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Magnetic classification of stony meteorites: 2. Non-ordinary chondrites

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Abstract–A database of magnetic susceptibility (χ) measurements on different non-ordinary chondrites (C, E, R, and ungrouped) populations is presented and compared to our previous similar work on ordinary chondrites. It provides an exhaustive study of the amount of iron-nickel magnetic phases (essentially metal and magnetite) in these meteorites. In contrast with all the other classes, CM and CV show a wide range of magnetic mineral content, with a two orders of magnitude variation of χ. Whether this is due to primary parent body differences, metamorphism or alteration, remains unclear. C3–4 and C2 yield similar χ values to the ones shown by CK and CM, respectively. By order of increasing χ, the classes with well-grouped χ are: R << CO < CK ≈ CI < Kak < CR < E ≈ CH < CB. Based on magnetism, EH and EL classes have indistinguishable metal content. Outliers that we suggest may need to have their classifications reconsidered are Acfer 202 (CO), Elephant Moraine (EET) 96026 (C4–5), Meteorite Hills (MET) 01149, and Northwest Africa (NWA) 521 (CK), Asuka (A)-88198, LaPaz Icefield (LAP) 031156, and Sahara 98248 (R). χ values can also be used to define affinities of ungrouped chondrites, and propose pairing, particularly in the case of CM and CV meteorites.

INTRODUCTION

The world's collection of meteorites amounts to nearly 50,000 different meteorites, among which 95% are stony types. Among these the ordinary chondrite (OC) class makes 90%, the other (or non-ordinary) chondrites 6% and the stony achondrites 4% (Grady 2000). In a companion paper we have investigated systematically the magnetic properties of ordinary chondrites (Rochette et al. 2003). The present paper follows this scheme on non-ordinary chondrites, while a third paper will deal with achondrites. The magnetization (M) of matter can be induced by an external field (H) or be present in zero field, i.e., "remanent". The magnetic properties mostly discussed here will be magnetic susceptibility, i.e., the ratio M/H of induced magnetization to inducing field (of low intensity: <5 mT), and the remanence measured after applying a "saturating" field (1 to 3 Teslas). Both parameters have the advantage, contrary to natural remanence, of being independent of the magnetic history of the sample, including exposure to magnets.

Low-field magnetic susceptibility (χ) has been demonstrated to provide a rapid and non-destructive way to sort the OC into LL, L, and H groups, based on non-overlapping range of metal amount (Rochette et al. 2003). Saturation remanence (M_{rs}) was also compiled for OC, to evaluate the range of likely remanent magnetization for asteroids with OC-like composition. Besides being a classification tool and a first step in more sophisticated magnetic applications (paleomagnetism: see Gattacceca et al. 2004; magnetic anisotropy: see Gattacceca et al. 2005), both parameters have applications in solar system exploration (e.g., Pesonen et al. 1993; Rochette et al. 2004). Therefore the same parameters will be analyzed on the various non-ordinary chondrites groups: carbonaceous (C), enstatite (E), and rumurutite (R), as well as ungrouped chondrites including the Kakangari grouplet. Compared to OC these groups cover a much wider range of oxidation state and thus of magnetic mineralogy. Numerous magnetic studies have dealt with C chondrites (reviewed in Sugiura and Strangway 1987), while only one specific investigation was devoted to E chondrites (Sugiura and Strangway 1983) and none to R and Kakangari chondrites.

Rochette et al. (2001a) presented a common database of the published data of Terho et al. (1991, 1993) together with a number of new magnetic susceptibility measurements from the Vatican meteorite collection and the major collections from Italy (see Table 1). Since then, the collections of Natural History museums in Madrid and Paris, and of the Ecole des Mines in Paris, have been measured and used in the Rochette et al. (2003) paper. After that publication, new collections that have been investigated are, in chronological order, those of Chicago (Field Museum), Albuquerque (IOM), London (NHM), Moscow (University and Science Academy), Rio de Janeiro (Museu Nacional), Tokyo (NIPR), Vienna (NHM), Houston (JSC), Washington (Smithsonian Institution), New York (AMNH), Zurich (ETH), Bern (NHM), Christchurch (Canterbury Museum), Los Angeles (UCLA), as well as various private collections. In addition, the Ottawa collection (Smith et al. 2006) and five European collections (Kohout et al. 2006) have been investigated independently, and the data merged for this publication with the CEREGE database. While the Ottawa and Moscow collections were investigated systematically, only a small selection (mostly non-OC) were measured in the other collections (see Table 1).

The total number of non-OC specimens currently in the database is 841; these are from 325 different meteorites, after tentative pairings of hot and cold desert ones. The total mass investigated is 25 kg. Table 1 summarizes the different collections used in the database and how they were measured. For the coherency of the database we use the preferred classification given by the Meteoritical Bulletin Database (at http://tin.er.usgs.gov/meteor/metbull.php). Cases where there is is controversy in the literature over these classifications will be discussed in the text. Note that several ANSMET Antarctic meteorites (especially ungrouped C2, C3) will be subjected to classification changes in the near future (K. Righter, personal communication).

MAGNETIC MINERALOGY OF NON-ORDINARY CHONDRITES

In non-ordinary chondrites, the abundances of the magnetic elements Fe and Ni vary according to geochemical class in the following wt% ranges, respectively: 19–24 and 0.2–1.4 for C chondrites (Jarosewich 1990), with the exception of CH-CB with up to 70% Fe; 21–31 and 1–2 for E chondrites (Jarosewich 1990; Zhang et al. 1995); 23–25 and 0.2–1.4 for R chondrites (Kallenmeyn et al. 1996). Other magnetic elements (Co, Cr, Mn, . . .) are present in negligible amounts, relative to Fe and Ni.

The possibly strongly magnetic phases encountered in meteorites are, according to increasing reduction state, magnetite (Fe_3O_4), monoclinic pyrrhotite (Fe_7S_8), metastable hexagonal pyrrhotite (Fe_9S_{10}), Fe-Ni alloys (e.g., Nagata 1979), and carbide ($(Fe,Ni)_3C$: cohenite) or phosphide ($(Fe,Ni)_3P$: schreibersite). Oxide, metal, carbide, and pyrrhotite have been reported in the C chondrites, E chondrites bear metal, carbide, and phosphide, while only pyrrhotite is abundant in R chondrites (Rubin 1997; Brearley and Jones 1998). All these minerals except pyrrhotite yield similar apparent volumic susceptibility of 3 SI for a sphere, because they have a true susceptibility >>1 SI (e.g., Heider et al. 1996). Therefore, depending on density, the specific susceptibility varies in the $400–600 \times 10^{-6}$ m^3/kg range. In the case of pyrrhotite, depending on grain size, specific susceptibility varies in the $10–60 \times 10^{-6}$ m^3/kg range (Dekkers 1988). Table 2 summarizes the properties of the main magnetic minerals in chondrites, and the groups where they can be found (according to Endress et al. 1994; Schulze et al. 1994; Geiger and Bischoff 1995; Rubin 1997; Brearley and Jones 1998; Krot et al. 2002). The good correlation between susceptibility and metal amount was demonstrated for ordinary chondrites in Rochette et al. (2003) although dispersion may arise in case of abundant tetrataenite and due to grain shape and interactions. For magnetite-bearing carbonaceous chondrites such a correlation is described in the Magnetite-Bearing CK and Ungrouped C3-4 Chondrites section.

For comparison, the other Fe or Ni bearing phases, paramagnetic silicates or oxides and antiferromagnetic troilite, have no remanence and comparatively very low susceptibility at room temperature: the most Fe-rich minerals, fayalite and troilite, yield susceptibility values of 1.2 and 0.2×10^{-6} m^3/kg, respectively (Carmichael 1989; Coey et al. 1976). In the case of negligible amount of strongly magnetic phase, and assuming all iron is in 2^+ non-interacting paramagnetic state, one can predict that $\chi = F \times 25.2\ 10^{-9}$ m^3/kg, where F is the weight % of Fe, neglecting the other magnetic elements: Ni, Cr, Mn . . . (Rochette 1987). Therefore the maximum paramagnetic susceptibility of non-OC meteorites should range from 0.48 to 0.78 10^{-6} m^3/kg.

MEASUREMENT AND DATABASE CONSTRUCTION

Measurement procedures have been discussed in detail in Rochette et al. (2001a, 2003) and will only be summarized here. A large coil (8 cm) alternating field bridge KLY-2 (manufactured by AGICO, or its custom-made equivalent, for the Helsinki data) was used, allowing samples up to a mass of 450 g to be measured, although coil saturation may be reached for 50–100 g highly magnetic samples. The high homogeneity of the solenoid coil internal field allowed us to obtain reliable

Table 1. List of meteorite collections entered in the database (ordered by chronological order of measurements, same numbering as in Rochette et al. 2003), with number of specimen measured and instrument used. 1–5, 6–7, 17, and 22 were previously partly published in Rochette et al. (2001a), Thero et al. (1993), Smith et al. (2006) and Kohout et al. (2006). For 22 the different collections included are Berlin (7 specimens), Stockholm (3), Münster (2), Oslö (1), and Olsztyn (1).

#	N	Collection	Instruments
1	24	Vatican Observatory, Castel Gandolfo	KLY-2
2	5	University La Sapienza, Roma	KLY-2
3	13	Museo Nazionale dell' Antartide, Siena	KLY-2, MS2B
5	63	Private collections	KLY-2, MS2B,SM30
6	5	Prague Museum	KLY-2
7	16	Helsinki database (1993)	KLY-2, RISTO 5
8	165	Natural History Museum, Paris	KLY-2, MS2B,SM30
9	3	Natural History Museum, Madrid	KLY-2
10	6	School of Mines Museum, Paris	MS2B, SM30
11	22	Russian Academy of Science and Moscow University	MS2B, SM30
12	26	Natural History Museum London	MS2B, SM30
13	2	Field Museum, Chicago	SM30
14	6	NIPR, Tokyo	KLY-2
15	12	IOM University of New Mexico	MS2B, SM30
16	34	Natural History Museum, Vienna	MS2B, SM30
17	36	Geological Survey, Ottawa	SI-2B
18	13	Museu Nacional, Rio de Janeiro	MS2B, SM30
19	195	Johnson Space Center, Houston	MS2B, SM30
20	46	Smithsonian Institution, Washington D.C.	MS2B, SM30
21	63	American Museum of Natural History, New York	MS2B, SM30
22	14	Helsinki database (2006)	TH1
23	12	Natural History Museum, Bern	MS2B, SM30
24	4	ETH, Zürich	MS2B, SM30
25	6	Canterbury Museum, Christchurch	SM30
26	58	UCLA, Los Angeles	MS2B, SM30

Table 2. List of magnetic minerals (with spontaneous magnetization at room temperature) relevant to stony meteorites with their density (d in 10^3 kg/m^3), magnetic susceptibility (χ in 10^{-6} m^3/kg), saturation magnetization (M_s in Am^2/kg), Curie temperature (T_C), and group of meteorite bearing this mineral (in bold when it is the major magnetic mineral). The various form of Fe,Ni alloys are not detailed. M_s and T_c of schreibersite are likely similar to the ones of cohenite. Ferric phases, occasionally described in type-3 chondrites and also formed by terrestrial weathering are not listed. χ is the theoretical lower limit of apparent susceptibility (calculated for non interacting spheres) except for pyrrhotite.

Mineral	Formula	d	χ	M_s	T_c (°C)	Chondrite group
Metal	(Fe,Ni)	7.9	380	≤218	550–770	**CB–CH–CR**, **CO**, **CV**, **E**, **Kak**, CM/C2, R
Magnetite	Fe_3O_4	5.2	580	92	580	**CI**, **CK**, **CM/C2**, **CV**, CO, CR
Cohenite	$(Fe,Ni)_3C$	7.4	400	128	210	CO, E
Schreibersite	$(Fe,Ni)_3P$	7.4	400	–	–	CM, CR, E
Pyrrhotite	$Fe_{(1-x)}S$	4.6	10–60	15–20	290–320	**R**, CM/C2, CI, CK, CR

results on samples with unequant shape (fragments, slice, full stones). For each measured specimen, the decimal logarithm of apparent mass specific susceptibility χ is tabulated (in 10^{-9} m^3/kg). The use of log units is justified for presentation reasons (as data varies on 3 orders of magnitude) and also by the fact that χ is expected for a given formation or parent body to follow a log normal distribution (Latham et al. 1989). Therefore it is more representative to average data as logχ rather than as χ. We selected specimens with a minimum mass of 3 g (i.e., about one cubic centimeter). Smaller masses were measured only in case of rare meteorites for which no larger specimens were available. In any case the precision remained better than 0.01 (in logχ). As the KLY-2 is quite uneasy to transport, we used for a number of collections a more portable coil system, the MS2B instrument (manufactured by Bartington). This instrument is less precise than the KLY-2 but reasonably cross-calibrated with the KLY-2 (Sagnotti et al. 2003). The Ottawa collection has been measured using a SI-2B bridge (from Sapphire; Smith et al. 2006). Cross calibration with KLY2 is not specifically provided, but correlating the measurements from CEREGE and Canadian database on the same meteorite (Smith et al. 2006) show a good 1/1 correspondance. Therefore the Canadian data were merged in our database without any correction. Cross-calibration with the Helsinki (1993) data was discussed in Rochette et al. (2003). For the Helsinki (2006) database Kohout et al. (2006) used a portable instrument (Hämäläinen TH-1) of low sensitivity with respect to KLY-2. Therefore we merged in our database only the data with sufficient accuracy (i.e., large enough mass and logχ), except for Rumuruti for which no other data was available. The given logχ value of this meteorite is therefore poorly constrained. Smith et al. (2006) evidenced a noticeable frequency dependence of χ on meteorites. Therefore we choose to use data obtained with the lowest frequency: 900, 1000, 815 Hz for the KLY-2, MS2B, and SI-2B, respectively.

For samples not fitting in the KLY-2 or MS2B coils we used another instrument: the SM30 (manufactured by ZH instruments) or its older version, KT5. It is a LC oscillator, which uses a flat coil to be applied on the surface of the sample to be measured. Due to the highly variable magnetic field created at the coil front, the output critically depends on the shape of the sample, especially on its surface facing the instrument; the optimal configuration is a flat cut surface. About 99% of the signal comes from a cylinder of 8 cm in diameter and 5 cm in thickness; volume susceptibility can be directly taken as the instrument output for an end-cut stone larger than this volume. Cross-calibration of the KT5 or SM30 with the KLY-2 instrument is described by Lecoanet et al. (1999) and Gattacceca et al. (2004). For a slice of constant thickness less than 5 cm, a known correction factor can be applied. Furthermore, Gattacceca et al. (2004) provide a calibration curve for correcting SM30 measurements on uneven shaped samples like full stones or fragments. This procedure has been further exemplified in Folco et al. (2006). In order to obtain mass specific values from SM30 measurements, the output has to be divided by density (for the same meteorite, if available, or else from its type average), as obtained from the Pesonen et al. (1993) and Britt and Consolmagno (2003) databases. Gattacceca et al. (2004) demonstrated the good agreement between SM30 and KLY-2 on a wide range of meteorites.

The various sources of error in low field susceptibility measurements of meteorite specimens have been detailed by Terho et al. (1993) and Rochette et al. (2001a). The effect of a fusion crust has been shown to be negligible for pieces of more than 1 cm^3 with logχ greater than 3.5. The anisotropy of magnetic susceptibility (AMS), due either to a preferred orientation of magnetic grains or to the shape of the sample, is a more severe problem. Tests and models have shown that the error in mean logχ due to anisotropy can reach ±0.1 when only one arbitrary direction is measured. Therefore, whenever it was possible, χ was averaged from measurements along three perpendicular directions. Gattacceca et al. (2005) provide a database of the anisotropy ratio observed in C and R chondrites. It is less than 1.1 (except for CR and Leoville), much below the range observed in OC (from 1.1 to 2; Gattacceca et al. 2005). Shape effect becomes marginal for logχ ≤ 4.9.

Our database has one entry per specimen (except for the Terho et al. (1991, 1993) data where the average per meteorite was used), listing the mass of the specimen (or group of specimens), logχ, and the collection provenance. Only average data for each meteorite is shown in Tables 3 and 4. In the average (arithmetic mean of logχ in agreement with the log normal distribution invoked previously), equal weight has been given to each entry from the same meteorite with mass larger than 3 g. In case of three entries with, for instance, masses of 1, 20, and 30 g, only the latter two were used. On the other hand we use several samples of less than three grams to derive the mean when large samples are missing. Obvious outliers (12 samples) are not used in the means as long as the number of outliers is minor with respect to the total number of samples. Outliers are defined by difference with the mean exceeding 3 s.d. Typically, s.d. for a given meteorite is less than 0.1 (see specific values in tables 3–4 and mean values in Table 5, see also Rochette et al. 2003). Larger s.d. are observed only when shape anisotropy becomes important (CR, CH-CB, E) or in case of variable terrestrial weathering (see e.g., CO3 finds). As an example of the strong magnetic homogeneity of the studied chondrites one can consider the case of Allende, with a s.d. of 0.06 on 30 samples from 8 collections. In ordinary chondrites brecciation appeared to have generally no influence on the mean logχ and its s.d.; the same observation applies for non-ordinary chondrites. As observed in OC, outlying specimens most often correspond to mislabeled-misidentified ones. For example, we found in the Vatican collection a "Murray" piece (logχ of 1.4 instead of 3.8), that appeared to be a terrestrial shale, and a "Daniel's Kuil" sample (logχ of 3.4 instead of 5.4) that was revealed to be a terrestrial basalt based on thin section observation and Mn analysis. Figure 1 (after Table 5) presents the average logχ for each class investigated. Suspected pairs in Sahara, Oman or Antarctic finds are counted as a single entry for such means. This pairing, based on geographical proximity, similar petrography, and logχ values, was necessary to avoid an overweight of Antarctic and hot desert samples on the group means. We acknowledge that we may have pooled actually unpaired meteorites, but as they share very similar logχ values, it will not affect the interpretation.

MAGNETIC SUSCEPTIBILITY RESULTS

Carbonaceous Chondrites

CO3 Chondrites

CO3 chondrites are characterized by abundant metal, mixed with magnetite and cohenite (Shibata 1996). The presence of metal results in a large sensitivity to weathering and subsequent decrease in logχ, well demonstrated previously in OC (Rochette et al. 2003). This is likely an important cause of dispersion of the results. Only for CO3 is the number of falls sufficient to compute separate means: 4.54 ± 0.20 and 4.49 ± 0.28, for falls and finds, respectively.

Table 3. Decimal logχ (in 10^{-9} m^3/kg) for carbonaceaous chondrites, after tentative pairing for desert finds. If more than 4 meteorites are paired only the earliest number is given with full list in the footnotes. Arithmetic mean and standard deviation (s. d.) of logχ are provided when more than one specimen was measured. N: number of specimen used in the mean (in brackets number of outliers); m: cumulated mass measured. Provenance code: see # in Table 1. Anomalies not included in Table 5 means are listed at the end.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
NWA 4765	C1/2	3.69		1	1.2	5
Acfer 094	C2	4.62		1	15.9	16
Adelaide	C2	4.76	0.12	2	42.3	8, 12
Bells	C2	4.82	0.07	4	7.1	12, 13, 21
EET 92006	C2	3.82		1	0.6	19
EET 96029	C2	4.22		1	7.8	19
Essebi	C2	4.85	0.02	3	24.2	5, 2
GRA 98005	C2	3.82		1	118.9	19
GRO 95566	C2	3.45		1	32.2	19
LON 94101	C2	3.70		1	230.0	19
MAC 87300	C2	4.94		1	7.2	19
MCY 92500	C2	3.78		1	4.0	19
QUE 94582	C2	4.61		1	5.2	19
QUE 94734	C2	3.63		1	3.1	19
RKP 92400	C2	3.85		1	3.9	19
Tagish Lake	C2	4.94	0.04	2	1.0	5
TIL 91722	C2	4.06		1	43.8	19
WIS 91600	C2	4.78	0.07	2	88.8	19
DaG 55-56-430	C3	4.77	0.06	6	116.7	8, 12, 16, 21
EET 96010	C3	4.19	0.03	2	13.5	19
LEW 85332	C3	4.53		1	31.8	19
MAC 88107	C3	4.86		1	2.5	19
Ningqiang	C3	4.72	0.02	3	34.7	8, 26
Sahara 00177-182	C3	5.15	0.03	2	14.7	8, 21
Coolidge	C4	4.94	0.15	5	23.4	8, 17, 20, 21, 26
HaH 073	C4	4.89		1	17.3	16
Longanaal	C4	4.97	0.03	2(1)	4.3	15, 17
QUE 94570	C4	4.49		1	7.7	19
Bencubbin	CB	5.63	0.09	2	255.3	8, 25
Fountain Hill	CB	5.72		1	34	5
GRO 95551	CB-like	5.42	0.19	2	8.2	19
Gujba	CB	5.65	0.07	4	507.7	8, 12, 22, 26
HaH 237	CB	5.63	0.46	2	78.1	8
Isheyevo	CB	5.84		1	50	5
NWA 1814	CB	5.54		1	11.1	8
QUE 94627	CB	5.61	0.01	2	32.1	20
Weatherford	CB	5.79		1	58.6	8
Acfer 182-207-214	CH	5.19	0.07	6	70.9	11, 15, 21
ALH 85085	CH	5.34	0.13	2	4.3	19
NWA 739	CH	5.65	0.05	2	8.6	15
PCA 91328	CH	5.26		1	9.3	19
Alais	CI	4.56	0.10	4(1)	23.8	1, 8
Ivuna	CI	4.74	0.04	4	22.1	8, 21
Orgueil	CI	4.78	0.05	9(1)	190.4	1, 6, 7, 8, 10, 11
Revelstoke	CI	4.58		1		See text
Tonk	CI	4.67		1	1.3	20
NWA 4422-4423	CK	4.79	0.13	2	31.2	8
NWA 1559	CK3	4.38	0.03	2	17.6	5, 16
Dho 15	CK3	4.51		1	18.8	11
DaG 431	CK3	4.54	0.11	4	173.2	8
NWA 4425	CK3	4.60		1	30.2	8
ALH 85002	CK4	4.45		1	185.7	19
DAV 92300	CK4	4.87		1	3.5	19

Table 3. *(Continued).* Decimal logχ (in 10^{-9} m^3/kg) for carbonaceaous chondrites, after tentative pairing for desert finds. If more than 4 meteorites are paired only the earliest number is given with full list in the footnotes. Arithmetic mean and standard deviation (s. d.) of logχ are provided when more than one specimen was measured. N: number of specimen used in the mean (in brackets number of outliers); m: cumulated mass measured. Provenance code: see # in Table 1. Anomalies not included in Table 5 means are listed at the end.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
EET 92002-99430	CK4	4.55	0.03	3	19.2	19
HaH 280	CK4	4.48		1	4.2	5
Karoonda	CK4	4.63	0.07	8	157.8	8, 17, 22, 25
Lucerne Valley 028-29-35-37	CK4	4.46	0.06	5	36.6	26
Maralinga	CK4	4.66	0.02	3	25.0	8, 17, 21
MET 00739	CK4	4.93		1	4.1	19
NWA 1112	CK4	4.72		1	5.1	26
NWA 2519	CK4	4.57	0.00	2	15.9	8
NWA 4679	CK4	4.50		1	9.5	8
PCA 91470	CK4	4.51		1	3.8	19
TNZ 57	CK4	4.62	0.04	4	685.8	5, 26
DAG 250-275-412	CK4/5	4.65	0.06	3	84.9	16
NWA 765	CK4/5	4.72	0.01	4	118.8	5, 8, 26
NWA1284-1560	CK4/5	4.53	0.02	3	25.0	16, 26
Yamato-693	CK4/5	4.84		1		14
EET 87507	CK5	4.72		1	2.9	19
NWA 060-1112-1563	CK5	4.67	0.07	4	51.5	5, 16, 6
QUE 99680	CK5	4.81	0.01	2	14.2	19
NWA 1558	CK5/6	4.61		1	20.3	16
LEW 87009	CK6	4.51	0.00	2	20.5	19
Acfer 331	CM2	3.40	0.02	2	9.6	5
ALH 82100	CM2	4.34		1	0.6	19
ALH 83100	CM1/2	3.68	0.08	4	226	19
ALH 85005-85013	CM2	4.06	0.13	2	14.5	19
ALHA77306[a]	CM2	3.69	0.10	9	62.7	19, 20
Banten	CM2	4.04	0.14	3	23.9	8, 11, 17
Boriskino	CM2	3.96	0.12	4	71.9	8, 11, 21
Cimarron	CM2	4.31	0.11	5	20.4	21
Cochabamba	CM2	3.67		1	11.0	16
Cold Bokkeveld	CM2	3.65	0.14	7	171.6	1, 7, 8, 17
Crescent	CM	4.33	0.10	2	5.3	12, 13
DaG 557	CM2	4.13	0.07	2	63.5	5, 8
Dho 225	CM2	4.05		1	17.4	11
Dho 735	CM2	4.23		1	78.5	11
EET 87522-99437	CM2	4.20	0.13	3	17.2	19
EET 90021	CM2	4.58		1	6.9	19
EET 92005	CM2	3.85		1	3.6	19
El Quss Abou Said	CM2	4.28		1	25.1	12
Erakot	CM2	3.43	0.33	2	5.6	21, 26
GRA 98074	CM2	4.09		1	12.4	19
GRO 85202	CM2	3.49		1	3.6	19
Haripura	CM2	4.11		1	0.5	21
Kivesvara	CM2	3.61	0.03	4	32.5	7, 12, 20
LAP 02333	CM2	3.89	0.10	2	113.7	19
LEW 85306-87022-87148	CM2	3.56	0.04	3	33.2	19, 20
LEW 85311	CM2	3.90		1	34.3	19
LEW 88002	CM2	4.80		1	3.7	19
LEW 90500	CM2	3.19		1	1.6	19
Lookout Hill	CM2	3.46		1	1.1	12
MAC 02606	CM2	4.79		1	4.8	19
MAC 88100-02535	CM2	3.92	0.10	3	15.4	19
MAC 88101	CM2	3.25	0.01	2	12.7	
MET 00431	CM2	3.30		1	3.6	19

Table 3. *(Continued).* Decimal logχ (in 10^{-9} m^3/kg) for carbonaceaous chondrites, after tentative pairing for desert finds. If more than 4 meteorites are paired only the earliest number is given with full list in the footnotes. Arithmetic mean and standard deviation (s. d.) of logχ are provided when more than one specimen was measured. N: number of specimen used in the mean (in brackets number of outliers); m: cumulated mass measured. Provenance code: see # in Table 1. Anomalies not included in Table 5 means are listed at the end.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
MET 00433[b]	CM2	3.71	0.10	16	127.6	19
MET 00434-01076	CM2	4.16	0.07	2	7.9	19
MET 01077	CM2	4.69	0.06	3	16.0	19
MET 01070	CM1	3.63	0.05	3	28.4	19
Mighei	CM2	3.45	0.08	7(2)	108.2	1, 2, 6, 7, 8, 17
Murchison	CM2	3.86	0.17	13(1)	769.7	3, 8, 17, 18, 21, 25, 26
Murray	CM2	3.82	0.22	7	162.1	8, 15, 17, 21
Nawapali	CM2	3.38	0.06	2	10.7	8
Niger I	CM2	4.89	0.02	2	9.3	8
Nogoya	CM2	3.81	0.11	7	130.6	1, 8, 10, 17
NWA 1758	CM2	4.41	0.02	4	16.8	8
NWA 4428	CM2	3.08		1	3.9	5
PCA 02010	CM2	3.82		1	9.9	19
Pollen	CM2	3.55	0.27	3	181.3	8, 12
QUE 93005	CM2	4.21	0.00	2	9.4	19
QUE 97077-99355	CM2	3.48	0.12	4	37.0	19
QUE 99886	CM2	4.00		1	8.9	19
Santa Cruz	CM2	3.49	0.02	4	56.8	7, 8, 12, 26
TNZ 082	CM2	4.29	0.12	2	58.6	8
Yamato-74662	CM2	3.89	0.01	2	4.8	8
Felix	CO3.3	4.52	0.01	3	107.8	7, 8, 20
Kainsaz	CO3.2	4.86	0.10	6	195.9	3, 8, 11, 21, 26
Lance	CO3.5	4.49	0.16	11	283.8	1, 2, 7, 9, 10, 21
Moss	CO3.6	4.68	0.03	3	1.4	5
Ornans	CO3.4	4.29	0.06	6	87.3	1, 7, 8, 10, 11, 17
Warrenton	CO3.7	4.45	0.04	5	175.8	1, 7, 17
Acfer 243	CO3	4.38		1	16.2	16
Acfer 332	CO3	4.57	0.05	2	101.8	5
Acfer 333	CO3	4.99		1	9.0	5
ALH 83108	CO3.5	4.47		1	6.3	19
ALHA77307	CO3.0	4.81		1	6.8	19
Colony	CO3.1	4.50	0.09	4	65.9	8, 17
DaG 005[c]	CO3	4.47	0.18	7	149.8	3, 16, 21, 22
EET 90043	CO3	4.94		1	6.4	19
FRO 90006-95002-99040	CO3	4.63	0.05	3	146.5	3
HaH 043	CO3	4.07		1	14.1	16
Isna	CO3.8	4.16	0.18	7	242.8	8, 11, 17, 21, 26
JaH 084	CO3	4.83		1	49.2	23
MET 00694	CO3	4.68		1	14.6	19
NWA 062	CO3.3	4.15	0.03	2	162.8	26
NWA 1232-1277-1292	CO3	4.35	0.05	3	108.3	26
NWA 4421	CO3	4.57		1	13.7	8
NWA 763-1631-1757	CO3	3.99	0.10	4	81.0	8
QUE 97416	CO3	4.08		1	10.9	19
Sahara 02502	CO3	4.55		1	31.2	8
Sahara 98067	CO3	4.38		1	4.6	8
Tiffa 8	CO3	4.54		1	1000	5
Yamato-81020	CO3.0	4.57		1	1.9	14
Acfer 59[d]	CR2	5.10	0.10	12	136.2	7, 11, 15, 16, 21, 22
DaG 574	CR2	4.91	0.08	2	22.1	5, 8
EET 87770-92048-92065	CR2	5.13	0.03	5	96.7	19
GRA 95229-98025	CR2	4.86	0.26	3	14.6	19
MAC 87320	CR2	5.13		1	10.0	19

Table 3. *(Continued).* Decimal logχ (in 10^{-9} m^3/kg) for carbonaceaous chondrites, after tentative pairing for desert finds. If more than 4 meteorites are paired only the earliest number is given with full list in the footnotes. Arithmetic mean and standard deviation (s. d.) of logχ are provided when more than one specimen was measured. N: number of specimen used in the mean (in brackets number of outliers); m: cumulated mass measured. Provenance code: see # in Table 1. Anomalies not included in Table 5 means are listed at the end.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
MET 00426-01017	CR2	4.86	0.26	3	14.6	19
NWA 1616-2196	CR2	4.57	0.12	2	33.3	26
NWA 801[e]	CR2	5.01	0.13	14	131.9	5, 12, 17, 21
PCA 91082	CR2	5.01		1	12.5	19
QUE 99177	CR2	5.08		1	5.8	19
Renazzo	CR2	5.17	0.16	6	144.4	1, 2, 8, 22
Shişhr 33	CR2	4.51		1	195.9	23
Temple Bar	CR2	4.97	0.14	2	45.3	5
Yamato-793495	CR2	5.15		1	0.2	7
Al Rais	CR2-an	4.97	0.03	3	18.7	12, 20
Kaidun	CR2-an	4.69	0.08	3	9.0	11
Tafafasset	CR-an	5.26	0.16	4(1)	11.8	8
GRO 95577	CR1	4.48		1	7.7	19
Acfer 082	CV3	4.10		1	12	16
Acfer 328	CV3	4.12	0.03	2	32	5
Acfer 272	CV3	4.39		1	14.9	16
Acfer 086	CV3	4.54		1	23.2	16
ALH 84028	CV3.2	3.92		1	311.4	19
ALH 85006	CV3	4.52		1	22.3	19
ALHA81003	CV3.0	3.68	0.02	2	3.8	19
Allende	CV3o	3.62	0.06	30(4)	6550	1, 7, 9, 10, 15, 18, 22, 26
Arch	CV3r	4.11	0.05	2	781.4	8, 26
Axtell	CV3o	3.14		1	85.2	8
Bali	CV3o	4.27	0.07	2	13.3	8
Bukhara	CV3	4.37	0.13	2	326.1	11
DaG 521-526-533-535	CV3	4.49	0.05	5	97.8	3
EET 96286	CV3	5.11		1	10.3	19
Efremovka	CV3r	4.83	0.10	4	125.3	8, 11
GRO 95652	CV3	4.23	0.07	2	11.8	19
Grosnaja	CV3o	3.97	0.03	5	90.0	1, 2, 7, 8
Kaba	CV3o	4.85	0.05	4(1)	8.2	6, 8, 21
LAP 02206-02228	CV3	3.69	0.17	4	347.9	19
Leoville	CV3.0	4.53	0.10	5(1)	62.2	8, 17, 21
MAC 02528	CV3	3.60		1	4.6	19
MET 00429[f]	CV3	4.63	0.08	8	205.8	19
Mokoia	CV3o	4.60	0.04	7	114.9	8, 20, 25, 26
Nova 002	CV3	3.88	0.23	2	1.9	15, 21
NWA 2086-2364-3118	CV3	3.16	0.07	3	77.1	17, 21, 26
NWA 3004	CV3	4.12		1	9.1	21
NWA 723	CV3o	4.19		1	17.6	8
NWA 760	CV3o	3.74	0.15	2	34.0	5, 8
NWA 1152	CV3	4.73		1	9.5	12
NWA 1465	CV3	4.70		1	8.0	5
NWA 1763	CV3.5	4.37	0.02	4	15.1	8
NWA 779	CV3	3.35		1	10.1	5
NWA 3192	CV3	3.89		1	3.5	26
NWA 989	CV3	4.09		1	19.6	26
QUE 94688	CV3	3.07	0.05	2	4.8	19
QUE 97186	CV3	4.01		1	15.4	19
Sahara 02503	CV3	4.42		1	216.0	5
Sahara 98044	CV3o	4.08	0.01	2	26.5	8, 21
SaU 202	CV3	4.19		1	232.5	23
RaS 221	CV3	3.74		1	28.7	23

Table 3. *(Continued)*. Decimal logχ (in 10^{-9} m^3/kg) for carbonaceaous chondrites, after tentative pairing for desert finds. If more than 4 meteorites are paired only the earliest number is given with full list in the footnotes. Arithmetic mean and standard deviation (s. d.) of logχ are provided when more than one specimen was measured. N: number of specimen used in the mean (in brackets number of outliers); m: cumulated mass measured. Provenance code: see # in Table 1. Anomalies not included in Table 5 means are listed at the end.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
RaS 251	CV3	3.31		1	90.3	23
Tungsten Mountain 011	CV3	3.99	0.08	2	15.1	26
Tibbobura	CV3	4.71		1	0.2	21
Vigarano	CV3r	4.36	0.07	5	121.0	1, 7, 8, 10
Anomalies						
Acfer 202	CO3	3.64		1	12.0	11
EET 96026	C4-5	3.77	0.45	5	18.5	19
NWA 521	CK4	2.95		1	17.3	26
MET 01149	CK3	3.54		1	8.7	19

[a]ALH 7306-9950-83100-84030-31-32-35-45-48-53.
[b]MET 00433-435-630-633-639-781-810-1070-72-75-78.
[c]DaG 5-6-25-27-67-303-628.
[d]Acfer 59-87-97-139-187-209-270, El Djouf 001.
[e]NWA 530-721-801-1083-1180.
[f]MET 00429-00430-00747-00761-011074.

Table 4. Decimal $^{l}og^{c}$ (in 10-9 m3/kg) for E, R, and ungrouped chondrites. Pairing notes: (1) ALH 84170-188-189-200-206, (2) EET 83254-307-332-87746.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
Abee	EH4	5.54	0.08	5	89.7	7, 17, 18
Qingzen	EH3	5.22	0.09	6	45.7	5, 12, 21, 26
Parsa	EH3	4.93		1	3.1	26
Galim B	EH3/4	5.64		1	13.9	8
Adhi Kot	EH4	5.68	0.20	4	75.0	11, 20, 21
Indarch	EH4	5.34	0.11	5	118.7	1, 6, 17, 22
Saint Sauveur	EH5	5.49	0.16	3	247.3	8
St. Mark’s	EH5	5.47	0.16	2	64.0	8, 20
Daniel’s Kuil	EL6	5.45	0.17	4(1)	48.0	8, 17, 20
Hvittis	EL6	5.44	0.11	3	75.2	1, 7
Jajh Deh Kot Lalu	EL6	5.42	0.02	3	46.5	12, 20
Khairpur	EL6	5.48	0.06	3	112.8	8, 17
Neuschweinstein	EL6	5.48	0.03	2	9.6	5, 22
Pillister	EL6	5.54	0.13	7	182.2	1, 6, 7, 11, 17
Ufana	EL6	5.44	0.12	2	14.6	5, 2
Finds						
Adrar Bous	EL5	5.35	0.10	2(1)	40.0	5, 9
ALH 82132	EH4	4.84			3.9	20
ALH 84170 (1)	EH3	5.24	0.09	5	29.9	19, 20
ALH 85119	EL3	5.16		1	11.6	19
ALHA77295	EH3	5.06	0.17	2	3.2	19
ALHA81021-83018	EL6	5.21	0.06	3	42.4	19, 20
Atlanta	EL6	5.34	0.00	2	39.0	8, 17
Bethune	EH4/5	4.52	0.05	2	37.5	12, 21
Blithfield	EL6	5.45	0.10	2	59.4	8, 17
DaG 734	EL4	4.61	0.14	2	3.9	5, 15
Dho 1015	EH4	4.55		1	37.2	23
Eagle	EL6	5.45	0.09	3	49.8	3, 17, 21
EET 83254 (2)	EH3	4.95	0.18	6	37.6	19, 20
EET 90102-92063	EL6	5.15	0.18	2	29.5	19
EET 90299	EL3	5.22		1	6.5	19
EET 96103-135-217	EH4-5	5.10	0.10	3	26.6	19

Table 4. *(Continued)*. Decimal logc (in 10-9 m3/kg) for E, R, and ungrouped chondrites. Pairing notes: (1) ALH 84170-188-189-200-206, (2) EET 83254-307-332-87746.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
El Atchane 12	EL6	5.70		1	19.0	8
FRO 03005	EL4	4.98		1	20.7	3
GRO 95517	EH3	5.03		1	149.0	19
GRO 95626	EL6	5.01		1	13.9	19
HaH 317	EL4	5.28		1	0.8	12
Happy Canyon	EL6/7	4.22	0.40	4	157.0	8, 17
Ilafegh 009	EL7	5.49	0.12	3	63.2	16, 21
Itqiy	EH7	5.75	0.01	2	52.5	5, 8
KLE 98300	EH3	5.19		1	12.4	19
Kota-Kota	EH3	5.19	0.04	2	9.4	8
LAP 02225	EH	5.21		1	6.6	19
LEW 87119	EL6	4.77		1	8.3	19
LEW 87220-223	E3-an	5.34	0.01	2	14.0	19
LEW 88180	EH5	5.31		1	7.1	19
LON 94100	EL6	5.31		1	3.3	19
MAC 88136-02635	EL3	4.99	0.00	2	20.8	19
MET 00783	EH4	5.31		1	23.3	19
MET 00951	EL6	4.97		1	29.9	19
MET 01018	EH3	5.35		1	166.5	19
Northwest Forrest	EL6	4.65	0.34	3	27.5	12, 20
NWA 002	EL6	4.56	0.08	2	16.6	5, 11
NWA 1222	EL5	5.59		1	3.9	21
NWA 305	E3	4.35		1	4.4	21
NWA 4282	EL6	3.19		1	10.9	5
NWA 974	EH6	5.47		1	11.6	5
NWA 1949-2036	EL6	5.61	0.07	2	26.5	5
PCA 91020	EL3	5.28		1	6.3	19
QUE 93372	EH5	5.43		1	6.1	19
QUE 94594	EL3	4.87		1	6.3	19
QUE 99158-387	E	5.14	0.27	2	12.1	19
RKPA 80259	E5	4.70		1	10.7	19
Roach Dry Lake 030	EL6	4.56		1	2.7	26
Sahara 97096-162	EH3	5.4	0.03	3	301.6	5, 8, 21
SaU 281	EH3	4.79		1	13.0	22
SaU 188	EL4	4.84		1	92.8	23
South Oman	EH4/5	5.55	0.11	3	19.2	12, 20
TIL 91714	E5	5.03		1	149.7	19
TNZ 031	EL5	4.50		1	5.3	16
Yamato-793161	E3	4.92		1	0.2	14
Yamato-691	EH3	5.41		1		14
Yilmia	EL6	4.90	0.22	4	22.9	5, 12, 17, 18
LAP 02238-03645	R	3.10	0.26	2	15.3	19
NWA 1472-6-7-8	R3	3.1	0.07	4	70.3	24
PRE 95404-10-11	R3	3.36	0.05	3	7.6	19
Sahara 03013	R3	3.48		1	17.5	9
DaG 013	R3.5-6	3.16		1	20.9	16
ALH 85151	R3.6	3.14	0.04	2	8.7	19
PCA 91002-241	R3.6-6	3.11	0.05	4	61.1	19
Carlisles Lake	R3.8	3.05		1	4.8	12
NWA 978	R3.8	2.96	0.01	3	1.0	5
NWA 1774	R3.8/6	3.26		1	6.9	8
Acfer 217	R3.8-5	2.86		1	12.5	16
Rumuruti	R3.8-6	3.09		1	48.8	22
NWA 753	R3.9	2.96	0.09	9	78.2	5, 8, 17, 18
DaG 417	R3-4	3.29	0.03	2	26.0	8, 21
Sahara 99527-31	R3-5	3.23	0.0371	3	7.7	5, 8

Table 4. *(Continued)*. Decimal $^{l}og^{c}$ (in 10-9 m3/kg) for E, R, and ungrouped chondrites. Pairing notes: (1) ALH 84170-188-189-200-206, (2) EET 83254-307-332-87746.

Meteorite	Type	Logχ	S. d.	Nb sample	Mass (g)	Collection
Hughes 30	R3-6	3.20		1	14.6	5
HaH 119	R4	3.03	0.08	3	18.8	5, 16, 21
NWA 2198	R4	2.99		1	6.6	26
NWA 800	R4	3.10	0.14	2	1.1	5, 18
NWA 1784	R4/5	3.31	0.09	5	17.5	8
RAS 201-249–JAH 234	R5	3.67	0.08	4	529.5	23
NWA 830	R5	3.37		1	5.2	26
NWA 1668	R5	2.99		1	3.4	17
LAP 04840	R6	3.57		1	1.3	19
Anomalies				1		
LAP 031156	R4	4.29		1	1.0	19
Sahara 98248	R4	4.14	0.02	3	8.3	8
Asuka-881988	R4	4.17		1	0.7	14
Kakangari	K	4.88	0.07	3	148.3	8, 12, 21
Lea County 002	K	4.70	0.07	2	8.0	12, 20
LEW 87232	K	4.96	0.07	2	14.3	19
Deakin 001	UNGR	4.28		1	7.2	12
HaH 180	UNGR	3.11	0.17	2	53.8	12, 16
Motpenab	UNGR	4.44		1	9.7	12
NWA 517	UNGR	3.48		1	5.3	26
NWA 960	UNGR	3.74		1	2.3	5

The moderate decrease in logχ and increase of s.d. for finds versus falls provide a measure of the effect of weathering. No outliers appeared for falls, but Acfer 202, with a logχ of 3.64, would deserve further investigation. Another source of scatter for CO3 appears to be the effect of metamorphism. Recently Quirico et al. (2003) have proposed a calibration of metamorphic grade in type 3 chondrites, based on the characteristics of the Raman spectroscopy signature of organic matter. They have shown that this is a much better proxy for metamorphism than the standard thermoluminescence technique, especially for carbonaceous chondrites (Bonal et al. 2006). Figure 2 shows a general decrease of logχ with metamorphic grade as measured by the Raman parameter I_D/I_G (Bonal et al. 2007), not including the strongly weathered and thus metal-depleted meteorites Allan Hills (ALH) 77307 and Colony. For the purpose of increasing the database we have performed a Raman spectroscopy study for two meteorites not included in Bonal et al. (2007) study: Frontier Mountain (FRO) 90006, an Antarctic find, and Moss, fallen in 2006. The Raman spectra yield the following parameters: FWHM-D = 96 ± 12 and I_D/I_G = 1.24 ± 0.01 for FRO 9006, FWHM-D = 79 ± 2 and I_D/I_G = 1.48 ± 0.07 for Moss. Both appear to be grade 3.6 according to the organic maturation grade. Moss, along with Warrenton, stands out in Fig. 2 as being more magnetic than predicted by the I_D/I_G parameter. A plot of logχ versus the other Raman parameter FWHM-D shows exactly the same relationship. We note that our Moss 3.6 classification agrees with the petrographic classification by J. Grossman (The Meteoritical Bulletin Database at http://tin.er.usgs.gov/meteor/metbull.php). Macroscopically Moss also stands out with respect to other CO3 by being very friable, indicating an atypical history. The source of dispersion in Fig. 2 may tentatively be ascribed to variable hydrothermal alteration history.

Metal-Rich CB, CH, and CR Chondrites

These three metal-rich groups have been shown to be part of the same "clan" of very primitive chondrites (Krot et al. 2002). While metal dominates the magnetic mineralogy, magnetite and pyrrhotite are also present (e.g., Endress et al. 1994). For CH a mean logχ of 5.36 ± 0.20 is obtained on four meteorites. Obviously, the weathering of some desert CH meteorites (e.g., Acfer and Antarctic meteorites) biases this mean toward lower logχ. CB show a higher average, 5.65 ± 0.13 on nine meteorites, in agreement with a higher metal content (Krot et al. 2002).

For CR we excluded two strongly weathered meteorites (Shişhr 33 at 4.51 and Northwest Africa (NWA) 1616 at 4.57), the anomalous Kaidun fall (mixed lithologies from different chondrite groups) and the only CR1 (GRO 95577) from the mean: 5.04 ± 0.12. It is still likely displaced toward a lower value due to weathering, although finds exhibit a mean logχ of 5.04 ± 0.12. The two falls Renazzo and El Rais exhibit logχ of 5.17 (the highest among CR2) and 4.97, respectively. This conforms with the fact that El Rais is somewhat anomalous for a CR (with distinctly higher hydrothermal alteration, Brearley and Jones 1998) and suggests that the effect of weathering may correspond to an average decrease of 0.13 in logχ (taking Renazzo as the reference). Tafassasset, whose classification is controversial, shares a similar logχ value with Renazzo (5.26), supporting the suggestion that it is a metamorphosed CR (Bourot-Denise et al. 2002). Kaidun,

Table 5. Mean logχ with standard deviation and number of meteorites for the different chondrite groups discussed in the present paper. Within brackets is the number of meteorites excluded from the mean if any (see discussion in the text). The mean of individual s.d. (obtained on several specimens of the same meteorite) is also indicated.

Class	logχ	S.d.	N	Mean s.d.
C2	4.24	0.54	18	0.06
C3–4	4.75	0.28	10(1)	0.05
CB	5.65	0.13	9	0.16
CH	5.36	0.20	4	0.09
CI	4.66	0.09	5	0.06
CK	4.62	0.14	27(2)	0.04
CM	3.90	0.43	52	0.10
CO3 falls	4.54	0.20	6	0.06
CO3 finds	4.49	0.28	21(1)	0.09
CR	5.04	0.12	14(4)	0.14
CV	4.12	0.49	43	0.07
E finds	5.05	0.43	56(1)	0.12
EH falls	5.48	0.16	7 (1)	0.16
EL falls	5.46	0.04	7	0.09
K	4.85	0.13	3	0.07
R	3.18	0.20	24(3)	0.08
LL falls	4.11	0.30	43	0.09
L falls	4.87	0.10	140	0.06
H falls	5.32	0.10	143	0.06

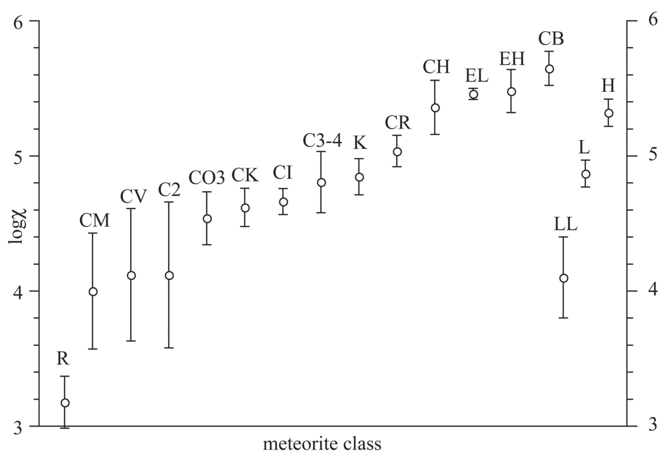

Fig. 1. Mean magnetic susceptibility (logχ with χ in 10^{-9} m^3/kg) for the different studied groups (Table 4), compared to ordinary chondrite groups. Falls only are used for OC (after Rochette et al. 2003) CO3, and E chondrites.

with its mixed lithologies (including CI and CM/C2; e.g., Zolensky and Ivanov 2001) has a logχ of 4.69, tending to CI or CM/C2 values (see the CI, CM, and C2 Chondrites section below), although the CR lithology dominates. In terms of hydrothermal metamorphism we may point out a distinct decrease of logχ with increasing hydration from Renazzo to El Rais, Kaidun and the CR1 GRO 95577, a very fresh meteorite with a logχ of only 4.48.

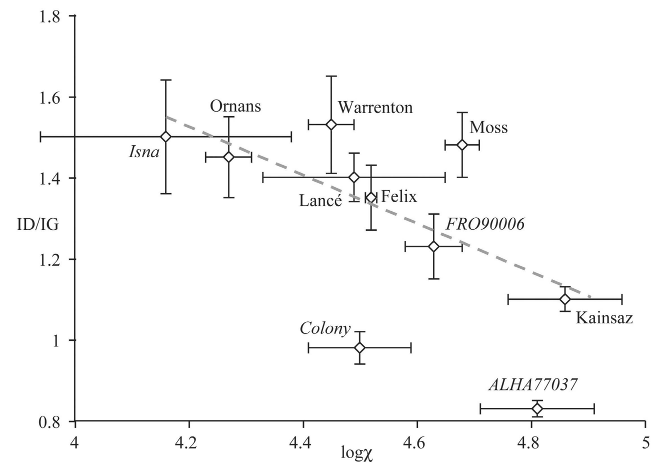

Fig. 2. Logχ versus metamorphic grade as measured by the Raman parameter I_D/I_G for CO3 (after Bonal et al. 2007). Metamorphism increases with I_D/I_G. Finds are labelled in italics.

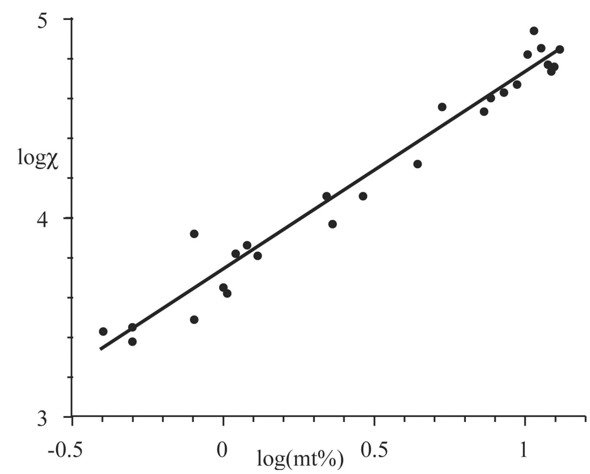

Fig. 3. Logχ versus magnetite amount (in wt%) as measured by the saturation magnetization (see text for references).

Magnetite-Bearing CK and Ungrouped C3-4 Chondrites

For these meteorites, as well as C2, CI, CM2, and oxidized CV, previous magnetic studies have estimated the magnetite amount using saturation magnetization measurements on very small samples (Larson et al. 1974; Watson et al. 1975; Herndon et al. 1976; Hyman and Rowe 1986; Thorpe et al. 2002). Figure 3 presents the correlation between their magnetite weight % (mt%) and our logχ measurements. We obtain log(mt%) = 0.994 logχ + 3.73 with $R^2 = 0.96$. The correlation is quite satisfactory, demonstrating in particular that these meteorites are on average homogeneous even at the 0.1 g level. Dispersion, besides heterogeneity and measurement errors, can arise from the contribution of other magnetic minerals than magnetite. The obtained correlation predicts a specific susceptibility for magnetite of 5.4×10^{-4} m^3/kg, compared to the theoretical value of 5.8×10^{-4} m^3/kg. We used this correlation

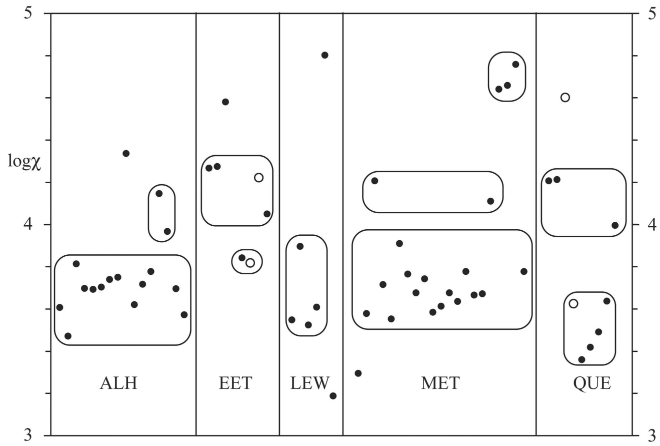

Fig. 4. Pairing hypotheses for CM and C2 (full and open dots, respectively) of the Antarctic sites ALH, EET, LEW, MET, and QUE, based on logχ values. All specimens (eventually several per meteorite) are plotted along the x axis by numbering order for every site. CM and C2 have been considered together but are listed separately in Table 3.

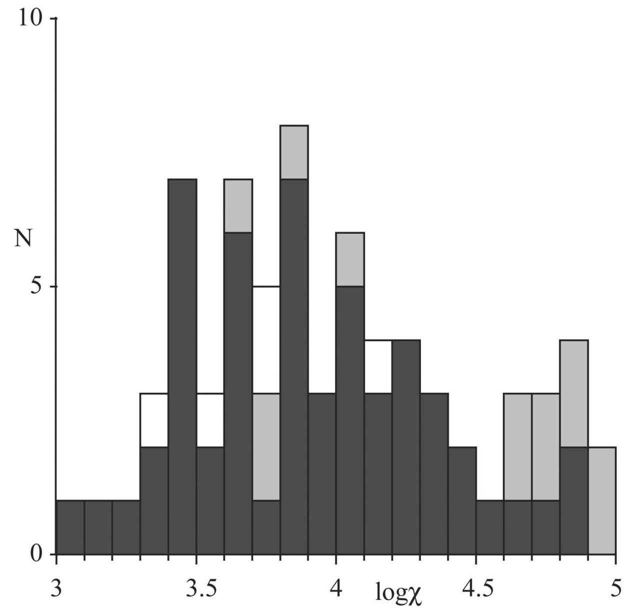

Fig. 5. Frequency histograms of individual meteorite logχ for CM (dark gray), unpaired C2 (light gray), and Antarctic C2 paired with CM2 (white; see text).

to extrapolate the logχ value for Revelstoke (from Larson et al. 1974).

CK show a well-grouped mean logχ, at 4.62 ± 0.14. No trend with metamorphic grade is observed. As magnetite is the major magnetic mineral (Geiger et al. 1995) we expect little bias due to weathering. Meteorite Hills (MET) 01149 (logχ = 3.5) stands out as an outlier. The present classification of this meteorite (CK3 based on petrographic examination only) is defined as preliminary and deserves further investigation. It could be a CV3 instead (see below). The other outlier, NWA 521 (logχ = 2.95), could be a R chondrite.

The ungrouped C3 and C4 chondrites, although showing a larger variation, yield a mean logχ in the same range as CK: 4.75 ± 0.28, with no difference between grade 3 and 4. One may consider that some of the ungrouped C3 and C4 (especially among the Antarctic ones) are in fact CK, like Ningqiang which is alternatively classified as C3 or CK3. Elephant Moraine (EET) 96026, first classified as R and now as C4-5 (Tonui et al. 2002), is much less magnetic, with a logχ = 3.77 ± 0.45. It is definitely anomalous, and shows an unusually high heterogeneity.

CI, CM, and C2 Chondrites

Despite the limited number of meteorites (5) CI yield a well-defined mean logχ, at 4.66 ± 0.09 (or 4.69 ± 0.09 excluding the extrapolated Revelstoke value), the extremes being Alais and Orgueil, at 4.56 and 4.78, respectively. As Orgueil has suffered a large terrestrial weathering of its pyrrhotite into sulfates (Gounelle and Zolensky 2001) it suggests that pyrrhotite has a minor contribution to logχ in CI, with respect to magnetite.

Both CM and C2 show a wide range of logχ, over more than two orders of magnitude (from 3.19 to 4.94). Even with the proposed pairings (see Table 3) made for Antarctic chondrites, half of the CM entries and all but four C2 (Acfer 94, Adelaide, Bells, Essebi and Tagish Lake) are of Antarctic origin. As an example of the pairing hypothesis allowed by the large scatter of logχ in theses meteorites (Fig. 4 and Table 3), one can consider the Elephant Moraine case: 3 different C2 falls may be proposed corresponding to the 90, 92 and 96 series, with logχ at 4.76 ± 0.25, 3.83 ± 0.02, and 4.22, respectively. ALH, Lewis Cliff (LEW), MET, and Queen Alexandra Range (QUE) also show 3 or 4 different C2 or CM2 values. Figure 5 presents the histograms obtained both in C2 and CM2 (including also the CM1 MET 01070). The similarities observed in both classes suggest that the vast majority of "C2" are CM2 yet to be characterized beyond the initial petrographic description (T. McCoy, personal communication). Indeed it is commonly observed in the ANSMET collection that meteorites initially declared C2 are later reclassified as CM2. Therefore we merged the two classes, thus implying a further pairing of 5 ANSMET C2 with CM2 from the same field (Fig. 4). As an example EET 96029 (C2) would pair with EET 87522–99437 (CM2) and EET 92006 (C2) would pair with EET 92005 (CM2) as they have identical logχ. We acknowledge that these proposed pairings are somewhat arbitrary and need to be tested with thin section observations and a more precise comparison of the locations where they were found.

Based on the histogram of merged CM/C2 (Fig. 5), one can distinguish 3 groups, according to the amount of magnetite, which we will call "low", "intermediate" and "high," by analogy to OC. The main "low" group (35 meteorites with logχ ≤3.92) may be considered as the "normal" CM2, as it includes for example Mighei, Murchinson, Murray, Nogoya. The only CM1 measured (MET 01070) also belongs to this group. The

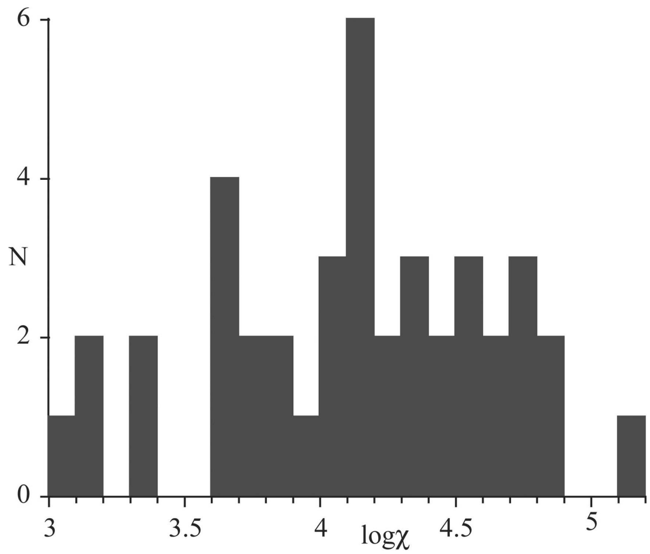

Fig. 6. Frequency histogram of individual meteorite logχ for CV3 chondrites.

"high" group (13 meteorites with logχ ≥4.58) is quite distinct and contains a majority of C2—Acfer 94, Adelaide, Bells, Essebi, Tagish Lake, MAC 87300, QUE 94582, WIS 91600—as well as some CM2: Niger I, EET 90021, LEW 88002, MAC 02606, MET 01077. Part of this subgroup has already been pointed out as "anomalous" with affinities to CI (Clayton and Mayeda 1999a). The rest (17 meteorites with logχ between 4 and 4.41, including Banten, Cimarron, Crescent, El Quss Abou Said, Haripura) can be considered as intermediate between the above two groups.

Neither terrestrial weathering nor parent body aqueous alteration seems to be clearly at the origin of the observed range of logχ. Falls are found in the whole range of values. The "low" group includes the only CM1 measured (MET 01070), and both the least and most hydrothermally altered CM2 according to Browning et al. (1996), Murchinson and Cold Bokkeveld, respectively. Unfortunately, CM2 studied by Browning et al. (1996) belong only to the low group. We also found no correlation between oxygen isotopic values (after Clayton and Mayeda 1999b) and logχ on 22 common data encompassing the whole logχ range (see further arguments on alteration effects in the discussion).

CV3 Chondrites

CV3 chondrites are characterized by highly variable amount of magnetite and metal (McSween 1977). This is verified by the scatter in logχ (from 3.07 to 5.11; Table 5; Fig. 6), even larger than in the C2/CM case. Distinct subgroups like those in C2/CM cannot be distinguished. The large majority of CVs are in the 4–4.8 logχ range; this is in agreement with the suggestion that CV and CK (with a mean logχ of 4.6) are related (Greenwood et al. 2004). One can point out as "anomalous" the most magnetic CV EET 96286 (logχ = 5.1) and the least magnetic Axtell, NWA 2364, QUE 94688 (logχ = 3.07–3.16). In the case of the least magnetic the effect of terrestrial weathering may play a role, but this cannot explain the whole scatter of logχ in CV. Also the oxidised or reduced character (McSween 1977) cannot be used as an explanation, as for example the oxidized CV Allende and Kaba are found at the two extremes (see Fig. 7). One may note a global tendency for the reduced CV to have larger logχ. On the other hand, metamorphism may provide the best explanation for the scatter of logχ: as in CO3 logχ appears to decrease with metamorphism (Fig. 7), as measured by the Raman spectroscopy of organic matter (Bonal et al. 2006). The large dispersion in this correlation may again be ascribed to different types of hydrothermal alteration (before or after metamorphism, with fluids of different redox state).

Enstatite Chondrites

For falls, the EH (Parsa excluded) and EL subgroups appears indistinguishable: 5.48 ± 0.16 and 5.46 ± 0.04, respectively (Table 5). The EH and EL subgroups have been defined from the beginning by high and low Fe/Si ratio. The actual dichotomity is confirmed by the most recent review (Zhang et al. 1995). However, the inference that EH are richer in metal than EL (e.g., Brearley and Jones 1998, p.10) has been made based on only a few modal analysis data (including finds) and is not confirmed by Zhang et al. (1995; their Table 2) and recent textbook (Krot et al. 2005). The inclusion of Happy Canon (with only 1% metal according to Jarosewich [1990]) in the statistics may be alone responsible for the apparently significant lower average metal in EL in some previous studies. Happy Canon appears to show among the lowest logχ, 4.22, due to both weathering and the escape of metal in this impact melt. Therefore, our nearly exhaustive study of EH and EL falls indicate that they show identical amount of metal (plus carbide and phosphide). Actually, when taking into account sulfides, a higher content of reduced iron still characterizes EH compared to EL. However, one may wonder if the lower sulfide content in EL could be due to their higher metamorphic grade, not to a different parent body (e.g., Kong et al. 1997). EL falls (only grade 6) yield an exceptionally low s.d. for their mean logχ, suggesting that they all come from the same homogeneous asteroid fragment.

The Parsa fall has a low logχ in agreement with the strong terrestrial weathering (abundant limonite and lawrencite) noted by Bhandari et al. (1980). As expected the finds show a large scatter due to weathering (Fig. 8). The lowest values are found in hot desert finds. An extreme case (not included in Fig. 8) is the anomalous NWA 4282 (Brandstatter and Kurat 2006), with a logχ = 3.2, indicating the total dissolution of metal. Alternatively the classification as an aubrite would explain the metal depletion.

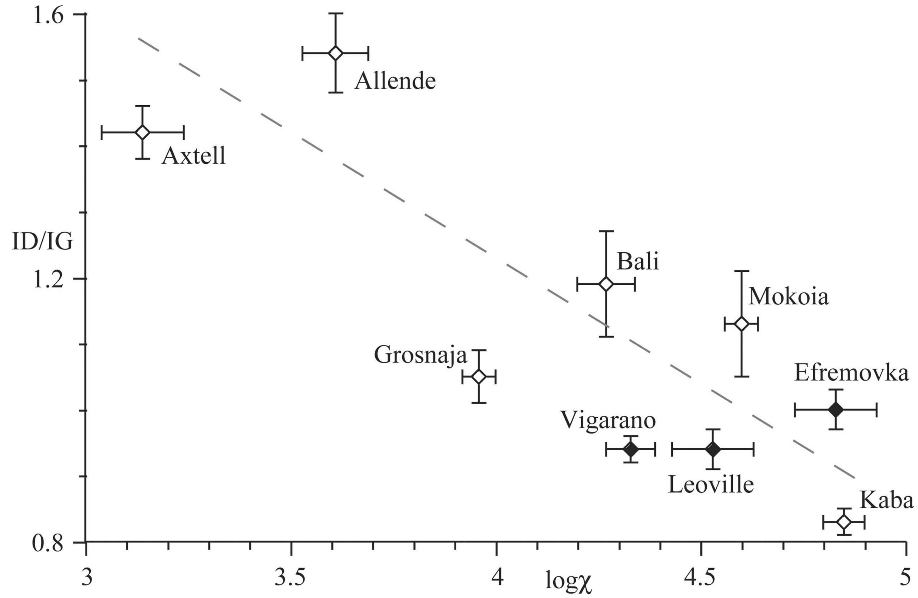

Fig. 7. Logχ versus metamorphic grade as measured by the Raman parameter I_D/I_G for CV3 after Bonal et al. (2006). Reduced CV appear with closed symbols.

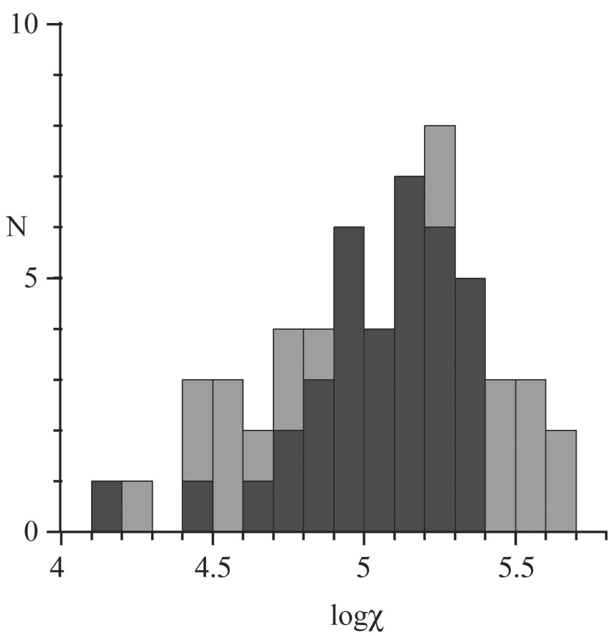

Fig. 8. Frequency histograms of individual meteorite logχ for E finds The light gray bars show the hot desert meteorites only (Sahara, Oman, Australia).

R Chondrites

The major opaque (and eventually magnetic) mineral in R chondrites is pyrrhotite, with an average modal abundance of 6% (Schulze et al. 1994; Kallemeyn et al. 1996). Magnetite and metal are extremely rare. The pyrrhotite analyses (Schulze et al. 1994; Kallemeyn et al. 1996) point toward hexagonal pyrrhotite ($Fe_{0.93–0.96}S$, normally antiferromagnetic) instead of the ferrimagnetic monoclinic pyrrhotite ($Fe_{0.87}S$). However, we will show that the magnetic mineral in R chondrites is pyrrhotite. This situation mimics the shergottite case (Rochette et al. 2001b, 2005) where the same contradiction exists, implying that hexagonal pyrrhotite is present in a metastable ferrrimagnetic state. A forthcoming paper will detail the magnetic properties of R chondrites. Evidence for pyrrhotite as the carrier of magnetization can be found in the hysteresis parameters and in the Curie temperature as shown in Fig. 9. In fact the thermal demagnetization curve is identical to the one obtained on the NWA 1068 shergottite, with a main maximum unblocking temperature lower than the one of monoclinic pyrrhotite (320 °C) and close to the one of hexagonal pyrrhotite (290 °C, see Schwarz 1975). The small bump in between 290 and 320 °C indicates minor monoclinic pyrrhotite that could be either formed during heating by conversion of the hexagonal form, or initially present in the sample.

The magnetic susceptibility of R chondrites is very low with respect to the other non-OC (except some CM and CV)—average logχ at 3.18 ± 0.20—not much above the lower limit defined by paramagnetism at 2.8 (see section 2). This corresponds to a low amount of ferromagnetic pyrrhotite (a few %) and an intrinsic susceptibility of pyrrhotite lower than that of metal and magnetite. Although poorly defined, the Rumuruti value fits within the mean.

Three anomalies arise, with a logχ near 4.2: Asuka-881988, LAP 031156, and Sahara 98248, all of type 4. To explain a logχ at 4.2 with pyrrhotite only, one needs at least 25 weight % of pyrrhotite. According to hysteresis loops the main magnetic mineral in Asuka-881988 and LAP 031156 is magnetite, further calling into question the R classification.

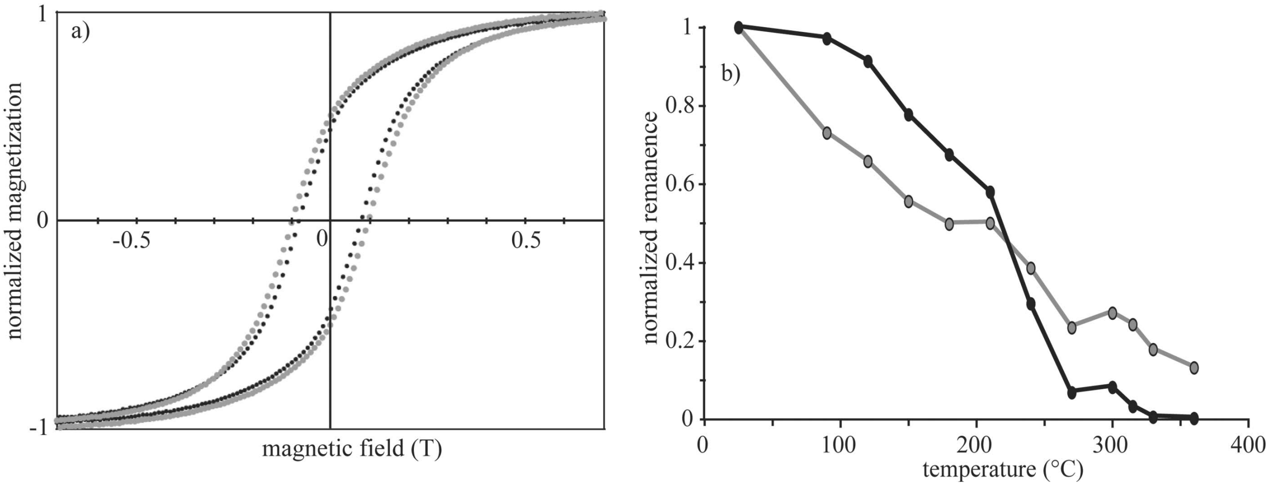

Fig. 9. a) Room temperature normalized hysteresis curve for a R chondrite (NWA 998) and a basaltic shergottite (NWA 1068; black and gray symbols, respectively); magnetization was measured up to 1 T and corrected from a linear slope fitted above 0.7 T; remanent coercive fields are respectively 127 and 134 mT; b) thermal demagnetization of saturation remanence (IRM) normalized to initial value for the same meteorites. NWA 1068 data after Rochette et al. (2005).

On the other hand oxygen isotope measurements confirms the R classification of Asuka. These three meteorites may constitute a magnetite-bearing sub-group in the R group. Finally, we note that there is no statistically significant effect of metamorphism on logχ, although the highest values (apart from the three anomalous R4 discussed above) are found in the R5 RaS 201 (3.7) and the R6 LAP 04840 (3.6).

Ungrouped Chondrites

In the Kakangari chondrites grouplet only three data points are available, providing a well-defined mean logχ at 4.85 ± 0.13.

Hammadah al Hamra (HaH) 180, at 3.11, has a value typical of a R chondrite, but it could also fit with the weakest CV. However, its petrology seems to exclude both affinities (A. Bischoff, personal communication). Type 3 NWA 960, with a logχ of 3.7, is in the same situation, but its δ^{18}O suggest an affinity with ordinary chondrites (Rumble et al. 2007). However, both are much less magnetic than LL3 chondrites (Rochette et al. 2003). Deakin1 and Motpena(b), both Australian finds at logχ = 4.3–4.4, could be fit with a number of classes: LL, weathered L, CO, CV, CK, etc. The Fa content of 11.7 for Motpena(b) seems to exclude ordinary chondrites. Deakin 001 (a type 3) fits with LL except for its very high δ^{18}O coupled with Δ^{17}O (Bevan and Binns 1989), which suggests affinities with NWA 960. Rumble et al. (2007) provide a further discussion of ungrouped metal-poor ordinary chondrite-related meteorites.

SATURATION REMANENCE OF NON-ORDINARY CHONDRITES

Measurement of saturation remanence (M_{rs}) needs to be done in a paleomagnetic laboratory, usually requires a small fragment (<5 g), and destroys the paleomagnetic signal. Therefore it was not performed systematically like our susceptibility measurements, but rather as a byproduct of paleomagnetic studies. In Table 6 we have compiled average log M_{rs} (in 10^{-3} Am^2/kg), based on our unpublished measurements and on the following references: Brecher and Arrhenius (1974), Gattacceca et al. (2004), Nagata (1979), Sugiura (1977), Sugiura and Strangway (1983 and 1987), Thero et al. (1993), Thorpe et al. (2002), Wasilewski (1981). Dispersion of the data for a given meteorite is larger than for logχ (on average 0.12 instead of 0.08) but not such as to prevent to define a representative value. As an example, the most studied meteorite, Allende (14 samples from 6 independent studies), yields quite consistent data. Part of the observed dispersion could be due to poor cross-calibration or different values of saturation field between the various studies, but also to the fact that M_{rs} is not only proportional to the amount of ferromagnetic minerals, but also to their grain size and shape, presence of crystallographic defects, etc. This multiplies the sources of heterogeneity for a given meteorite. Also, saturation remanence was measured on smaller samples than magnetic susceptibility.

The meteorites with low logχ (R, CM and some CV like Allende) also have low log M_{rs}. It is interesting to note that for R, CM, and CV one can see a linear correlation between the two parameters, contrary to OC and the other non-OC considered here (Fig. 10) (Rochette et al. 2003). This would mean in the R, CM, and CV cases that the grains carrying susceptibility and remanence are the same (or covariate), while in the other groups the remanence-bearing and susceptibility-bearing grains or zones in the grains are independent. The different slopes between CM-CV and R reflect the difference in magnetic minerals: magnetite and pyrrhotite, respectively. Pyrrhotite shows, as expected (e.g., Rochette et al. 2005), a higher M_{rs}/χ ratio. Asuka-88198, an

Table 6. Mean $\log M_{rs}$ (in 10^{-3} Am^2/kg) for non-ordinary chondrites. Reference code: 1: this study; 2: Gattacceca and Rochette (2004), 3: Thero et al. (1993); 4: Brecher and Arrhenius (1974); 5: Sugiura (1977), Sugiura and Strangway (1983, 1987); 6: Nagata (1979); 7: Thorpe et al. (2002); 8: Wasilewski (1981).

Meteorite	Type	logMrs	S.d.	Nb sample	Reference
Tagish Lake	C2	2.69	0.23	2	2, 7
EET 96026	C4–5	1.42		1	2
Ivuna	CI	2.81		1	5
Orgueil	CI	2.83	0.18	5	3, 4, 5, 7
HaH 280	CK4	3.12		1	1
Karoonda	CK4	3.00	0.10	1	5
Yamato-693	CK4	3.18	0.10	3	5, 6
Acfer 331	CM2	1.65	0.03	2	2
Cold Bokkeveld	CM2	1.67	0.11	2	1, 3
Kivesvara	CM2	1.81		1	5
Mighei	CM2	1.66	0.01	2	4, 5
Murchinson	CM2	2.12	0.31	3	1, 5, 7
Murray	CM2	1.93	0.21	3	4, 5, 7
Pollen	CM2	1.69		1	1
Yamato-74662	CM2	2.01		1	6
Acfer 333	CO3	3.42	0.02	2	2
Felix	CO3	2.65	0.08	2	1, 3
FRO 99040	CO3	2.69		1	1
Isna	CO3	2.57		1	1
Kainzaz	CO3	2.42		1	1
Lance	CO3	2.57		1	1
Moss	CO3	2.63	0.01	2	1
Ornans	CO3	2.37		1	1
Warrenton	CO3	3.02	0.23	2	1, 3
Renazzo	CR2	2.72	0.13	2	1, 5
Acfer 328	CV3	1.78		1	2
Allende	CV3o	1.81	0.06	14	1, 3, 4, 5, 7, 8
Axtell	CV3o	1.64		1	1
Efremovka	CV3r	3.10		1	1
Mokoia	CV3o	3.18	0.08	2	1, 5
Leoville	CV3r	2.77		1	5
Vigarano	CV3r	3.01	0.01	2	1,
Abee	EH	2.70	0.25	4	1, 3, 4
Yamato-691	EH3	2.54		1	5
Saint Sauveur	EH5	2.42		1	1
DaG 734	EL4	2.48		1	1
Eagle	EL6	1.83		1	1
Hvittis	EL6	2.12	0.30	2	1, 3
Neuschweinstein	EL6	1.83		1	1
Pfillister	EL6	2.08		2	1, 3
Yilma	EL6	1.93		1	1
ALH 85151	R	1.71		1	2
Asuka-881988	R	2.55		1	2
LAP 02238	R	1.71		1	1
LAP 03645	R	1.35		1	1
NWA 753	R3.9	1.57		1	1
PRE 95410	R3	1.91		1	1
NWA 978	R3.8/6	1.57		1	1
PCA 91002	R3.8/6	1.61		1	2
PRE 95411	R3.8/6	2.13		1	2
PCA 91241	R3.8-6	1.59		1	1
NWA 800	R4	0.49		1	1
NWA 1668	R5	1.70		1	1

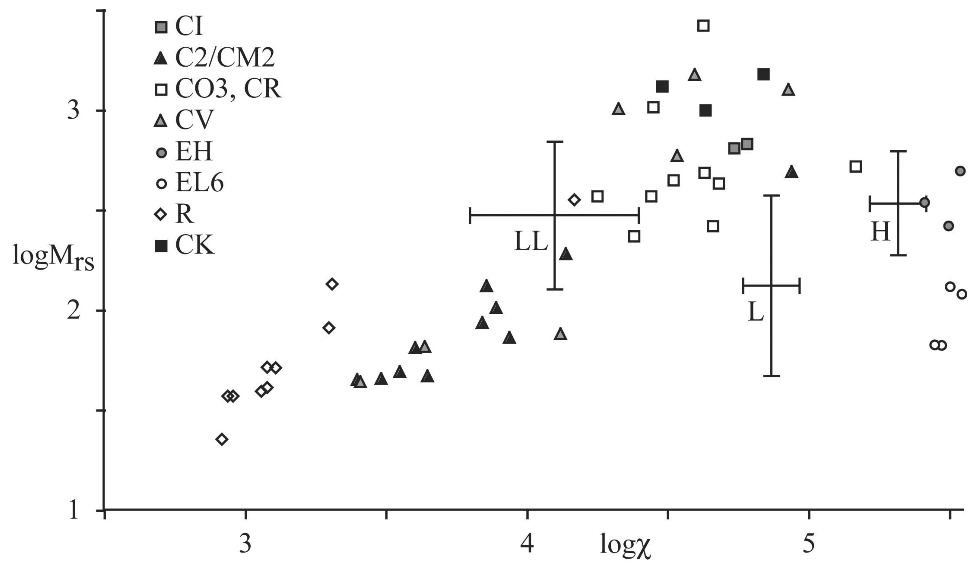

Fig. 10. Log of saturation remanent magnetization M_{rs} (in 10^{-3} Am^2/kg) as a function of logχ for non-ordinary chondrites compiled in Table 6 (see text) compared to mean values for OC (error bars without symbol) after Rochette et al. (2003). The only CR (Renazzo) is grouped with CO3 and the only C2 (Tagish Lake) with CM.

anomalous R chondrite according to our logχ measurements, is also strongly anomalous for M_{rs}, confirming that it deserves further examination. The same is true for EET 96026 (Table 6).

The metal-bearing E chondrites (selecting falls and two finds with fall-like logχ as metal weathering deeply affects the remanence) have relatively weak M_{rs}, like L and H OC. M_{rs} values are distinctively lower in EL6 compared to EH. This may be linked to the distinct Ni and Si contents in kamacite (Zhang et al. 1995) as well as distinct metamorphic history. The more magnetic carbonaceous chondrites have on average a larger remanence than OC. We attribute this to both the larger remanence potential of magnetite with respect to metal, and to the low metamorphic grade that preserves a small grain size and crystallographic defects. In particular the largest saturation remanence (log M_{rs} ≥3) is found in the magnetite-bearing CK, CO, and CV. The larger remanence, combined with larger coercivity (see Gattacceca et al. 2004, and references cited above) indicates that asteroids made of this type of carbonaceous material (C2, CI, CK, CO, or CV like) are the best candidates for the presence of a stable natural remanent magnetization, detectable in space or studied on meteorites in the laboratory.

DISCUSSION

The use of magnetic susceptibility measurement as a classification tool in non-ordinary chondrites is not as straightforward as in the case of ordinary chondrite falls. This is due to the overlap among different groups and to the very large spread observed in CM/C2 and CV. More criteria are needed, such as petrographic grade, presence of magnetite or metal, etc., to narrow the possibilities. Logχ similarities can be used among other criteria to define affinities between unclassified or anomalous non-OC and a given group, as done for the ungrouped chondrites in the Ungrouped Chondrites section above.

Concerning the anomalies pointed out in the previous sections, Acfer 202 (CO3?), MET 01149 (CK3?), and EET 96046 (C4–5?) all share a logχ value around 3.6, like NWA 960. They may deserve to be reexamined altogether as their "oddity" may receive a common explanation (see Rumble et al. 2007). Based on logχ values the most likely guess would be to relate them to CV. For those containing magnetite, an affinity to R chondrite is excluded, if we consider that pyrrhotite and eventually metal traces are the characteristic phases in R chondrites.

For CV3 and CO3, an effect of metamorphism on logχ has been proposed in the previous sections, if we assume that the apparent inverse correlation between the two indicates a causal relationship. What could be the origin of such a correlation? A change of redox conditions during early metamorphism (type 3) has been invoked in ordinary chondrites (Menzies et al. 2005). For higher grade OC it was also advocated by Gastineau et al. (2002) but not confirmed by magnetic susceptibility (Rochette et al. 2003). By that hypothesis, our observation would indicate an oxidation (responsible for the decrease in metal amount) during metamorphism, in the case of CO and reduced CV (see Krot et al. 2003). However, the case of Kaba (magnetite-bearing) points to the other way. We may propose as a working hypothesis an alternative isochemical explanation, at constant global redox state. The least metamorphosed CO3 (Shibata 1996) and CV3 (McSween 1977; Rubin 1997) are characterized by the coexistence of reduced (metal, cohenite) and oxidized (magnetite or even maghemite) phases. Equilibration of such

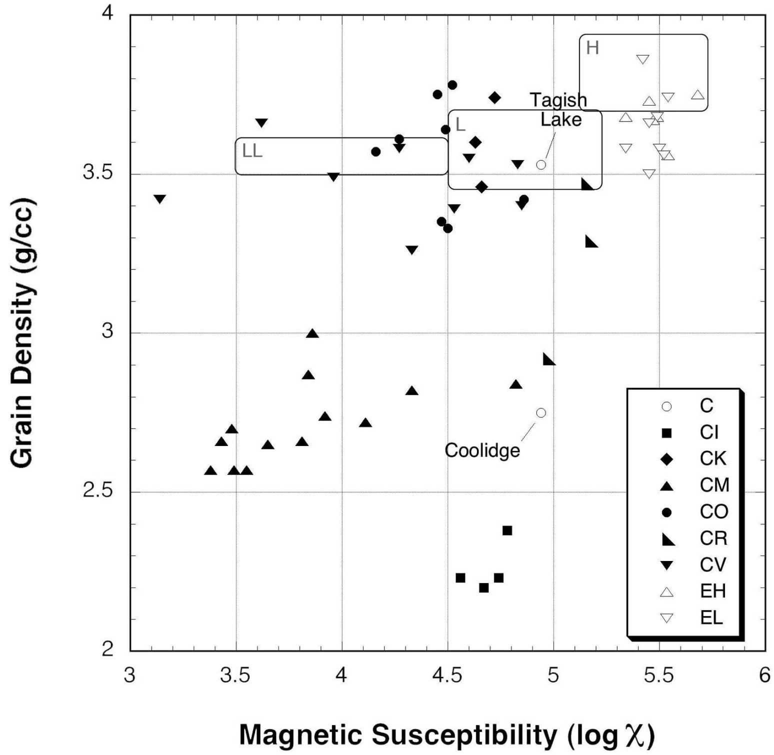

Fig. 11. Grain density (after Britt and Consolmagno 2003) as a function of $\log\chi$ for non-ordinary chondrites. Boxes delineate the zone for ordinary chondrites (LL, L, H).

an assemblage should necessarily produce a lower amount of magnetic minerals (metal + cohenite + magnetite). The following reaction with enstatite may be relevant: $Fe+Fe_3O_4+4\ MgSiO_3 => 4\ MgFeSiO_4$. If SiO_2 is available another reaction may be favored: $Fe+Fe_3O_4+4\ SiO_2 => 4\ FeSiO_3$. Whether these reactions are kinetically possible at a mild metamorphism (e.g., 300 °C as invoked for grade 3.7 according to Bonal et al. 2006) remains to be investigated. Water may serve as a catalyst to reach equilibrium at such low temperature and cohenite (found only in the least metamorphosed CO3 by Shibata 1996) may be more reactive than metal. Cohenite is found adjacent to magnetite grains so its decomposition may be favored by the reaction: $Fe_3C+Fe_3O_4 => 3\ Fe+C+Fe3O4 => CO+3\ Fe+3\ FeO$. One interesting application of our findings is that log may be used as a proxy of metamorphism for CO3 and CV3 meteorite lacking petrographic evidence, provided that the effect of weathering is minor. This will be particularly efficient for CV3 due to the large spread observed. One may hypothesize that the same guide could be applied for CM2/C2, i.e., the most pristine material would correspond to the strongly magnetic subgroup (Bells, Essebi, Tagish Lake).

To further delineate the effect of hydrothermal metamorphism on $\log\chi$, we may compare it to another independent modal mineralogy proxy, grain density (Britt and Consolmagno 2003, Fig.11). Grain density variations indicate changes in the proportion of heavy (metal, sulfide, magnetite) or light (hydrated silicates, carbonates) minerals with respect to the dominant chondritic anhydrous silicates, as well as a change of iron content in these silicates. The proportion of metal or magnetite can play a role only in the strongly magnetic groups, e.g., CR and E, as shown by the identical grain density for LL and L chondrites. Grain density confirms that EL and EH metal contents do not significantly differ, while a faint trend is visible for CR with lower grain density for lower $\log\chi$. In the other groups grain density is mainly a measure of the amount of hydrothermal alteration resulting in higher amounts of light hydrated minerals. No correlation between $\log\chi$ and grain density appears for CO3 and CV3, while a rather clear positive trend appears for CM2. This suggests that at least part of the log dispersion is controlled by hydrothermal metamorphism in CM2 (magnetite amount decreasing with increasing hydratation), while no effect of hydrothermalism is evidenced in CO3 and CV3. However, this remains a hypothesis not confirmed by petrographic observations and oxygen isotope studies (see the Ungrouped Chondrites section) and contradicted by the large amount of magnetite in the most hydrated CI group. On the other hand, a decrease of metal content with increasing hydration is apparent in CR2.

It is worth mentioning that a percentage of magnetic minerals (magnetite or metal) within about 7–15% (i.e., $\log\chi$ in the 4.6–4.9 range) seems to characterize a wide variety of chondrites besides L: CK, K, CI, ungrouped C3-4, upper end member for CO, CM/C2, and CV(see Fig. 1). This indicates that this metal or magnetite content may be the average one of the asteroid belt. Higher content (H, CB, CH, CR, E) or lower content (LL, lower end member for CO, CM/C2, CV, and R) may be linked to specific situations, e.g., secondary redox processes.

CONCLUSIONS

The measurement of magnetic properties, mainly magnetic susceptibility (χ), provides a fast and fully non-destructive technique to quantify the modal composition of meteorites in terms of ferromagnetic iron minerals (mainly metal and magnetite, and accessorily pyrrhotite, schreibersite, cohenite). In ordinary chondrites it has proved very efficient as a classification tool and to identify anomalous samples (misclassified, mislabeled, etc.; see Gattacceca et al. 2007), thanks to the restricted range of logχ for LL, L, and H. Based on our compilation of the large majority of all declared non-ordinary chondrites we can now expand this classification scheme to a number of groups that also show a restricted range of logχ. They are, listed by logχ mean values: R << CO < CKC I ≈ C3-4 < Kak < CR < EL = EH ≈ CH < CB. In those groups a few outliers were evidenced, for which we suggest their classifications be reconsidered: Acfer 202 (CO), EET 96026 (C4-5), MET 01149, and NWA 521 (CK), Asuka-881988, LAP 031156, and Sahara 98248 (R).

For three groups we observed a scatter of magnetic susceptibility of two orders of magnitude: C2, CM2, and CV3. C2 and CM2 show the same dispersion and we suggest that most C2 (essentially from ANSMET) are in fact CM2. In the merged C2/CM2 population we can distinguish 3 sub-groups by order of magnetic mineral amount, which we propose to call "low," "intermediate" and "high," by analogy with the OC. The "low" group corresponds to the "normal" CM2, e.g., Mighei, Murchinson, Murray, Nogoya. The "high" (i.e., magnetite-rich) group includes in particular Tagish Lake, Adelaide, Bells, Essebi, Niger I, with affinities with CI. In CV3 the scatter seems to correlate with thermal metamorphism, as measured by the Raman spectra of organic matter: logχ decreases with increasing metamorphism. The same correlation is observed for CO3, with a much more restricted spread. We suggest that this correlation eventually corresponds to the reaction of reduced (e.g., metal) and oxidized (e.g., magnetite) magnetic phases initially present in the more pristine material. However, the observed correlation may not mean that metamorphism is actually the cause of the decrease in magnetic mineral amounts in those meteorites with complex history. Hydrothermal alteration seems to decrease logχ values in CM/C2 and CR2, while no effect is visible in CO3 and CV3. Finally, the large spread of logχ in C2/CM2 and CV3 can be used as a pairing tool for desert finds.

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