (1990). The metal in all of the CR clan chondrites has a similar positive Ni-Co correlation, with a solar ratio, suggesting the primitive nature of this component. Data from: BISCHOFF et al. (1993a,b), KALLEMEYN et al. (1994), RUBIN and KALLEMEYN (1990), WEISBERG et al. (1990, 1993b).

are very magnesian (Type I), with strong peaks at $Fa_{\leq 4}$ (Fig. 2), and the olivine is Cr- and Ca-rich (up to ~1.2% Cr_2O_3 and ~0.6% CaO). Most of the cryptocrystalline chondrules also have low FeO/(FeO+MgO) ratios (≤0.02). FeO-rich mineral fragments and type II chondrules are present, but are much less common.

FeNi metal in the CR clan chondrites is compositionally similar. Compositions range from ~4–14 wt% Ni, with rare grains having up to 22% Ni. The range in Acfer 182 and ALH 85085-like chondrites is very similar to that of the CR chondrites, but compositions are more restricted in LEW 85332 and the Bencubbin-like chondrites, both having only up to ~8% Ni (Table 2, Fig. 3). Additionally, rare Si-bearing metal grains were found in ALH 85085-like chondrites (3.3–7.5% Si) and Bencubbin (2.3% Si). In all CR clan chondrites Ni and Co in metal exhibits a positive correlation, with an approximately solar ratio (Fig. 3). This characteristic contrasts with metal in most other chondrites in which kamacite and taenite occur, and in these Co is partitioned into kamacite, the low-Ni metallic mineral.

Refractory inclusions have been described in all of the CR clan chondrites with the exception of Bencubbin (GROSSMAN *et al.*, 1988; MACPHERSON *et al.*, 1989; RUBIN and KALLEMEYN, 1990; WEISBERG and PRINZ, 1990; WEISBERG *et al.*, 1991, 1993b; BISCHOFF *et al.*, 1992, 1993a, b, 1994; PRINZ and WEISBERG, 1992; WEBER and BISCHOFF, 1992a, b; KIMURA *et al.*, 1993; WEBER *et al.*, 1994a, b). Modally, they make up only a small fraction; generally ≤2 vol% in CR chondrites (BISCHOFF *et al.*, 1993a; WEISBERG *et al.*, 1993b), ~0.05% in LEW 85332 (RUBIN and KALLEMEYN, 1990), <1% in Acfer 182 (BISCHOFF *et al.*, 1993b) and ~0.1% in ALH 85085-like chondrites (GROSSMAN *et al.*, 1988; BISCHOFF *et al.*, 1993b).

In CR chondrites, amoeboid olivine aggregates, melilite-rich fluffy type A inclusions and spinel-pyroxene aggregates are the most abundant types, but grossite (Ca-dialuminate)-rich inclusions have also been found. Type B inclusions have been found in some CR chondrites but are generally rare. In LEW 85332 only two inclusions, both type A, have been described, to date. In Acfer 182, type A and grossite-rich inclusions are the common varieties, with most of the grossite-rich inclusions having >30 vol% grossite and some with up to 80%. The refractory inclusions in ALH 85085-like chondrites are unlike those in the other CR clan chondrites in that most are small (<110 μm), spherical and have igneous textures (refractory-rich chondrules), in contrast to the irregular-shaped, fine-grained inclusions common in the other CR clan chondrites. Many of the inclusions in ALH 85085-like chondrites are grossite-rich, as in Acfer 182. In general, the occurence of grossite-rich inclusions is a characterisitic feature of some CR clan chondrites, and Type B inclusions are rare.

To summarize, despite marked differences in the petrographic characteristics (chondrule sizes, modal abundances, and degree of hydration) among the five CR clan members, there are important mineralogic characteristics that are distinctive and which indicate their kinship. These include their relatively metal-rich nature, the solar Ni:Co ratio of the metal, the reduced (Mg-rich) olivine and pyroxene compositions, and (except for Bencubbin-like chondrites) their hydrous matrix and/or DI, with similar mineralogic characteristics.

3. Bulk Compositions

All CR clan members have similar bulk compositions. Refractory and moderately volatile lithophile element abundances are $\sim 1\times$CI, and more volatile lithophiles (Mn, Na, K) are highly depleted (Fig. 4a). The Acfer 182, LEW 85332 and ALH 85085-like chondrites have lower volatiles than those of the average CR chondrite, and the Bencubbin-like chondrites have the lowest volatile lithophile abundances (KALLEMEYN *et al.*, 1978; WASSON and KALLEMEYN, 1990; GOSSELIN and LAUL, 1990; KALLEMEYN *et al.*, 1994). This must be mainly due to matrix+DI abundances since

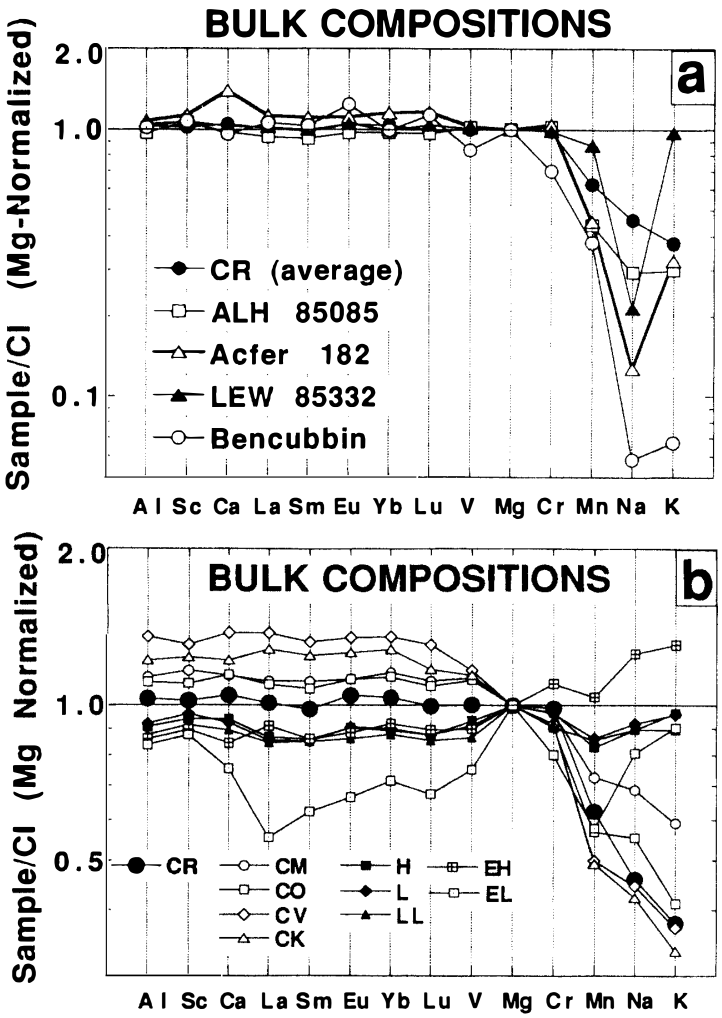

Fig. 4. Mg-normalized bulk composition/CI of (a) the CR clan chondrites and (b) the average CR group compared to averages of ten major chondrite groups. Refractory lithophiles are ~1×CI for all CR clan chondrites and the volatile lithophiles are generally depleted (a). This contrasts with other carbonaceous chondrites which have super-solar refractory lithophile elemental abundances and with ordinary and enstatite chondrites which have sub-solar abundances. Volatile lithophiles are generally lower in the CR clan chondrites than in most other chondrite groups. Data from: KALLEMEYN et al. (1978, 1994), WASSON and KALLEMEYN (1988, 1990), GOSSELIN and LAUL (1990).

these appear to be the main carriers of volatiles in CR clan chondrites (WEISBERG *et al.*, 1988, 1993b; BISCHOFF *et al.*, 1993b); the Acfer 182, LEW 85332 and ALH 85085-like chondrites have lower matrix abundances than the CR chondrites, and the matrix component is absent in the Bencubbin-like chondrites. Some of the anomalies in the lithophile elemental abundances, such as the high Ca in Acfer 182 and the high K in LEW 85332, could be attributed to terrestrial weathering. Both of these chondrites are highly weathered (RUBIN and KALLEMEYN, 1990: BISCHOFF *et al.*, 1993b).

The CR clan chondrites have refractory lithophiles (all data are Mg-normalized) that are at or close to CI abundances. Most carbonaceous chondrites (CM, CO, CV, CK) have refractory lithophile abundances that are greater than CI and the ordinary (H, L, LL) and enstatite (EH, EL) chondrites have abundances that are less than CI. With respect to the volatile lithophiles, most chondrite groups have Na abundances that are $>0.4\times$CI, whereas Na is $\leq 0.3\times$CI in LEW 85332, Acfer 182, the ALH 85085-like chondrites and Bencubbin-like chondrites; the average CR chondrite has Na abundances similar to that of the average CV chondrite ($\sim 0.45\times$CI). K abundances are low ($\leq 0.3\times$CI) in Acfer 182, the ALH 85085-like and the Bencubbin-like chondrites and in the average CR chondrite it is $\sim 0.4\times$CI, similar to that of the average CV.

4. Oxygen Isotopic Compositions

Oxygen isotopic compositions of CR clan whole-chondrites and separated components are presented in Table 3. Whole-rock oxygen isotopic compositions of all of the CR clan chondrites (WEISBERG *et al.*, 1993b; PRINZ *et al.*, 1993a, 1994; CLAYTON and MAYEDA, 1978) plot on or close to the CR mixing line of slope-0.7 (Fig. 5). The

Table 3. Oxygen isotopic compositions of CR clan whole rocks, chondrules and matrix.

Whole rock	$\delta^{18}O$	$\delta^{17}O$	Chondrules[+]	$\delta^{18}O$	$\delta^{17}O$	Matrix	$\delta^{18}O$	$\delta^{17}O$
CR chondrites								
Renazzo	6.25	2.29	Re-1	4.60	1.35	MX1	10.44	5.01
			Re-2	3.33	−0.09	MX2	9.90	5.41
			Re-3	2.41	−0.61	Re-Ba[a]	10.00	5.86
			<500 nm[c]	0.87	−1.86			
			>500 nm[d]	−1.22	−3.03			
			Re-Ab[b]	0.79	−0.98			
			Magnetite	3.95	1.67			
Al Rais	10.94	4.68	AR-1	4.72	1.56	MX1	10.77	5.09
			AR-2	4.11	0.49	AR-3[a]	13.26	6.68
			AR-4	4.73	0.82	<2.85[f]	13.84	6.90
			AR-5	5.46	1.98	<2.85[f]	13.47	6.69
			AR-9	4.80	1.04	Carbonate[g]	29.40	
			AR-10	4.59	1.01			
			3.08–3.33[e]	−0.72	−3.14			
			3.08–3.42[e]	−0.72	−2.83			

Table 3. (Continued)

Whole rock	$\delta^{18}O$	$\delta^{17}O$	Chondrules⁺	$\delta^{18}O$	$\delta^{17}O$	Matrix	$\delta^{18}O$	$\delta^{17}O$
El Djouf 001	4.61	0.93	ED1 (core)*	4.11	1.12	ED5[a]	5.59	0.98
			ED1 (rim)*	6.14	2.51	A114[a]	3.39	−0.81
			ED2 (core)*	3.54	0.66	A139[a]	5.60	0.99
			ED2 (rim)*	5.2	1.76			
			ED3 (core)*	2.02	−0.92			
			ED3 (rim)*	3.15	−0.11			
Kaidun[h]			01.3.13e	5.43	1.42	01.3.10[h]	10.52	4.76
						01.3.19[b]	15.03	7.00
EET 87770	2.76	0.22	E87-1	−0.20	−2.52	Matrix	9.58	4.08
			E87-2	1.71	−0.82			
MAC 87320	1.79	−0.87	M87-1	1.31	−1.73	Matrix	4.76	0.51
			M87-2	3.03	0.55			
			M87-3	1.92	−0.53			
			M87-4	1.83	−0.97			
			M87-5	0.16	−2.39			
Y-790112	2.39	−0.32						
Y-793495	1.39	−0.91						
<u>LEW 85332</u>								
LEW 85332	−0.23	−2.54	C1	4.31	2.54	Matrix	8.06	2.54
			C3	−2.76	−3.98			
			C4 (comp. of 3)	0.36	−1.52			
			C5	3.89	2.39			
<u>Acfer 182</u>								
Acfer 182	5.47	1.29						
<u>ALH 85085-like chondrites</u>								
ALH 85085	2.47	−0.16						
PCA 91328	1.63	−0.66						
PCA 91452	0.44	−1.04						
PCA 91467	−0.44	−1.70						
PAT 91546	0.69	−0.87	Comp. of 100	−0.14	−1.75	Comp. of 5[a]	4.47	1.64
						P91-1[a]	3.70	−1.35
<u>Bencubbin-like chondrites</u>								
Bencubbin	0.90	−1.80						
Weatherford	1.69	−1.65						

Comp.-sample run as a composite of a number of chondrules or inclusions due to the small size of the components analyzed.

[a]Dark Inclusion. [b]White Inclusion. [c]<500 mesh, nonmagnetic (olivine and pyroxene). [d]>500 mesh, nonmagnetic (olivine and pyroxene). [e]Density separates (olivine and pyroxene). [f]Density separates (low density matrix component). [g]$\delta^{13}C$=73.4‰. [h]Kaidun is a chondrite breccia containing a variety of clasts, most of which appear to be CR chondrite.

*ED1–ED3 are layered chondrules in which core and rim layers were analyzed separately.

Data from: Bischoff *et al.* (1993a, b); Clayton and Mayeda (1978); Clayton *et al.* (1994); Endress *et al.* (1994); Prinz *et al.* (1993, 1994); Weisberg *et al.* (1993a, b); unpublished data.

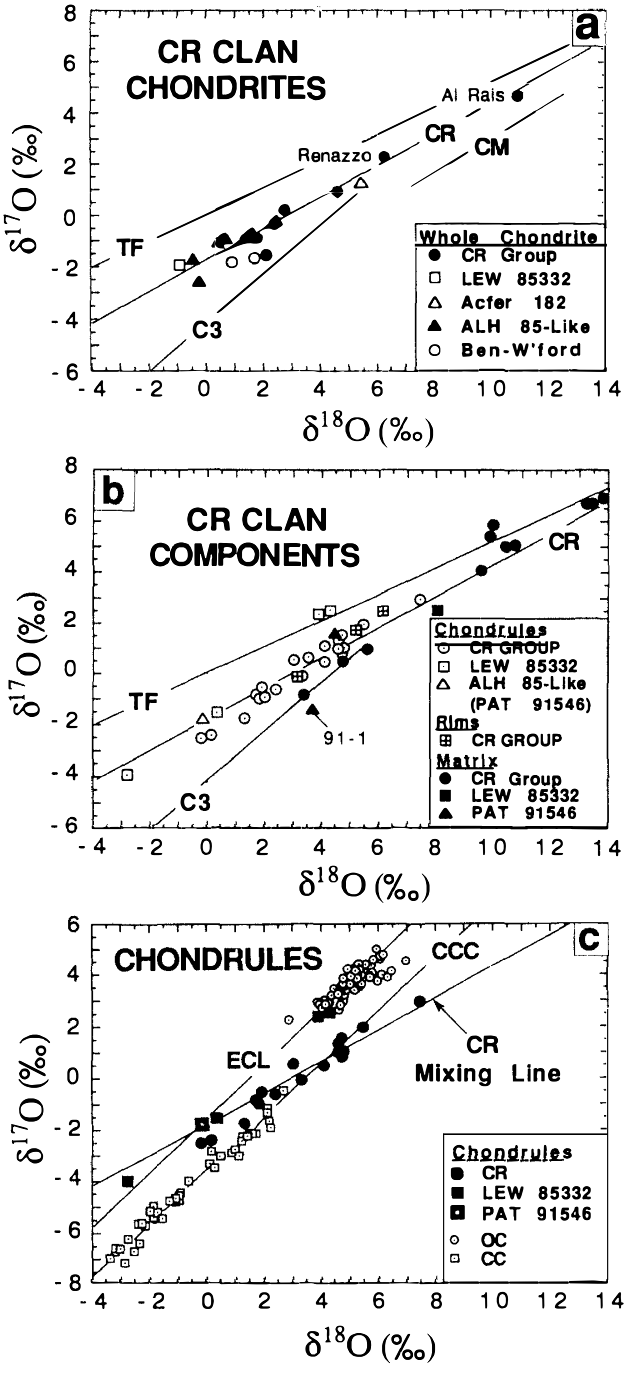

Fig. 5. Oxygen 3-isotope plot showing the oxygen isotopic compositions of (a) whole-rock CR clan chondrites, (b) separated components from the CR clan chondrites, and (c) chondrules in the CR clan chondrites compared to those in other chondrite groups. TF=terrestrial mass fractionation line, CR= CR mixing line, C3=C3 mixing line, ECL=equilibrated (ordinary) chondrite line, CCC=carbonaceous chondrite line, and Ben-W'ford=Bencubbin and Weatherford. One LEW 85332 chondrule is a composite of three chondrules and the chondrule point for PAT 91546 (ALH 85085-like) is a composite of ~100 chondrules. One of the dark inclusion points for PAT 91546 is a composite of 5 inclusions and the other (91–1) is a single anomalous large DI. Whole-rock compositions of the CR clan chondrites plot on or near the slope-0.7 CR chondrite mixing line (a). Separated chondrules and matrix also plot on or near the CR line with the more hydrated matrix having heavier oxygen than the less hydrated and anhydrous chondrules, in most cases (b). The anhydrous chondrules from LEW 85332 differ from those in other carbonaceous chondrites in that they plot on the ECL and not the CCC mixing line (c). The chondrule composite from the PAT 91546 (ALH 85085-like) chondrite plots at the intersection of the ECL with the CR mixing line. Data from: WEISBERG et al. (1993a), PRINZ et al. (1993a, 1994), CLAYTON and MAYEDA (1978), CLAYTON et al. (1991), and unpublished data.

CR mixing line is a best-fit line defined by compositions of CR chondrite whole-rocks and separates and it connects predominantly anhydrous silicates at the lower left end of the line with hydrous silicates at the upper right end (WEISBERG *et al.*, 1993b). The CR mixing line contrasts with the slope-0.52 terrestrial mass fractionation line (TF) line and the slope-1 C3 mixing line (Fig. 5a). Separated components (chondrules and matrix+DI) from CR chondrites also plot on or close to the CR mixing line, as do the chondrule and matrix+DI separates from the PAT 91546 (A85085-like) and LEW

85332 chondrites, strengthening the relationship between these meteorites (Fig. 5b).

Of the whole-rock CR chondrite compositions, Al Rais has the highest $\delta^{17}O$ and $\delta^{18}O$ values and LEW 85332 the lowest (Fig. 5a). It is noteworthy that Al Rais is the most hydrated member of the CR clan and has the highest matrix abundance, whereas in LEW 85332 nearly all chondrules are anhydrous and the hydrous matrix+DI abundance is relatively low. Although direct correlations between the whole-rock oxygen isotopic composition, the degree of hydration, and the matrix+DI abundances are not always clear, it is clear that, in most cases, matrices (generally more hydrated than chondrules) have heavier oxygen than their coexisting chondrules in the same meteorite (Fig. 5b).

The oxygen isotopic compositions of the chondrules separated from most of the carbonaceous chondrites plot along a slope-1 mixing line termed the "carbonaceous chondrite chondrule" line (CCC), as shown in Fig. 5c. Chondrules separated from the ordinary chondrites also plot on a slope-1 line, this one coincident with the equilibrated ordinary chondrite line (ECL) of CLAYTON *et al.* (1991), also shown in Fig. 5c. These slope-1 mixing lines are indicative of two oxygen isotopic reservoirs. The chondrules from the CR chondrites (which are hydrated to varying degrees) do not plot on a slope-1 mixing line but fall instead on or close to the slope-0.7 CR mixing line like the whole-rock compositions, indicative of a third heavy oxygen isotopic reservoir (water). LEW 85332, however, contains only anhydrous chondrules and their oxygen isotopic compositions fall on the slope-1 ECL (like the ordinary chondrite chondrules), and this differs from all other carbonaceous chondrites. The average chondrule composition of the PAT 91546 (ALH 85085-like) chondrite (a composite of ~100 chondrules) also plots on the ECL near where it intersects with CR chondrite mixing line (Fig. 5c). The hydrous matrix and DI in both of these meteorites fall on the CR mixing line (Fig. 5b). Thus, anhydrous chondrules in the CR clan plot on or near the ECL, and the hydrated CR chondrules and matrix+DI fall on the hydrated CR mixing line of slope~0.7.

5. Nitrogen Isotopic Compositions

The nitrogen isotopic compositions of all of the CR clan chondrites have remarkably high $^{15}N/^{14}N$ ratios, with $\delta^{15}N$ values of ~190‰ in CR chondrites, ~300‰ in LEW 85332, ~1000‰ in the Bencubbin-like chondrites, ~1500‰ in the ALH 85085-like chondrites, and ~1600‰ in Acfer 182 (KUNG and CLAYTON, 1978; ROBERT and EPSTEIN, 1982; PROMBO and CLAYTON, 1985; FRANCHI *et al.*, 1986; KEELING *et al.*, 1987; GRADY and PILLINGER, 1990, 1993; GRADY *et al.*, 1991a,b and Table 4, Fig. 6). This contrasts with nearly all other chondrite groups which range from only −90 to +50‰. The only other meteorites that have similar high ^{15}N abundances are the IIC irons, the EET 83309 polymict ureilite, and the Bells CM2 chondrite.

Although the occurrence of a ^{15}N-rich component is characteristic of CR clan chondrites, the identity of the nitrogen carrier(s) is unknown. In the Bencubbin-like chondrites the heavy nitrogen is present in the metal and silicate. The $\delta^{15}N$ of the CR chondrites is lower than in the other CR clan chondrites, although still high compared

Table 4. Nitrogen isotopic compositions of the five kinds of chondrites in the CR chondrite clan.

Clan member	$\delta^{15}N$ Bulk	$\delta^{15}N$ Max.	Ref.
CR group	140–190		1-5
LEW 85332	249	306	6
ALH 85085	858	>1500	7
Acfer 182	541	>1500	8
Bencubbin	923–974	>1000	9, 10

References: (1) ROBERT and EPSTEIN (1982), (2) GRADY *et al.* (1983), (3) KERRIDGE (1985), (4) GRADY *et al.* (1991a, b), (5) KUNG and CLAYTON (1978), (6) PRINZ *et al.* (1992), (7) GRADY and PILLINGER (1990), (8) GRADY *et al.* (1991b), (9) PROMBO and CLAYTON (1985), (10) FRANCHI *et al.* (1986).

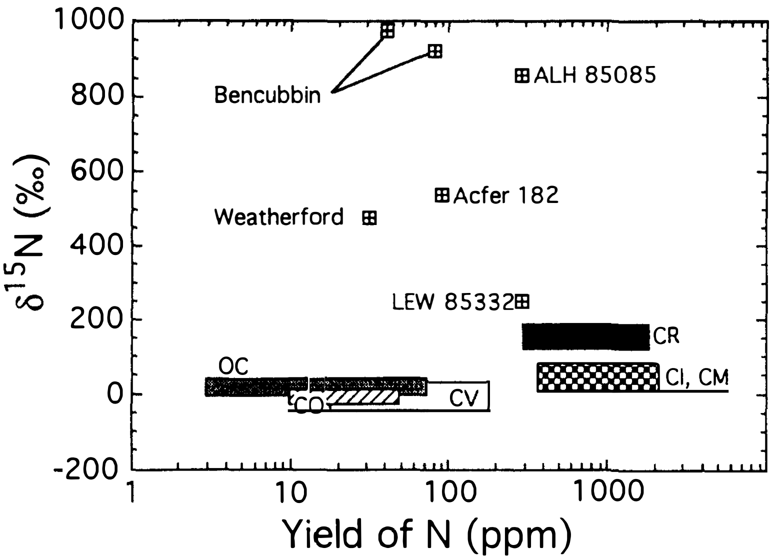

Fig. 6. Plot of total N (ppm) vs. $\delta^{15}N$ (‰) showing nitrogen compositions of the CR clan chondrites compared with other chondrite groups. All CR clan chondrites have ^{15}N anomalies with whole-rock $\delta^{15}N$ values that range from 140–190‰ in the CR chondrites to 974‰ in Bencubbin. These values are higher than in any other chondrite group and suggest the presence of a presolar component in the CR clan chondrites, which attests to the primitive nature of this chondritic clan. The only other meteorites that have similar high ^{15}N abundances are the IIC irons, the EET 83309 polymict ureilite, and the Bells CM2 chondrite. Data from: KUNG and CLAYTON (1978), ROBERT and EPSTEIN (1982), PROMBO and CLAYTON (1985), FRANCHI et al. (1986), KEELING et al. (1987), GRADY and PILLINGER (1990, 1993), GRADY et al. (1991a).

to other chondrite groups, and the reason for this is unknown. It should be noted, however, that the combustion release temperatures of the ^{15}N-rich component(s) differ among the CR clan chondrites, suggesting differences in the distribution of the heavy nitrogen component(s) in these meteorites (GRADY and PILLINGER, 1990). It has been suggested that the brecciation process may be responsible, in part, for introducing or enhancing the ^{15}N components in these meteorites (GRADY and PILLINGER, 1990, 1993), but there is no direct evidence to support this hypothesis.

6. Discussion

6.1. Evidence for a relationship among the CR clan chondrites

The five kinds of chondrites–CR group, LEW 85332, Acfer 182, ALH 85085-like, and Bencubbin-like chondrites–have marked petrographic differences in: (1) chondrule sizes, (2) modal abundances of components, (3) degree of hydration, (4) relative abundances of chondrule textural types, and (5) distribution and textural setting of FeNi metal. Additionally, some whole-rock lithophile and siderophile element abundance ratios that are generally used to demonstrate group-level affiliations of chondrites (*e.g.,* Al/Mn, Zn/Mn, Sb/Mg, and Ga/Mg) differ among the five kinds of chondrites (KALLEMEYN *et al.*, 1994). Thus, the five kinds of chondrites should not be batched into the same group.

Despite the differences among the five kinds of chondrites, the mineralogical, bulk chemical, and oxygen and nitrogen isotopic data provide compelling evidence for a strong relationship between them. (1) Their anhydrous mafic silicates are reduced (Mg-rich). (2) They contain hydrous matrix and/or dark inclusions with similar petrologic characteristics (serpentine-rich phyllosilicates, sulfides, framboidal and platelet magnetites), except for the Bencubbin-like chondrites. (3) They are metal-rich or contain metal-rich chondrules, although metal abundances vary among them. (4) Their FeNi metal is compositionally similar and has a solar Ni:Co ratio. (5) Rare Si-bearing metal is present in some of these chondrites. (6) They have solar (CI) abundances of refractory and moderately volatile lithophile elements, and are highly depleted in the volatile lithophile elements. (7) Oxygen isotopic compositions of whole-rocks and separated components (chondrules, matrix and DI) plot on or near the CR mixing line on an 3-isotope diagram. (8) They have ^{15}N anomalies that distinguish them from any of the other chondritic groups. We conclude that the five kinds of chondrites are closely related and should be considered members of the CR chondrite clan.

6.2. Significance of the relationship between the CR clan chondrites

The oxygen isotopic compositions of the CR clan chondrites suggest that they formed in the same local region of the nebula. This is further supported by their similar high Mg-rich mafic silicate and metal abundances, suggesting that the chondrules in CR clan chondrites formed under similar reducing conditions. The CI-level non-volatile and highly depleted volatile lithophile element abundances indicate that these meteorites may have formed at similar heliocentric distances, possibly further from the sun than the other chondrite groups, assuming that elemental abundances in chondrite groups are related to the heliocentric distance at which they formed (*i.e.*, WASSON, 1985).

Some of the differences between the members of the CR clan may be related to their time of formation, or sorting processes. For example, the Bencubbin (barred olivine) silicates have the greatest volatile depletions and may have formed from

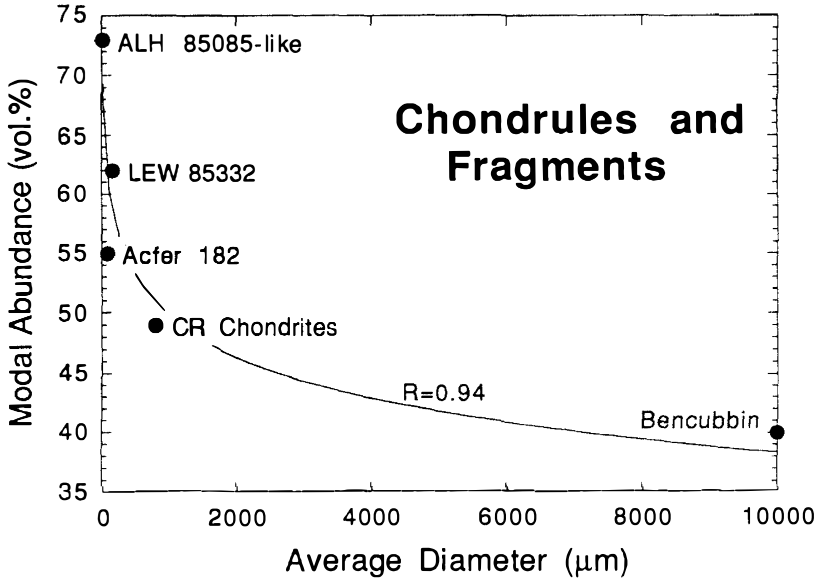

Fig. 7. Plot of the average diameter (μm) vs. modal abundance (vol%) of chondrules and fragments in the five kinds of CR clan chondrites. The curve is a best-fit logarithmic curve and the logarithmic correlation coefficient is 0.94, which suggests a strong logarithmic relationship between these two parameters in the CR clan chondrites.

earlier, higher temperature materials that accreted before condensation of the more volatile lithophiles. Another possibility is that the sorting of materials resulted in some CR clan members acquiring a higher proportion of volatile-rich materials (*i.e.*, matrix and DI), while others such as Bencubbin did not receive their share of these volatile-rich materials.

There appears to be a relationship between the modal abundances and average diameters of chondrules and fragments in the CR clan chondrites. ALH 85085-like chondrites have the smallest chondrule and fragment sizes and highest abundance of chondrules and fragments, whereas Bencubbin has the largest chondrule and fragment sizes and lowest abundance of chondrules and fragments (Table 2). Fragments that are produced as a result of crushing have log-normal size distributions (*e.g.*, ROSIN and RAMMLER, 1933). The relationship between chondrule (and fragment) sizes and their abundance in the memebers of the CR clan is logarithmic, with a logarithmic correlation coefficient of 0.94 (Fig. 7). This relationship may indicate that the narrow size range within each of the five clan members resulted from collisional fragmentation of an originally larger range of chondrule sizes, followed by sorting. The CR clan chondrites would, therefore, represent a suite of size fractions derived from the same parental material that was being fragmented and sorted. We caution that this hypothesis is presently speculative and further investigations of sizes/abundance relationships in chondrites are required.

6.3. *Primitive components in the CR clan chondrites*

CR clan chondrites are among the most primitive of all chondritic groups. They contain components that have early solar or presolar signatures that have been overprinted by secondary processing in most other chondrite groups. These signatures include their metal compositions and ^{15}N enrichments.

FeNi metal in CR clan chondrites have preserved a solar Ni:Co ratio which is inherited from primary condensation in the nebula. By comparison, the unequilibrated ordinary chondrites have two metal phases, kamacite and taenite, which show no systematic Ni-Co relationship, except in rare cases (AFIATTALAB and WASSON, 1980). In the equilibrated ordinary chondrites, Co is strongly partitioned into the low-Ni metal phase kamacite. In the oxidized CV chondrites, the major metal phase is the Ni-rich mineral awaruite, formed as a product of the oxidation of Fe. Thus, the metal compositions of most chondrite groups reflect secondary processes such as metamorphism or oxidation.

It has been suggested (NEWSOM and DRAKE, 1979; GROSSMAN *et al.*, 1988; WEISBERG *et al.*, 1988, 1990, 1993b) that the range in Ni-Co contents in CR clan metal, with a solar Ni:Co ratio, is the result of fractional condensation in the early nebula. During this process, after earlier-formed higher-Ni metal condensed, it became isolated and prevented from reacting with the nebula at lower temperatures, and thus preserved its primary composition. This was originally suggested by GROSSMAN and OLSEN (1974), who showed a similar Ni-Co trend in CM metal. It has also been suggested, however, that the variations in metal compositions in CR chondrites are due to reduction processes either during or following chondrule formation (LEE *et al.*, 1992; ZANDA *et al.*, 1993). Reduction of Fe could serve to dilute the Ni and Co contents in metal, but retain the relative abundances of these two elements and result in the Ni-Co trend observed in CR clan metal.

Models in which it is envisaged that the metal compositions are direct results of condensation fall short because fractional condensation of metal is poorly understood, as are any mechanisms for preserving primary high temperature metal compositions. Models in which it is envisaged that metal forms through reduction of Fe during chondrule formation have been shown to be inconsistent with the siderophile element abundances in chondrules (GROSSMAN and WASSON, 1985). Additionally, in the ZANDA *et al.* (1993) model, the heterogeneity of metal compositions and the negative correlation of Ni-Co, that they found in "least melted" chondrules in Renazzo, is interpreted to be representative of the composition of chondrule precursors. They therefore conclude that the positive Ni-Co trend in metal from CR chondrites is the result of reduction during chondrule formation. However, both the heterogeneous compositions and the negative Ni-Co trend that they observe could also be due to fine exsolution of taenite (high-Ni metal) with Co partitioning into kamacite (low-Ni metal). Reduction models also fail in that they cannot easily explain the compositional difference between the metal in the cores (higher-Ni) and their rims (lower-Ni metal) in layered chondrules from CR chondrites (WEISBERG *et al.*, 1988, 1993b). On balance, the metal compositions are more likely to be the result of early nebular condensation processes.

The high ^{15}N anomalies in the CR clan chondrites (Fig. 6, Table 4) suggest the presence of ^{15}N-rich components which are almost certainly presolar and escaped homogenization of nitrogen in the nebula or parent body. Such remarkably high whole-rock $\delta^{15}N$ values are not a common feature in any other chondrite group. CI and CM chondrites, which have normal whole-rock nitrogen compositions, have been shown to contain interstellar grains with remarkable ^{15}N enrichments up to

$\delta^{15}N = 30000‰$ (AMARI *et al.*, 1992). The ^{15}N enrichments in the CR clan chondrites have also been interpreted as being largely due to the presence of interstellar grains (GRADY and PILLINGER, 1993). The occurrence of ^{15}N enrichments in metal as well as silicate components in the CR clan chondrites, and their even distribution over whole-rock samples, may be due to vaporization, recondensation, and mixing which could have resulted in trapping or implantation of nitrogen into silicate and metal.

6.4. *Prelithification hydration of the CR clan chondrites*

There is considerable evidence for prelithification hydration in the CR clan chondrites. WEISBERG *et al.* (1993) discussed several petrologic observations that led to the conclusion that hydration predated final lithification of the CR chondrites, including: (1) highly variable degrees of hydration from one chondrule or dark inclusion to another in the same chondrite, (2) calcite- and serpentine-rich rims on broken chondrules that are found only on the original curved chondrule surface, but not on the broken edges, indicating that the rim formed on the chondrule prior to breakage and incorporation into the host chondrite, and (3) calcite veins in dark inclusions that end abruptly at the sharp boundary of the inclusion. The LEW 85332, Acfer 182 and ALH 85085-like chondrites contain anhydrous chondrules coexisting with hydrous matrix and dark inclusions. This is demonstrated by their mineralogy, but also by the oxygen isotopic compositions, as discussed above.

It can therefore be concluded that the CR clan chondrites are breccias that contain components which experienced vastly different alteration histories. These components must have been altered separately either (1) in the solar nebula prior to accretion of their parent bodies, (2) on different parts of the same parent body prior to brecciation and final lithification, or (3) on many different parent bodies which were subsequently broken up and reassembled to result in the observed mixtures of materials. None of these possibilities can be easily ruled out.

Based on petrographic observations, pre-accretionary (nebular) aqueous alteration has also been proposed for CM chondrites (NAKAMURA *et al.*, 1991; TOMEOKA *et al.*, 1991; METZLER *et al.*, 1992; IKEDA and PRINZ, 1993) and for the formation of some of the hydrous phases in CV chondrites (HASHIMOTO and GROSSMAN, 1987; KELLER and BUSECK, 1990). METZLER *et al.* (1992) presented strong textural evidence in favor of nebular hydration of components in CM chondrites. They demonstrated that hydrated accretionary rims, which were accreted onto chondrules in the nebula, were hydrated prior to their accretion onto chondrule surfaces and thus must have been hydrated in the nebula. The strongest argument commonly put forth against nebular alteration is that the CO_2 partial pressures necessary for carbonate stability could not be attained in the nebula (ARMSTRONG *et al.*, 1982). Additionally, C isotopic compositions of carbonates in CI, CM and CR chondrites have ^{13}C enrichments that suggest carbonate formation within parent bodies since ^{13}C enrichments in carbonate-forming fluids would have been diluted with isotopically normal C in the nebula gas (HALBOUT *et al.*, 1986; GRADY *et al.*, 1988). Arguments against carbonate formation do not preclude formation of other hydrous phases in the nebula and evidence for parent body alteration does not weaken the possibility of an earlier nebular alteration history.

For the CR clan chondrites we can only conclude that alteration occurred prior to final lithification of the meteorite. Further work is clearly needed to resolve the issue of where the alteration took place. Combinations of petrologic and isotopic data will be necessary. For example, recent work is being done on *in situ* analyses of D/H ratios of the water from hydrated phases in CR chondrites (DELOULE and ROBERT, 1994). A search for isotopic heterogeneity, or lack of it, will help decipher whether alteration of the components in these brecciated chondrites could have taken place on a single parent body, multiple bodies or in the nebula.

7. Conclusions

The CR group, LEW 85332, Acfer 182, ALH 85085-like and Bencubbin-like chondrites are all closely related and are members of the CR chondrite clan. The CR clan chondrites have marked petrographic differences, but mineralogic, bulk chemical and isotopic similarities that distinguish them from other chondrites and link them together. Their components appear to have formed under similar reducing conditions from a common oxygen isotopic reservoir in the solar nebula. The clan contains primitive metal and ^{15}N-rich components that preserve primary solar and presolar signatures, which indicate that the CR clan may be one of the most primitive chondrite groupings. Hydration of some components in the CR clan chondrites occurred prior to final lithification.

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