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

Gregory W. Kallemeyn, Alan E. Rubin and John T. Wasson*
Institute of Geophysics and Planetary Physics,
University of California, Los Angeles, CA 90024, USA

---

* Also Department of Earth and Space Sciences and Department of Chemistry and Biochemistry

---

Abstract--Petrographic data and bulk compositional data for 27 elements reveal the existence of a new group of carbonaceous chondrites. The group consists of the observed fall, Karoonda, and 4-11 finds from five sites in Antarctica. Ningqiang, also an observed 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 CK members are metamorphosed; petrographic grades range from 4 to 6. Some contain shock veins and all are shock blackened as a result of the mobilization of sulfides and magnetite and their ubiquitous deposition as fine particles in silicates. Only one other group (EL) has no unequilibrated members, and in no other group are all of the members so heavily

as submitted to GCA 7 June 1990

shocked.

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 1.23× 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; curiously, 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 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 negligible contents of refractory inclusions, 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. All other specimens were recovered from Antarctic ice fields. We propose to follow the widely accepted tradition (Van Schmus, 1969; Wasson, 1974) of naming the group after a prominent member and to designate it 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) found that Karoonda has refractory lithophile abundances lower than those in CV chondrites.

Both the petrographic and the compositional data are consistent with the conclusion that the 5-8 "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.

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 ALH84038,8; EET83311,9; EET87507,18; EET87514,8; EET87519,6; EET87526,18; 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, and Karoonda section 3970-3 from the American Museum of Natural History were studied microscopically in transmitted and reflected light. Silicate and oxide phases were analyzed in ALH84038, LEW87009 and LEW87214 using crystal spectrometers with the UCLA automated ARL electron microprobe; Bence-Albee corrections were applied. Sulfide phases were analyzed using the crystal spectrometers of the UCLA automated Cameca "Camebax-microbeam" electron microprobe; ZAF corrections were applied. Microprobe analyses of additional samples are in progress.

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 four hours to determine long-lived nuclides, and for two minutes 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 unpublished 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 Antarctic finds, appears to be a more important factor leading 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 YAM6903) 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 CK-an. The Ningqiang chondrite (previously classified CV-an; Rubin et al., 1988) is petrographically unresolvable from 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 two other chondrites, ALH85002 and YAM82104, show that they are probably CK chondrites, but we have not yet had an opportunity to analyze them. All CK chondrites 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). We made slight modifications of several of these criteria to make them applicable to the CK chondrites: (1) homogeneity of olivine composition: $[\sigma\text{Fa}/(\text{mean Fa})]\times 100 < 5$ indicates type 4-6; (2) mean diameter (d) of plagioclase grains: type 3, absent; type 4, $d<2$ µm; type 5, $2<d<50$ 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, ≤0.1-10 µm; type 4, 5-30 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 highly oxidized meteorites contain Ni-rich sulfides irrespective of their 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, LEW86258 and LEW87214 are the least recrystallized type-4 members of the group. Chondrules are well-defined (Fig. 1a,b), but chondrule/groundmass boundaries are in some cases (e.g., Fig. 1a) difficult to define. Their groundmasses, which have typical grain sizes of 8-20 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 chondrites include ALH82135, ALH84038 and ALH85002; all of these have been moderately recrystallized. Their chondrules are readily discernable, but the chondrule/groundmass boundaries are quite indistinct (Fig. 1c). The groundmasses of these meteorites are somewhat coarser (i.e., 20-40 µm) than those of Karoonda, LEW86258 and LEW87214.

EET87860 (type 5) has a very coarse (75-300 µm) subgranular texture. 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 (~25 µm) than the other EET87507 specimens; either 87519 is type 4, or its finer grain size 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 CK of all is 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. The meteorite has been assigned to petrologic type 6.

A key question is how much of the textural record of nebular assemblages has been destroyed in the CK4-6 chondrites by recrystallization. This is particularly relevant to the estimation of the premetamorphism abundance of chondrules and of refractory inclusions. For Karoonda, LEW86258 and LEW87214, only fine-grained (<20 µm) objects would have been obliterated by metamorphic recrystallization; progressively coarser objects could have been obliterated in the other CK4-6 chondrites.

Chondrules

Chondrules constitute only about 10-15% of the volume of CK chondrites. Ningqiang contains 22% 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 (Scott and Taylor, 1985; this study). No nonporphyritic chondrules (e.g., radial pyroxene or cryptocrystalline types) 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 CK-an LEW86258 and PCA82500 have mean diameters of ~700 and ~1000 µm; respectively, consistent with their assignment to the CK group. In Ningqiang the mean chondrule diameter is 770 µm.

CO3 chondrules (~150 µm; Rubin, 1989) and CM2 chondrules (~270 µm; Rubin and Wasson, 1986) are much smaller than CK4 chondrules, whereas CV3 chondrules (~1000 µm; Grossman et al., 1988) appear to be 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. The mean size of chondrules in Ningqiang is about the same as that in the CK4-6 chondrites. Chondrules in most CK chondrites are distinctly smaller than those in most CV3 chondrites. In addition, ~50% of CV chondrules are surrounded by coarse-grained silicate- and sulfide-rich rims (Rubin, 1984); in contrast, only 5% of Ningqiang chondrules are surrounded by such rims, and no rims have been observed surrounding CK4 chondrules. The chondrule data show that CK chondrites are texturally distinct from established carbonaceous chondrite groups.

Groundmass

The Ningqiang matrix consists of poorly-sorted angular, anhedral ≤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 ~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 (Rubin, 1990a).

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 have not been found in CK4-6 chondrites (e.g., McSween, 1977a). Although tiny, fine-grained refractory inclusions may have been recrystallized beyond recognition, the 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 typically 200-300 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 CK4-6 chondrites (Geiger and Bischoff, 1989) are reminiscent of those in the portions of refractory inclusions sometimes designated fremdlinge (El Goresy et al., 1978; Armstrong et al., 1985).

McSween (1977b) reported numerous amoeboid olivine inclusions (olivine aggregates) in Karoonda, and Rubin (1990a) reported a few recrystallized rimmed olivine aggregates (up to 150×420 µm) in LEW87214 and LEW86258. Ningqiang contains 8.2 vol.% olivine aggregates, more than all CV3 chondrites 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 contain ilmenite and spinel exsolution lamellae (Geiger and Bischoff, 1990). Pyrite has not been reported to occur in any chondrite outside the CK group (except for Mulga (west); Geiger and Bischoff, 1990), and has not been found in Ningqiang. 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 CV3-an 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 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 -- highly oxidized portions of the Ca-Al-rich inclusions of CV chondrites. El Goresy _et_ _al_. (1978) reported Mo, W and V sulfide phases in fremdlinge from the Allende and Leoville CV chondrites. 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 very rare in CK chondrites. Small amounts of metallic Fe-Ni were reported in the "anomalous" members PCA82500 and LEW86258 by B. Mason* although Scott and Taylor (1985) were unable to confirm this report and our own searches have been fruitless. Okada (1975) reported trace amounts of metallic Fe-Ni in CK-an YAM6903, Graham and Yanai (1986) reported rare metal in YAM82104, and Rubin _et_ _al_. (1988) reported 0.5 vol.% awaruite in Ningqiang.

The opaque assemblage in CK chondrites reflects the high

---

*B. Mason gave preliminary petrographic descriptions of all of the Antarctic meteorites discussed in this paper. References to these descriptions are cited in Score and Lindstrom (1990).

oxidation state 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 much of the Fe is oxidized).

Silicate mineralogy

Olivine is homogeneous in each individual CK4-6 chondrite (Table 1), e.g., 31.3 ± 0.3 mol% Fa in LEW87214 (Rubin, 1990a). The mean Fa content of the CK group is 30.1 mol%, and the range is from Fa 28 in EET87860 (B. Mason) to Fa 32.1 in LEW87009 (Rubin, 1990a). The overall range of ~4 mol% is less than but generally similar to that of LL-group chondrites (Fa 26.6-32.4; Rubin, 1990b). The CK range essentially overlaps that of one of the two mildly metamorphosed CO3 chondrites, Isna and Warrenton (32.2 and 33.9 mol%, respectively; McSween, 1977a), but is very different from that of the CV4-an chondrite Coolidge (14 mol%) (Scott and Taylor, 1985). The equilibrated meteorites we designate CK-an show very similar olivine compositions (Table 1).

A few CK chondrites contain rare aberrant olivine grains that are significantly out of equilibrium with the majority (Rubin, 1990a). The most extreme case is in ALH84038, where a grain of Fa 39 composition was reported by B. Mason; if we use

Rubin's (1990a) mean, Fa=28.8±0.4, the aberrant grain is 25 standard deviations above the mean. The occurrence of aberrant grains may indicate that some CK chondrites are fragmental breccias, although petrographic observations are needed to rule out fractionation during formation or crystallization of shock melt.

Both low-Ca and Ca-rich pyroxene occur in CK4-6 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 (Rubin, 1990a) and An 13-95 in CK-an PCA82500 (Scott and Taylor, 1985). Even in type-6 LEW87009, plagioclase ranges from An 45-78. The mean plagioclase composition in each CK chondrite is in the An 40-60 range; thus the plagioclase can only account for about half of the Na in these meteorites. The heterogeneity of plagioclase probably reflects 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. Bulk Na abundances of most CK chondrites are near mean CV chondrite levels; thus there is no evidence of Na loss by shock-devolatilization. The siting of the Na that cannot be accounted for by the plagioclase is not known. Plagioclase is absent from Ningqiang.

Shock effects

A remarkable observation is that all CK chondrites (including the three CK-an finds) exhibit pronounced shock blackening; this is observed in Karoonda, ALH82135, ALH84038, EET83311, EET87507, EET87860, LEW87009, LEW87214, in CK-related PCA82500, LEW86258 and YAM6903, and in the probable CK chondrite YAM82104. 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). Black, glassy to microcrystalline shock veins up to several millimeters in length occur in EET83311, in EET87526 and EET87529 (both paired with EET87507), and in LEW87009 (Fig. 1d). These veins are filled with numerous submicrometer grains of pentlandite and magnetite. Ningqiang exhibits few shock effects. Although other chondrite groups have individual meteorites that are highly shocked, it appears that the LL group has the next largest fraction of members (~70%) showing prominent shock effects (including pronounced brecciation).

Weathering

Karoonda is the only observed fall among the normal and probable CK chondrites; the others are Antarctic 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 the 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, CK-an PCA82500 is extensively weathered;

silicates are thoroughly stained and the meteorite contains large cavities where material has been lost. CK-an LEW86258 is moderately brown-stained with several patches of dark brown staining. The meteorite has a very low abundance of pentlandite (<1 vol.%), possibly due to selective weathering of this phase. The low abundances of siderophile and chalcophile elements in this meteorite (see below) may be a direct consequence of pentlandite weathering.

Bulk compositional results; alteration by weathering

Our bulk data are listed in Table 2. For completeness we include the Karoonda analysis published by Kallemeyn and Wasson (1982); an additional analysis of Karoonda is in progress and will be included in the revised version of this paper. We also included analyses of ALH82135 and PCA82500 from Kallemeyn (1987) and Ningqiang by Rubin *et al*. (1988).

Examination of our data on scatter diagrams show 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 are low Sc in ALH82135 and PCA82500, low Zn and Ni and high Ir in LEW86258, low Zn in PCA82500, and low Ni and high Ir in ALH84038. Ningqiang is anomalous in several of its elemental abundances including low refractory lithophiles and high Ga, Sb, Se and Zn.

Compositional taxonomic evidence

The CK meteorites contain chondrules. They are shocked but do not appear to be polymict. They show the common compositional signatures of chondritic meteorites: subequal 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 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, YAM82104 and CK-related PCA82500 and YAM6903 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 chondrites 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." 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 higher $\delta^{18}O$ values near 2-4 ‰, their total range overlaps that of the CK chondrites; thus, the O-isotope evidence regarding links to CO and CV appears to be equivocal.

We noted above that the large chondrule sizes in CK chondrites are inconsistent with a close relationship between CK and CO chondrites. Our chief compositional taxonomic parameter, Mg-normalized refractory lithophile abundances, confirm 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 very low abundances of refractory lithophiles, unresolvable from 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 ~6 µg/g, Sb ~80 ng/g) and the much higher concentrations (Ga ~7 µg/g, Sb ~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 anomalous CK chondrites PCA82500 and LEW86258 have low Sb contents and LEW86258 also has low Ga; we tentatively attribute these low values to weathering. The anomalous CK YAM6903 plots directly in the CK cluster and not with the CV chondrites to which it had previously been assigned.

The fact that CK6 LEW87009 has the lowest Sb and CK5 EET87507 and EET87860 the next lowest Sb contents among the normal CK members suggests loss during metamorphism-related heating; concentrations of highly volatile elements such as Cd and In show such a trend in ordinary chondrites (Tandon and Wasson, 1968). It is conceivable that minor (5-10%) Ga and Sb loss occurred during the metamorphism of the CK4 chondrites, and thus that their initial contents were similar to those of the CV3 chondrites or Ningqiang.

In Fig. 5 we show that Zn/Mn and Al/Mn ratios also offer clues regarding intergroup relationships. Zn is one of the most volatile and Mn one of the least volatile elements in our suite; 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, because 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 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 a 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. Because seven 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). The remaining values generally show distributions that appear to be random and that have relatively small variance.

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.

The eight refractory lithophiles show the nearly constant abundance ratios observed in all chondrite groups except EL (viz. Wasson and Kallemeyn, 1988). The mean of these values (with Al and Ca given double weight) is 1.20, intermediate between the mean CV ratio of 1.35 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. Ningqiang's mean refractory lithophile abundance ratio 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 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.

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 in ALH82135, 4× higher than typical values in the other CK chondrites. Becuase 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 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. We suggest that the nebular condensation and accumulation of CK-chondrite material was similar to that for CV materials. Because of the difficulty of correcting for possible losses during metamorphism and weathering, it does not appear fruitful to attempt more detailed modelling at this time.

Differences between Antarctic and non-Antarctic meteorites

About 8000 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 2800.

The CK chondrites are the first group that has been defined almost entirely (all members save one; we use 8 for our estimate) on the basis of Antarctic meteorites. The unknown degree of pairing of Antarctic meteorites prevents us from attempting a quantitative comparison of the non-Antarctic CK fraction (1/2800 = 0.0004) with the Antarctic fraction (~8/1500 = 0.005). The small (median size ~40 g) of CK chondrites hindered recovery outside of Antarctica; the Antarctic CK abundance is probably representative of the small size fraction (mass ≤500 g), but cannot easily be extrapolated to large size fractions.

The apparently significantly 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 (Koeberl _et_ _al_., 1989).

Wasson (1990) discussed the factors that could lead to the enhanced abundance of certain meteorite classes in Antarctica. In the case of the ungrouped irons he showed that the anomalously high ungrouped/total fraction (~0.39) in Antarctica was almost certainly not due to latitudinal effects or to differences in terrestrial ages. Instead, the enhanced fraction (relative to

0.15 outside Antarctica) appears to reflect the ca. 100× smaller median size of Antarctic irons. Wasson (1990) pointed out two mechanisms that would cause the orbits of small meteoroids to differ from those of the parent asteroid to a greater degree than those of large meteoroids, viz. higher impact launch velocities and greater change in orbital velocities resulting from collisions. As a result, small meteoroids tend to sample a much larger set of parent bodies than large meteoroids.

The high CK abundance in Antarctica may be size related; the median size of a CK chondrite is only ~40 g. However, since all appear to have originated on the same asteroid and possibly in a small volume region of the parent asteroid, factors specific to their parent body may also have been important.

Of the four carbonaceous chondrites with the highest cosmic-ray exposure ages (CO3 Felix, 53 Ma; CK4 Karoonda, 52 Ma; CK3-an Ningqiang, 43 Ma; and CK4/5-an PCA82500, 39 Ma; Eugster et al., 1988), two belong to the CK group and Ningqiang is closely related to CK. Noble gas data exist for one additional CK chondrite, 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 for friable meteorites such as carbonaceous chondrites probably indicate that they are in unusual orbits that result in fewer collisions with asteroidal debris than experienced by typical meteoroids. Such unusual orbital properites might include high inclinations or aphelia inside 2.2 AU or beyond 4 AU.

As discussed by Halliday and Griffin (1982), meteoroids in a stream (i.e., in very similar orbits produced by cratering or fragmentation of an Earth-crossing asteroid) tend to fall within about 90° of the "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) but much lower probabilities of falling in northern temperate latitudes, consistent with the distribution of the CK chondrites. Because such a stream will disperse within about 1 ka, such an explanation requires that the Antarctic CK chondrites fell during one brief period. This seems unlikely considering their high cosmic-ray ages, the very high terrestrial age of PCA82500 (280 ka; Nishiizumi et al., 1989) and the very young terrestrial age of Karoonda.

The tiny size of all save one of the Antarctic CK chondrites is almost certainly related to their anomalously high abundance. Virtually none of these would have been recovered had they fallen outside Antarctica. Although *a priori* we would expect the size distribution of CK chondrites 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. Such a mechanism could lead to enhanced recovery of rare groups from Antarctica relative to other terrestrial locations where small meteoroids are rarely recovered.

Acknowledgements

We thank the Antarctic Meteorite Working Group (USA) and K. Yanai of the National Institute of Polar Research (Japan) for samples and thin sections, and M. Prinz of the American Museum of Natural History for a thin seciton of Karoonda. We thank T. Jen, J. Ma, R.E. Jones and R. Score for technical assistance. Neutron irradiations were carried out by P. Rogers and G. Miller. This research was mainly supported by NSF grant EAR 88-16895.

Appendix: 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 related) chondrites were found in five main locations: Allan Hills (ALH), Elephant Moraine (EET), Lewis Cliff (LEW), Pecora Escarpment (PCA) and Yamato Mountains (YAM).

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 are extensively shock-blackened (Fig. 1c); but ALH85002 appears less brecciated (Geiger and Bischoff, 1989). Olivines were analyzed in all three specimens by Geiger and Bischoff (1989) who found similar compositions in ALH82135 and ALH84038 (Fa 29.4±0.7 and 28.6±0.6 mol%, respectively) but significantly more ferroan values in ALH85002 (Fa 31.1±0.6 mol%). ALH82135 and ALH84038 were found <9 km apart, but ALH85002 was found ~50 km farther west. We tentatively accept that ALH82135 and ALH84038 are paired, but that ALH85002 (for which our INAA study is in progress) is a separate fall. The low abundance of Sc in 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 type 4). 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 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 is more recrystallized than the other EET specimens; it has a very coarse, subgranular texture. Olivine (Fa 28) appears to be less ferroan than in the other EET specimens. 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 also is recrystallized and assigned to type 5, but was reported by B. Mason to have significantly more ferroan olivines (Fa 31) than the EET87507 specimens (Fa 29). 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. Both have similar petrographic characteristics and were paired by B. Mason. Their more ferroan olivines and more sodic plagioclase 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 YAM. YAM6903 (CK4-an) is significantly less recrystallized than YAM82104 (type 5), and is probably an independent fall.

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

References

Armstrong J.T., Hutcheon I.D. and Waserburg G.I. (1985) Ni-Pt-Ge-rich fremdlinge: indicators of a turbulent early solar nebula (abstract). Meteoritics **20**, 603-604.

Clarke R.S. (1986) Antarctic iron meteorites: An unexpectedly high proportion of falls of unusual interest (abstract). In International Workshop on Antarctic Meteorites (J.O. Annexsted, L. Schultz and H. Wänke, eds.), pp. 28-29. LPI Tech. Rpt. 86-01. Lunar and Planetary Institute, Houston.

Clayton R.N. and Mayeda T.K. (1989) Oxygen isotope classification of carbonaceous chondrites (abstract). Lunar Planet. Sci. **20**, 169-170.

El Goresy A., Nagel K. and Ramdohr P. (1978) Fremdlinge and their noble relatives. Proc. Lunar Planet. Sci. Conf. **9th**, 1279-1303.

Eugster O. (1988) Cosmic-ray production rates for ^{3}He, ^{21}Ne, ^{38}Ar, ^{83}Kr, and ^{126}Xe in chondrites based on ^{81}Kr-Kr exposure ages. Geochim. Cosmochim. Acta **52**, 1649-1662.

Eugster O., Michel Th. and Niedermann S. (1988) Guangnan (L6) and Ningqiang (CV3): Exposure ages and radiogenic ages of two unusual chondrites. Meteoritics **23**, 25-27.

Fitzgerald M.J. and Jones J.B. (1977) Adelaide and Bench Crater -- Members of a new subgroup of the carbonaceous chondrites. Meteoritics **12**, 443-458.

Geiger T. and Bischoff A. (1989) Mineralogy of metamorphosed carbonaceous chondrites (abstract). Meteoritics **24**, 269-270.

Geiger T. and Bischoff A. (1990) Exsolution of spinel and ilmenite in magnetites from type 4-5 carbonaceous chondrites -- indications for metamorphic processes (abstract). Lunar Planet. Sci. **21**, 409-410.

Gibson E.K., Moore C.B. and Lewis C.F. (1971) Total nitrogen and carbon abundances in carbonaceous chondrites. Geochim. Cosmochim. Acta **35**, 599-604.

Graham A.L. and Yanai K. (1986) A review of the Yamato-80, -81 and -82 meteorite collections. Mem. Natl. Inst. Polar Res. Spec. Iss. **41**, 167-180.

Grossman J.N., Rubin A.E., Nagahara H. and King E.A. (1988) Properties of chondrules. In Meteorites and the Early Solar System (ed. J.F. Kerridge and M.S. Matthews), Univ. Arizona Press, Tucson, 619-659.

Halliday I. and Griffin A.A. (1982) A study of the relative rates of meteorite falls on the Earth's surface. Meteoritics **17**, 31-46.

Jarosewich E. (1990) Chemical analyses of meteorites: A compilation of stony and iron meteorite analyses. Meteoritics, submitted.

Kallemeyn G.W. (1987) Compositional comparisons of metamorphosed carbonaceous chondrites. Mem. Natl. Inst. Polar Res. Spec. Iss. **46**, 151-161.

Kallemeyn G.W. and Wasson J.T. (1981) The compositional classification of chondrites: I. The carbonaceous chondrite groups. Geochim. Cosmochim. Acta **45**, 1217-1230.

Kallemeyn G.W. and Wasson J.T. (1982) The compositional classification of chondrites: III. Ungrouped carbonaceous chondrites. Geochim. Cosmochim. Acta **46**, 2217-2228.

Kallemeyn G.W., Rubin A.E., Wang D. and Wasson J.T. (1989) Ordinary chondrites: Bulk compositions, classification, lithophile-element fractionations, and composition-petrographic type relationships. Geochim. Cosmochim. Acta **53**, 2747-2767.

Koeberl C., Warren P.H., Lindstrom M.M., Spettel B. and Fukuoka T. (1989) Preliminary examination of the Yamato-86032 lunar meteorite: II. Major and trace element chemistry. Proc. NIPR Symp. Antarct. Meteorites **2**, 15-24.

Mayeda T.K., Clayton R.N. and Yanai K. (1987) Oxygen isotopic compositions of several Antarctic meteorites. Mem. Natl. Inst. Polar Res. Spec. Iss. **46**, 144-150.

McSween H.Y. (1977a) Carbonaceous chondrites of the Ornans type: A metamorphic sequence. Geochim. Cosmochim. Acta **41**, 479-491.

McSween H.Y. (1977b) Petrologic and chemical studies of the (C3) carbonaceous chondritic meteorites. Ph.D. dissertation, Harvard University, 232 pp.

McSween H.Y. (1977c) Petrographic variations among carbonaceous chondrites of the Vigarano type. Geochim. Cosmochim. Acta **41**, 1777-1790.

McSween H.Y. (1979) Are carbonaceous chondrites primitive or processed? A review. Rev. Geophys. Space Phys. **17**, 1059-1078.

Nishiizumi K., Elmore D. and Kubik P.W. (1989) Update on terrestrial ages of Antarctic meteorites. Earth Planet. Sci. Lett. **93**, 299-313.

Okada A. (1975) Petrological studies of the Yamato meteorites. Part 1. Mineralogy of the Yamato meteorites. Mem. Natl. Inst. Polar Res. Spec. Iss. **5**, 14-66.

Ramdohr P. (1973) The Opaque Minerals in Stony Meteorites. Elsevier, Amsterdam.

Rubin A.E. (1984) Coarse-grained chondrule rims in type 3 chondrites. Geochim. Cosmochim. Acta **48**, 1779-1789.

Rubin A.E. (1989) Size-frequency distributions of chondrules in CO3 chondrites. Meteoritics **24**, 179-189.

Rubin A.E. (1990a) Shock effects in carbonaceous chondrites. Proc. Lunar Planet. Sci. Conf. 21st, submitted.

Rubin A.E. (1990b) Kamacite and olivine in ordinary chondrites: Intergroup and intragroup relationships. Geochim. Cosmochim. Acta **54**, 1217-1232.

Rubin A.E. and Grossman J.N. (1987) Size-frequency-distributions of EH3 chondrules. Meteoritics **22**, 237-251.

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

Rubin A.E. and Wasson J.T. (1986) Chondrules in the Murray CM2 meteorite and compositional differences between CM-CO and ordinary chondrite chondrules. Geochim. Cosmochim. Acta **50**, 307-315.

Rubin A.E., Wang D., Kallemeyn G.W. and Wasson J.T. (1988) The Ningqiang meteorite: Classification and petrology of an anomalous CV chondrite. Meteoritics **23**, 13-23.

Schaal R.B., Hörz F., Thompson T.D. and Bauer J.F. (1979) Shock metamorphism of granulated lunar basalt. Proc. Lunar Planet.

Sci. Conf. **10th**, 2547-2571.

Score R. and Lindstrom M.M. (1990) Guide to the U.S. Collection of Antarctic meteorites. Ant. Met. Newslett. **13**, No. 1, 1-135.

Scott E.R.D. and Taylor G.J. (1985) Petrology of types 4-6 carbonaceous chondrites. Proc. Lunar Planet. Sci. Conf. 15th, C699-C709.

Sears D.W., Kallemeyn G.W. and Wasson J.T. (1982) The compositional classification of chondrites: II The enstatite chondrite groups. Geochim. Cosmochim. Acta **46**, 597-608.

Takeda H. (1990) Comparisons of Antarctic and non-Antarctic achondrites and a possible origin of the difference. In Workshop on Differences Between Antarctic and Non-Antarctic Meteorites (C. Koeberl and W.A. Cassidy, eds.) pp. 86-90. LPI Tech. Rpt. 90-01. Lunar and Planetary Institute, Houston.

Takeda H., Wooden J.L., Mori H., Delaney J.S., Prinz M. and Nyquist L.E. (1983) Comparison of Yamato and Victoria Land polymict eucrites: A view from mineralogical and isotopic studies. Proc. Lunar Planet. Sci. Conf. **14th**, B245-B256.

Tandon S.N. and Wasson J.T. (1968) Gallium, germanium, indium and iridium variations in a suite of L-group chondrites. Geochim. Cosmochim. Acta **32**, 1087-1109.

Van Schmus W.R. (1969) Mineralogy, petrology, and classification of types 3 and 4 carbonaceous chondrites. In Meteorite Research (P.M. Millman, ed.) pp. 480-491, D. Reidel, Hingham, Mass.

Van Schmus W.R. and Wood J.A. (1967) A chemical-petrologic classification for the chondritic meteorites. Geochim. Cosmochim. Acta 31, 747-765.

Wasson J.T. (1974) Meteorites -- Classification and Properties. Springer-Verlag, Berlin, 316 pp.

Wasson J.T. (1985) Meteorites: Their Record of Early Solar System History. W.H. Freeman, New York, 267 pp.

Wasson J.T. (1990) Ungrouped iron meteorites in Antarctica: Origin of anomalously high abundance. Science, in press.

Wasson J.T. and Kallemeyn G.W. (1988) Compositions of chondrites. Phil. Trans. R. Soc. Lond. A **325**, 535-544.

Wieler R., Baur H., Graf Th. and Signer P. (1985) He, Ne, and Ar in Antarctic meteorites: Solar noble gas in an enstatite chondrite (abstract). Lunar Planet Sci. **16**, 902-903.

Wilkening L.L. (1978) Carbonaceous chondritic material in the solar system. Naturwissenschaften **65**, 73-79.

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	3970-3[x]	4	30.7	6-25	19-75	pt,py,ch,prh,mg
ALH82135	12.1		4	29.4	23-28	20-66	pt,py,mg
ALH84038	12.3	8	4	28.8	26-28	20-85	pt,mg
EET83311	15.3	9	4	31	n.i.	49	pt,mg
EET87507[§]	36.2	18[+]	4	29	24	49	pt,mg
EET87860	32.8	13	5	28	n.i.	21-72	pt,py,prh,mk,mg
LEW87009	50.5	15	6	32.1	Ca-px	45-78	pt,py,mg
LEW87214	0.4	2	4	31.3	Ca-px	54-63	pt,mk,mg
CK-an chondrites (probably CK)							
LEW86258	24.1	9	4	29	Ca-px	84-89	pt,mg
PCA82500	90.9	34	4/5	30.7	1-25	13-95	pt,ch,prh,mg
YAM6903	150	12-2	4	30	27	29-97	tr,pt,mg,mt
CK-an chondrites (not CK but closely related)							
Ningqiang[*]	4610	419-422[γ]	3	3	1	n.i.	tr,pt,mk,mg,mt
Not studied by us, but probably CK							
ALH85002	438		4	31.1	23-29	38-73	pt,py,mg
YAM82104	9.8		5	29.9	rare	19-61	tr,mg,mt

[α] Phase compositional data for ALH84038, LEW87009 and LEW87214 from this study; other values from the literature: Okada (1975); Scott and Taylor (1985); Graham and Yanai (1986); Geiger and Bischoff (1989); *Ant. Met. Newslett.* Opaque phases for meteorites for which thin section numbers are listed are from this study; other meteorites have literature data listed.

[*] 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).

[+] also studied: EET87514,8; 87519,6; 87526,18; 87529,13.

[γ] from UCLA.

n.i. = not identified.

opaques: tr=troilite; pt=pentlandite; py=pyrite, ch=chalcopyrite, prh=pyrrhotite, mg=magnetite, mk=mackinawite, mt=metallic Fe-Ni.

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^{+}
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	**3.38**	**145**	**15.8**	**316**	**17.2**	**10.3**	**96**	**3.52**	**1.45**	**228**	**591**	**12.1**	**101**	**5.6**	**1.36**	**7.8**	**0.4**	**1090**	**74**	**418**	**251**	**100**	**278**	**42**	**840**	**784**	**>93**$^{+}$
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*	**3.08**	**152**	**16.7**	**324**	**17.7**	**10.9**	**100**	**3.77**	**1.43**	**242**	**681**	**13.8**	**91**	**5.4**	**1.32**	**7.3**	**0.7**	**1180**	**74**	**435**	**271**	**110**	**308**	**46**	**880**	**838**	**136**
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	**3.25**	**148**	**16.1**	**300**	**17.3**	**11.0**	**96**	**3.61**	**1.46**	**233**	**649**	**12.7**	**101**	**5.6**	**1.46**	**7.1**	**0.4**	**1120**	**72**	**435**	**267**	**104**	**293**	**43**	**818**	**765**	**136**
CK-related chondrites (classification uncertain)																											
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^{+}
mean	**2.42**	**151**	**15.8**	**249**	**16.5**	**10.8**	**96**	**3.69**	**1.24**	**238**	**320**	**3.7**	**47**	**4.2**	**1.75**	**4.2**	**0.3**	**1030**	**50**	**307**	**186**	**77**	**231**	**35**	**830**	**858**	**100**
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**
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**
YAM6903*	**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**

* 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

Figure Captions

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 "shock-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 shock 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 is much less shock darkened than ALH84038 (Fig. 1c).

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-δ^{18}O side.

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.

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 1.23× 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.

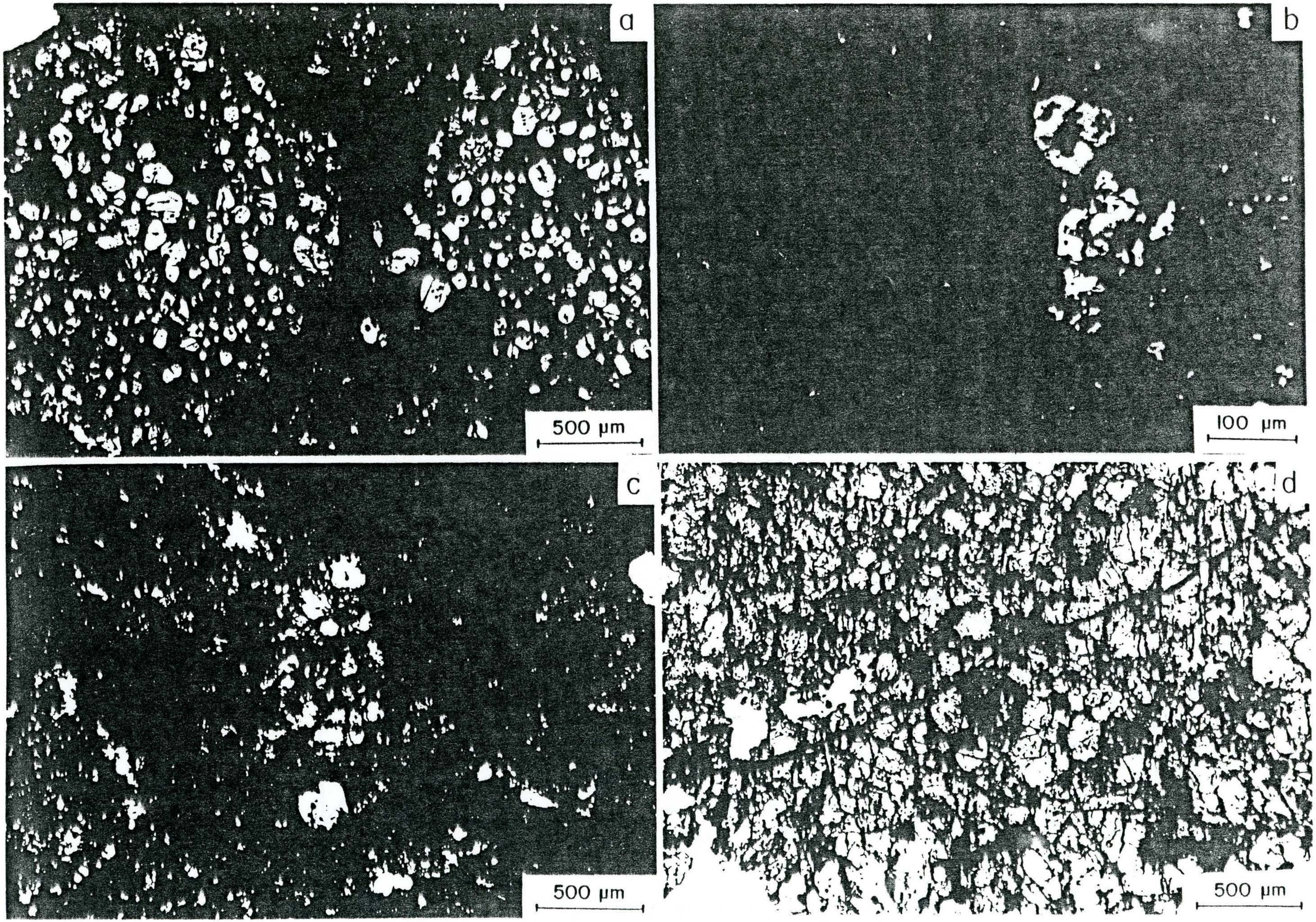


Fig. 1

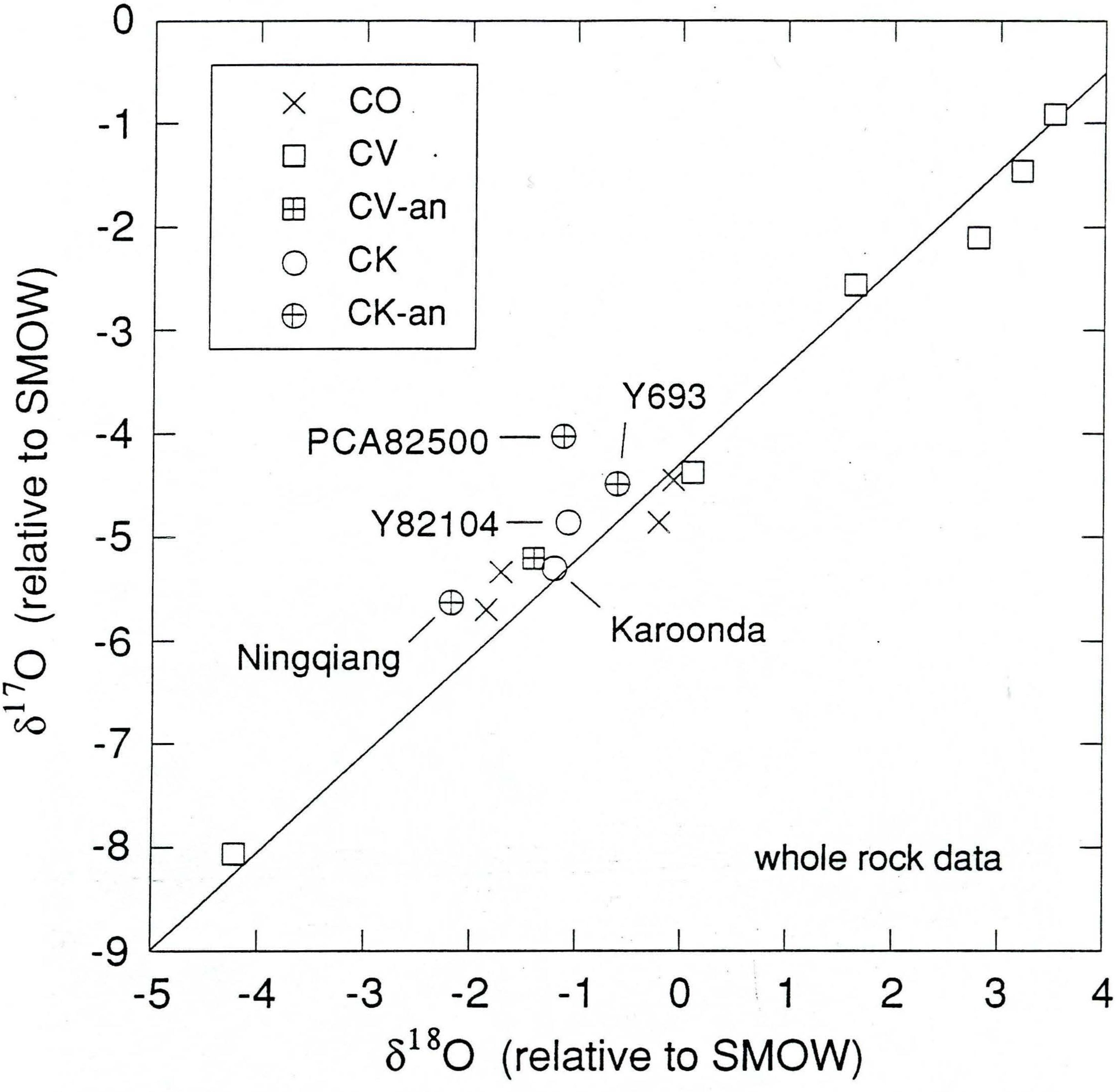
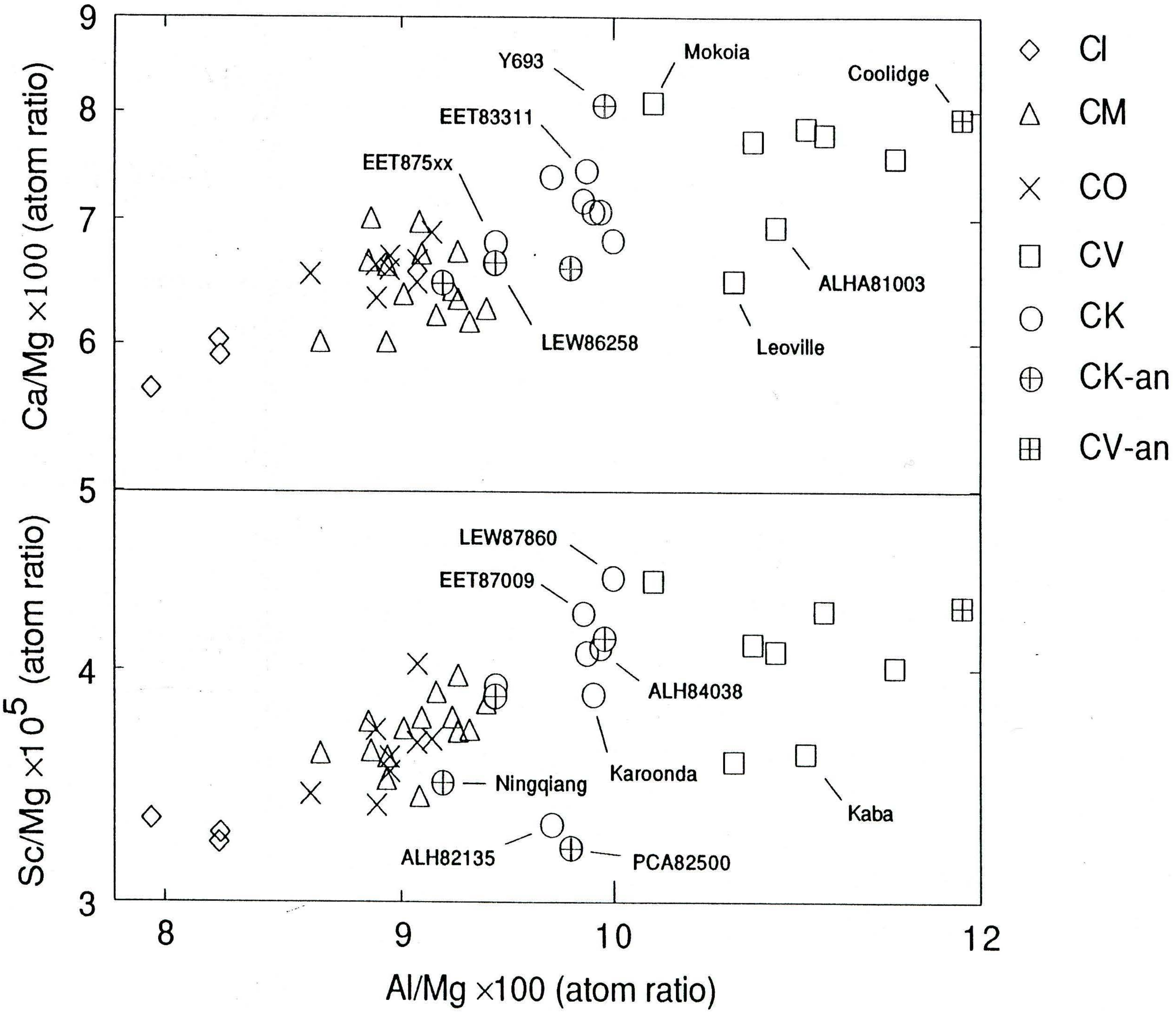

0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-5
-4
-3
-2
-1
0
1
2
3
4
× CO
□ CV
⊞ CV-an
○ CK
⊕ CK-an
PCA82500
Y693
Y82104
Karoonda
Ningqiang
whole rock data
δ^{17}O (relative to SMOW)
δ^{18}O (relative to SMOW)

Fig. 2



9
8
7
6
5
4
3
Ca/Mg ×100 (atom ratio)
Sc/Mg ×10^5 (atom ratio)
8
9
10
12
Al/Mg ×100 (atom ratio)
Y693
Mokoia
Coolidge
EET83311
EET875xx
ALHA81003
LEW86258
Leoville
LEW87860
EET87009
ALH84038
Karoonda
Kaba
Ningqiang
ALH82135
PCA82500
◇ CI
△ CM
× CO
□ CV
○ CK
⊕ CK-an
⊞ CV-an

Fig. 3

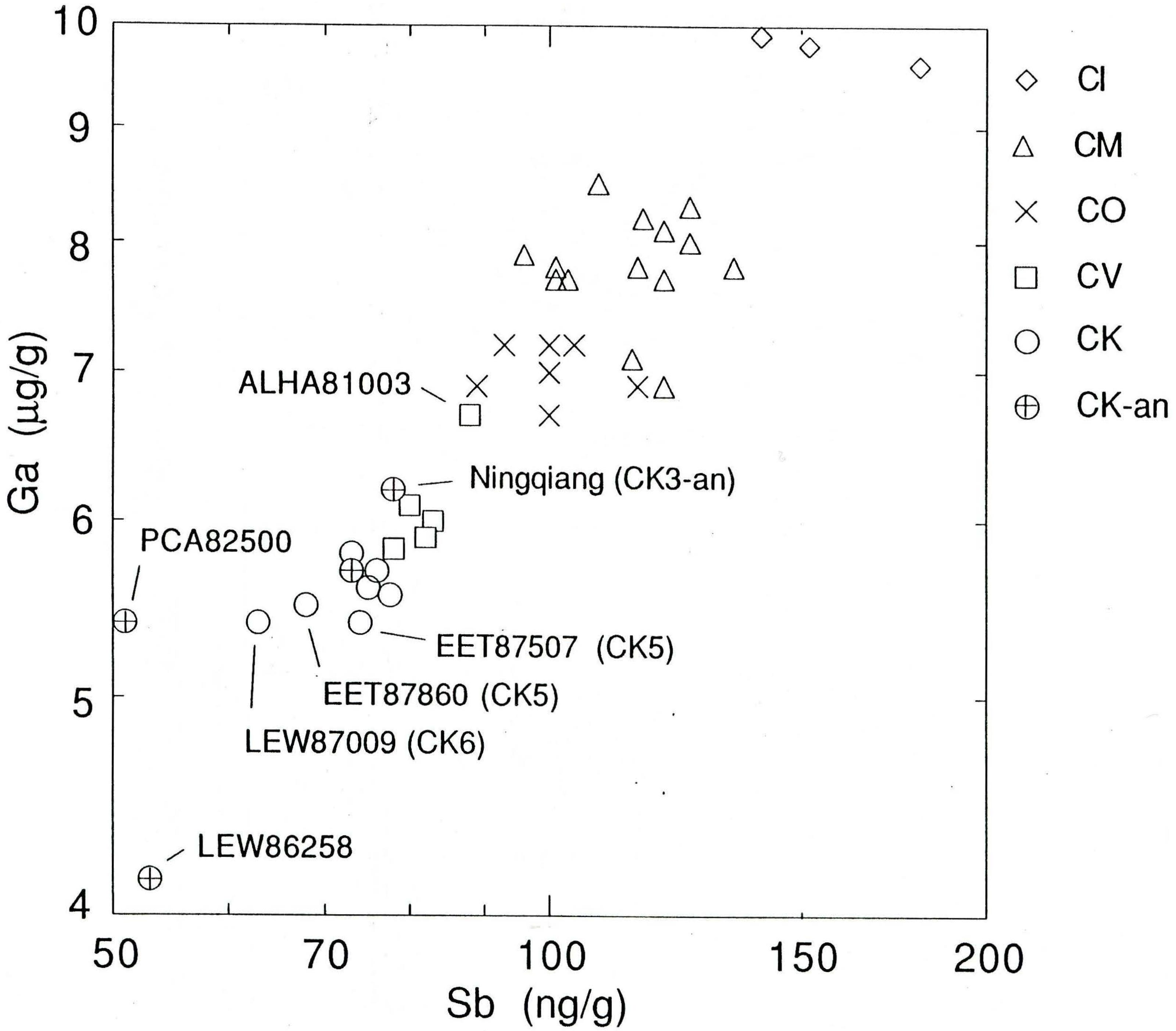
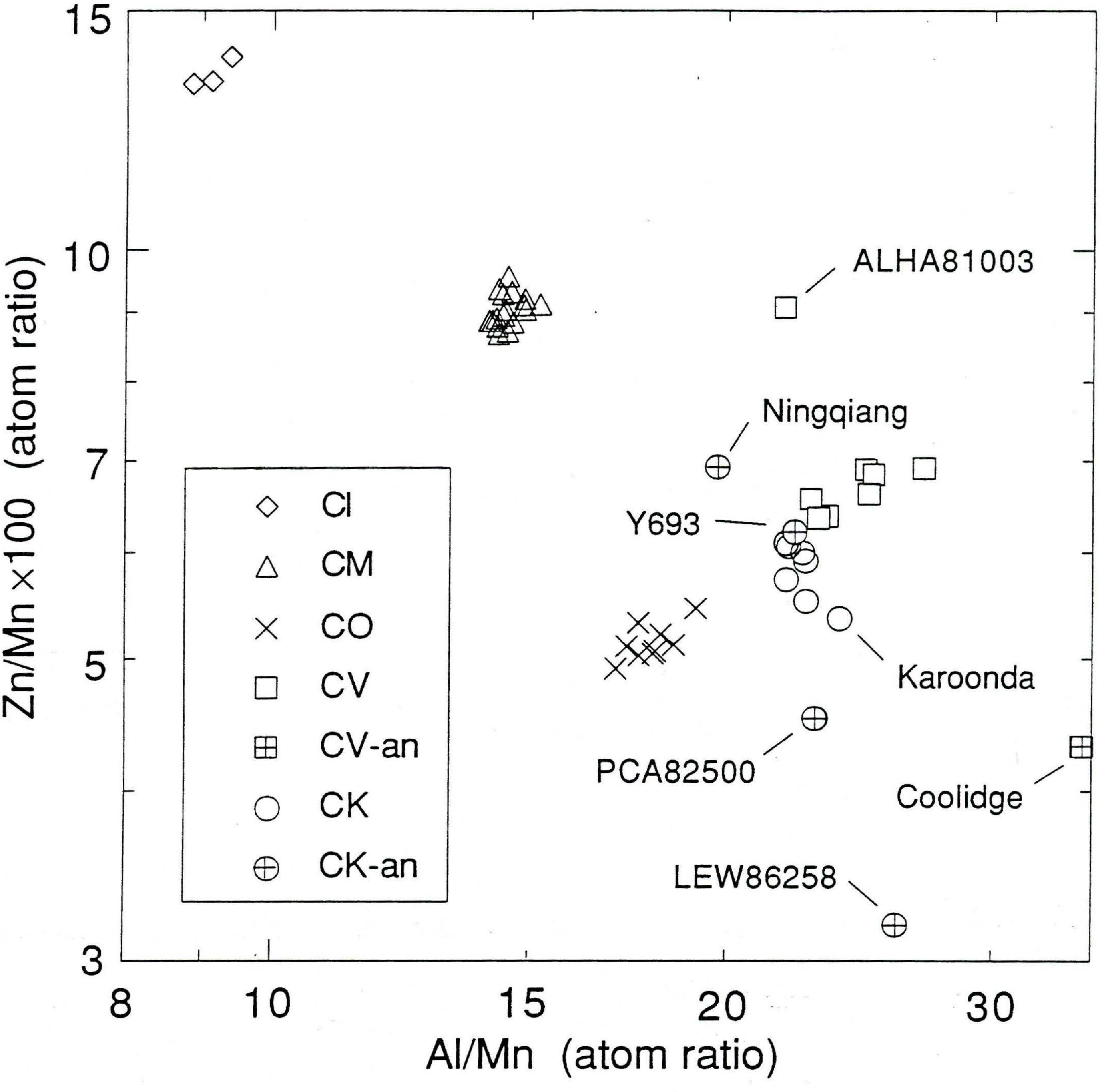
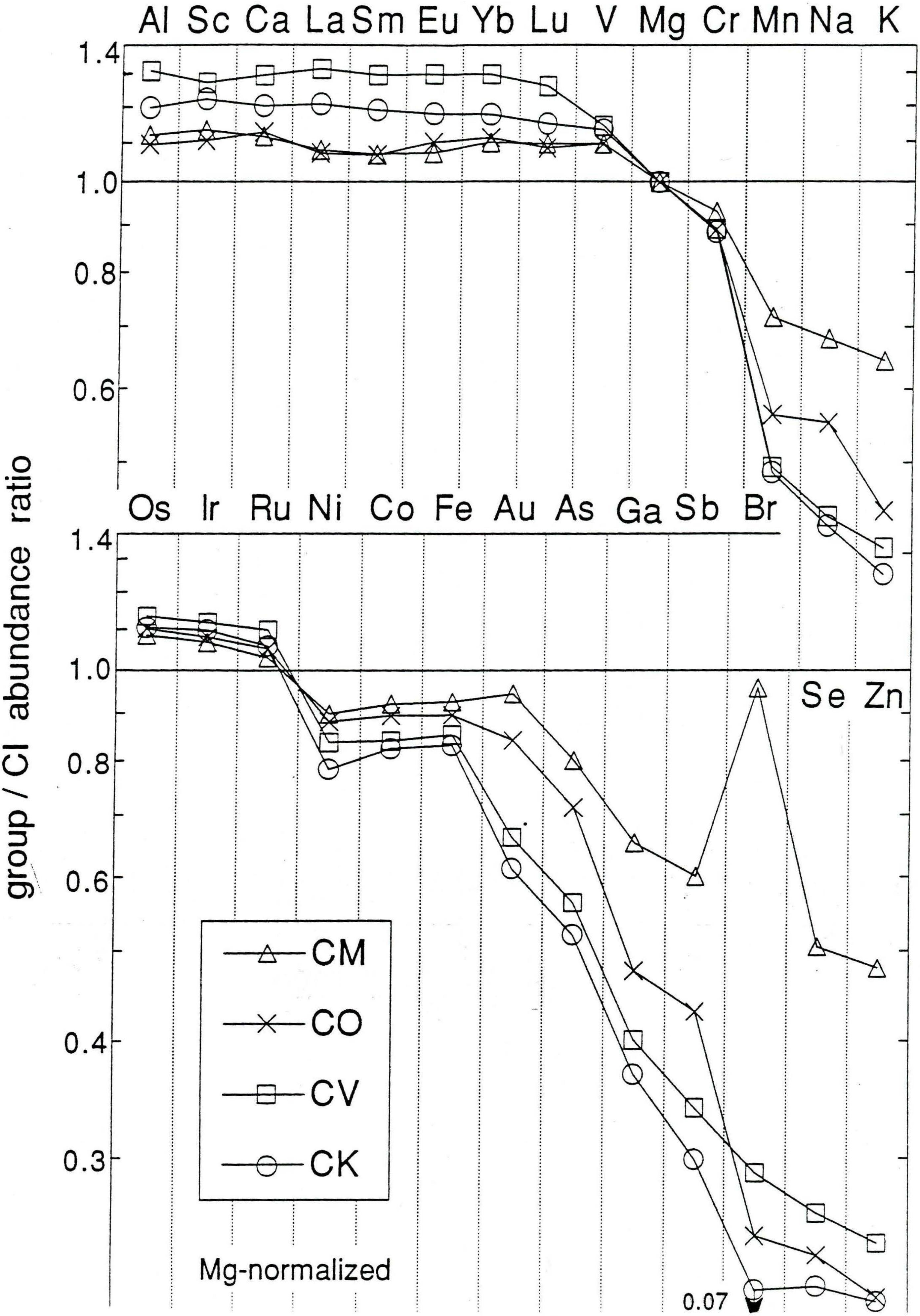

10
9
8
7
6
5
4
Ga (µg/g)
50
70
100
150
200
Sb (ng/g)
◇ CI
△ CM
× CO
□ CV
○ CK
⊕ CK-an
ALHA81003
Ningqiang (CK3-an)
PCA82500
EET87507 (CK5)
EET87860 (CK5)
LEW87009 (CK6)
LEW86258

Fig. 4



15
10
7
5
3
8
10
15
20
30
Zn/Mn ×100 (atom ratio)
Al/Mn (atom ratio)
◇ CI
△ CM
× CO
□ CV
⊞ CV-an
○ CK
⊕ CK-an
ALHA81003
Ningqiang
Y693
Karoonda
PCA82500
Coolidge
LEW86258

Fig. 5



Al Sc Ca La Sm Eu Yb Lu V Mg Cr Mn Na K
1.4
1.0
0.8
0.6
Os Ir Ru Ni Co Fe Au As Ga Sb Br
Se Zn
1.4
1.0
0.8
0.6
0.4
0.3
group / CI abundance ratio
CM
CO
CV
CK
Mg-normalized
0.07