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Changes in mean magnetic susceptibility and its anisotropy of rock samples as a result of alternating field demagnetization

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Abstract

Measurements of low-field magnetic susceptibility (K) and its anisotropy (AMS) on different rock types during stepwise alternating field (AF) demagnetization in increasing fields revealed not only significant changes of the AMS principal susceptibilities, but also an increase of the mean magnetic susceptibility (K_m). Studied collections of loess/paleosol samples from different sections in Belgium, Bulgaria, China, Siberia and Tadjikistan and diorites, granites and gneisses from Antarctica show systematic K_m-increase, between 2 and 27% as compared to the initial values, after AF-demagnetization up to 100 or 200 mT maximum amplitude. The relationships between magnetic susceptibility increase and magnetic hysteresis parameters and their ratios, indicate that the K_m-increase is due to changes in magnetic domain configuration of the initial natural remanent magnetization (NRM) state of the remanence carriers during AF-treatment. The obtained linear relationship between K-increase and the degree of anisotropy P' for strongly anisotropic gneiss samples suggests that magnetostatic interactions also play a role in the observed AF-effect on K_m.

Keywords: magnetic susceptibility; AF-demagnetization; multidomain grains; loess; intrusive rocks; gneiss

1. Introduction

Room-temperature low-field magnetic susceptibility is one of the basic parameters used for the magnetic characterization of rocks and environmental materials. Generally it gives an estimate of the ability of the material to react to an external weak magnetic field (e.g. [1]). The absolute values of magnetic susceptibility depend on various factors: the chemical composition of the magnetic minerals in the material, their concentration, grain sizes, as well as their structural characteristics like internal stress and lattice imperfections (dislocations, voids, inclusions, etc.) [2]. Some particular cases of pressure-dependence of susceptibility of pyrrhotite-

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bearing rocks have been reported by Kapicka et al. [3]. These authors observed, for some samples from the KTB borehole, taken at depths between 5200 and 7000 m, a strong increase of mean susceptibility K_m, between 20 and 120%, after pressure treatment. Thus, in order to be used as a reliable parameter for mineral magnetic identification, magnetic susceptibility has to be considered in its complexity or dependence on many factors.

The effect of application of an alternating magnetic field on the anisotropy of magnetic susceptibility (AMS) has been widely observed and reported in a number of publications [4–9]. However, no mention of changes in the absolute values of low-field mean magnetic susceptibility (K_m) was made. In 1999, Jordanova and Hus observed a significant increase in K_m in loess–paleosol samples after alternating field (AF) demagnetization, which the authors attributed to the presence of multidomain grains in the samples (Jordanova and Hus, unpublished DWTC report).

During a study of AMS of intrusive and metamorphic rocks from Antarctica by Henry et al. [10], similar significant K_m variations were noticed, and even high changes in some cases, during alternating field (AF) demagnetization.

In the following, data of the effect of AF-demagnetization on K_m and AMS, obtained on a large collection of rock samples of different nature, geologic settings and ages will be given, followed by a qualitative discussion of the observed phenomena.

2. Samples and methods

Three different rock types were investigated:

- diorite samples from dykes from Livingston Island, in Antarctica [11,12];
- gneisses and granites from Terre Adélie, in Antarctica [13];
- sediment samples from different loess–paleosol sections: Rocourt in Belgium, Viatovo in Bulgaria, Huangling and Jiachun in China, Kurtak in Russian Siberia and Tadijar in Tadjikistan (Jordanova and Hus, unpublished DWTC report, 1999).

Samples from Antarctica in their initial natural remanent magnetization (NRM) state have been stepwise demagnetized in AF fields from 2 mT to 100 mT maximum amplitude using Molspin and laboratory-made AF-demagnetizer. For each demagnetization step, the alternating field was applied subsequently along three perpendicular sample axes *x*, *y* and *z*. After each AF-treatment, AMS was measured in a KLY-2 or KLY-3 Kappabridge (AGICO, Brno). This allows to determine the variation of the three principal susceptibilities ($K_1 \geq K_2 \geq K_3$) and of the mean susceptibility $K_m = (K_1 + K_2 + K_3)/3$. The same experiment was repeated for one sample from Terre Adélie, but by applying increasing direct fields (approach used in [3]) instead of alternating fields. The loess–paleosol samples were investigated starting from two different initial states: natural undisturbed sediments carrying a NRM and in artificial samples prepared from loose material. In the latter case, the loose grains were fixed with gum lacquer in order to eliminate the effect of any overall initial remanent magnetization and to prevent grain movement during AF-treatment and measurement. Stepwise AF-demagnetization until maximum amplitude of 200 mT along the *x*-axis was carried out in a 2G demagnetizer at 200 Hz and AMS measured after each step using KLY-3 Kappabridge. A larger collection of samples was demagnetized only in three steps at 100, 125 and 200 mT and the magnitude of the susceptibility change as compared to the initial value (before demagnetization) was calculated.

Magnetic hysteresis parameters were determined on small samples (about 3 cm^3) in order to obtain information on the effective magnetic domain state of the ferrimagnetic carriers. Hysteresis measurements were done in a translation inductometer installed in the air gap of an electromagnet in a maximum applied field of 0.8 T in the Paleomagnetic Laboratory at Saint Maur.

Thermomagnetic analyses of high-temperature and low-temperature dependence of low-field magnetic susceptibility were carried out respectively in the high- and low-temperature CS2/3 attachments in a Kappabridge KLY-3, on loose samples in Ar and air atmospheres, for the determination of characteristic transition temperatures (Curie and Néel temperatures, Verwey transition) of the magnetic minerals.

Frequency dependence of magnetic susceptibility of the loess–paleosol samples was measured in a Bartington susceptibility meter at frequencies 0.47 and 4.7 kHz.

3. Experimental results

3.1. Change in mean susceptibility

For all the samples but one, the diorite sample KD2c, an increase of mean susceptibility K_m has been observed (Fig. 1). Application of AFs with small amplitude, between 0 and 10 mT, results in relatively weak changes, expressed by an increase or decrease for the different samples. The most significant K_m-increase is observed in the amplitude range of 20–50 mT amplitude of the alternating field. In higher-fields, the variations in K_m are relatively moderate.

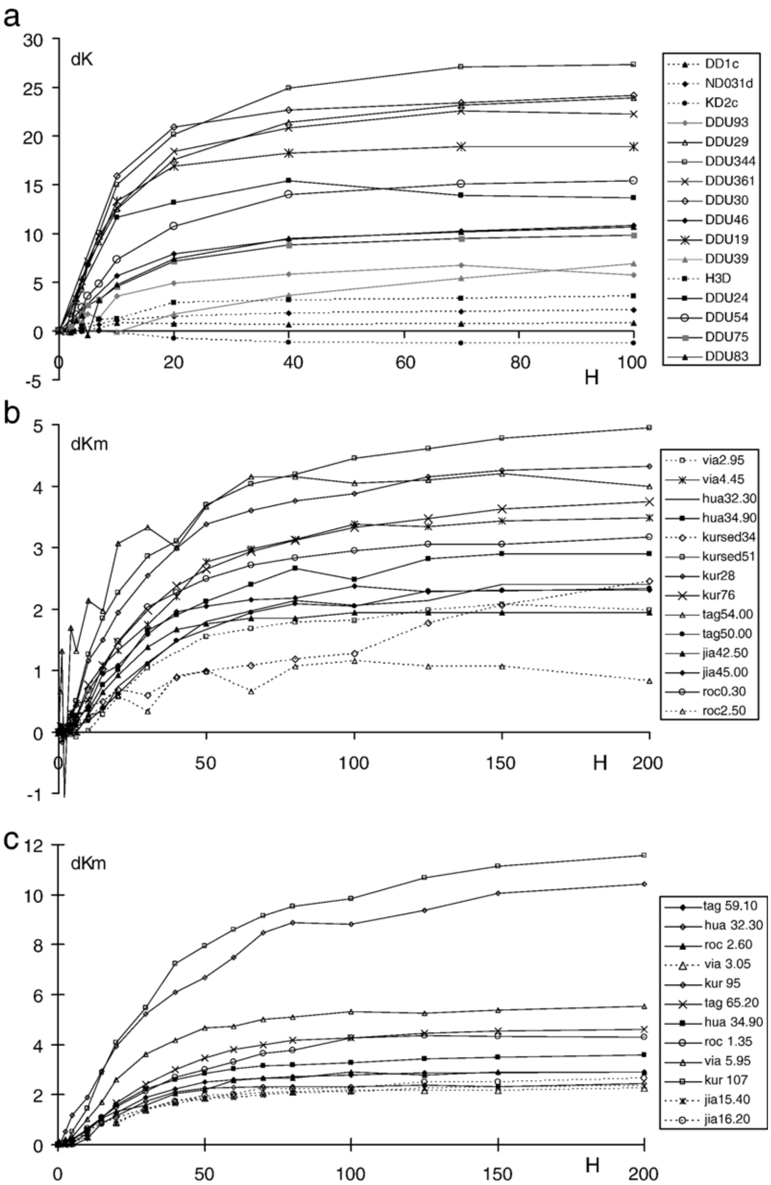

Fig. 1. Percentage of variation of the mean susceptibility K_m (dK_m) as a function of the applied AF (H, in mT) for (a) Terre Adélie rocks (samples DDU) and diorites, (b, c) loess and paleosols in original state (b) or powder form (c).

The maximum percentage of K_m-increase is 27% observed in a gneiss sample from Terre Adélie. On two specimens cut from the same gneiss sample with high magnetic anisotropy, AF-demagnetization and stepwise acquisition of SIRM have the same effect, with a similar K-increase for the same field amplitude.

Comparing the AF-effect on K_m for loess samples in "natural undisturbed" and "loose" (i.e. without any overall remanent magnetization) states, the shape of the curves is perfectly similar (Fig. 1b and c). The percentage of K_m-increase seems to be lower in the "natural undisturbed" samples (maximum 5%) than in the "loose" samples (maximum 11.6%, but only 5.6% for 10 of the 12 samples).

3.2. Changes in principal susceptibilities

Like for the mean susceptibility K_m, all the samples examined, except KD2c, show a gradual increase of the three principal susceptibilities K_1, K_2 and K_3

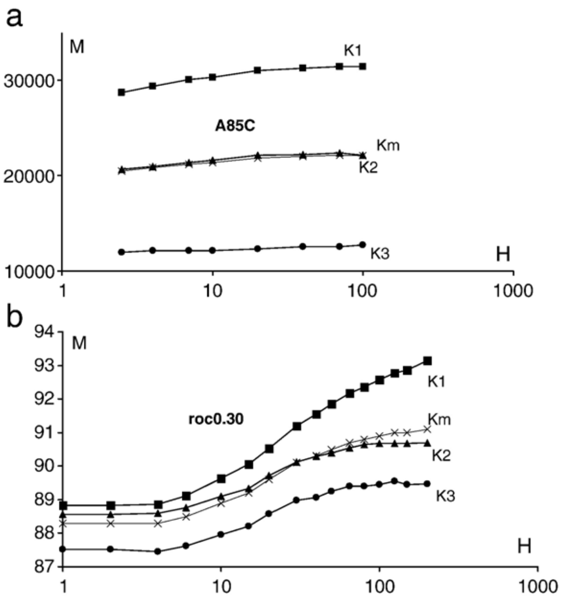

Fig. 2. Variation of K_1, K_2, K_3 and K_m (10^{-6} SI) as a function of the applied AF (*H*, in mT) for Terre Adélie sample AP85c (a) and loess sample roc0.30 (b).

with increasing maximum amplitude of the AF (Figs. 2 and 3). The evolution of the principal susceptibilities K_1, K_2, K_3 can give a more precise view on the mechanism of the observed K_m changes. For this purpose, a parameter Sams = abs (K_1-K_m) + abs (K_2-K_m) + abs (K_3-K_m) was introduced. This parameter measures the sum of the deviations of the principal susceptibilities from K_m value.

Fig. 4 shows the change of the two parameters – Sams and K_m – relative to their initial values during the stepwise AF-demagnetization for the granite and gneiss samples examined from Terre Adélie. It is obvious that there exists a relationship between the two parameters that is site and/or sample specific.

Similar relationships are found for samples from Bulgarian, Chinese and Siberian loess/paleosol sections (Fig. 5), also revealing different behavior depending on the sample.

The observed variations in the directions of principal susceptibilities with application of an AF field are described in another publication [14].

3.3. Magnetic mineralogy

Detailed presentation of the mineral magnetic characterization of the diorite samples from Livingston Island has been given by Henry et al. [11]. On the basis of magnetic properties and SEM/EDX analysis, titanomaghemite was identified as the main ferrimagnetic carrier.

Thermomagnetic *K*(*T*) analysis of gneisses and granites from Terre Adélie clearly shows, through the observed Verwey transition and Curie temperature of 580 °C (Fig. 6) the presence of pure magnetite. Weak magnetic alteration during heating around 370 °C probably reflects the presence of titanomaghemite. Elongated opaque minerals concentrated in narrow stripes were observed in the thin section of the gneisses. Microprobe analysis confirms the presence of pure magnetite and of Ti-poor titanomaghemite or ilmeno hematite (about 84% Fe). Thus, AMS of these rocks, mostly with high anisotropy degree P' [16] in the average of 1.43, is probably partly caused by a distribution anisotropy [15].

The magnetic mineralogy of the loess/paleosol samples, although from very different geological settings and ages, is quite similar. Mössbauer spectra on magnetically enriched samples showed that in the paleosols, as well as in the loess of the Chinese Loess Plateau, the main magnetic minerals are magnetite, oxidised magnetite, hematite and goethite and that the soils contain more oxidized magnetite and maghemite compared to the parent loess [17]. The behavior of magnetic susceptibility during high-temperature *K*(*T*) thermomagnetic analysis (heating in Ar atmosphere) indicates that the main ferrimagnetic phase in Viatovo samples from Bulgaria is magnetite. This is deduced from the obtained Curie temperature of about 580 °C close to Curie temperature of pure magnetite. The observed increase of *K* after 270–300 °C in the loess samples corresponds to the formation of a new magnetic phase during heating (Fig. 7a). Magnetic properties and thermomagnetic analysis by measuring *K*(*T*) showed that magnetite is also the principal magnetic carrier in the Rocourt sample from Belgium [18], Tadjijar samples from Tadjikistan and the Kurtak samples from Siberia (Fig. 7b). The decrease of the signal after 300 °C in the samples from Kurtak, when heating in air, could indicate maghemite inversion to hematite [19,20].

3.4. Hysteresis parameters

3.4.1. Diorites, granites and gneisses from Antarctica

Collection of diorites, granites and gneisses is relatively small. As the diorites possess a highly variable magnetic mineralogy, this impedes obtaining a significant relation between the hysteresis parameters and the change in K_m as a result of AF-demagnetization. Coercivity (B_{cr} = remanence coercivity, B_c = coercive force) and magnetization (M_s = saturation magnetization, M_{rs} = saturation remanent magnetization) values, as well as ratios (M_{rs}/M_s, B_{cr}/B_c) are given in Table 1.

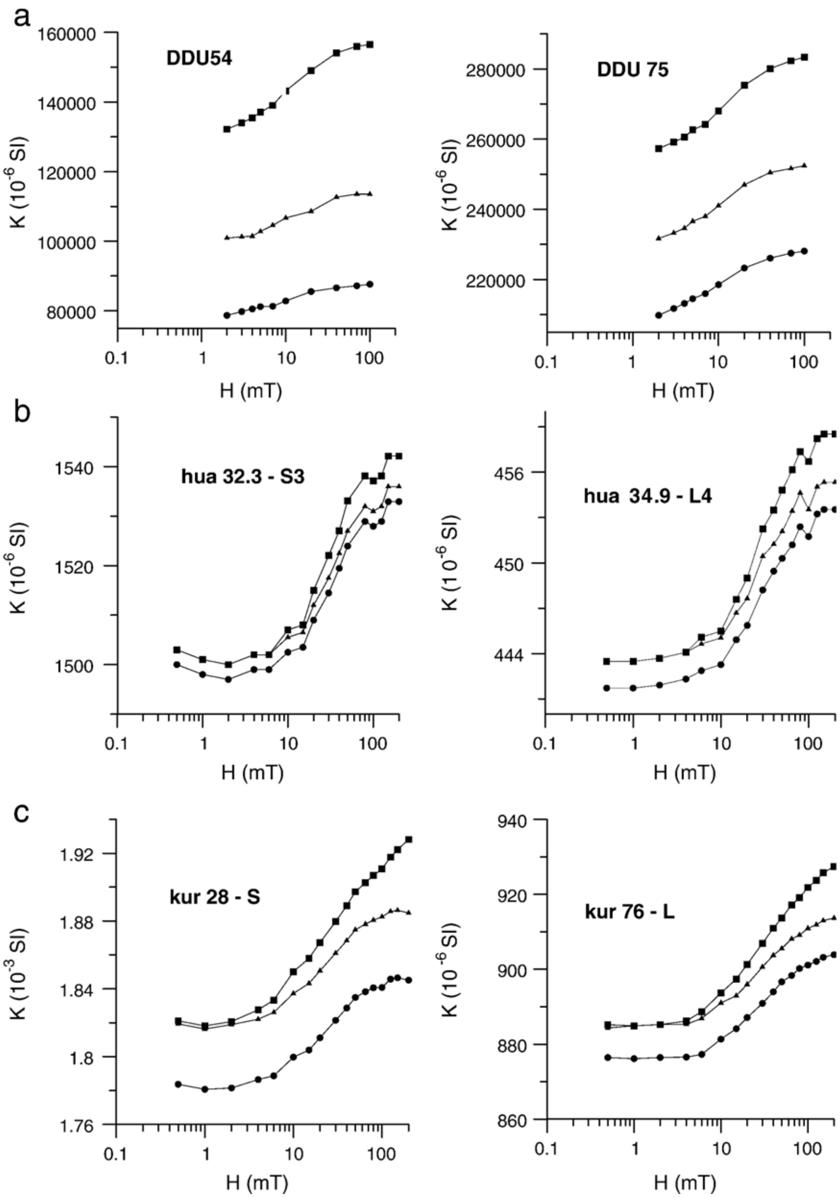

Fig. 3. Change of the values of principal magnetic susceptibilities (K_1 — squares, K_2 — triangles, K_3 — circles) during progressive AF-demagnetization: a) gneiss samples from Terre Adélie; b) loess and paleosol samples from Huangling (China) and c) loess and paleosol samples from Kurtak (Siberia).

In order to characterize the change in susceptibility as a result of 100 mT AF-demagnetization ($K_{AF100mT}$), the percent change, as compared to the initially measured values before AF-treatment (K_{init}), is calculated as follows:

$$dK_{100} = 100^*(K_{AF100mT} - K_{init})/K_{init}$$

Fig. 8 shows the obtained linear dependence between the volume susceptibility K_m and dK_{100}. The same relation is valid for the degree of anisotropy P' and dK_{100} (Fig. 8b). The magnetic mineralogy of the granites and gneisses is dominated by pure magnetite. B_{cr}/B_c ratios higher than 5 confirm the MD grain size observed in thin sections.

3.4.2. Loess–paleosol samples

The results, presented in Fig. 9 show that samples from the Kurtak loess–paleosol sequence in Siberia exhibit entirely distinct behavior as compared to the data

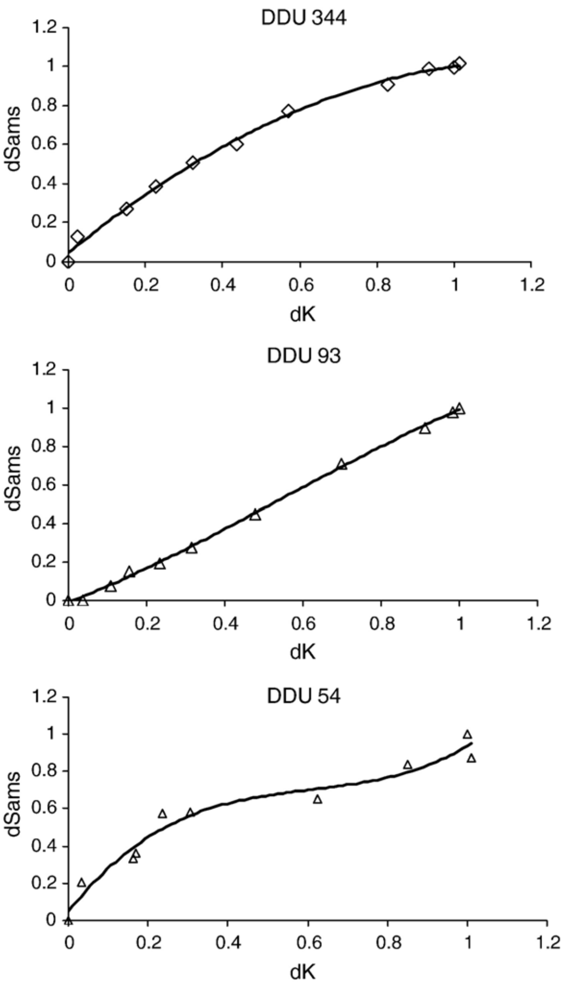

Fig. 4. Relationship between the change in Sams parameter and percent increase of magnetic susceptibility dK_{mean} (both normalized by their maximum value) during progressive AF-demagnetization for samples from Antarctica.

from other loess–paleosol sections from Europe and Asia. It supports the different magnetic enhancement models that were proposed for the Siberian loess sections and loess–paleosol sequences of the temperate climate belt: the wind vigor model for the first and the pedogenic model for the latter.

Similarly as for rocks from Antarctica, $dK_{200} = 100 * (K_{AF200mT} - K_{init})/K_{init}$ has been determined from initial susceptibility (K_{init}) and susceptibility after 200 mT AF-demagnetization ($K_{AF200mT}$).

Loess samples from the Kurtak section are characterized by true MD behavior ($B_{cr}/B_c > 5$). They display the most significant K (AF) dependence, with dK increasing when susceptibility increases (Fig. 9a — samples with dK > 10%). The opposite trend is obtained for paleosol samples from the sections in Bulgaria, China and Tadjikistan. Here, the increase of K-values is connected with an increase in the content of SP magnetic grains of pedogenic origin. Loess samples show less well pronounced dK (K) dependence but higher dK values are obtained as compared to paleosols. Fig. 9b,c shows that there is a direct relation between the low-field mass-specific magnetic susceptibility (χ), the coercivity ratio B_{cr}/B_c and the ratio χ/M_s [21] with the change in K caused by AF-demagnetization at maximum amplitude of 200 mT.

4. Discussion

AF-treatment is a non-destructive demagnetization technique in the sense that it does not cause any mineralogical (chemical) or structural changes of the rock-forming minerals. The same is true for the magnetic domain state of the minerals that remains unaltered when they are in the SP and SD state. Changes in low-field magnetic susceptibility of rocks resulting from the application of alternating magnetic field demagnetization must therefore be related to the magnetic fraction consisting of PSD-MD grains. The observed K-variations indicate changes in the domain pattern of large ferrimagnetic grains. In the usual case of rocks with broad grain-size distributions and mixing of SP, SD, PSD and MD domain states, susceptibility results from all the grains. Low-field susceptibility of monodomain particles (SD) is considered as the lowest limit for the corresponding ferrimagnetic minerals with magnetocrystalline anisotropy, because it is determined by the values of saturation magnetization and magnetocrystalline anisotropy constant [22,23]. Intrinsic susceptibility χ_i of MD particles can be considered as a sum of the response to a weak field of domains with parallel (χ_{II}) or perpendicular ($\chi_{\perp}$) orientation according to the direction of the applied external field [2,4]. However, due to internal demagnetizing fields, measured apparent susceptibilities (χ_o) are affected by the demagnetizing factor N ($\chi_o = \chi_i/(1 + N\chi_i)$ [23].

AF-demagnetization technique consists of polarizing magnetic moments of domains with coercivities lower than the maximum amplitude of the AF field. For each individual grain, the effect on domain pattern of AF and DC fields is similar, giving resulting magnetization along the easy magnetization axis, which is closest to the field direction. The difference between the effect of AF and DC fields appears when considering all the grains, half of individual grains having magnetization direction opposite to that of the other half for AF, and all grains having the same direction for DC. This similarity at the grain scale explains the comparable susceptibility variation observed after application of AF and DC fields.

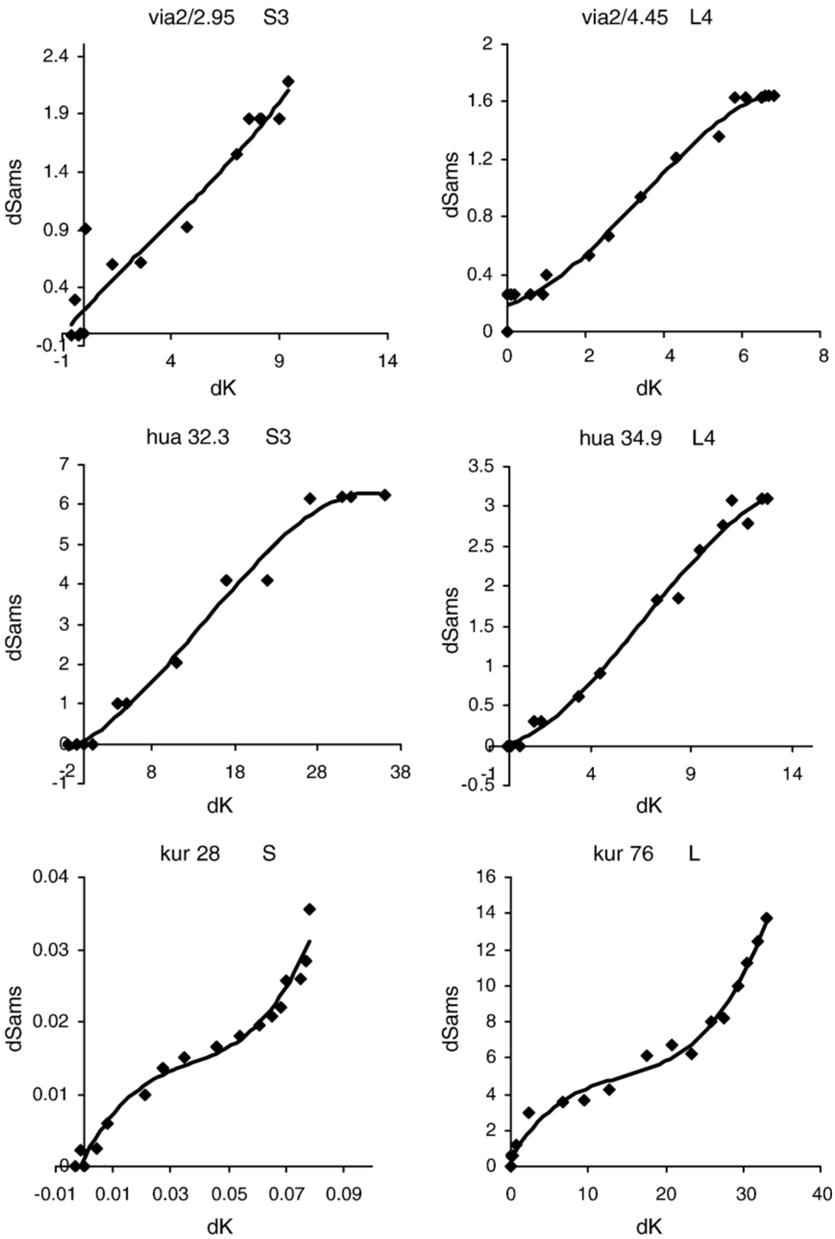

Fig. 5. Relationship between the change in Sams parameter and increase of magnetic susceptibility dK_{mean} (both in 10^{-6} SI) during progressive AF-demagnetization for loess/paleosol samples.

When applying a decreasing AF field, domain walls will oscillate and be pulled out of their stable position (potential wells). Thus, this process causes changes in the domain structure and number of domains. Magnetic susceptibility due to displacement of domain walls is very sensitive to irregularities and imperfections in the material whereas that due to the rotation of domains depends only on the magnitude of the magnetocrystalline anisotropy, which is fairly insensitive to the presence of impurities or weak internal stresses. The obtained experimental results suggest that the changes in K_m and AMS with AF are systematic and in most of the cases of magnetite-bearing rocks lead to an increase of the mean value of the low-field magnetic susceptibility. Besides, for two highly anisotropic specimens taken from the same block sample, direct steady and alternating fields have the same effects on K_m and on the AMS principal susceptibilities.

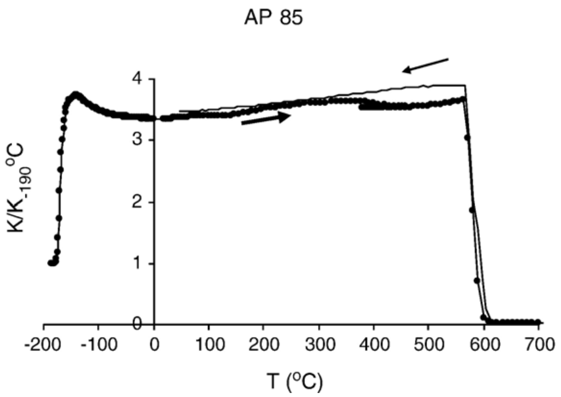

Fig. 6. Thermomagnetic analysis of magnetic susceptibility $K(T)$ (low- and high-temperature runs) for gneiss sample AP85 from Terre Adélie, Antarctica. Arrows indicate heating and cooling for the high-temperature run.

4.1. Diorites, granites and gneisses from Antarctica

Magnetic mineralogy of the diorite samples, discussed in a previous study [11] shows that except for magnetite, titanomagnetites/titanomaghemites contribute significantly to the magnetic signature. Thus, measured hysteresis parameters (Table 1) represent in this case only effective values which cannot be used as direct grain-size indicators. The origin of the observed changes in susceptibility for the diorite samples can be also inferred by considering their formation conditions and the type of remanence in the initial state (NRM). Most of the diorites (samples DD1c, KD2c, and ND03-1) come from dykes, which cut a plutonic body (sample H03d). Thus, the lower magnetic stability of H03d (see coercivity values in Table 1) compared to samples from dykes is a result of the longer crystallization time of the pluton compared to the dykes intrusion. The longer crystallization time also suggests lower density of crystal imperfections, defects, etc. in the pluton sample resulting in lower coercivity [24]. Consequently, the established domain pattern during cooling and acquisition of Thermo-Remanent Magnetization (TRM) will be probably simpler in the plutonic body as far as less pinning sites for domain walls nucleation are present. The obtained domain structure during TRM acquisition is determined by the distribution of internal stress [2,25]. The magnetic state of the grains is therefore not the global energy minimum equilibrium state but a metastable local energy minimum state. Lower stress level in H03d results in higher mobility of the domain walls, and then in larger increase of mean susceptibility

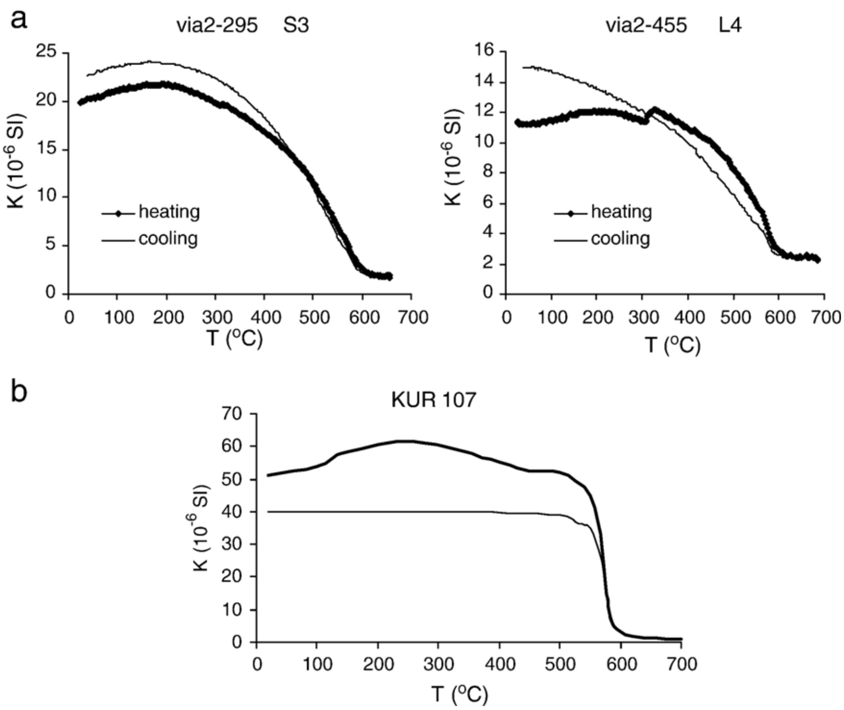

Fig. 7. Thermomagnetic analysis $K(T)$ in Ar atmosphere for loess and paleosol samples from Viatovo (Bulgaria) (a) and in air for a loess sample from Kurtak section (Siberia) (b). Heating is shown by thick line, cooling — by thin line.

Table 1
Hysteresis parameters and ratios for diorite samples from Livingston Island (Antarctica) and gneiss sample AP85 from Terre Adélie (Antarctica)

Sample	Nature	B_c (mT)	B_{cr} (mT)	M_s (mAm^2/kg)	M_{rs} (mAm^2/kg)	M_{rs}/M_s	B_{cr}/B_c
DD1c	Quartz–diorite	8.27	18.2	1872	194.5	0.104	2.2
ND03	Diorite	10.34	57.6	1929	145.5	0.075	5.57
Kd2c	Gabbro–diorite	10.24	23.6	2505	295.5	0.118	2.30
H03d	Diorite	3.49	12.6	2177	73.1	0.034	3.61
AP 85	Gneiss	2.69	12.9	1027	44.9	0.044	5.39

after AF-demagnetization. The results presented by Halgedahl and Fuller [26], showing a decrease of room-temperature susceptibility of up to 7% after progressive AF-demagnetization of pyrrhotite-containing samples, compare the changes relative to a different initial state — of thermally demagnetized TRM. On the other hand, Kapicka et al. [3] obtained strong K_m-increase (between 20 and 120%) after a pressure treatment of some samples from KTB borehole. This effect was observed only in some samples containing both ferrimagnetic and antiferromagnetic pyrrhotites. Kapicka et al. [3] interpreted this variation as resulting from irreversible domain walls movement, because, before application of laboratory treatment, the pyrrhotite was "quenched" in a metastable state during its quick transport to the surface. They underlined the importance of the intergrowth of the two pyrrhotite phases, but also mentioned that the effects of lattice defects and of magnetic interactions may not be negligible.

The obtained small K-decrease only observed for sample KD2c may be due to a particular case of micro-coercivity distribution, which impedes redistribution of the domain walls.

Part of the data points in Fig. 8 corresponds to the gneiss samples from Terre Adélie. Their magnetic mineralogy also consists of a mixture of magnetite and of titanomaghemite (Fig. 6). The increase of K-change with increasing degree of anisotropy (Fig. 8b) indicates that the observed AF-effect depends on the anisotropy of the rocks (either shape or distribution in origin). In case of MD grains both types are probably playing role in the gneiss sample. The distribution of opaque minerals in narrow stripes favors the establishment of domain patterns of mainly lamellar domains linked by closure domains [2]. The possible presence of magnetostatic interactions in the present case facilitated by quite strong distribution anisotropy further increases the internal demagnetizing field and leads to very low magnetic stability [2]. These are probably the main reasons for the observed strong K_m-increase, up to 27%, after AF-demagnetization at 100 mT. As discussed by Bathal and Stacey [4], in case of magnetite, with [111] as easy magnetization directions, the domain rotation in the presence of external AF field is completed at about 38 mT. Thus, the obtained strongest K_m-increase between 20 and 50 mT AF-amplitude (Fig. 1a) suggests again that the redistribution of the domain walls plays the major role. Different trends in the changes of Sams parameter with increase of mean susceptibility K_m (Fig. 4), similar to loess/paleosol samples (Fig. 5), probably is caused by different coercivity distributions, but here strongly affected by magnetostatic interactions.

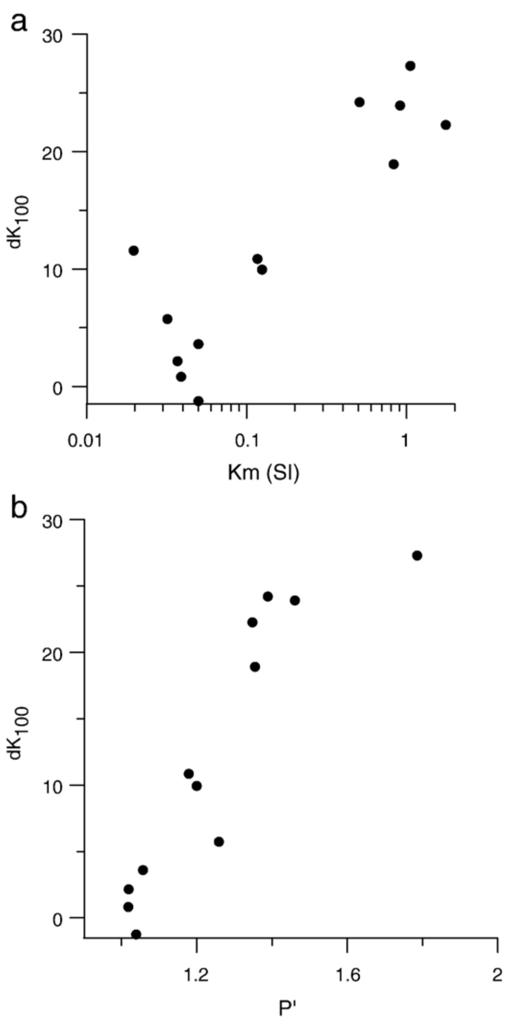

Fig. 8. Percent change of magnetic susceptibility dK_{100} as a function of initial susceptibility (K) (a), and the degree of anisotropy P' (b) for samples from Antarctica.

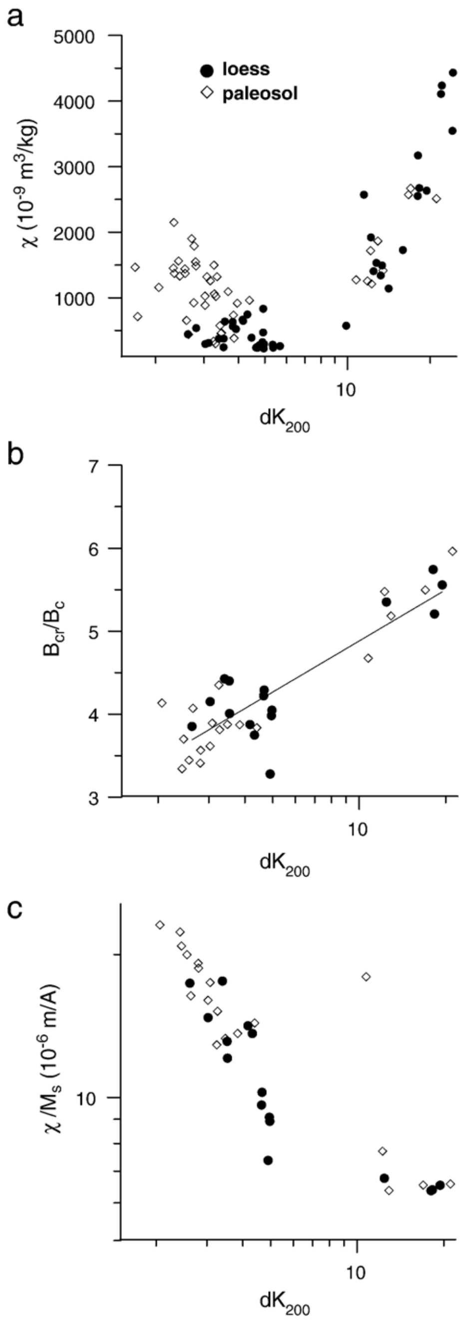

Fig. 9. Changes in the mean mass-specific susceptibility (a), ratio B_{cr}/B_c (b) and ratio χ/M_s (c) as a function of percent change in magnetic susceptibility dK_{200} for loess and paleosol samples.

4.2. Loess/paleosol samples

The magnetic enhancement model of paleosols that is accepted for the Chinese Loess Plateau and for other loess–paleosol sequences from the temperate climatic belt [27,28] considers the "in situ" pedogenic formation of fine grained magnetite/maghemite as the main process, responsible for the enhanced magnetic properties of paleosol horizons. Thus, each sample from a loess–paleosol sequence will contain varying amounts of lithogenic (detrital), pedogenic and weathering components. In contrast, magnetic susceptibility variations along loess/paleosol profiles from Siberia [29,30] and Alaska [31,32] are shown to result mainly from the variation in the amount of detrital magnetic grains, depending primarily on the wind strength and the distance from the source area. The two mentioned mechanisms involve two different sets of processes which are clearly reflected in the obtained relationships in the present study (Fig. 9).

On the basis of the above mentioned properties, the observed relationships between different parameters (χ, B_{cr}/B_c, χ/M_s) and the percent increase of susceptibility after AF-demagnetization with maximum amplitude of 200 mT, support the following interpretation of the results. The observed effect of AF-demagnetization on the low-field susceptibility is closely related to the relative amount and size of the large MD magnetite-like particles. It is clear from Fig. 9a that the strongest dK–χ dependence is typical for the Kurtak samples. According to the wind vigor model [33], increased χ-values of the loess horizons in comparison with the corresponding paleosols, are due to larger detrital grains entrained by strong wind, as well as their increased concentration during glacial periods. Such situation brings about higher B_{cr}/B_c values for the loess samples (Fig. 9b). The effect of mixing is well expressed for the collection of samples from the Asian and European loesses. A higher amount of fine pedogenic SP particles results in the observed negative trend in the χ–dK relation, especially for the paleosol samples (Fig. 9a). The same conclusion is supported by the strong decrease of the ratio χ/M_s with an increase of dK (Fig. 9c). As far as χ/M_s eliminates the effect of mineralogy through the normalization with M_s [21], it expresses the dependence on the amount of the SP particles.

Consequently, the observed increase of χ during AF-demagnetization is most probably related to changes in the domain pattern of MD particles, caused by polarization of the magnetic moments as a reaction to AF. Alternating field demagnetization on natural undisturbed samples with an initial NRM and on samples in loose form, fixed by resin, gave similar response (similar shape of curves) but higher percent K_m-increase for the latter (Fig. 1). "Switching on" of the significant K_m-increase after about 10 mT AF-demagnetization step (Figs. 1 and 3) suggests that the effect is connected with changes in domain pattern and redistribution of “hard” (pinned) domain walls [34]. Similar observation was made by Halgedahl and Fuller [26], who reported that a peak AF of several milliTesla was needed in order to visibly detect domain wall motion in a pyrrhotite polycrystal. In MD grains, the intrinsic reversible susceptibility χ_i linearly depends on the wall area and domain wall displacement [2]. Thus, the observation of susceptibility increase between the initial NRM and AF-demagnetized state implies that the domain wall area in a unit volume of the material, as well as the wall mobility should increase. Domain wall area may increase due to the bending of the domain walls. The observed effect may therefore be related to the occurrence of simpler domain patterns as a result of AF-demagnetization (e.g. mostly parallel 180° domain walls since this is the configuration with minimum energy) [26]. Moreover, Pokhil and Moskowitz [35] showed that repeated AF-demagnetization of magnetite grains of 5–20 μm size may cause domain walls to exist in several different local energy minimum (LEM) states. The weaker effect of χ-increase due to AF-demagnetization for the paleosol samples (Fig. 9a) probably results partly from the impeded domain walls mobility in magnetite grains, which suffered partial oxidation [36] during pedogenic alteration of loess material [18,37]. Therefore, the original domain configuration, with strongly pinned domain walls, is less susceptible to the effect on χ of AF-demagnetization.

The observed different relationships between the change in K_m and change in Sams parameter with AF-demagnetization are closely related to the site specific mineral magnetic characteristics of the loess/paleosol sediments (Fig. 5). Qualitative explanation of this behavior should take into account the physical mechanism behind AF-demagnetization process, e.g. as a reflection of the microcoercivity spectrum of the remanence-carrying ferriminerals [2] and mobility of domain walls [34]. A single linear trend in Fig. 5 probably results from a subsequent demagnetization affecting domains with relatively uniform and continuous distribution of microcoercivities of domain walls. The presence of segments with different slopes, especially well expressed for the Kurtak samples (Fig. 5c) would indicate the existence of different mineral magnetic phases or grain sizes with contrasting and non-overlapping coercivity spectra.

5. Conclusions

The results from the present investigation show that the widely applied magnetic cleaning technique of stepwise AF-demagnetization causes an increase of the mean susceptibility in intrusive rocks and loess–paleosol sediments, ranging from 2 up to 27% as compared to the initial values. It is therefore recommended to measure magnetic susceptibility and its AMS before any AF-treatment. This is especially important for relative paleointensity studies in sedimentary rocks, where often normalization by K_m is used. The same is true when K is used as an environmental indicator and in particular as a magnetic climate proxy.

It is found that the most significant changes occur in samples containing the largest MD magnetite-like ferriminerals. It is suggested that the observed changes are due to the changes in the domain pattern, and bending and unpinning of domain walls as a result of AF-demagnetization, leading generally to increased domain walls areas, as compared to these ones at the initial NRM state. The obtained correlation between the percent change in magnetic susceptibility and the degree of anisotropy P' for highly anisotropic gneisses (P' up to 2.45) suggests a significant role of magnetostatic interactions for the observed increase of susceptibility during AF-demagnetization.

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