

In situ identification, pairing, and classification of meteorites from Antarctica through magnetic susceptibility measurements

Luigi FOLCO^{1, 2*}, Pierre ROCHETTE¹, Jérôme GATTACCECA¹, and Natale PERCHIAZZI³

¹CEREGE, Université Aix-Marseille 3, Aix en Provence, France

²Museo Nazionale dell'Antartide, Siena, Italy

³Dipartimento di Scienze della Terra, Università di Pisa, Italy

*Corresponding author. E-mail: folco@unisi.it

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Abstract—We report on the effectiveness of using magnetic measurements in the search for meteorites on the Antarctic ice sheet, which is thus far the Earth's most productive terrain. Magnetic susceptibility measurements carried out with a pocket meter (SM30) during the 2003/04 PNRA meteorite collection expedition to northern Victoria Land (Antarctica) proved to be a rapid, sensitive, non-destructive means for the in situ identification, pairing, and classification of meteorites. In blue ice fields characterized by the presence of moraines and glacial drifts (e.g., Miller Butte, Roberts Butte, and Frontier Mountain), magnetic susceptibility measurements allowed discrimination of meteorites from abundant terrestrial stones that look like meteorites thanks to the relatively high magnetic susceptibility of the former with respect to terrestrial rocks. Comparative measurements helped identify 16 paired fragments found at Johannessen Nunataks, thereby reducing unnecessary duplication of laboratory analyses and statistical bias. Following classifications schemes developed by us in this and previous works, magnetic susceptibility measurements also helped classify stony meteorites directly in the field, thereby providing a means for selecting samples with higher research priority. A magnetic gradiometer capable of detecting perturbations in the Earth's magnetic field induced by the presence of meteorites was an efficient tool for locating meteorites buried in snow along the downwind margin of the Frontier Mountain blue ice field. Based on these results, we believe that magnetic sensors should constitute an additional payload for robotic search for meteorites on the Antarctic ice sheet and, by extension, on the surface of Mars where meteorite accumulations are predicted by theoretical works. Lastly, magnetic susceptibility data was successfully used to cross-check the later petrographic classification of the 123 recovered meteorites, allowing the detection of misclassified or peculiar specimens.

INTRODUCTION

Antarctica is one of the most fertile terrains for the search for meteorites on Earth. Each year various research programs retrieve hundreds to thousands of specimens from blue ice fields at the edge of the Antarctic plateau. The high number of finds is favored by concentration mechanisms produced by the glacial dynamics of the Antarctic ice sheet and by the low weathering rates determined by polar climatic conditions (Cassidy et al. 1992; Harvey 2003). As searches are usually carried out visually, the ease with which meteorites can be spotted on bare ice is another important factor contributing to the extraordinary number of finds. However, the latter condition is not always met, and there are several blue ice fields where the search for meteorites can be problematic.

Abundant dark terrestrial stones disseminated on the blue ice surface can be rather common (e.g., Lewis Cliff, Reckling Moraine, etc.) (Cassidy et al. 1992), making discrimination of meteorites extremely difficult even for well-trained searchers. Furthermore, the seasonal snow cover present in most blue ice fields can transiently hide meteorite accumulations (e.g., Frontier Mountain) (Folco et al. 2002). The high number of finds from Antarctica generates an enormous amount of curatorial work, in terms of classification and allocation of subsamples to the scientific community. Methods that can help find meteorites in the field, reduce curatorial costs, and contribute to the rapid and accurate classification of this unique sampling of the solar system materials are highly desirable.

Magnetic susceptibility measures the ability of a material

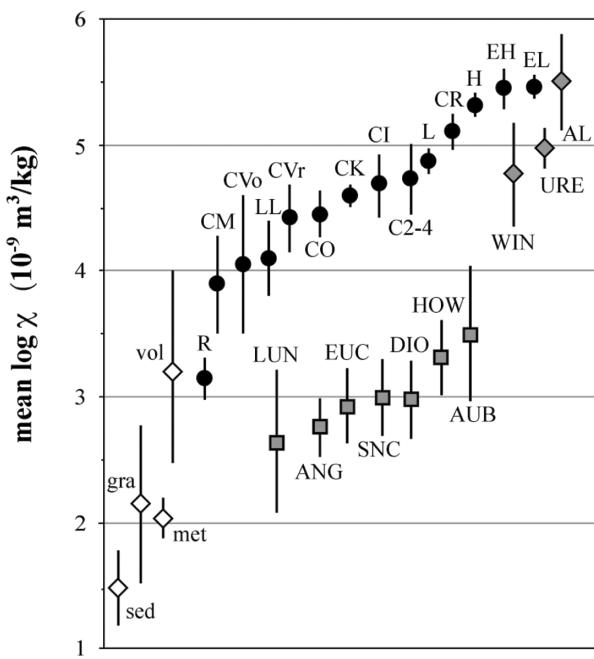


Fig. 1. The decimal logarithm of magnetic susceptibility χ in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$ for different classes of meteorites (mean value and standard deviation), as well as for plutonic, volcanic, metamorphic, and sedimentary rocks from northern Victoria Land, Antarctica, belonging to the McMurdo Volcanics, Ferrar Supergroup and Beacon Supergroup, Admiralty Intrusive, Granite Harbour Intrusive, Wilson Metamorphic Complex, and Bowers Metamorphic Complex. Weathered metal bearing meteorites show lower values than the means above (derived from falls).

to acquire a magnetization when placed in an external magnetic field. Rochette et al. (2003, 2004) have demonstrated that a given meteorite has a well-defined magnetic susceptibility and that the various meteorite classes have characteristic ranges of magnetic susceptibility, reflecting different contents of magnetic minerals (mainly metal and magnetite). We will show that the magnetic susceptibility of meteorites tends to be higher than that of the terrestrial rocks available at the Earth's surface. In order to provide a simple, sensitive, accurate, and non-destructive means for in situ magnetic susceptibility measurements of the whole stones of any size and shape, Gattacceca et al. (2004) calibrated a pocket contact probe (the SM30, by ZH Instruments). As such, magnetic susceptibility measurements can be used during a meteorite search campaign as a diagnostic parameter to discriminate meteorites from terrestrial rocks, to pair fragments belonging to the same fall, and to gain significant insight into their classification directly in the field. Moreover, the very high magnetic susceptibility of most meteorites can also be used to help locate them when they are buried in snow (or glacial or aeolian deposits) using a magnetic gradiometer.

We report henceforth on a test of these techniques carried out in the 2003/04 PNRA meteorite collection expedition to

Victoria Land, Antarctica, during which we visited the Miller Butte ($72^{\circ}42'S$, $160^{\circ}15'E$), Roberts Butte ($72^{\circ}39'S$, $160^{\circ}12'E$), Johannessen Nunataks ($72^{\circ}51'S$, $159^{\circ}50'E$), Mount Walton ($72^{\circ}27'S$, $160^{\circ}18'E$), Frontier Mountain ($72^{\circ}59'S$, $160^{\circ}20'E$) and Mount DeWitt ($77^{\circ}12'S$, $159^{\circ}50'E$) blue ice fields and recovered 123 meteorite specimens. We also discuss the application of these techniques in relation to robotic search for meteorites on the Antarctic ice sheet and other productive terrains in the solar system such as the surface of Mars.

THE MAGNETIC CLASSIFICATION OF METEORITES

Magnetic susceptibility reported here is the mass normalized one, χ , in m^3/kg , as mass is an easier parameter to measure than volume. Following Rochette et al. (2003), it will be expressed as the decimal logarithm of χ in $10^{-9} \text{ m}^3/\text{kg}$ in order to account for the 5 order of magnitude variation in rocks. For strongly magnetic material ($\log \chi > 3$), χ is proportional to the amount of Fe,Ni metal, magnetite, maghemite, cohenite, and schreibersite, i.e., minerals with practically equal specific χ . The contribution of less magnetic iron-bearing minerals, such as other iron oxides and hydroxides (including metal oxidation products), pyrrhotite, and paramagnetic iron-bearing silicates, is no longer negligible at $\log \chi \leq 3$. Laboratory instruments used to measure χ reported in this study are either the Kappabridge or the Bartington bridge (see Sagnotti et al. 2003 for their calibration). Instrumental precision is 1% or better, but as discussed in Rochette et al. (2003), irregular sample shape and anisotropy may lead to dispersion of duplicate measurements of up to 20% (i.e., 0.08 in log unit). A database of χ measurements on more than 1500 different meteorites (each represented by at least 3 g of material and one specimen) from various collections worldwide has been compiled using different laboratory instruments. Multiple specimen measurements for a single meteorite usually yield a standard deviation of less than 0.1 (Rochette et al. 2003). Figure 1, created by averaging $\log \chi$ values per meteorite class, shows means and standard deviations in the 0.1–0.5 range. Although irons and stony-irons were not included in this database due to specific measuring problems, they would obviously plot in the >5 range (Terho et al. 1993). One can distinguish three ranges of $\log \chi$: strongly magnetic (≥ 4.5), which includes 88% of the total world collection of meteorites; weakly magnetic (≤ 3.5), which is comprised of R chondrites, lunar, Martian, angrite, HED achondrites; and intermediate classes comprised of LL, CM, oxydized CV chondrites, and aubrites. As described in details for ordinary chondrite falls in Rochette et al. (2003), $\log \chi$ is potentially a very efficient tool for classifying meteorites, although non-unique assignments are obvious, especially around $\log \chi = 3$ or 5. Moreover, weathering induces a significant decrease in

$\log \chi$ for metal bearing meteorites, i.e., about 0.1–0.2 per weathering grade. For example, a $\log \chi$ of 4.9, which is typical of a fresh L, can also be found in a weathered H or E chondrite.

A database of $\log \chi$ values for terrestrial rocks was generated using samples of magmatic, metamorphic, and sedimentary rocks cropping out in northern Victoria Land where the PNRA expedition was carried out (Fig. 1) that were made available from the Sorting Center of the Museo Nazionale dell'Antartide in Siena. Values of $\log \chi$ for terrestrial sedimentary, metamorphic, and granitoid rocks are lower than those for meteorites, although some overlap exists between highly magnetic granitoids and some lunar meteorites (Fig. 1). Volcanic rocks (from the Ferrar Supergroup and from Cenozoic Ross Embayment magmatism) overlap with the weakly magnetic meteorite classes, with the most magnetic volcanic rocks falling into the ranges of intermediate classes.

SM30 MAGNETIC SUSCEPTIBILITY MEASUREMENTS

With the aim of obtaining data in the field as well as on large samples not fitting in the Kappabridge or Bartington coils, we developed the use of the pocket contact probe SM30 (ZH Instruments; dimensions: $100 \times 65 \times 25$ mm; weight: 180 g; energy consumption: 15 mW). This instrument determines the susceptibility of the infinite half space in front of the sensor with a sensitivity of 10^{-7} SI and an acquisition time of about 10 sec. Its penetration depth and exploration width can be visualized knowing that 99% of the signal comes from a flat cylinder 8 cm in diameter and 5 cm thick. The difference between field and room temperatures (up to 45 °C) may be an issue. However, tests show that the SM30 design provides a very small thermal drift (<1% on the -30 to +30 °C range), and furthermore, temperature has negligible impact on the susceptibility of metal and magnetite, contrary to paramagnetic minerals whose susceptibility in Antarctic conditions increases up to 13%.

Rochette et al. (2003; their Fig. 1) reported on a satisfactory cross-calibration between Kappabridge and SM30 measurements performed on large cut slabs. SM30 measurements were then geometrically calibrated for naturally shaped whole stones (Gattacceca et al. 2004). This empirical calibration is based on measurements of a large number of basaltic pebbles with both the Kappabridge and SM30. Results (Fig. 2) show that the calibration can provide a correct estimate of the susceptibility within $\pm 20\%$ (i.e., 0.08 log unit) for samples with an axial ratio in the 0.3–0.8 range, irrespective of the sample volume. Moreover, this uncertainty is reduced to about 10% when in the median axial ratio range (0.5–0.6). The accuracy of the calibration depends on how close the sample is to a smooth, ellipsoidal shape. More irregular shapes (as in the case of fragmented meteorites) may lead to larger errors, usually underestimating susceptibility.

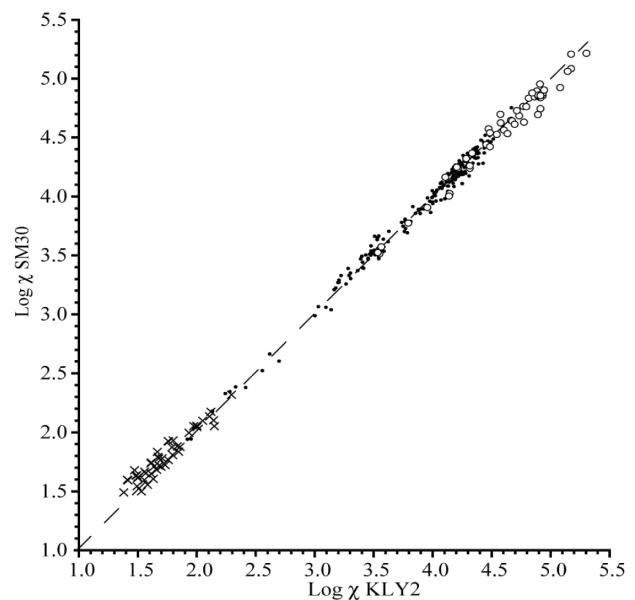


Fig. 2. A comparison of magnetic susceptibility measurements performed with a KLY2 kappabridge (x-axis) and a SM30 portable probe (y-axis). Measured samples are limestone pebbles (crosses), volcanic pebbles (dots) and meteorites (circles). The dashed line is the $y = x$ line.

This estimate of uncertainty does not take into account magnetic anisotropy effects (Gattacceca et al. 2005), such as shape anisotropy, which can be large for $\log \chi > 5$. A conservative estimate of maximum uncertainty may therefore be $\pm 40\%$, i.e., 0.15 log χ units. Besides calibration, the sample volume must be known to calculate $\log \chi$ from the raw SM30 measurements (Gattacceca et al. 2004). The easiest way is to use mass (measured with a portable scale, with a 0.1 g precision) and an educated guess for bulk density. An a priori bulk density of 3.3 g/cm³ can be assumed for stony meteorites (Britt and Consolmagno 2003). Once a classification is obtained, one can refine the $\log \chi$ estimate by entering the average bulk density for the given class, which can vary from 2.8 to 3.6 g/cm³ (CI, AM, irons, and stony-irons excluded). The uncertainty induced by the a priori density is therefore at most -0.07 , $+0.04$. Using the SM30, a portable scale and a simple spreadsheet run by a pocket computer (Excel spreadsheet available upon request), it only takes a minute to estimate $\log \chi$ directly in the field. To check dispersion for a single meteorite fall using this procedure, Saharan ordinary chondrite showers (Fig. 3) were investigated (Gattacceca et al. 2004). Indeed the standard deviation obtained by laboratory measurements on multiple stones of historic falls are in the same range (Rochette et al. 2003; Consolmagno et al. 2006). The standard deviation obtained for each meteorite ranged from 0.07 to 0.10, confirming the effective accuracy of the method on meteorites. Lastly, one should note that the SM30 detection system does not eliminate the electrical conductivity effect, which can be important for irons and stony irons. Tests

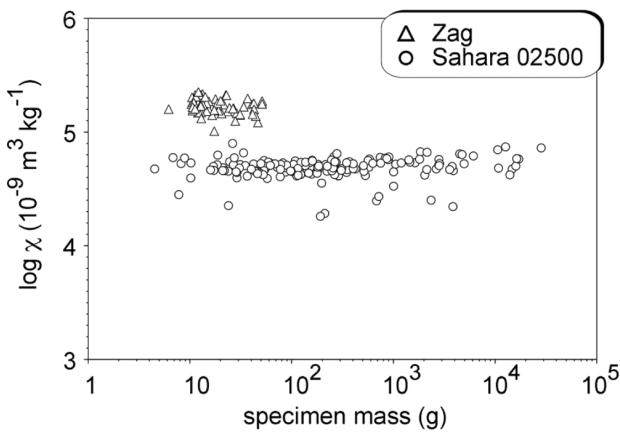


Fig. 3. Magnetic susceptibility χ in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$ versus sample mass for two ordinary chondrite showers, Zag (64 specimens) and Sahara 02500 (176 specimens). Note the log-scale of the abscissa.

indicate that SM30 provides spurious and strongly underestimated values for iron meteorites; however, they are generally easily identified in the field, especially if assisted by density measurements.

IDENTIFICATION OF METEORITES ON ANTARCTIC BLUE ICE FIELDS

We tested the above technique for the identification of meteorites at the Miller Butte and Roberts Butte ice fields (Outback Nunataks) where four meteorites were collected. Miller Butte and Roberts Butte are two granitic massifs consisting mainly of felsic granitoids belonging to the Granite Harbour Intrusive Complex (Gunn and Warren 1962) plus thermometamorphosed wall-rock schists (GANOVEX III 1987). Several piedmont and lateral supraglacial moraines of local debris occur on the blue ice fields located on the downflow side of the outcrops; myriads of stones of local origin are also scattered throughout the blue ice fields. Visual identification of meteorites was very difficult due to the presence of abundant rounded (due to wind transport) dark stones within the local drift. They mainly included oxidized, dark-brown stained, fine-grained metamorphic or magmatic stones resembling uncrusted, weathered equilibrated chondrites or primitive achondrites, and black schists with a smoothed external surface resembling fusion-crusted stony meteorites. Even for trained searchers, the SM30 measurements—without any data processing—were very helpful in deciding the terrestrial or extraterrestrial origin of some of the above finds (Figs. 4a and 4b). Indeed, the paramagnetic rocks cropping out in Victoria Land are about 1000 times less magnetic than most meteorites. The SM30 was also found to be extremely useful in identifying meteorites during searches at the Frontier Mountain Meteorite Valley moraine: the many small (typically <10 g), weathered chondrites that are frequently found in this moraine (Folco et al. 2002) can be easily confused with

weathered Fe-rich aplo-granitic fragments disseminated among the local debris (Figs. 4c and 4d).

In such lithological contexts, robotic search based on color and shape would clearly be a complete failure, whereas the addition of a magnetic susceptivimeter such as SM30 would lead to efficient recovery. Note that, unlike the “magnet test” carried out by many meteorite hunters for the identification of meteorites, the magnetic susceptibility measurement does not destroy the paleomagnetic signal of a meteorite (Wasilewsky and Dickinson 2000) and is more quantitative.

LOCATION OF METEORITES BURIED IN SNOW

The very high magnetic susceptibility of most meteorites can also be used to detect them when they are buried under snow or glacial or aeolian deposits of terrestrial rocks. We tested a rugged field magnetic gradiometer GA-72Cd from the Schonstedt company (Fig. 5) at the Frontier Mountain meteorite trap where we suspected the presence of meteorites buried in transient snow cover. Optimal conditions are found in Antarctica, since the terrestrial magnetic field is maximum ($B_t = 62 \mu\text{T}$ instead of $45 \mu\text{T}$ at middle latitudes) and vertical (thus giving the anomaly right over the target). The background gradient is also particularly stable due to ice coverage, lack of metal pollution, and magnetic rocks (apart from Ferrar Supergroup volcanics and rare metamorphic rocks outcrops). For shallow targets, the maximum vertical field “gradient,” ΔB , is basically the field created by the target on the lower sensor:

$$\frac{B_t m \chi}{2 \pi h^3}$$

with m and h corresponding to the sample mass and depth (assuming induced magnetization). In Antarctica, a 10 g sample of H chondrite at a depth of 10 cm produces a ΔB of 20 nT, whereas in the Frontier Mountain area, the typical background ΔB is 100 nT (compared to a sensitivity of 1 nT). The actual detection level (on previously found meteorites laid on and under the snow) was better than predicted from these computations. Searches with the magnetic gradiometer were conducted at the firm-ice edge aeolian meteorite accumulation site at Frontier Mountain (Folco et al. 2002), where the deposit can be transiently covered by seasonal snow cover. Four meteorites, one weighing 20 g and the others in the 1–2 g range, were recovered from under a few cm of snow; some of them were found within the snow-bridged crevasses present in the area. Their $\log \chi$ varies from 4.95 (for the 20 g specimen) to 5.24. We plan to compare the efficiency of this technique with that of a metal detector (D. Loretta, personal communication) in future expeditions. Magnetic detection may prove to be more effective for weathered or magnetite-bearing meteorites, with low conductivity but high susceptibility.



Fig. 4. An SM30 probe (width: 10 cm) with its raw output after measuring samples directly on the ice fields. a) An 11 g, fusion-crusted H chondrite, Miller Butte (MIB) 03003, on a supraglacial moraine at Miller Butte. b) A rounded dark schist found in the same moraine. c) A weathered H chondrite, Frontier Mountain (FRO) 03062, on the Meteorite Valley moraine at Frontier Mountain. d) A weathered Fe-rich aplogranitoid fragment in the same moraine. These photographs were taken within 15 minutes in each area.



Fig. 5. a) Searching in a snow-bridged crevasse with the magnetic gradiometer at the Frontier Mountain blue ice field. b) A small meteorite fragment found buried in ~10 cm snow indicated by P. R.



Fig. 6. Meteorites found at the Johannessen Nunataks (JOH) blue ice field measured in situ with SM30 (width 10 cm for scale). a) JOH 03015 is a relatively fresh category A L chondrite of 121.2 g with a $\log \chi$ of 4.64 ($10^{-9} \text{ m}^3 \text{ kg}^{-1}$). b) JOH 03001 is a relatively weathered category B H chondrite of 127.7 g with a $\log \chi$ of 5.18 ($10^{-9} \text{ m}^3 \text{ kg}^{-1}$). c) JOH 03003 is another relatively weathered category B H chondrite of 28.5 g with a $\log \chi$ of 5.22 ($10^{-9} \text{ m}^3 \text{ kg}^{-1}$), which is paired with JOH 03001. Note the much lower SM30 reading of JOH 03015 compared to the similar sized JOH 03001, readily indicating different chondrite chemical class, whereas the different SM30 readings between the JOH 03001 and JOH 03003 pairs is simply due to a size difference.

IN SITU PAIRING

Since SM30 gives clues on the meteorite classification during the field campaign (Figs. 1, 6a, and 6b) and because magnetic susceptibility dispersion is limited among fragments of the same meteorite (see discussion in the previous sections), the instrument also provided early evidence of paring and helped select rare types for priority laboratory investigations. For example, 14 fragments from 0.2 to 929 g (namely, Johannessen Nunataks [JOH] 03001, 02, 03, 04, 05, 06, 07, 08, 09, 10, 13, 17, 18, and 19) (Russell et al. 2004) found scattered in an $\sim 1 \text{ km}^2$ area of the Johannessen Nunataks blue ice field (Outback Nunataks) appeared very similar to each other on the basis of macroscopic observations: they were all completely or partially devoid of fusion crust, weathered crystalline stones with dark-brown staining. Magnetic susceptibility measurements yielded a mean $\log \chi$ of 5.08 ± 0.06 , providing a quantitative data confirming that they all belong to the same weathered H chondrite fall (Figs. 6b and 6c). Likewise, two chondritic fragments, JOH 03011 and 12 (Russell et al. 2004), found $\sim 10 \text{ m}$ apart and sharing several macroscopic features (oxidized fusion crust, yellowish stained interior, and faint chondritic structure) were identified as fragments of another weathered H chondrite fall thanks to their similar $\log \chi$ of 4.96 and 5.16, respectively. As a result, the pairing obtained by joining macroscopic observations and quantitative measurements of magnetic properties allowed us to save meteorite material and to reduce curatorial costs by $\sim 10\%$, since 14 out of 123 recovered specimens did not need petrographic classification, which entails preparation of polished thin sections (with obvious loss of material) and analyses under the optical microscope and electron microprobe. In addition, in situ pairing allowed us to correct field observations for statistical bias. For instance, it provided us with a better picture of the actual yield of the Johannessen Nunataks blue ice area directly in the field, reducing the 19 recovered specimens to 5 distinct falls. Such information can be used in the field to better guide searches. This is especially important in the context of Antarctic searches with long field seasons and high logistic costs; the more information that is available on samples and/or possible showers, the greater the efficiency of the meteorite search campaign will be.

VALIDATION OF THE IN SITU MAGNETIC CLASSIFICATION

In order to validate the in situ magnetic classification, we compare here the SM30 magnetic susceptibility data for the 123 meteorites recovered from the 2003/2004 PNRA expedition (henceforth PNRA_03) with the canonical petrographic classification. The decimal logarithm of magnetic susceptibility, $\log \chi$ ($10^{-9} \text{ m}^3 \text{ kg}^{-1}$), and petrographic classification can be found, along with other

Table 1. The average and standard deviations (1σ) of $\log \chi$ values (in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$) for 2003/04 PNRA meteorites (PNRA_03) measured in situ by means of SM30. Data for falls and finds are reported for comparison (obtained mainly using laboratory susceptibility meters, after Rochette et al. 2003 for ordinary chondrites and an unpublished database for other meteorites; see also Rochette et al. 2004).

	WG ^a	n ^b	$\log \chi^c$	Reference
H chondrites				
Falls		145	5.32 ± 0.10	Rochette et al. (2003)
Antarctic finds		234	5.08 ± 0.16	Rochette et al. (2003)
PNRA_03	All	98	5.02 ± 0.20	This work
	A	6	5.18 ± 0.11	This work
	B	47	5.09 ± 0.18	This work
	C	45	4.96 ± 0.15	This work
L chondrites				
Falls		144	4.87 ± 0.10	Rochette et al. (2003)
Antarctic finds		65	4.66 ± 0.26	Rochette et al. (2003)
PNRA_03	All	19	4.59 ± 0.26	This work
	A	4	4.83 ± 0.15^d	This work
	B	8	4.53 ± 0.19	This work
	C	6	4.42 ± 0.16	This work
LL chondrites				
Falls		44	4.10 ± 0.30	Rochette et al. (2003)
Antarctic finds		6	4.30 ± 0.16	Rochette et al. (2003)
PNRA_03	All	2	4.04	This work
PNRA_03 (DEW 03001)	A	1	4.11	This work
PNRA_03 (FRO 03011)	C	1	3.98	This work
EL chondrites				
Falls		9	5.47 ± 0.06	This work
Finds		13	4.92 ± 0.47	This work
PNRA_03 (FRO 03005)	B	1	4.98	This work
Acapulco-lodranites				
Falls		2	5.39 ± 0.46	This work
Finds		6	5.36 ± 0.38	This work
PNRA_03 (FRO 03001)	A	1	5.15	This work
Ureilites				
Falls		3	4.95 ± 0.15	This work
Finds		31	4.40 ± 0.30	This work
PNRA_03 (FRO 03022)	C	1	3.98	This work
Other FRO ureilites		1	3.95 ± 0.21	This work

^aMacroscopic terrestrial weathering categories according to ANSMET classification scheme (Satterwhite and Righter 2005) which is based, among others, on the level of oxidation of metal.

^bNumber of measured specimens.

^cGiven in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$.

^dThe outlier FRO 03026 (L6) is not included in the average for the reasons discussed in the text.

descriptive attributes, in the Meteoritical Bulletin Nos. 88 and 89 (Russell et al. 2004, 2005). The recovered specimens have masses ranging from 0.17 to 929.3 g, with an average of 44.5 and a median value of 6.1 g. They include 119 ordinary chondrites, one enstatite chondrite, one lodranite, one ureilite, and one iron (IID). Ordinary chondrites include 98 meteorites belonging to the H chemical class, 19 to the L class, and 2 to the LL class. Average and standard deviations (1σ) of $\log \chi$ values for PNRA_03 meteorites measured in situ by means of SM30 are reported in Table 1, along with higher precision laboratory data for ordinary chondrite, enstatite chondrite,

acapulco-lodranite, and ureilite falls and finds from this work and Rochette et al. (2003, 2004).

A good match is observed between SM30 data for PNRA_03 ordinary chondrites and literature data for Antarctic finds (Table 1 and Fig. 7a). PNRA_03 H and L chondrites have $\log \chi$ value of 5.02 ± 0.20 and 4.59 ± 0.26 in agreement (within the 0.1 uncertainty of the SM30 measurements) with the 5.08 ± 0.16 and 4.66 ± 0.26 values for Antarctic finds, respectively. Likewise, the two PNRA_03 LL chondrites have $\log \chi$ of 4.11 and 3.98. These values are in agreement with the 4.10 ± 0.30 for 44 LL falls, thereby

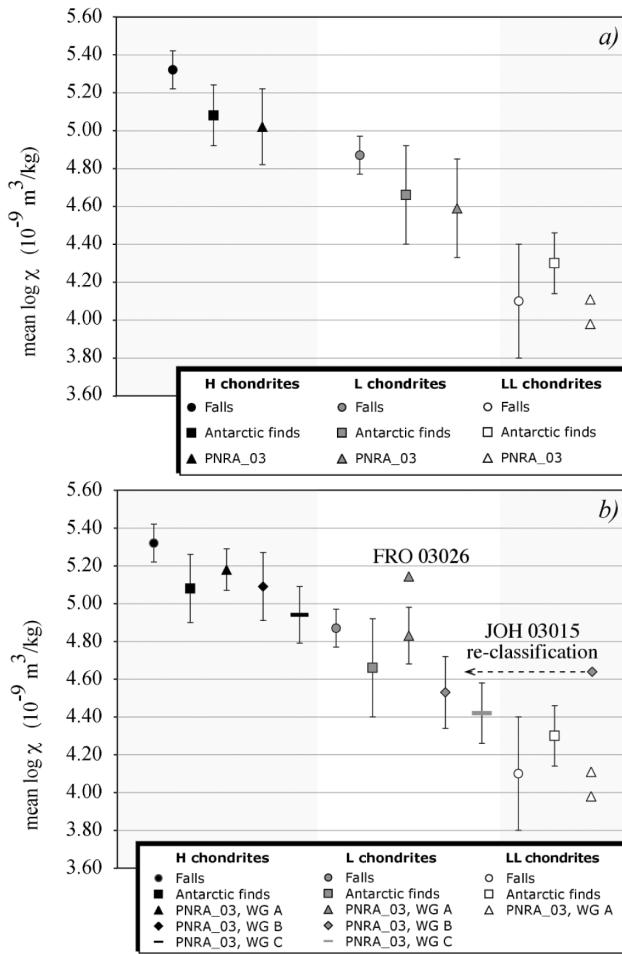


Fig. 7. a) The average and standard deviations (1σ) of $\log \chi$ values (in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$) for 2003/04 PNRA ordinary chondrites (PNRA_03) measured in situ by means of SM30. Laboratory data for ordinary chondrites falls and Antarctic finds from Rochette et al. (2003) are shown for comparison. b) As above, but PNRA_03 meteorites are grouped according to macroscopic weathering categories A, B, and C, following the ANSMET classification scheme (Satterwhite and Righter 2005). See the text for discussion on the FRO 03026 outlier. Also shown is JOH 03015, whose petrographic misclassification was spotted thanks to its anomalous $\log \chi$ value compared to LL chondrites; JOH 03015 is thus reclassified as an L5.

lowering the 4.30 ± 0.16 literature value for Antarctic finds obtained from limited (6 finds) statistics. Figure 7a also shows that meteorite finds from Antarctica have $\log \chi$ values that tend to be lower than literature values for falls. As demonstrated by Rochette et al (2003), this is due to the fact that the Antarctic populations include meteorites that have experienced various degrees of terrestrial weathering; terrestrial weathering causes oxidation of metal and, consequently, a decrease in magnetic susceptibility. As such, although there is a marked difference in $\log \chi$ values for falls belonging to the three ordinary chondritic chemical classes, Antarctic weathering can generate some overlap. In Fig. 7b, we have thus plotted $\log \chi$ values (averages and standard deviations are given in Table 1) for PNRA_03 meteorites

according to the macroscopic weathering categories “A,” “B” and “C” assigned in the field. The weathering categories correspond to those used by the ANSMET program (Satterwhite and Righter 2005). They provide a qualitative indication of the macroscopic level of oxidation of metal particles in chondrites: null or minor in category A, moderate in B, and severe in C. Log χ values for PNRA_03 meteorites decrease with increasing weathering (Table 1 and Fig. 6b), in agreement with Rochette et al. (2003). Meteorites in the A weathering category have values comparable to fresh falls, whereas H and L chondrites in the C category show some overlap with L and LL chondrite falls, respectively. For instance, a $\log \chi$ of 4.9 (in $10^{-9} \text{ m}^3 \text{ kg}^{-1}$) could either be consistent with a weathered H chondrite or a fresh L chondrite. Assessment of the macroscopic weathering level is therefore of crucial importance for the in situ discrimination of the three chemical classes of ordinary chondrites.

The JOH 03015 and FRO 03026 meteorites provide us with two examples for discussing the usefulness of magnetic susceptibility measurements in detecting misclassified and peculiar samples. JOH 03015 was petrographically classified as an LL5 chondrite (Russell et al. 2004). However, its high $\log \chi$ of 4.64 relative to LL chondrites prompted us to check the olivine and pyroxene compositions. New electron microprobe analyses yielded homogeneous olivine and orthopyroxene compositions, $\text{Fa}_{25.7}$ and $\text{Fs}_{21.5}$, consistent with L chondrites, as predicted by SM30 measurements. JOH 03015 is thus reclassified as an L5.

FRO 03026 is petrographically classified as a relatively fresh L6 breccia with olivine and enstatite compositions, $\text{Fa}_{22.4}$ and $\text{Fs}_{17.8}$ (Russell et al. 2005). Such compositions fall in between the typical fields for H and L chondrites in the Fa versus Fs plot for equilibrated ordinary chondrites, but close to two L chondritic outliers, Kramer Creek and Kendleton (Brearley and Jones 1998 and references therein). The latter evidence justifies the FRO 03026 L chondritic petrographic classification, whereas the former would indicate oxidation state intermediate between H and L chondrites. This is in agreement with the SM 30 $\log \chi$ value of 5.14 that is typical, within error, of H/L chondrites (Rochette et al. 2003).

The FRO 03011 meteorite also provides us with the opportunity to highlight the effectiveness of the SM30 method for a rapid assignment of type 3 ordinary chondrites to the correct chemical class, particularly in the case of very unequilibrated chondrites or specimens for which thin sections of limited extension hamper correct estimates of diagnostic parameters like chondrule size and metal content. FRO 03011 has variable olivine and enstatite compositions ranging from $\text{Fa}_{4.2}$ to $\text{Fa}_{23.8}$ (mean $\text{Fa}_{17.0} \pm 7.3$) and from $\text{Fs}_{10.1}$ to $\text{Fs}_{33.1}$ (mean $\text{Fs}_{18.5} \pm 8.5$), respectively (Russell et al. 2005). The chondrule size obtained from 62 measured chondrules ranges from 150 to 1900 μm with a mean value of $670 \pm 400 \mu\text{m}$ (Fig. 8a) which is best consistent with L chondrites (Brearley and Jones 1998). However, the SM30 $\log \chi = 3.98$ value is far too low for L chondrites (Fig. 7b), in agreement

with the <2 vol% metal abundance observed in thin section (Fig. 8a). FRO 03011 is therefore classified as an LL3.

FRO 03001 is a small meteorite of 1.46 g classified as a lodranite on a petrographic basis (Russell et al. 2004). It is a very fresh specimen with virtually no oxidation of metal that belongs to macroscopic weathering category A. Its $\log \chi$ is 4.98 which is lower than the expected value for unweathered (falls) acapulco-lodranites of 5.50 ± 0.38 (Table 1). The SM30 thus indicates that this sample contains less metal than typical acapulco-lodranites, namely ~8 wt% according to the Rochette et al. (2003) calibration. We therefore checked one thin section representative of the FRO 03001 specimen (Fig. 8b) and found that the metal content is ~5 vol%. Both observations indicate that the metal content of FRO 03001 is lower than the 8.5 and 12.8 vol% average values for acapulcoites and lodranites determined by Yugami et al. (1998). We therefore conclude that FRO 03001 is either a metal depleted lodranite or a non-representative sample of the lodranitic parent lithology.

FRO 03022 is a 2.47 g meteorite petrographically classified as a ureilite polymict breccia (Russell et al. 2005). It shows severe oxidation compatible with the macroscopic terrestrial weathering category B/C. Its $\log \chi = 3.98$ (Table 1) is lower than the 4.92 ± 0.25 value for fresh falls (three meteorites in our database), and lower than the 4.40 ± 0.30 value for finds (31 meteorites in our database), thus confirming its strong weathering grade. It is interesting to note, however, that the relatively low $\log \chi$ value of FRO 03022 is indistinguishable from the 3.95 ± 0.21 value (Table 1) of the 10 ureilite specimens recovered from Frontier Mountain during previous expeditions (FRO 90036, 90054, 90168, 90228, 90233, 93008, 95028, 97013, 01012, and 01030), strongly suggesting that all FRO ureilites are paired. This interpretation supports a previous preliminary study on FRO 90036, 90054, 90168, 90228, 90233, 95028, and 97013 by Smith et al. (2000).

As for the iron meteorite MIB 03002, the $\log \chi$ of 5.27 measured in the field is misleading, since it points to an H chondrite (for example). As mentioned early, the SM30 does not operate correctly on iron meteorites. Density measurements would allow easier discrimination in the field.

Lastly, two meteorite wrongs were collected during the 2003/04 PNRA field season. Both specimens turned out to be basalts, likely belonging to the Cenozoic Ross Embayment magmatism. Their identical $\log \chi = 4.24$ falls in the upper range of terrestrial basalts and illustrates the ambiguity of magnetic classification when strongly magnetic basalts are present in the field.

CONCLUDING REMARKS

Based on our test carried out during the 2003/04 PNRA meteorite collection expedition to northern Victoria Land, we have shown that rock magnetism probes are useful in the search for meteorites in Antarctica. In particular, following

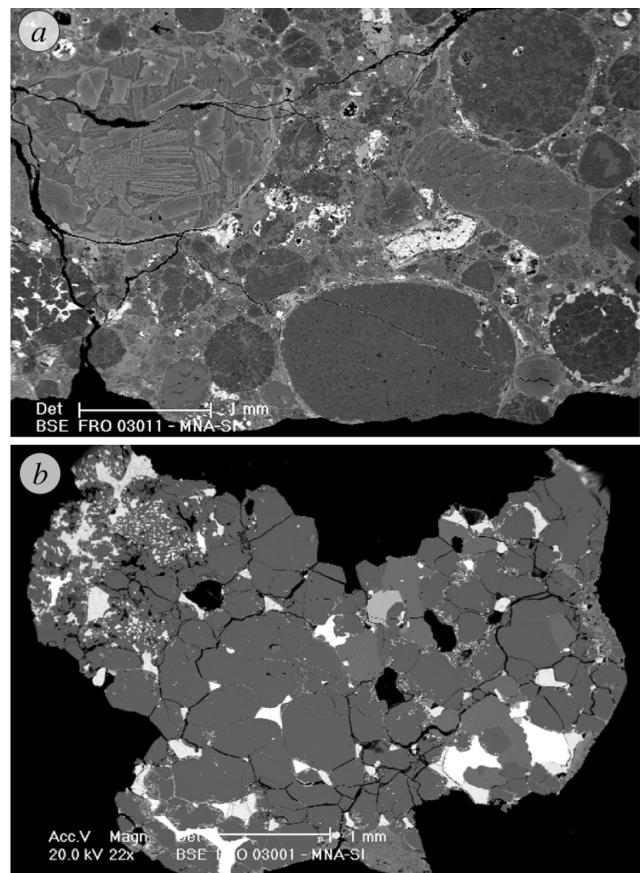


Fig. 8. a) A backscattered electron image of an FRO 03011 thin section showing details of the chondritic structure of this LL3 chondrite; note also that the opaque material (off-white) is principally sulfide. b) A backscattered electron image of an FRO 03001 thin section showing a relatively low (~5 vol%) metal (white) content compared to the average value for other lodranites (~13 vol%) (Yugami et al. 1998).

the methodologies developed by us in this and previous works (Rochette et al. 2003, 2004; Gattaccea et al. 2004), we have demonstrated that the SM30 pocket probe is a rapid, sensitive, non-destructive means for measuring magnetic susceptibility of specimens, thereby assisting to the in situ identification, pairing and classification of meteorites.

SM30 magnetic susceptibility measurements are technically simple and accurate even in the extreme Antarctic conditions. The pocket size ($100 \times 65 \times 25$ mm), lightweight (180 g) and limited energy consumption (15 mW) make the SM30 a very practical tool (Figs. 4 and 6). Magnetic susceptibility measurements take about a minute, including the reading itself with the SM30 probe (less than 10 sec), specimen weighing with a pocket scale and data processing with a hand-held computer. The SM30 is calibrated for measuring natural stones of any size and shape at temperatures as low as -30°C with a precision of $\pm 20\%$, corresponding to $0.08 \log \chi$ units. Furthermore, magnetic susceptibility measurements do not destroy the paleomagnetic signal of meteorites (Wasilewsky and Dickinson 2000).

Magnetic susceptibility measurements can be used to distinguish meteorites from terrestrial rocks thanks to the relatively higher magnetic susceptibility of the former (Fig. 1), although some ambiguity may exist in the case of strongly magnetic volcanic rocks. This is of great help when searching for meteorites in blue ice areas that are characterized by abundant local debris (e.g., supraglacial moraines) and terrestrial stones that look like meteorites, as was successfully tested at the downflow ice fields of Miller Butte, Roberts Butte, and Frontier Mountain (Fig. 4).

By providing a quantitative parameter to support qualitative observations of macroscopic features, comparative magnetic susceptibility measurements help identify paired meteorite fragments directly in the field (e.g., Fig. 6), thereby reducing both curatorial costs by avoiding material waste and unnecessary duplication of laboratory analyses and also statistical bias. The identification of 16 paired fragments (namely, JOH 03001, 02, 03, 04, 05, 06, 07, 08, 09, 10, 13, 17, 18, 19, and JOH 03011 and 12) among the 123 recovered meteorite specimens reduced curatorial costs for the 2003/04 PNRA meteorites by about 10%.

Following the classification scheme reported in Fig. 1, magnetic susceptibility measurements also help classify stony meteorites directly in the field (Fig. 6), as was validated by the comparison with the later petrographic classification of the 123 meteorites found during the 2003/04 PNRA expedition (Table 1 and Fig. 7). This is an important result for the curation of large collections, as it provides a means for selecting specimens with higher research priority directly in the field. For this purpose, however, the magnetic susceptibility database for Antarctic populations should be enlarged to gain a better picture of intra-class variations, particularly as a function of the degree of terrestrial weathering. It is also worth noting that magnetic susceptibility data is a powerful check for the later petrographic classification, allowing the detection of misclassified or anomalous specimens (as in the case of JOH 03015, FRO 03026 ordinary chondrites and the FRO 03001 lodranite) and assignment of type three ordinary chondrites to the correct chemical class (as in the case of the FRO 03011 LL3 chondrite).

Thanks to their simplicity and effectiveness in the search for meteorites and subsequent curatorial work, SM30 magnetic susceptibility measurements have become a part of the PNRA field curation procedure.

Magnetic gradiometers appear to be an effective tool for locating meteorites buried under snow or under glacial and aeolian deposits of terrestrial rocks, thanks to the high magnetic susceptibility of most meteorites, the maximal and ($B_t = 62 \mu\text{T}$) vertical magnetic field in Antarctica and the stable background gradient on the polar ice sheet. We tested a Schonstedt GA-72Cd gradiometer (Fig. 5) at the Frontier Mountain meteorite trap where we suspected the presence of meteorites buried in transient snow cover and found several

specimens in the 1–20 g range. This technique should certainly be developed (e.g., increasing its range of exploration, combination with metal detectors, and so forth) since many meteorites are likely buried in transient snow cover (typically <1 m thick) along the downflow and/or downwind margins of many meteorite stranding surfaces.

Because of their simplicity and effectiveness in discriminating terrestrial from extraterrestrial stones, magnetic susceptibility probes such as the SM30 meter could be of great interest for robotic search for meteorites lying on Antarctic blue ice fields (Apostopoulos et al. 2000). Magnetic gradiometers could also be an important addition to the instrumentations of rovers designed for locating meteorite accumulations buried in snow. Finally, following Gattacceca et al. (2004) and Rochette et al. (2004), we suggest that the development of such technologies would be of great interest for the search for meteorites on the surface of Mars (and possibly on other solid bodies of the solar system), where high concentrations of meteorites are predicted by theoretical works (Bland and Smith 2000), consistent with the recent find of the iron meteorite Meridiani Planum by the Mars Exploration Rover MER (Russell et al. 2005).

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