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MAGNETIC CLASSIFICATION OF METEORITES AND APPLICATION TO THE SOŁTMANY FALL

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Abstract: We review the use of magnetic susceptibility measurements to classify meteorites, showing that magnetic susceptibility of meteorites vary over 3 orders of magnitude and shows often a narrow range for a given meteorite group, especially in chondrites. Weathering of metal may bias the magnetic classification. For ordinary chondrite falls, the method is quite robust, as shown by its application to the recent Sołtmany fall.

Keywords: magnetic susceptibility, meteorite classification, Sołtmany

INTRODUCTION

The magnetic classification of meteorites, based on the measurement of magnetic susceptibility, has been developed in CEREGE, following the pioneering work of the Helsinki group (e.g., Pesonen et al. 1993). The complete method has been presented in Rochette et al. (2003, 2008, 2009, 2010) for ordinary chondrites, non-ordinary chondrites, achondrites (except lunar meteorites), and lunar material, respectively. This method provides a more rapid determination of meteorite classification than do standard petrographic techniques, although it cannot be used for meteorite classification as the only method. Unlike the traditional hand-magnet testing often promoted in meteorite recognition tutorials, the magnetic susceptibility method does not result in the resetting of natural remnant magnetization, thereby preserving potentially valuable scientific information (e.g., Gattacceca et al., 2004). A brief summary of the method and its application to the Sołtmany meteorite are presented here.

BACKGROUND

Mass-normalized magnetic susceptibility (χ in m^3/kg) is a measure of the ability of a material to acquire magnetization in an inducing field. It provides an estimate of the bulk content of magnetic phases in a meteorite sample without any sample preparation, and can be performed on a wide variety of masses and shapes. Only a few grams of most meteorites are needed to obtain representative data, although, with homogeneous specimens, samples of several tens of mg can be measured for results consistent with larger samples. There is no upper limit of mass that can be analyzed, and, with the SM30 instrument, we have measured stones of over 10 kg. Several instruments can be used depending on sample size and shape, but the contact probe SM30 is the most versatile (Fig. 1). However, for low mass or irregularly shaped samples, the SM30 is less precise than classical instruments, which require insertion of the sample within a coil. One source of uncertainty in magnetic susceptibility measurements is magnetic anisotropy, which can be quite strong in

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Fig. 1. Picture of SM30 while performing the "air" measurement on a large meteorite find from Atacama. Log χ value is obtained by substracting this air measurement from the one obtained at contact with the meteorite, and modeling the geometric correction following Gattacceca et al. (2004), using mass and bulk density. This geometric correction is required by the non-uniform field generated by the SM30 coil. In standard coils where the sample is inserted in a zone of uniform field inside the coil, this correction is not necessary, thus explaining the lower accuracy of SM30

deformed meteorites. This effect can be compensated for by averaging measurements in several directions. Very metal-rich meteorites (especially iron meteorites) may be difficult to measure, due to probe saturation. Measurements are reported as the base-10 logarithm of χ, expressed in 10^{-9} m^3/kg: a χ value of 10^{-6} m^3/kg is thus represented as log $\chi = 3$. The accuracy on log χ of the SM30 probe is ~0.1; coil systems have circa ten times higher precision.

Magnetic susceptibility in meteorites is proportional to the amount of the constituent primary ferromagnetic phases, including Fe-Ni metal, schreibersite, cohenite, magnetite, and pyrrhotite. As pure phases, the proportionality factor is about the same for all these minerals, which give log $\chi \sim 5.7$. Pyrrhotite is an exception to the rule: it has a smaller effect on χ. Some weathering products, including maghemite, can also contribute to magnetic susceptibility. For meteorites with very low amounts of ferromagnetic minerals (log $\chi < 3$), paramagnetic minerals like olivine and pyroxene become major contributors to susceptibility.

An advantage of the analysis provided by magnetic susceptibility, compared to that provided by petrographic observation of sections, is that the volume investigated is the whole sample, and it does not depend on grain size. Opaque grains are often dispersed partly as sub-micrometer-sized inclusions that cannot be easily seen under the microscope.

CLASSIFICATION SCHEME

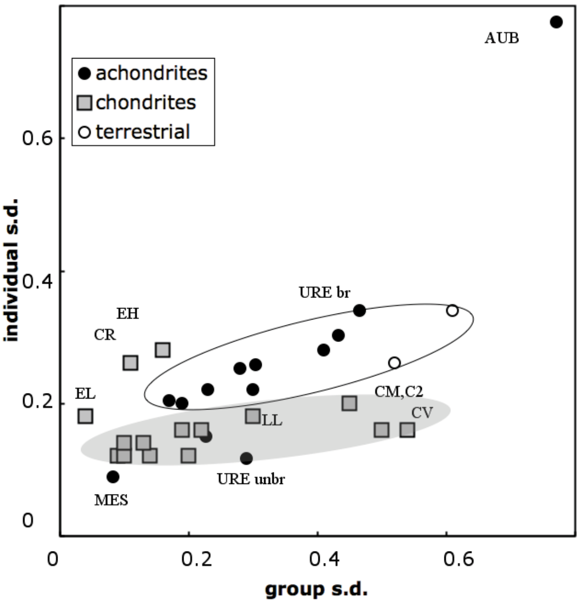

Fig. 2. Mean of log χ individual standard deviation (i.e. at the meteorite scale) versus standard deviation on mean meteorite value for achondrites groups, compared to chondrites and two sets of terrestrial magmatic rocks (after Rochette et al., 2003, 2008 and 2009). White and gray ellipses highlight the main trends for achondrites and chondrites, respectively

By performing log χ measurements and compiling measurements published by other teams (e.g., Smith et al., 2006; Kohout et al., 2008; Macke et al., 2011) in over 40 large meteorite collections around the world, we have assembled a database of over six thousand specimens. Analysis of several specimens per meteorite allows the determination of log χ dispersion at the scale of individual meteorites; analysis of multiple meteorites allows the variation within meteorite groups to be determined (Fig. 2). Log χ dispersion at the individual-meteorite scale is usually quite low, except in achondrites such as aubrites. Dispersion at the group scale is also low for most chondrites (except CM, C2 and CV), with a range of log χ from 2.3 to 5.6. These characteristics form the basis of the magnetic classification scheme (Fig. 3). Of course, a single parameter does not provide a unique classification, and other evidence should be used to narrow down the class, e.g. density (Consolmagno et al., 2006). For fresh ordinary chondrites, the scheme works well because the ranges of metal content are narrow and distinct for LL, L and H, although a few intermediate

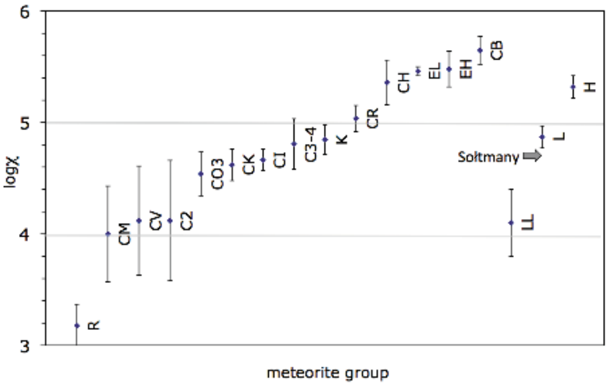

Fig. 3. Mean log χ with standard deviation for the different chondrite groups. Only meteorite falls were used for ordinary chondrites (H, L, LL), CO and E means. The value obtained on Sołtmany is indicated by an arrow

cases exist (often designated as L/LL and H/L chondrites).

Terrestrial weathering complicates classification because it oxidizes metal, lowering log χ. Rochette et al. (2003), using a database of meteorites from the Sahara, estimated the lowering of log χ at about 0.1–0.2 per weathering grade (WG, as defined by Wlotzka, 1993), so that an H chondrite of weathering grade W3 can give the same value as an L chondrite of grade W1. Our data on Atacama meteorites presented in Fig. 4, for which WG was consistently estimated by a single person, show less dispersion than the dataset of Rochette et al. (2003). Thus, for ordinary chondrite finds, log χ must be combined with WG in order to classify the meteorites, although with somewhat less confidence than for falls.

Presently, for equilibrated ordinary chondrite finds for which manpower and funds to perform full petrographic and geochemical characterization is lacking, the Meteorite Nomenclature Committee of the Meteoritical Society accepts classifications based on log χ plus visual inspection of sections.

The magnetic classification scheme is efficient in detecting anomalous chondrite samples in collections. These anomalies appear to be of two sorts: the misclassification of whole meteorites (e.g. Gattacceca et al., 2007), or the mislabeling of individual samples. We found that a significant number of historic meteorite samples were mixed up through the ages; for example, a number of L'Aigle (L6) specimens appeared to be H or L/LL chondrites (Consolmagno et al. 2006). It seems that in the early stages of meteorite science, meteorites were often considered to be "all the same" and became mixed up during exchanges among private collectors and museums. Unfortunately, we have also evidence that some mislabeling was the result of thievery (replacing rare samples with more common ones or even terrestrial rocks of similar appearance). Such cases can be easily detected by our method, since most of terrestrial rocks (except for some basalts) are much less magnetic than the vast majority of meteorites. Most ordinary chondrite historic falls were classified by Mason (1963) using an X-ray diffraction fayalite value. This technique is not as precise as modern electron probe micro-analysis (EPMA), thus explaining some of the misclassifications found. It is interesting to note that all Antarctic meteorites we identified as having log χ values inconsistent with their classifications were later proven to be misclassified (see ANTMET reclassification web page: http://curator.jsc.nasa.gov/antmet/amn/amnfeb10/reclassifications.htm). For unequilibrated ordinary chondrites, magnetic classification may be more conclusive than EPMA classification. Indeed, the metal content of unequilibrated chondrites is homogeneous for given groups while silicate compositions are heterogeneous.

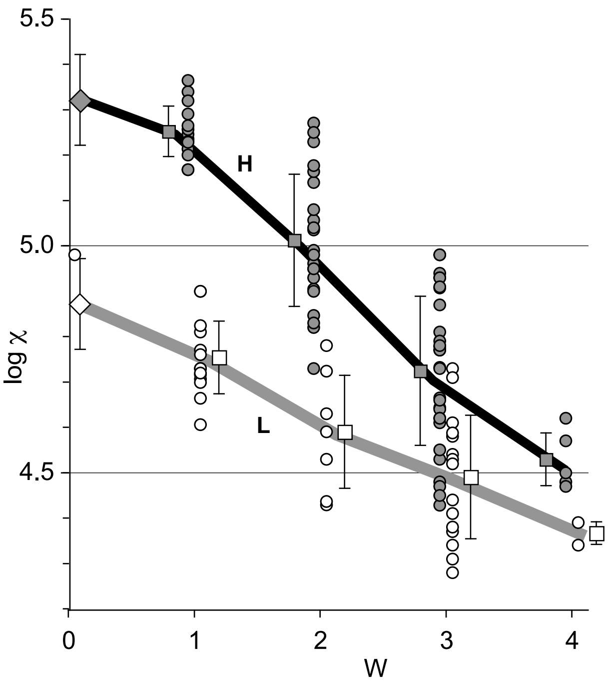

Fig. 4. Log χ as a function of weathering grade for 110 ordinary chondrite finds from the Atacama desert. Circles are measurements for individual meteorites (solid = H, open = L). Squares are mean values for each weathering grade with associated standard deviation (solid = H, open = L). Diamonds denotes mean values for falls

For achondrites, magnetic classification is less straightforward than for chondrites due to dispersion of log χ within single groups. For example, among the weakly magnetic groups (log χ near 3, including angrites, HEDs, and martian meteorites) strongly magnetic outliers exist (Fig. 5). Consequently, log

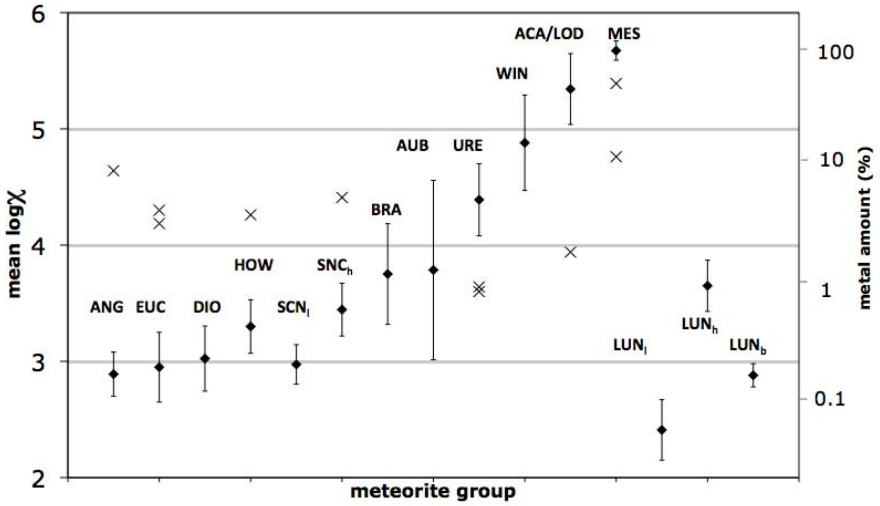

Fig. 5. Mean log χ for the different achondrite groups. Meteorites excluded from the mean appear with crosses. The metal amount (wt.%) indicated is a maximum value. Among lunar and martian (SNC) meteorites a low and high group (l and h) are distinguished, together with a mean for lunar basalts (b)

χ can be used to confirm that a meteorite is in the typical range of its group, but being outside this range may not indicate misclassification, and instead may be indicative of anomalous metal content. Until we measured lunar materials, we tended to consider that log χ < 2.5 was only characteristic of terrestrial material (with one exception: the LAP 03719 aubrite, with a log χ value of 1.96). However, lunar meteorites (Rochette et al., 2010) present a log χ range from 1.9 to 4.4, with the lowest values corresponding to anorthosites. An even larger range was found in Apollo and Luna materials, as negative χ values were obtained on some diamagnetic anorthosites (Cournede et al., 2012); in regolith breccias, log χ as high as 4.9 were observed.

MEASUREMENT OF SOŁTMANY

On May 12, 2011, soon after the fall of Sołtmany meteorite, we visited the meteorite collection of the Academy of Sciences in Krakow. Mr. Marek Wozniak kindly arranged for us to have access to 4.8 g of Sołtmany, in three fragments. Measurements performed in Krakow using a Bartington coil system yielded a mean log χ = 4.71 ± 0.04. The low standard deviation is remarkable for such small fragments (down to 0.8 g). Log χ clearly indicates an L chondrite classification (Fig. 3), although the inferred metal amount is in the low range for L (average log χ for L falls reported in Rochette et al., 2003, is 4.87 ± 0.10). The L chondrite classification was later confirmed by EPMA. The high fayalite content of olivine, 25.6, is in the upper range for L, and is consistent with the low metal content.

CONCLUSION

Magnetic susceptibility is a practical and effective way to rapidly obtain an initial classification for meteorites without time-consuming laboratory work, i.e. on the field or while visiting a meteorite repository. We demonstrated this technique on the Sołtmany meteorite measured soon after its fall. It is also very useful for detecting misclassified meteorites or mislabeled samples in collections. For hot and cold desert finds, it can help to determine pairings in the field (e.g. Folco et al., 2006; Gattacceca et al., 2011) and to focus subsequent petrographic work.

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