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433 Eros: Problems with the meteorite magnetism record in attempting an asteroid match

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Abstract–The magnetometer experiment (MAG) onboard the *Near-Earth Asteroid Rendezvous (NEAR)–Shoemaker* spacecraft detected no global scale magnetization and established a maximum magnetization of 2.1×10^{-6} Am^2 kg^{-1} for asteroid 433 Eros. This is in sharp contrast with the estimated magnetization of other S-class asteroids (Gaspra, ~2.4×10^{-2} Am^2 kg^{-1}; Braille, ~2.8×10^{-2} Am^2 kg^{-1}) and is below published values for all types of ordinary chondrites. This includes the L/LL types considered to most closely match 433 Eros based on preliminary interpretations of NEAR remote geochemical experiments.

The ordinary chondrite meteorite magnetization intensity data was reviewed in order to assess the reasonableness of an asteroid–meteorite match based on magnetic property measurements. Natural remanent magnetization (NRM) intensities for the ordinary chondrite meteorites show at least a 2 order of magnitude range within each of the H, L, and LL groups, all well above the 2.1×10^{-6} Am^2 kg^{-1} level for 433 Eros. The REM values (ratio of the NRM to the SIRM (saturation remanent magnetization)) range over 3 orders of magnitude for all chondrite groups indicating no clear relationship between NRM and the amount of magnetic material. Levels of magnetic noise in chondrite meteorites can be as much as 70% or more of the NRM. Consequently, published values of the NRM should be considered suspect unless careful evaluation of the noise sources is done. NASA Goddard SFC studies of per unit mass intensities in large (>10 000 g) and small (down to <1 g) samples from the same meteorite demonstrate magnetic intensity decreases as size increases. This would appear to be explained by demagnetization due to magnetic vector randomness at unknown scale sizes in the larger samples. This would then argue for some level of demagnetization of large objects such as an asteroid. The possibility that 433 Eros is an LL chondrite cannot be discounted.

INTRODUCTION

The primary objective of the near-Earth asteroid rendezvous (NEAR)–Shoemaker magnetometer experiment was to characterize the magnetic field of 433 Eros. 433 Eros may be a match with the L/LL chondrites based on the analysis of spectral and x-ray and gamma-ray data (McCoy *et al.*, 2001). The *NEAR–Shoemaker* spacecraft was inserted initially into a nearly circular 200 km orbit around Eros and subsequent orbit adjustments brought the spacecraft to near-circular orbits of 100, 50 and 35 km radius with respect to Eros' center of mass. Afterwards the spacecraft made close flyby passes of the asteroid with closest approach distances as low as 15, 5, and 1 km from the surface. On 2001 February 12, the spacecraft completed the first landing operation ever done on the surface of an asteroid. Magnetic field data were acquired during the entire mission when the magnetometer instrument was on (Acuña *et al.*, 1999). However, no magnetic signature that could be associated with the magnetization of Eros was detected. The instrument spacecraft system sensitivity performance was ~1 nT. Based on this number we can estimate by finite element methods the maximum magnetization of the asteroid that would have gone undetected assuming a uniform density and magnetization per unit mass for the entire object. The value derived for the natural remanent magnetization (NRM) per unit mass (kg^{-1}) is extremely low, $<2.1 \times 10^{-6}$ Am^2 kg^{-1} indicating that 433 Eros is less magnetic than the ordinary chondrites (Acuña *et al.*, 2001).

Gaspra, similarly considered to be an S-type asteroid (Kivelson *et al.*, 1993), is estimated to have a magnetization level of 0.024 (Am^2 kg^{-1}). Likewise the estimate for Braille (Q/S class) is a magnetization level of 0.028 (Am^2 kg^{-1}) (Richter *et al.*, 2001). These values are appropriate for the most magnetic of the H chondrites and some of the iron meteorites.

Given the low level of magnetization for 433 Eros and the suggested ordinary chondrite meteorite match with S-type asteroids, a review of the magnetization intensity of ordinary chondrite meteorites was undertaken to allow some insight into the reasonableness of such a match. Regardless that there exists a large amount of meteorite magnetism data, there is little experimental "rock magnetism" information about the magnetic mineralogy found in the chondrites, thereby making it a difficult task to arrive at what might be considered reliable estimates of uncontaminated NRM. Published ordinary chondrite magnetization intensity data sets show authorship variation which suggests variance in experimental methodology. These data, presented in Fig. 1, are arranged along vertical lines with authorship identified (Pesonen *et al.*, 1993; Sugiura and Strangway, 1987; Morden and Collinson, 1992). The Pesonen *et al.* (1993) data generally yield higher values than the other data sets, likely because the measurements truly represent the NRMs complete with contamination which was not considered in presenting the data. Sugiura and Strangway (1987) used alternating field (AF) demagnetization to arrive at magnetization levels that they considered would be free of viscous magnetization and other noise, while Morden and Collinson (1992), reporting data for LL ordinary chondrites, considered that their magnetic cleaning procedures provided the "true" primary magnetization. Figure 1 also illustrates data for Allan Hills (ALH) 76009 (L6 chondrite), representative of measurements for large (23 700 g) and small (<1 g) samples labeled, respectively, L and S. A line labeled Gaspra and Braille locates the magnetization level for these two asteroids (Kivelson *et al.*, 1993; Richter *et al.*, 2001) and at the bottom, the upper

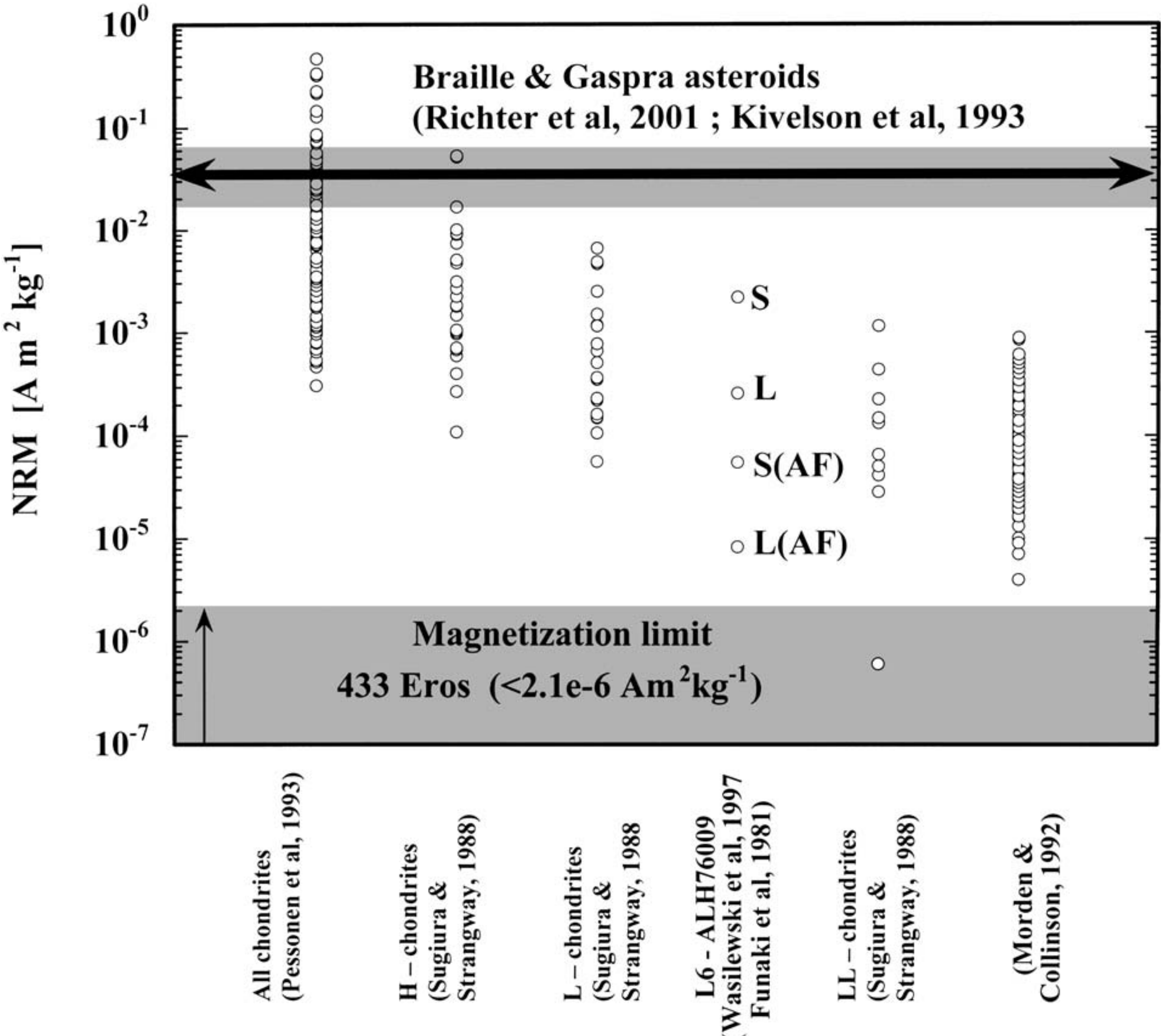

FIG. 1. Magnetization intensity of chondrite meteorites from indicated sources. Upper magnetization limit of Eros is indicated by the gray area at the bottom of diagram. The estimated magnetization level of Braille and Gaspra asteroids is also indicated. Magnetization data labeled by S and L relate to the magnetization of small and large fragments of meteorite ALH 76009, respectively, that were subsequently demagnetized in a 5 mT alternating magnetic field (samples S(AF), and L(AF)).

limit to the magnetization of 433 Eros at 2.1×10^{-6} Am^2 kg^{-1} is indicated.

The ordinary chondrite magnetic intensity variations (see Fig. 1; data from Sugiura and Strangway, 1987) document the systematic decrease in magnetization intensity in the sequence H > L > LL. This is commensurate with the respective 10, 5, 2% metal contents outside the chondrules (Brearley and Jones, 1998). This tendency was quantified with saturation magnetization measurements by Nagata (1980). The range in the NRMs for each chondrite group covers many orders of magnitude. When normalized with respect to the saturation remanent magnetization (SIRM), the NRM proves to be enigmatic as we describe in the REM section suggesting that there is no simple correlation between the NRM and the amount of magnetic material present in the specific chondrite meteorite. REM is the ratio of the NRM to the SIRM.

Numerous studies (Funaki *et al.*, 1981; Collinson, 1988; Morden and Collinson, 1992) identified randomness in the magnetizations measured in subsamples, removed with mutual orientation intact, from the ordinary chondrites. Consequently, to address this problem and in anticipation of the NEAR mission, large meteorites (>10 000 g) were measured and compared to the small sample data from the same meteorite (Wasilewski *et al.*, 1997). The per unit weight large sample magnetization intensities were lower than the small sample data. This suggests that randomization of small regions tends to demagnetize larger meteorites with significant implications for the interpretation of asteroidal magnetic records. Up to and in excess of 70% of the NRM intensity in chondrite meteorites appears to be noise; some is due to transit from space to Earth, and in general to residence in the geomagnetic field. In addition some NRM data is museum dependent and relates to human factors (Wasilewski and Dickinson, 2000). This is not surprising since many web sites and museums advertise that meteorite/earth rock discrimination can be accomplished with a hand magnet, leading to contamination of the samples and possible irreversible alteration of the magnetic record.

It is the purpose of this paper to attempt to reconcile the Eros data and the ordinary chondrite meteorite magnetization intensity data and thereby comment on the general problem of the S-class asteroid *vs.* ordinary chondrite meteorite match from a magnetic properties point of view.

MAGNETISM OF CHONDRITE METEORITES

General Aspects and Magnetic Mineralogy

The magnetic minerals in the ordinary chondrites, Fe-Ni alloys almost exclusively, are found as discrete grains of various sizes and shapes, grains inside and rimming the chondrules, as fine grains in silicates, and as various small grains in shock melt configurations. The amount of kamacite, (which is the low-Ni content alloy) relative to the total amount of magnetic material, decreases in the sequence H > L > LL (Nagata, 1980). It is this kamacite that is most often implicated with unstable magnetization. Likewise since the Ni content of the metal fraction follows the sequence H < L < LL, we would therefore expect larger taenite and tetrataenite components in the same sequence. The tetrataenite (which is the atomically ordered approximate Fe-Ni composition) is most often implicated with the hardest and therefore most stable magnetization. This is reflected in the magnetic hysteresis information where the magnetic hysteresis ratio R_I (which is the ratio of saturation remanence to saturation magnetization) and the coercivity, H_C, are greatest for LL chondrites and the mineral tetrataenite and least for H chondrites and the mineral kamacite (Sugiura and Strangway, 1988). Caution should be exercised here because the direct relationship of magnetic hysteresis properties and the remanent record has not considered fine metal grains found in dusty olivine and numerous shock structures. A modally insignificant stable mineral might be responsible for most of the useful remanence in some ordinary chondrite meteorites.

Afiattalab and Wasson (1980) explained how the progressive metamorphism, with attendant recrystallization of the chondritic meteorites, results in configurational changes in the metal size, distribution, and geometry. Trends are obvious in going from petrologic class 3 to class 6 and the authors explain that with increasing metamorphism—the fraction of metal-bearing chondrules decreases, the fraction of fine metal decreases, and the amount of coarse-grained metal increases. Consequently, there should be systematic variation in the magnetic characteristics with metamorphic grade and this would be in the direction of larger grain size with implied lower coercivity and magnetic stability.

Because of diffusion in the Fe-Ni system and the long cooling histories of meteorite parent bodies, the resultant microstructural evidence in the magnetic Fe-Ni phases can be diagnostic of the magnetic history. During subsolidus cooling of meteorites a homogeneous taenite (T or γ) phase will enter the two-phase (α-bcc (body-centered cubic) and γ-fcc (face-centered cubic)) field and as a consequence kamacite (K or α) nucleates at the edge of the taenite grain and grows inward (Brearley and Jones, 1998). As cooling continues the taenite cannot equilibrate and the characteristic M-shaped diffusion profile is developed with the magnitude of the difference between the Ni content of the core and the rim of the taenite being a function of the cooling rate. In the diffusion profile, tetrataenite, cloudy taenite, and martensite are the main mineralogies visible after a dilute solution of nitric acid in alcohol (NITAL) etch (Romig and Goldstein, 1981; Reuter *et al.*, 1989).

In Fig. 2a the important ferromagnetic phase relations are identified along a vertical line which corresponds to the cooling path whereby the appropriate phases become ferromagnetic and thereby able to hold magnetic remanence. T_c, the Curie point, and T_o, the ordering temperature, are the important magnetic transitions. Included in Fig. 2a are the estimated temperature ranges for petrologic classes 3 to 6 (Dodd, 1981). In the vicinity of 550 °C, kamacite is thermally demagnetized

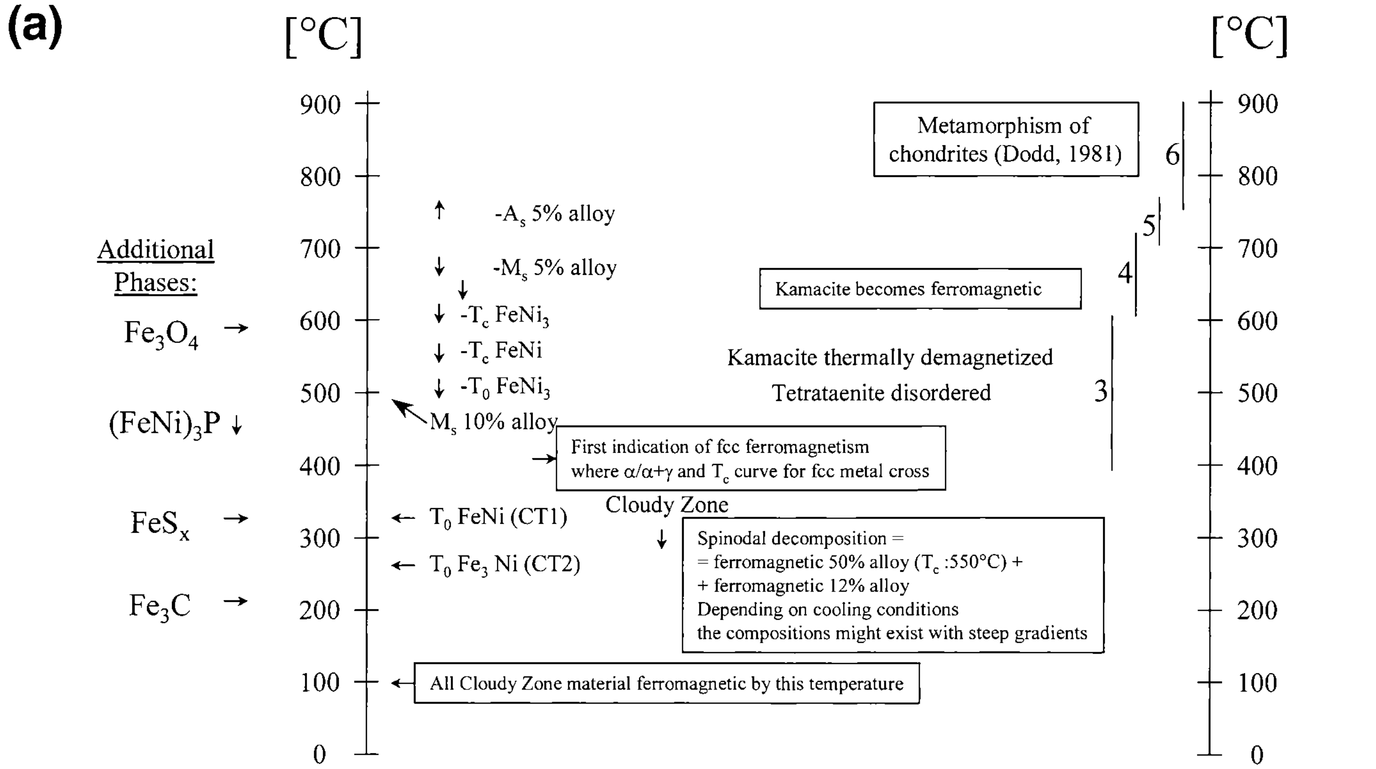

FIG. 2. (a) A schematic representation of the magnetic phase relations consequent to the subsolidus cooling history of the Fe-Ni alloys. In addition to the Fe-Ni alloys the various other phases that play an important role in magnetization of other than the ordinary chondrites are included to the left of the vertical line which represents the cooling path. T_0 is the ordering temperature, T_C is the Curie temperature, and M_S the martensitic temperature. The estimated metamorphic temperature ranges for the class 3 to class 6 chondrites is indicated (Dodd, 1981).

and tetrataenite experiences complete disordering. This would occur for any petrologic class. Also identified along the cooling line (Fig. 2a) are the Curie temperatures for magnetite, pyrrhotite, schreibersite, and cohenite, all important magnetic minerals found in meteorites though of minor significance for most ordinary chondrites.

In Fig. 2b (top), the M-shaped diffusion profile is presented as an exaggerated composition—distance (distance is traverse distance across the grain) schematic locating the basic magnetic phase relations. Based on their appearance in microscopic examination of NITAL-etched polished sections, five regions are identified in the idealized M-shaped diffusion profile. Below the schematic are the Curie point (thermomagnetic) curves demonstrating how each region could be identified if the phases could be discretely considered. (1) The kamacite (K or α phase) low-Ni bcc phase is a border phase on the diffusion profile. The austenite (A_S)–martensite (M_S) hysteresis typical of this bcc Fe-Ni alloy is shown as the bottom left thermomagnetic curve in Fig. 2b. This would be the first phase to be magnetized during cooling and during heating it would be thermally demagnetized at 550–600 °C even though the A_S temperature is near 700 °C. (2) The tetrataenite or clear taenite (CT1) phase with the highest Ni content is the atomically ordered near equiatomic Fe-Ni alloy. This Ni-content high point on the M-shaped profile would initially become ferromagnetic at ~360 °C when the composition reached 40% Ni and would do so in the presence of the already magnetized kamacite. However, it remains to be determined if this scenario would influence the direction and intensity of remanence in the 40% Ni taenite. As Ni is added, the Curie point would increase eventually reaching ~550 °C for the near equiatomic composition. Ordering would commence on cooling below 320 °C. The thermomagnetic curve indicated is for Appley Bridge tetrataenite and is typical for tetrataenite. The magnetization intensity is almost flat on heating out to ~500 °C and thereafter the decay is rapid reflecting the disordering rather than a Curie point. On cooling the Curie point of taenite at 525–550 °C is observed and the convex upward curve shape for a normal ferromagnet material is the final shape. (3) The cloudy zone (the zone named for its appearance after etching with NITAL) is a mixture of tetrataenite and martensite with the composition of the honeycomb martensite and the size of the globular tetrataenite regions dependent on the cooling history. The cloudy zone tetrataenite would be indistinguishable from CT1 during the thermomagnetic measurement. The cloudy zone, which is identified in the thermomagnetic heating curve shown in Fig. 2B for a Bjurbole chondrule, is not a discrete phase but rather a mixture that includes tetrataenite from CT1 and the

(b)

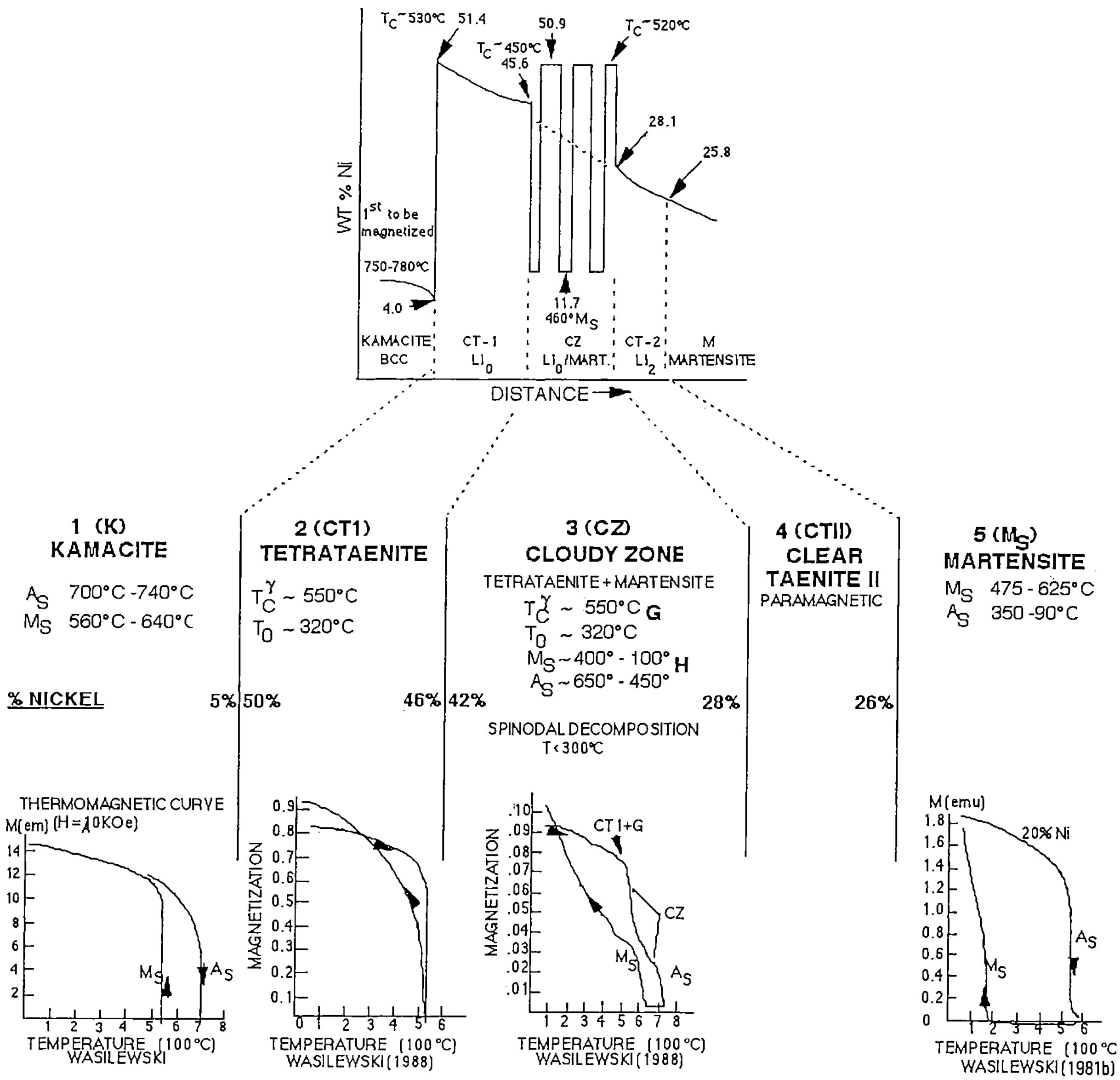

Fig. 2. *Continued.* (b) Schematic of the diffusion profile indicating the composition range and the nature of the chemical gradients which greatly complicate the magnetic story in such configurations. The toothed structure represents the globular tetrataenite and the honeycomb martensite in the cloudy zone. Below the schematic is an indication of the thermomagnetic behavior associated with the different parts of the profile. The Bjurbole chondrule example representing the cloudy zone actually contains all five zones in the complete thermomagnetic curve.

cloudy zone and the honeycomb martensite as well as the central martensite (see (5)). The heating and cooling curves have the kamacite A_S–M_S transition identified but otherwise no other discrete phase can be identified. Repeat thermomagnetic curves are irreversible, the curve shapes change in response to rapid chemical changes in steep chemical gradients reflecting the behavior of the martensite in the cloudy zone and if present at the center of the M-shaped profile. (4) Clear taenite (CT2) is paramagnetic and therefore no details would be available in a thermomagnetic curve and (5) martensite (M_S) is identified by its characteristic microstructure. The martensite thermomagnetic curve shows the classic A_S–M_S hysteresis noted for all bcc alloys but as described for (3)—the cloudy zone—this martensite would be part of the composite curve makeup.

Though tetrataenite is the obvious ultrastable magnetic carrier in meteorites and its uniqueness (Wasilewski, 1988) is well established, there is little known about how the stable remanence actually is locked during the ordering process. The possibility that tetrataenite may be responsible for some of the randomness observed in detailed subsample studies requires investigation. Magnetic anisotropy control of the remanence vector directionality may be possible in view of the strong magnetic anisotropy of the tetrataenite. If two polyphase grains with tetrataenite are randomly magnetized all that would be observed during thermal demagnetization would be the vector sum up to the point where disordering took place and thereafter randomness would result. This is indeed an interpretation that is valid for some of the thermal demagnetization results. In all petrologic classes any significant shock heating would reset the remanent magnetization as the transition temperatures and the tetrataenite disordering temperature thresholds are in the vicinity of 500 °C and lower. Wasilewski (1988) experimentally demonstrated that an isothermal anneal at 490 °C would in a matter of hours disorder the tetrataenite. Consequently, longer times at slightly lower temperatures would elicit the same effect. Therefore any tetrataenite magnetic recording would postdate peak metamorphism regardless of the class. Moderate shock heating would disorder the tetrataenite created on cooling from metamorphic temperatures. The shock-heating aspect that would reset the ordering is an important consideration that fortunately can be identified (Bennett and McSween, 1996).

Possible Contamination

Meteorite magnetism researchers have considered the possible influence of the fusion crust, created during the transit from space through the atmosphere to the surface of the Earth, on the remanent magnetism record. The influence of the crust is minor and exists as a near-surface rind extending mere millimeters into the bulk meteorite. Wasilewski (1981a) showed that the fusion crust on the Allende meteorite had a REM value of 0.022, similar to what would be found in a basaltic rock cooling in the geomagnetic field, while the bulk interior of Allende had REM values ranging from 0.0046 to 0.0065. Sugiura (1977) and Guskova (1963) attempted to assess the possible terrestrial influences other than the fusion crust that could interfere with the identification of the primary remanence in the chondrite meteorites. They evaluated the viscous magnetization which is that time-dependent magnetization acquired when the meteorite is resident in the geomagnetic field. Both authors considered that this effect, though present, would be minor. Guskova (1963) and Sugiura (1977) established in the same studies that small magnetic fields up to 1 mT could produce magnetization intensities of the same level as the observed NRM. Consequently, the chondrite is easily contaminated.

It would appear that there are at least three levels of noise which in some cases may interfere with the identification of the primary component. There exists an ultrasoft component that responds rapidly to the geomagnetic field effectively providing a component along the laboratory field direction during an exposure time of minutes. This is the component considered by Morden (1992) to be responsible for the zigzag demagnetization curves. The viscous component, which is the second noise component, would be expected to imprint the NRM record over the residence time in the geomagnetic field. From the initial measurements with Bjurbole (Fig. 3a) there would appear to be at least two levels of viscosity, one with time constant of hours to days, and another with an undetermined longer time constant. The third noise component would be that due to hand magnet contamination and other haphazard contact with magnetic fields in the museums or during collection. This third level of noise depends on the strength of the magnetic field and importantly the type of mineralogy in the meteorite (Wasilewski and Dickinson, 2000).

The identification of two of the three components is illustrated in Fig. 3a,b. The 7 g piece of the Bjurbole meteorite was cooled to liquid nitrogen temperature in order to ascertain the effect of the full range of temperature that might be experienced by the meteorite from its residence in space to its entry and residence at the surface of the Earth. Though the main event already happened, if the meteorite is in the laboratory, the experiment is instructive. The sample was cooled to 78 K and warmed to 295 K in the low field (<10 nT) cryoshield environment of the superconducting magnetometer. The initial NRM of 2.61 (10^{-4} Am^2 kg^{-1}) was reduced to 1.9 on cooling to 78 K in "magnetic vacuum" and then decreased to 1.7 on warmup to 295 K in the same vacuum. This 1.7 value is the starting point in Fig. 3a. The horizontal magnetic field axis has milli-Tesla values which correspond to the distance out of the cryogenic shield A magnetization of 2.1 was achieved soon after reaching the lab field. Additional experiments for days and as long as a month resulted in magnetization levels up to 4.25. The discrepency betwen the NRM and the larger experimental value is due to different sample orientations in the field during the experiment

The curves below the NRM curve in Fig. 3a represent the result of the same experiment as was applied to the NRM described above except that the sample was demagnetized at successive alternating fields of 1.2, 2.5, and 5.0 mT in order to discover the constancy of the ultrasoft component and the behavior of the stepped-down total remanence which would include viscous components and any manmade contamination. Always the base magnetization at the zero field level identified on the Fig. 3a field axis could be achieved by cooling to 78 K and warming for a short time in the magnetic vacuum. At the right side of Fig. 3a, corresponding to the magnetic field = 0.048 mT, the magnetization would be acquired as magnetic viscosity but with variable time constants. This aspect of the field exposure/time-dependent behavior is being carefully evaluated at present. The ultrasoft noise component is identical throughout the demagnetization step phase of the experiment. In Fig. 3b the ultrasoft component is characterized by subtracting the magnetization vector after the cryogenic step from the magnetization vector of the individual acquisition steps demonstrating that the ultrasoft component is present and constant, regardless of other demagnetization treatment, and this indicates an existence of a discrete fraction of magnetic grains essentially magnetically independent of the AF demagnetization treatment.

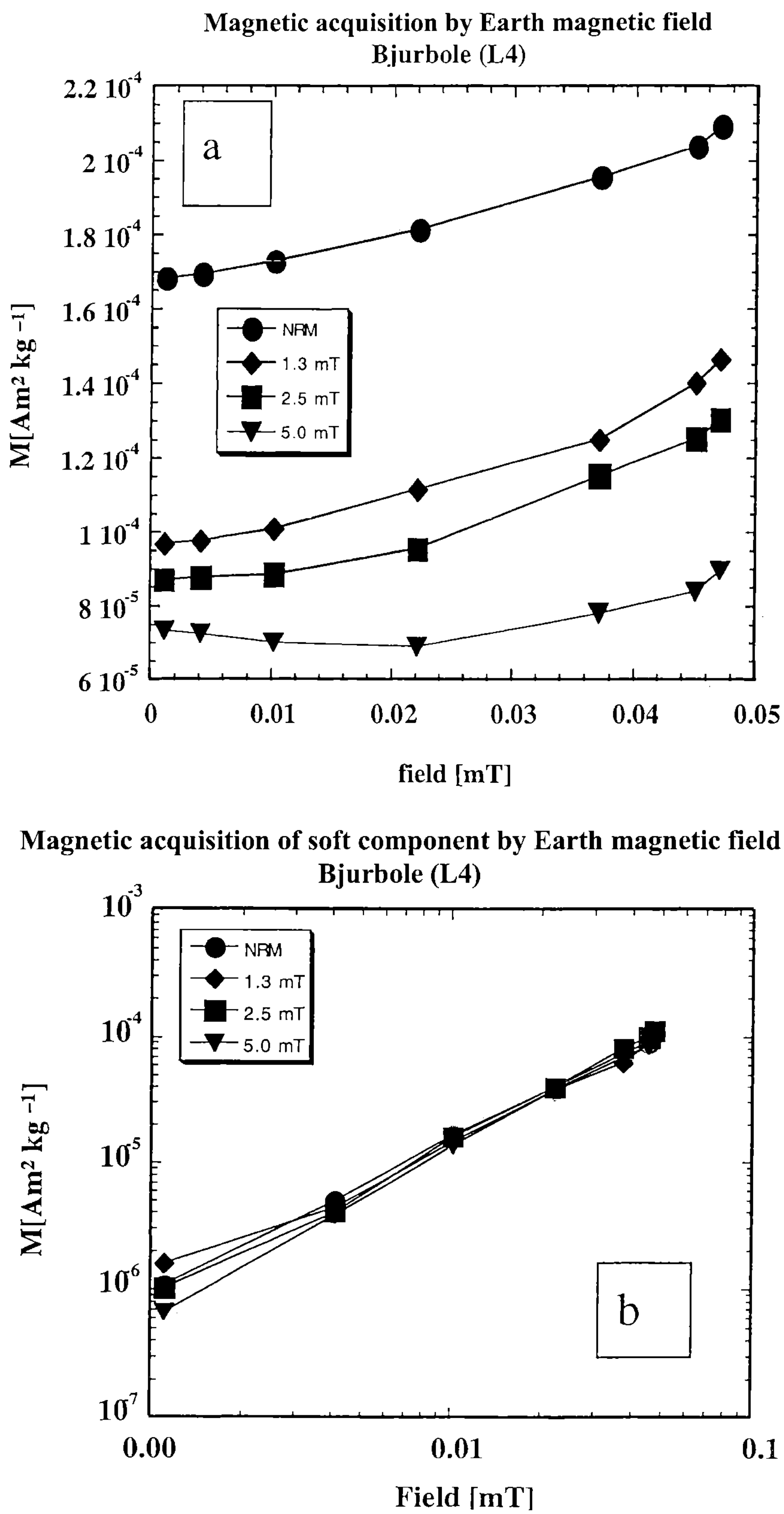

FIG. 3. Acquisition of soft magnetization in the terrestrial environment. (a) The original sample of Bjurbole was cooled to liquid nitrogen temperature and warmed up to 300 K in a magnetic vacuum (field-free space). The sample was then exposed to increasingly higher, but low magnetic fields that reached the maximum Earth field. This was repeated after demagnetization by alternating fields up to a maximum 5 mT. (b) The soft vector component acquired in (a) was extracted from each acquisition curve and plotted separately.

Ratio of Natural Remanent to Saturation Remanent Magnetization Values

Remanent magnetism acquired by standard mechanisms in known magnetic fields (see Wasilewski, 1974, 1977) can be shown to have narrowly limited values of the NRM/SIRM ratio (called REM). For example, with a magnetic mineral such as magnetite, the SIRM and the thermoremanent magnetization (TRM) (in the geomagnetic field) intensities would increase with decreasing grain size however the REM would remain essentially constant near 0.02 because the changes are proportional. Wasilewski (1981b) evaluated the "TRM" acquisition in Fe-Ni alloys and found that the REM remained essentially constant for alloys up to 10% Ni. This appears to be a basic remanence acquisition principle for magnetic materials. There are exceptions, such as hematite and titanohematite (Kletetschka *et al.*, 2000), which might become important if terrestrial oxidation of the metal in the chondrite is significant. We would expect the acquired chemical remanent magnetism (CRM) associated with the oxidation products to be unidirectional for an immobile sample and this may be the only part of the NRM record with this characteristic. Other examples of the use of REM more accurately referred to as "REM" incorporates demagnetized NRMs or SIRMs. "REM" as noted by Wasilewski and Dickinson (2000) may include NRMs and SIRMs that have been demagnetized. A notable application of the "REM" with lunar samples attempts to assess a relative intensity scale for the paleo-lunar magnetic field by using the NRM/SIRM ratio after both the NRM and the SIRM are demagnetized in a 20 mT alternating magnetic field (Cisowski and Fuller, 1986).

In Fig. 4 we can track across the L, LL, and H groupings at a constant SIRM and cover over 4 orders of magnitude in NRM with a REM overlapping range of <0.0001 to 0.1. The LL chondrites have REMs ranging from 0.00008 to 0.02 while the H chondrites range from 0.002 to 0.2 with the L chondrites showing a greater range and overlapping LL and H with REM ranging from near 0.0001 to 0.2. The REM range may relate directly to the complex history of the meteorites/asteroids including the role of magnetic field intensity; however, we must first describe what part of it is due to terrestrial influences.

If the chondrites were magnetized under the same conditions the REM values would be expected to be tightly grouped. Some of the ways that the REM can be altered in chondrite meteorites are as follows:

(1) For a TRM acquisition mechanism the TRM intensity would depend on the magnitude of the external field and since the SIRM would remain constant, REM would be a measure of the strength of the external field for the Fe-Ni alloy minerals insofar as we are able to ascertain. This would apply regardless of the grain size. This might only apply to kamacite and in particular to metal in shock melt veins. It is not at all clear what would happen in tetrataenite, which acquires its exotic magnetic properties below 320 °C (Wasilewski, 1988).

(2) A kamacite grain subject to an impact near 10 GPa would have the SIRM increase and providing that the impact heating would not anneal the shock microstructure the transformation remanence (TMRM) (Dickinson and Wasilewski, 2000) direction and intensity would depend on the presence of a magnetic field but might be orders of magnitude less than a TRM, resulting in the diminishing of the REM. However the impact mechanism would tend to order the orientation, perhaps removing widespread randomness, and may result in an increase of the bulk magnetization.

(3) The amount of magnetically soft kamacite increases in the sequence LL < L < H and consequently the influence of the geomagnetic field should follow this sequence being proportionate to the kamacite content. This may increase the REM in the same sequence.

NRM and SIRM data for 87 non-oriented chondrules from the Bjurbole (L4) meteorite, indicating a range of REM from ~0.0005 to 0.3, are included in Fig. 4 together with the chondrite meteorites. This consideration of the chondrules addresses the relative magnetization intensity for components that had an external magnetic history prior to accretion and which then experienced a history as part of a meteorite with a low level of shock and of low petrologic type. We might expect a similar REM for all chondrules but this is not the observation. We examined in detail about 25 of these, covering the broad REM range, and find that tetrataenite is present in all of the examined chondrules. The liquid nitrogen–room temperature experiments (Kletetschka *et al.*, 2001) performed on some of the chondrules does identify the existence of various levels of "noise" in the magnetic record and may add to the broad REM record for the chondrule suite. One might conclude from this data set that the specific chondrule magnetic histories were different before being incorporated into the meteorite and that the record had not been seriously altered since. If the meteorite was thermally demagnetized, as would be the case for L4 Bjurbole, in zero magnetic field the new tetrataenite remanence would be acquired in zero magnetic field. This would suggest minimal remanence which again is not the observation.

Random Magnetization

In their quest to better understand the magnetic record in the chondritic meteorites, many researchers separated individual chondrules, metal, matrix, or simply small subsamples preserving the mutual orientation so that the spatial coherence of the magnetic vector record could be ascertained. Almost always scatter of the oriented sample vectors was observed. An example of this characteristic is shown in Fig. 5 where the vector directions of 83 individual small mutually oriented subsamples removed from the Bjurbole chondrite are presented. These data represent the NRM records and it is clear that the geomagnetic field or any unidirectional overprint cannot be responsible for the observations. The bulk measurement would be a composition of the weighted sum of these

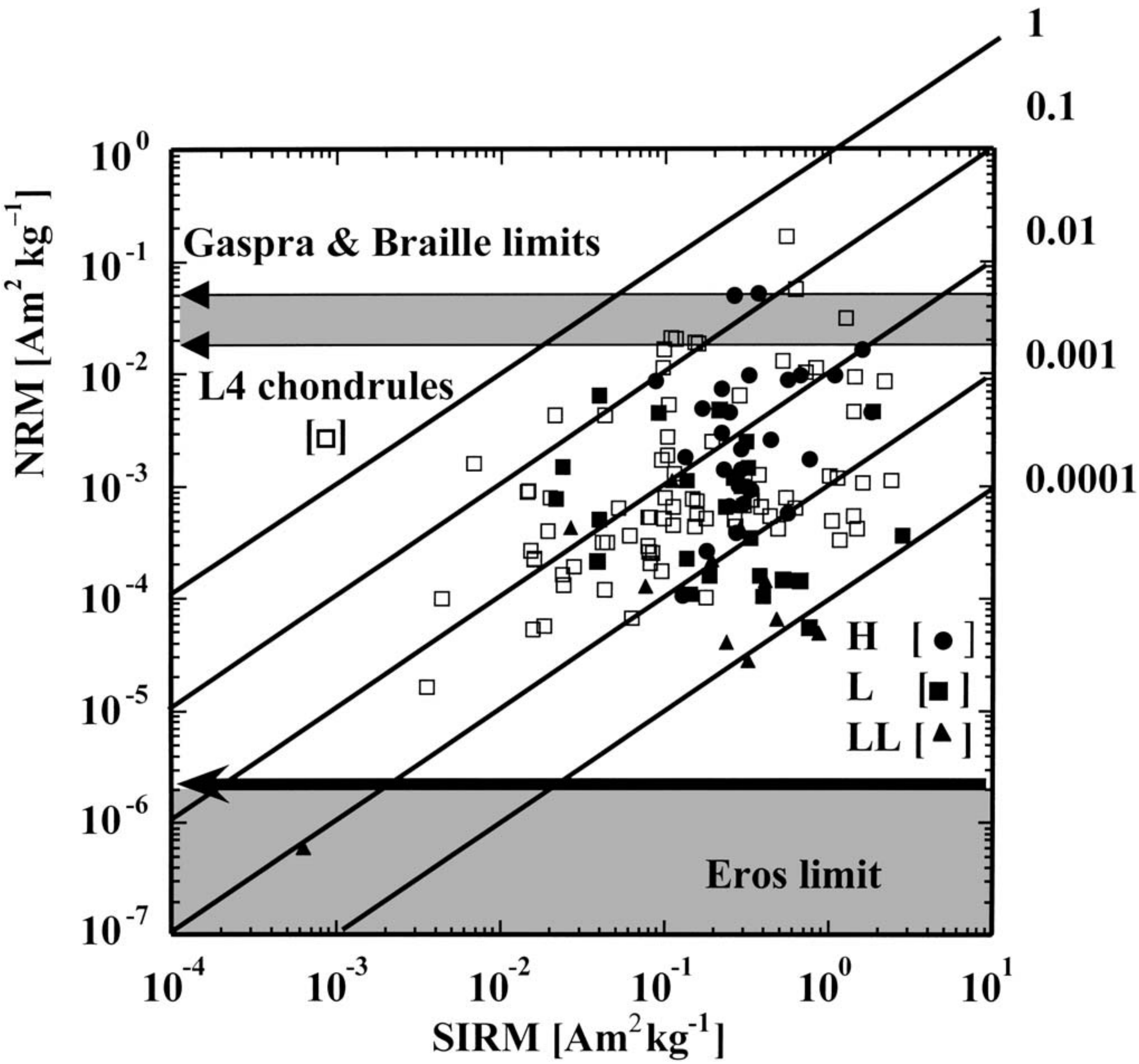

FIG. 4. Plot of the NRM against the saturation remanence magnetization (SIRM) for H (solid circles), L (solid squares), and LL (solid triangles) chondrite meteorites (Sugiura and Strangway, 1988) together with the the same for chondrules from the Bjurbole (L4) meteorite (our data depicted by empty squares). The diagonal lines indicate different values of REM, the NRM/SIRM ratio.

vectors. This appears to be the real situation for some ordinary chondrite meteorites. The most serious attempt to characterize the vector records of mutually oriented components was done by Funaki *et al.* (1981) and more recently by Morden and Collinson (1992). These studies were done with the caveat that the randomness could not exist if hot metamorphism in the presence or absence of a magnetic field was responsible for the metamorphic grades (the petrologic classes), which is the conventional wisdom of the meteorite community.

We chose to address this issue by using the magnetic records of large meteorites, which would accommodate the randomness issue and thereby enable a better understanding of the bulk magnetization of an asteroid (Wasilewski *et al.*, 1997). Samples of large meteorites (ALH 76009, 23.7 kg; Allende, 17.2 kg; Canyon Diablo, 454 kg) were measured using techniques and methodology similar to the 433 Eros encounter. Using the Goddard Space Flight Center (GSFC) Magnetic Test Site (where the intensity and gradient of the magnetic field is fully controlled), the NRM and the remanence after demagnetization by a 5 mT alternating magnetic field were measured in near-zero magnetic field. Results show that large samples have lower magnetization intensity than small samples, which points either to a larger potential for contamination of small samples or to the vector subtraction associated with randomly oriented

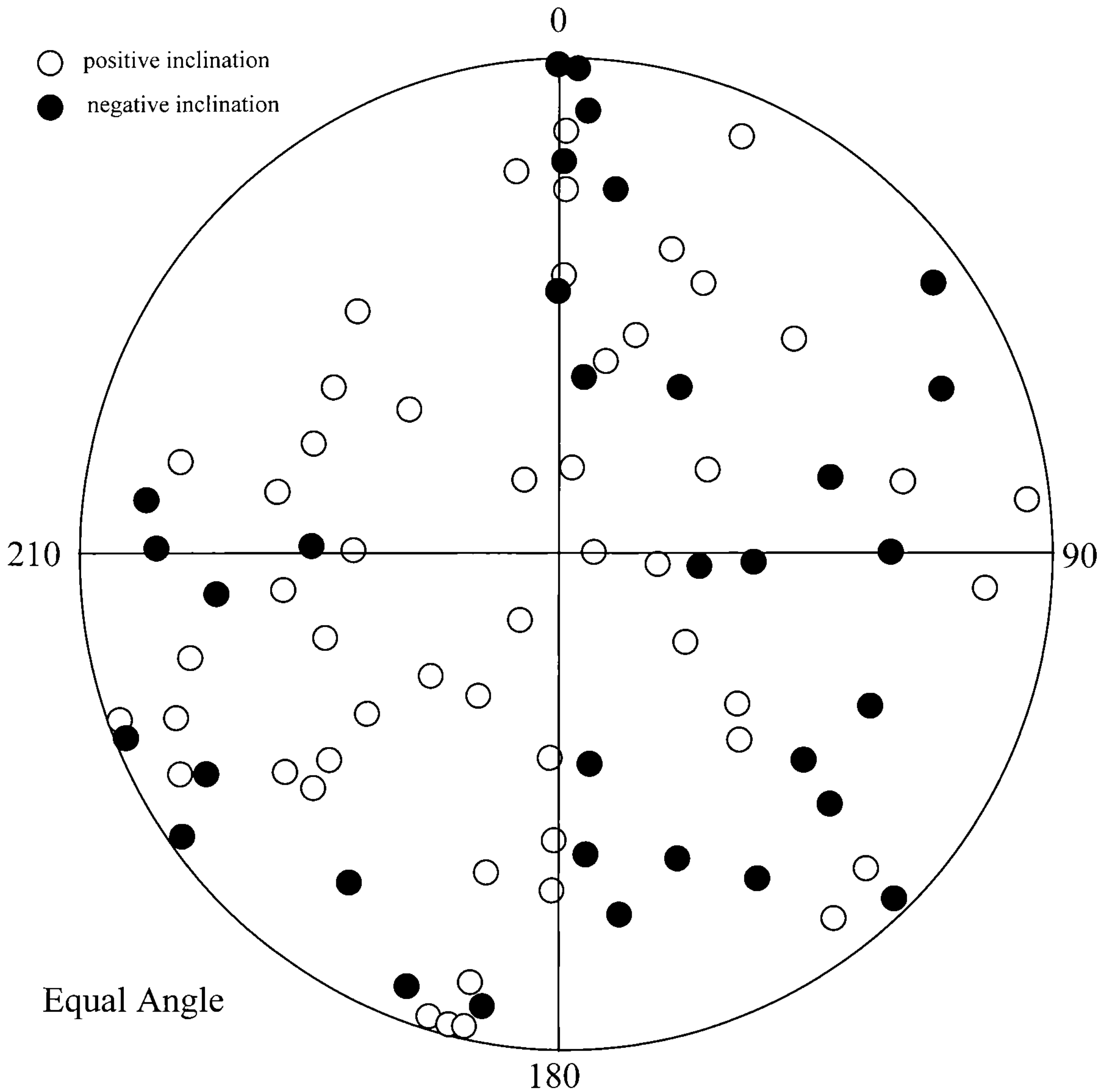

FIG. 5. Equal angle stereo graphic projection plots of NRM vector orientation records for 83 individual mutually oriented subsamples from the Bjurbole meteorite (L4-S1).

magnetized regions within the large meteorites. In Fig. 6 the magnetization is plotted against the approximate diameter of the meteorite. The Bjurbole sample was the 7 g friable piece that we measured in its original form and then after separating smaller fragments. The Bjurbole meteorite data clearly describes a size-dependent decrease of remanent magnetization. A thin slab (5 mm in thickness) of the Plainview (H5) meteorite was cut from a larger piece. The slab was then carefully cut into 5 mm cubes and vector magnetization was measured for all mutually oriented cubes. Vector magnetizations were summed providing a magnetization estimate of a large cube built from the small sample cubes. The same cubes were then used to build cubes of any reasonable size whose total magnetization was calculated. The large sample of Allende was measured at the GSFC Magnetic Test Site and the small samples were measured in the laboratory (Wasilewski, 1981). The data always shows that magnetization is less for the larger samples, including Allende which is a C3V chondrite .

The large/small contrast of most interest in Table 1 and Fig. 6 is that presented by the L6 chondrite ALH 76009 which loses 97% of its NRM upon demagnetization at 5 mT. This end result translates to a magnetization of 8.4×10^{-6} $Am^2 kg^{-1}$ for the mini-asteroid. These results do not explain the nature of the distribution of the randomness, a question that remains unanswered. Though the ALH 76009 chondrite loses 97% of its intensity at a demagnetization level of 5 mT the same analysis applied to metal grains, chondrules, and matrix samples reveals that only a maximum of 60% of the intensity is demagnetized.

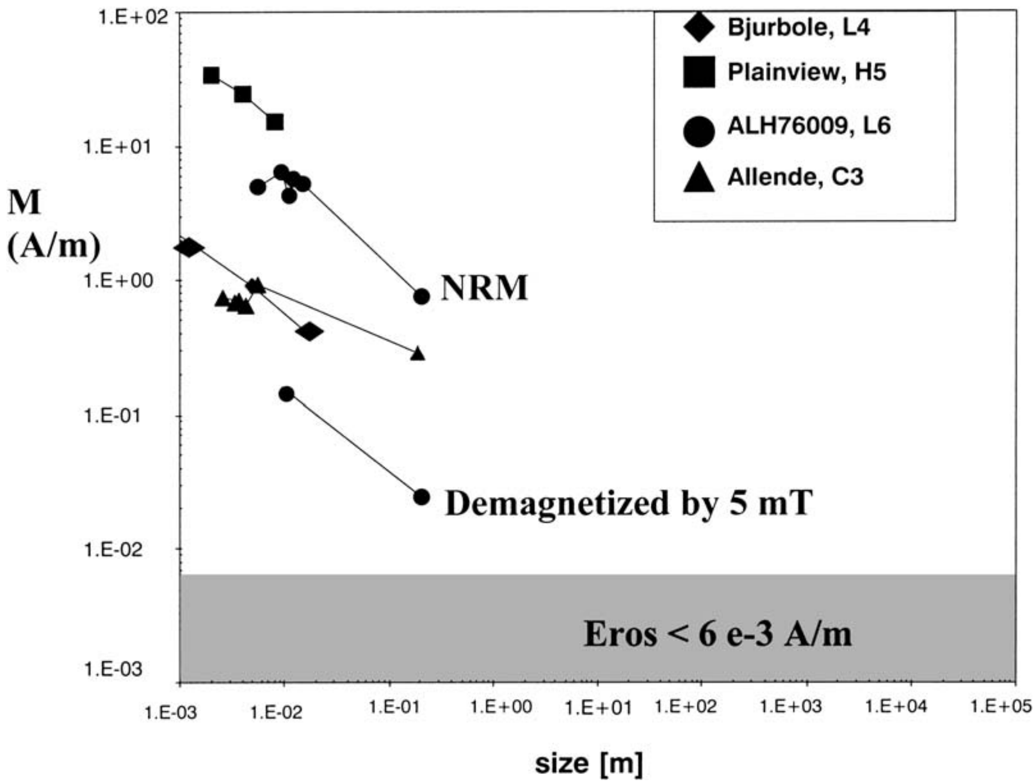

FIG. 6. The large/small contrast: size-dependent magnetization of meteorites compared with the Eros estimate.

TABLE 1. Magnetization data for large meteorites, comparative small samples and laboratory introduced TRM in Fe-Ni alloys of kamacite compositions.

	Canyon Diablo	Allende	Allan Hills 76009
Dipole moment	782.9×10^{-3} A m^2	1.8×10^{-3} A m^2	6.2×10^{-3} A m^2
Dipole moment after demagnetization	515×10^{-3} A m^2	–	0.2×10^{-3} A m^2
Weight	454 kg	17.2 kg	23.7 kg
Density	7500 kg^{-3}	2750 kg^{-3}	2890 kg^{-3}
Magnetization intensity	12.94 A m^{-1}	0.288 A m^{-1}	0.756 A m^{-1}
Magnetization per unit mass	17.25×10^{-4} A m^2 kg^{-1}	1.1×10^{-4} A m^2 kg^{-1}	2.63×10^{-4} A m^2 kg^{-1}
(Demagnetization)	(11.38×10^{-4} A m^2 kg^{-1})	–	(0.084×10^{-4} A m^2 kg^{-1})
Small bulk samples		(Wasilewski, 1981a)	(Funaki *et al.*, 1981)
Magnetization/g	–	$(2.37–2.64) \times 10^{-4}$ A m^2 kg^{-1}	22.1×10^{-4} A m^2 kg^{-1}
REM = NRM/SIRM	–	0.0042–0.0054	0.0065
(SIRM = saturation remanence)			

For Fe-Ni spheres (0–9% Ni) acquiring a TRM in the geomagnetic field TRM = $(7.6–25.2) \times 10^{-4}$ Am^2 kg^{-1} (linear with Ni content). These spheres have REM values between 0.02 and 0.03.

Role of Impact

433 Eros has been subject to an impact history beginning with its possible fragmentation from a parent body and further supported by the NEAR imaging which clearly documents an impact record.

Based on detailed studies of a broad range of ordinary chondrites, Stöffler *et al.* (1991) consider that the shock histories of the parent bodies for the H, L, and LL meteorites are similar. They find that the most common shock stage is S3, which they call lightly shocked. The S2/S3 transition is identified to be in the range 5–10 GPa and the S3/S4 transition near 15–20 GPa, which would have the kamacite in most of the meteorites demagnetized and then remagnetized *via* the TMRM mechanism active at ~10 GPa for kamacite compositions as described in Dickinson and Wasilewski (2000).

The role of shock impact in the evaluation of the asteroid/chondritic magnetic record must be considered as shock effects are pervasive in chondritic meteorites and consequently where present the original magnetization record has been modified. Rubin (1985) reviewed the characterization of impact melt products in chondritic meteorites. The presence of shock veins, metal-troilite mixtures of various types, metal nodules and veins, and melt pockets with metal massses are pervasive. These shock-induced features are likely to contain the only evidence of a magnetic field associated with the shock event. The shock features are isolated and independent of the rest of the meteorite and they contain fine-grained metal which may be capable of preserving any magnetic signature acquired during the short time after the shock event. Bennett and McSween (1996) clarified the effects of shock stage on Fe-Ni alteration, clearly related to post-shock temperature. Their work extended the realm of information that can be gleaned from viewing the microstructure in Fe-Ni. In particular they emphasize that the shock effects postdate the thermal metamorphism that defines the petrologic classes. This is an important operational feature for the development of magnetic analysis protocols.

Consequently, shock classifications allow insight into the level of the impact and the alteration of the magnetic record that might be a consequence. This type of scenario was considered by Wasilewski (1974) who described the metallographic features that could serve to identify magnetic alterations relatable to the shock record. An example of this is evident with the record in kamacite. Shock twinning is found in kamacite up to the 10 GPa transformation and should result in increasing magnetic hardness. Thereafter the transformation microstructure can be found. However it is absent in the chondrite kamacite and instead we find polycrystalline kamacite which is likely due to the anneal of the transformation microstructure associated with elevated post-shock temperature in porous target material. Described in Bennett and McSween (1996), the appearance of the polycrystalline kamacite coincides with the appearance of fine metal in various types of shock melt configurations. In these configurations we will find a new thermal magnetization record if a magnetic field were present. In any case it is important to know what the record in the shock melt configurations is compared to the rest of the meteorite. These types of experiments have not been completed.

Chen *et al.* (1995) considered that the magnetism of small bodies in the solar system may have resulted from the shock-induced first-order phase transformation (TMRM) as described by Wasilewski (1977) and Dickinson and Wasilewski (2000). In the study by Chen *et al.* (1995) the material was presumed to be shocked at a level in excess of the shock transition but not to the point where thermal effects would become important. Therefore, the materials would have had to experience shock levels in the vicinity of shock stage 3 (Stöffler *et al.*, 1992) (*i.e.*, near 12 GPa), in order to have the transformation mechanism be effective.

DISCUSSION

433 Eros has a level of magnetization undetectable at the surface of the asteroid at the 1 nT level, translating to a magnetization per unit mass of $<2.1 \times 10^{-6}$ Am^2 kg^{-1}. This indicates a great disparity between the 433 Eros measurements and the estimates for Gaspra and Braille, which are also considered S-type asteroids. The 433 Eros magnetization is less than the least intense LL-type ordinary chondrites and the Gaspra and Braille estimates are larger than most of the highly magnetic H-group ordinary chondrites if we consider the published ordinary chondrite magnetic data.

We have summarized the published magnetization records for the ordinary chondrite meteorites and are able to show that the 433 Eros magnetization is less intense than the ordinary chondrites regardless of the type. A considerable degree of reevaluation of magnetic records was done so that we could be confident what the primary magnetization actually is. For the ordinary chondrites the metal content decreases, the proportionate amount of kamacite decreases, the amount of tetrataenite increases, and the magnetic hardness increases as we evaluate the sequence H > L > LL. The data in Fig. 1 is consistent with the metal content trends, but no estimates of the primary intensity is made and with the data sets available we cannot discover this. Sugiura and Strangway (1988) suggested that the Antarctic chondrite meteorites have smaller NRMs and consequent REMs and their intensities are more resistant to demagnetization than the NRMs in non-Antarctic chondrites. It is clear that the intensities presented in the literature may be overestmates of the primary magnetization intensity consistent with a consideration of the possible noise levels in the chondrites.

The large sample experiments provide better insight into the ordinary chondrite phenomenon that is referred to as random magnetization. In the particular experiments involving ALH 76009 (L6), 97% of the NRM could be reduced in a 5 mT demagnetization field, which we can conclude is noise. The amount of noise removed from the small and large samples is proportionately the same but what is important is the geometry of the spatial distribution of magnetic vector records as the large sample studies demonstrate. Consideration of the magnetization of the large and small meteorite samples in the context of the random magnetization, characteristic of the ordinary chondrite records brings to question the nature of the asteroidal magnetic signature as this aspect would further reduce the actual intensity of a large body such as an asteroid.

It is clear that impact will influence an asteroidal signature but there is little information about magnetic remanence effects due to impact of meteorites or Fe-Ni metal other than Dickinson and Wasilewski (2000) which is based on earlier work (Wasilewski, 1977, 1981c). It would be a mistake to translate the work with terrestrial rocks (Cisowski and Fuller, 1978) to meteorites. Metals respond differently to impact and they record the impact evidence in different ways as Bennett and

McSween (1995) and many others have shown. In general from what is known we could assume that shocks up to ~9 GPa might demagnetize the chondrite. Shocks in excess of ~10 GPa would demagnetize and then remagnetize the meteorite if a magnetic field were present as the shock transition at 10 GPa would be operative. At higher shock levels the influence of post-shock temperature would become more important and cooling in the presence or absence of a magnetic field would be a critical factor.

The nature of the magnetic signature of a chondrite meteorite is obscure as the example of ALH 76009 (Funaki *et al.*, 1981) indicates. About 97% of the NRM record in the bulk chondrite could be considered noise. However only about 40 to 60% of the NRM in the component metal, chondrules, and matrix could be considered noise. The understanding of the basic properties of the magnetic mineralogy is missing from the meteorite magnetism research framework and this is the reason why a better understanding of meteorite magnetism is not possible at the present time.

CONCLUSION

Based on the consideration of available meteorite magnetism data, 433 Eros cannot be matched with the ordinary chondrite H and L groups. The magnetization intensity of 433 Eros is determined to be $<2.1 \times 10^{-6}$ Am^2 kg^{-1}. This would begin to approach the magnetization level of the least magnetic of the LL chondrites (Fig. 1). Reevaluation of the meteorite magnetism intensity data suggests that most ordinary chondrite data has been published as an overestimate, with the LL data least so. Large meteorite studies (Wasilewski *et al.*, 1997) considered together with the random magnetization observed in all careful ordinary chondrite studies suggest that the intensities may be lowered further when large objects such as an asteroid are considered. This is simply due to the juxtaposition of regions of randomly oriented material in massive objects such as asteroids. Shock effects are not easily interpreted as there is little information about the connection between shock level and magnetization. We do know, however, that levels of impact which do not provide a large post-shock temperature are likely to serve to demagnetize and harden existent remanence. Given the above considerations of ordinary chonrite magnetization intensity, the possibility that 433 Eros is an LL chondrite cannot be discounted.

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