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Magnetic properties of lunar materials: Meteorites, Luna and Apollo returned samples

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ABSTRACT

We present the first comprehensive study of the magnetic properties of lunar meteorites and compare them with measurements from Apollo and Luna returned samples. 37 unpaired lunar meteorites were studied, while new susceptibility measurements were performed on 88 Luna soil and rock samples, to complement published Luna and Apollo data. New magnetic data were also obtained on 4 Apollo mare basalt samples. Magnetic susceptibility and saturation remanence appear mainly controlled by the amount of metallic iron added by the regolith-forming processes and meteoritic contamination, as shown by a positive correlation with Ni and Ir content, a decrease with depth in regolith core profiles, and a decrease with increasing soil size fraction. The three sources of lunar materials provide coherent range of magnetic properties, although the much larger abundance of anorthositic highland samples in the meteorite collection allows one to better describe the properties of this major lunar lithology. The observed range of saturation remanence implies that mare basalts cannot contribute significantly to the patchy lunar crustal magnetizations, which must be attributed to superficial impact processed feldspathic or mafic lithologies.

1. Introduction

Our natural satellite is the only body in the solar system from which samples are available through two completely different processes: sampling through man made spacecrafts, i.e. « returned sample », and natural sampling by impact and transport to the Earth, i.e. meteorites.

The lunar surface has been sampled at 9 sites (Fig. 1), covering a restricted range of latitude (45°) and longitude (85°) in the near-sided and near equatorial part of the Moon (Heiken et al., 1991). The iron-rich lithologies, essentially basalts from the maria, are overrepresented in the returned samples. The main lunar crustal type, the iron-poor feldspathic highland rocks, makes only 2.5% of the sample returned collection in mass (present in Apollo 16 and Luna 20 collection mostly, see Wieczorek et al., 2006). Lunar meteorites, although sampled by impacts in unknown position and depth, present the advantage of potentially providing lithologies not sampled by lunar missions. In particular the high latitudes and far side of the Moon are suspected to show quite different lithologies and lunar meteorites appear to provide a more representative average lunar crustal composition (Korotev et al., 2003; Demidova et al., 2007).

While the samples returned by the Apollo 11 to 17 missions from 1969 to 1972 (380 kg of soils and rocks) and by the Luna 16, 20 and 24 missions from 1970 to 1976 (320 g of soils and minute rock fragments) have been the subject of considerable work in the years following missions (see Ivanov et al., 1980; Fuller and Cisowski, 1987), lunar meteorites have not been subjected to any magnetic study, except the Yamato 791197 (Nagata and Funaki, 1986) and ALHA 81005 (Morris, 1983). Morris (1983) reported only saturation magnetization measurements together with ferromagnetic resonance data. The aim of the present work is thus to present a comprehensive study of lunar meteorites, and compare it to published data on the Apollo and Luna missions. We also provide new data from the Luna 16 and 20 surface soil samples, from the Luna 24 two meters long core, and from a few Apollo rocks.

In the framework of building a database of magnetic properties of meteorites, we have compiled and measured in a large number of meteorite collections the magnetic susceptibility (χ) of more than 5000 samples (Rochette et al., 2003, 2008, 2009). Magnetic susceptibility has the advantage of providing rapid and non-destructive bulk measurements, using portable instruments that can be operated in the repository rooms, without any sample preparation. It allows measuring large and small masses of multiple samples and thus estimating meteorite

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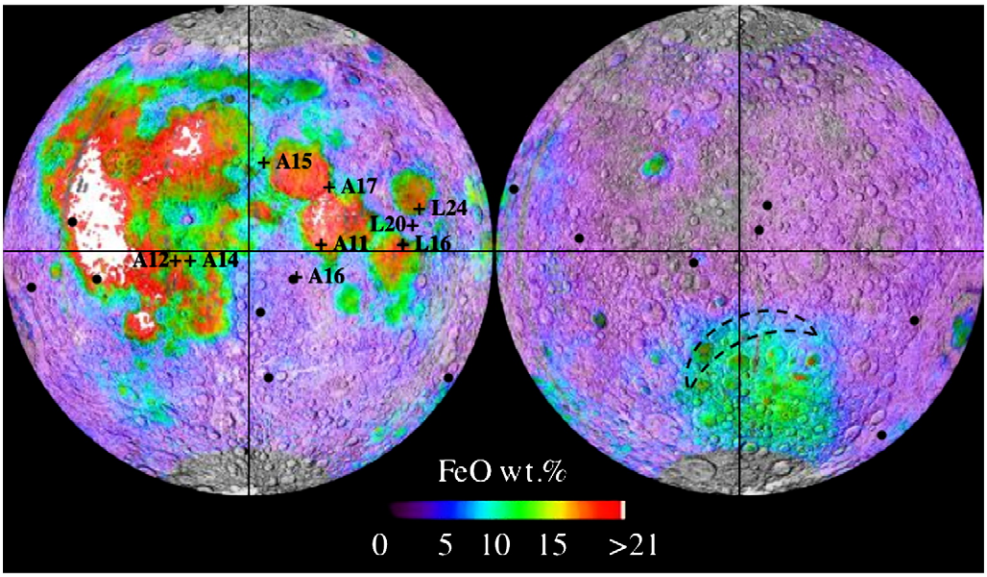

Fig. 1. Map of the lunar surface FeO content after Gillis et al. (2004). Maria appears as red or white. Left is near side and right is far side of the Moon. South Pole-Aitken basin appear as a green disk on the far side. The crosses represent Apollo (A) and Luna (L) landing sites. The dots are the approximate centers of the main magnetized spots (with field >3 nT at 40 km altitude) and the 3 nT contour is schematically shown for the largest anomaly of Aitken basin (simplified from Richmond and Hood, 2008).

heterogeneity at the centimeter to meter scales. Therefore the present work will rely mainly on magnetic susceptibility measurements, and secondarily on saturation remanence measurements (M_{rs}), mostly obtained by compiling literature.

Reviewing such intrinsic magnetic properties for lunar material has various applications: (1) providing clues for meteorite classification (i.e. distinction between lunar meteorites and other achondrites, Rochette et al., 2009), (2) better defining the processes responsible for the presence of metallic iron in lunar materials and discuss e.g. soil maturity (Korotev et al., 1997), and (3) providing a detailed framework for the interpretation of the paleomagnetic signal of lunar rocks and the origin of crustal magnetization (Fuller and Cisowski, 1987). The lunar crustal magnetization, contrary to the Martian case, appears to be limited to a few isolated patches based on magnetic field measurements by Lunar Prospector (Fig. 1 after Richmond and Hood, 2008). According to electron reflectometer data (Mitchell et al., 2008), these patches (of >3 nT at 40 km altitude) correspond to somehow more extended magnetized zone at the surface, with fields than can reach over 100 nT. Clearly most magnetized zones are found in highlands terranes, and their interpretation may not be feasible based on sample returned data only. Understanding how and in what magnetic field these magnetizations were acquired is a major pending question about the lunar interior structure and history, related to the still hypothetic existence of a metallic core and an early dynamo (Fuller, 1998; Wieczorek et al., 2006; Hood and Artemieva, 2008; Lawrence et al., 2008; Garrick-Bethell et al., 2009).

2. Samples, magnetic mineralogy and measurements

Total iron content varies from 2 to >21 wt.% FeO in lunar rocks based on laboratory analyses and spectroscopic mapping by the Clementine mission (Lucey et al., 2000; Gillis et al., 2004; Fig. 1). The low iron content of highland rocks (mostly in the 2–5% FeO range) is unique among other bulk solar system materials that all have FeO content well above 8% (Rochette et al., 2008, 2009), except some aubrites. MnO and Cr_2O_3 contents are on average about 0.1 wt.% in highland rocks and 0.3 wt.% in mare basalts. Most of Fe, Mn and Cr are present in paramagnetic minerals. Other magnetic elements are quite negligible in lunar rocks: Ni and Co contents are generally lower than 150 and 80 ppm in mare lithologies and pristine highland rocks and are up to 500 and 40 ppm in lunar soils and highland breccias. The enhanced Ni concentrations in the highland lithologies are symptomatic of chondritic contamination by accretion at the lunar surface.

The ferromagnetic minerals in lunar materials are essentially metallic iron (Fe^0) eventually associated with schreibersite and cohenite in highland breccias and regolith samples (Misra et al., 1976; Papike et al., 1998), while the other iron bearing minerals are paramagnetic (chromite, ulvospinel, ilmenite, olivine, and pyroxene) or antiferromagnetic (troilite). In mare basalts Fe^0 is mainly a late-stage minor phase and can be a product of igneous crystallization or subsolidus reduction of ulvospinel, ilmenite and fayalite or breakdown of troilite (Hewins and Goldstein, 1974; El Goresy and Ramdohr, 1975). These metal nuggets are poorer in Ni and higher in Co/Ni as compared with metal of meteorite origin. In highland breccias and regolith samples metal particles are commonly present and have mainly meteoritic composition. The average content of the Fe,Ni metal in the lunar highland crust can be estimated to be 0.3 wt.% based on a crustal mean Ni content of 150 ppm, and the assumption that Ni is totally concentrated in the metal inclusions, which contain on average 5 wt.% of Ni (Demidova et al., 2007). In addition there are nanometric metal iron grains occurring on surface of regolith particles. These metal grains result from space weathering (e.g. Pieters et al., 2000). Schreibersite and cohenite are commonly associated to meteoritic contamination, but El Goresy et al. (1971) provide evidence of schreibersite in pristine basalt.

Following procedures of Rochette et al. (2003, 2008), we have measured (usually in the sample repository) the magnetic susceptibility of 4 Apollo rock samples, 88 Luna soil sized fractions and rock fragments and 78 samples from 58 lunar meteorites. For Apollo and Luna samples total mass and median sample mass were 10.3 and 2.8, 14.6 and 0.11 g, respectively. For the meteorites total mass and median mass were 12.5 kg and 3.9 g, respectively. Among these meteorites 27 are from Oman (mostly Dhofar), 19 from Sahara (Anoual, Dar al Gani, NEA and NWA) and 12 from Antarctica. However, several of the Dhofar meteorites are likely paired (i.e. fragments of the same fall) based on close location and similar petrology and we have averaged data to obtain means on 11 unpaired meteorites from Oman. Petrologically unpaired meteorites may actually be from the same fall as lunar meteorites are mainly breccias composed of very distinct lithologies. For Dhofar 302 and the Dhofar 303 serie, we considered them unpaired following Korotev rather that Nazarov et al. (2003), because they are

magnetically quite different. The same applies to Anoual and NWA 773/2727. Data were obtained from the following collections (by order of importance): the Vernadsky institute (Moscow), ANSMET (Houston), various private collections, NHM (Vienna), UPMC (Paris), MNHM (London), Museu Nacional (Rio de Janeiro) and Vatican Observatory.

Depending on location, availability and sample size, we used the KLY2, MFK1, MS2, SM30 or Imvo devices. While the characteristics of the first four instruments are detailed in Rochette et al. (2003, 2008), the Imvo instrument (borrowed from Moscow State University) was used for the first time in the Vernadsky institute (see Rochette et al., 2009). This bridge system allows measuring large samples (up to 500 g) with good sensitivity (10^{-7} SI for 100 cm^3 sample) and precision (1 to 10% depending of the range). All instruments were cross-calibrated using KLY2 as the reference (see Sagnotti et al., 2003). The anisotropy of magnetic susceptibility was measured on Apollo and some meteorite samples using either KLY2 or MFK1 instruments (see Gattacceca et al., 2008, for details on the methodology).

Other rock magnetic parameters were obtained on 8 meteorites and 4 Apollo samples in CEREGE using a cryogenic magnetometer (for saturation remanence acquired in 3 Tesla with a pulse magnetizer) and the Micromag VSM for hysteresis at room temperature.

3. Summary of magnetic properties of Apollo samples

Numerous authors have studied the magnetic properties of Apollo samples (e.g. Nagata et al., 1972; Brecher et al., 1973; Collinson et al., 1973; Wasilewski and Fuller, 1975). Fuller and Cisowski (1987, see also Fuller, 1998) have reviewed the rock magnetic data available on Apollo samples and present in particular a susceptibility (χ) and saturation remanence (M_{rs}) database on 60 samples (20 non brecciated rocks, 26 breccias, 14 soils, from all missions). This database is not representative for highland pristine rocks: it contains one anorthosite, one dunite, no norite, troctolite and KREEP rock samples. We crosschecked this database with original data in Nagata et al. (1972, 1973), and found 3 samples not reported in Fuller and Cisowski (1987). To complement this database, we added the data of Collinson et al. (1973) on one Apollo 16 anorthosite and six Apollo 15 samples (3 basalts, 2 regolith breccias, one soil). On one basalt sample also reported in Fuller and Cisowski (1987) the data from the two studies is nearly identical. We have computed $\log\chi$ (in 10^{-9} m^3/kg) based on their susceptibility data (called X below), listed in 10^{-3} G/Oe/g. Assuming proper cross calibration and cgs units interpretation, this leads to $\log\chi = \log X + 4.1$ (see Table A in the Appendix). Among our new Apollo mare basalt samples, measured with the MFK-1 bridge in CEREGE, 3 were reported in Fuller and Cisowski (1987) and one in Collinson et al. (1973). The average difference in $\log\chi$ for the two datasets is -0.01 ± 0.10. We have also reviewed the data of Brecher et al. (1973, 1974) on Apollo 16 (2 breccias) and 17 (3 basalt, 4 breccias and 2 soil samples). Their susceptibility data is likely poorly constrained as it was obtained from the slope of hysteresis loop at zero field on small chips (typically 20 mg). We also use the above-mentioned references to obtain $\log M_{rs}$ values (in 10^{-3} Am^2/kg) on the same samples (with larger masses in the case of Brecher et al., 1973, 1974). Finally, we also added data from Pearce et al. (1973, 1974) on Apollo 15, 16 and 17, with 2 basalts, 11 breccias and 4 soil samples. We note that Fuller and Cisowski (1987) report apparently erroneous (by a factor ten: printing error?) M_{rs} data in 3 cases: (1) for basalt sample with anomalously high M_{rs} (but low $\log\chi$) 10024 reported M_{rs} is 15 instead of 1.5 10^{-2} emu/g in Nagata et al. (1972); once corrected the M_{rs}/M_s ratio is normal for a mare basalt (0.01); (2) for basalt 74275 the anomalously low M_{rs} of 0.01 10^{-2} emu/g implies an unrealistic M_{rs}/M_s ratio (0.0002) while Brecher et al. (1974) report a M_{rs} of 0.13 10^{-2} emu/g (and consistent susceptibility); and (3) for breccia 67455 listed M_{rs} of 1 10^{-2} emu/g translates into an anomalous M_{rs}/M_s of 0.2, while it is reported to be 0.02 in Fig. 2. We present here the corrected $\log M_{rs}$ values for these three samples (see Table A in the Appendix). Nagata and Funaki (1986) report a much lower $\log M_{rs}$ than Fuller and Cisowski (1987) for 68815 (0.48 instead of 1.76). We used the former value as it is much more in agreement with average value for non-regolithic breccia. Two breccia samples (72275 and 77135) measured both by Pearce et al. (1974) and Brecher et al. (1974) reveal similar $\log M_{rs}$ but an order of magnitude larger $\log\chi$ in Brecher et al. (1974). We suspect a transcription error again and did not use the later data in the analysis. For our new mare basalt sample the average difference with the published $\log M_{rs}$ data is 0.28 ± 0.19. This rather large difference is partly due to the heterogeneity of 14053 (see below). Without this sample the average difference decreases to 0.19 ± 0.08. The lithological classification for each sample has been checked using the Lunar Sample Compendium or detailed sample catalogs (www.curator.jsc.nasa.gov/lunar/compendium.cfm) which in a few case give a class different from the original publication.

Fig. 2 shows a general linear correlation between the two magnetic parameters. Soils and regolith breccias (mean $\log\chi$ of 4.39 ± 0.2 and 4.25 ± 0.33, respectively) are equally strongly magnetic. Apollo 17 yields two samples of a magnetically anomalous soil type, called orange soil (74220), which were excluded from the mean. On the other hand, mare basalts (excluding 14053) and non-regolithic breccias (at 3.01 ± 0.25 and 3.48 ± 0.44, respectively) are about ten times less magnetic. The lowest Apollo values (≤ 2.6) are encountered in an anorthosite (1.4), a mare basalt (2.6), and two breccias (2.4 and 2.6). High saturation remanence ($\log M_{rs} > 1$) characterizes soils and regolith breccias, the weakest remanence being found in mare basalts and an anorthosite, while other breccias are intermediate.

High field susceptibility measurements, essentially corresponding to paramagnetic contributions χ_p, have been reviewed by Wasilewski and Fuller (1975). The ranges of $\log\chi_p$ for mare basalts, KREEP basalts plus norites and anorthosites were 2.58–2.74, 2.21–2.4 and 1.8–2.14, respectively.

Hysteresis parameters and other magnetic investigations show that multidomain or superparamagnetic metal grains dominate: M_{rs}/M_s is less than 0.1 in all samples, and often below 0.01 for rocks. Remanent coercive field B_{cr} varies from 8 to 80 mT (with on average higher values in soils and regolith breccias) and B_{cr}/B_c is usually >10 (Fuller and Cisowski, 1987; Table 2). Our measured high field susceptibilities are consistent with Wasilewski and Fuller (1975). Normalized hysteresis loops are shown in Fig. A in the Appendix; the multidomain metal signature is visible by the curvature up to 0.8 T (due to the high demagnetizing field) and coincidence between the ascending and descending curves. Hardly significant superparamagnetic contribution is indicated by the weak frequency dependence (1 to 3%) of low field susceptibility measured on the MFK1 (between 976 Hz and 15,616 Hz).

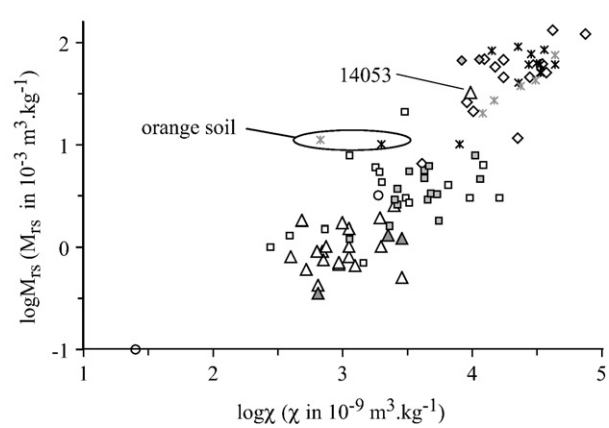

Fig. 2. Saturation remanence ($\log M_{rs}$ with M_{rs} in 10^{-3} Am^2/kg^{-1}) versus magnetic susceptibility ($\log\chi$ with χ in 10^{-9} m^3 kg^{-1}) for Apollo samples after Fuller and Cisowski (1987) for various lithologies (data in Table A in the Appendix): soils (crosses), regolith breccias (diamonds), other breccias (squares), basalt (triangles) and anorthosite (circles). Data of Brecher et al. (1973, 1974) and Pearce et al. (1973 and 1974) appear in gray.

Sample 14053 is distinct from the other three mare basalts by having a steeper initial slope indicative of lower demagnetizing field. This may indicate either elongated metal grains or the presence of another phase with lower spontaneous magnetization. Curie temperatures or maximum unblocking temperature are mostly in the 750–780 °C range, typical of pure or nearly pure metallic Fe (Fuller and Cisowski, 1987). The only mare basalt with strong saturation remanence and susceptibility, 14053, is among the few measured lunar sample with low unblocking temperature: NRM is lost mostly below 300 °C (see Fuller and Cisowski, 1987); 10017 also show such a low unblocking temperature (Hoffmann et al., 1979). This suggests that another mineral than metal, with low Curie temperature like cohenite or schreibersite, may contribute to remanence. This could be consistent with the lower demagnetizing field observed on the hysteresis loop. 14053 is a typical example for metal formed by oxides and olivine subsolidus reduction (El Goresy and Ramdohr, 1975). El Goresy et al. (1971) report the presence of schreibersite in 14310, which has a very similar lithology to 14053 (studied in the same reference).

We have also measured the anisotropy of magnetic susceptibility of our four mare basalt samples (Table 3). The ferromagnetic anisotropy degree P_f is computed from the measured anisotropy degree P using measured high field magnetic susceptibility and assuming an isotropic paramagnetic contribution (Gattacceca et al., 2008). The three "standard" samples (with $\log\chi$ in the range 2.92–3.06) show low anisotropy degree (P_f around 1.02) and prolate to neutral fabric while the anomalously strongly magnetic sample 14053 have $P_f = 1.08$ and oblate fabric, consistent with its regolithic impact processing.

4. Review and new data from Luna samples

4.1. New magnetic susceptibility data

We will present here the newly performed measurements of the samples studied by Ivanov et al. (1980, see also Ivanov and Gorshkov, 1979) and compared it to published data by Pillinger et al. (1978) (Tables A and B in the Appendix). Barsukov (1977) presented the general characteristics of the Luna 24 core that provided continuous sampling from 73 to 225 cm nominal depth, the drilling tube being inclined at 30° from the vertical. Above 73 cm (unit 1) have been recovered only a few fragments >1 mm, the finer fraction being lost during drilling process. Below the material consists in three main types: rock fragments or mineral grains (either naturally present in the soil or fragmented by the drill bit from larger rocks), breccias or melted material resulting from impact reworking of previous materials, and agglutinates. Agglutinates are clods of very fine material (mostly <1 μm) rich in glass and metal nanoparticles. This material is produced near the lunar surface by combination of space weathering and impacts. From 73 to 225 cm, three units have been distinguished (Fig. 3). Unit 2, down to 133 cm, is a homogeneous layer likely corresponding to a single ejecta blanket from the nearby (18 km) crater Farenheit (of 6.5 km diameter). A typical in-situ profile of space weathering is observed, with the exponential decay of agglutinate content. Below unit 3 (133–165 cm) is a breccia rich layer, pre-exposed to space weathering as shown by the increased agglutinate content at its top. Finally, unit 4 is composed of multiple layers of more gabbro-rich material with minor agglutinate content.

For our own susceptibility measurements, performed with a KLY2 bridge, precision on raw data is always better than 1%. We subtracted the diamagnetic signal of the sample container plus holder (about −200 digits in the highest sensitivity range). It was at most equal in absolute value to sample signal. Precision on χ depends on precision on the sample mass, which ranges from 20 to 1000 mg, with an uncertainty better than 1 mg.

On Luna 24 the higher resolution sampling is available for the <200 μ fraction: 25 samples on 5–10 cm interval. Susceptibility for this fraction shows a nearly regular decrease of $\log\chi$ versus depth, in close match

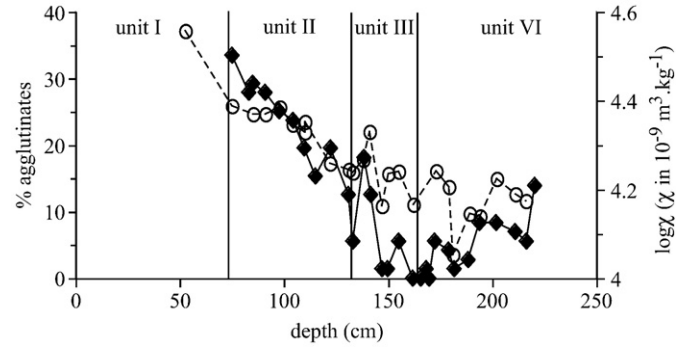

Fig. 3. Percentage of agglutinate (full diamonds) versus depth in Luna 24 drill core, after Barsukov (1977), and magnetic susceptibility ($\log\chi$ with χ in $10^{-9}\,m^3\,kg^{-1}$; open circles) versus depth for the <200 μm fraction (this study). Limits of lithological units are indicated by vertical lines. Data are available in Table B in the Appendix.

with decreasing amount of agglutinate (Fig. 3). Such decrease of metal amount versus depth has also been observed in the Apollo 15 and 16 cores, but not in Apollo 17 (Korotev et al., 1997; Papike et al., 1998). Discontinuities in the $\log\chi$ trend (in particular at 133 and 165 cm) correspond to lithological changes through the core.

We obtained data on 12 levels separated in 4 size fractions in the Luna 24 core as well as on the surface samples of Luna 16 and 20. Fig. 4 (and Fig. B in the Appendix) shows that susceptibility systematically decreases for increasing grain size. When compared to the upper level of Luna 24 (at 72 cm; see Fig. 4) the Luna 16 soil appears much more mature (i.e. metal rich), although it is poorer in total FeO (16.8 versus 19.5 wt.% in Heiken et al., 1991). Luna 20 may seem less mature but it may be related to lower total FeO: 7.5 wt.%.

Fig. 5 shows that the various size fractions show parallel trends versus depth. Bulk samples have susceptibility just lower than the <200 μm (except in one case) and much higher than the 200–370 μm fraction, where rock fragments dominate. We did not measure the whole >1 mm fraction, but several individual or pooled fragments >1 mm. For near-surface samples (Fig. 5) the fragments (from 60 and 67 cm) are more magnetic than the 200–370 μm fraction (from 72 cm). However, the two fragments from 143 cm are much less magnetic than the 200–370 μm fraction from the same depth.

Morris (1978) presented estimates of metal amount based on ferromagnetic resonance and saturation magnetization measurements

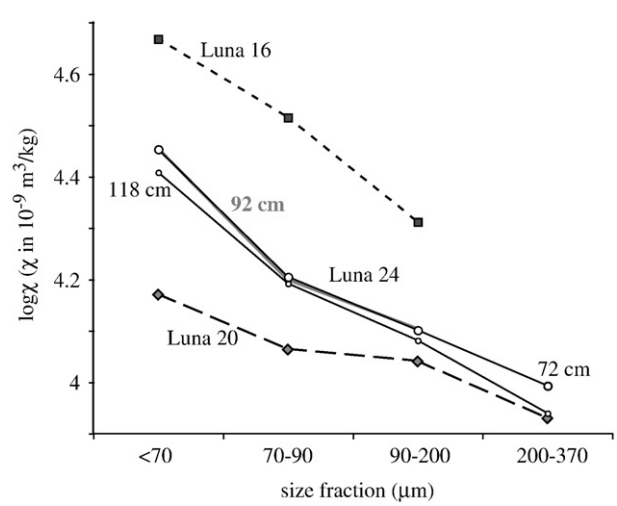

Fig. 4. Grain size dependence of magnetic susceptibility ($\log\chi$ with χ in $10^{-9}\,m^3\,kg^{-1}$) for near-surface samples of Luna 16, 20 and 24 measured in this study; fractions for Luna 16–20 are different from the ones indicated (for Luna 24): <80, 80–130, 130–200, and 200–450 μm. Note that data for 72 and 92 cm are superposed.

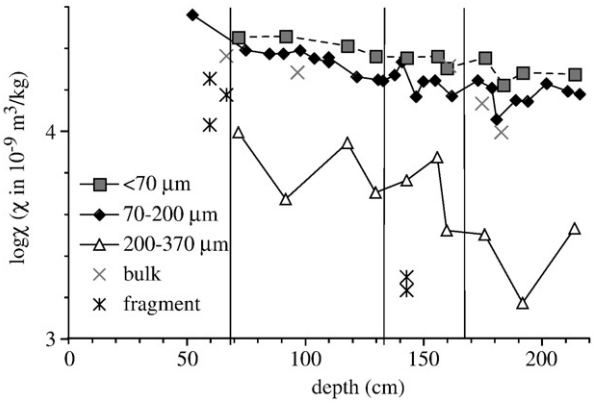

Fig. 5. Magnetic susceptibility (logχ with χ in 10^{-9} m^{3}kg^{-1}) versus depth for various size fractions of Luna 24 core. Limits of lithologic units are indicated by vertical lines.

on six levels, separated in five fractions <250 µm. His data show qualitatively the same decreasing trend with increasing grain size and depth. Pillinger et al. (1978) provided magnetic susceptibility measurements on sieved fractions (10) from three levels of the Luna 24 core, at 90, 125 and 196 cm depth (Fig. B in the Appendix). Although they do not correspond to the same depth and size fractions as our measurements, the general agreement in logχ values (except for the >1 mm fraction) confirms that the Pillinger et al. (1978) measurements are reasonably well cross-calibrated with our measurements. Surprisingly, the >1 mm fraction is reported to be much more magnetic than the 0.5–1 mm fraction (2.4 to 4.5 times). This anomalously high logχ for the >1 mm fraction of Pillinger et al. (1978) does not fit with the spread of individual >1 mm fragments data in Stephenson et al. (1978), although they should, when pooled, correspond to the same sample analyzed by Pillinger et al. (1978). We suspect a measurement error or bias to explain this discrepancy.

4.2. Saturation remanence

Literature data provide little if any information on the instruments used for the measurements and uncertainty on the tabulated susceptibility and remanence values. Some data (five for susceptibility and one for remanence) from Stephenson et al. (1978) were too close to noise level of the used instruments to be reliable. In their study IRM was acquired in a 0.26 T field.

Fig. 6a shows a close linear correlation between saturation remanence and susceptibility of the sized fractions of Luna 24 (Pillinger et al., 1978), showing that both parameters are mostly related to the amount of fine-grained metal enriched fraction.

The individual grains >1 mm studied by Stephenson et al. (1978) in the same three levels than the Pillinger et al. (1978) study can be separated in two categories: the agglutinate clods and sintered fine materials that are likely to show similar properties with the fine fractions, and rock fragments (basalts, norite, anorthosite and impact melt). Note that most rock samples from 90 cm depth were not measurable. Fig. 6b shows for these agglutinates and sintered fine materials the same trend as found in the soil fractions, with much smaller values for the rocks fragments. Rocks fragments show the same mean values than exhibited in the Apollo non regolithic samples (Table 1). Luna agglutinate fragments and soil fractions match Apollo soils and regolith breccias for the remanence, but their average susceptibility is lower in accordance with the lower FeO content in Luna 20 and 24 sites. On the other hand the Luna 16 mare basalt site show the same range of logχ as Apollo soils. The fractions >1 mm of Pillinger et al. (1978) appear to give the same logχ values as the agglutinate grains from Stephenson et al. (1978).

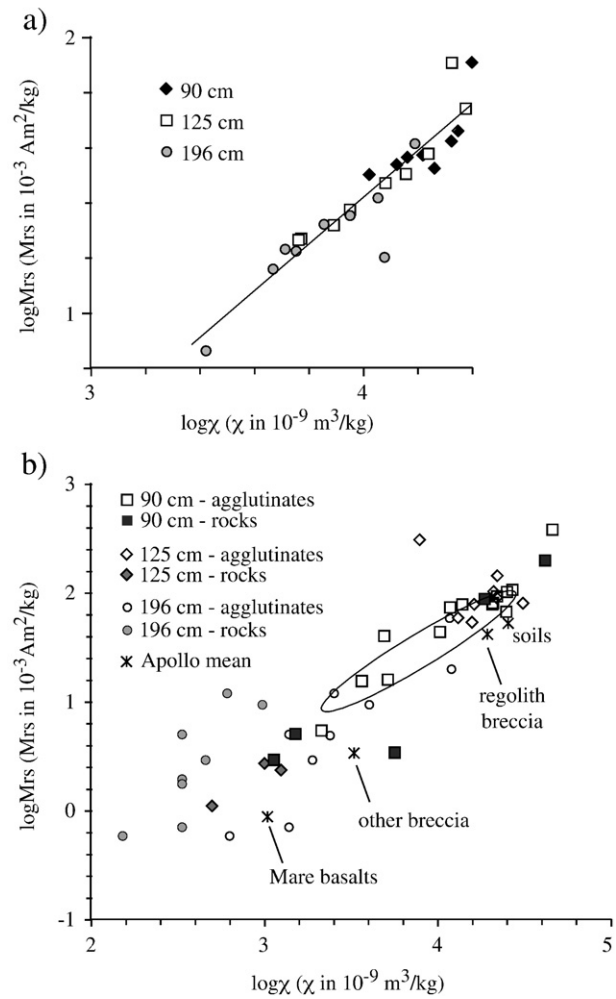

Fig. 6. Saturation remanence (logM_{rs} with M_{rs} in 10^{-3} Am^2/kg^{-1}) versus magnetic susceptibility (logχ with χ in 10^{-9} m^{3}kg^{-1}) for the Luna 24 samples (data in Table A in the Appendix): (a) sized fractions of Pillinger et al. (1978); and (b) single grains >1 mm studied by Stephenson et al. (1978) on rocks (closed symbols) and agglutinates (open symbols) separating the different levels. The trend of (a) is reported, together with mean values for the different Apollo lithologies (see Table 1).

Table 1
Mean logχ and logM_{rs} values of various lunar materials (after Tables 2 and 3 and Table A in the Appendix) with standard deviation and sample number. For the Luna 24 rock fragments two highly magnetic samples from 90 cm depth have been excluded from the mean.

	logχ	s.d.	*N*	logM_{rs}	s.d.	*N*
Apollo (after Fuller and Cisowski, 1987)						
Soils (excl. orange)	4.39	0.20	18	1.69	0.24	18
Regolith breccia	4.25	0.33	15	1.58	0.43	16
Other breccia	3.48	0.44	31	0.55	0.38	31
Mare basalts (excl. 14053)	3.01	0.25	23	−0.08	0.30	24
Luna 24 (after Pillinger et al. and Stephenson et al., 1978)						
Soils fractions	4.06	0.26	27	1.56	0.24	27
Rock fragments	3.19	0.27	15	0.41	0.37	19
Agglutinate	4.11	0.35	25	1.76	0.45	25
Meteorites						
All	3.07	0.59	37	0.37	0.60	9
Highland high	3.65	0.22	9	1.20	0.44	2
Highland low	2.41	0.26	11	0.06	0.43	4
Mare basalts	2.88	0.10	5	0.50	0.50	2
Mafic breccia	3.33	0.46	12	0.30		1

5. Meteorites magnetic properties

5.1. Magnetic susceptibility

After tentative pairing following Korotev (http://meteorites.wustl.edu/), Nazarov et al. (2003) and Demidova et al. (2007) we obtained average data from 37 out of the 66 unpaired declared lunar meteorites (Table C in the Appendix), plus the ungrouped GRA 06128 meteorite, petrographically similar to some lunar materials although oxygen isotopic data point toward affinities with brachinites (Zeigler et al., 2008; Day et al., 2009). We separated (simplifying Korotev's scheme) lunar meteorites into 3 groups: mare basalts, highland feldspathic breccias (FeO<8%) and mafic or mixed breccias (FeO>8%). This last group may not necessarily contain a mare basalt component.

There is a very large spread in logχ values of lunar highland meteorites, from 1.9 (Dho 733) to 4.33 (NWA 3136), with a mean of 3.07 ± 0.59. The s.d. is particularly large compared to other weakly magnetic achondrite groups (Rochette et al., 2009). No highland sample yielded logχ values in between 2.73 and 3.39. Therefore we separate among highland samples a "low magnetic" group (2.41 ± 0.26) and a "high magnetic" group (3.65 ± 0.22; see Table 1). The low lunar highland group appears to be the least magnetic meteorite group (Rochette et al., 2009). A single aubrite (LAP 03719) has such a very low logχ (1.96), still higher than the least magnetic lunar meteorite. In the low magnetic susceptibility group paramagnetic minerals contributes significantly (14 to 74%) to total susceptibility, as found by comparison with the paramagnetic susceptibility χ_p derived from total iron amount (after Rochette et al., 2009; Table C in the Appendix). An estimate of metal amount can be derived from ferromagnetic susceptibility $\chi_f = \chi - \chi_p$ and the specific susceptibility of dispersed metal (Rochette et al., 2009). The metal amount estimate is from 40 to 800 ppm in the low group, and from 0.4 to 1.8% in the high group. Fig. 7a and b shows that metal amount in highland rocks is reasonably well correlated with the trace elements signing the contamination by meteoritic input, Ni and Ir. Linear correlation coefficient R^2 are respectively 0.78 and 0.66. The petrographic identification of a regolithic component (according to Korotev classification) usually but not systematically corresponds to high metal content: 5 over 8 meteorites in the high group have a regolithic component, against only 4 over 11 in the low group. However, we note that this petrographic identification of a regolithic component is quite difficult and controversial.

Mare basalts have a consistent logχ value, 2.88 ± 0.10, signing a strong paramagnetic contribution (38 to 75%) and low metal content (from 300 to 1100 ppm).

Impact-reworked dominantly mafic meteorites have more variable and stronger logχ mean at 3.33 ± 0.46), with paramagnetic contribution varying from 1 to 41% and estimated metal amount from 800 ppm to 3.8%. The more metal rich ones show a correlation with Ni and Ir similar to highland rocks (Fig. 7a and b).

Interestingly, there is not any correlation between logχ values and Ba content (Fig. C in the Appendix) of highland meteorites from hot deserts. Ba content indicates weathering grade of hot desert meteorite stones (Nazarov et al., 2003; Al-Kathiri et al., 2005) and therefore weathering processes does not appear to change significantly metal amount, in contradiction with observations in chondrites (Rochette et al., 2003, 2008). This may be due to the small grain size and low content of metal and low porosity of lunar meteorites (Macke et al., 2010). The effect of weathering much likely exists but appears as second order with respect to primary sources of metal content variation.

The GRA 06128 ungrouped meteorite has a logχ in the low magnetic group (2.47) in agreement with its feldspathic lithology. Therefore its magnetic susceptibility is compatible with a lunar origin. The only other match is with the least magnetic eucrite Talampaya (Rochette et al., 2009). GRA 06128 is much less magnetic than brachinites, to which it has been related based on oxygen isotopes (Zeigler et al., 2008).

We were not able to reproduce the logχ versus Ni or Ir content correlation in Apollo samples (Ni data available for 20 samples with magnetic measurements). This is likely due to the fact that most data (11) correspond to mare basalts, with no data from regolith breccias.

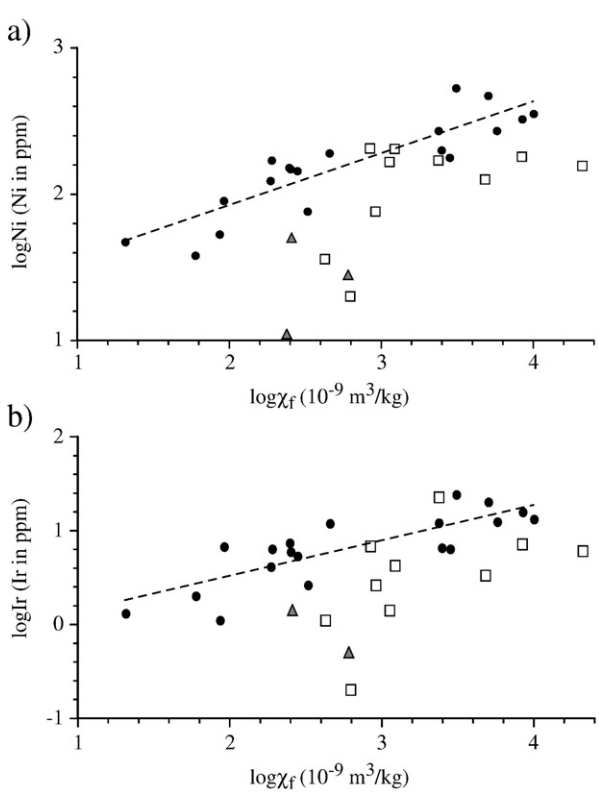

Fig. 7. Correlation between ferromagnetic susceptibility (χ_f) and Ni (a) or Ir (b) content of lunar meteorites, for highland rocks (circles), mare basalt (triangles) and mafic breccias (squares). The linear correlation indicated for a and b is valid for highland rocks only.

5.2. Other magnetic properties

From the present study and Nagata and Funaki (1986) we have obtained saturation remanence and hysteresis data on 9 meteorites (Table 2). Our data is usually obtained on very small fragments (down

Table 2
Saturation remanence M_{rs} (measured on the cryogenic magnetometer) and hysteresis parameters (measured on VSM) for Apollo samples and lunar meteorites (with mare basalts first), plus the unique meteorite GRA 06128: M_{rs}/M_s , B_c , B_{cr} and high field susceptibility χ_{hf}. Maximum field used for M_{rs} and hysteresis are 3 and 1 T, respectively. Some parameters were not measurable (nm) due to strong paramagnetic signal and low mass.

	logM_{rs}	M_{rs}/M_s	B_c (mT)	B_{cr} (mT)	logχ_{hf}	logχ
Apollo 14053	0.96	0.008	1.5	10	2.72	3.80
Apollo 15555	−0.31	0.004	1.5	31	2.69	2.93
Apollo 15556	−0.28	0.005	1.5	37	2.69	2.91
Apollo 70215	0.10	0.006	2	48	2.63	3.04
Anoual	0.30	0.18	17	63	2.60	2.71
DaG 400	0.21	0.03	nm	nm	1.77	2.47
Dho 81	−0.20	nm	nm	nm	1.69	2.18
NEA 001	0.60	0.04	13	80	1.98	2.64
NWA 032	0.15	nm	nm	nm	2.55	2.98
NWA 3163	−0.36	0.04	7	74	1.92	2.10
NWA 4734	0.85	0.16	27	60	2.63	2.83
NWA 5406	0.89	0.009	3	44	2.24	3.64
Y 791197	1.51	0.07	5	56	2.11	3.47
GRA 06128	1.13	0.26	63	130	2.10	2.49

to 4 mg), but they yield logχ very consistent with the larger samples values. Due to the very low ferromagnetic signal with respect to the paramagnetic signal (Fig. A in the Appendix) it was in some samples impossible to define accurately the hysteresis parameters. Saturation remanence (M_{rs} in 10^{-3} Am^2/kg) will be expressed in log units. Log M_{rs} data will be further analyzed in the discussion.

Hysteresis parameters (M_{rs}, saturation magnetization M_s, induced and remanent coercive fields B_c and B_{cr}) show low M_{rs}/M_s ratio, and B_{cr} in the range 50–80mT, like Apollo materials and typical for multidomain or superparamagnetic metal in kamacite–taenite bearing meteorites. The mare basalt sample Anoual and NWA 4734 have somehow high M_{rs}/M_s and B_c with respect to Apollo basalts. This may be due to some metal weathering (increasing remanence and coercivity) and uncertainties in subtracting a strong paramagnetic signal.

The ungrouped meteorite GRA 06128, show much higher coercivity than lunar materials: $M_{rs}/M_s = 0.26$, $B_{cr}/B_c = 2$ and $B_{cr} = 130$ mT (Fig. A in the Appendix). Such values are typical of tetrataenite, like in LL chondrites (Gattacceca et al., 2003). Metal in this meteorite is described as tiny Ni rich inclusions in olivine. Composition is near $FeNi_3$, pointing towards the ordered phase awaruite, likely of as high coercivity as the one of tetrataenite (Wasilewski, 1988). This odd magnetic mineralogy is not supportive of a lunar origin of this meteorite.

Anisotropy of magnetic susceptibility has been measured on four samples (mass in the 1.3 to 21 g range; Table 3). We comment here on the T parameter defining the shape of the ellipsoid, varying from -1 (prolate) to $+1$ (oblate), and the ratio P_f of maximum to minimum susceptibility, corrected from paramagnetic contribution. All measured samples show strongly oblate shaped ellipsoid, with $T > 0.76$, that could result from impact compaction for the anorthositic breccias, and eventually from magmatic deposition fabric in the brecciated mare basalt sample with regolithic component (Dho 287). This sample shows accordingly a low anisotropy degree P_f (1.08), like the Apollo impact-processes mare basalt 14053. Three anorthositic breccias (Dho 730, Dho 960, MAC 88105) have higher P_f values: from 1.11 to 1.39. Such values are similar to those observed in HED meteorites (see Gattacceca et al., 2008).

6. Discussion

Overall lunar meteorites share the same range of magnetic properties as rock samples from Apollo and Luna missions (see Table 1), although lower magnetic susceptibilities are more frequent in the meteorites, in agreement with the much larger abundance of anorthositic samples. On the other hand anorthositic samples with meteoritic contamination are among the most magnetic lunar rocks.

When compared to other metal bearing evolved achondrites (the howardites–eucrites–diogenites clan i.e. HED, and aubrites after Rochette et al., 2009), it appears that lunar materials may show higher magnetization, as expected according to the regolithic origin of metal enrichment and larger imprint of regolithic processes in lunar materials (Fig. 8). One can also see a higher M_{rs}/χ ratio for lunar material with respect to HED. This corresponds to a higher content in fine-grained (near 20 nm) single domain metal grains, characteristic of the space weathering process. However, we are faced with the contradiction that howardites are considered as the regolith of the HED parent body (likely Vesta), in agreement with their enrichment in metal with respect to eucrites and diogenites. To account for the lower M_{rs}/χ ratio and lower logχ in howardites compared to regolithic lunar material, we propose that howardite lacks the fine-grained metal typical of space weathering and are enriched in metal (and eventually magnetite) only due to the accretion of chondritic material. This interpretation is in agreement with the observation of Vernazza et al. (2006) that Vesta must be magnetically protected from the solar wind to account for the lack of space weathering signature in its IR spectra. Moreover, the excess Ne content in the Kapoeta howardite, once taken as a proof of solar wind exposure of Vesta regolith, has been reinterpreted as due to galactic cosmic rays (GCRs) exposure (Wieler et al., 2000). GCRs are too energetic to be screened by a magnetosphere but do not produce space weathering.

Identifying the lithologies and formations able to carry the observed patchy natural remanent magnetization (NRM) at the Moon surface can be addressed with the present data. The largest magnetic anomalies measured by orbiters are of the order of 10 to 30 nT at 50 km altitude (Hood et al., 2001; Richmond and Hood, 2008). There has been a consensus on the fact that all large anomalies are located on formation of Imbrian age (about 3.8 Ga) or older formation reworked at that period. Magnetization of the rocks responsible for these anomalies would thus be of Imbrian age, in agreement with the period of strong lunar magnetic field suggested by paleomagnetism (Fuller and Cisowski, 1987). This consensus has been challenged recently (Lawrence et al., 2008; Garrick-Bethell et al., 2009) and earlier magnetization ages invoked. Interestingly large anomalies are found in both iron-rich and poor areas (Fig. 1) and have been related to impact ejecta formation or antipodal impact reworked material rather than mare basalts (Strangway et al., 1973; Hood and Huang, 1991; Hood et al., 2001; Richmond et al., 2005). Maximum magnetic field measured at the lunar surface (Apollo 16 site) is about 300 nT (Fuller and Cisowski, 1987), in agreement with electron reflectometry data (Mitchell et al., 2008). This translates into a minimum magnetization of 0.24 A/m for an infinite vertically magnetized plate (NRM $= B/\mu_0$). Using a specific gravity of 2.6 and a NRM/M_{rs} ratio of at most 2.5% (the maximum ratio measured in lunar rocks by Fuller, 1998) translates into a minimum M_{rs} of 4 10^{-3} Am^2/kg. Note that

Table 3
Anisotropy of magnetic susceptibility data; the anisotropy degree ($P = K_{max}/K_{min}$) is provided as measured and after correction from isotropic paramagnetic susceptibility.

Sample	Mass (g)	P	P_f	T
Apollo 14053	1.39	1.076	1.080	0.339
Apollo 15555	3.24	1.014	1.033	−0.002
Apollo 15556	2.49	1.008	1.020	−0.351
Apollo 70215	3.23	1.016	1.025	−0.299
Dhofar 287	12.27	1.054	1.099	0.763
Dhofar 730	21.31	1.140	1.233	0.765
Dhofar 960	4.43	1.353	1.391	0.835
MAC 88105	1.36	1.083	1.113	0.936

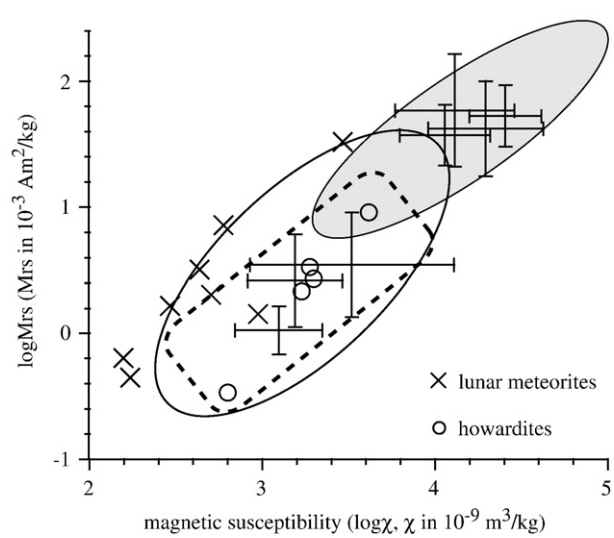

Fig. 8. Saturation remanence (logM_{rs} with M_{rs} in 10^{-3} Am^2/kg^{-1}) versus magnetic susceptibility (logχ with χ in 10^{-9} m^{3}kg^{-1}) of lunar meteorites (crosses), compared to the range of Apollo and Luna data (means with s.d. according to Table 1, as well as ellipses of dispersion for soils + regolith breccias in gray and other rocks in white), the field for HED and aubrites (dashed rectangle) and individual data for howardites (circles).

maximum NRM/M_{rs} measured in lunar rocks was 2.5% (Fuller, 1998). However, the conditions taken (NRM = B/μ_0, NRM/M_{rs} = 2.5%) are optimistic and it is more realistic to use a $M_{rs} = 10^{-2}$ Am^2/kg threshold, i.e. 2.5 times higher. For Rainer Gamma satellite anomaly (50 nT at 18 km), Nicholas et al. (2007; see also Hood, 1980) modeling indicates a rather thin surface layer of minimum NRM = 1 A/m (for a 1 km thick layer) which again translates into a minimum M_{rs} of the order 10^{-2} Am^2/kg. This translates into a minimum logM_{rs} of the order of 1 (using M_{rs} in 10^{-3} Am^2/kg) .

Apart from soils, such logM_{rs} values have been found in the Yamato 791197 meteorite (a feldspathic regolith breccia), in a few Luna gabbro and melt rock fragments and in most Apollo regolithic breccias (Figs. 2 and 8). Only one other breccia, 14303, and one Apollo mare basalt sample, 14053, exhibit logM_{rs}>1, most basalts being near 0 value. Taylor et al. (2004) propose that the late-stage reduction of 14053 basalt block occurred in the regolith during its incorporation in an impact breccia. This strongly suggests that mare basalts at depth are unable to carry significant magnetization in agreement with the rarity of measurable magnetic anomalies at satellite altitude (Fig. 1) in lunar maria. The lithologies more likely to generate the observed anomalies are impact related materials in agreement with the thin sheet model of Nicholas et al. (2007). Accordingly, the strongest and densest magnetic anomaly group is located at the edge of the South Pole-Aitken basin, the largest one on the Moon (Fig. 1; Richmond and Hood, 2008).

Thanks to the correlation between magnetic susceptibility and saturation remanence (Figs. 2, 6 and 8), magnetic susceptibility can be used as a proxy for the potential for remanent magnetization of a lunar sample. The condition logM_{rs}>1 translates into logχ>3.5, and is fulfilled among the meteorites in the "highland high" group and some mafic breccias. As this measurement is not destructive and easy to perform in sample repository and on large samples, we foresee that the measurement of the whole Apollo collection (which has been only very partially investigated magnetically until now) could bring a much more reliable estimate of the remanence range. In particular, measuring large samples rather than the usual small chips (tens of mg) for paleomagnetic study will provide a much more representative database. The same is true for the still unstudied lunar meteorites.

7. Conclusions

Lunar materials, both meteorites and returned samples, are rare materials that as far as possible require non-destructive methods for their systematic study. Magnetic properties provide such a non-destructive method, essentially probing the amount and nature of metallic iron particles, ubiquitous in lunar materials although in small amount ($\ll$5 wt.%). The magnetic method allows to measure such amount with high sensitivity (down to the order of 10 ppm depending on mass and measurement method) and representativity due to the large volume measured. The first comprehensive magnetic study of lunar meteorites show that they share similar range of magnetic properties with Apollo and Luna samples, although the abundance of highland rocks provides new information on this lithology that forms the major part of the lunar crust. The highland rocks show two groups with low and high magnetic susceptibility. The low group yields the lowest magnetic susceptibility of all extraterrestrial macroscopic materials. We have demonstrated that in highland rocks metal amount is correlated to the meteoritic contamination (measured by Ni and Ir content), which increases with regolith and impact processing. This contamination effect is also clearly evidenced on the Luna 24 regolith core that shows decreasing metal amount with depth for a given size fraction, and decreasing metal amount with increasing grain size. Larger magnetization can be found in highland rocks and mixed breccias compared to mare basalts. We have shown that saturation remanence is reasonably correlated with magnetic susceptibility that can be used as a proxy to estimate the potential natural remanence. The sources of significant lunar crustal remanent magnetizations is thus to be found in near-surface impact processed materials (both from anorthositic highlands and mafic zones). Based on their saturation remanence, the more strongly magnetic lunar rocks have the potential to quantitatively account for the observed crustal magnetization, even if such magnetized layers are restricted to the first km from the surface, as expected for ejecta blanket and impact processed layers.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.02.007.

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