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PHYSICAL PROPERTIES OF 368 METEORITES: IMPLICATIONS FOR METEORITE MAGNETISM AND PLANETARY GEOPHYSICS

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Abstract: Petrophysical studies (susceptibility, intensity of natural remanent magnetisation (NRM) and dry bulk density) of 368 meteorites are reviewed together with magnetic hysteresis data for 50 achondrites and chondrites. The relationships between dry bulk density, metallic FeNi-content and porosity will be discussed in the case of L-chondrites. Using the petrophysical classification scheme the meteorite class and the petrologic group of a sample can be determined in most of the cases providing a rapid means for determining a preliminary classification of a new sample. In addition, the petrophysical database provides a direct source of basic physical properties of the small bodies in the solar system. Paleointensity determinations with Thellier technique will be presented for 16 meteorites representing different chondrite groups. The results yield high paleofield values ranging from 51 μT to 728 μT for the magnetically hardest meteorites consistent with previous studies. However, these values must be looked with caution, because of possible physico-chemical or mineralogical alterations during heating.

1. Introduction

Meteorites yield direct information about the geology, composition and physical properties of their parent bodies (asteroids, comets, the Moon, Mars). In particular the magnetic properties of meteorites provide valuable information about the magnetic field intensity during the formation and/or during subsequent metamorphism of the parent bodies (CISOWSKI, 1987; COLLINSON, 1989). A more thorough study of the early planetary and interplanetary magnetic fields would greatly benefit the construction of the evolutionary models of the solar system (LEVY and SONETT, 1978). So far studies of the physical properties of meteorites have not received very much attention among meteorite investigators.

During the last ten years we have measured petrophysical properties (dry bulk density, magnetic susceptibility and natural remanent magnetisation, NRM) of 368 meteorites from Finnish, Swedish and Australian collections and compiled the results in a database (KUKKONEN and PESONEN, 1983; TERHO *et al.*, 1992a). The petrophysical properties have been substantiated with magnetic hysteresis determinations to study the magnetic grain size variations and simultaneously to classify the meteorites with the hysteresis classification scheme of Sugiura (SUGIURA, 1977). In addition, Thellier paleointensity (THELLIER and THELLIER, 1959) measurements on 16 meteorite samples have been carried out.

There are three main branches of applications of our database: (i) preliminary classification of meteorites by their physical properties (a good correlation exists between standard chemical-petrological classification and physical properties (see KUKKONEN and PESONEN, 1983; TERHO *et al.*, 1992a, b for details); (ii) modelling of magnetic and gravity data to be measured during satellite fly-passes of small bodies (asteroids, comets, planetary satellites) and landings (Moon, Mars, planetary satellites) (KUKKONEN *et al.*, 1991), and (iii) studies of the ancient magnetic fields (interplanetary or parental) during the accretion or during subsequent geological evolution of the meteorite parent bodies, planets and their moons (LEVY and SONETT, 1978; SONETT, 1978; CISOWSKI, 1987).

In this paper we present a summary of petrophysical properties of 368 meteorites together with hysteresis properties of 50 meteorites. The effects of FeNi-content and porosity on density and susceptibility will be discussed. We then discuss the aspects of obtaining a preliminary classification of meteorites by petrophysical and by magnetic hysteresis methods. New paleointensity results obtained with the modified Thellier technique (THELLIER and THELLIER, 1959; COE, 1967) on sixteen chondrite and achondrite samples will be presented. An estimate of the interplanetary magnetic field obtained by the Sonett-technique as applied to susceptibility and NRM data of ordinary chondrites (SONETT, 1978) will be also presented.

2. Measurement Techniques

The physical quantities measured at the Geological Survey of Finland (GSF) include dry bulk density ($\mathrm{kg\,m^{-3}}$), magnetic susceptibility (SI), and intensity of NRM ($\mathrm{A\,m^{-1}}$).

The applied methods and techniques are described in detail in PURANEN and PURANEN (1977), KUKKONEN and PESONEN (1983) and TERHO *et al.* (1992a) and will be only briefly outlined here. For all these measurements (except the hysteresis determinations) it was not necessary to prepare the meteorite samples by any means: they were measured as hand specimens in dry conditions as they appear in museums.

2.1. *Density*

Density ($\mathrm{kg\,m^{-3}}$) has been determined by weighing the sample in air and in water (Archimedes principle). The soaking time is only about a few seconds, which does not allow the sample to become saturated by water (and thus not contaminated harmfully; see, however, the porosity determinations in the next chapter). The precision of the method is about $5\,\mathrm{kg\,m^{-3}}$ for typical meteorite specimen sizes (mass >20 g), but is much less for very small pieces. Since the samples are measured in the same conditions as they appear in museum collections, the measured quantity is the *dry bulk density* (D_b) which is an underestimate of the density due to porosity. Since the porosity of meteorites can rise up to 20% (HAMANO and YOMOGIDA, 1982) it produces systematic errors to density data. Another factor which strongly influences the measured dry density values of meteorites is the FeNi-content of the samples: this is in fact the major cause of density increase from achondrites→chondrites→stony-irons→irons as will be shown (Fig. 1). In the next, the density value from which the FeNi-content (by wt%) has been removed (eq. 1) is called the *FeNi-corrected density* (D_c). We shall discuss the effect of porosity and FeNi-content on bulk density later in Section 3.1.

2.2. Susceptibility

The susceptibility here generally refers to *volume susceptibility* (dimensionless in SI-units). However, in investigating the relationship in meteorites between susceptibility and FeNi-content (wt%) it is more practical to use the *mass susceptibility* ($m^3\,kg^{-1}$) (Fig. 2). The susceptibilities were measured with susceptibility bridge K-3B, designed and built at GSF (PURANEN and PURANEN, 1977; PURANEN, 1989) and operating with a frequency of 1025 Hz. The precision of the instrument for typical sample sizes (mass > 20 g) is about $10^{-9}\,m^3\,kg^{-1}$ (or $\sim 4 \cdot 10^{-6}$ SI) but is less for very small specimens. All suspectibility values are corrected for sample shape demagnetisation effects by approximating the sample with an ellipsoid or with a prism, respectively (see details in TERHO *et al.*, 1992a). However many other factors, such as grain size and shape of the metallic particles, weathering, impurities, electrical conductivity of the sample and applied frequency (1025 Hz) of the susceptibility bridge, introduce scatter in susceptibility values in addition to the major effect of increasing FeNi-content from achondrites to irons (Figs. 1A and 2).

2.3. NRM

The intensity ($A\,m^{-1}$) and direction of the NRM were measured with a flux-gate magnetometer R2 (PURANEN and PURANEN, 1977) which permits the measurement of hand samples of different shape and size (petrophysical determinations) or with a spinner magnetometer SM2 built in GSF (Thellier determinations; PESONEN *et al.*, 1983). The precision of these instruments is about $10\,mA\,m^{-1}$ (flux-gate) and $1\,mA\,m^{-1}$ (spinner), respectively. All NRM intensities are corrected for shape demagnetisation effects (see above). The directions are with respect to an artificial mark drawn on the samples; the precision is about $\pm 5°$.

2.4. Hysteresis

Magnetic hysteresis properties of 50 achondrite and chondrite samples were measured at the Technical Research Centre of Finland, Espoo, using the vibrating sample magnetometer (VSM) (MEINANDER, personal commun. 1992). Small disks of 7 mm in diameter and 4 mm in thickness were prepared for the hysteresis measurements.

3. Results

During 1979–1991 we have measured the petrophysical properties of 489 meteorite samples from 368 known meteorites preserved in Finnish, Swedish and Australian meteorite collections (KUKKONEN and PESONEN, 1983; TERHO *et al.*, 1992a, b). The samples include all the main classes (achondrites, chondrites, stony-irons and irons) and almost all of the petrological-chemical groups. Table 1 lists the mean values of petrohysical properties of the main meteorite classes and of the chondrite groups; a complete list of the data can be found in TERHO *et al.* (1992a).

The physical properties of the 368 meteorite samples reveal definite trends when

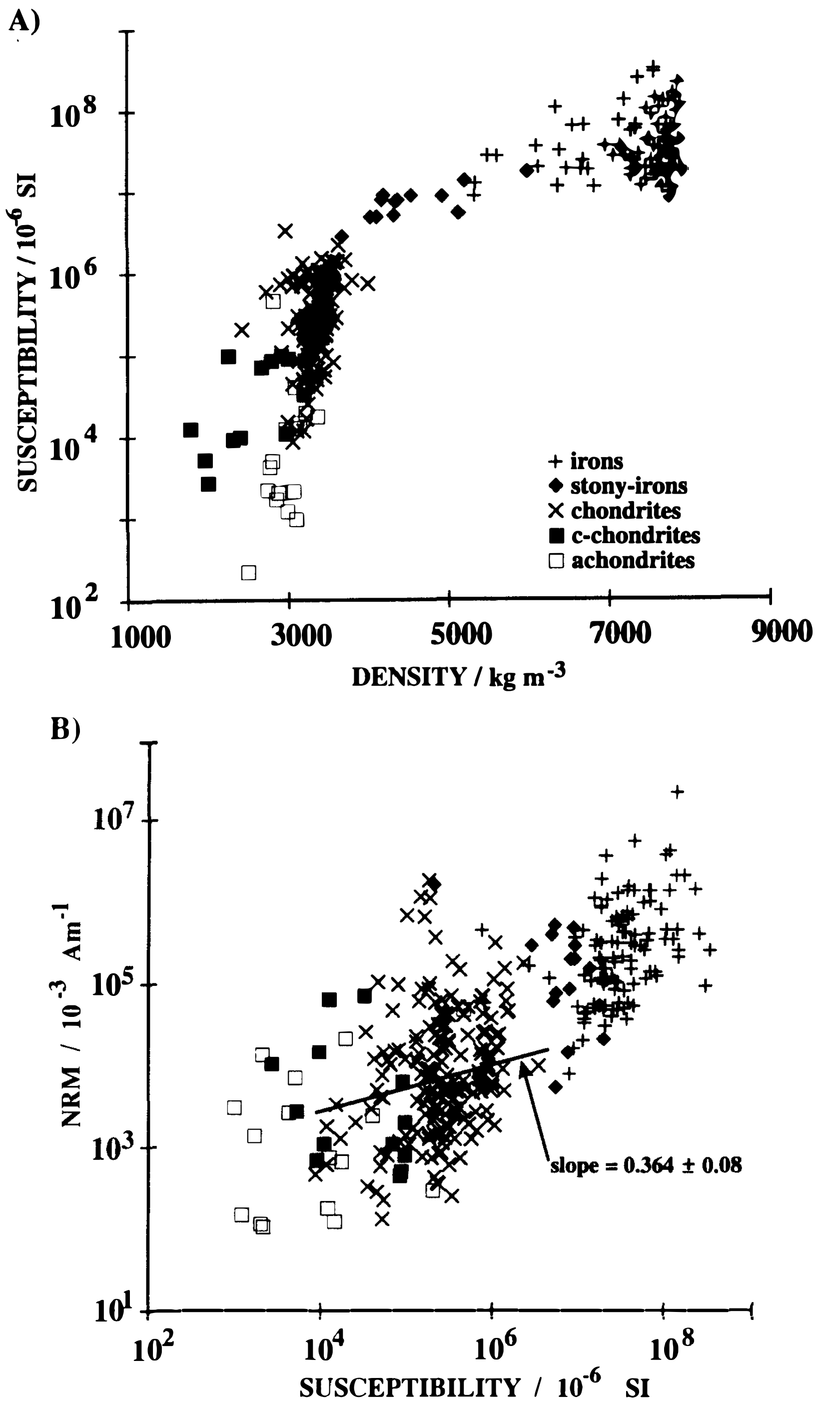

Fig. 1. Examples of the petrophysical bivariate relation plots used in classifying meteorites by their physical properties. A) magnetic susceptibility vs. dry bulk density, B) natural remanent magnetization (NRM) vs. susceptibility and C), D) the corresponding cluster plots. Data on 368 meteorite samples from Finnish meteorite collections. All data are on bulk hand samples. The susceptibility and NRM-data are corrected for sample shape demagnetization effects and densities are apparent values (no correction for porosity and FeNi-content). A complete list of the meteorite petrophysical data is in TERHO *et al. (1992a). The slope in (B) is the NRM/susceptibility ratio for ordinary chondrites, which will be used to evaluate the strength of the interplanetary magnetic field using the technique of* SONETT *(1978) (see Section 5). The symbols for different meteorite classes and petrologic groups are shown in Fig. 1A.*

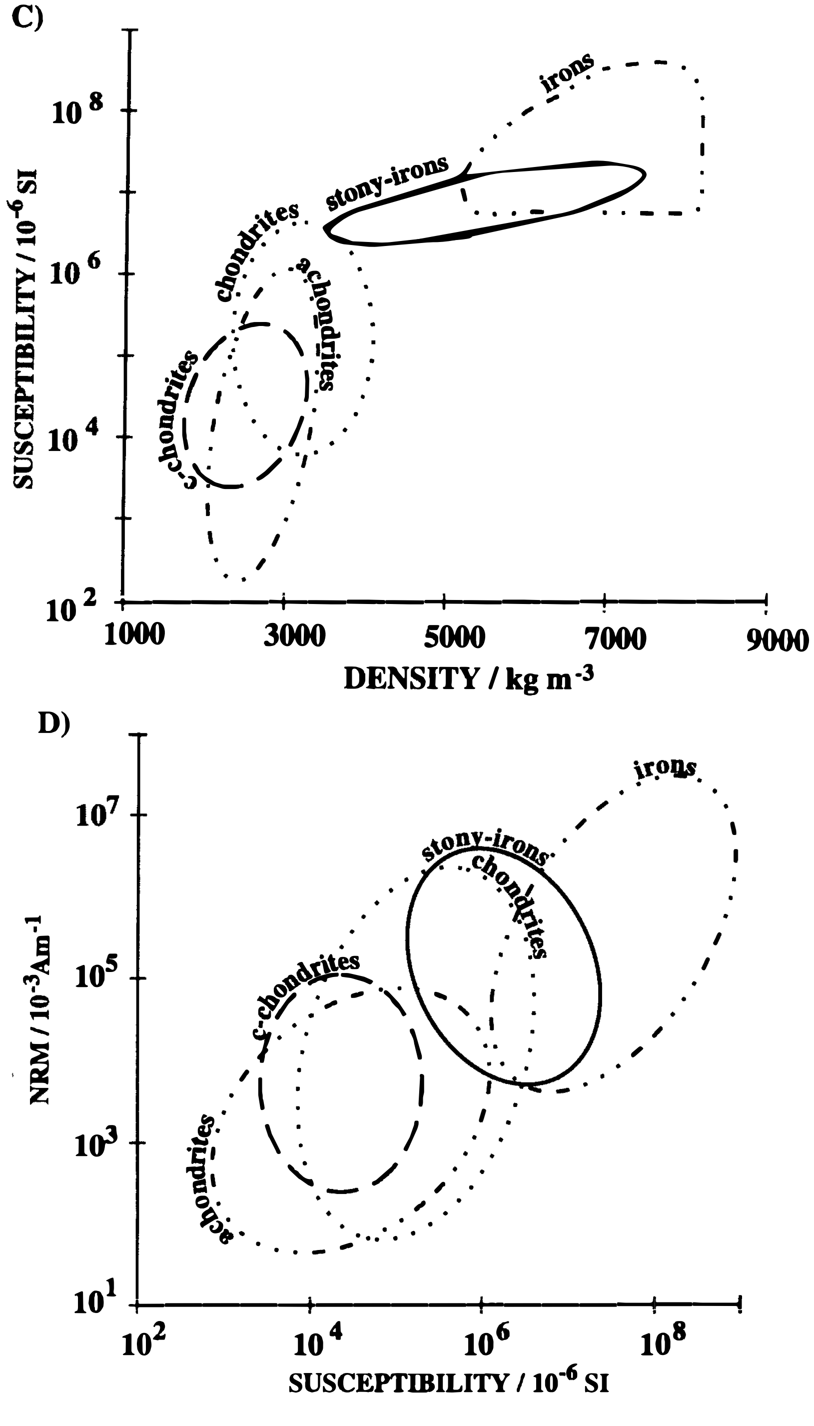

Fig. 1 (Continued).

the data are shown on bivariate relation diagrams, such as susceptibility *vs.* density (Fig. 1A) or NRM *vs.* susceptibility (Fig. 1B; see *e.g.*, SONETT, 1978; KUKKONEN and PESONEN, 1983). The main reason for the increase in susceptibility, NRM and density is the progressive increase in metallic FeNi-content in the sequence achondrites→ chondrites→stony-irons→irons. Figure 2 shows the effect of increasing metallic FeNi

Table 1. Mean values of petrophysical properties for four meteorite classes and five petrophysical groups of Finnsh measurements. N = number of samples, D_b = dry bulk density, χ = volume susceptibility, NRM = intensity of natural remanent magnetisation, FeNi = FeNi-content, N_{FeNi} = number of samples for FeNi-content.

Class/group	N	D_b $kg m^{-3}$	χ SI	NRM Am^{-1}	FeNi wt%	N_{FeNi}
Achondrites	19	2978	0.0797	10.4	1.52	10
C-chondrites	13	2609	0.0436	11.7	1.89	18
LL-chondrites	16	3229	0.0538	1.9	3.23	13
L-chondrites	87	3333	0.2642	22.4	8.25	53
H-chondrites	82	3375	0.6198	19.6	14.81	33
E-chondrites	4	3649	1.1582	98.1	23.51	8
LL+L+H+E	189	3398	0.806	45.5	12.45	107
Stony-irons	17	4526	5.647	202.3	25.86	6
Irons	131	7300	43.141	150.1	72.36	4

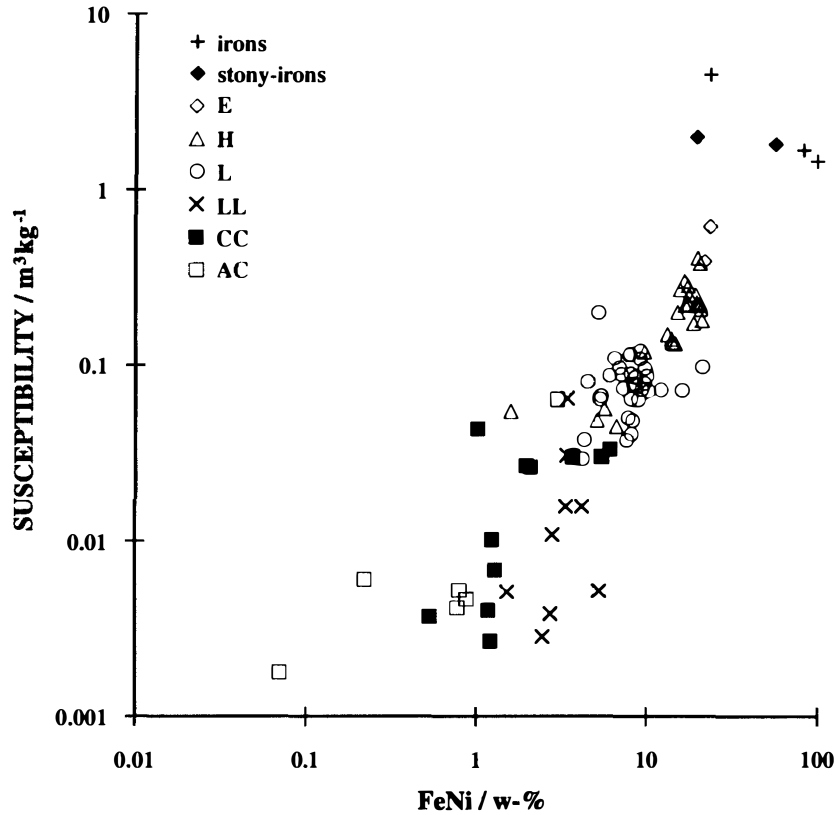

Fig. 2. The susceptibility vs. FeNi-content (weight percent) of metallic phase, where the latter data are taken from literature (UREY and CRAIG, 1953; MASON and WIIK 1964; JAROSEWICH 1990).

(wt%) on susceptibility for the main classes and petrologic groups. The main chemical classes can be identified on the petrophysical plots of Fig. 1, which can thus be used to give a preliminary estimate of the class of a sample not previously classified (see *e.g.*, KUKKONEN and PESONEN, 1983). In fact, this is often the case with the petrological

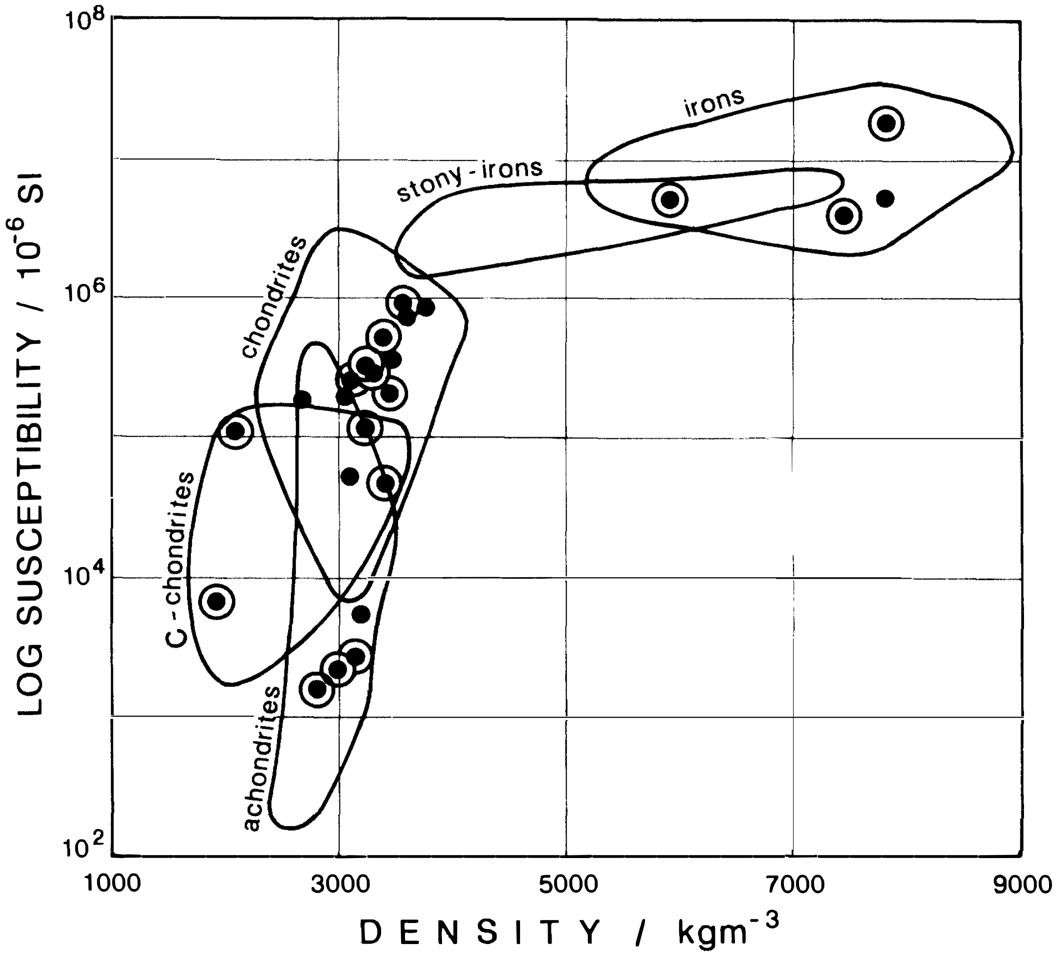

Fig. 3. Test examples of the preliminary classification of meteorites using petrophysical relation diagrams. The susceptibility and dry bulk density data of 24 test meteorites have been plotted in the magnetic susceptibility vs. density cluster plot (susceptibilities are without self-demagnetisation correction). The encircled (non-encircled) datapoints indicate that the classification is correct (incorrect). Test samples were obtained from Czechoslovak meteorite collections. See TERHO *et al. (1992b).*

groups as well (*e.g.*, TERHO *et al.*, 1992a, b), but the discrimination power is not sufficient to determine uniquely the group and metamorphic degree of a meteorite.

In order to test the efficiency of the petrophysical classification technique a test was arranged (TERHO *et al.*, 1992b). A total of 28 meteorite samples (24 from Czechoslovak, 3 from Swedish and one from Australian meteorite collections) was measured and their classifications were determined petrophysically by plotting the measured physical property on the relation diagrams of Fig. 1 and by "reading" the main class or the petrologic group, respectively. In spite of the uncertainties and unambiguities involved (the data overlap), we were able to estimate correctly the main chemical class for all test samples, and in ~50% of the cases (chondrites and chondrites) also the petrological group (Fig. 3; TERHO *et al.*, 1992b).

In addition to complex variations in metallic constituents (*e.g.*, the variation in the Ni-content, amount of troilite, presence of tetrataenite or magnetite, *etc.*), the

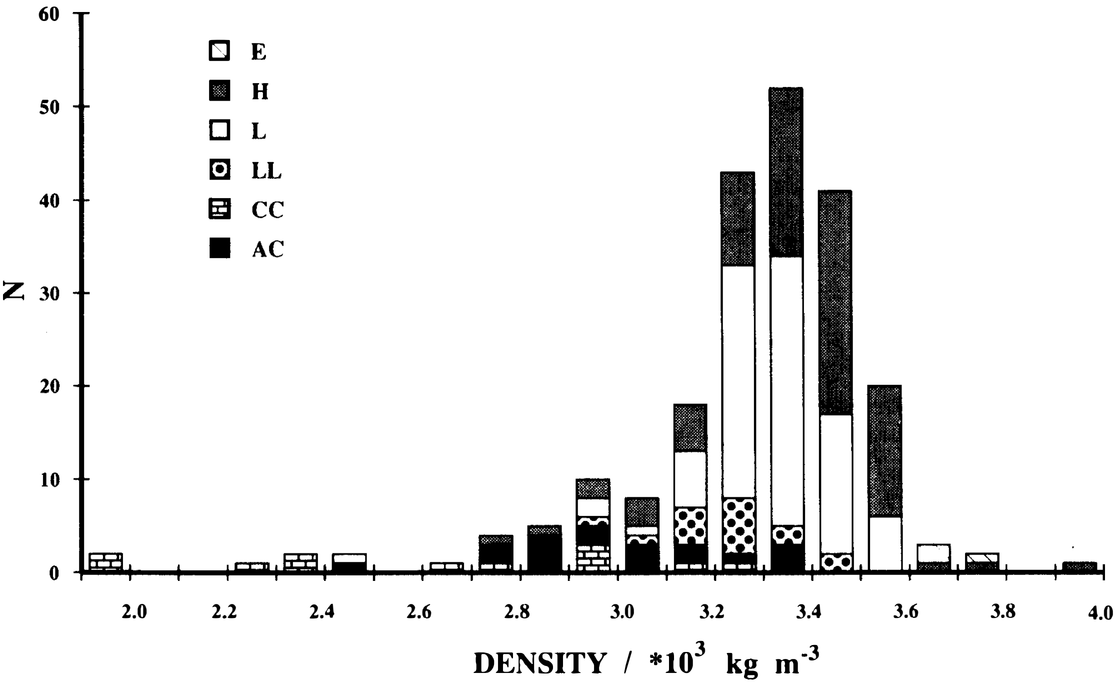

Fig. 4. The dry bulk density histogram for 257 stony meteorites. N is the number of data points.

failures can be attributed to non-uniqueness problems (cluster plots overlaps), porosity, weathering effects, self-demagnetisation, grain size and grain shape effects, electrical conductivity of the meteorite sample and the used frequency of the susceptibility bridge (see KUKKONEN and PESONEN, 1983; TERHO *et al.*, 1992a). The overall increase in density (Fig. 1A) from achondrites through chondrites and stony-irons to irons is, however, clearly due to the increase of metallic FeNi-content.

Figure 4 shows the dry bulk density histogram for achondrites (AC) and chondrite groups (CC, LL, L, H, E). The densities represent apparent values where no correction for porosity has been made. These values are thus underestimates of the density (see discussion on porosity effects in the next chapter). Nevertheless, the bulk density has a tendency to increase roughly in a sequence from CC→AC→LL→L→H→E with considerable overlaps between groups (Fig. 4, Table 1).

3.1. FeNi-corrected density

The increase in density in a sequence from CC→AC→C→SI→IR (Fig. 1A) is mainly due to the increase of FeNi (and other metals) content of metallic constituents. Figure 5 shows the effect of metallic FeNi-content for densities in the case of stony meteorites. The FeNi-correction on density has been calculated with eq. (1):

$$D_c = \frac{(1-p)\cdot D_{FeNi}}{(D_{FeNi} - p\cdot D_b)/D_b}, \tag{1}$$

where D_c is the FeNi-corrected density ($kg\,m^{-3}$), p is the metallic FeNi-content (wt%/100) (data from UREY and GRAIG, 1953; MASON and WIIK, 1964; JAROSEWICH, 1990), D_{FeNi} is the density of FeNi-alloy of a meteorite ($kg\,m^{-3}$) and D_b is the

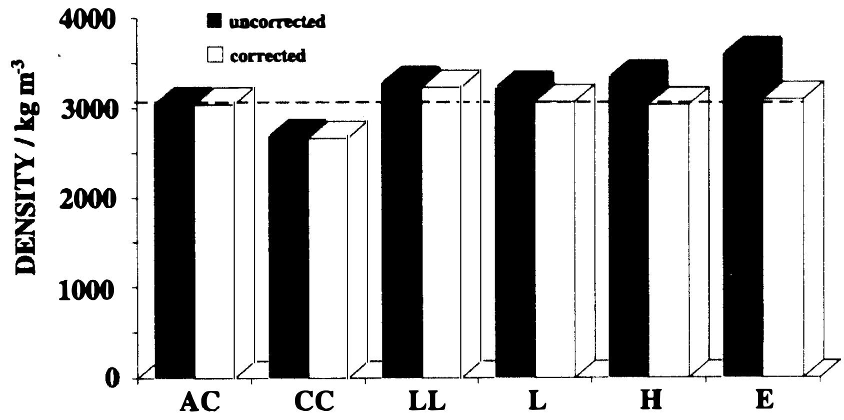

Fig. 5. The density histograms for stony meteorite groups before (closed columns) and after (open columns) the reduction for the metallic FeNi-content. Other metals (e.g. FeS) are not taken into account. The FeNi-contents are from UREY *and* CRAIG *(1953),* MASON *and* WIIK *(1964) and* JAROSEWICH *(1990) and the FeNi-correction on density has been calculated with eq. (1).*

measured dry density (kg m^{-3}). We can see (Fig. 5) that the densities before the FeNi-correction (closed columns) increase from achondrites (AC) to LL-, L-, H- and E-chondrites but will become very similar after the correction (open columns). The broken line denotes a rough overall estimate of the FeNi-corrected density (~3050 kg m^{-3}). The C-chondrites (CC) fall slighly below this line and the LL-chondrites slighly above. These departures probably reflect true differences in the composition of the matrix material with respect to other groups.

3.2. *Porosity*

As shown by HAMANO and YOMOGIDA (1982) the porosity can reduce the density values in meteorites up to ~20%. For preservation reasons (and since no He-gas facility was available) we were not allowed to measure the porosities in our laboratory with the Archimedes-technique (this would require a soaking of the sample in water more than days in contrast to bulk density measurements, where the soaking takes only a few seconds; TERHO *et al.*, 1992a). Only L-chondrites provided sufficient data for the porosity study. Excluding the densities over 3200 (kg m^{-3}) the results in (Fig. 6) show the expected general decrease of FeNi-corrected density when porosity increases (see also YOMOGIDA and MATSUI, 1982). Since the contribution of FeNi-content to these density data was eliminated in Fig. 6 the major reason for the observed trends in FeNi-corrected density within a group is thus porosity. Therefore the FeNi-corrected density *vs.* porosity graphs can be used to obtain a rough estimate of porosity for those chondrites for which porosity has not been directly measured. In Fig. 6 we have drawn the area of the porosity of L-chondrites (data by HAMANO and YOMOGIDA, 1982; YOMOGIDA and MATSUI, 1982) plotted against the FeNi-corrected density as defined by eq. (1). The data form an expected trend of decreasing density (D_c) when porosity increases. However, at higher densities (>3200 kg m^{-3}) the data are very scattered and no clear trend is seen (broken lines). This could be due to low number of available porosity data of high density L-chondrites. The plot can

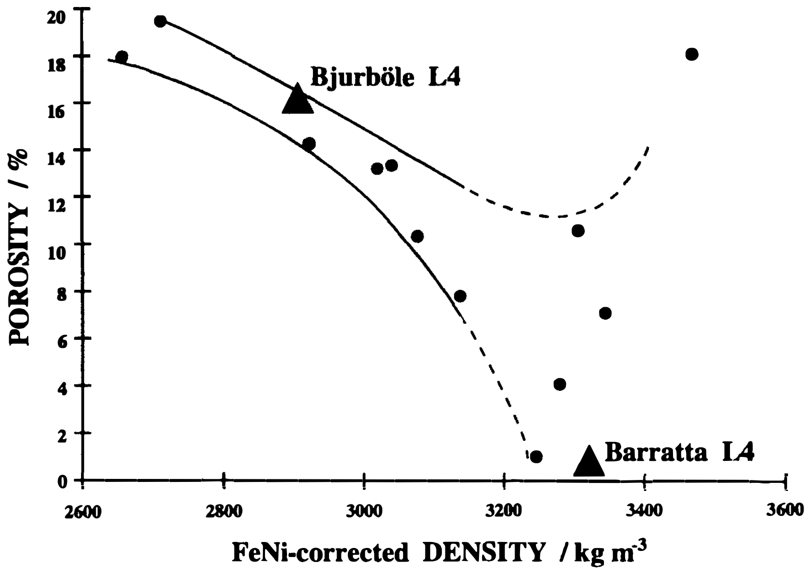

Fig. 6. The FeNi-corrected density vs. porosity for 12 L-chondrites (data points shown as dots). The porosity data are from HAMANO and YOMOGIDA (1982) and YOMOGIDA and MATSUI (1982). The data form a belt of increasing density with decreasing porosity as expected. The broken lines indicate larger scatter of data at higher densities. The two test data are the Bjurbole and the Barratta L4-chondrites (see text).

neverthless be used to obtain a rough estimate of porosity for those L-chondrites for which no porosity determinations is available. In an example, we have plotted the FeNi-corrected density of Bjurböle and Barratta L4-chondrites (measured in GSF and FeNi-correction made according to eq. (1)) on Fig. 6 from which the estimate of porosities for Bjurböle and Barratta are between 14.4–16.7% and 0–12%, respectively which are within the measurement limits of the known porosities (16.3% and 0.7%) for these samples.

We will further investigate this technique for other (E, H, LL) chondrites for which abundant bulk density and porosity data are available (HAMANO and YOMOGIDA, 1982; JAROSEWICH, 1990).

4. Hysteresis Data

A compilation of the magnetic hysteresis data is shown in Fig. 7, where the J_r/J_s (saturation remanence/saturation magnetisation) is plotted against H_c (coercive force) for 50 achondrites and chondrites from Finnish collections. The roughly linear (log scale) increases in J_r/J_s and H_c in a series from E→H→L→CC→LL reflects the increase in magnetic hardness of chondrites, respectively (SUGIURA, 1977). Since there is considerable spreading between data of various groups, the J_r/J_s *vs.* H_c-plot provides another magnetic method to classify meteorites rapidly (SUGIURA, 1977). Note that the magnetically hardest samples (highest values for J_r/J_s and for H_c; Fig. 7) are found in the C- and LL-chondrites (as also found by SUGIURA, 1977); these groups also possess the hardest NRM and IRM (isothermal remanent magnetisation) as found by comparing the alternating field demagnetisation characteristics of NRM

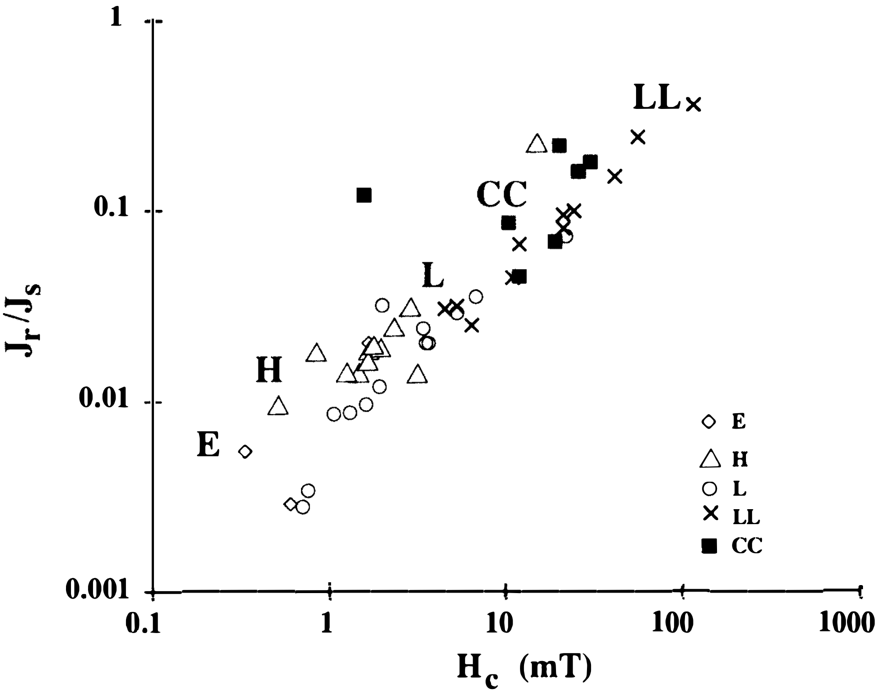

Fig. 7. Magnetic hysteresis classification of 50 chondrites from the Finnish collections. The J_r/J_s is plotted against H_c, where J_s, J_r are the saturation and saturation remanent magnetizations, respectively, and H_c is the coercive force.

and IRM (TERHO *et al.*, 1992a). The causes for variations in magnetic hardness have not been studied in detail but variations in grain size of the metallic FeNi-particles and the variation of tetrataenite content are the two major factors effecting the values of magnetic hardness (see *e.g.*, MORDEN, 1990).

5. Paleointensity Studies

Paleointensity was measured of 16 meteorite samples with the modified Thellier double heating technique (THELLIER and THELLIER, 1959; COE, 1967; TERHO *et al.*, 1992a) using bulk meteorite samples rather than individual chondrules (see *e.g.* SUGIURA *et al.*, 1979; COLLINSON, 1989). The applied laboratory field used in these experiments was 50 μT. The Thellier runs showed complex behaviours in most of the studied samples with no reliable paleointensity values. The reasons of failure are numerous but physico-chemical alterations during the course of Thellier run, magnetic instability, non-uniform NRM and failures to fulfil basic assumptions in the Thellier technique are the most important ones (MORDEN, 1990; TERHO, 1992a).

Examples of more promising results are the paleointensity runs for Guidder (LL5; Fig. 8), for Fleming (H3; Fig. 9) and for Kivesvaara (CM2; Fig. 10). In all cases the direction of NRM is quite stable, but a secondary component at low temperatures is present in each case. This component could be the signature of present Earth's field or it has been caused by warming and subsequent cooling of the sample during its passage through the Earth's atmosphere.

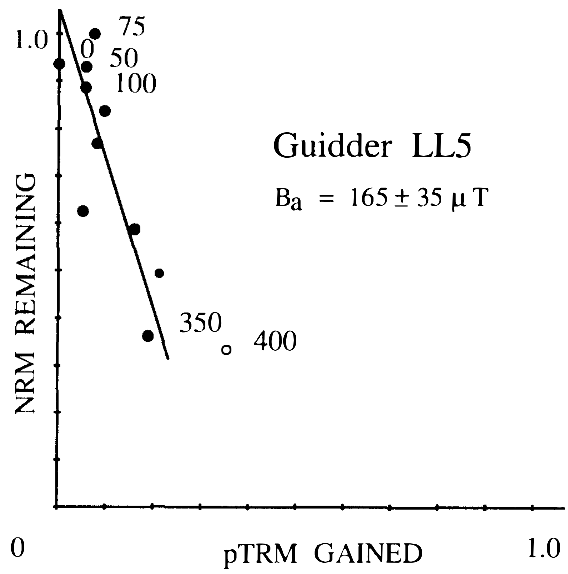

Fig. 8. Paleointensity B_a (in μT) of Guidder LL5 chondrite by the Thellier technique. The temperature range for paleointensity determination is 20–350°C. Both axes are normalized with room temperature NRM intensity.

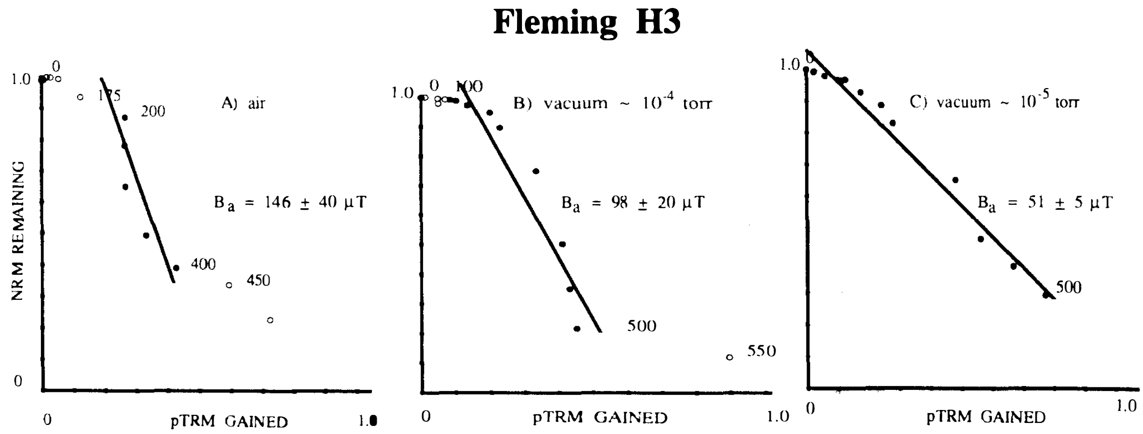

Fig. 9. Thellier paleointensities (B_a) of Fleming H3 chondrite in three different laboratory environments. (A) normal laboratory conditions (air), (B) 10^{-4} torr vacuum and (C) 10^{-5} torr vacuum. For axis, see Fig. 8.

Our palaeointensity plots with steep gradients are strikingly similar to those of SUGIURA (1977) and WESTPHAL and WHITECHURCH (1983). The six magnetically hardest samples (from C-, LL-, L- and H3-chondrites) reveal very steep paleointensity plots indicating high paleofields ranging from 51 μT to 728 μT during the formation or during the last metamorphism of these meteorites or their parent bodies. Similar high paleofield values with Thellier technique have been previously found by other groups for the same meteorite types (BANERJEE and HARGRAVES, 1972; SUGIURA, 1977; SUGIURA and STRANGWAY, 1982; WESTPHAL and WHITECHURCH, 1983). However, these values are suspect since they are not repeatable in laboratory experiments (WESTPHAL, 1986). We are further investigating the causes for the high paleointensity data so often obtained of stony meteorites.

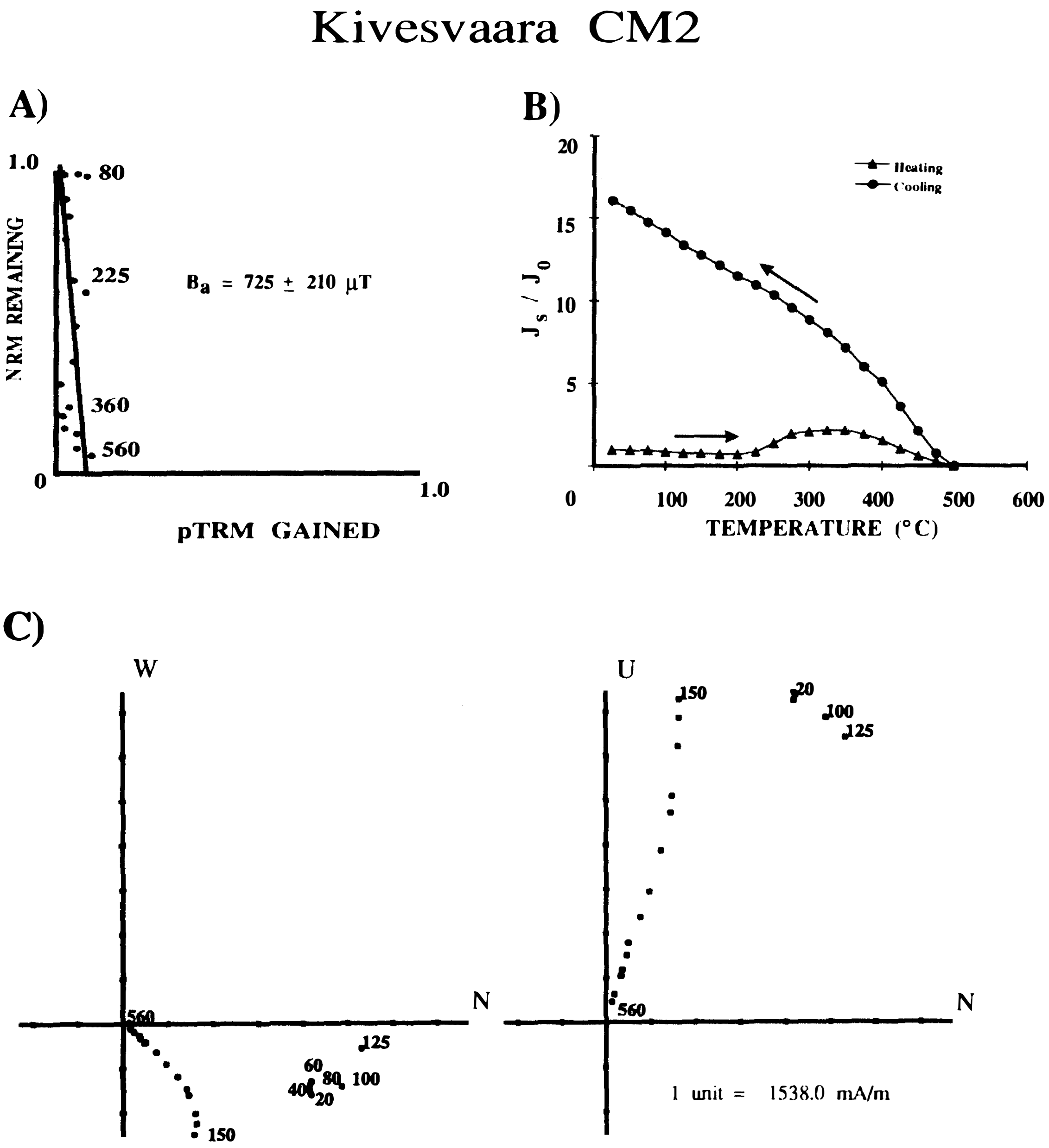

Fig. 10. Thellier paleointensity of Kivesvaara CM2 carbonaceous chondrite. (A) The "Arai-plot", where B_a is the paleointensity (μT). The temperature range for paleointensity determination is 20–560°C. For axis, see Fig. 8. (B) saturation magnetisation (normalized with room temperature value) vs. temperature, measured by N. SUGIURA. (C) Zijderveld orthogonal plot of NRM. The straight line indicates that a stable component has been erased. Points 1–6 (20–125°C) indicates the presence of a secondary low temperature component, as discussed in text.

We also applied the technique of SONETT (1978) to see whether our petrophysical database yields any evidence for the interplanetary magnetic field that has probably affected all the meteorites. The slope of the NRM *vs.* susceptibility data (Fig. 1B), from which the estimate of the interplanetary magnetic field can be obtained (see details in SONETT, 1978), is ~0.364±0.08 for ordinary chondrites: this is slightly higher than that (0.18) found by SONETT (1978) of a large data set of magnetic properties of Russian chondrites. However, the value for the interplanetary field, if real at all, is difficult to estimate since the linearity of NRM *vs.* susceptibility plot is affected by many other factors than the FeNi-content (which is the main cause for the linearity) (SONETT, 1978; TERHO *et al.*, 1992a, b). Moreover, the method requires a knowledge of the average grain demagnetisation factor (N) for each sample, which can vary from 0 to 1. An extreme lower limit for the interplanetary field is $\sim 2.8\,\mu$T (when $N=1$ SI is used) which is close to that (1–2 μT) found by BRECHER and RANGANAYAKI (1975) for primeval interplanetary magnetic field using paleointensity data of ordinary chondrites.

6. Discussion and Conclusions

The petrophysical data are quite useful for a rapid (but very preliminary) classification of an unknown meteorite sample, as for example, the meteorites from Antarctica or from Sahara. It can be applied also to distinguish a meteorite from terrestrial rocks except in the case of achondrites (TERHO *et al.*, 1992a). Another potential application is modelling of magnetic and gravity data measured during satellite fly-passes of small bodies (asteroids, comets, planetary satellites) and landings (Moon, Mars, planetary satellites). Also studies of the ancient magnetic fields (interplanetary or parental) during the accretion or during subsequent geological evolution of the meteorite parent bodies, of the planets and their moons can be carried out (KUKKONEN *et al.*, 1991).

Porosity produces systematic errors to density, volume susceptibility and NRM values. Other error sources include the grain size and grain shape effects on magnetic properties and errors produced by electric conductivity on susceptibility especially for irons (see KUKKONEN and PESONEN, 1983; TERHO *et al.*, 1992a).

The paleointensities obtained by the Thellier double heating method are quite high (ranging from 51 μT to 728 μT), but similar results have been introduced before (see BUTLER, 1972; BANERJEE and HARGRAVES, 1972; SUGIURA *et al.*, 1979; WESTPHAL and WHITECHURCH, 1983). However all of the high Thellier paleointensities must be regarded with caution since, as shown by WESTPHAL (1986), they are not repeatable in laboratory.

There are numerous factors which can cause the Thellier plots (and thus the paleointensities) to become too steep. One possibility is that the double heating method causes linear alterations in mineral compositions causing high apparent paleointensities. For example, primary tetrataenite can disappear during severe heatings because of tetrataenite disorders at 320°C and it can re-ordering only if the cooling rate is as low as 1–10°/Ma (MORDEN, 1990) compared to a much faster laboratory cooling rate. Fig. 10B clearly shows that mineralogical or physico-chemical alterations take place in heating for example in the Kivesvaara CM2 chondrite since the J_s-T-curve is irreversible. Another problem is the dissimilarity of the applied laboratory field ($\sim 50\,\mu$T) compared to the obtained paleofields (51–728 μT), since the Thellier plot (and thus the paleofield) depends on the applied laboratory field itself (see AITKEN *et al.*, 1986). Several other problems can be raised: for example, we do not know what is the age of the measured ancient magnetic field. Does it represent the ancient field of the parent body during the early solar system, or does it reflect the magnetic field during the last metamorphism in the parent body? Another error source could be the terrestrial magnetic field contamination. All measured samples have been in museums for long time and have probably acquired terrestrial secondary components (laboratory field contamination, viscous component by the Earth's field) which can produce high apparent paleointensities (MORDEN, 1990). One problem in all paleointensity determinations is related to the uniformity of NRM since measurements have been carried out on bulk samples and not on individual chondrules (COLLINSON, 1989). It could also be that other techniques, such as those involving anhysteretic remanent magnetisation (ARM) or isothermal remanent magnetisation (IRM) can in fact give more reliable result for chondrites than the Thellier technique (CISOWSKI, 1987; MORDEN, 1990). These paleointensity techniques have yielded much lower values (1–74 μT) of paleointensity for chondrites than the Thellier technique (STACEY *et al.*, 1961; GUS'KOVA, 1963; BRECHER and RANGANAYAKI, 1975; SUGIURA and STRANGWAY, 1982).

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