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The compositional classification of chondrites: V. The Karoonda (CK) group of carbonaceous chondrites

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Abstract—Petrographic and bulk compositional data reveal the existence of a new group of carbonaceous chondrites consisting of the observed fall, Karoonda, one large find from Maralinga, Australia, and 6–11 small finds from five sites in Antarctica. Ningqiang, also a fall, is genetically related to the group. Compositional, textural, and O-isotope data show that the new group is closely related to CV and CO chondrites. In keeping with the practice of naming carbonaceous chondrite groups after a prominent member, we designate it the Karoonda or CK group.

All normal CK members are metamorphosed; petrographic grades range from 4 to 6. Some contain shock veins and all exhibit various degrees of blackening due to the dispersion of fine particles of sulfides and magnetite in silicates. Only one other group (EL) has no unequilibrated members. The unequilibrated Ningqiang chondrite is more similar to CK than to CV or CO chondrites, but differs significantly (e.g., low refractory lithophiles, high Mn and Na) in detailed composition.

Elemental abundance patterns in CK chondrites are similar to those in CO chondrites, and even more similar to those in CV chondrites. Refractory lithophile abundances are about 1.21× greater than in CI chondrites, a level intermediate between those in CO and CV chondrites; CK refractory siderophile abundances are also intermediate between CV and CO levels. The CK volatile abundance pattern is quite similar to the CV pattern, with CK abundances of most volatiles 10–20% lower than CV values. It appears that nebular conditions and processes were closely similar at the CK and CV formation locations.

Although precise probability calculations are difficult because of uncertainties regarding pairing and because so few samples are known, the exceptional abundance of CK chondrites in Antarctica requires an explanation. We suggest that compared to other groups, such as CO or CV, the fragmentation of the CK parent object(s) produced a substantially larger proportion of small meteoroids.

INTRODUCTION

THERE ARE FOUR well-defined groups of carbonaceous chondrites; interestingly, two groups (CO, CV) contain little carbonaceous matter and one (CI) contains no chondrules. For *anhydrous* meteorites of unquestioned nebular origins, the current *de facto* definition of a carbonaceous chondrite appears to consist of

1) group/CI refractory-lithophile abundance ratios ≥ 1.0,
2) a moderate to high degree of Fe oxidation,
3) groundmass/chondrule ratios >1,
4) the presence of an appreciable (≥1%) abundance of refractory inclusions, and
5) O-isotope composition appreciably below the terrestrial fractionation line and on or near the CCAM (carbonaceous chondrite anhydrous minerals) mixing line.

In this paper we report the compositional and petrographic resolution of a new group of anhydrous carbonaceous chondrites that contains chondrules, has very low (<1 mg/g; GIBSON et al., 1971; JAROSEWICH, 1990) contents of C, has high refractory-lithophile abundances, is highly oxidized, has high groundmass/chondrule ratios, has very low contents of refractory inclusions (an exception to criterion 4), and has O-isotope compositions near the CCAM line.

Karoonda is the only member of this new group that is an observed fall. Ningqiang, also an observed fall, is compositionally closely related to, but resolvable from, this group. Maralinga is a large (≥34 kg), weathered find from Australia. All other specimens were recovered from Antarctic ice fields. We propose to follow the widely accepted tradition (VAN SCHMUS, 1969; WASSON, 1974) of naming carbonaceous-chondrite groups after a prominent member and designate this the Karoonda or CK group, where the C refers to its affinity to the other groups of carbonaceous chondrites.

There are two previous references to CK groups in the literature. FITZGERALD and JONES (1977) proposed that three widely divergent chondrites (Adelaide, Bench Crater, and Kakangari) formed a "CK" chondrite "grouplet" (we use five as the minimum number of meteorites required to form a group) principally on the basis of low bulk Ca/Al ratios; however, later workers (e.g., MCSWEEN, 1979) discredited this grouplet. The CK label was also used by WILKENING (1978) to denote a Karoonda grouplet, with Karoonda as the only member. Although MCSWEEN (1979) instead classified Karoonda CV, KALLEMEYN and WASSON (1982) showed that refractory lithophile abundances are lower in Karoonda than in CV chondrites.

Both the petrographic and the compositional data are consistent with the conclusion that the 6–10 "core" members of this group share properties that are of a sufficiently limited range to warrant designation as a group but are sufficiently different from those of the other carbonaceous chondrite groups to eliminate the possibility of their inclusion in those groups.

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EXPERIMENTAL METHODS

Petrographic Procedures

Exposed surfaces of the whole-rocks of ALH82135, ALH84038, LEW87009, LEW87214, and PCA82500 were studied at the NASA Johnson Space Center (JSC) in Houston, Texas. Polished thin sections ALH82135,19; ALH84038,8; ALH85002,22; EET83311,9; EET87507,18; EET87508,4; EET87514,8; EET87519,6; EET-87525,2; EET87526,18; EET87527,2; EET87529,13; EET87860,13; LEW86258,19; LEW87009,15; LEW87214,2; and PCA82500,34 from JSC; Y6903-12-2 from the National Institute of Polar Research, Japan; Karoonda section 3970-2 from the American Museum of Natural History; and UCLA 431 of Maralinga were studied microscopically in transmitted and reflected light. B. Mason gave preliminary petrographic descriptions of all of the meteorites from Victoria Land, Antarctica, discussed in this paper; references to these descriptions are cited in SCORE and LINDSTORM (1990). We compare our petrographic assignments to those of Mason throughout the paper. Silicate and oxide phases were analyzed using crystal spectrometers with the UCLA automated ARL electron microprobe; Bence-Albee corrections were applied. Typically, 10–20 olivine and 5–10 plagioclase grains were analyzed in each meteorite. Sulfide phases were analyzed using the crystal spectrometers of the UCLA automated Cameca "Camebax-microbeam" electron microprobe; ZAF corrections were applied.

Neutron Activation Procedures

Bulk compositions were determined by instrumental neutron activation analysis (INAA). Sample masses ranging from 250 to 300 mg consisted of gently crushed chips. Replicate samples were run in separate irradiations, if enough mass was available. Irradiations were carried out at the University of California, Irvine, with a neutron flux of 1.8×10^{12} neutrons cm^{-1} s^{-1}. Samples were irradiated for 4 h to determine long-lived nuclides, and for 2 min to determine short-lived nuclides. Details of the INAA procedure are given in KALLEMEYN et al. (1989).

An aliquot of ~250 mg of Allende standard powder (Smithsonian Institution split 13, position 4) was included in each run as a control; the recent data agree well with previous UCLA analyses (KALLEMEYN and WASSON, 1981, and unpubl. data), differing by <5% for all elements except for Ru (≤10%). Relative precisions of elemental concentrations in a homogeneous sample can be estimated from our analyses of the Allende standard powder. Relative sample standard deviations are <5% for Na, Mg, Al, Ca, V, Cr, Mn, Fe, Co, Ni, Zn, Ga, As, Se, Sb, La, Sm, Eu, Yb, Lu, Os, Ir, and Au; and 5–10% for Sc, K, Br, and Ru. Sample inhomogeneity, particularly in weathered finds, appears to contribute more than analytical error to concentration differences between replicates.

PETROGRAPHIC CHARACTERISTICS OF CK CHONDRITES

The probable members of the CK chondrite group are listed in Table 1. In the following discussion we will treat the classification of the three chondrites LEW86258, PCA82500, and Yamato 6903 (henceforth Y6903) as uncertain, and not include their properties in generalizations regarding the group. In fact, our best assessment is that the three are CK members that may be slightly anomalous in their properties, and we designate them as probably CK. The Ningqiang chondrite (previously classified CV-an; RUBIN et al., 1988) is petro-

Table 1. Properties of members of the CK chondrite group and related chondrites.[α]

meteorite	mass (g)	thin section	type	olivine Fa (mol%)	low-Ca px Fs (mol%)	plag An (mol%)	opaque phases
CK chondrites							
Karoonda*	42000	3970-2[x]	4	31.2±0.6	26-28	14-69	pt,py,ch,prh,mg
ALH82135	12.1	19	4	28.9±0.7	25-26	16-69	pt,py,mg
ALH84038	12.3	8	4	28.8±0.4	26-28	22-82	pt,mg
ALH85002	438	22	4	30.2±0.4	23-29	30-66	pt,py,mg
EET83311	15.3	9	5	33.2±0.5	Ca-px	60-69	pt,mg
EET87507[§]	36.2	18[+]	5	32.2±0.3	28	22-72	pt,mg
EET87860	32.8	13	5/6	30.0±1.0	28	20-56	pt,py,prh,mk,mg
LEW87009	50.5	15	6	32.1±0.4	Ca-px	45-78	pt,py,mg
LEW87214[β]	0.4	2	4	31.3±0.3	Ca-px	44-63	pt,mk,mg
Weathered chondrites (probably CK)							
LEW86258	24.1	9	4	32.2±0.2	26	31-83	pt,mg
Maralinga	>34000	431[γ]	4	33.3±0.5	28	33-54	pt,mg
PCA82500	90.9	34	4/5	33.1±0.6	1-25	17-81	pt,ch,prh,mg
Y6903	150	12-2	4	29.4±0.4	26	28-72	tr,pt,mg
CK-an chondrite							
Ningqiang*	4610	419-422[γ]	3	2.8±1.8	1	n.i.[δ]	tr,pt,mk,mg,mt
Not studied by us, but probably CK							
Y82104	9.8		5	29.9	rare	19-61	tr,mg,mt

[α] phase compositional data from this study except for Y82104 (Graham and Yanai, 1986).
* observed fall; Karoonda, 25 November 1930; Ningqiang, 25 June 1983.
[x] from American Museum of Natural History.
[§] probably paired with EET87508, 87514, 87519, 87525, 87526, 87527, 87529 (total mass of all eight specimens = 246 g).
[β] probably paired with LEW87250 (Fa 30.6; Ca-px; An 20-89).
[+] also studied: EET87508,4; 87514,8; 87519,6; 87525,2; 87526,18; 87527,2; 87529,13.
[γ] from UCLA.
[δ] n.i. = not identified; plagioclase in Ningqiang was only found inside a refractory inclusion.
opaques: tr=troilite; pt=pentlandite; py=pyrite, ch=chalcopyrite, prh=pyrrhotite, mg=magnetite, mk=mackinawite, mt=metallic Fe-Ni.

graphically very similar to CK and chemically more closely related to CK than CV. Nevertheless, it is clearly resolvable from CK in terms of several chemical characteristics, particularly its lower abundances of refractory lithophiles and higher abundances of moderately volatile elements. We classify it CK-an to help insure that it is included in future CK studies, but we do not include it in our generalizations regarding the CK group. Literature data for one other chondrite, Y82104, show that it is probably a CK chondrite, but we have not yet had an opportunity to analyze it. All CK chondrites except Ningqiang are petrologic type 4–6 and, thus, have had their textural characteristics modified by thermal metamorphism. The only other chondrite group consisting exclusively of equilibrated meteorites is EL (e.g., SEARS et al., 1982), which only includes types ≥ 5.

Recrystallization

Various petrologic criteria have been used to distinguish the different petrologic types of ordinary chondrites (VAN SCHMUS and WOOD, 1967; WASSON, 1985). We made slight modifications of several of these criteria to make them applicable to the CK chondrites:

1) homogeneity of olivine composition: $[\sigma\mathrm{Fa}/(\text{mean Fa})] \times 100 < 3$ indicates type 4–6,
2) mean diameter (d) of plagioclase grains: type 3, absent; type 4, $d < 4$ μm; type 5, $4 < d < 50$ μm; type 6, $d \geq 50$ μm,
3) absence of primary glass indicates type 4–6,
4) chondrule delineation: type 3, very sharply defined; type 4, well-defined; type 5, readily discernable; type 6, poorly-defined,
5) coarseness of groundmass grains: type 3, $\leq$0.1–10 μm; type 4, 5–50 μm; type 5, 50–200 μm; type 6, 50–300 μm.

Three criteria that are used to distinguish different petrologic types of ordinary chondrites cannot be applied to the CK4–6 chondrites. These include (a) the abundance of monoclinic low-Ca pyroxene (because the CK chondrites contain little low-Ca pyroxene), (b) the compositional heterogeneity of metallic Fe-Ni grains (because metal is very rare in CK chondrites), and (c) the Ni content of sulfide minerals (because low-metal, oxidized meteorites contain Ni-rich sulfides irrespective of petrologic type).

The CK chondrites form a metamorphic sequence. The closely related CK3-an Ningqiang is unrecrystallized and has heterogeneous olivine (PMD = 44) and low-Ca pyroxene (PMD = 46) (RUBIN et al., 1988). Karoonda, ALH82135, ALH85002, LEW86258, LEW87214, and Maralinga (all type-4) have well-defined chondrules (Fig. 1a,b). Their groundmasses, which have typical grain sizes of 5–20 μm, have been completely recrystallized (Fig. 1b), obliterating textures of nebular matrix material or fine-grained inclusions that may have originally been present. The other CK4 chondrite, ALH84038, is more recrystallized and has a somewhat coarser (i.e., 20–40 μm) groundmass than the other CK4 chondrites.

EET87860 (type 5/6) has a very coarse (75–300 μm) subgranular texture; it was previously classified as type 5. Only rare relict, highly recrystallized chondrules are discernable. We have reassigned EET83311 and EET87507 (and its paired specimens) to type 5 (both were previously classified type 4) on the basis of their coarse silicate groundmass (50–200 μm) and highly recrystallized, barely discernable chondrules. However, EET87519 has a finer-grained groundmass ($\sim$25 μm) than the other EET87507 specimens; because its mean olivine content (Fa 32.2) is virtually identical to that of other EET875xx specimens (Fa 32.3), we infer that it is paired with the others and that the difference in groundmass size probably reflects sample inhomogeneity. PCA82500 is roughly intermediate between 4 and 5 in its degree of recrystallization. Its groundmass has a typical grain size of 20–60 μm.

The most recrystallized sample is CK6 LEW87009 (Fig. 1d). This chondrite possesses a coarse (50–300 μm) granular texture. Rare concentrations of small (40 μm) olivine grains are the only indications of the former presence of (porphyritic) chondrules. Plagioclase occurs as grains typically 200 μm in size.

Chondrules

Chondrules constitute only about 10–15 vol% of CK chondrites. Ningqiang contains 22 vol% chondrules. Textural types of chondrules in CK chondrites include barred olivine (Fig. 1b), small-phenocryst-bearing (type I) porphyritic olivine (Fig. 1a) and porphyritic olivine-pyroxene, and a few coarse-phenocryst-bearing (type II) porphyritic olivine (SCOTT and TAYLOR, 1985; this study). One 650-μm diameter radial pyroxene chondrule was observed in ALH85002; no other non-porphyritic chondrules have been observed or reported. Chondrules range in apparent diameter (i.e., measured in thin section—all mentioned diameters are apparent) from about 150 to 2000 μm and average between 500 and 750 μm. Chondrules vary in size; in the one available thin section of CK4 EET87519 (paired with EET87507), the four discernable chondrules have diameters of 900–1500 μm, whereas other EET87507-paired chondrites have smaller mean chondrule sizes. The few discernable chondrules in the probable CK chondrites LEW86258 and PCA82500 have mean diameters of $\sim$700 and $\sim$1000 μm, respectively, roughly consistent with their assignment to the CK group. In Ningqiang the mean chondrule diameter is 770 μm.

CO3 chondrules ($\sim$150 μm; RUBIN, 1989) and CM2 chondrules ($\sim$270 μm; RUBIN and WASSON, 1986) are much smaller than CK4 chondrules, whereas CV3 chondrules ($\sim$1000 μm; GROSSMAN et al., 1988) appear to be somewhat larger. Although mean chondrule size can be increased by metamorphic recrystallization of small chondrules (RUBIN and GROSSMAN, 1987), the effect should be relatively minor for type-4 chondrites; in fact, the mean size of chondrules in Ningqiang is about the same as that in the CK4–6 chondrites. Although $\sim$50% of CV chondrules are surrounded by coarse-grained silicate- and sulfide-rich rims (RUBIN, 1984), only 5% of Ningqiang chondrules are surrounded by such rims, and no rims have been observed surrounding CK4 chondrules. Thus, CK chondrules are texturally distinct from those in other carbonaceous chondrite groups.

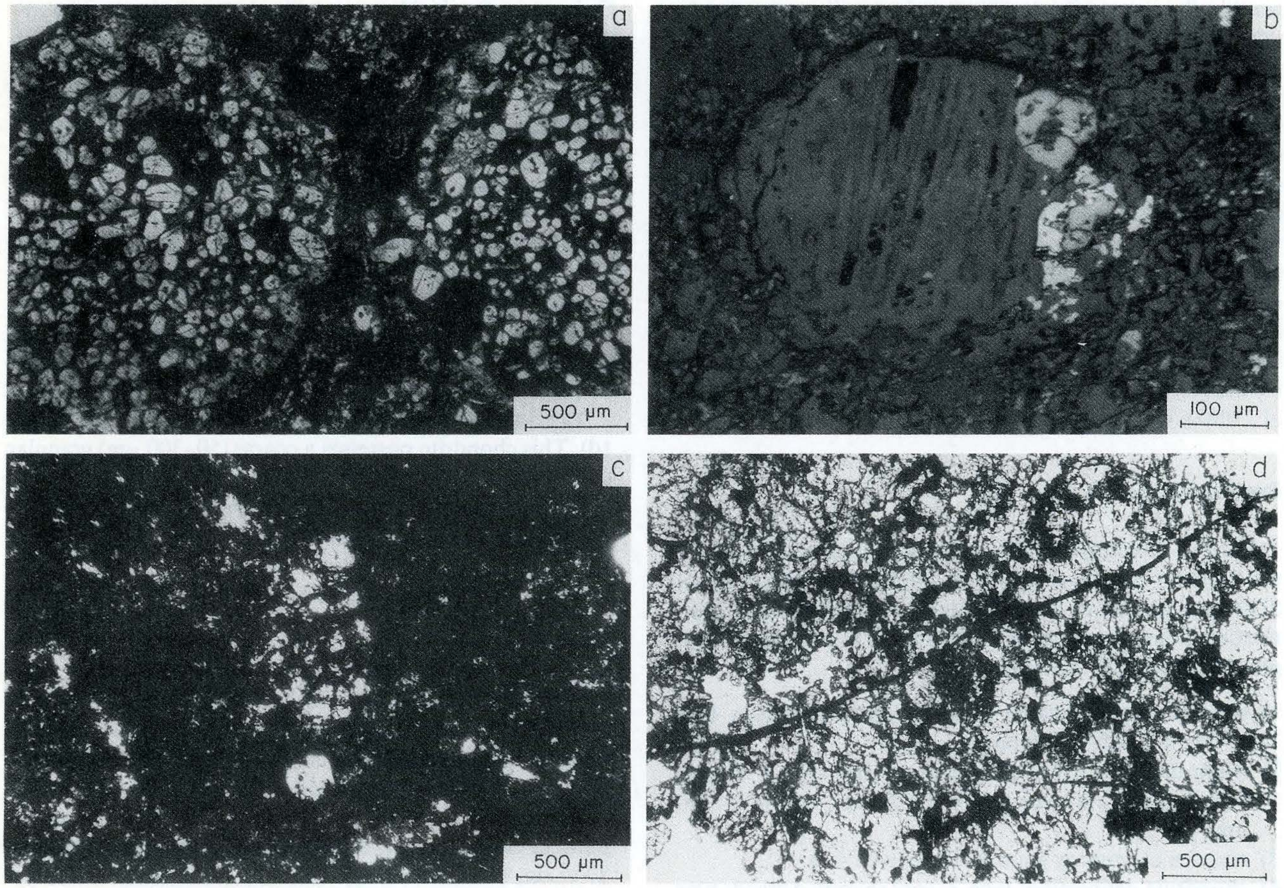

FIG. 1. Photomicrographs of CK chondrite thin sections. (a) Two large type-I porphyritic olivine chondrules in Karoonda (CK4). The dark color of the recrystallized groundmass surrounding the chondrules is due to the dispersion of tiny magnetite and pentlandite grains inside silicate. This effect is known as "silicate-darkening." Transmitted light. (b) Barred olivine chondrule in Karoonda. The dark grey material between the olivine bars is recrystallized mesostasis. The medium grey area at upper right of chondrule is a large magnetite grain; the very light grey grains at chondrule right are pentlandite. Tiny magnetite grains outside the chondrule permeate the interiors of silicates. Reflected light. (c) Typical, very black region in ALH84038 (CK4) due to pronounced silicate darkening. A fragment of a porphyritic olivine chondrule is at center. Transmitted light. (d) Branching, black glassy to microcrystalline shock vein in LEW87009 (CK6) filled with tiny magnetite and pentlandite grains. The silicate grains in this highly recrystallized meteorite have a nearly granular texture. The rock has much less silicate-darkening than ALH84038 (Fig. 1c).

Groundmass

The Ningqiang matrix consists of poorly-sorted, angular, anhedral $\leq$0.1–10 μm grains of olivine and lesser amounts of awaruite ($FeNi_3$), pentlandite, troilite, and magnetite (RUBIN et al., 1988). The Karoonda groundmass (e.g., Fig. 1b) consists principally of 10–25-μm-size grains of olivine with minor low-Ca pyroxene and plagioclase. Many CK4 chondrites contain numerous isolated silicate crystals ranging in size from $\sim$1000 μm down to <20-μm-size grains that grade into the recrystallized groundmass. The vast majority of the isolated silicates are olivine; a few are pyroxene. LEW87009, the only CK6 chondrite, has a highly recrystallized granular texture with an average grain size of 120 μm (Fig. 1d) and no discernable isolated silicate grains.

Inclusions

Although CK refractory lithophile abundances are high and roughly similar to those in CO, CM, and CV chondrites, in contrast to these groups, refractory inclusions are very rare in CK chondrites (e.g., MCSWEEN, 1977a). The sole exception is a 1.6 $\times$ 2.2 mm fassaite-olivine-pleonaste-bearing inclusion in Karoonda (MACPHERSON and DELANEY, 1985). Although tiny, fine-grained refractory inclusions may have been recrystallized beyond recognition, the general absence of discernable refractory inclusions seems to indicate that there were very few millimeter or larger inclusions (such as those that occur in CO, CM, and CV chondrites) prior to metamorphism. Ningqiang contains only $1.0^{+1.0}_{-0.5}$ vol% refractory inclusions: most are fine-grained and roughly 200 μm in size; only one coarse-grained inclusion was observed. RUBIN et al. (1988) reported observations by Y. Lin of two 100–200-μm-size refractory inclusions in Ningqiang—one compact type A and one fluffy type A. The refractory metal sulfides discussed below that have been reported in a few CK chondrites (GEIGER and BISCHOFF, 1989) are reminiscent of those in fremdlinge in CV chondrite refractory inclusions (EL GORESY et al., 1978; ARMSTRONG et al., 1985).

McSWEEN (1977b) reported numerous amoeboid olivine inclusions (olivine aggregates) in Karoonda, and we have found a few recrystallized rimmed olivine aggregates (up to 150×420 μm) in LEW87214 and LEW86258. Ningqiang contains 8.2 vol% olivine aggregates (RUBIN et al., 1988), more than every CV3 chondrite except Efremovka (8.6 vol%; McSWEEN, 1977c).

Opaque Phases

The predominant opaque phases in CK chondrites are magnetite and pentlandite; minor phases include pyrrhotite, pyrite, chalcopyrite, and mackinawite; metallic Fe-Ni is exceedingly rare (Table 1). Ningqiang contains magnetite, pentlandite, troilite, mackinawite, and awaruite. Many large magnetite grains in CK chondrites contain ilmenite and spinel exsolution lamellae (GEIGER and BISCHOFF, 1990). Pyrite has been reported in only one chondrite outside the CK group (Mulga (west); GEIGER and BISCHOFF, 1990). Chalcopyrite is also rare; outside of Karoonda, it has been reported only in H6 Estacado (RAMDOHR, 1973), the highly-oxidized chondrite, ALH85151 (RUBIN and KALLEMEYN, 1989), PCA82500 (SCOTT and TAYLOR, 1985), and Coolidge (GEIGER and BISCHOFF, 1990). Mackinawite [$(Fe,Ni,Co)S_{1-x}$] has previously been reported in H5 Ehole, CM2 Murray, and Ningqiang (RAMDOHR, 1973; RUBIN et al., 1988). Besides the CK group, pyrrhotite and pentlandite occur in highly-oxidized chondrites such as Carlisle Lakes (RUBIN and KALLEMEYN, 1989), and pentlandite occurs in some LL chondrites.

A solid solution between laurite (RuS_2) and ehrlichmanite (OsS_2) with some dissolved Ir has been reported by GEIGER and BISCHOFF (1989, 1990) as a rare phase in Karoonda, ALH82135, ALH84038, ALH85002, and PCA82500 (as well as Mulga (west)). GEIGER and BISCHOFF (1989) also reported PtS in ALH82135, chengbolite ($PtTe_2$) in Karoonda, and a Pt-Au-telluride in ALH85002. Sulfides rich in refractory metals have been found only in fremdlinge in CV chondrite refractory inclusions. EL GORESY et al. (1978) reported Mo, W, and V sulfide phases in fremdlinge from Allende and Leoville (both CV). ARMSTRONG et al. (1985) reported Te in a Ni-Ge sulfide in a fremdling in the Bali CV chondrite. If this fremdling had been more reduced, it might have formed Pt and Pt-Au tellurides, similar to those in CK chondrites.

Metallic Fe-Ni, which is an important phase in CO3 and CV3 chondrites, is rare in CK chondrites. Small amounts of metallic Fe-Ni were reported in the weathered members PCA82500 and LEW86258 by B. Mason but neither SCOTT and TAYLOR (1985) nor we were able to confirm this report. OKADA (1975) reported trace amounts of metallic Fe-Ni in CK-an Y6903, GRAHAM and YANAI (1986) reported rare metal in Y82104, and RUBIN et al. (1988) reported 0.5 vol% awaruite (Ni_3Fe) in Ningqiang.

The opaque assemblage in CK chondrites reflects the high degree of oxidation of these meteorites. Oxidation of virtually all of the metallic Fe-Ni results in the formation of (a) abundant magnetite and FeO-rich mafic silicates, (b) pyrrhotite with its high S/(Fe+Ni) ratio, (c) chalcopyrite (because Cu, normally dissolved in metallic Fe-Ni combines with S when the Fe-Ni is oxidized; SCOTT and TAYLOR, 1985), (d) pentlandite with a high-Ni content (generally 24–38 wt%) (because so much Fe is bound to O in magnetite and silicates), and (e) awaruite in Ningqiang and possibly in some CK chondrites (because the amount of reduced Fe is much less than the amount of reduced Ni).

A remarkable observation is that all CK chondrites (including the weathered CK finds and the probable CK Y82104) exhibit pronounced silicate blackening: abundant, tiny (<0.3–10 μm) grains of magnetite and pentlandite permeate the interiors of many silicates, causing them to appear dark in transmitted light (Fig. 1b,c). The cause of the blackening is at present unknown but may be due to shock mobilization of opaque grains.

Silicate Compositions

Olivine is relatively homogeneous in each individual CK chondrite (Table 1), e.g., 31.3 ± 0.3 mol% Fa in LEW87214. (Although SCOTT and TAYLOR (1985) reported a range of Fa 2–33 for Karoonda, our analyses indicate that the mean olivine composition $\pm$ 1s is Fa 31.2 ± 0.6.) The mean Fa content of the CK group is 31.1 mol%, and the range is from Fa 28.8 in ALH84038 to Fa 33.3 in Maralinga (Table 1). The overall range of 4.5 mol% is generally similar to that of LL-group chondrites (Fa 26.6–32.4; RUBIN, 1990). The CK range overlaps that of Isna (Fa 32.2; McSWEEN, 1977a), one of the two most metamorphosed CO3 chondrites, but is very different from that of the CV4-an chondrite Coolidge (14 mol%; SCOTT and TAYLOR, 1985). The weathered meteorites we designate as probable CK chondrites show very similar olivine compositions (Table 1).

More than half of the CK chondrites contain rare aberrant olivine grains that are significantly out of equilibrium with the majority. The most extreme case is in LEW86258, wherein a grain of Fa 59 composition occurs; this grain is >100 standard deviations above the mean olivine value of Fa 32.2 ± 0.2. The occurrence of aberrant grains suggests that many CK chondrites are fragmental breccias, but more detailed petrographic observations are needed to rule out fractionation during formation or crystallization of shock melt.

Both low-Ca and Ca-rich pyroxene occur in CK chondrites as minor to accessory phases. Low-Ca pyroxene is more heterogeneous than olivine, as is typical for partially equilibrated chondrites. In several CK chondrites only Ca-rich pyroxene (diopside and augite) was identified (Table 1).

Plagioclase is very heterogeneous, e.g., An 22–82 in ALH84038 (Table 1). Even in type-6 LEW87009, plagioclase ranges from An 45–78. The heterogeneity of plagioclase may reflect fractionation during shock melting or crystallization; because of its low impedance to shock compression (SCHAAL et al., 1979), plagioclase is more readily melted than other silicates. Plagioclase in Ningqiang is absent outside of the rare refractory inclusions.

Shock Veins

Black, glassy to microcrystalline shock veins up to several millimeters in length occur in EET83311, EET87508, EET87526, and EET87529 (all three of which are paired with

EET87507), and in LEW87009 (Fig. 1d). These veins are filled with submicrometer grains of pentlandite and magnetite. Ningqiang exhibits few shock metamorphic effects.

Weathering

Karoonda is the only observed fall among the normal and probable CK chondrites; the others are Antarctic and Australian finds that have been weathered to varying extents. All of the Victoria Land finds have been assigned to weathering categories A to B (SCORE and LINDSTROM, 1990); a few contain discernable evaporite deposits on exposed surfaces and are labelled Ae or Be. Our observations show that these meteorites vary significantly in their degree of brown (iron-oxide) staining of silicates. For example, LEW87214 is only slightly weathered with rare brown-staining of silicates. In contrast, PCA82500 is extensively weathered; silicates are thoroughly stained, and the meteorite contains large cavities interpreted to reflect the loss of material by leaching. The meteorite also contains numerous veins of Ni-rich, Mg-sulfate of Antarctic origin (GOODING, 1984). LEW86258 is moderately brown-stained with several patches of dark brown staining. The meteorite has a low abundance of pentlandite (<1 vol%), possibly due to weathering loss. The low abundances of siderophile and chalcophile elements in this meteorite (see below) may be a direct consequence of pentlandite weathering. Maralinga, the sole find from Australia, is significantly weathered: there is extensive dark brown staining around most large magnetite grains, moderate staining of the groundmass, and minor staining of large olivine phenocrysts in some chondrules. A few coarse (up to 50 μm) grains of limonite also occur.

BULK COMPOSITIONAL RESULTS; ALTERATION BY WEATHERING

Our new bulk data are listed in Table 2. For completeness we also include previous analyses of Karoonda from KALLEMEYN and WASSON (1982), of ALH82135 and PCA82500 by KALLEMEYN (1987), and of Ningqiang from RUBIN et al. (1988).

Examination of our data on scatter diagrams (e.g., Figs. 3–5) shows that most of the "normal" CK chondrites define relatively small fields, despite the fact that Karoonda is the only observed fall in the set of samples. The most deviant values on these diagrams are low Sc in Maralinga, ALH82135, and PCA82500, low Zn and Ni and high Ir in LEW86258,

Table 2. Replicate INAA concentration data for 26 elements in CK chondrites. Single determinations and means are shown in bold; asterisks indicate those previously published. Concentrations in the listed units per g.

	Na mg	Mg mg	Al mg	K µg	Ca mg	Sc µg	V µg	Cr mg	Mn mg	Fe mg	Co µg	Ni mg	Zn µg	Ga µg	As µg	Se µg	Br µg	Ru ng	Sb ng	La ng	Sm ng	Eu ng	Yb ng	Lu ng	Os ng	Ir ng	Au ng
CK chondrites																											
ALH82135*	3.27	144	15.5	302	17.5	8.8+	97	3.24=	1.44	215=	618	12.1	98	5.6	1.32	8.0	0.4	1000	75	405	240	100	275	42	820	757	559+
ALH82135	3.16	148	16.2	261	16.4	10.2	95	3.52	1.48	229	558	10.7	100	5.7	1.52	5.9	0.4	1010	79	412	247	101	295	43	710	746	94
ALH84038	3.50	146	16.1	331	17.0	11.1	96	3.66	1.46	240	564	9.6+	104	5.7	1.40	7.5	0.4	1180	73	430	262	99	280	42	860	810	93
mean	**3.31**	**146**	**15.9**	**298**	**17.0**	**10.6**	**96**	**3.52**	**1.46**	**231**	**580**	**11.4**	**101**	**5.7**	**1.41**	**7.1**	**0.4**	**1060**	**76**	**416**	**250**	**100**	**283**	**42**	**816**	**771**	**94+**
ALH85002	3.13	149	16.6	251	17.7	11.0	96	3.65	1.43	238	681	13.6	77+	4.6	1.25	6.0	0.4	1160	59	503	295	113	325	46	764	755	76+
ALH85002	3.00	150	15.4	243	16.5	11.2	95	3.88	1.45	249	739	14.3	89	5.6	1.62	7.4	0.4	1140	67	439	252	106	307	42	878	838	95
mean	**3.06**	**150**	**16.0**	**247=**	**17.1**	**11.1**	**96**	**3.76**	**1.44**	**244**	**710**	**13.9**	**89**	**5.1**	**1.44**	**6.7**	**0.4**	**1150**	**63**	**471**	**274**	**109**	**316**	**44**	**821**	**796**	**95**
EET83311	**3.27**	**147**	**16.1**	**259=**	**18.0**	**11.1**	**96**	**3.54**	**1.45**	**221**	**620**	**11.1=**	**95**	**5.7**	**1.53**	**6.3**	**0.3**	**1000**	**76**	**408**	**285**	**109**	**279**	**38**	**760**	**721**	**73+**
EET87507	3.02	150	14.9	246	17.5	11.2	97	3.79	1.44	239	460	8.0	106	5.8	1.47	7.5	0.4	990	72	438	255	98	287	41	850	718	184
EET87514	3.52	139	15.6	354	16.8	10.3	95	3.67	1.44	240	716	17.4	116	5.8	1.41	8.4	0.3	1160	80	445	244	104	273	38	820	724	112
EET87519	3.19	151	15.6	300	17.4	11.4	96	3.64	1.45	240	411	7.6	96	5.6	1.90	6.7	0.4	900	92	517	327	125	288	39	740	752	178
EET87526	3.05	150	14.9	284	14.2	9.8=	94	3.75	1.46	242	552	10.7	107	5.8	1.37	7.1	0.3	1050	60	377	226	80	260	37	800	747	148
EET87526	3.30	149	14.9	285	15.4	10.3	94	3.61	1.47	237	568	10.9	104	5.0	1.48	7.4	0.3	1400	61	435	276	93	300	43	900	818	172
EET87529	3.36	149	15.6	274	16.2	11.0	96	3.77	1.45	238	528	10.2	102	4.8	1.92	7.3	0.3	1240	83	430	271	99	281	38	916	874	125
mean	**3.25**	**149**	**15.6**	**292**	**16.7**	**10.7**	**96**	**3.71**	**1.45**	**239**	**538**	**10.8=**	**105**	**5.6**	**1.62**	**7.4**	**0.3**	**1070**	**78**	**447**	**270**	**103**	**288**	**41**	**835**	**770**	**152**
EET87860	3.41	146	16.4	294	16.2	12.1	93	3.59	1.51	240	690	14.7	110	5.7	1.55	8.0	0.3	1250	75	470	252	96	309	43	897	802	133
EET87860	3.05	147	16.0	187+	16.6	11.9	94	3.67	1.49	237	672	13.4	107	5.3	1.55	6.5	0.2	1270	61	499	301	112	342	51	854	794	87+
mean	**3.23**	**146**	**16.2**	**294**	**16.4**	**12.0=**	**94**	**3.63**	**1.50**	**238**	**681**	**14.0**	**108**	**5.5**	**1.55**	**7.2**	**0.3**	**1260**	**68**	**484**	**276**	**104**	**325**	**47**	**876**	**798**	**133**
Karoonda*	2.96	153	16.8	298	18.0	10.8	100	3.76	1.43	243	684	14.6	93	5.3	1.32	7.3	0.7	1330	61	438	276	109	301	45	880	821	131
Karoonda*	3.20	151	16.6	350	17.3	11.1	100	3.78	1.42	241	678	13.0	88	5.2	1.33	7.3	0.7	1030	88	433	266	111	314	47	-	856	141
Karoonda	3.15	150	16.5	258	17.0	11.5	98	3.71	1.42	236	685	13.3	94	5.2	1.05	7.1	0.6	1250	53	480	282	106	320	45	935	883	141
mean	**3.10**	**151**	**16.6**	**302**	**17.4**	**11.1**	**99**	**3.75**	**1.42**	**240**	**682**	**13.6**	**92**	**5.2**	**1.23**	**7.2**	**0.7**	**1200**	**67**	**450**	**275**	**109**	**312**	**46**	**907**	**853**	**138**
LEW87009	3.14	149	16.6	266	18.4	12.6+	96	3.58	1.44	232	647	12.5	100	5.6	0.47	6.7	0.3	840	73	557	270	125	395	54	694	649	123
LEW87009	3.12	150	16.1	277	17.0	11.2	96	3.85	1.53	242	646	12.3	108	5.2	0.61	5.5	0.3	1230	53	560	342	115	350	51	700	679	54+
mean	**3.13**	**150**	**16.4**	**272**	**17.7**	**11.2**	**96**	**3.72**	**1.48**	**237**	**646**	**12.4**	**104**	**5.4**	**0.54+**	**6.1**	**0.3**	**1040**	**63**	**558**	**356**	**120**	**372**	**52**	**697**	**664**	**123**
CK mean	**3.19**	**148**	**16.1**	**285**	**17.2**	**11.0**	**96**	**3.66**	**1.46**	**236**	**637**	**12.7**	**98**	**5.5**	**1.48**	**6.9**	**0.4**	**1110**	**70**	**462**	**284**	**108**	**311**	**44**	**813**	**767**	**136**
Weathered chondrites (probably CK)																											
LEW86258	2.44	150	16.0	234	17.2	10.6	98	3.68	1.24	238	317	3.6	47	4.1	1.82	4.3	0.2	1020	48	292	175	77	223	34	810	879	100
LEW86258	2.41	152	15.5	264	15.2	10.9	95	3.70	1.23	238	323	3.8	47	4.2	1.69	4.0	0.4	1040	52	322	198	77	240	36	850	837	58+
LEW86258	2.82	146	16.3	260	15.6	11.2	94	3.89	1.16	245	334	3.8	52	4.4	1.93	4.3	0.3	1040	59	343	251	99	280	43	790	860	77+
mean	**2.56**	**149**	**15.9**	**253**	**16.0**	**10.9**	**96**	**3.76**	**1.21**	**240**	**325**	**3.8**	**49**	**4.3**	**1.81**	**4.2**	**0.3**	**1030**	**53**	**319**	**208**	**84**	**248**	**38**	**817**	**859**	**100**
Maralinga	**2.75**	**147**	**15.6**	**365**	**23.6**	**10.3**	**92**	**3.62**	**1.34**	**232**	**367**	**3.5**	**57**	**5.0**	**1.48**	**1.7**	**1.0**	**1050**	**60**	**428**	**259**	**100**	**299**	**42**	**710**	**694**	**51**
PCA82500*	**3.13**	**139**	**15.1**	**234**	**15.1**	**8.2**	**94**	**3.21**	**1.34**	**218**	**504**	**10.5**	**72**	**5.4**	**1.04**	**7.5**	**0.4**	**953**	**51**	**349**	**214**	**89**	**242**	**36**	**715**	**620**	**138**
Y6903*	**3.16**	**143**	**15.8**	**317**	**19.0**	**11.0**	**97**	**3.83**	**1.45**	**240**	**751**	**14.3**	**107**	**5.7**	**1.67**	**9.0**	**0.6**	**1250**	**73**	**483**	**298**	**115**	**311**	**47**	**960**	**920**	**120**
CK-anomalous chondrite																											
Ningqiang*	**3.76**	**151**	**15.4**	**315**	**16.1**	**9.7**	**85**	**3.64**	**1.59**	**245**	**679**	**13.6**	**131**	**6.2**	**1.70**	**10.1**	**1.7**	**1110**	**78**	**397**	**242**	**98**	**275**	**41**	**820**	**746**	**160**

* ALH82135, PCA82500 and YAM6903 data from Kallemeyn (1986); Karoonda data from Kallemeyn and Wasson (1982); Ningqiang data from Rubin et al. (1988). + not included in the mean = give 1/2 weight in the mean

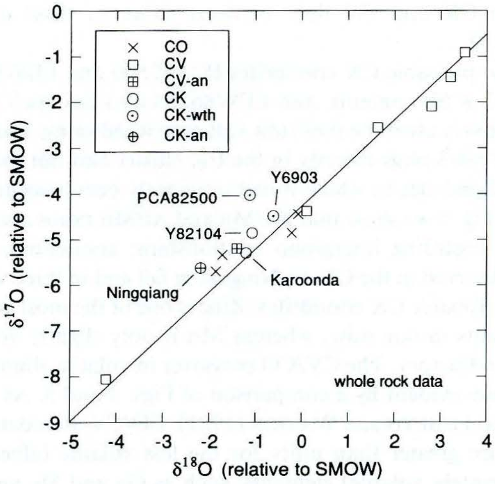

FIG. 2. Published O-isotope data for CV, CO, CK, and CK-related meteorites show very similar values for CO and CK near the CCAM (carbonaceous chondrite anhydrous minerals) mixing line. CV-chondrite data plot along the line on both sides of the CO-CK field, but are generally on the high-$\delta^{18}O$ side.

low Zn in Maralinga and PCA82500, and low Ni and high Ir in ALH84038. Our Au values scatter to a degree that is far higher than normal for this well-determined element. We speculate that an appreciable fraction is in minor phases (such as the platinum-gold-telluride) that are particularly susceptible to alteration during weathering. The occurrence of Ni-rich, Mg-sulfate in PCA82500 indicates that Antarctic weathering was capable of mobilizing siderophiles. CK-an Ningqiang deviates from the normal CK chondrites in several of its elemental abundances including low refractory lithophiles and high Mn, Na, Ga, Sb, Se, and Zn.

COMPOSITIONAL TAXONOMIC EVIDENCE

The CK meteorites contain chondrules and show the common compositional signatures of chondritic meteorites: subequal atomic abundances of Fe, Mg, and Si and roughly 10 times lower abundances of Ca, Al, and Na. As a result, we start this section with their chondrite nature as a given and focus on the question of the compositional links among the CK chondrites and their relationships to other groups of carbonaceous chondrites.

Oxygen isotope data for the CK chondrites Karoonda, ALH82135, EET83311, Y82104, and probable CKs PCA82500 and Y6903 were reported by CLAYTON and MAYEDA (1989) and MAYEDA et al. (1987). RUBIN et al. (1988) reported the Clayton-Mayeda O-isotope data for Ningqiang. All values plot within the CO field which straddles the CCAM (carbonaceous chondrite anhydrous minerals) mixing line between $\delta^{17}O = -6$, $\delta^{18}O = -2$, and $\delta^{17}O = -4$, $\delta^{18}O = 0‰$ relative to SMOW. CLAYTON and MAYEDA (1989) stated that these results are "probably the most unequivocal evidence associating the C4-5 meteorites with a single C3 (i.e., CV or CO) group," implying that the C4-5 meteorites are closely related to CO chondrites. Published CK, CO, and CV O-isotope data are shown in Fig. 2. In fact, although most CV chondrite compositions plot along the CCAM line at $\delta^{18}O$ values near 2–4‰, higher than the CK field, their total range overlaps that of the CK chondrites; thus, the O-isotope evidence is equivocal as regards links to CO and CV.

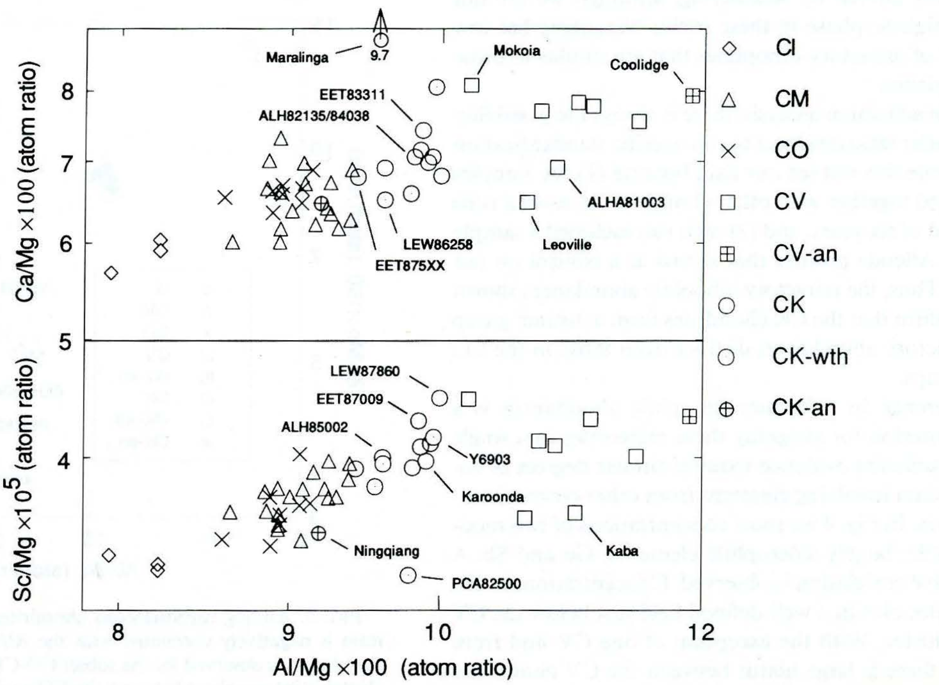

FIG. 3. Carbonaceous-chondrite refractory-lithophile abundances increase through the sequence CI < CM = CO < CV. The CK chondrites form a field intermediate between CO and CV. Low Sc/Mg and Ca/Mg abundances are limited to finds (with the exception of CV Kaba) and are attributed to weathering.

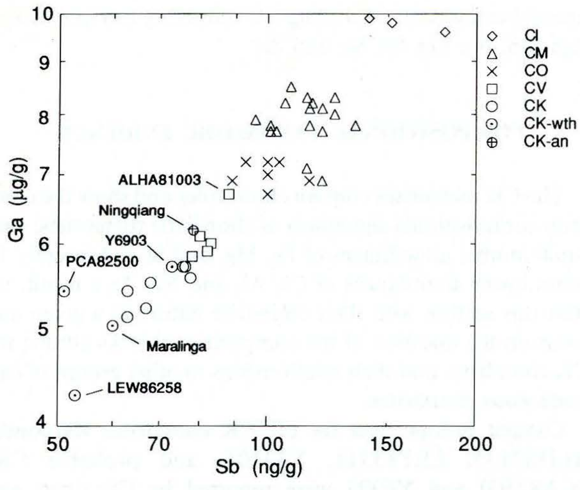

FIG. 4. Gallium and Sb concentrations are strongly correlated in the carbonaceous chondrites. Concentrations of both elements are slightly lower in CK chondrites than in CV chondrites, and 20% lower in CK than in CO chondrites. This is one of several indications that CK chondrites are more closely related to CV than to CO chondrites. Ningqiang (CK-an) plots with the CV chondrites.

We noted above that the large chondrule sizes in CK chondrites are inconsistent with a close relationship to the CO chondrites. Our chief compositional taxonomic parameter, Mg-normalized refractory lithophile abundances, confirms this conclusion. In Fig. 3 we plot Mg-normalized abundances of the refractory lithophiles Ca, Sc, and Al. With rare exceptions, CK ratios are intermediate between those in CV and CO chondrites. The two specimens (ALH82135 and PCA82500) having low Sc contents (and low Sc/Mg ratios) were probably altered by weathering, although we are not aware of a high-Sc phase in these rocks. Ningqiang has low abundances of refractory lithophiles that are similar to those of CO chondrites.

In neutron activation analysis, there is always the possibility that a particular ratio is subject to run-specific standardization errors. We rule this out for our data because (1) the samples were analyzed together with other chondrites in several runs over a period of six years, and (2) each run included a sample of standard Allende powder that served as a control on our calibration. Thus, the refractory lithophile abundances shown in Fig. 3 confirm that the CK chondrites form a distinct group having refractory abundances distinct from those in the CO and CV groups.

The coherence in refractory lithophile abundances is a necessary criterion for assigning these meteorites to a single group, but sufficient evidence requires similar degrees of coherence for data involving elements from other cosmochemical categories. In Fig. 4 we show concentrations of two moderately volatile, largely siderophile elements, Ga and Sb. A strong positive correlation is observed. Concentrations in the CK chondrites plot in a well-defined field just below the CV chondrite cluster. With the exception of one CV find from Antarctica, there is large hiatus between the CV chondrites (Ga $\sim$6 μg/g, Sb $\sim$80 ng/g) and the much higher concentrations (Ga $\sim$7 μg/g, Sb $\sim$100 ng/g) in CO chondrites. These data, like the chondrule size data, indicate a closer link between CK and CV than between either of these groups and CO.

The probable CK chondrites PCA82500 and LEW86258 have low Sb contents, and LEW86258 also has low Ga; we tentatively attribute these low values to weathering. Probable CK Y6903 plots directly in the CK cluster and not with the CV chondrites to which it had previously been assigned.

In Fig. 5 we show that Zn/Mn and Al/Mn ratios also offer clues regarding intergroup relationships; anomalous ratios are observed in the CK-an Ningqiang fall and in three weathered probable CK chondrites. Zinc is one of the most volatile elements in our suite, whereas Mn is only slightly volatile; Al is refractory. The CV/CO crossover in volatile abundance is made evident by a comparison of Figs. 4 and 5. As noted by KALLEMEYN and WASSON (1981), CO/CV abundance ratios are greater than unity for the less volatile (albeit still moderately volatile) elements, such as Ga and Sb, and less than unity for the more volatile elements, such as Zn. The Zn/Mn ratios in CK chondrites are intermediate between the higher CV atom ratios near 6.6 and the lower CO ratios near 5.2; CK ratios show minor overlap with each group. The Al/Mn ratio completely resolves CO from CK but fails to resolve CK from CV. It is important, however, that the mean CK Al/Mn ratio appears to be significantly lower than that of CV; this rules out formation of CK4 chondrites from CV3-like starting materials. Note that Mn is slightly volatile, and that any loss of Mn during metamorphism would have increased the CK Al/Mn ratio. Ningqiang has a CV-like Zn/Mn ratio and an Al/Mn ratio below the CK field.

In summary, the compositional evidence (O-isotopes, refractory lithophile and moderately volatile element data) indicate that the CK chondrites constitute a well-defined group

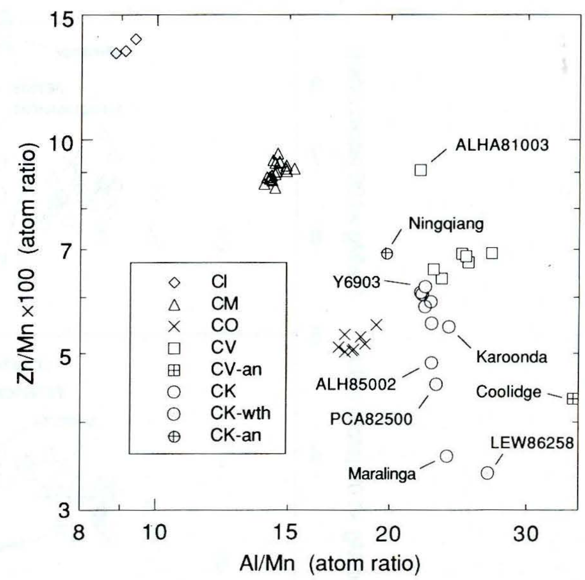

FIG. 5. Among carbonaceous chondrites as a whole the Zn/Mn ratio is negatively correlated with the Al/Mn ratio, but a positive correlation is observed for the subset CO-CK-CV. The CK-chondrite cluster is intermediate between the CO and CV cluster, but closer to the latter. The CK mean Al/Mn ratio is lower than that in CV, inconsistent with formation of CK chondrites by metamorphism of CV.

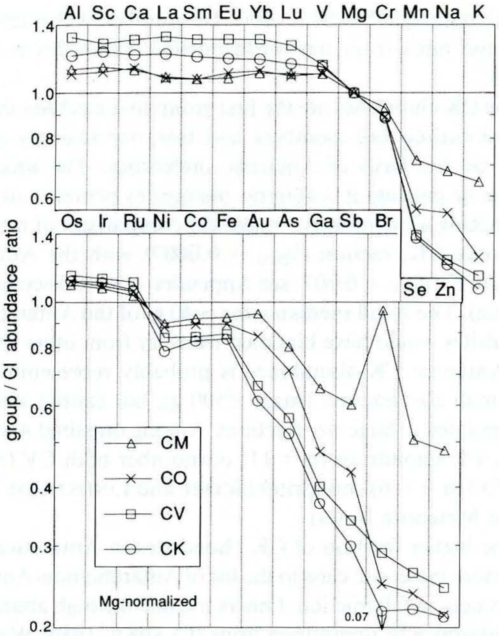

FIG. 6. On a group/CI abundance ratio diagram the CK pattern is similar to the CO and CV patterns. Elements are separated into lithophiles in the top portion of the diagram and siderophiles and sulfide-formers in the lower portion of the diagram, and are ordered in terms of decreasing nebular condensation temperature to the right. CK refractory lithophile abundances average 1.21 × CI abundances; CK volatile abundances are similar to or slightly lower than those in CV chondrites. Ningqiang has lower refractory lithophile abundances than CK (mean, 1.09 × CI) and similar to CO. The CK-CV volatile pattern is distinctly different from the CO pattern. See text for details.

occupying small compositional fields on diagrams involving taxonomically useful parameters. The compositions of the CK chondrites are closely related to those of the CO and CV chondrites. The chemical data indicate a closer relationship to CV than to CO, but some features (e.g., the Al/Mn or Al/Mg ratio) are not consistent with the formation of CK4 from CV3 chondrites or from the CK-related chondrite Ningqiang. On an O-isotope diagram the CK chondrites fall within the CO field, but the CV field overlaps the CO-CK field.

ABUNDANCE RATIO PATTERNS

A valuable way to compare the compositions of the carbonaceous chondrite groups is in terms of their abundance ratio patterns; in Fig. 6 we show the patterns in the five well-defined groups. On this group/CI abundance ratio diagram we divide the set of elements into lithophiles (at the top) and siderophiles and others, mainly sulfide-formers (at the bottom). In each portion the elements are ordered in terms of rightward decreasing nebular 50% condensation temperature (WASSON, 1985). All elements are normalized to Mg.

Because several of the CK chondrites are weathered Antarctic finds, we have been forced to discard or give lower weight to a number of our determinations (Table 2); most of these discarded data are from the four weathered chondrites LEW87009, LEW86258, Maralinga, and PCA82500. In Fig. 7 CK-normalized abundance patterns for individual CK chondrites are shown with distinctive symbols used for these four weathered chondrites, for moderately deviant Y6903, and for Ningqiang. Values from the remaining CK chondrites generally show distributions that appear to be random and that have relatively small variance. The eight refractory lithophiles show more-or-less constant CI-normalized abundance ratios (Fig. 6) in CK, as is also observed in all chondrite groups except EL (i.e., WASSON and KALLEMEYN, 1988). The mean of these values (with Al and Ca given double weight) is 1.21 in CK, intermediate between the mean CV ratio of 1.33 and the mean CO ratio of 1.12. The CK abundance of semirefractory V is only slightly lower than that of the refractory lithophiles. None of the remaining lithophiles resolve CK from CV (the CK K abundance is relatively uncertain), whereas mean CO Mn, Na, and K abundances are significantly higher than those in CV or CK. The mean refractory lithophile abundance ratio of Ningqiang is 1.09, close to that of CO chondrites.

CK abundances of the refractory siderophiles Os, Ir, and Ru show the same monotonic decrease with increasing volatility in the four plotted abundance ratios observed in the other groups. The CK abundance ratios are intermediate between, but only marginally resolvable from those in CV and CO.

We find that concentrations of the next element, Ni, are often strongly reduced by weathering. We have attempted to allow for this by giving less (or no) weight to the lowest values when calculating the mean, but we are confident that the Ni

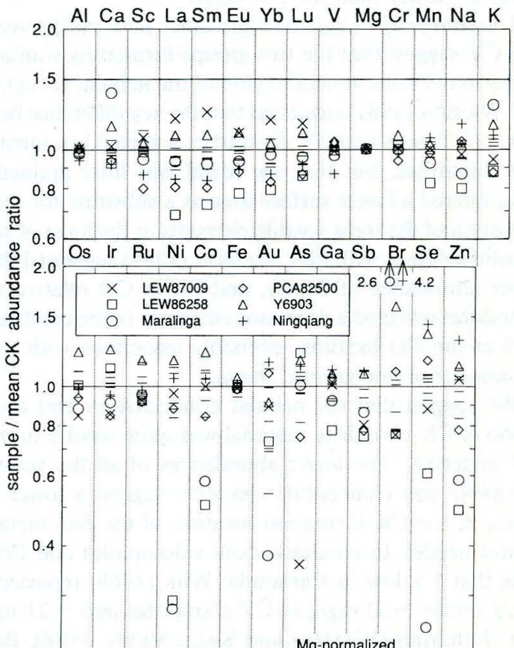

FIG. 7. This abundance ratio diagram shows CK-normalized patterns for individual CK chondrites. The most deviant CK values are associated with the highly weathered chondrites LEW86258, LEW87009, Maralinga, and PCA82500. The large scatter in Au, the element showing the greatest scatter, may reflect enrichment in unusual minerals (e.g., tellurides) that are readily altered by weathering processes. Ningqiang, an unweathered observed fall, shows small but significant deviations from the CK mean for refractory lithophiles, Mn, Na, Ga, Sb, and Se.

abundance ratio is still too low and that the Ni abundance in unweathered CK chondrites is similar to those plotted for Co and Fe, and marginally lower than the mean CV ratios. The exceptional sensitivity of Ni to weathering suggests that it is mainly in a soluble phase (pentlandite?) that contains only minor fractions of the Fe and Co.

We also find Au to be remarkably variable in Antarctic chondrites. The most peculiar datum in our entire set is the 559 ng/g Au found in a previous analysis of ALH82135, 4× higher than typical values in the other CK chondrites. This reflects, in order of decreasing likelihood,

1) a large amount of a cosmic Au-rich phase (e.g., the platinum-gold telluride of GEIGER and BISCHOFF, 1989),
2) an exceptional electrochemical enhancement during terrestrial oxidation, and/or
3) contamination during handling.

Analysis of a new sample yielded a much lower value (94 ng/g) similar to that of the paired meteorite ALH84038. Because of the high scatter in our results the uncertainty in our mean Au abundance is about ±10%.

CK abundances for five of the next six volatiles are parallel to, but 10–20% lower than, CV abundances: CO abundances are much higher for As, Ga, and Sb but below CV and similar to CK for Se and Zn. The very low Br abundance in CK compared to CV and CO probably reflects loss from CK during metamorphism. Although some Antarctic samples may have lost Br during weathering, the Karoonda Br abundance is still 2× lower than the CV value.

The similarity in volatile abundance patterns between CK and CV suggest that the two groups formed by similar processes in the same general region of the nebula. KALLEMEYN and WASSON (1981) suggested that the key difference between CO and CV was that CV chondrites accreted less metal than CO chondrites, but that the metal was finer grained and, thus, offered a larger surface area as a substrate for the condensation of the most volatile elements in the form of sulfides in solid solution with FeS. WASSON (1985) suggested that the lower abundance of Br, Se, and Zn in CO relative to CV chondrites reflected a decreased efficiency in the condensation of S at the CO location, probably associated with a lower abundance of fine-grained metal.

We suggest that the nebular condensation and accumulation of CK-chondrite material was quite similar to that for CV materials. The lower abundances of all the volatile siderophile and chalcophile elements suggest a lower abundance at the CK formation location of the fine metal substrates needed to condense both siderophiles and FeS. We note that S is low in Karoonda; WIIK (1969) reported ~16 mg/g versus ~20 mg/g in CV chondrites and ~21 mg/g in CO chondrites (WASSON and KALLEMEYN, 1988). Because of the difficulty of correcting for possible elemental losses during metamorphism and weathering, it does not appear fruitful to attempt more detailed modeling at this time.

DIFFERENCES BETWEEN ANTARCTIC AND NON-ANTARCTIC METEORITES

About 8,000 meteorite specimens have been collected in Antarctica; the number of distinct falls represented is not certain but might be about 1500. The number of characterized falls and finds from the world outside Antarctica is about 2,800.

The CK chondrites are the first group that has been defined almost entirely (all members save two; one strongly weathered) on the basis of Antarctic meteorites. The unknown degree of pairing of Antarctic meteorites prevents us from attempting a quantitative statistical comparison of the non-Antarctic CK fraction ($^{2}/_{2800}$ = 0.0007) with the Antarctic fraction ($^{\sim 11}/_{1500}$ = 0.007; see Appendix A for a discussion of pairing). The small median size (~40 g) of the Antarctic CK chondrites would have hindered recovery from other regions; the Antarctic CK abundance is probably representative of the small size fraction (mass ≤500 g), but cannot easily be extrapolated to large size fractions. Among unpaired Antarctic finds, CK chondrites (n = 11) outnumber both CV (n = 5) and CO (n = ~6) chondrites (SCORE and LINDSTROM, 1990; Japan Meteorite News).

The higher fraction of CK chondrites in Antarctica adds one more meteorite class to the list of Antarctic/non-Antarctic differences in fall fraction. Others include the high abundance in Antarctica of ungrouped irons (CLARKE, 1986; WASSON, 1990), magnesian ureilites (TAKEDA, 1990), polymict eucrites (TAKEDA et al., 1983), and lunar meteorites (EUGSTER, 1989).

It is conceivable that the localization of CK recovery sites in the southern hemisphere reflects their association with one or two meteoroid streams produced by the recent fragmentation of an Earth-crossing asteroid. HALLIDAY and GRIFFIN (1982) noted that meteoroids in a stream tend to fall within about 90° of the terrestrial "target latitude"; thus, if the target latitude were 60–80°S, the meteoroids would have a moderate probability of falling in Australia (as did Karoonda and Maralinga) but much lower probabilities of falling in northern temperate latitudes, consistent with the distribution of known CK chondrites. Because such a stream will disperse within about 10 Ka, such an explanation requires that the CK chondrites fell during one or two brief periods. Two periods are the minimum to account for the high terrestrial age of PCA82500 (280 Ka; NISHIIZUMI et al., 1989) and the young terrestrial age of Karoonda (~60 a).

Some support for shared histories is found in the exceptionally high cosmic-ray exposure ages of three CK or CK-related chondrites: CK4 Karoonda, 52 Ma; CK3-an Ningqiang, 43 Ma; and probable CK4/5 PCA82500, 39 Ma (EUGSTER et al., 1988). Noble gas data exist for one other CK, ALH82135 (WIELER et al., 1985); using the ^{3}He cosmic-ray production rate of EUGSTER (1988), we calculate a much shorter exposure age of 7.0 Ma for this meteorite. High exposure ages probably indicate unusual orbits that result in fewer collisions with asteroidal debris than experienced by typical meteoroids. Such unusual orbital properties might include high inclinations or aphelia inside 2.2 AU or beyond 4 AU.

WASSON (1990) discussed the factors that could lead to the enhanced abundance of certain meteorite classes in Antarctica. He showed that the anomalously high ungrouped/total fraction in Antarctica was not due to latitudinal effects or to differences in terrestrial ages, but to the ca. 100× smaller median size of Antarctic irons. It seems probable that the high CK abundance in Antarctica is also related to their small size. Because of their tiny size (7 out of 11 are ≤50 g), the Antarctic CK chondrites would probably not have been recovered had they fallen elsewhere in the world. Although *a priori* we would expect the CK size distribution in space (prior to atmospheric entry) to be about the same as that for CV and CO chondrites, this need not have been the case. Most of the Antarctic CK chondrites could have been produced by the breakup of an Earth-crossing body under circumstances (e.g., small size of target body, high impact velocity of the projectile) that produced a size distribution biased toward smaller masses. One test of this idea is that rare-gas and ^{26}Al levels should be consistent with these meteorites having been in small meteoroids in space (^{26}Al data are currently available only for non-Antarctic Karoonda and Ningqiang; NISHIIZUMI, 1987). In general, mechanisms that could lead to size distributions biased in favor of smaller masses will yield enhanced abundances in Antarctic collections relative to those from other terrestrial locations where small meteoroids are rarely recovered.

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APPENDIX A: PAIRING OF CK CHONDRITES

An ongoing difficulty associated with research on Antarctic chondrites is the identification of paired specimens resulting from breakup during atmospheric passage or terrestrial weathering. The Antarctic CK (and probable CK) chondrites were found in five main locations: Allan Hills (ALH), Elephant Moraine (EET), Lewis Cliff (LEW), Pecora Escarpment (PCA), and Yamato Mountains (Y).

The three ALH specimens (82135, 84038, and 85002) are all from the Far Western Icefield and were tentatively paired by B. Mason. ALH82135 and ALH84038 exhibit extensive silicate-blackening (Fig. 1c), but ALH85002 is less blackened (this study) and appears less brecciated (GEIGER and BISCHOFF, 1989). Olivines in ALH82135 and ALH84038 are virtually identical (i.e., Fa 28.9 ± 0.7 and 28.8 ± 0.4, respectively), but those in ALH85002 are more ferroan (Fa 30.2 ± 0.4). ALH82135 and ALH84038 were found <9 km apart, but ALH85002 was found ~50 km farther west. Although ALH82135 appears somewhat less recrystallized than ALH84038, this could be a result of sample textural heterogeneity. We conclude that ALH82135 and ALH84038 are paired, but that ALH85002 is a separate fall. The low abundance of Sc in one sample of ALH82135 is probably due to sample inhomogeneity and/or weathering; the low abundances of Ni and Co in ALH84038 are due to weathering.

Ten specimens were recovered from EET. Eight of them (EET87507, 87508, 87514, 87519, 87525, 87526, 87527, and 87529) were recovered within 7 km of one another (and four of them, 87507, 87508, 87525, and 87529, within 650 m). All 87507-related meteorites are small (5.8–88.2 g). They are all significantly recrystallized (except for 87519) and are all classified here as type 5 (an increase from the type 4 assignment by B. Mason). There are minor petrographic variations among them (e.g., the few discernable chondrules in 87519 appear to be significantly larger than average; 87519 appears less recrystallized than the others; and 87508, 87526, and 87529 contain shock veins whereas available sections of the other specimens do not). These variations are most likely attributable to sample heterogeneity. All eight specimens were paired by B. Mason, and we tentatively accept this conclusion.

EET87860 (type 5/6) is more recrystallized than the other EET specimens; it has a very coarse, subgranular texture. Olivine (Fa 30.0) appears to be less ferroan than in the EET87507 specimens (Fa 32.2). Although EET87860 was found within the 87507 field, it seems probable that EET87860 represents a separate fall. EET83311 was found ~60 km away from the nearest 87507-related specimen; it has somewhat more ferroan olivines (Fa 33.2) than the EET87507 specimens. At this juncture it seems best to consider EET83311 as a separate meteorite.

Four specimens were recovered from LEW. LEW86258 is petrographic type 4 and has an anomalously low abundance of pentlandite (perhaps due to weathering), unlike that of any other CK chondrite. It is the only one in the set that was found on the Upper Ice Tongue of the LEW region; it is probably a separate meteorite. LEW87214 and 87250 are tiny CK4 specimens (0.4 and 1.7 g, respectively) found close together in South Lewis Cliff; they have similar petrographic characteristics and, as noted by B. Mason, are probably paired. Their somewhat less ferroan olivines suggest that they are not paired with LEW86258. The remaining LEW specimen (LEW87009) is the only CK6 chondrite. It clearly is a separate meteorite.

Two specimens were recovered from the Yamato Mountains. Y6903 (probable CK4) is significantly less recrystallized than Y82104 (type 5); they are probably independent falls.

Only one CK-related specimen was found in the PCA region (PCA82500). It clearly is a separate meteorite.

APPENDIX B: CLASSIFICATION OF ALH84096 AND ALH85151

Two other meteorites, ALH84096 and ALH85151, were classified as C4 chondrites by B. Mason (SCORE and LINDSTROM, 1990). In fact, neither is a carbonaceous chondrite. ALH84096 is an LL6 chondrite: olivine (Fa 31.3) and low Ca pyroxene (Fa 26.9) are consistent with either an LL or CK classification; however, plagioclase (An 13 Or 5) is typical of ordinary chondrites and is far more sodic than the great majority of plagioclase grains in CK chondrites. ALH84096 also contains 2–3 wt% metallic Fe-Ni, far more than any CK 4–6 chondrite. The meteorite contains several shock veins and melt pockets; a few 30–55 μm patches of maskelynite were identified. Neutron activation analysis (G. W. KALLEMEYN, unpubl. data, 1990) confirms its classification as an LL chondrite.

ALH85151 is a member of a new grouplet of chondrites (along with Carlisle Lakes) characterized by FeO-rich silicates, unusual O isotopic composition, and abundant recrystallized matrix material. A detailed description was given by RUBIN and KALLEMEYN (1989).