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Magnetic classification of stony meteorites: 1. Ordinary chondrites

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Abstract–We present a database of magnetic susceptibility measurements on 971 ordinary chondrites. It demonstrates that this parameter can be successfully used to characterize and classify ordinary chondrite meteorites. In ordinary chondrites, this rapid and non-destructive measurement essentially determines the amount of metal in the sample, which occurs in a very narrow range for each chondrite class (though terrestrial weathering can result in a variable decrease in susceptibility, especially in finds). This technique is particularly useful not only for a rapid classification of new meteorites, but also as a check against curation errors in large collections (i.e., unweathered meteorites, the measured susceptibility of which lies outside the expected range, may well be misclassified or misidentified samples). Magnetic remanence, related to magnetic field measurements around asteroids, is also discussed.

INTRODUCTION

The world's collection of meteorites amounts to more than 24,000 different falls or finds, among which 95% are stony types. The rate of discovery of new meteorites, mainly from Antarctica and hot desert areas, is about a thousand per year. Thus, there is a need for a rapid, systematic, and non-destructive means to characterize this unique sampling of solar system materials. Beside classifying meteorites by the nature and amount of their magnetic minerals, the magnetic properties of meteorites have a direct implication for the interpretation of magnetic field measurements by space probes studying asteroids (Kivelson et al. 1993; Richter et al. 2001; Acuña et al. 2002), the Moon (Hood et al. 2001), or Mars (Acuña et al. 1999).

Magnetic properties, such as low-field magnetic susceptibility (χ) and natural remanent magnetization (NRM), can potentially fill this need. NRM would seem to be more relevant for this purpose, because the measured magnetic field around asteroids is due to the *in situ* remanence of the body, whereas induced magnetization (proportional to χ) is negligible in the absence of an internal dynamo field. However, for a given meteorite, it appears that NRM values show a much larger dispersion than susceptibility values due to various secondary magnetizations irrelevant for estimating the natural remanence of their parent body (e.g., Wasilewski and Dickinson 2000; Rochette et al. 2001b). And the evaluation of these secondary magnetizations involves a tedious and destructive investigation.

By contrast, measuring room temperature low-field magnetic susceptibility provides an easy, systematic, nondestructive scan of meteorite collections. Unlike other types of rock magnetic measurements (hysteresis, thermomagnetic curves, NRM demagnetization, etc.), the measurement of magnetic susceptibility is particularly appealing as it does not involve destruction of the paleomagnetic signal, nor is it necessary to cut the main mass of the meteorite being studied.

Low field magnetic susceptibility, the ratio of the induced magnetization of a material to the strength of an applied magnetic field (<1 mT), depends on the capacity of the material to be affected by, or respond to, such a field. It is a function of the abundance of the various phases in the sample, weighed by their specific susceptibility. Since the major ordinary chondrite classes (H, L, and LL) are defined in part by their metallic iron content (the most magnetic material) one can see that in principle, following the early proposal of Sugiura (1977) and

Nagata (1979) to use saturation magnetization (M_s) as a classification proxy, this technique should provide a very robust way of classifying these meteorites. Indeed, M_s and χ appear proportional in ordinary chondrites (Sugiura 1977).

However, although hundreds of studies dealing with various meteorite magnetic properties have been published, only two systematic studies (i.e., on the scale of hundreds of samples) of magnetic susceptibility have been conducted previously. Russian studies have been reported by Herndon et al. (1972; see also Gus'kova 1976), who produced a synthetic table including 197 stony meteorite samples from 113 different meteorites. Unfortunately, this database, as given, is poorly self-consistent and does not fit with our database (see discussion in Rochette et al. 2001a). Work derived from Herndon et al. (e.g., Sonett 1978) may need to be re-examined. More recently, Terho et al. (1991 and 1993) reported a study of samples of 221 different stony meteorites from the Helsinki and Prague collections. In addition, Sugiura and Strangway (1987) made various compilations, but the data they used were not tabulated and their provenance is ambiguous (the main part probably came from Sugiura and co-workers' studies of Antarctic finds).

Rochette et al. (2001a) presented a common database of both the data of Terho et al. (1991 and 1993), a number of new magnetic susceptibility measurements from the Vatican meteorite collection (Consolmagno 2001), and the major collections from Italy. These collections include meteorites hosted in the Antarctic Museum in Siena (Folco and Rastelli 2000), the University at "La Sapienza" in Rome (Cavaretta Maras 1975), and at the "Giorgio Abetti" Museum in San Giovani in Persiceto (Levi-Donati 1996). Note, that the Antarctic Museum in Siena curates both the Italian Antarctic (Frontier Mountain) meteorite collection as well as a large number of Saharan meteorites. The collections of Natural History museums in Madrid (Muñoz-Espada et al. 2002) and Paris, as well as the Ecole des Mines in Paris have been measured and a few samples have been obtained from the Museum of Natural History (MNH) in London and from various private collections. Moreover, a number of newly classified meteorites (from the Sahara and Antarctica) have recently been measured in Siena. Thus, this paper is based on a much larger database than the one of Rochette et al. (2001a).

The scope of this study has been limited to stony meteorites because the magnetic measurement of massive metal pieces is quite delicate and requires different specific instruments. In the Vatican collection, all measurable samples were studied. In the other collections, the choice was limited to ordinary chondrite falls not present (or present with a low mass) in the Vatican collection (including the Antarctic and Saharan collections in Siena) and to non-ordinary chondrites. In the present paper, we will report only the measurements on ordinary chondrites, corresponding to about 80% of the database.

The total number of ordinary chondrite specimens presently in the database is about 1600; these are from 971 different stones, and correspond to a total mass of about 100 kg. Magnetic susceptibility is probably the most representative single parameter ever measured on meteorites, considering combined mass and stone number. With respect to Rochette et al. (2001a), the originality of the present contribution, besides adding numerous new data from the Siena, Paris, and Madrid collections, is to analyze the database and discuss its connection with petrogeochemical studies of meteorites based on the bibliography as well as a re-examination of some falls. Moreover, a saturation remanence (M_{rs}) database will also be put forward.

MAGNETIC MINERALOGY OF ORDINARY CHONDRITES

In ordinary chondrites, the abundances of the magnetic elements Fe and Ni vary according to geochemical class in the 18–28 and 0.6–1.8 wt% ranges, respectively (Jarosewich 1990). The most strongly magnetic ordinary chondrite phases are Fe-Ni alloys (e.g., Nagata 1979), which are responsible for the bulk of ordinary chondrite remanence and the major part of the magnetic susceptibility. Indeed, the other Fe or Ni bearing phases, paramagnetic silicates 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). For comparison, the observed ordinary chondrite range is 3 to 480 (10^{-6} m^3/kg).

A sphere of pure multidomain (MD) kamacite or taenite gives an apparent volumic susceptibility of K = 3 in SI units; the theoretical χ value for kamacite-taenite spheres is therefore 380×10^{-6} m^3/kg, based on a density of 7.9 g/cm^3 (Consolmagno and Britt 1998). The presence of non-negligible amounts of single domain or superparamagnetic metal grains in ordinary chondrites is highly unlikely, as the grain-size threshold to observe these magnetic states is about 20 nm (Butler and Banerjee 1975). Thus, χ measurements should represent a reliable proxy for metal concentration, independent of grain size down to 20 nm.

However, two complications occur. First, if metal grains are unequant, the average apparent susceptibility will increase with respect to the spherical case (see the Discussion section below). Second, tetrataenite, a highly anisotropic-ordered alloy specific to meteorites, has a lower χ than kamacite-taenite. No reference data are available on the specific susceptibility for tetrataenite. The observation of hysteresis loops of tetrataenite rich meteorites (Wasilewski 1988; Collinson 1987; Morden and Collinson 1992), before and after thermal conversion to taenite, suggests a χ about 5 times lower. In fact, χ values derived from hysteresis loops of nearly pure tetrataenite published by Funaki, Nagata, and

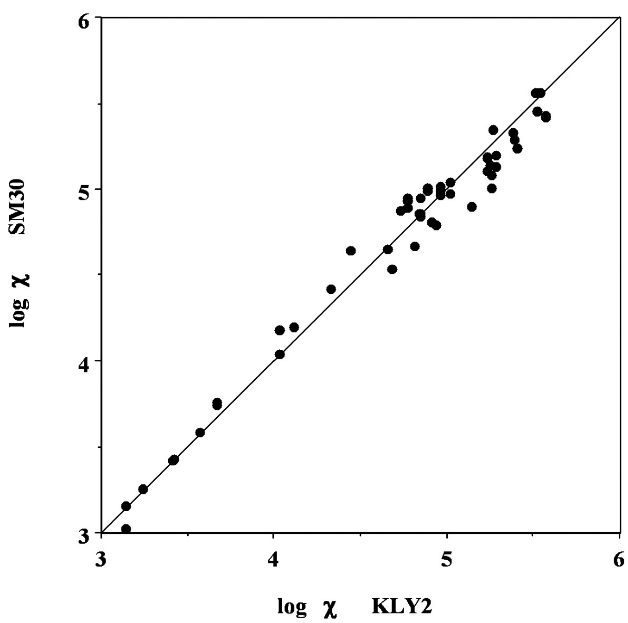

Fig. 1. Correlation of the logχ (in 10^{-9} m^3/kg) value obtained with the SM30 (or KT5) on end cuts or slices >8 cm versus the value obtained with the KLY-2 (mean of different samples <8 cm, after Table 1) on the same meteorite. Includes finds and a few non-ordinary chondrites.

Danon (1986) and Néel et al. (1964) are similar to the taenite theoretical value. In addition, a non-magnetic form of ordered Fe-Ni, antitaenite, has been described (Rancourt and Scorzelli 1995). Consequences of these complications in the χ versus metal amount relationship will be discussed in the following sections.

Besides metal, the presence of magnetite has been described in a few unequilibrated ordinary chondrites (Krot et al. 1997; Menzies et al. 2002 and pers. comm.), as well as in shock veins (Chen et al. 2002). In terms of apparent volumic susceptibility, magnetite is, in fact, equivalent to kamacite-taenite, so that it can be safely merged with the metal phase in the analysis of χ data.

MEASUREMENT AND DATABASE CONSTRUCTION

Measurement procedures have been discussed in detail in Rochette et al. (2001a) and will only be summarized here. A large coil (8 cm) alternating field bridge KLY-2 (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 already be reached for 50–100 g highly magnetic samples. The high homogeneity of the solenoid coil internal field allowed us to obtain reliable results on samples with unequant shape (fragments, slices, full stones). For each measured specimen, the decimal logarithm of apparent mass specific susceptibility χ is tabulated (in 10^{-9} m^3/kg). In selecting specimens, a minimum mass of 3 g (i.e., about one cubic centimeter) was set. Smaller masses were measured only in the case of rare meteorites for which no larger specimens were available. In any case, the precision remained better than 0.01 (in logχ).

For samples not fitting in the KLY-2 large coil, we tested another instrument: the SM30 (or its older version, KT5). This instrument is an LC oscillator that applies a flat coil to 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 the 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 thick. Volume susceptibility can be directly evaluated for an end-cut stone larger than this volume. Cross calibration of the KT5 with the KLY-2 instrument is described by Lecoanet, Leveque, and Segura (1999). For a slice of constant thickness less than 5 cm, a known correction factor can be applied. Using a Bartington dual frequency instrument, we checked meteorite samples as well as dispersed synthetic iron powders to ensure that no frequency dependence of magnetic susceptibility was observed.

In order to obtain mass specific values from SM30 measurements, the output has to be divided by the density (of the same meteorite, if available, or else of its type average), as obtained from the Terho, Pesonen, Kukkonen (1991) and Consolmagno and Britt (1998) databases. Fig. 1 compares data obtained from selected meteorites using both the SM30 (or KT5) and KLY-2 on different samples, including some non-ordinary chondrite samples. The correlation is very good, and it will be seen that the difference between the two measurements is in the same range shown by the variability of KLY-2 values obtained on different samples. Slightly lower values above 5 for SM30 may be due to the self-demagnetization field. Therefore the few SM30 (or KT5) data obtained on meteorites not measured with the KLY-2 can be included in the database with confidence.

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 (which is the case for ordinary chondrites). The anisotropy of the 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.

This paper is based on a comprehensive database, which includes data previously published in Rochette et al. (2001a) plus new measurements from Madrid, Paris, and Siena. This database has one entry per specimen (except for the Terho et al.

Table 1. Decimal log (in 10^{-9} m^3/kg) for ordinary chondrite falls. 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 (Ntot: total number of measured samples, if different from N); m: cumulated mass measured.

Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]	Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]
Djermaia	H	5.20	0.08	3	359	8	Ambapur Nagla	H5	5.31	0.01	3	197	1, 7, 8
Tieschitz	H/L3	4.97	0.13	3	82	2, 6, 7	Assisi	H5	5.21	0.09	2	113	1, 2
Bremervorde	H/L3	4.98	–	1	16	1	Barbotan	H5	5.29	0.12	1	–	1, 2, 7
Luponnas	H3-5	5.24	0.18	3/4	72	8, (1), 10	Beardsley	H5	5.16	0.11	3	39	1, 7
Fermo	H3-5	5.25	0.02	2	47	4	Bur Gheluai	H5	5.41	0.24	2/3	23	2, (9)
Hainaut	H3-6	5.35	0.08	2	193	7, 8	Cangas de Onis	H5	5.25	0.01	3	61	1, 7
Zag	H3-6	5.24	–	1	27	4	Castalia	H5	5.12	0.08	3	80	1, 2, 7
Dhajala	H3.8	5.12	–	1	48	8	Cereseto	H5	5.29	–	1	12	1
Akbarpur	H4	5.50	–	1	17	8	Chiang Khan	H5	5.29	–	1	14	4
Ankober	H4	5.46	–	1	77	8	Collescipoli	H5	5.36	0.08	3	135	1, 7, 9
Avanhandava	H4	5.20	–	1	3	8	Cosina	H5	5.36	0.08	2	128	8
Bath	H4	5.31	0.05	5/6	187	1, 8, (7), 9, 10	Cronstad	H5	5.37	0.01	2	12	1, 8
Beaver Creek	H4	5.28	0.02	3	23	1, 2, 7	Cross Roads	H5	5.36	0.09	2	5	1, 8
Bielokrynitschie	H4	5.31	0.08	3	63	1, 2, 7	Darmstadt	H5	5.68	–	–	24	8
Birni N'konni	H4	5.22	0.04	2	459	8	Dokachi	H5	5.28	0.07	2	108	8
Canellas	H4	5.35	0.03	3	56	1, 2, 9	El Hamammi	H5	5.55	–	1	32	3
Conquista	H4	5.28	–	1	19	8	Epinal	H5	5.31	0.08	2	204	1, 8
Feid Chair	H4	5.21	–	1	21	8	Favars	H5	5.50	–	1	15	1
Forest Vale	H4	5.33	0.08	2	398	8	Forest City	H5	5.27	0.05	3/4	221	1, 7, 10
Galkiv	H4	5.25	–	1	6	8	Gao-Guenie	H5	5.25	0.05	4	292	3, 4, 5
Grunenberg	H4	5.31	0.05	3	39	1, 8	Gross Divina	H5	5.37	–	–	9	1
Gursum	H4	5.09	–	1	2	3	Grzempach	H5	5.51	–	–	22	8
Gutersloh	H4	5.20	–	1	3	8	Gumoschnik	H5	5.27	–	–	46	8
Kesen	H4	5.29	0.03	3	230	2, 7	Heredia	H5	5.22	0.09	3	99	1, 8, 10
Lixna	H4	5.20	–	1	8	9	Hessle	H5	5.25	0.05	7	306	1, 7, 9, 10
Marilia	H4	5.32	–	1	3	8	Isthilart	H5	5.29	–	–	29	8
Menow	H4	5.31	0.07	2	75	1, 7	Jilin	H5	5.39	0.03	5	115	4, 5, 7, 10
Monroe	H4	5.38	0.00	2	64	1	Juancheng	H5	5.26	–	1	21	4
Motta di Conti	H4	5.39	0.03	3	25	2, 8	Kerilis	H5	5.38	0.06	2	75	1, 10
Nassirah	H4	5.22	0.06	2	309	8	Kiffa	H5	5.33	0.01	2	156	7, 8
Noventa Vicentina	H4	5.43	–	1	20	4	Kilbourn	H5	5.28	0.02	2	37	1, 2
Ochansk	H4	5.35	0.04	5	63	1, 2, 7, 9	Kunya Urgench	H5	5.25	–	–	31	4
Ourique	H4	5.23	–	1	16	5	La Colina	H5	5.32	–	–	50	8
Phu Hong	H4	5.27	0.07	3	426	1, 8	Laborel	H5	5.28	0.08	4/5	234	1, 8, (7)
Phum Sambo	H4	5.39	0.03	2	368	8	Limerick	H5	5.34	0.09	2	47	1
Quenggouk	H4	5.38	0.05	2	53	1,7	Macau	H5	5.44	0.02	2/3	248	8, (1)
Ste. Marguerite	H4	5.19	0.01	3/4	68	8, (10)	Malotas	H5	5.40	0.05	2	231	8
Sao Jose de R. Preto	H4	5.22	–	1	4	8	Merua	H5	5.34	–	–	25	8
Sena	H4	5.26	0.07	4	126	8, 9	Misshof	H5	5.40	0.01	2	11	1, 7
Seres	H4	5.33	0.17	2	6	7, 8	Molina	H5	5.42	0.16	2	19	1, 2
Tysnes Island	H4	5.24	–	1	12	1	Mooresfort	H5	5.35	0.04	2	16	2, 7
Weston	H4	5.22	0.01	2	20	1, 6	Mornans	H5	5.37	–	–	29	8
Agen	H5	5.20	0.07	5	107	1, 7, 9, 10	Nadiabondi	H5	5.20	0.08	2	32	4, 5
Alessandria	H5	5.35	–	1	50	2	Nammianthal	H5	5.17	–	1	30	7
Allegan	H5	5.32	0.04	7/8	78	1, 2, 7, 9, (10)	Nuevo Mercurio	H5	5.39	0.08	3	59	4, 7

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Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]	Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]
Ohaba	H5	5.27	0.08	2	240	8	St. Germain	H6	5.38	–	1	27	1
Olmedilla de Alar.	H5	5.28	0.03	3	52	8, 9	Supuhee	H6	5.29	0.15	3	414	1, 8
Oviedo	H5	5.29	0.37	2	17	8, 9	Takenouchi	H6	5.45	–	1	5	2
Pokhra	H5	5.34	–	1	13	8	Tjabe	H6	5.53	–	1	25	2
Pribram	H5	5.38	–	1	105	6	Torino	H6	5.40	0.00	2	200	1
Pultusk	H5	5.35	0.07	14/17	394	1, 2, 7, 9, 10	Toulouse	H6	5.32	0.04	2	48	1
Raco	H5	5.17	–	1	1	9	Trenzano	H6	5.43	0.11	4	47	1, 7, 9
Richardton	H5	5.46	0.09	2	227	1, 8	Vago	H6	5.27	–	1	8	8
Searsmont	H5	5.36	0.06	4	41	1, 8, 9	Vernon County	H6	5.51	–	1	26	7
Seldebourak	H5	5.25	0.03	2	98	8	Zhovtnevyi	H6	5.27	–	1	240	8
Sindhri	H5	5.29	0.04	3	19	8	Zvonkov	H6	5.36	–	1	129	8
Slavetic	H5	5.45	–	–	31	8	Bjurböle	L/LL4	4.56	0.03	5	3169	1, 7, 9, 10
Ställdalen	H5	5.40	0.07	2	189	1, 7	Cynthiana	L/LL4	4.45	0.03	2	8	1, 7
Tabor	H5	5.25	0.00	2/3	21	1, 7, (2)	Knyahinya	L/LL5	4.68	0.06	7	196	1, 7, 9, 10
Timochin	H5	5.35	0.08	3/4	59	1,.8, (7)	Holbrook	L/LL6	4.69	0.09	17/20	1093	1, 2, 3, 7
Uberaba	H5	5.30	0.02	2	31	1, 7	Mulletiwu	L	4.87	–	1	26	8
Udipi	H5	5.39	0.03	2	48	8	Bovedy	L3	5.07	–	1	16	4
Yatoor	H5	5.29	0.11	3	81	1, 8	Hallingeberg	L3	4.78	–	1	11	8
Djoumine	H5-6	5.32	0.05	2	6	4, 5	Khohar	L3.6	4.87	0.05	2	223	8
Benoni	H6	5.29	–	1	20	8	Hedjaz	L3.7	4.93	0.11	2	41	1
Bjelaja	H6	5.41	–	1	13	1	Mezo Madaras	L3.7	4.79	0.07	5/6	136	1, 6, 7, (9), 10
Butsura	H6	5.53	0.06	2	143	8	Kendleton	L4	4.87	–	1	120	1
Cape Girardeau	H6	5.36	0.06	2	104	1, 7	Lanzenkirchen	L4	5.04	–	1	19	7
Charsonville	H6	5.44	0.26	3	29	1, 7, 10	Rio Negro	L4	4.79	–	1	379	1
Djati-Pengilon	H6	5.19	0.04	3	70	1, 7, 9	Saratov	L4	4.88	–	1	90	1
Doroninsk	H6	5.30	0.13	2	3	1, 8	Tennasilm	L4	4.83	0.01	2	755	1, 7
Erxleben	H6	5.45	0.04	3	23	1, 7	Rupota	L4-6	4.69	–	1	110	8
Galapian	H6	5.34	–	1	30	8	Ausson	L5	4.95	0.05	6	227	1, 6, 7, (9), 10
Gopalpur	H6	5.37	–	1	46	8	Barwell	L5	4.87	–	1	85	8
Guarena	H6	5.23	0.06	2	168	1, 9	Chandakapur	L5	4.85	0.02	2	9	1, 7
Judesegeri	H6	5.31	–	1	30	8	Crumlin	L5	4.84	0.11	2	248	8
Kernouve	H6	5.51	0.03	5	117	1, 7, 9, 10	Domanitch	L5	4.93	0.01	2	431	8
Kikino	H6	5.24		1	9	2	Elenovka	L5	4.94	–	1	145	8
Klein Wenden	H6	5.21	0.01	2	6	1, 8	Ergheo	L5	4.84	0.06	3/5	105	1, 7, (9)
Lancon	H6	5.34	0.18	3	185	1, 7, 9	Farmington	L5	4.89	0.05	4	350	1, 7, 9
Moti-Ka-Nagla	H6	5.25	0.09	2	134	8	Homestead	L5	5.10	0.06	7	324	1, 8, 9, 10
Mount Browne	H6	5.36	–	1	25	7	Honolulu	L5	4.77	0.02	3	115	1, 9, 10
Nanjemoy	H6	5.42	–	1	28	7	Jhung	L5	4.93	0.02	2	120	8
Naoki	H6	5.41	0.03	2	253	8	Marmande	L5	4.95	–	1	25	1
Naragh	H6	5.34	–	1	62	2	Monte Das Fortes	L5	4.91	0.00	2	177	8
Nulles	H6	5.26	0.04	6	197	1, 8, 9	Monte Milone	L5	4.66	0.04	2	10	1, 2
Ogi	H6	5.35	0.05	3	57	8, 9	Mt. Tazerzait	L5	4.84	–	1	17	3
Orvinio	H6	5.15	0.01	2/3	228	1, 2, (7)	Muddoor	L5	4.94	0.18	2	62	8
Paitan	H6	5.20	–	1	23	8	Ohuma	L5	4.93	–	1	7	4
Peekskill	H6	5.13	–	1	32	1	Pampanga	L5	4.95	–	1	89	8

Table 1. Decimal log (in 10^{-9} m^3/kg) for ordinary chondrite falls. 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 (Ntot: total number of measured samples, if different from N); m: cumulated mass measured. *Continued.*

Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]	Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]
Reliegos	L5	4.95	–	1	8	9	Karkh	L6	4.93	0.04	2	129	8
Sevrukovo	L5	4.94	0.07	2	39	1, 7	Kisvarsany	L6	4.86	–	1	24	7
Shelburne	L5	4.87	0.16	2	81	1	Kukschin	L6	4.64	–	1	35	8
Tadjera	L5	5.00	–	1	31	1	Kunashak	L6	4.93	–	1	13	5
Tjerebon	L5	4.83	–	1	38	8	Kuttippuram	L6	4.71	–	1	402	8
Valera	L5	4,80	0,01	2	17	3, 5	Kyushu	L6	4.91	0.02	2	65	1, 7
Mbale	L5/6	4.99	–	1	15	3	L'Aigle	L6	4.88	0.08	12/16	1663	1, 2, 7, 8, 9, 10
Air	L6	4.96	–	1	9	5	La Becasse	L6	4.84	–	1	10	1
Akaba	L6	4.92	–	1	22	8	La Criolla	L6	4.79	0.06	2	42	4
Alfianello	L6	4.83	0.08	6/7	618	1, 7, 9, 10	Lalitpur	L6	4.94	–	1	21	8
Aleppo	L6	4.75	0.08	2	147	2, 7	Leedey	L6	4.93	–	1	22	1
Angers	L6	4.76	0.07	3	94	1, 8	Les Ormes	L6	4.94	–	1	67	8
Apt	L6	4.91	–	1	50	1	Lesves	L6	4.84	0.03	3	33	1, 8
Atoka	L6	4.88	–	1	17	1	Linum	L6	4.78	–	1	24	7
Aumale	L6	5.01	0.01	2	147	1, 9	Lissa	L6	4.93	0.04	6	61	1, 6, 7, 9
Aumieres	L6	4.67	0.05	3	96	1, 9	Los Martinez	L6	4.77	–	1	20	9
Bachmut	L6	4.84	–	1	13	1	Lundsgard	L6	4.96	0.00	2	47	1, 7
Bath Furnace	L6	4.88	0.06	2	71	1, 7	Madrid	L6	4.92	0.01	2	21	8, 9
Beni M'hira	L6	5.01	0.02	2	29	3	Mainz	L6	4.68	–	1	16	1
Berlanguillas	L6	4.94	–	1	11	1	Marion	L6	4.80	0.17	3	139	1, 7, 9
Bori	L6	4.95	0.08	2	24	1, 7	Mascombes	L6	4.90	0.08	3	424	1, 8
Bruderheim	L6	4.94	0.06	2	90	1, 7	Mauerkirchen	L6	4.85	0.09	3	32	1, 7, 9
Bushoff	L6	4.75	0.03	4	145	1, 2, 7, 10	Mern	L6	4.86	–	1	14	1
Cabezo de Mayo	L6	4.93	0.01	2/3	73	1, 7, (9)	Mezel	L6	4.78	–	1	45	8
Chandpur	L6	4.65	0.05	2	68	8	Milena	L6	4.96	0.12	2	97	2, 7
Chantonnay	L6	4.97	0.06	4/5	376	1, 8, (7), 10	Mocs	L6	4.87	0.05	15	1515	1, 2, 7, 9, 10
Chitenay	L6	4.84	–	–	230	8	Modoc (1905)	L6	4.66	0.05	3	677	4
Chateau-Renard	L6	4.98	0.06	6	116	1, 7, 9, 10	Montlivaut	L6	4.80	0.02	2	435	1
Claxton	L6	4.94	–	–	9	4	Monze	L6	4.93	0.03	2	191	1, 7
Colby (Wisconsin)	L6	4.90	0.00	2	248	8	Nerft	L6	5.07	0.08	3	52	1, 4, 7
Dandapur	L6	4.57	0.04	2	286	8	New Concord	L6	4.99	0.03	4	541	1, 7, 9, 10
Danville	L6	4.90	–	–	12	7	Oesel	L6	4.78	0.03	2	46	1, 7
Dolgovoli	L6	4.88	–	–	59	8	Ojuelos Altos	L6	4.91	0.05	2	70	8, 9
Dosso	L6	4.82	–	–	65	8	Ovambo	L6	4.92	–	1	40	7
Drake Creek	L6	4.65	0.04	2/3	177	8, (1)	Pacula	L6	4.83	0.03	2	27	1, 7
Durala	L6	4.88	0.03	2	60	1, 7	Pavlograd	L6	4.77	0.01	2	66	1, 9
El Tigre	L6	5.03	–	–	11	4	Peace River	L6	4.92	–	–	4	4
Fisher	L6	4.92	0.03	2	264	1, 9	Perpeti	L6	4.88	0.02	2	407	8
Gambat	L6	4.83	–	1	98	1	Pervomaisky	L6	4.91	–	1	462	8
Girgenti	L6	4.94	0.04	4	172	1, 5, 7, 9	Pnom Pehn	L6	4.83	0.04	2/3	53	8
Granes	L6	4.91	0.02	2	94	8	Pricetown	L6	4.82	–	1	30	1
Grossliebenthal	L6	4.66	0.06	3	218	1, 7	Putinga	L6	5.03	–	1	13	1
Jackalsfontein	L6	4.89	0.16	3	79	7, 8	Quincay	L6	4.82	–	1	10	8
Jumapalo	L6	4.64	–	1	3	5	Rakovka	L6	4.93	0.00	2	61	1, 9
Kalumbi	L6	4.85	–	1	378	8	Saint Caprais	L6	4.86	0.13	2	127	1, 8

Table 1. Decimal log (in 10^{-9} m^3/kg) for ordinary chondrite falls. 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 (Ntot: total number of measured samples, if different from N); m: cumulated mass measured. *Continued.*

Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]
Saint Chinian	L6	4.68	–	1	56	8
Santa Isabel	L6	4.92	–	1	33	8
Sauguis	L6	4.53	0.11	3	132	8, 10
Schonenberg	L6	4.80	–	1	14	1
Sinai	L6	5.03	–	1	132	8
Songyuan	L6	4.87	–	1	7	5
St. Christophe	L6	4.92	–	1	38	1
Saint Denis West.	L6	4.86	0.04	3	32	1, 8
St. Michel	L6	4.83	0.11	3	91	1, 7
Stavropol	L6	4.91	–	1	17	8
Tenham	L6	4.72	0.07	3	64	1,3, 7
Tillaberi	L6	4.87	–	1	113	8
Tourinnes	L6	4.92	0.08	3	55	1, 7, 10
Tuan Tuc	L6	4.90	0.09	2	63	8
Utrecht	L6	4.89	0.02	2/3	28	1, 8, (2)
Valdinizza	L6	4.92	–	1	2	8
Virba	L6	4.86	0.04	3	54	1, 8
Vouille	L6	5.02	0.05	6/7	276	1, 4, 7, 8, 9
Wold Cottage	L6	4.84	0.05	2	110	8
Woolgorong	L6	4.75	0.04	2	8	3, 4
Zaborzika	L6	4.80	0.06	3/4	96	8, (1)
Zavid	L6	4.99	0.05	3/4	332	1, 7, 9
Zemaitkiemis	L6	4.89	0.06	2	79	7, 8
Adzhi-Bogdo	LL3-6	4.07	–	1	6	8
Semarkona	LL3.0	4.59	–	1	6	8
Bishunpur	LL3.1	4.67	–	1	45	8
Krymka	LL3.1	4.03	–	1	30	4
Chainpur	LL3.4	4.46	–	1	65	8
Manych	LL3.4	4.48	–	1	2	8
Ngawi	LL3.6	4.20	–	1/2	96	8
Parnallee	LL3.6	4.49	0.04	6	495	1, 6, 7, 9, 10
Benares (A)	LL4	3.58	0.04	3	33	8
Hamlet	LL4	4.43	–	1	11	8
Savtschenskoje	LL4	4.32	–	1	15	1

Meteorite	Class	Logχ	s.d.	N/Ntot	m (g)	Provenance[a]
Sevilla	LL4	4.31	0.00	2	63	8, 9
Soko-Banja	LL4	4.26	0.06	6	259	1, 6, 7, 9, 10
Aldsworth	LL5	4.54	–	1	9	8
Alta'ameen	LL5	4.26	–	1	11	7
Guidder	LL5	3.78	0.07	3	746	7, 8
Khanpur	LL5	3.83	–	1	6	8
Krahenberg	LL5	4.10	0.50	2	3	8
Nyirabrany	LL5	4.19	–	1	21	7
Olivenza	LL5	3.70	0.07	4	291	1, 3, 9
Paragould	LL5	4.54	–	1	6	7
Parambu	LL5	3.86	–	1	5	8
Richmond	LL5	4.45	–	1	9	8
Siena	LL5	4.19	0.04	2/3	112	2, (3)
Tuxtuac	LL5	4.11	0.00	2	10	3, 7
Bandong	LL6	3.85	0.03	2	47	1, 10
Bensour	LL6	3.71	0.06	2	12	5
Borgo San Donino	LL6	3.84	0.11	4/5	463	2, 8, 10, (1)
Dahmani	LL6	3.91	0.14	2	99	8
Dhurmsala	LL6	4.27	0.08	4	283	1, 7, 10
Douar Mghila	LL6	4.04	–	1	634	8
Ensisheim	LL6	4.14	0.09	6/7	82	1, 6, 8, (7), 10
Galim A	LL6	4.27	–	1	14	8
Jelica	LL6	3.56	0.14	3	154	1, 7
Karatu	LL6	3.83	–	1	9	5
Kilabo	LL6	3.68	0.05	3	26	5
Manbhoom	LL6	3.63	0.06	2	4	1, 7
Mangwendi	LL6	4.16	–	–	92	1
Ottawa	LL6	4.25	–	–	36	8
Oubari	LL6	4.00	0.01	2	671	8
Oued El Adjar	LL6	4.09	–	–	3	5
Saint Severin	LL6	4.02	0.07	5	554	4, 5, 8, 10
St. Mesmin	LL6	4.18	0.10	4	68	1, 8, 10
Vavilovka	LL6	3.62	0.06	2	43	1, 7

[a]Provenance Code: 1) Vatican Observatory, 2) University La Sapienza of Roma, 3) Antarctic Museum in Siena, 4) Museum Giorgio Abetti in San Giovani Persiceto, 5) Private collections (CEREGE, Matteo Chinellato), 6) Prague, 7) Helsinki, 8) MNHN Paris, 9) MNSC Madrid, 10) Ecole des Mines Paris.
Provenance of outliers appears in brackets. The corresponding Excel file is available on request by e-mail (rochette@cerege.fr).

[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 meteorite falls is shown in Table 1. For finds and individual specimen data, see Rochette et al. (2001a). In the average (arithmetic mean of logχ), 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 are not used in the mean as long as the number of outliers is less than half the total number of samples. The identification and significance of these outliers are discussed in the next section.

MAGNETIC SUSCEPTIBILITY OF FALLS

Dispersion for a Given Fall

A large number of individual stones, held today in various collections, of the historical Bjürbole, Holbrook, L'Aigle, Mocs, and Pultusk falls have been measured, providing a good test for logχ dispersion (Fig. 2). In our analysis of this dispersion, each individual measurement from Terho, Pesonen, and Kukkonen (1991), rather than just the mean, is taken into account.

Some outliers with respect to the "normal" dispersion do clearly appear, however. The criteria to identify outliers include a deviation of more than 0.3 in logχ or 4 standard deviations, very low mass, and, of course, a number of "outliers" significantly less than the number of remaining samples.

Dispersion can be due to measurement errors, anisotropy, weathering, heterogeneous distribution of metal within the meteorite, misidentification, or misclassification of the meteorite. Fig. 2 clearly shows that, for samples whose volume is greater than 1 cm^3, dispersion does not depend on mass.

Measurement error should be marginal. For example, several outliers from the Vatican collection were remeasured (both χ and mass) at a later date and the original results were confirmed. On the other hand, we note that the Bjürbole data (mostly from Terho, Pesonen, and Kukkonen (1991) who measured 72 different samples, half of them weighing less than 30 g) yield a standard deviation of 0.08, while our database (using only the mean value of the Terho, Pesonen, and Kukkonen [1991] data) gives a standard deviation of only 0.03. This may indicate a slightly lower precision for their database, hence the decision in our analysis of the logχ mean values to include only the mean value of each meteorite in the Terho, Pesonen, and Kukkonen (1991) set. On the other hand, this may be an effect of larger dispersion for a lower susceptibility meteorite such as Bjürbole rather than a difference in precision between Terho, Pesonen, and Kukkonen (1991) and our new measurements.

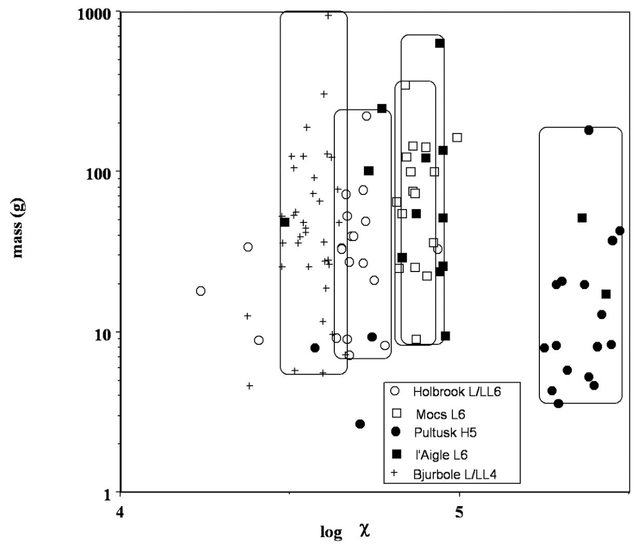

Fig. 2. Mass (in grams) versus logχ (in 10^{-9} m^3/kg) for different specimens of Bjürbole, Holbrook, L'Aigle, Mocs, and Pultusk. The samples considered as representative are enclosed in a box. Dispersion of logχ does not depend on mass over 3 g (1 cm^3).

Heterogeneity may be primary, due to brecciation or to the presence of metal veins or xenoliths, or secondary, due to variable weathering-induced metal oxidation, which decreases logχ values. This oxidation effect probably explains the weak logχ of some Holbrook specimens; collections often contain Holbrook pieces that were collected several decades after the fall, and this meteorite is known to rust easily. Metal segregation associated with partial melting is clearly exemplified in Portales Valley, discussed later. The larger data set of Fig. 3 shows that the standard deviation (computed using the outliers) tends to increase with the age of the fall (increasing the probability for weathering and misassignment). Higher average standard deviations are encountered for heterogeneous types (0.09 instead of 0.06) and for petrographic grade 6 (0.08), where metal mobilization is more likely. This confirms that heterogeneity is probably the main source of dispersion for intermediate deviations.

Misassignment may be suspected for the three outliers of Pultusk, small complete stones from the Vatican and University of Rome collections that are in fact more consistent with Holbrook according to their logχ values. Indeed, the smallest of these stones was acquired in a rock shop and donated to the University of Rome. A confusion between small complete stones of Holbrook and Pultusk could quite possibly occur in a shop if these very similar-looking samples were stored in open containers or manipulated by numerous persons.

This same line of reasoning could apply to the two outliers of L'Aigle (both from the Vatican collection), one fitting better with Pultusk, the other with Holbrook. All four L'Aigle pieces measured in Paris (weighing more than 100 g)

Table 2. Mean logχ with standard deviation and number of meteorites (in parenthesis) for falls (excluding anomalies) versus petrographic grades (except L/LL and H/L) and finds, separating Antarctic and non-Antarctic.

Class	LL	L	H
Falls			
All	4.10 ± 0.30 (44)	4.87 ± 0.10 (142)	5.32 ± 0.10 (144)
Grade 3	4.37 ± 0.24 (8)	4.89 ± 0.12 (5)	5.26 ± 0.09 (5)
Grade 4	4.18 ± 0.34 (5)	4.85 ± 0.12 (6)	5.29 ± 0.09 (34)
Grade 5	4.13 ± 0.29 (12)	4.90 ± 0.09 (25)	5.32 ± 0.10 (67)
Grade 6	3.95 ± 0.23 (19)	4.86 ± 0.11 (105)	5.35 ± 0.11 (37)
L/LL and H/L	4.60 ± 0.11 (4)	4.98 ± 0.01 (2)	
Finds			
Antarctic	4.30 ± 0.23 (6)	4.66 ± 0.26 (65)	5.08 ± 0.18 (234)
Non-Antarctic	3.98 ± 0.41 (23)	4.55 ± 0.28 (129)	4.89 ± 0.31 (157)

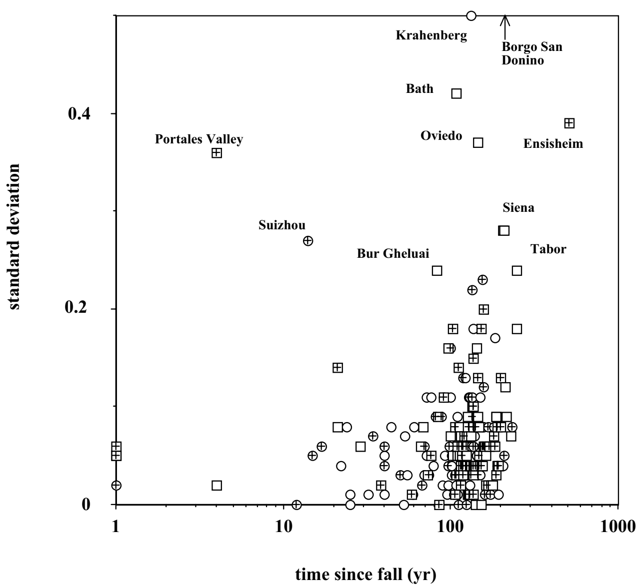

Fig. 3. Standard deviation (including outliers) of logχ for a given fall versus age the of the fall. Square symbol: brecciated, xenolithic, or veined samples. Cross: petrographic grade 6. Dispersion of logχ data tends to increase with the age of the fall.

are within the normal dispersion range. Another possible example may be Ensisheim, another old French fall. Among the six pieces measured, the only outlier—a 3.5 g piece, 6.5 standard deviations above the mean—is from Helsinki, while larger pieces from Paris and Vatican (donated by the French collector Marquis du Mauroy) fall within the correct range. Further examples of misassignment for outliers will be discussed in the Interpretation of Anomalies and Outliers section.

Finally, to demonstrate the problem with the Herndon et al. (1972) translation of the Russian database, note that the standard deviation derived for Pultusk's logχ—among the most consistent in the Russian database—is 0.17 for the Herndon et al. (1972) set of 38 samples but only 0.07 for the 14 samples listed here (excluding 3 outliers).

In the following, we will discuss only the mean data (Table 1 for falls), excluding outliers.

General Susceptibility Distribution

Quite narrow ranges of logχ values characterize the H, L, and LL classes (Figs. 4 and 5, Table 2). Overall, each subclass has a very narrow range of logχ. The standard deviation for a subclass, 0.09 to 0.12 for H and L chondrites and 0.23 to 0.34 for LL chondrites, is not much larger than the standard deviation for a given meteorite, highlighting the very strong homogeneity of ordinary chondrite parent bodies. In addition, the H/L and L/LL subclasses are well separated from the main classes. Considering individual data (Table 1), while a clear gap is visible between H/L and H, there are 10 L meteorites with logχ above the H/L values and 14 L meteorites within the L/LL logχ values. This suggests that more L/LL and H/L meteorites exist among the meteorites presently classified as L.

The LL histogram shows a larger spread than the L and H histograms, with multiple modes (Fig. 4). This is due to the dichotomy between low petrographic types (containing mainly high-χ kamacite-taenite) and high petrographic types (containing mainly tetrataenite, with a smaller specific χ), as documented in Table 2.

Tetrataenite does not have a noticeable effect in L and H chondrites. Logχ is independent of the petrographic type in L chondrites and increases slightly with metamorphism in H chondrites (Fig. 5). This interpretation is confirmed by Fig. 6, where the metal content from Jarosewich (1990) is compared with logχ. L and H class data plot close to the kamacite-taenite theoretical line with a smaller dispersion than for LL chondrites. Tetrataenite-rich LL5 or LL6 meteorites, like Olivenza (Collinson 1987), show a logχ almost one order of magnitude less than the predicted line, contrary to LL3 chondrites. Interestingly, within a given class, χ and metal content appear uncorrelated; this is discussed further below.

As with the meteorites discussed in the previous section, outliers are found within the data for each meteorite class. The lack of overlap of the histograms is due to exclusion of these anomalous falls. But, their inclusion would not modify the mean (when a meteorite was represented by only two divergent samples, we tried to obtain further samples from other collections).

In addition, 21 magnetically anomalous falls have been

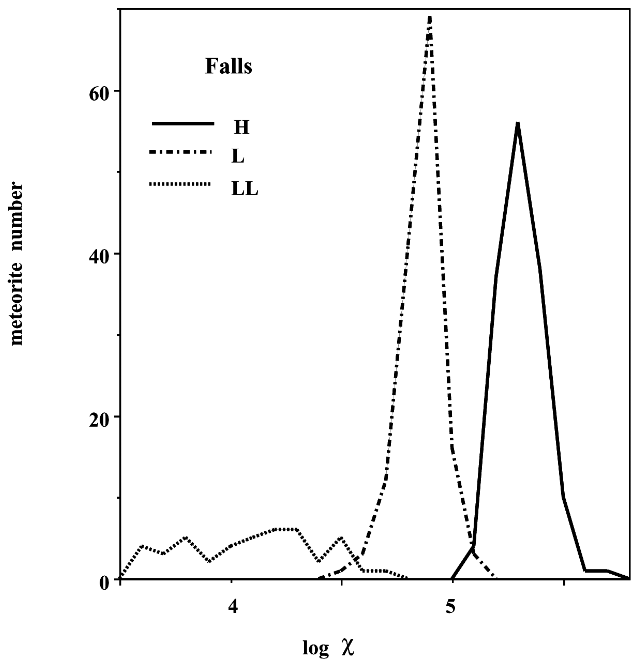

Fig. 4. Histograms of logχ (in 10^{-9} m^3/kg) for H, L, and LL falls (excluding L/LL, H/L, and outliers of Table 3). Class interval is 0.1.

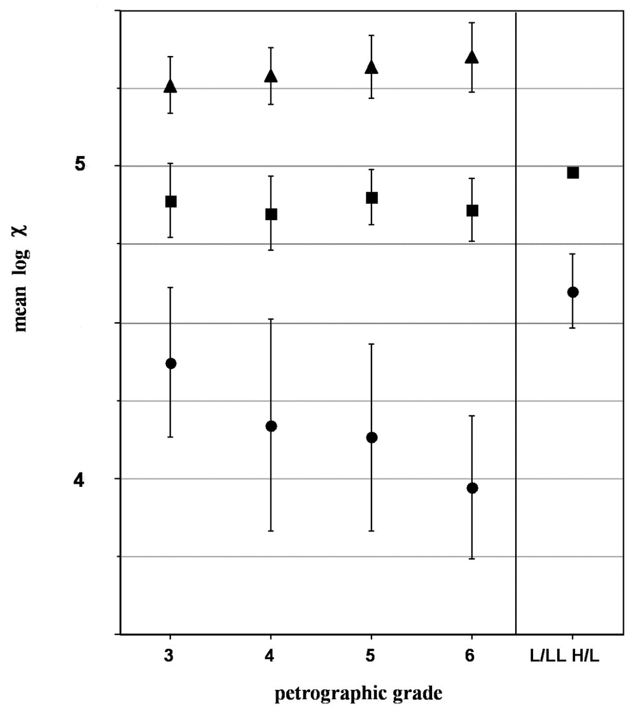

Fig. 5. Mean logχ (in 10^{-9} m^3/kg) with standard deviation (bars) versus petrographic grade for H (triangles), L (squares), and LL (circles) chondrites; H/L(square) and L/LL(circle) means are computed for all grades.

identified and tabulated separately (Table 3; see the following section). The criteria for identifying these anomalies were either a large standard deviation with no way to clearly define outliers or an anomalous mean with a small standard deviation with respect to the petrographic class (see next section). Both anomalies and outliers involve only a minor part of the database, 21 falls and 38 specimens, compared to a total of 357 meteorites and 842 specimens in the fall database.

Interpretation of Anomalies and Outliers

The homogeneity in susceptibility distributions seen in the previous section explains why we are motivated to seek a specific explanation for each anomaly listed in Table 3 rather than attributing them to an overall regular fluctuation of metal content in the chondrite parent bodies.

Four sources of discrepancies can be identified: an intrinsic one corresponding to the heterogeneous distribution of metal; a secondary but natural one, weathering; and two artifacts: misidentified samples (i.e. not corresponding to the actual meteorite on which classification was done) or misclassified meteorites.

Heterogeneous metal distribution can explain negative and positive anomalies, but it should be associated with large standard deviations or many outliers (unless only one sample was measured). Such heterogeneity at a scale of centimeters should be expected only for meteorites where petrological heterogeneity is also observed. Although a faint correlation between average standard deviation and the presence of brecciation, veins, or xenoliths is observed, this cannot account for large discrepancies (recall, 0.3 in logχ means a factor 2 in χ). Indeed, the presence of outliers or anomalies is not systematically correlated with such facies.

On the other hand, discrepancies in some type 6 chondrites could be associated with metal segregation due to partial melting. This is clearly demonstrated by the H6 Portales Valley. Two samples with large metal veins yield logχ higher than the average for H6 chondrites, while two samples without metal veins have logχ in the L class range. On average though, the mean logχ of Portales Valley is in the H class range, suggesting that the metal segregation is local. Such behavior may be also responsible for the large standard deviations observed in other grade 6 meteorites, such as Salles and Futtehpur.

Weathering can strongly deplete metal, and thus, logχ, as demonstrated in finds (next section) and likely, by the case of the Holbrook outliers. It probably also explains the anomalously low value of Pirgunje (L6) and Wiluna (H5) obtained on weathered samples from the Vatican and Paris. Fresh pieces of both meteorites from London give a non-anomalous result (logχ of 4.81 and 5.30, respectively). On the other hand, some obviously weathered falls, such as Valera, which remained outdoors in a tropical climate for 25 years, do not show high negative anomalies (Table 1). Another test can be to compare specimens of the same historical fall from the Vatican and Paris collections, as the Paris pieces show a less weathered appearance. However, the logχ values for the

Table 3. Magnetically anomalous falls with deviation (in logχ) from mean of Grady catalogue class (Table 2). An alternative "magnetic" classification is suggested, with, in parentheses, the reclassification proposed after petrographic examination and literature (see text and Table 4). N(m): number (total mass in g) of specimen analyzed.

Meteorite	Class	Deviation	Alternative	N(m)
Ceniceros	H3.7	–0.64	L/LL (L3.7)	1(116)
Sharps	H3.4	–0.29	H/L or L (H/L3.4)	1(25)
Kabo	H4	–0.45	L (L6)	2(17)
Sithatali	H5	–0.84	L/LL (LL3.9)	2(34)
Wiluna	H5	–0.64	L or weathering	1(63)
Chitado	H6	–0.51	L (L6)	1(74)
Esnandes	H6	–0.46	L	2(20)
Portales Valley	H6	–0.55 + 0.14	mobile metal	4(616)
Salles	H6	–0.55	L (L5)	3(148)
Albareto	L4	–0.28	L/LL (L/LL4)	1(138)
Beyrouth	L4	–0.35	L/LL (LL3.8)	1(48)
Clohars	L4	+0.36	H (CR2)	1(4.4)
Slobodka	L4	+0.50	H (H4)	1(37)
Borkut	L5	–0.54 + 0.19	? (L4)	2(18)
Beuste	L5	+0.30	H or H/L (L5)	2(340)
Futtehpur	L6	–0.05 + 0.54	H or mobile metal (H5)	4(286)
Le Pressoir	L6	+0.61	H (H5)	5(201)
Pirgunje	L6	–0.36	L/LL or weathering	1(3.8)
Segowlie	L6	–0.52	L/LL or LL (LL6)	2(26)
Suizhou	L6	–0.39	L/LL or weathering	2(28)
Niger III	LL6	+0.80	L (L6)	1(2.7)

Vatican pieces are not systematically lower than the Paris values. We therefore conclude that small degrees of weathering can only marginally explain the observed discrepancies.

We undertook a systematic check for misclassification or petrological anomalies on all magnetic anomalies and a few outliers. In several cases, this involved the examination and microprobe analyses of sections taken from the magnetically measured pieces. A few cases have also been checked by measuring samples of the same meteorite from the London collection. The microprobe analyses obtained are listed in Table 4, together with reclassification in Table 3. Falls for which a reclassification is proposed are highlighted in bold.

Albareto, alternatively cited as an L4 or LL4 in Grady (2000), actually fits exactly with the logχ of Bjürbole and Cynthiana, as well as the find Vera (L/LL4). Reconsidering the Kallemeyn et al. (1989) data, their LL classification based on Co in kamacite and mole %Fa in olivine is quite arbitrary. It is, in fact, closer to Bjürbole than to the average LL. We suggest classifying Albareto, which is definitely not an L, as an L/LL rather than LL. Segowlie (L6, logχ like an LL or L/LL) has a low metal content according to Jarosewich (1990). Our thin section observations and microprobe analyses clearly point toward LL6. Niger III (LL6, logχ like an L) appears indeed to be an L6, identical to Niger II (L6). We thus propose to reclassify Niger III as an L6, paired with Niger II. This solves the puzzle of the presence of LL6 and L6 stones in the same fall. Beyrouth and Slobodka, classified as L4, appear to be an LL3.8 and H4, respectively, according to microprobe and magnetic data.

Ceniceros (H3.7) has a logχ value like L/LL chondrites, and less than Bishunpur (LL3). A thin section from the Paris piece shows large chondrules and metal grains typical of L chondrites, as well as equivalent modal amounts of sulfide and metal. We thus propose that Ceniceros be reclassified as an L3.7. This is an agreement with its platinum group elements signature (Horan, Walker, and Rubin 2001), intermediate between L and LL chondrites, unlike any H chondrites, and with the low metal content revealed by Mössbauer spectroscopy (Menzies et al. 2002).

Speaking of petrographic grade 3 meteorites, the most magnetic LL, Bishunpur (logχ of 4.67), is not considered an anomaly since it is not outside the overall dispersion of LL3 chondrites. It is therefore not listed in Table 3. However, it is worth noting that Mössbauer spectroscopy confirms that it is anomalously rich in metal (Menzies et al. 2002). It also has a very low Co content in kamacite compared to other LL chondrites (Kallemeyn et al. 1989). One may wonder if it does not belong in the L/LL class.

Chitado (H6, but in logχ like an L) appears to be an L6. Esnandes and Salles (H6, but in logχ like L chondrites), as well as Le Pressoir (L6, but logχ like H chondrites), were classified by Mason (1963)—like many of our anomalies—using XRD or optical olivine composition estimates. These techniques are less reliable than microprobe analysis. Indeed, the analyses of Le Pressoir and Salles in Paris indicate H5 and L5 classes, respectively. The Esnandes specimen is unfortunately too small for thin section preparation.

Sharps (H3.4) would magnetically fit perfectly with the two H/L3 meteorites, Bremevorde and Tieschitz, in

Table 4. Olivine (% fayalite) and pyroxene (% ferrosilite) composition with their standard deviation (s.d.) from microprobe analyses performed in Paris and Siena on new sections from MNHN and MNA collections showing magnetic anomalies, except a control sample shown with *.

Meteorite	Fa%	s.d.	Fs%	s.d.
Beuste	24.85	0.42	21.29	0.89
Beyrouth	26.39	0.26	17.93	4.34
Borkut	25.20	0.18	23.18	1.42
Chitado	25.01	0.18	21.03	0.31
Futtehpur	16.85	0.26	18.54	0.19
Kabo	24.9	–	20.9	–
Le Pressoir	18.29	0.39	15.88	0.18
Ngawi 1513	19.34	1.21	17.69	0.36
Niger III	25.72	0.01	21.25	0.04
Pnom Pehn 2708*	19.10	0.33	17.60	0.62
Pnom Pehn 583	25.54	0.27	21.37	0.23
Salles	25.45	0.02	21.42	0.06
Segowlie	26.06	0.68	22.16	1.12
Slobodka	19.32	0.23	17.19	0.05
Sitathali	25.82	0.22	23.44	1.30

agreement with the low Fe metal content reported by Jarosewich (1990): 12% compared to the average 16–17% for H chondrites. Fine-grained metal and small chondrules are quite typical of H3.

Sitathali, classified as an H5 but with a logχ value like an LL or L/LL based on the large samples from Paris, is reported to be anomalously poor in total iron (Grady 2000; 24% total iron instead of the average 27% for H). On the other hand, two 1 g Sitathali pieces from the Vatican and London collections give typical H logχ of 5.58 and 5.50. Thin section inspection of the "Sitathali" piece from Paris reveals a LL3.9 type with shock stage 2 and weathering grade 0. As no other falls of this class (or even LL3.8 or 3.7) exists in Paris or in any other collection, this Paris "Sitathali" may be a new meteorite.

Futtehpur (L6) and Borkut (L5) share the particularity of showing widely variable values, from different museums or within the same museum. Outlier pieces from Paris examined in thin section have been reclassified as H5 and L4, respectively, thus confirming the anomaly for Futtehpur. Whether Futtehpur has to be reclassified or if this is due to mislabeled samples remains to be evaluated. Finally, Beuste (L5), whose logχ is 0.3 above the mean for other L5 meteorites, is confirmed to be an L type by microprobe. Its high shock stage (4/5) and abundant metal enriched melt veins may explain its somewhat too high susceptibility. The same reasoning could be applied to Homestead, which is the strongest L (logχ = 5.08) in Table 1.

Among outliers from a common meteorite, several specimen were analyzed further. In the Vatican collection, the sample labeled Luponnas (a brecciated meteorite described as a shock-blackened H3-5 but in logχ like an LL) is almost certainly mislabeled, or else a very anomalous piece of this breccia. The Vatican hand sample is not visibly blackened, and in thin section, there is neither the metal content expected of an H, nor the large and well formed chondrules expected for lower petrographic grades. It is probably a mislabeled, unidentified L6. Likewise, a piece in the Vatican collection identified as Borgo San Donino (LL6 but in logχ like an L), in fact looks like a typical L in thin section, and was probably also mislabeled.

In Paris, an outlier from Phnom Penh (L6, but logχ like an H) appears to be an H5/H3.8 shocked breccia. This is at odds with the other samples, which have been reanalyzed as weakly shocked L6. Similarly, the outlier for Ngawi (LL3.6, but logχ like an H) turned out to be a highly shocked H5, while the other measured sample is really an LL3.6, in agreement with the logχ data.

These examples are quite likely explained by label exchanges with other meteorites in the collection. Indeed, an anomalous sample labeled Clohars (L4) in the Paris collection has in fact been identified as a mislabeled sample of Renazzo (CR2)!

Among other anomalous H chondrites, the Kabo piece in Siena has been reclassified as an L6 on a petrographic basis. It is unlikely that the genuine Kabo is misclassified. In particular, Jarosewich (1990) gives the right metal composition for Kabo, and a 3.5 g piece from London gives a logχ of 5.26. We therefore conclude that the samples from Siena and San Giovanni Persiceto, acquired from a private dealer, are not Kabo pieces.

Several outliers remain to be examined, but it is telling that, so far, in every case where an unweathered sample's value of logχ is at odds with our mean for the same meteorite or for its class, further examination of the sample in question has provided strong evidence that it has been misclassified or mislabeled. It thus appears that magnetic measurements are able to detect misclassified meteorites or misidentified specimens with a rather high success rate. The only "magnetic anomalies" that have not been confirmed by thin section

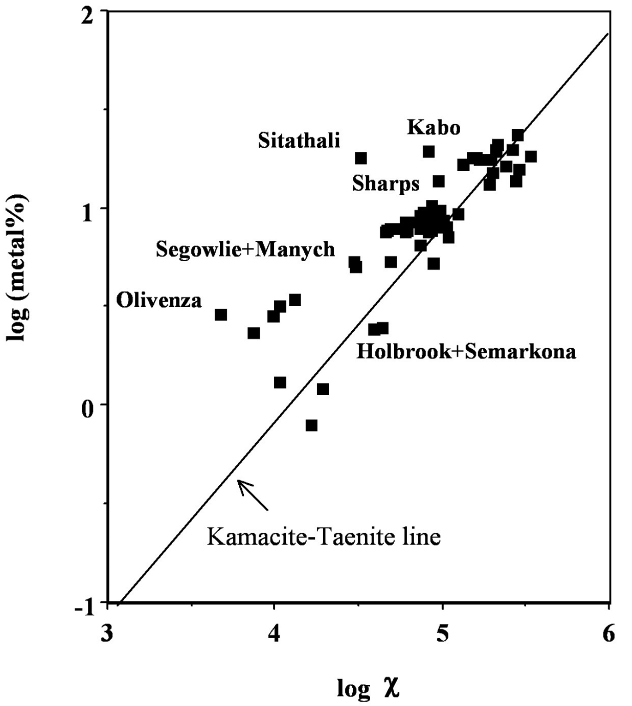

Fig. 6. Logχ (in 10^{-9} m^3/kg) versus log weight % of metal from Jarosewich (1990) for falls, including the following anomalies: Kabo, Segowlie, Sharps, Sitathali. The kamacite-taenite theoretical line is derived for multidomain spheres (see text).

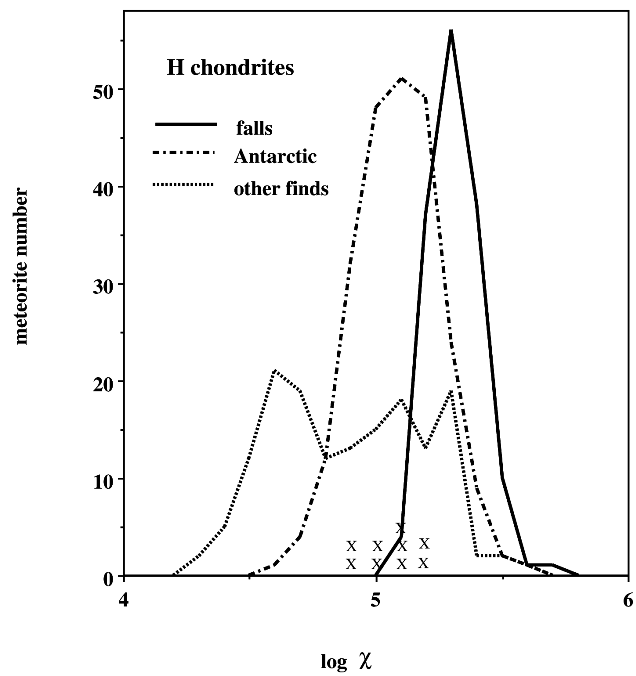

Fig. 7. Histogram of logχ (in 10^{-9} m^3/kg) for H chondrites separating falls, Antarctic and non-Antarctic finds. Values from samples belonging to the Frontier Mountains "shower" after Welten et al. (2001) are shown by crosses (one per sample).

analysis are Beuste and Borkut. More delicate in some cases is the discrimination between misclassification and misidentification.

MAGNETIC SUSCEPTIBILITY OF FINDS AND WEATHERING EFFECTS

Measurements of ordinary chondrite finds have been tabulated in Rochette et al. (2001a) and in Table 2. Further data have been obtained on LL meteorites to increase the statistical significance of the mean, as well as on new Antarctic and Sahara finds classified in 2002 in Siena and Paris. Multiple measurements of various specimens of the same meteorite have been obtained on a limited number of cases (generally excluding Antarctica or Sahara finds). Finds show a somewhat larger logχ standard deviation than falls. This may be explained by heterogeneous metal alteration.

Compared to falls, a clear decrease of logχ for H and L meteorites due to variable oxidation of metal can be seen (Figures 7 and 8, Table 2), and non-Antarctic finds show a large spread in their histograms, in agreement with the spread of weathering stages. This explains why previous studies (Terho et al. 1993), which had failed to separate falls from finds, concluded that there was an overlap of magnetic properties in different ordinary chondrite classes.

Fig. 9 shows the correlation of logχ with weathering grade (W# according to Wlotzka 1993) for Saharan finds (mostly from Dar al Gani). A decrease is already visible in W1, and beyond W3, no values are within the range of falls. On average, Saharan finds are more weathered that the others.

Antarctic finds (mostly from Frontier Mountain: FRO) appear, on average, less affected by weathering, although the logχ histogram is clearly shifted toward low values. Interestingly, the FRO histograms exhibit quite narrow peaks compared to non-Antarctic finds. This could be explained by a predominance of a few individual showers, as suggested by Welten et al. (2001), according to cosmogenic isotope concentrations. In particular, the FRO H chondrite samples of the major suspected shower (FRO 90001) have a logχ value concentrated near the peak of the histogram. The double peak of the FRO L chondrites histogram may also correspond to a predominance of two shower falls, one strongly and one weakly affected by terrestrial weathering.

The LL metallic phase appears much more resistant to weathering, possibly due to high Ni content, tetrataenite phase, and the dissemination of metal protected by silicates. However, due to the small number of samples and the intrinsic spread of LL logχ values, conclusions drawn from Table 2 on LL finds have a low statistical significance.

DISCUSSION

Our conclusion that within each class ordinary chondrites are very homogeneous in susceptibility (both at the single fall level and at the whole class level) may be suspected to be

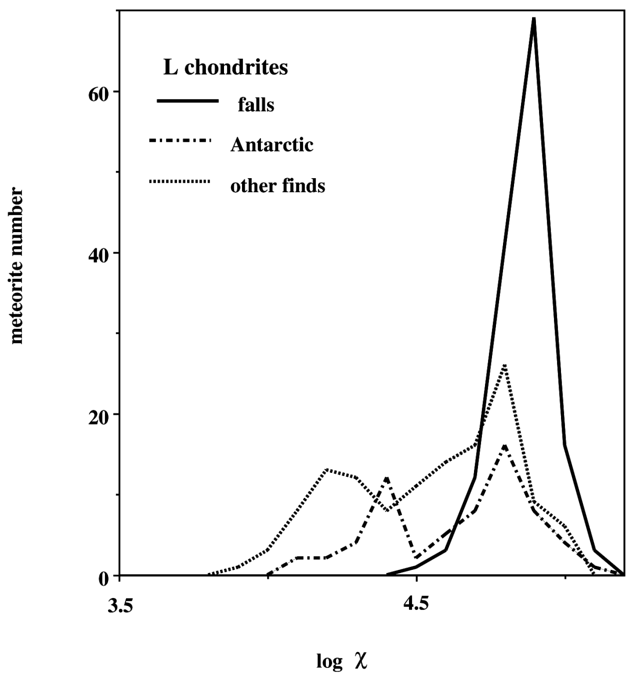

Fig. 8. Histogram of logχ (in 10^{-9} m^3/kg) for L chondrites separating falls, Antarctic and non-Antarctic finds.

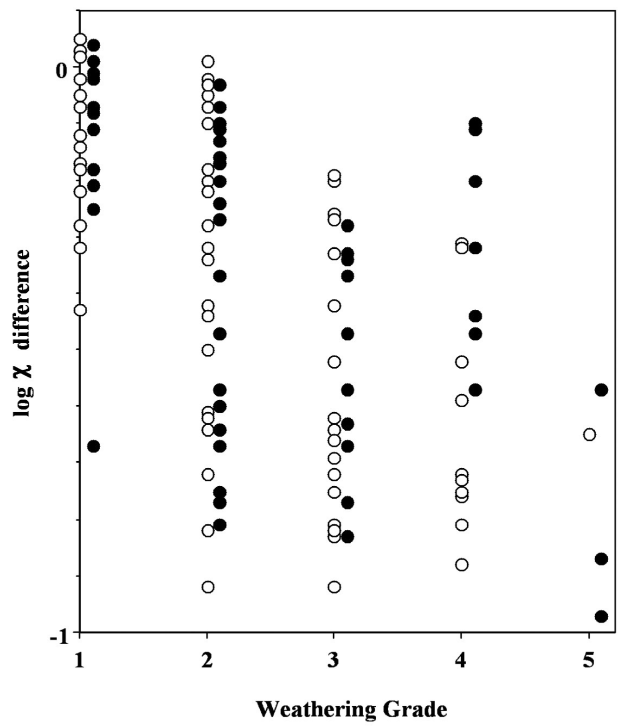

Fig. 9. Difference in logχ between sample value and mean fall value (after Table 2) versus weathering stage for H and L (open and closed circles, respectively) Saharan finds.

biased by our removal of anomalies and outliers from the means. However, it has been shown above that a large number of these discarded data were misclassified meteorites or misidentified samples, thus confirming our interpretation scheme. The average first order behavior of logχ from falls shows that magnetic susceptibility measurements can be a very efficient way to rapidly classify ordinary chondrites, and scan a whole collection to detect anomalies and misclassified or misidentified meteorites.

It is thus tempting to use a second order feature, the variation of logχ with metamorphic grade, to evaluate, on a large statistical basis, the suggestion that oxidation of Fe metal occurs during metamorphism. Gastineau-Lyons, McSween, and Gaffey (2002), based on modal analysis on polished sections of a few L and LL chondrites, claimed to demonstrate increasing oxidation with metamorphism, with in particular, a decrease in metal amount. However, assuming logχ is a good proxy for metal content, then our data shows a constant oxidation state with metamorphism for L chondrites, and reduction with metamorphism for H chondrites. Our conclusion fits with Mössbauer evidence of Fe^{3+} restricted to type 3, which are thus more oxidized than type 4–6 (Menzies et al. 2002).

However, the decrease of logχ in LL chondrites, which we attributed entirely to increasing tetrataenite content, could also be partly due to decreasing metal content. The Jarosewich (1990) database for LL class metal content does not show any correlation with metamorphic grade, supporting our interpretation of constant metal in LL chondrites.

Within L chondrites, the lack of correlation of metal content with logχ could be due to the variable amount of tetrataenite. Indeed, a large proportion of tetrataenite has been described in an L5 (Scorzelli et al. 1998). As all theoretical and observational evidence points toward increasing tetrataenite with increasing metamorphism, our data on L chondrites could be due to the contrasting effects of reduction (increasing metal, as in H chondrites) versus the increase in tetrataenite. Tetrataenite should be a minor phase in H chondrites, due to the low Ni/Fe ratio.

The effect of metal grain shapes could also be responsible for an increase of logχ at constant metal amount, if average grain elongation increases significantly with metamorphism. The mean susceptibility for an ellipsoid of revolution can be calculated as a function of the demagnetization factor N along the revolution axis of the ellipsoid: $K = (N + 1/3)/N(1 - N)$, where N is 1/3 for a sphere, 0 for an infinite needle, and 1 for an infinite plane (e.g., Carmichael 1989). The observed increase of $\alpha = 0.10$ in logχ from H3 to H6 could thus be interpreted assuming a constant metal amount but with grains being spherical in H3, evolving to grains with N values of 0.15 or 0.58 (these values are the solutions of equation $[N + 1/3]/N[1 - N] = 10^{\alpha}/3$). The corresponding aspect ratios, 2 and 0.4, represent prolate and 0.4 oblate ellipsoids, respectively, and the grain magnetic anisotropy ratio $P = K_1/K_3$ would be 2.8 and 2.7, respectively. These anisotropy ratios, at the grain scale, would be observed

Table 5. $\log M_{rs}$ in 10^{-3} Am^2/kg for falls measured for this study or obtained from the literature. When several samples are available, a mean and standard deviation are given: 1) this study; 2) Thero et al. (1993); 3) Sugiura (1977), Sugiura and Strangway (1982); 4) Brecher et al. (1975, 1977, 1979); 5) Collinson (1987), Morden and Collinson (1992); 6) Yamanaka et al. (1995); 7) Ramana and Poornachandra Rao (1996); 8) Krol and Lang (1996); 9) Nagata et al. (1986); 10) Wasilewski and Dickinson (2000).

Meteorite	Class	$\log M_{rs}$	s.d.	Ref.	Meteorite	Class	$\log M_{rs}$	s.d.	Ref.
Tieschitz	H/L3.6	2.51	–	2	Sevrukovo	L5	2.57	–	2
Hainaut	H3-6	2.49	–	2	Tadjera	L5	1.43	–	4
Dhajala	H3.8	2.29	–	7	Alfianello	L6	1.51	–	2
Bath	H4	2.47	–	4	Andover	L6	2.38	–	4
Kabo	H4	2.44	–	1	Aumale	L6	2.00	–	4
Kesen	H4	2.70	0.27	3, 4	Beni Mh'ira	L6	1.58	–	1
Ochansk	H4	2.68	0.07	2, 4	Bushoff	L6	2.25	–	2
Wiluna	H4	2.67	–	1	Gifu	L6	2.32	–	3
Barbotan	H5	2.42	–	4	Girgenti	L6	1.83	–	1
Castalia	H5	2.48	–	4	Pirgunje	L6	2.45	–	1
Collescipoli	H5	2.72	–	2	Tenham	L6	2.11	–	6
Forest City	H5	2.65	–	2	Vouille	L6	1.98	–	1
Jilin	H5	2.68	–	2	Parnallee	LL3.6	2.42	0.10	4, 5
Pultusk	H5	2.44	–	4	Soko-Banja	LL4	2.67	0.12	2, 4
Sitathali	H5	2.62	–	1	Alta'ameen	LL5	2.75	–	2
Moti-Ka-Nagla	H6	2.40	–	4	Guidder	LL5	2.80	–	2
Mount Browne	H6	2.70	–	4	Khanpur	LL5	2.78	–	5
Nadiabiondi	H6	3.00	–	1	Nyirabrany	LL5	2.89	–	2
Rose City	H6	1.67	–	4	Olivenza	LL5	2.80	0.12	4, 5
Bjurbole	L/LL4	2.67	0.28	3, 4, 10	Tuxtuac	LL5	1.48	–	6
Knyahinya	L/LL5	1.45	–	2	Appley Bridge	LL6	2.08	–	9
Holbrook	L/LL6	2.21	–	4	Bensour	LL6	2.50	0.13	1
Mezo Madaras	L3.7	2.30	–	2	Dhurmsala	LL6	2.45	–	4
Bald Mountain	L4	1.65	–	4	Ensisheim	LL6	2.55	–	4
Lanzenkirchen	L4	2.26	–	2	Jelica	LL6	1.99	0.12	4
Tennasilm	L4	2.87	–	2	Kilabo	LL6	2.46	0.25	1
Ausson	L5	1.66	–	4	Saint Severin	LL6	2.78	0.18	3, 5, 7, 9
Baszkovka	L5	1.81	–	8	St Mesmin	LL6	2.51	0.07	1
Fukutoni	L5	2.85	–	3	Vavilovka	LL6	2.19	0.18	2, 4

at the bulk scale if the preferred orientation of grains were perfect.

AMS measurements on ordinary chondrites have been reported by Sneed et al. (1988), Morden and Collinson (1992), and Rochette et al. (2001a). The AMS ratio may be high, but the highest observed is only 1.7, with an average at about 1.5. No correlation of P with metamorphic grade is reported. Grains are already quite anisometric in grade 3–4 meteorites. We conclude that the increase in $\log\chi$ corresponds to a real increase in metal content and therefore a reduction with metamorphism. The lack of such evidence in the analyses of Jarosewich (1990), hence the lack of correlation in Fig. 6, may be interpreted as being due to uncertainties in metal amount, a parameter difficult to accurately obtain (Jarosewich 1990).

Can the narrow range of $\log\chi$ for a given class be extrapolated to other magnetic parameters, including natural remanent magnetization, of central interest for interpreting spatial magnetometer data? As already pointed out, NRM is highly variable even for the same meteorite (Wasilewski and Dickinson 2000; Terho et al. 1993). Therefore, we will discuss the intensity of saturation remanence (M_{rs}), which is dependent solely on the amount and characteristics of magnetic grains.

Previous compilations do show a large spread in M_{rs} values (see Acuña et al. 2002; Wasilewski, Acuña, and Kletetschka 2002), but this could originate from the use of both falls and finds. In fact, one would expect that weathering would have an even greater effect on remanence than on susceptibility, and according to the database of Terho, Pesonen, and Kukkonen (1991), M_{rs} increases with weathering. The use of single measurements for very small samples (Bjürbole chondrules case in above reference) instead of the meteorite average is also of concern as the extrema are unrelated to bulk properties.

We thus present a compilation of published or original $\log M_{rs}$ values for 58 ordinary chondrite falls (Fig. 10 and Table 5; units in 10^{-3} Am^2/kg). In the case of several measurements, the mean and standard deviation have been computed. In a few cases, where $\log\chi$ was not available, the

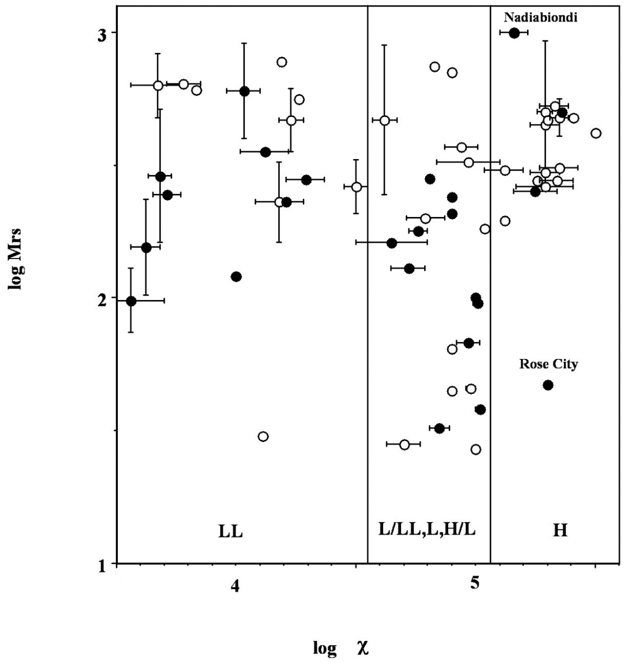

Fig. 10. LogM_{rs} (with M_{rs} in 10^{-3} Am^2kg^{-1}) versus logχ for ordinary chondrite falls after Tables 1 and 5. Petrographic grade 6 samples are in closed symbols.

average of the appropriate meteorite class was used to compare against the logM_{rs} value.

Fig. 10 reveals several interesting features: 1) LogM_{rs} is, on average, of the same magnitude for LL (2.47 ± 0.37), L (2.12 ± 0.45), and H (2.53 ± 0.26) chondrites. This means that the increase in metal content (indicated by an increase in logχ or M_s) is compensated for by a decrease in M_{rs}/M_s and coercivity, as already pointed out by Sugiura and Strangway (1987) and Terho et al. (1993); 2) While logM_{rs} is tightly grouped for H chondrites (except the impact melt breccia Rose City and the strongly weathered Nadiabiondi sample), there is a large spread for L and LL chondrites, although smaller than that advocated in Acuña et al. (2002). This could be attributed to variable amounts of tetrataenite, which shows much larger remanence than kamacite-taenite due to its much higher anisotropy. However, it appears that, on average, L6 or LL6 chondrites have a lower logM_{rs}, in contrast with the preceding inference. Discussing the origin of this variability is beyond the scope of this paper. Moreover, the small size and heterogeneity of the database (cross-calibration between the different studies is not provided) prevent a more detailed analysis of the M_{rs} data.

However, it is interesting to note the coincidence between the amount of dispersion in logM_{rs} and in cosmic rays exposure ages. Both have a much narrower distribution in H than in L and LL chondrites, with younger ages for H chondrites. The effect of artificial neutron irradiation on remanence coercivity (Butler and Cox 1971) and tetrataenite formation (Paulevé et al. 1962; Néel et al. 1964) have indeed been demonstrated. Cosmic rays exposure may thus be partly responsible for the variable remanence properties of ordinary chondrites.

Compared to the recent compilation of Wasilewski, Acuña, and Kletetschka (2002), our selection of falls and return to the source papers greatly decrease the spread in values and do not reproduce their claimed increase from LL to H. Moreover, our upper bound of 2.8 for logM_{rs} is at odds with the estimate of Gaspra and Braillé NRM, in the 1.3–1.7 range according to Wasilewski, Acuña, and Kletetschka (2002). Indeed, this indicates a REM (NRM/M_{rs}) value in the vicinity of 0.1, at least one order of magnitude above the maximum value advocated by Wasilewski, Acuña, and Kletetschka (2002) for large volume bodies. Therefore, either Gaspra and Braillé are not composed of ordinary chondrites or magnetic field measurements have been misinterpreted. Recent simulation of solar wind interaction with an asteroid (Blanco-Cano, Omidi, and Russell 2003) does indicate that the observed magnetic fields are not likely of remanence origin.

CONCLUSIONS

A consistent database of magnetic susceptibility of ordinary chondrites, including 357 falls and 614 finds, has been presented. Multiple specimen measurements show that this parameter is very homogeneous for a given meteorite. For falls, the ordinary chondrite classes (LL, L/LL, L, and H) exhibit narrow, non-overlapping, increasing ranges of logχ values, once outliers are excluded. This corresponds to their increasing metal content with a narrow metal content range for each class.

We conclude that logχ measurements can be a valuable tool for the rapid classification of meteorites. These simple, quick, and nondestructive measurements can be made in the laboratory or in the field, both on Earth and remotely by spacecraft at an asteroid's surface.

Further petrogeochemical investigations of outlying measurements has demonstrated that, in a few cases, the measurements correspond to strongly weathered samples or to high petrographic types, which experienced metal segregation such as seen in Portales Valley. In most cases, anomalous logχ values are due to misidentified (mislabeled or misclassified) samples.

Using logχ measurements and petrogeochemical analysis of thin sections, we propose to reclassify Ceniceros as L3.7 (formerly H3.7); Sharps as H/L3.4 (formerly H3.4); Chitado and Esnandes as L6 (formerly H6); Le Pressoir as H5 (formerly L6); Salles as L5 (formerly H6); Beyrouth as LL3.8 (formerly L4); Albareto as L/LL4 (formerly alternatively reported as LL4 or L4); Niger III (formerly LL6) as L6 (i.e. like Niger II); Segowlie as LL6 (formerly L6); and Slobodka as an H4 (formerly L4). However, these propositions rely on the assumption that the pieces analyzed are not misidentified.

Finds show a systematic lowering in logχ for a given class, corresponding to metal alteration due to weathering. Although Antarctic finds are less magnetically depleted, the alteration effect is already large. This sheds strong suspicion on paleomagnetic data obtained in ordinary chondrite finds.

Saturation remanence does not follow the same trend as logχ. In general, it is the same for LL, L, and H chondrites, but with H chondrites showing a much smaller dispersion. Our approach to take into account falls only, with meteorite average values of both saturation remanence and susceptibility, produces a quite different, less scattered, picture than previous compilations.

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