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Compositions and taxonomy of 15 unusual carbonaceous chondrites

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Abstract–We used instrumental neutron activation analysis and petrography to determine bulk and phase compositions and textural characteristics of 15 carbonaceous chondrites of uncertain classification: Acfer 094 (type 3.0, ungrouped CM-related); Belgica-7904 (mildly metamorphosed, anomalous, CM-like chondrite, possibly a member of a new grouplet that includes Wisconsin Range (WIS) 91600, Dhofar 225, and Yamato-86720); Dar al Gani (DaG) 055 and its paired specimen DaG 056 (anomalous, reduced CV3-like); DaG 978 (type 3 ungrouped); Dominion Range 03238 (anomalous, magnetite-rich CO3.1); Elephant Moraine 90043 (anomalous, magnetite-bearing CO3); Graves Nunataks 98025 (type 2 or type 3 ungrouped); Grosvenor Mountains (GRO) 95566 (anomalous CM2 with a low degree of aqueous alteration); Hammadah al Hamra (HaH) 073 (type 4 ungrouped, possibly related to the Coolidge-Loongana [C-L] 001 grouplet); Lewis Cliff (LEW) 85311 (anomalous CM2 with a low degree of aqueous alteration); Northwest Africa 1152 (anomalous CV3); Pecora Escarpment (PCA) 91008 (anomalous, metamorphosed CM); Queen Alexandra Range 99038 (type 2 ungrouped); Sahara 00182 (type 3 ungrouped, possibly related to HaH 073 and/or to C-L 001); and WIS 91600 (mildly metamorphosed, anomalous, CM-like chondrite, possibly a member of a new grouplet that includes Belgica-7904, Dhofar 225, and Y-86720). Many of these meteorites show fractionated abundance patterns, especially among the volatile elements. Impact volatilization and dehydration as well as elemental transport caused by terrestrial weathering are probably responsible for most of these compositional anomalies. The metamorphosed CM chondrites comprise two distinct clusters on the basis of their $\Delta^{17}O$ values: approximately −4‰ for PCA 91008, GRO 95566, DaG 978, and LEW 85311, and approximately 0‰ for Belgica-7904 and WIS 91600. These six meteorites must have been derived from different asteroidal regions.

INTRODUCTION

The essential characteristics of carbonaceous chondrites include having CI- and Mg-normalized refractory-lithophile-element abundances ≥1, whole-rock O-isotopic compositions below the terrestrial fractionation (TF) line on the three-isotope diagrams (except for CI and a few CM-related chondrites which lie approximately on the TF line), abundant fine-grained silicate-rich matrix material, and relatively abundant refractory inclusions (again, except for CI chondrites, which have no intact chondrules or inclusions). Carbonaceous chondrites comprise six normal groups (CI, CM, CO, CV, CK, CR), two unusual groups whose properties have been affected by impact processes (CH and CB), and two grouplets (Coolidge-Loongana [C-L] 001 and Kakangari-Lewis Cliff [LEW] 87232–Lea County 002; Kallemeyn and Rubin 1995; Weisberg et al. 1996). There are also many apparently ungrouped individuals (e.g., Adelaide; Belgica-7904; Dhofar 225; Essebi; Elephant Moraine (EET) 96026; LEW 85332; LEW 88002; MacAlpine Hills [MAC] 87300; MAC 88107; Roberts Massif [RBT] 04133; Y-86029; Y-86720) (Davy et al. 1978; Skirius et al. 1986; Rubin and

Table 1. Sources of whole-rock samples and thin sections.

Meteorite	Sample source	Thin section number
Acfer 094	NHMW	M9324 NHMW
Belgica-7904	NIPR	Section 96-1 NIPR
DaG 055	NHMB	PL05024 IP-M
DaG 056	NHMB	PL05029 IP-M
DaG 978	UCLA 2228	UCLA 1869
DOM 03238	Sample 7 JSC	Section 6 JSC
EET 90043	Sample 13 JSC	Sections 7, 15 JSC
GRA 98025	Sample 11 JSC	Section 6 JSC
GRO 95566	Sample 6 JSC	Section 13 JSC
HaH 073	NHMB	PL05027 IP-M
LEW 85311	JSC	Section 15 JSC
NWA 1152	NHML	–
PCA 91008	Sample 19 JSC	Sections 14, 21 JSC
QUE 99038	Sample 6 JSC	Section 10 JSC
Sahara 00182	UCLA IN-1877	UCLA 1853
WIS 91600	Sample 8 JSC	Sections 18, 19, 21 JSC
Y-86720	–	Section 71-1 NIPR

NHMW = Natural History Museum, Vienna; NIPR = National Institute of Polar Research, Tokyo; NHMB = Natural History Museum, Berlin; IP-M = Institute for Planetology, Münster; UCLA = University of California, Los Angeles; JSC = NASA Johnson Space Center, Houston; NHML = Natural History Museum, London.

Kallemeyn 1990; Kallemeyn 1992; Metzler et al. 1992; Zolensky et al. 1993; Weisberg et al. 1996; Clayton and Mayeda 1999, 2003; Ivanova et al. 2002; Davidson et al. 2009). Several of these may be the only representatives of their parent asteroids, but because impact processes can produce very different fractionation patterns from a uniform target (e.g., Rubin et al. 2009), it seems more probable that some chondrites with unusual patterns originate on the same parent asteroid as a major group or grouplet. In such cases, all petrographic and compositional characteristics may be needed to yield an adequate classification. Analysis of unusual, ungrouped carbonaceous chondrites thus offers the potential for recognizing new groups and grouplets and expanding the ranges in bulk composition and petrographic characteristics of established chondrite groups.

ANALYTICAL PROCEDURES

Samples (Table 1) were analyzed by instrumental neutron activation analysis (INAA) following the general procedures of Huber et al. (2006a). Short- and long-lived nuclides were measured during four successive counting periods. Most samples were analyzed in duplicate. Samples were irradiated at the TRIGA Mark I reactor of the University of California, Irvine with a neutron flux of 1.8×10^{12} neutrons cm^{-2} s^{-1}. Sample masses were in the range of 240 ± 90 mg and, when possible, were cut into 3 mm thick rectangular blocks. Standards included the Allende meteorite (Kallemeyn et al. 1989), the USGS reference materials granite GSP-1, SCo-1, and BHVO-1 (Govindaraju, 1994), and the Filomena fragment of the North Chile IIAB iron meteorite (Wasson et al. 2007).

Our typical uncertainties can be judged from histograms plotted in Fig. 1 of Kallemeyn et al. (1989). For most elements, 90% confidence limits on the means of duplicate analyses are generally approximately 3–5% relative; elements determined with less precision are Sb, Yb, Lu, and Os. In samples that have been impact altered, sampling errors can be much larger than 5%.

Thin sections of 14 of the 16 meteorites were examined microscopically in transmitted and reflected light (Table 1); sections of Meteorite Hills (MET) 01017 and Northwest Africa (NWA) 1152 were unavailable. The sizes of chondrules and ameboid olivine inclusions (AOIs) were measured microscopically in transmitted light using a calibrated reticule.

COMPOSITIONAL TOOLS FOR CLASSIFYING CARBONACEOUS CHONDRITES

The most useful parameters for chondrite classification are bulk elemental compositional data, O-isotope data (Fig. 1), and mineralogical/petrological features.

Bulk Compositional Data

Bulk elemental compositional data offer several features that are useful for the classification of chondritic meteorites in general and for distinguishing among different carbonaceous-chondrite groups in particular. Examples of the taxonomic use of carbonaceous-chondrite bulk compositions can be found in Kallemeyn et al. (1991, 1994).

Perhaps, the best overview of the compositional data is in abundance diagrams normalized to a common element and to a chondrite group. In earlier studies, we used Mg as the normalizing element, but here we used Cr because Mg data were not available for all samples. Abundances of Cr are closely proportional to those of Si (which we cannot determine) and to Mg (for which our data set was incomplete); sampling variations are slightly larger for Cr than for Mg. When we consider several groups of chondrites (as in the present manuscript), we use CI chondrites (Wasson and Kallemeyn 1988) for the primary normalization. In the abundance diagrams, we separate the elements into two sets (Figs. 2–5); the upper diagrams show lithophiles; the lower diagrams show siderophiles and chalcophiles. Within each diagram, volatility (based on 50% condensation temperatures) increases to the right. For

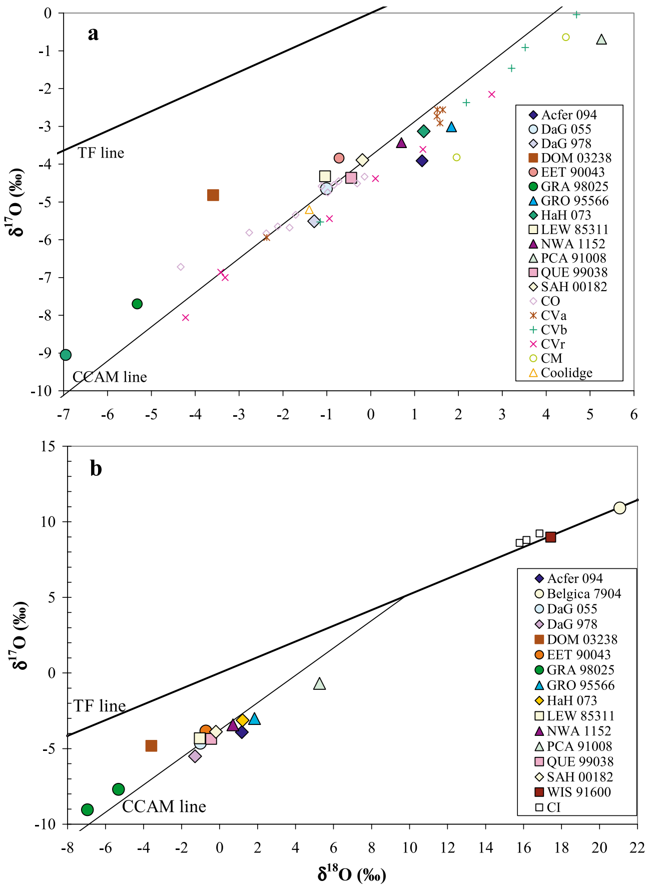

Fig. 1. Oxygen-isotopic compositions of unusual carbonaceous chondrites relative to established groups. Two reference lines are shown: CCAM (carbonaceous-chondrite anhydrous minerals) and TF (terrestrial mass fractionation). Data are in per mil and relative to standard mean ocean water. a) Thirteen of the studied chondrites plot near the CCAM line in the range $-7 \leq \delta^{18}O \leq +6‰$. Small symbols show locations of CO, CV, and two CM chondrites (data mainly from Clayton and Mayeda 1999). b) Expanded O-isotope diagram (to $\delta^{18}O = 22‰$) allowing the plotting of Belgica-7904 and WIS 91600.

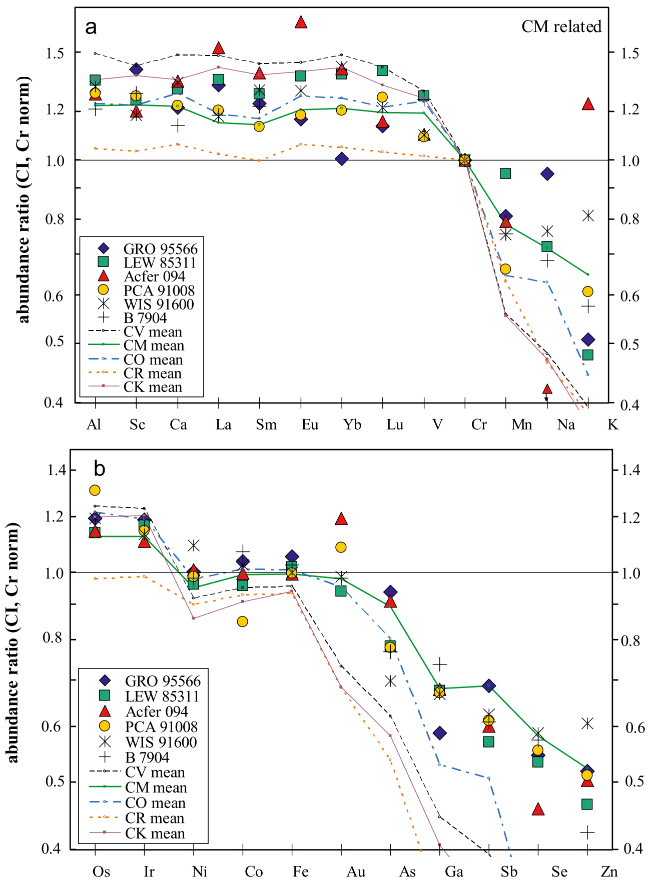

Fig. 2. Abundance diagram for CM-related chondrites showing a) lithophile elements and b) siderophile and chalcophile elements. Elements in each diagram are listed from left to right in order of increasing volatility. Data are normalized to Cr and to CI chondrites. Curves show mean compositions of the six carbonaceous-chondrite groups.

convenience, we divide the volatility sequence into refractory elements, common elements, and volatile elements. The common elements sensu stricto are Fe, Mg, and Si (which happen to have similar volatilities) but we also designate as common elements three that have similar 50% condensation temperatures: Cr, Ni, and Co. As noted above, we normalized to Cr on our abundance diagrams. To make it possible to compare the new abundance data with those of the established groups, we plot as continuous curves the mean abundances for CV, CK, CM, CO, and CR chondrites.

On the lithophile abundance plots, the groups fall into three sets based on refractory lithophiles: the two highest, at approximately 1.4 × CI, are the CV and CK sets. Slightly lower, at approximately 1.2 × CI, are the CM and CO sets. The CR chondrites plot on (or a few percent above) the CI (normalizing) line. Thus, it is generally possible to resolve a member of one set from members of other sets based on refractory lithophiles, but it is not possible to distinguish between the two chondrite-group members of each set. Generally, pairs of groups differ in their abundances of the three volatile lithophiles (Mn, Na, and K); CV and CK are exceptions.

On the siderophile and chalcophile diagram, the ratio of the refractory (Os, Ir) to common (Ni, Co, Fe) siderophile abundances resolves CV, CK, CM, and CO from CR and CI. The CV–CK set is marginally higher than the CM–CO set, but the sampling scatter in data for a new meteorite may hinder assignment based on this criterion. Volatile siderophiles and chalcophiles can resolve all the groups, e.g., Au separates CM, CO, and CI from the other three groups (but some Au values scatter in the present data set). Each of the four most

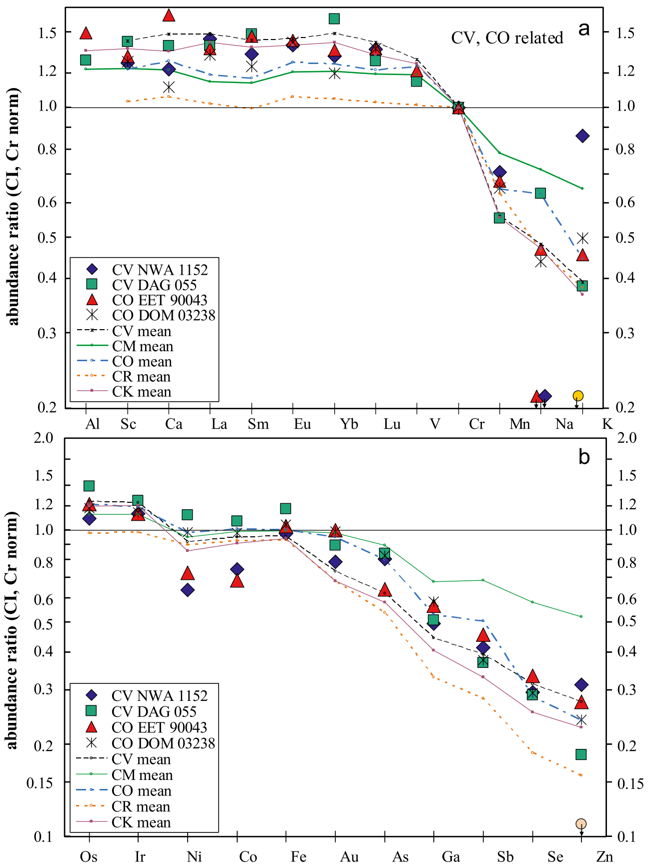

Fig. 3. Abundance diagram for CV- and CO-related chondrites showing a) lithophile elements and b) siderophile and chalcophile elements. Cr- and CI-normalized abundances are listed from left to right in order of increasing volatility. Curves show mean compositions of carbonaceous-chondrite groups.

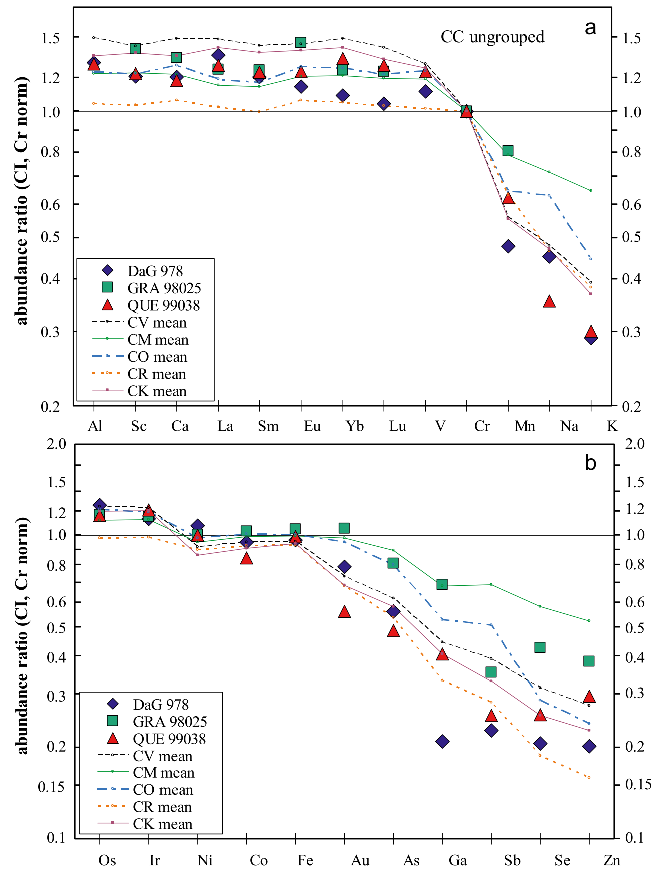

Fig. 4. Abundance diagram for ungrouped carbonaceous chondrites showing a) lithophile elements and b) siderophile and chalcophile elements. Cr- and CI-normalized abundances are listed from left to right in order of increasing volatility. Curves show mean compositions of carbonaceous-chondrite groups.

volatile siderophile and chalcophile elements resolves all groups by factors >1.09 with the exception of Ga (CV~1.09 CK) and Se (CV~1.09 CO).

If ungrouped carbonaceous chondrites were pristine nebular materials, their bulk chemical compositions should be readily resolvable based on the volatile siderophiles and chalcophiles. Smooth patterns, as observed in the group abundance curves, are due to elements of similar chemical affinities having similar abundances; these patterns are interpreted to be the normal result of nebular condensation and agglomeration processes. In contrast, many of the analyzed meteorites show erratic patterns; some or most of these patterns could be a consequence of impact processes, although other sources of variation (e.g., metamorphism; aqueous alteration) are possible. In addition, all of these meteorites are finds; leaching of certain elements during terrestrial weathering can significantly alter chondrite bulk compositions, both by additions and subtractions. With the exception of HaH 073 we have restricted our analyses to meteorites having weathering grades of W0–2 (or A–B), but we still see element depletions and augmentations (e.g., K) that we attribute to weathering. Especially egregious are weathering effects in many chondrites from hot deserts (e.g., Kallemeyn et al. 1994; Al-Kathiri et al. 2005; Bland et al. 2006; Huber et al. 2006b).

We show our carbonaceous-chondrite abundance data on four diagrams (Figs. 2–5) with two to six meteorites plotted on each. We have tried to group like with like to facilitate important comparisons.

Oxygen Isotope Data

Bulk O-isotopic data have also proven valuable for classifying chondrites. The general idea is that chondrites with similar O-isotopic compositions have the potential of belonging to the same group whereas

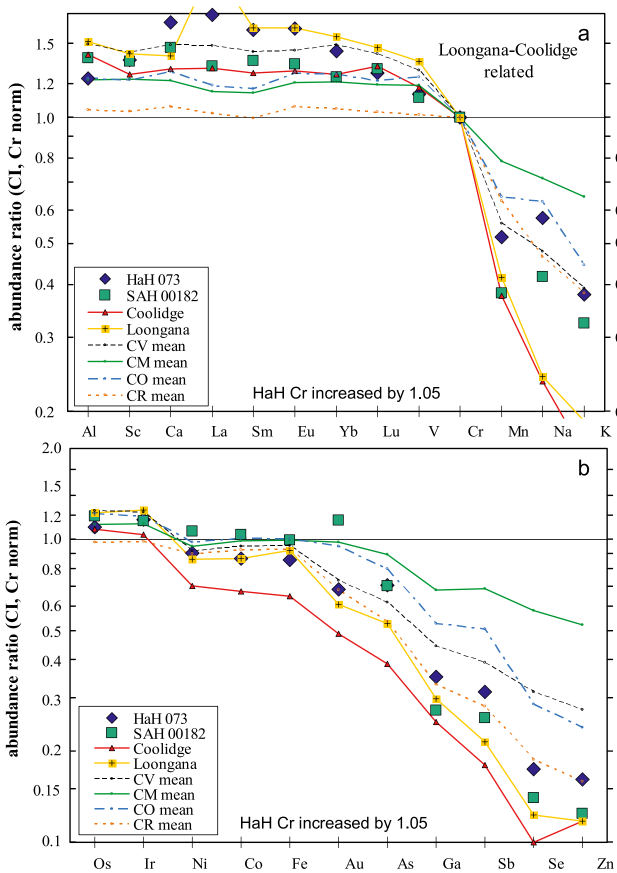

Fig. 5. Abundance diagram for the Coolidge-Loongana grouplet and possibly related meteorites showing a) lithophile elements and siderophile and b) chalcophile elements. Cr- and CI-normalized abundances are listed from left to right in order of increasing volatility. Curves show mean compositions of carbonaceous-chondrite groups as well as Coolidge and Loongana 001.

chondrites with very different compositions (e.g., δ^{18}O values separated by $>5‰$), with rare exceptions, do not belong to the same group.

The carbonaceous chondrites that have experienced minimal degrees of aqueous alteration (i.e., those belonging to or related to groups other than CI, CM, or CR) tend to scatter along the carbonaceous-chondrite anhydrous minerals (CCAM) line on a δ^{17}O–δ^{18}O diagram (Figs. 1a and 1b) whereas the aqueously altered carbonaceous chondrites commonly plot in the triangular space between the anhydrous carbonaceous chondrites and a point along the TF line near δ^{18}O = 22‰.

All but three of the chondrites we studied plot near the CCAM line. To help assess how these meteorites relate to the members of established groups, we plot as background points compositions (taken largely from Clayton and Mayeda 1999) of members of the primitive (unequilibrated) anhydrous groups: CO chondrites and the three CV subgroups ($CV3_{oxA}$, $CV3_{oxB}$, and $CV3_R$; see below). The CO chondrites form a compact cluster ranging from δ^{18}O approximately −4‰ in Allan Hills (ALH) A77307 to 0‰ in Lancé and Acfer 243.

There are three recognized subgroups of CV chondrites: the reduced subgroup ($CV3_R$), the Allende-like oxidized subgroup ($CV3_{oxA}$), and the Bali-like oxidized subgroup ($CV3_{oxB}$) (McSween 1977b; Weisberg et al. 1997; Krot et al. 1998). It has been pointed out previously (e.g., in CR chondrites by Weisberg et al., 1995) that aqueous alteration causes the bulk O-isotopic composition of carbonaceous chondrites to become heavier, i.e., for δ^{17}O and δ^{18}O values to increase. It is therefore not surprising that, on Fig. 1a, the more oxidized $CV3_{oxA}$ and $CV3_{oxB}$ chondrites are, on average, heavier than the $CV3_R$ chondrites. Although each of the CV subgroups shows a wider range than observed in the CO chondrites, some of these variations may reflect unrepresentative sampling.

The large range of CV_{oxA} samples is due entirely to Tibooburra, a small (18.6 g) chondrite with some uncertainty in its classification; it seems probable that the analyzed sample was unrepresentative. The CV_{oxB} range overlaps CO chondrites only because one of the two plotted samples for Bali falls in this range; the other Bali sample is the highest CV_{oxB} point. The other CV_{oxB} points do not overlap CO. The $CV3_R$ range encompasses all CO members. Although it is not possible to use O-isotopic evidence to decide whether a carbonaceous chondrite is CO or CV_R, the taxonomic value of O-isotopic evidence on these meteorites would be greatly improved by the use of homogenized powders.

Because several of our samples are related to CM chondrites, we also plotted on Fig. 1a the only CM data of Clayton and Mayeda (1999) that fall within the boundaries of the diagram. One of these (Y-82054, the lower one) is, like several of the samples we studied, listed as a metamorphosed CM.

Petrographic Data

Carbonaceous-chondrite properties are reviewed in Table 2. All carbonaceous chondrites are matrix rich. All of them except CI contain intact chondrules, Ca-Al-rich inclusions (CAIs), and AOIs. The latter two types of objects distinguish carbonaceous chondrites from other chondrite classes in which CAIs are rare and AOIs are extremely rare to absent. The different groups of carbonaceous chondrites can themselves be distinguished on the basis of a number of petrographic characteristics including chondrule size, proportion of chondrules with convoluted or igneous rims,

Table 2. Summary of properties of major carbonaceous-chondrite groups.

Group	Refractory lithophiles/Mg relative to CI	Chondrule diameter (μm)	Chondrules (vol%)	Metallic Fe-Ni (vol%)	Mean matrix abundance (vol%)	$\Delta^{17}O$ (‰)	Petrologic types
CI	1.00	–	< 0.1	< 0.01	~95	~0.4	1
CR	1.03	~700	~55	5–8	~42	−3 to −1	2–3
CM	1.15	~270	5–16	0–1	~60	−4 to 0	2.0–2.6
CO	1.13	~150	~38	1–5	~34	−5 to −4	3.0–3.8
CV	1.35	~910	40–50	0–5	~35	−5 to −2	3
CK	1.21	~870	~40	< 0.1	~50	−5 to −3	3–6

O-isotope data after Clayton and Mayeda (1999).
Compositional and petrographic data modified from Scott and Krot (2005).
CK chondrule sizes and abundances and matrix abundance are based on CK3 NWA 1559.

proportions of chondrules of different textural types, proportion of chondrules with large metal grains, whole-rock modal abundance of metallic Fe-Ni, whole-rock modal abundance of matrix, the abundance of phyllosilicates and PCP (i.e., intergrown serpentine-tochilinite) in the matrix, and the matrix texture. These properties are summarized below for the major chondrite groups and for the C-L 001 grouplet. (Hereafter, we drop 001 from the grouplet label.)

CI chondrites contain rare isolated grains of olivine and pyroxene, but no intact chondrules or refractory inclusions. These rocks consist predominantly of phyllosilicate-rich matrix and minor to accessory amounts of other components including sulfide, magnetite, carbonate, goethite, and organic materials.

CM chondrites contain approximately 60 vol% phyllosilicate-rich matrix (McSween 1979; Wasson 2008). Chondrules and chondrule fragments constitute 5–16 vol% of CM chondrites (McSween 1979); the average apparent diameter (diameter measured in thin section with a relative uncertainty of approximately 15%) of intact chondrules is 270 μm (Rubin 2000); few (≤1%) of the chondrules are surrounded by coarse-grained igneous rims (Rubin 1984). CM chondrites vary significantly in their degree of preterrestrial aqueous alteration (Browning et al. 1996; Hanowski and Brearley 2000; Rubin et al. 2007). The least altered samples (CM2.6) contain unaltered olivine and pyroxene grains and approximately 1 vol% metallic Fe-Ni. The most altered samples (CM2.0) consist largely of phyllosilicate; they contain no olivine or pyroxene grains and essentially no metallic Fe-Ni.

CO chondrites contain 30–40 vol% matrix (McSween 1977a) with little phyllosilicate. Intact chondrules constitute approximately 38 vol% of CO chondrites; the average apparent chondrule diameter is 150 μm (Rubin 2000); very few chondrules are surrounded by igneous rims. An important question is whether CO chondrules are, on average, smaller than CM chondrules; it is possible that preferential destruction of small chondrules during the extensive parent-body aqueous alteration experienced by CM chondrules increased the average size of intact chondrules. CM matrix is texturally heterogeneous and many CM chondrites contain small, irregular polymineralic silicate assemblages that could be chondrule fragments or chondrules with eroded surfaces. (Rubin [1998] surmised that the correlation between chondrule size and petrologic subtype in CO3 chondrites was due to alteration having made the smallest chondrules unrecognizable in the more-altered samples.)

About 95% of the chondrules in CO chondrites are porphyritic (porphyritic olivine—PO, porphyritic pyroxene—PP, porphyritic olivine–pyroxene—POP), 2% are barred olivine (BO), 2% are radial pyroxene (RP), 1% are cryptocrystalline (C), and < 0.1% are granular olivine–pyroxene (GOP) (Rubin 1989). Metallic Fe-Ni constitutes 1–6 vol% of CO-chondrite whole rocks (McSween 1977a), implying an appreciable range in the degree of oxidation.

Among CV chondrites, the reduced subgroup ($CV3_R$) contains approximately 35 vol% matrix material (with little phyllosilicate), 40–50 vol% intact chondrules, 1–5 vol% metallic Fe-Ni, approximately 1–2 vol% sulfide, and approximately 0.2–0.5 vol% magnetite (e.g., McSween 1977b). Data from McSween (1977b) show that the Allende-like subgroup ($CV3_{oxA}$) contains approximately 40 vol% matrix material (with little phyllosilicate), 40–50 vol% intact chondrules, and approximately 0.2 vol% metallic Fe-Ni; the Bali-like subgroup ($CV3_{oxB}$) contains 40–50 vol% phyllosilicate-bearing matrix material, 35–45 vol% intact chondrules, and only trace amounts of metallic Fe-Ni. The CV_{oxA} subgroup contains a wide variety of secondary alteration products (e.g., andradite, hedenbergite, nepheline, sodalite, wollastonite; e.g., Krot et al. 1995, 1998) that are uncommon in CV_{oxB} meteorites. The average apparent chondrule diameter in all three CV-chondrite subgroups is approximately 750 μm (May et al. 1999). About 40–60% of CV chondrules are surrounded by coarse-grained igneous rims that have an average thickness of 400 μm (Rubin 1984). The chondrule textural types are approximately 93% porphyritic, 6% BO, 0.2% RP, and 0.1% C (Rubin 1989).

CK chondrites resemble CV chondrites in several respects. CK chondrules average 870 μm in diameter (about the same size as CV chondrules). About 32% of CK chondrules are surrounded by igneous rims, similar to that of CV chondrules (approximately 50%; Rubin 1984). Most CK chondrites are metamorphosed (petrologic type 4–6); the coarseness of the groundmass matrix grains increases with metamorphic grade, ranging from ≤0.1–10 μm in rare CK3 samples to 50–300 μm in CK6 (Kallemeyn et al. 1991). Intact chondrules constitute approximately 15 vol% of CK chondrites (Rubin 2000). The principal opaque phases are magnetite and pentlandite; metallic Fe-Ni is very rare.

CR chondrites contain 30–50 vol% phyllosilicate-bearing matrix (Weisberg et al. 1993); the CR-an chondrite Al Rais is even richer in matrix material. Intact chondrules constitute approximately 55 vol% of normal CR chondrites; the average apparent chondrule diameter is 700 μm (Rubin 2000). Many chondrules are compound; enveloping compound chondrules are common, and many chondrules are surrounded by convoluted igneous rims having moderate grain sizes. Metallic Fe-Ni constitutes 5–8 vol% of the whole rocks (Weisberg et al. 1993); large metallic Fe-Ni grains occur in the matrix and near the surfaces of many of the porphyritic chondrules. The vast majority of chondrules are porphyritic; BO chondrules are present, but RP and C chondrules are very rare.

Coolidge and Loongana 001 are mildly metamorphosed rocks (petrologic type 3.8–4) that contain 20–30 vol% matrix and have a mean chondrule size of 600–700 μm. Porphyritic chondrules are abundant, BO chondrules are present, and RP and C chondrules together constitute approximately 4% of all chondrules (Kallemeyn and Rubin 1995). Metallic Fe-Ni constitutes approximately 4 vol% of Coolidge (McSween 1977b). Both rocks are shock-stage S2 (Kallemeyn and Rubin 1995).

Some anomalous carbonaceous chondrites appear to have undergone extensive aqueous alteration similar to that experienced by CM or CI chondrites, but have experienced heating/annealing that dehydrated some of the matrix phyllosilicates (e.g., Tomeoka et al. 1989a, 1989b; Tomeoka 1990; Akai 1990; Ikeda 1992; Matsuoka et al. 1996; Wang and Lipschutz 1998; Lipschutz et al. 1999; Tonui et al. 2002, 2003). Three of the meteorites in the present study (Pecora Escarpment [PCA] 91008, Wisconsin Range [WIS] 91600, and Belgica-7904) show evidence of metamorphic heating of hydrated precursors; a detailed examination might show that others (Grosvenor Mountains [GRO] 95566, LEW 85311) have had a similar history.

RESULTS AND DISCUSSION

Effects of Terrestrial Weathering on Bulk Chemical Composition

All of the samples in this study are finds and have been subjected to terrestrial weathering. The most obvious effects involve the transformation of metallic Fe-Ni into goethite, magnetite, and other oxides and hydroxides (e.g., Buddhue 1957) and sulfides into sulfate (e.g., Bland et al. 2006). These transformations may be accompanied by bulk loss of siderophiles (e.g., Ni and Co) and chalcophiles (e.g., S, Se, Zn, and in some cases, Sb) (Huber et al. 2006b). Whereas formation of carbonates in the terrestrial environment (e.g., Velbel et al. 1991) can increase the bulk C content of OC (Gibson and Bogard 1978), the destruction of organic material in carbonaceous chondrites during weathering can deplete these rocks in C (Ash and Pillinger 1992). Many weathered chondrites have also acquired appreciable amounts of terrestrial water (Jarosewich 1990).

Meteorites from hot and cold deserts react differently to terrestrial alteration. Hot-desert meteorites can become enriched in sulfates, Ca carbonate, and silica (Bland et al. 2006). Low concentrations of Na in Saharan carbonaceous chondrites may have been caused by the leaching of sulfates (Presper et al. 1993; Kallemeyn et al. 1994). High concentrations of K are common in hot-desert chondrites, an effect attributed to an-as-yet-unidentified weathering process (Kallemeyn et al. 1994; Huber et al. 2006b).

Cold-desert meteorites can become enriched in hydrated carbonates (Miyamoto 1991). Many Antarctic meteorites are also contaminated with I, Br, and Cl, presumably derived from sea spray (e.g., Ebihara et al. 1989; Kallemeyn et al. 1994; Langenauer and Krähenbühl 1993).

Complexities of Impact Processing

Projectiles differ in size, mass, mass distribution, bulk density, composition, relative velocity, and angle of impact. They may collide with their targets as single objects or, in rare cases, as part of a swarm. Upon impact, the projectiles themselves could vaporize, melt, or shatter. The same region of a target might be struck multiple times. Targets also differ in size, mass, mass distribution, bulk density, and composition; in addition, they may be covered (or partially covered) by regoliths of variable thickness. Given the myriad of collisional parameters, it is to be expected that impact effects would be highly variable. They include minor fracturing of mineral grains, moderate brecciation, veining, preferential melting of phases with low impedances to shock compression, formation of immiscible metal-sulfide and silicate liquids, and total melting of whole rocks. Redox effects may also occur. Targets may suffer different degrees of annealing, melting, and devolatilization; vaporized material could be lost from the parent body or transported a short distance and condensed. Although shock heating is typically followed by rapid cooling, impacted materials can be incorporated into ejecta blankets of low thermal diffusivity and cool slowly. Melted or partly melted target materials can incorporate pieces of the projectile or surrounding unmelted debris from the host.

Whereas chondrites with regular elemental abundance patterns probably preserve nebular processing, chondrites with irregular patterns (like many of those in the present study) could reflect devolatilization or preferential melting and loss of minor phases due to impact processing. The "metamorphosed" CM-like chondrites may have been annealed by impacts with concomitant loss of some water that affected the O-isotopic composition of the final sample.

Petrography and Bulk Composition

CM-Related Chondrites: Belgica-7904, WIS 91600, Acfer 094, GRO 95566, LEW 85311, and PCA 91008

CM chondrites are the most abundant group among carbonaceous-chondrite falls and finds on Earth (Grady 2000). They have experienced varying degrees of preterrestrial aqueous alteration (Browning et al. 1996; Hanowski and Brearley 2000; Rubin et al. 2007) and impact processing (Metzler et al. 1992; Zolensky et al. 1997; Trigo-Rodríguez et al. 2006); it is thus not surprising that there would be a large number of CM-related chondrites with anomalous properties. We start our discussion with two chondrites, Belgica-7904 and WIS 91600, that have extreme O-isotopic compositions.

Belgica-7904. Belgica-7904 is a shock-stage S1 rock (Table 3) that has experienced minor terrestrial weathering (W1). It was described by Skirius et al. (1986), Tomeoka (1990), and Scorzelli and Souza Azevedo (1994) as a mildly metamorphosed CM-like carbonaceous chondrite. It has abundant phyllosilicate-rich matrix (photo 384 of Yanai and Kojima 1987) that yields high analytical totals (approaching 100 wt%) consistent with partial dehydration. As reported by Tomeoka (1990), magnetite is rare and PCP is absent; our backscattered electron (BSE) imaging confirms the absence of PCP. Ca-rich veins, possibly composed of calcium carbonate, occur in the matrix; it is unclear if these veins formed in the terrestrial environment. Intact chondrules (mainly PO) and chondrule fragments occur; many have aqueously altered mesostases. In terms of the degree of alteration of mafic silicate phenocrysts in chondrules, the rock is equivalent to a CM chondrite of subtype 2.3–2.4 (cf. Table 5 of Rubin et al. 2007).

Olivine aggregates and spinel-rich CAI fragments are also present in Belgica-7904 (Tomeoka 1990). Pyroxene appears to be absent (Skirius et al. 1986; Tomeoka 1990). The chondrules range in apparent diameter from 100 to 1000 μm (Tomeoka 1990); the mean diameter is 350 μm ($n = 29$), approximating the mean size of CM chondrules (270 μm; Rubin 2000). Many of the chondrules and aggregates in Belgica-7904 are surrounded by 10–50 μm thick rims rich in Fe and S. Troilite is the most abundant sulfide phase; it occurs mainly in the matrix as < 10 μm size grains, although there are some rounded approximately 100 μm diameter troilite aggregates with minor metallic Fe-Ni. In some olivine aggregates, troilite is intergrown with taenite (Tomeoka 1990).

Almost all of the olivine grains are forsteritic, although olivine in one BO chondrule analyzed by Tomeoka (1990) was compositionally zoned (Fa29–45). Skirius et al. (1986) reported three types of olivine grains with different cathodoluminescence (CL) properties: red, blue, and no CL. The red and blue cathodoluminescent olivines overlap in their mineral compositions (Fa1–2); the nonluminescent olivines are more ferroan and have a broader range (Fa17–59).

It is apparent from Fig. 1b that the average O-isotopic composition of three whole-rock samples of Belgica-7904 plots essentially on the TF line ($\Delta^{17}O = -0.05‰$; Clayton and Mayeda 1999) distinctly higher in $\delta^{17}O$ than CI chondrites (e.g., Fig. 1 of Mayeda and Clayton 1990). Several related carbonaceous chondrites have similar O-isotopic compositions, i.e., Y-86720, Y-82162, Y-86029, Y-86789, Dhofar 225, and WIS 91600 (Clayton and Mayeda 1999, 2003); the latter is discussed below. Dhofar 225 was described by Ivanova et al. (2002).

The four Yamato meteorites have different classifications according to the online Meteoritical Bulletin Database (Y-86720 = C2 ungrouped; Y-82162 = C1/2 ungrouped; Y-86029 = CI1; Y-86789 = C2 ungrouped) and somewhat different petrologic characteristics (e.g., Tomeoka et al. 1989a, 1989b). Nevertheless, it seems possible that some, and perhaps all, of these rocks are paired.

Table 3. Selected petrologic and bulk chemical properties of 15 unusual carbonaceous chondrites.

Meteorite	Total known weight	Recommended classification	Shock stage	Weathering grade	Olivine (mole% Fa)	Low-Ca pyroxene (mole% Fs)	Metallic Fe-Ni	Mean chondrule size (μm)	Matrix fraction (%)	Common siderophile abundances[a]	Refractory lithophile abundances[a]	$\Delta^{17}O$ (‰)	Ref.
Acfer 0094	82	Type 3.0, ungrouped CM-related	S1	W2	0–75	0–7		240 (100)	62.5	0.99	1.22	−4.52	1
Belgica-7904	1234	Metamorphosed, anomalous, CM-like	S1	W1	1–59	Absent		350 (29)		1.03	1.21	−0.02	2, 3
DaG 055, DaG 056	451, 703	Anomalous, reduced, CV3-like	S1	W1	0.4–32	0.6–6	4.2 vol% (1500)	790 (100)		1.12	1.38	−4.12	4
DaG 978	~250	Type 3 ungrouped	S1	W0/1	17.4–31.8	2.9–21.7		800 (50)		1.00	1.21		5
DOM 03238	54.2	Anomalous, magnetite-rich CO3.1	S1	A/B	1–55			220[b] (50)	28	1.00	1.28		6
EET 90043	12.5	Anomalous, magnetite-bearing CO3	S1	B	1–49	1–9	< 0.1 vol% (918)	180 (50)		0.82	1.48	−3.47	7
GRA 98025	14.36	Type 2 ungrouped	S1	W1	1–37	1–3	~2–3	210 (100)		1.03	1.36	−5.2	8
GRO 95566	50.7	Anomalous CM2 with a low degree of alteration	S1	A/Be	1–35	2–4	0.38 vol% (1563)	310 (50)		1.04	1.31	−3.97	9
HaH 073	569	Type 4; Coolidge-Loongana grouplet?	S1	W3	17.6–18.2	5.7–11.3		540 (100)	35	0.92	1.6	−3.76	4
LEW 85311	199.5	Anomalous CM2 with a low degree of alteration	S1	Be	0.4–36	0.9–1.1		190 (100)		0.98	1.28	−3.78	10
NWA 1152	98	Anomalous CV3	S2	W2	0.3–5.7	0.8		900	42.8	0.78	1.24	−3.79	11
PCA 91008	51.7	Anomalous, metamorphosed CM	S1	B	1–37	1–7		180 (91)		0.94	1.25	−3.43	10
QUE 99038	52.7	Type 2 ungrouped	S1	A/B	1–39		< 0.1 vol%	590 (120)		0.95	1.21		12
Sahara 00182	70	Type 3; Coolidge-Loongana grouplet?	S2	W2	2.7–8.3	6.7	4.4 vol% (1674)	790 (100)	27.6	1.11	1.51	−3.79	11
WIS 91600	184.1	Metamorphosed, anomalous CM-like	S1	W1	1–39	1–15	< 0.1 vol%	400 (66)		1.04	1.26	−0.08	10

n-values are given in parentheses.

[a]Abundances normalized to Cr and to CI chondrites. Total known weight in grams.

[b]B-G. Choi (personal communication).

Petrographic and mineralogical data from the present study and the following references: 1 = Wlotzka (1991); 2 = Tomeoka (1990); 3 = Skirius et al. (1986); 4 = Grossman (1996); 5 = Russell et al. (2003); 6 = Grossman and Rubin (2006); 7 = Huber et al. (2006a, 2006b); 8 = Grossman (2000); 9 = Grossman (1998); 10 = Grossman (1994); 11 = Smith et al. (2004); 12 = Grossman and Zipfel (2001). Sources for the O-isotopic data are cited in the text.

Table 4. Mean concentrations of 26 elements in 15 carbonaceous chondrites (DaG 055 and DaG 056 counted as one meteorite).

	Na (mg g^{-1})	Mg (mg g^{-1})	Al (mg g^{-1})	K (μg g^{-1})	Ca (mg g^{-1})	Sc (μg g^{-1})	V (μg g^{-1})	Cr (mg g^{-1})	Mn (mg g^{-1})	Fe (mg g^{-1})	Co (μg g^{-1})	Ni (mg g^{-1})	Zn (μg g^{-1})	Ga (μg g^{-1})	As (μg g^{-1})	Se (μg g^{-1})	Ru (μg g^{-1})	Sb (ng g^{-1})	La (ng g^{-1})	Sm (ng g^{-1})	Eu (ng g^{-1})	Yb (ng g^{-1})	Lu (ng g^{-1})	Os (ng g^{-1})	Ir (ng g^{-1})	Au (ng g^{-1})
Acfer 094	1.24	100	13.9	874	15.6	8.8	76	3.34	1.90	228	639	13.6	198	8.4	2.11	11.3	920	116	455	261	119	283	35	709	642	217
Belgica-7904	5.60	136	13.4	530	15.6	11.1	89	3.31	1.84	226	634	12.8	140	7.5	1.78	14.8	840	100	384	230	92	250	35	738	703	162
DaG 055	3.41	130	12.2	237	14.1	9.1	69	2.92	1.16	235	599	13.2	64	5.5	1.07	6.2		62	362	243	117	281	34	751	634	142
DaG 056	2.44	136	13.7	159	14.2	9.2	85	3.09	1.21	237	686	13.6	95	4.9	1.60	6.9		62	352	243	108	278	41	807	716	145
DAG 978	3.02	133	15.3	221	15.1	9.6	84	3.61	1.24	240	657	15.7	86	2.8	1.40	5.5		47	437	245	87	236	34	839	712	155
DOM 03238	2.68			347	12.8	9.2		3.30	1.54	237	619	13.1	94	7.1	1.89	7.2	930	72	390	231	99	238	41	720	656	178
EET 90043	2.72	127	15.2	302	17.9	9.0	79	3.14	1.52	223	414	9.2	102	6.6	1.40	7.8		83	384	259	95	257	39	708	617	171
GRA 98025	0.66			108	13.6	9.0		2.93	1.69	211	579	11.9	133	7.5	1.65	9.2	1030	60	328	206	90	220	33	635	585	168
GRO 95566	4.78			292	11.5	8.4		2.72	1.58	197	541	11.0	166	5.9	1.77	11.0	1010	108	321	189	67	164	28	601	562	237
HaH 073	3.69	128	13.9	278	20.2	10.4	82	3.30	1.29	204	575	12.6	66	4.5	1.70	4.5		63	540	314	119	299	40	703	699	129
LEW 85311	3.68	111	12.1	279	12.5	7.6	73	2.76	1.88	193	506	10.7	151	6.9	1.50	10.9		91	333	199	80	229	35	581	559	141
NWA 1152	0.76			646	15.2	9.9		3.56	1.81	238	510	9.2	131	6.5	1.99	7.8	1300	85	457	267	105	281	44	718	701	153
PCA 91008	1.80	122	13.1	404	13.4	8.7	71	3.14	1.49	215	511	12.5	189	7.8	1.69	12.9		111	337	200	78	227	36	761	625	185
QUE 99038	2.14	140	13.7	207	13.4	8.8	84	3.26	1.46	222	528	13.2	113	4.9	1.31	6.2		48	373	227	86	261	38	702	686	100
SAH 00182	2.68	146	15.6	237	17.6	10.3	80	3.24	0.95	237	691	14.9	51	3.5	1.69	3.6		52	409	266	98	259	41	765	695	218
WIS 91600	4.23	116	12.8	513	13.9	7.8	68	2.99	1.62	205	587	13.2	214	7.4	1.45	13.0	860	108	314	219	82	255	33	661	589	160

Belgica-7904 is compositionally closely related to CM chondrites (Fig. 2). Refractory lithophiles are in the CM–CO range (Table 4); volatile lithophiles are CM-like for Mn and Na, but K is low by approximately 10%. The refractory, common, and volatile siderophile abundances are all CM-like, although Zn is low by approximately 15%. Belgica-7904 may form a new grouplet with WIS 91600. Some of the Yamato chondrites with similar O-isotopic compositions may also be members of this grouplet, but the textural and mineralogical characteristics of these rocks need to be determined before grouplet assignment can be definitive.

WIS 91600. WIS 91600 is of shock-stage S1 and weathering grade W1 or A/Be (Table 3). It was described by Tonui et al. (2002) as a mildly metamorphosed CM-like carbonaceous chondrite containing a tochilinite-free, phyllosilicate-rich matrix and mafic-silicate-phenocryst-bearing chondrules with altered mesostases. Rare glass patches contain up to 3.0 wt% P_2O_5 and 7.7 wt% Cr_2O_3 (Birjukov and Ulyanov 1996). Chondrules (PO, POP, and BO types) have a mean size of 400 μm (n = 66). As reported by Rubin et al. (2007), a few PO chondrules and chondrule fragments contain approximately 0.2 vol% metal blebs 1–38 μm in diameter; some POP chondrules contain sulfide and no metal. Some chondrules have broad (approximately 70 μm thick) rims consisting of fine-grained sulfide and silicate matrix material. The AOIs in WIS 91600 are typically 300–450 μm in size.

The degree of aqueous alteration of chondrule phenocrysts in chondrules in WIS 91600 is approximately equivalent to that of a CM2.4 chondrite (cf. Table 5 of Rubin et al. 2007).

Sulfides (pentlandite, minor troilite, and accessory pyrrhotite) are the most abundant opaque phases. Magnetite is abundant, far more abundant than in typical CM2 chondrites; magnetite occurs in the WIS 91600 matrix as framboids, plaquettes, and euhedral and irregular grains, in some cases intergrown with sulfide. Small grains of Ca carbonate are also present in the matrix.

The meteorite is unequilibrated: olivines have a large compositional range (Fa1–39; Grossman 1994).

As shown in Fig. 1b, the O-isotopic composition of WIS 91600 ($\Delta^{17}O$ = −0.08‰; Clayton and Mayeda 2003) lies essentially on the TF line, slightly higher in $\delta^{18}O$ than the compact CI-chondrite field, consistent with a large degree of asteroidal aqueous alteration, but unusual for a chondrite with intact chondrules and appreciable metal (i.e., as in a CM-like chondrite). This composition is very similar to that of Belgica-7904.

WIS 91600 is compositionally closely related to CM chondrites (e.g., Moriarty et al. 2009). Refractory

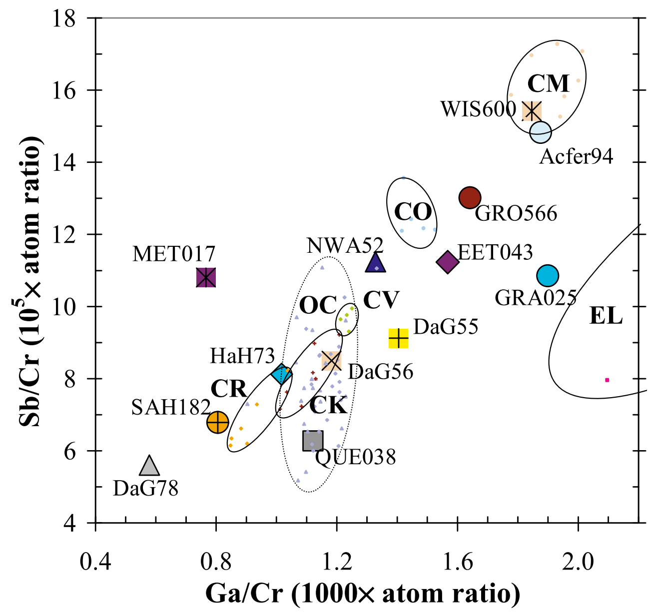

Fig. 6. Established chondrite groups form distinct compositional clusters on a plot of Sb/Cr versus Ga/Cr. Some of the unusual carbonaceous chondrites studied here plot near established groups, e.g., Acfer 094, WIS 91600, and PCA 91008 plot near the CM chondrites; ungrouped meteorites (e.g., DaG 978, QUE 99038) plot far from the fields of the established groups. Although GRA 98025 (an ungrouped, type 2 carbonaceous chondrite) plots in the EL field, it is not closely related to enstatite chondrites. See text for additional details.

lithophiles are nearer CM–CO than CV–CK (Fig. 2) but show some scatter; volatile lithophiles are CM-like for Mn and Na, but K is high by a factor of 1.3. The refractory, common, and volatile siderophile abundances are all CM-like (Fig. 2). On the Sb-Ga diagram (Fig. 6), WIS 91600 plots within the CM field, but on the Zn-Sm diagram (Fig. 7), it plots high by a factor of 1.2 in both elements. There is little doubt that WIS 91600 forms a grouplet with Belgica-7904 and Y-86720. Although this grouplet is closely related to the "common" CM chondrites, we suggest that it be designated the Belgica-7904 grouplet until there is stronger evidence that these meteorites and normal CM chondrites originated on the same asteroid.

Acfer 094. Acfer 094 is an unshocked (shock-stage S1) carbonaceous chondrite of weathering grade W2 (Table 3). It preserves few hydrated phases (e.g., Greshake 1997) and contains no coarse clumps of PCP. A peculiar phase dubbed "cosmic symplectite," an intergrowth of magnetite and pentlandite, also seems to be a product of aqueous alteration (Sakamoto et al. 2007; Seto et al. 2008). However, its extreme O-isotopic composition ($\delta^{17,18}O$ = approximately +180‰) indicates an origin outside the Acfer 094 parent body.

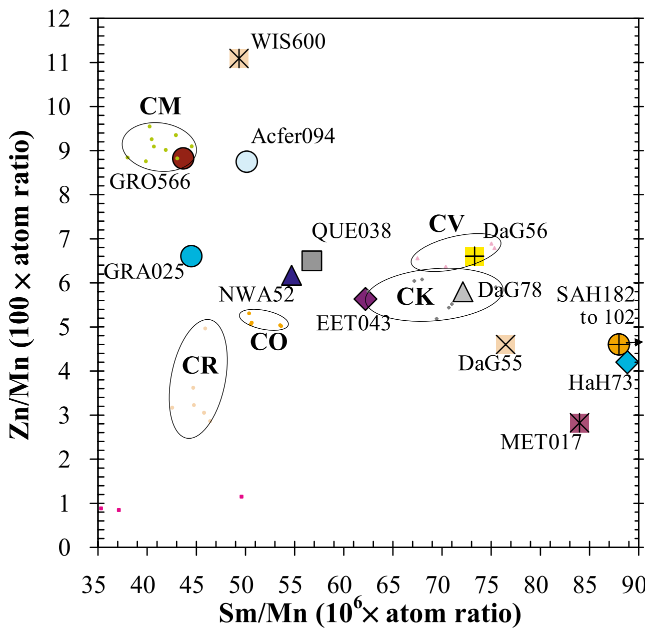

Fig. 7. Established chondrite groups form distinct compositional clusters on a plot of Zn/Mn versus Sm/Mn. These three elements differ significantly in 50%-nebular condensation temperatures (Sm > Mn > Zn). The anomalous CM-related chondrites plot in the vicinity of the CM field (some closer than others). The ungrouped GRA 98025 plots far from any group. Although EET 90043 and DaG 978 plot within the CK field, they are not closely related to CK chondrites. HaH 073 and Sahara 00182 have the highest Sm/Mn ratios; they may both belong to the Coolidge-Loongana grouplet. See text for additional details.

Chondrules in Acfer 094 are well defined and have a mean size of 240 μm (*n* = 100), close to the CM chondrule mean (270 μm; Rubin 2000). Chondrule types include PO, PP, POP, BO, and rare C and glassy chondrules; Bischoff and Geiger (1994) reported RP chondrules as well. Many of the porphyritic chondrules are nonspherical in shape. The texture of Acfer 094 shows much evidence of crushing—numerous small (5–25 μm size) angular chondrule fragments occur throughout the matrix. Also present in Acfer 094 are refractory inclusions (e.g., Bischoff and Geiger 1994; Greshake 1997) and 90–500 μm size AOIs. Acfer 094 has a high matrix fraction (62.5 vol%; Newton et al. 1995) (Table 3), similar to that of CM2 Murchison (63.6 vol%; table 1 of McSween 1979). The rock has the highest known content of presolar SiC grains and the second highest content of presolar diamonds after CI Orgueil (Newton et al. 1995).

The meteorite is highly unequilibrated. Chondrule olivines have a narrow peak at low Fa contents (Fa0–2) and a broad tail extending to Fa75 (Fig. 1 of Bischoff and Geiger 1994). Grossman and Brearley (2005) plotted Acfer 094 among the CO3.0 chondrites on their metamorphism scale based on the Cr_2O_3 contents of ferroan olivine grains; their data imply that ALHA77307 is the most primitive of these rocks, followed by Acfer 094 and then by Y-81020 and Colony (which plot side by side). This is a measure of Acfer 094's primitiveness, not an indication that the meteorite is a CO3 chondrite.

The O-isotopic composition of Acfer 094 (Bischoff et al. 1991) lies below the CCAM line on the standard three-isotope graph near the metamorphosed CM chondrite Y-82054 (Fig. 1a).

Spettel et al. (1992) reported high contents of the volatile metals Zn and Se, suggesting an affinity with CM chondrites. Our INAA data (Fig. 2), like those of Spettel et al., are based on a single analysis (Table 4); too little material was available to permit duplicate study. Acfer 094 plots within the CM fields on the Sb/Ga diagram (Fig. 6); it is about 10% away from the CM field on the Zn/Sm diagram (i.e., Sm is 10% high) (Fig. 7), but much more distant from other carbonaceous-chondrite groups. On the lithophile abundance diagram (Fig. 2), our data scatter, with Ca, La, Sm, Eu, and Yb having abundances in the CV–CK range, but Al, Sc, Lu, and V values falling in the CM–CO range. The three volatile lithophiles show considerable scatter; Mn is CM-like, but Na is very low and K is very high. It is possible that all of these differences (and the fractionated rare earth element [REE] pattern) reflect Saharan weathering processes, but impact-induced volatile loss may also be present. The textural evidence in Acfer 094 for impact processing is the paucity of intact chondrules (e.g., Fig. 1 of Newton et al. 1995) and the high abundance of shards derived from chondrule fragments (Wasson and Rubin 2010). Siderophile and chalcophile abundances are very similar to CM, with only Au (1.2× high) and Se (1.2× low) deviating appreciably from the CM pattern.

We classify Acfer 094 as a type 3.0, ungrouped, CM-related carbonaceous chondrite. Wasson and Rubin (2010) suggested that Acfer 094 suffered impact-induced fractionations including H_2O loss. It is plausible that, at temperatures of approximately 350 K, H_2O could be lost but that other volatiles (e.g., Se) would be largely retained and that the contents of diamonds and SiC would be only minimally unaffected (e.g., Huss and Lewis 1995; Huss et al. 2006).

GRO 95566. GRO 95566 is a shock-stage S1, weathering grade A/Be rock that contains PO, PP, POP, BO, and (rare) RP chondrules averaging 310 μm in apparent diameter (*n* = 50) (Table 3). Also present are 100–200 μm size AOIs and numerous small chondrule fragments and isolated mafic silicate grains (mostly olivine). Chondrule mesostases have been altered to phyllosilicate. The BSE image shows that many chondrules and inclusions are partially surrounded by fine-grained dark mantles as in CM chondrites (e.g., Metzler et al. 1992; Trigo-Rodríguez et al. 2006). Outside the mantles, the fine-grained matrix material contains several volume-percent light-colored PCP intergrown with sulfide. Although this regular arrangement occurs in a few cases, most chondrules and inclusions are fragmental and are surrounded by adjacent irregular patches of dark mantles and PCP-bearing matrix material.

The rock contains approximately 0.38 vol% (n = 1563 points) of 1–100 μm size metallic Fe-Ni grains; approximately half of the opaque grains occur inside porphyritic chondrules, the remainder in the matrix. Mason (1997) found that most olivine grains are close in composition to pure forsterite but that some grains are more ferroan; the few low-Ca pyroxene grains that he analyzed are very magnesian, close to enstatite in composition. Refractory lithophiles are intermediate between CV–CK and CM–CO (Fig. 2). Volatile lithophiles are roughly CM-like, but Na is 30% high and K is 30% low. Refractory siderophiles are also in the CM–CO–CV range. Volatile siderophiles and chalcophiles are CM-like except for Au (very high, probably because of contamination), and Sb (which is approximately 20% low). The meteorite falls within the CM field on the Zn-Sm diagram (Fig. 7) and between the CM and CO fields on the Sb-Ga diagram (Fig. 6).

As shown in Fig. 1a, the O-isotopic composition of GRO 95566 ($\Delta^{17}O = -3.97‰$; Clayton and Mayeda 1999) has a $\Delta^{17}O$ value that is unusually low for a CM chondrite; such low CM values are found only in the "metamorphosed" CM Y-82054 (the low CM point in Fig. 1a) and in PCA 91008 (which also appears to be metamorphosed; Tonui et al. 2001, 2002). It is possible that GRO 95566 also experienced mild metamorphism.

Because of its unusual O-isotopic composition, we classify this meteorite as an anomalous CM2 chondrite. If it is truly part of the CM sequence then it is one of the least aqueously altered CM chondrites known. Nevertheless, the presence of serpentine and PCP indicates that the rock is not an unaltered CM chondrite. It may have suffered late-stage thermal effects causing loss of some water.

LEW 85311. LEW 85311 is a shock-stage S1 carbonaceous chondrite of weathering grade Be (Table 3). It appears to be a CM2 chondrite that experienced moderately low degrees of aqueous alteration. Metallic Fe-Ni constitutes approximately 2 vol% of the rock and occurs both in chondrules and the matrix. LEW 85311 has small chondrules, averaging 190 μm in apparent diameter (n = 100), similar to those in mean CM chondrites (270 μm; Rubin 2000). Chondrule types include PO, PP, POP, and BO varieties; the AOIs range in maximum dimension from 150 to 800 μm. Almost all chondrules, chondrule fragments and isolated mafic silicate grains are surrounded by fine-grained light-colored (in BSE) mantles of matrix material; the mantles vary from 4 to 80 μm in thickness. The matrix material outside the mantles contains small amounts (≤1%) of PCP.

The meteorite is highly unequilibrated: olivine ranges from Fa0.4 to 36 (Grossman 1994); low-Ca pyroxene has a much narrower range (Fs0.9–1.1).

As shown in Fig. 1a, the whole-rock O-isotopic composition of LEW 85311 ($\Delta^{17}O = -3.78‰$; R. N. Clayton, personal communication, correction of values from tables 2 and 3 of Clayton and Mayeda 1999) lies along the CCAM line, and about 3‰ lower in $\delta^{18}O$ than its nearest CM neighbor, the metamorphosed CM Y-82054. It is about 2‰ lower in $\delta^{18}O$ than Acfer 094.

Refractory lithophiles are on the high side of the CM–CO range (Fig. 2) and closer to CK–CV. Although raising the Cr content several percent would improve the agreement, we did not do this because it would move the siderophile and chalcophile abundances farther from CM. Thus, uncertainties in the analytical data do not allow simultaneous agreement with mean CM chondrites for siderophiles, chalcophiles, and refractory lithophiles. We suspect, however, that a higher Cr value and the concomitantly anomalous siderophiles and chalcophiles would be closer to the actual composition of the whole rock.

Among the moderately volatile lithophiles, Mn is relatively high (i.e., approximately 1.2× CM), Na is exactly CM, and K is low by a factor of 1.25 (Fig. 2). The refractory and common siderophiles and chalcophiles are slightly below the CM trend, whereas the volatiles are, with the exception of Ga, 10–15% lower than CM. On the Sb-Ga diagram (Fig. 6), LEW 85311 is just below the CM field; on the Zn-Sm diagram (Fig. 7), the meteorite is approximately 1.3× lower than the CM field.

We classify LEW 85311 as an anomalous CM2 chondrite due to its high refractory lithophiles, low volatiles and its unusual O-isotopic composition. Because the abundance pattern is smooth, there is no compositional evidence of impact alteration; nevertheless, the low volatile content might reflect some impact reheating. There may have been some attendant water loss. We infer that LEW 85311 experienced a low degree of aqueous alteration, consistent with its abundant unaltered mafic silicate grains and low amount of PCP. We tentatively classify this meteorite as subtype 2.6–2.7. Because it is so primitive, it might have a high content of presolar grains.

PCA 91008. PCA 91008 is of shock-stage S1 and weathering grade B (Table 3). Its chondrules have a mean size of 180 µm (n = 91), similar to those in CM and CO chondrites. Chondrule types include PO, PP, POP, BO, and C; most chondrules have phyllosilicate-rich mesostases. AOIs range in size from 300 to 410 µm in maximum dimension.

Most grains of olivine and low-Ca pyroxene are very magnesian, but the overall olivine compositional distribution spans the range from Fa1 to Fa37 (Grossman 1994). The low-Ca pyroxene range is much narrower (Fs1–7; Grossman 1994). Tonui et al. (2001, 2002) concluded that this rock was thermally metamorphosed because of the absence of tochilinite and carbonates, the textural integration of chondrules and matrix, and the high analytical totals of matrix serpentines.

The bulk O-isotopic composition ($\Delta^{17}O = -3.43‰$; Clayton and Mayeda 2003) (Fig. 1a) lies to the right of the CCAM line, near the small open circle representing LEW 87016, a small (16.8 g) and relatively unstudied CM2 chondrite.

The refractory lithophile abundances in PCA 91008 are in the CM–CO range (Table 4). Among the volatile lithophile elements, Mn is in the CO–CV–CR range and is about 15% lower than CM, Na is 1.5× lower than CR and about 2× lower than CM, and K is CM-like and approximately 1.25× higher than CV (Fig. 2). The ratio of refractory to common siderophiles is in the CM–CO–CV range, although Os is slightly (1.1×) high and Co approximately 1.2× low (perhaps due to minor loss of kamacite during terrestrial weathering). Volatile siderophiles are CM-like, but Au is high (1.15×) and As is low (approximately 1.1×). On the Sb-Ga diagram (Fig. 6), PCA 91008 is in the CM field; on the Zn-Sm diagram (Fig. 7), it is higher than CM by approximately 1.2× for both elements, a reflection of the relatively low content of the Mn normalizing element.

The apparent loss of some mobile trace elements (Cs, Se, Ag, Te, Zn, In, and Bi) implies metamorphic temperatures of 500–600 °C (Wang and Lipschutz 1998; Tonui et al. 2002). We conclude that PCA 91008 is an anomalous (low-volatile, slightly metamorphosed) CM chondrite.

CV-Related Chondrites: DaG 055, DaG 056, and NWA 1152

The three subgroups that constitute the CV chondrites indicate that a wide variety of alteration processes occurred on the parent body of this group. Two meteorites in the current study (we assume that DaG 055 and 056 are paired) seem to be closely related to the CV chondrites.

DaG 055 and 056. DaG 055 and the probably paired specimen DaG 056 are shock-stage S1 rocks (Table 3) that have experienced minor terrestrial weathering (weathering grade W1). They contain relatively large PO, PP, POP, BO, and rare RP chondrules (averaging 790 µm; n = 100), many with igneous rims. Millimeter-size AOIs are present but CAIs are rare (Weber et al. 1996). Despite the low abundance of CAIs, DaG 055 and 056 resemble CV chondrites (which have a mean chondrule size of approximately 750 µm and wherein approximately 50% of the chondrules have igneous rims; Rubin 1984; May et al. 1999). The rock texturally resembles a reduced CV chondrite (e.g., Efremovka). Although several reduced CV chondrites exhibit a petrofabric manifested by flattened and aligned chondrules and inclusions (e.g., Cain et al. 1986), available thin sections of DaG 055 and 056 show no noticeable petrofabric. Opaques in DaG 055 (as in reduced CV chondrites) consist mainly of metallic Fe-Ni and sulfide.

Olivine (Fa0.4–32) and low-Ca pyroxene (Fs0.6–6) are unequilibrated (Weber et al. 1996). Our modal analyses indicate that the rock contains 4.2 vol% metallic Fe-Ni (n = 1500 points), much higher than observed in $CV3_{oxA}$ chondrites (approximately 0.2 vol% metallic Fe-Ni) or $CV3_{oxB}$ chondrites (only trace amounts of metallic Fe-Ni) (McSween 1977b).

The O-isotopic composition of DaG 055 (Clayton and Mayeda 1999) lies along the CCAM line (Fig. 1b) and within the CO field and the three CV fields.

The bulk compositions of DaG 055 and 056 are similar (Table 4), consistent with pairing. Small differences (up to a factor of 1.5) in K, V, and Zn probably reflect sampling variations. On the Sb/Ga and Zn/Sm diagrams (Figs. 6 and 7), data for these two meteorites (and thus their means) plot in the vicinity of the CK and CV fields. On the lithophile abundance diagram (Fig. 3), the refractory lithophiles plot higher than all chondrite groups, and the three volatiles plot lower than all groups. On the siderophile abundance diagram (Fig. 3) the common and refractory siderophiles are slightly high; the volatile siderophiles and chalcophiles are close to CV (although Sb is 25% low).

Although DaG 055 is closely related to the $CV3_R$ chondrites, its high refractory lithophile abundances and low Sb suggest that it is best considered an anomalous member of this subgroup.

NWA 1152. NWA 1152 was not available in thin section. It is listed in the *Meteoritical Bulletin 86*

(Russell et al. 2002) as being of shock-stage S2 and weathering grade W2/3 (Table 3). Smith et al. (2004) reported that most chondrules are PO and POP types and that chondrule mafic silicates are mainly magnesian (Fa1.2; Fs2.3). The matrix constitutes approximately 40 vol% of the rock and contains sulfide, magnetite, and metallic Fe-Ni. Both tetrataenite and kamacite occur, with tetrataenite being the more abundant phase; together they constitute approximately 0.7 vol% of the meteorite. Refractory inclusions and AOIs are rare (0.3 vol%); most of the CAIs are spinel–pyroxene aggregates. No phyllosilicates were reported.

As shown in Fig. 1a, the bulk O-isotopic composition ($\Delta^{17}O = -3.79$‰; Smith et al. 2004) lies nearer the centroids of the fields of $CV3_{oxA}$ and $CV3_{oxB}$ than to $CV3_{R}$, but consistent with membership in any of these subgroups.

NWA 1152 has high but scattered refractory lithophile abundances, with REE abundances both higher and lower than mean CV–CK chondrites (Fig. 3; Table 4). The volatile lithophile abundances do not form a coherent pattern: Mn is in the CM–CO–CR range, Na is extremely low (a factor of several below CR chondrites) and K is high (a factor of 2 above the CO–CV–CR range) (Fig. 3). These unusual alkali compositions may reflect weathering effects.

Refractory and common siderophile abundances (Fig. 3) are close to the CM–CO–CV range, although Ni and Co are 25–35% low (probably due to loss of some metal during significant terrestrial weathering). The volatile siderophiles and chalcophiles in NWA 1152 scatter around the CO and CV abundance levels. NWA 1152 falls between CV and CO on the Sb-Ga (Fig. 6) and Zn-Sm (Fig. 7) diagrams; on the latter diagram, it also falls near CK chondrites. On the basis of the O-isotopic and bulk chemical compositions, we tentatively classify NWA 1152 as an anomalous CV chondrite of undetermined subgroup.

CO-Related Chondrites: Dominion Range (DOM) 03238 and EET 90043

The CO3 chondrites comprise a metamorphic/alteration sequence (McSween 1977a; Scott and Jones 1990; Chizmadia et al. 2002). Although abundant magnetite is produced via alteration in CI chondrites (e.g., Jedwab 1967; Kerridge 1970), it is rare in normal CO chondrites. The two CO-related meteorites described here are magnetite rich.

DOM 03238. DOM 03238 is an unshocked (S1), highly unequilibrated (Fa1–55) rock containing 28 vol% matrix (Table 3); it was tentatively classified by Grossman and Rubin (2006) as a CO3.1 chondrite. Although listed in *Meteoritical Bulletin 91* (Connolly et al. 2007) as being of weathering grade B, the meteorite appears relatively unweathered in thin section and contains only 0.3 vol% limonite. Chondrules are predominantly porphyritic and average 220 μm in apparent diameter ($n = 50$) (B-G. Choi, personal communication). In contrast to typical CO3 chondrites (which contain $\ll 0.1$ vol% magnetite), DOM 03238 contains 7.6 vol% magnetite, occurring mainly as massive grains (Grossman and Rubin 2006). Other opaque phases include metallic Fe-Ni (1.2 vol%) and troilite (4.2 vol%). Phyllosilicates and carbonates are rare to absent in the meteorite. DOM 03238 most closely resembles the magnetite-bearing CO3 chondrite, EET 90043, described below.

Magnetite in DOM 03238 occurs in two types of petrographic assemblages that differ in their $\delta^{18}O$, but not their $\Delta^{17}O$ values (Choi et al. 2008): subhedral magnetite grains in chondrules and in the matrix ($\delta^{18}O = +4.0 \pm 0.8$‰; $\Delta^{17}O = -2.0 \pm 0.6$‰) and irregular magnetite grains associated with circular or ellipsoidal opaque assemblages ($\delta^{18}O = +0.2 \pm 0.8$‰; $\Delta^{17}O = -2.5 \pm 0.6$‰). The $\Delta^{17}O$ values of DOM 03238 magnetite are similar to those in magnetite from CV3 Allende and C3- an Ningqiang (−2‰ to −3‰) (Choi et al. 2008).

The CI- and Cr-normalized refractory lithophile abundances in DOM 03238 (approximately 1.2 × CI) are in the CM–CO range (Fig. 3) and are nearly identical to mean CO chondrites except for Ca, which is approximately 10% low. Manganese and K are in the CO range, but Na is low by approximately 30%. Refractory, common, and volatile siderophiles (Fig. 3) are the same as mean CO chondrites; the only exception is Sb, which is low by approximately 35%. We confirm the classification of Grossman and Rubin (2006); DOM 03238 is an anomalous (magnetite rich) CO3.1 chondrite.

EET 90043. EET 90043 is unshocked (S1) and moderately weathered (weathering grade B). It was initially classified as a C2 chondrite because it contains some phyllosilicates (M. E. Zolensky, personal communication). It is a highly unequilibrated rock (Fa1–49; Huber et al. 2006a) containing PO, POP, and PP chondrules averaging 170 μm in apparent diameter ($n = 71$) (Table 3). A few PO chondrules possess clear, colorless glassy mesostases. Terrestrial weathering has transformed most of the metallic Fe-Ni into limonite. Prior to terrestrial weathering, the opaque assemblage appears to have consisted of abundant metallic Fe-Ni, sulfide, and magnetite. The meteorite most closely resembles the magnetite-rich CO3.1 chondrite DOM 03238 described above. Despite the unequilibrated nature and the presence of chondrule glass in EET 90043, Tonui et al. (2002) suggested that the rock was heated sufficiently to lose some mobile trace elements and undergo partial dehydration.

The O-isotopic composition of EET 90043 lies just above the upper part of the CO-chondrite field (Fig. 1a).

The CI- and Cr-normalized refractory lithophile abundances in EET 90043 scatter, but are mostly in the CK-chondrite range (Table 4), appreciably higher than those in mean CO–CM chondrites. Common and volatile siderophiles and chalcophiles (Fig. 3) show little scatter and are CO-like with the exception of Ni and Co (which are 30% low in EET 90043, presumably due to extensive weathering). On the basis of the available data, we suggest that this rock be classified as an anomalous (magnetite-bearing) CO3 chondrite, similar to DOM 03238.

Ungrouped Carbonaceous Chondrites: DaG 978, Graves Nunataks (GRA) 98025, and Queen Alexandra Range (QUE) 99038

Some carbonaceous chondrites differ sufficiently in their mineralogical, textural, bulk chemical, and/or O-isotopic properties from established groups and recognized grouplets that they do not appear to be closely related to any of them. Our study includes three such meteorites.

DaG 978. DaG 978 is listed as having a mass of 44.4 g, but there appears to be an additional approximately 200 g: 34.5 g at UCLA and approximately 160 g in a private collection. This is a shock-stage S1 rock (Table 3) with little evidence of weathering (weathering grade W0/1). It contains numerous PO, POP, and BO chondrules, many with thick irregular rims; the mean chondrule size (590 μm; n = 120) is broadly similar to that of CR (700 μm) and much larger than those of CM (270 μm) or CO (150 μm) chondrites (Rubin 2000). Large AOIs (700–2000 μm in maximum dimension) also occur. DaG 978 contains approximately 3 vol% metal, much of it within chondrules; a few chondrules contain large metal blebs near their margins as in CR chondrites. However, olivine in DaG 978 is much more ferroan and more equilibrated (Fa17.4–31.8; Russell et al. 2003) than in CR chondrites, which are dominated by forsterite (e.g., Mason and Wiik 1962).

O-isotope data for DaG 978 determined by Insoo Ahn show that it plots at $\Delta^{17}O = -4.8‰$, similar to CO and CV chondrites, DaG 055, LEW 85311, EET 90043, and QUE 99038, and lower than in the least-altered CR chondrites (Choi et al. 2009).

The refractory lithophile abundances scatter somewhat, but appear to be mainly in the CO–CM range (Table 4); volatile siderophiles and Se are below those in mean CO and CM and are most similar to CR. Refractory siderophiles are CM–CO–CV-like, higher than those in CR chondrites. Volatile siderophile and chalcophile abundances are low, similar to or somewhat lower than those in CR chondrites (Fig. 4). In general, low volatiles and erratic variations in lithophiles of all volatilities suggest impact alteration, but there is no petrographic evidence of significant shock in this meteorite.

With large chondrules, CM–CO refractory lithophile abundances, and CV–CM–CO refractory siderophile abundances, DaG 978 is not closely related to any major group. It is thus classified as a type 3 ungrouped carbonaceous chondrite.

GRA 98025. GRA 98025 is an unshocked (S1) rock (Table 3), initially classified as CR2 by McBride and McCoy (2000). Although the *Meteoritical Bulletin 84* (Grossman 2000) lists it as weathering grade C, terrestrial weathering is minor in most of the available thin section, equivalent to weathering grade W1. There is, however, a swath that traverses the section that appears to be more weathered. Metallic Fe-Ni is depleted in this swath and tends to have moderately thick rims of limonite.

The rock appears unbrecciated. It contains well-defined chondrules averaging 210 μm in diameter (n = 100). Most of the porphyritic chondrules are nonspherical; many appear to be fragments. The RP chondrules are rare and tend to be spherical and small (approximately 100 μm). There are no BO or classic C chondrules in the available thin section (GRA 98025,3). In addition to chondrules, the meteorite contains CAIs (McBride and McCoy 2000) as well as AOIs that are 250–1500 μm in maximum dimension. Many of the porphyritic chondrules contain small blebs of metallic Fe-Ni, both in the interiors and at the margins. Some metal grains occur in the matrix; these average approximately 80 μm in size and range up to 270 × 490 μm. The total modal abundance of metallic Fe-Ni is approximately 2–3 vol% (Table 3).

Most metal grains are kamacite averaging (in wt%): 0.14% P, 0.35% Cr, 92.6% Fe, 0.30% Co, and 5.1% Ni. One metal grain was found to be of martensitic composition: < 0.04% P, 0.08% Cr, 88.2% Fe, 0.42% Co, and 10.0% Ni.

Sulfide is less common than metal in GRA 98025 and has a modal abundance of approximately 0.5–1 vol%, in the lower end of the range of many CM chondrites (0.4–2.8 vol%; table 2 of Rubin et al. 2007). Two sulfide phases are present: troilite is the common phase (which averages approximately 0.4 wt% Cr); pentlandite with approximately 17 wt% Ni forms small patches within troilite grains. The whole-rock abundances of Sb, Se, and Zn are low relative to CM chondrites, consistent with appreciable amounts of sulfide having been lost during terrestrial weathering. If this is correct, then the original Se abundance was probably in the CM range.

The meteorite is highly unequilibrated. McBride and McCoy (2000) found olivine ranging from Fa1 to Fa37 mole% with most grains being Fa0–2 mole%. These workers reported a much narrower compositional range for low-Ca pyroxene: Fs1–3Wo1–3. Many of the porphyritic chondrules and chondrule fragments contain polysynthetically twinned low-Ca clinopyroxene.

GRA 98025 has suffered aqueous alteration. Porphyritic chondrule mesostases have been altered to phyllosilicate. The matrix, which has a modal abundance of approximately 30–35 vol%, is reported to consist largely of FeO-rich phyllosilicate (McBride and McCoy 2000), indicating a type 2 classification. PCP was not observed.

The two O-isotopic analyses (D. Rumble, personal communication) are both very low in $\delta^{18}O$ and unusually far to the left of the CCAM line. We tentatively assume that the higher sample (at $\delta^{18}O = -5.3‰$) is more representative.

Most refractory lithophiles plot between CM–CO and CV–CK (Fig. 4). Manganese (a moderately volatile lithophile) is relatively high (in the CM range), but Na and K are very low. Refractory siderophiles are also in the CM–CO–CK–CV range (Fig. 4). Volatile siderophiles and chalcophiles are nearest CV, but some (Ga, Se, Zn) are high, not inconsistent with CM and CO. On the Sb-Ga diagram (Fig. 6), Sb is CK-like, but Ga is CM-like. On the Zn-Sm diagram (Fig. 7), Zn is CV-like, but Sm is CM- or CR-like. Because of the low Na, K, and S and the ambiguous volatile siderophile pattern, it is not possible to assign GRA 98025 to a specific carbonaceous-chondrite group. Based on the small chondrule size and the refractory lithophile abundances, the closest link seems to be CM–CO. The evidence of aqueous alteration and the high Se and Zn favor CM, but the $\delta^{18}O$ is far lower than known CM chondrites. We tentatively classify GRA 98025 as an ungrouped (type 2 or type 3) carbonaceous chondrite.

QUE 99038. QUE 99038 is a shock-stage S1 rock of weathering grade A/B (Table 3). It is an aqueously altered C2 chondrite with a phyllosilicate-rich matrix; chondrule mesostases have also been altered. However, it is not a CM chondrite as originally classified. Chondrules in the rock (PO, POP, and BO types) average 590 μm ($n = 120$) in apparent diameter, much larger than the average chondrule diameter in CM chondrites (270 μm) and closer to the mean of CR chondrites (700 μm) (Rubin 2000). However, the metal in QUE 99038 is unlike that in CR chondrites (which contain abundant metallic Fe-Ni and where metal is present as coarse grains on the surfaces of many porphyritic chondrules). QUE 99038 contains <0.1 vol% metallic Fe-Ni (Table 3); little metal occurs in chondrules and there are no coarse metal grains at chondrule margins. The AOIs in QUE 99038 range in size from 300 to 1150 μm.

Olivine in QUE 99038 ranges from Fa1 to Fa39 (Grossman and Zipfel 2001), but most grains are forsteritic (Fa0–3).

The O-isotopic composition ($\Delta^{17}O = -4.1‰$; I. Ahn, personal communication) plots far down the CCAM line, suggesting loss of H_2O.

The refractory lithophile abundances are intermediate between CM–CO and CV–CK (Fig. 4). Among the volatile lithophiles, Mn is in the CR–CO–CV range, and Na and K are lower than the abundances of all the major carbonaceous-chondrite groups. Refractory and common siderophiles are in the CM–CO–CV range. The low abundances of volatile siderophiles and chalcophiles are like those in CR chondrites except for Se ($1.35 \times$ CR) and Zn ($2.9 \times$ CR) (which are closer to mean CO chondrites) and Au ($0.82 \times$ CR) which is depleted (Table 4). The lithophile and siderophile/chalcophile patterns exhibited by QUE 99038 (Fig. 4) are relatively smooth, implying to us that the bulk composition was largely inherited from the nebula and had not been appreciably modified by shock or terrestrial weathering processes. On the Sb-Ga diagram (Fig. 6), QUE 99038 plots lower than all major chondrite groups, well below CR chondrites; on the Zn-Sm diagram (Fig. 7), this meteorite plots in between CO and CV chondrites. The bulk composition of QUE 99038 does not resemble that of CR chondrites or any other major carbonaceous-chondrite group. We thus classify QUE 99038 as a devolatilized type 2 ungrouped carbonaceous chondrite. It may be equivalent in its degree of alteration to a CM chondrite of subtype 2.3–2.4 (cf. Rubin et al. 2007).

The C-L Grouplet: HaH 073 and Sahara 00182

Coolidge and Loonagana 001 are metamorphosed carbonaceous chondrites that were probably derived from the same parent asteroid. Two meteorites from the present study may be new members of this grouplet.

Hammadah al Hamra (HaH) 073. HaH 073 is a shock-stage S1 rock (Table 3) that experienced significant terrestrial weathering (W3). It contains equilibrated olivine (Fa17.6–18.2) and less-equilibrated low-Ca pyroxene (Fs5.7–11.3); it has a moderately recrystallized texture indicative of petrologic type 4. Chondrule types include PO, PP, POP, BO, RP, and C varieties. Also present are 200 μm size AOIs as well as some refractory objects containing Cr-hercynite, ilmenite and anorthite (Weber et al. 1996). The rock contains 35 vol% matrix material (348/1005 points). Most of the metallic Fe-Ni and sulfide has been transformed into terrestrial weathering products, but remnants of a primary opaque assemblage (kamacite, taenite, and troilite) are preserved within some porphyritic chondrules.

Weckwerth and Weber (1998) suggested that HaH 073 is the third member of the C-L grouplet. Although the latter meteorites have more magnesian olivines (Fa13.4–13.8 and Fa10.7–12.9, respectively; Kallemeyn and Rubin 1995) than in HaH 073, all are similarly equilibrated. Chondrules in HaH 073 average 540 μm; similar in size to those in Coolidge (610 μm) and Loongana 001 (700 μm) (Kallemeyn and Rubin 1995).

As shown in Fig. 1a, the O-isotopic composition of HaH 073 is outside the CO field ($\Delta^{17}O = -3.76‰$; Weber et al. 1996) and plots in the oxidized CV region near the CCAM line. Coolidge (the open triangle) also plots near the CCAM line about 3‰ from HaH 073. Terrestrial weathering may have affected these data. In particular, HaH would probably have plotted lower had the specimen been acid-washed. No O-isotope data are available for Loongana 001.

Refractory lithophiles are high (Fig. 5) and show scatter: Ca, Sm, and Eu are about $1.5 \times$ CI; refractory lithophile abundances in C-L are $1.40 \times$ CI (Fig. 5). The high refractory lithophiles in HaH 073 probably are not due to using Cr values that are too low because the common siderophiles Ni, Co, and Fe are about 10% low. The volatile lithophiles are high relative to C-L, roughly similar to CR chondrites, but the high refractory lithophiles are inconsistent with a CR classification. The abundances of Au and Ga in HaH 073 (Table 4) are similar to those in Loongana 001. On the Zn/Sm diagram (Fig. 7), the Zn value of HaH 073 is CR-like, but Sm is far higher than in any carbonaceous chondrite except Sahara 00182. On the Sb/Ga diagram (Fig. 6), Sb is CV-like, but Ga is below all carbonaceous-chondrite groups and is similar to that in Sahara 00182 (at the edge of the CR field).

We find that HaH 073 is related to Sahara 00182 and, possibly also to the C-L grouplet. These relationships are discussed in more detail below.

Sahara 00182. Sahara 00182 contains olivine grains that exhibit undulose extinction, making this a shock-stage S2 rock (Table 3). It has experienced moderate terrestrial weathering (grade W2). It has large PO, POP, BO, and C chondrules (averaging 790 μm; $n = 100$) with irregular thick, igneous rims; many chondrules have coarse metal grains in their interiors and at their edges. The AOIs range in size from 180 to 3000 μm. Matrix constitutes approximately 30 vol% of the meteorite (Smith et al. 2004) and contains no observable phyllosilicates; refractory inclusions constitute 1.1 vol% of the rock. Metallic Fe-Ni constitutes 4.4 vol% of Sahara 00182 ($n = 1674$ points) (Table 3).

Chondrule phenocrysts are predominantly magnesium-rich and average Fa7.8 and Fs4.4 (Smith et al. 2004).

The O-isotopic composition of Sahara 00182 ($\Delta^{17}O = -3.79‰$; Smith et al. 2004) plots close to the CCAM line between Coolidge and HaH 073 (Fig. 1b).

To enhance agreement with the major carbonaceous-chondrite groups for plotting purposes, we increased the bulk Cr concentration of Sahara 00182 by a factor of 1.07 (Fig. 5). This had the effect of lowering the refractory lithophile abundances into the range between CM–CO and CV–CK. Volatile lithophiles are low, lower than CR chondrites by factors of 1.2–1.5.

Refractory and common siderophile abundances (based on the enhanced Cr concentration) are in the CM–CO–CV range (Table 4), but Ni and Co are marginally higher (enhanced by factors of 1.05). Among the volatile siderophiles and chalcophiles, Au is high ($1.2 \times$ CI), As is in the CO–CV range and appreciably higher than CR chondrites, Sb is close to CR, and Ga, Se, and Zn are lower than CR. The volatile patterns are not quite smooth (Fig. 5), but the Na and K abundances show no obvious terrestrial weathering effects. On the Sb-Ga diagram (Fig. 6), Sahara 00182 is at the edge of the CR field; on the Zn-Sm diagram (Fig. 7), it has the highest Sm/Mn ratio, in large part reflecting the low Mn content.

The rock was classified as a primitive carbonaceous chondrite with affinities to CR and CV chondrites (Smith et al. 2004). Although the chondrules most closely resemble those in CR chondrites, Smith et al. (2004) reported no phyllosilicates in the matrix and several element concentrations are inconsistent with a CR classification.

The volatile siderophile and chalcophile pattern is parallel to that of HaH 073, but lower by a factor of approximately 2/3 (Fig. 5). It seems possible that these two meteorites and C-L are closely related. We suspect that all four have been heated and fractionated as the result of impacts.

Are HaH 073 and Sahara 00182 Members of the C-L Grouplet?

Coolidge and Loongana 001 were identified as a grouplet by Kallemeyn and Rubin (1995) largely on the basis of the following shared characteristics: (1) moderately abundant fine-grained silicate matrix material (20–30 vol%), (2) similar petrographic type (3.8–4), (3) mean chondrule size (600–700 μm), (4) similar equilibrated mean olivine compositions (Fa11.8 and 13.6 mole%), (5) high, CV-like, refractory lithophile and refractory siderophile abundances, (6) low abundances of volatile lithophiles, siderophiles, and chalcophiles, and (7) a similar primary opaque mineral assemblage (kamacite, taenite, troilite).

HaH 073 resembles this grouplet in several, but not in all characteristics. (1) It contains moderately abundant fine-grained silicate matrix material (35 vol%), close to the amount in Coolidge (30 vol%). (2) It is of petrographic type 4, like Coolidge. (3) Its mean chondrule size (540 μm) is close to that of Coolidge (610 μm). (4) It has an equilibrated mean olivine composition (Fa17.6–18.2 mole%), but it is more ferroan than the mean values in Coolidge (Fa13.6) or Loongana 001 (Fa11.8). (5) It has high refractory lithophile and refractory siderophile abundances, similar to those in Loongana 001. (6) It has low abundances of some volatiles (Mn, Au, Ga), like those in C-L; however, other volatiles (Na, K, Sb, Se, Zn) are appreciably higher than those in Coolidge or Loongana 001. (7) HaH 073 has a similar primary opaque assemblage consisting of kamacite, taenite, and troilite. In addition, the O-isotopic composition of HaH 073 ($\Delta^{17}O = -3.76‰$; Fig. 1b) lies close to the CCAM line about 3‰ in $\delta^{18}O$ above Coolidge ($\Delta^{17}O = -4.50‰$).

If HaH 073 is a member of the C-L grouplet, then the range in mean olivine composition (Fa12–18) for this grouplet is somewhat wider than that of CK chondrites (Fa29–33; Kallemeyn et al. 1991), the only major group of metamorphosed carbonaceous chondrites. However, this does not appear to be a sufficient reason to rule out grouplet membership for HaH 073.

If HaH 073 is a member of the C-L grouplet, then this grouplet is somewhat more heterogeneous in its volatile-element abundances (Table 4) than in well-behaved members of most established carbonaceous-chondrite groups. For example, Se varies by 29% in the augmented C-L–HaH 073 grouplet (Table 4), and by 17% in CM, 8% in CO, 13% in CV, 15% in CK, and 29% in CR chondrites (if the weathered Acfer and El Djouf CR chondrites are excluded) (data from Kallemeyn and Wasson 1981; Kallemeyn et al. 1991, 1994).

Sahara 00182 is related to HaH 073 and might possibly be a fourth member of the C-L grouplet. If so, then this grouplet is even more diverse in its bulk compositional characteristics (Fig. 5; Table 4) than established carbonaceous-chondrite groups.

The alternative to membership in the C-L grouplet is that HaH 073 is an ungrouped type 4 carbonaceous chondrite, presumably derived from a separate and poorly sampled parent asteroid that is related to Sahara 00182 and more distantly related to Coolidge and Loongana 001.

A Possible Grouplet Consisting of Belgica-7904, WIS 91600, Y-86720, and Dhofar 225

Belgica-7904, WIS 91600, and Y-86720 share a number of properties that indicate that they are likely to be members of a single grouplet. (1) Their matrices yield high analytical totals and have fewer phyllosilicates than those in normal CM chondrites, consistent with dehydration due to mild to moderate heating (e.g., Tomeoka et al. 1989a; Zolensky et al. 1989; Tomeoka 1990; Tonui et al. 2002). Dehydration of some phyllosilicates is supported by TEM studies (e.g., Akai 1990), by spectral studies indicating loss of OH (e.g., Hiroi et al. 1996), by synchrotron X-ray diffraction analysis of matrices (Nakamura 2005), and by chemical studies showing low H_2O and C contents (Haramura et al. 1983; Shimoyama and Harada 1984). (2) Their bulk chemical compositions are CM-like (Yamamoto and Nakamura 1989; Moriarty et al. 2009; Fig. 2). (3) Their O-isotopic compositions are very similar (e.g., Fig. 2) and fall near the CI chondrites on the standard three-isotope diagram, but generally with still higher $\delta^{17}O$ and $\delta^{18}O$ values (Mayeda and Clayton 1990; Mayeda et al. 1991; Clayton and Mayeda 1999, 2003). Other meteorites with similar O-isotopic compositions that may be members of this group include Y-86789 and Dhofar 225. The $\delta^{18}O$ values of all of these rocks range from 17‰ to 23‰ (Clayton and Mayeda 1999, 2003).

Belgica-7904, WIS 91600, and Y-86720 did not experience identical histories. Chondrules in Y-86720 have been completely replaced by secondary alteration products (Tomeoka et al. 1989a), i.e., olivine and pyroxene are absent from chondrules. The average diameter of these chondrule pseudomorphs is 350 μm ($n = 10$) (this study), but the mean value prior to alteration was surely lower. In Belgica-7904 and WIS 91600, chondrule mesostases have been replaced, but olivine is abundant in Belgica-7904 chondrules (Tomeoka 1990) and both olivine and pyroxene are abundant in WIS 91600 chondrules (this study). Of the three meteorites, Y-86720 suffered the most extensive aqueous alteration, as indicated by its essentially complete replacement of chondrule mafic silicates (it is equivalent to a CM chondrite of subtype 2.0) and, perhaps, its slightly heavier whole-rock O-isotopic composition (although more extensive loss of H_2O

during subsequent heating could have also produced this).

Y-86720 also seems to have suffered the greatest degree of annealing among members of the grouplet (e.g., Tomeoka 1990; Akai 1990; Tonui et al. 2002), although Nakamura (2005) placed Y-86720 in the same advanced "heating stage" as Belgica-7904. Matrix phyllosilicates are rare in Y-86720; the matrix consists largely of ferroan olivine, amorphous Si-, Mg-, and Fe-bearing material, and an Fe-rich phase that is probably ferrihydrite [$Fe_{4\text{-}5}(OH,O)_{12}$] (Tomeoka et al. 1989a). Abundant troilite occurs in the matrix; most grains are small, but also present are blades ranging in size from 3×10 to 80×300 μm.

Although Dhofar 225 is classified as an anomalous CM chondrite, it has a similar O-isotopic composition to the members of the Belgica-7904 grouplet (Clayton and Mayeda 2003) and some phyllosilicates experienced dehydration (Ivanova et al. 2002). Unlike other members of the grouplet, Dhofar 225 contains PCP and tochilinite with intergrown phyllosilicates (Ivanova et al. 2002).

The Belgica-7904 grouplet seems to have experienced a complex history. The individual meteorites experienced different degrees of aqueous alteration, moderate in the case of WIS 91600, more extensive in the cases of Belgica-7904 and Dhofar 225, and very extensive in the case of Y-86720. Subsequent heating of these materials caused them to suffer dehydration and loss of isotopically light water (with an O-isotopic composition near the TF line; e.g., Mayeda and Clayton 1998; Clayton and Mayeda 2009). The proximate cause of the heating and dehydration could have been impacts. The absence of PCP and the abundance of small sulfide grains in the matrices of Belgica-7904, Y-86720, and WIS 91600 are consistent with the inferred breakdown of PCP during extensive aqueous alteration (Rubin et al. 2007). It is also possible that subsequent impact-induced heating and dehydration could have destroyed some of the PCP if any of it remained after aqueous alteration.

The fact that the members of the Belgica-7904 grouplet have somewhat different petrologic characteristics (e.g., Tomeoka et al. 1989a, 1989b; Nakamura 2005; this study) indicates that impact-dehydration processes, operating on materials that probably had suffered different degrees of aqueous alteration, can produce highly variable properties.

Tochilinite breaks down at approximately 520 K (Fuchs et al. 1973). This process is inferred to have occurred in Belgica-7904 and Y-86720 (which have low abundances of matrix phyllosilicates; e.g., Tomeoka et al. 1989a). It seems likely that these rocks were heated to the approximately 800 K range.

Because tochilinite is produced by aqueous alteration (Tomeoka and Buseck 1985), its presence in Dhofar 225 (Ivanova et al. 2002) may indicate that, unlike other members of the grouplet, this rock experienced an episode of *postimpact* aqueous alteration. Alternatively, tochilinite could have survived in Dhofar 225 if the shock-heating period was very brief.

There are two principal alternative origins of the Belgica-7904 grouplet: (1) their members formed from normal CM chondrites and (2) they were derived from a separate carbonaceous-chondrite asteroidal region.

Formation from Normal CM Chondrites

There are several properties of the Belgica-7904 grouplet that are consistent with the model that these meteorites were derived from normal CM chondrites. (1) Their bulk chemical compositions are very similar to mean CM chondrites. (2) The chondrules (or chondrule pseudomorphs) have about the same size and distribution of textural types as those in high-subtype CM chondrites. (3) Many of the chondrules or chondrule pseudomorphs are surrounded by fine-grained mantles (e.g., Tomeoka et al. 1989a; Zolensky et al. 1989; Tomeoka 1990) similar in size and shape to those around chondrules in CM chondrites (e.g., Metzler et al. 1992; Trigo-Rodríguez et al. 2006).

However, there are difficulties in explaining the extreme O-isotopic compositions of grouplet members. Our preferred explanation of the high $\delta^{18}O$ values of these rocks is that a precursor material with lower $\delta^{18}O$ values lost water that had still lower $\delta^{18}O$. It is well known that, under equilibrium conditions, $\delta^{18}O$ in water is lower than that in coexisting phyllosilicate (e.g., Clayton and Mayeda 2009). Complications arise, however, with linking these precursor materials with normal CM chondrites. Because nebular water had $\Delta^{17}O$ values $>0‰$ (e.g., Rowe et al. 1994) and common CM chondrites have $\Delta^{17}O$ values between $-2.0‰$ and $-3.2‰$ (Clayton and Mayeda 1999), it is not possible to produce bulk $\Delta^{17}O$ values near $0‰$ by loss of water having a composition $>0‰$. It thus seems unlikely that the Belgica-7904 grouplet was derived from the regions that produced normal CM chondrites.

Derivation from a Separate Asteroidal Region

The simplest scenario to account for the O-isotopic compositions of the Belgica-7904 grouplet is one in which the precursor materials of the grouplet already had equilibrated with nebular water, resulting in the silicates and oxides having the same $\Delta^{17}O$ (approximately $0‰$) as the (now evolved) water. This is plausible because magnetite is thought to record the $\Delta^{17}O$ of the water, and Belgica-7904 magnetite grains are mostly in the range $+1.3‰$ to $+1.7‰$ in CI chondrites and in the ungrouped C2 chondrite Essebi (Rowe et al. 1994). Loss of as much as 10% of bulk O in the form of such water would only change the bulk value of a precursor near the TF line by 0.1–0.2‰.

However, if the precursor of the Belgica-7904 grouplet had water near 0‰, it differed by ≥2‰ from the $\Delta^{17}O$ values commonly encountered among CM whole rocks (Clayton and Mayeda 1999). Therefore, our preferred classification of the grouplet is that it is distinct from CM. Further study may show that these meteorites should be classified as a new group of chondrites. Nevertheless, it seems possible that they were derived from an impact-metamorphosed region on a CM asteroid.

CONCLUSIONS

On the basis of new bulk chemical compositions, petrographic characteristics and literature data, we recommend the following classifications for these 15 unusual carbonaceous chondrites: Acfer 094 (type 3.0, ungrouped CM-related); Belgica-7904 (mildly metamorphosed, anomalous, CM-like chondrite, possibly a member of a new grouplet that includes WIS 91600 and Y-86720); DaG 055 and its paired specimen 056 (anomalous, reduced CV3-like); DaG 978 (type 3 ungrouped); DOM 03238 (anomalous, magnetite-rich CO3.1); EET 90043 (anomalous, magnetite-bearing CO3); GRA 98025 (type 2 or type 3 ungrouped); GRO 95566 (anomalous CM2 with a low degree of aqueous alteration); HaH 073 (type 4 ungrouped, possibly related to the C-L 001 grouplet); LEW 85311 (anomalous CM2 with a low degree of aqueous alteration); NWA 1152 (anomalous CV3); PCA 91008 (anomalous, metamorphosed CM); QUE 99038 (type 2 ungrouped); Sahara 00182 (type 3 ungrouped, possibly related to HaH 073 and/or to C-L 001); and WIS 91600 (mildly metamorphosed, anomalous, CM-like chondrite, possibly a member of a new grouplet that includes Belgica-7904 and Y-86720).

Most of these meteorites are anomalous. Many have suffered a late thermal event that resulted in loss of H_2O and, in some cases, volatile metals. These heating events and compositional irregularities implying phase transport are likely to be the product of impact events. The Belgica-7904 grouplet may have experienced a complex series of events involving aqueous alteration and impact dehydration.

We studied a number of carbonaceous chondrites that have been classified as metamorphosed CM chondrites. Most have CM-like bulk compositions, but they fall into two distinct fields on a plot of $\delta^{17}O$ versus $\delta^{18}O$ with respective $\Delta^{17}O$ values of approximately −4‰ (PCA 91008; GRO 95566; DaG 978; LEW 85311) and approximately 0‰ (Belgica-7904; WIS 91600). They are clearly not from the same asteroidal region and probably not from the same asteroid.

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