Alternating field-impressed AMS in rocks

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SUMMARY

We studied the evolution of anisotropy of magnetic susceptibility (AMS) during stepwise alternating fields (AF) demagnetization on various kinds of rock samples (loess and palaeosols, diorite, granite, gneiss) with very different degree of magnetic anisotropy. The variation of the magnetic fabric appears to be related to both the magnetic fabric before AF demagnetization and to the direction of AF application. The anisotropy change is mainly controlled by the initial magnetic fabric. The more anisotropic is the initial magnetic fabric, the less is the effect of the direction of field application. This can be clearly shown by determination of the difference of the susceptibility ellipsoids after and before AF application. Even for rocks with weak magnetic anisotropy, the effect of the initial AMS is significant. The difference ellipsoids allow in particular cases to point out that the initial magnetic fabric is composite.

Key words: alternating field, anisotropy, magnetic susceptibility.

INTRODUCTION

Anisotropy of magnetic susceptibility (AMS) is widely used to understand rock fabrics. This technique is usually applied on 'untreated' rocks, that is, before any physical or chemical treatment after field sampling. However, laboratory heating has been used to modify the magnetic fabric of rocks in order to yield more information on their petrofabric. It can simply enhance part of a pre-existing fabric (e.g. Bascou *et al.* 2005) or reveal a different fabric (e.g. Silva *et al.* 2006). Relative to the pre-heating magnetic fabric, this different magnetic fabric may be characterized by permutations between the principal susceptibility axes related to the magnetic mineralogy, for example an inverse fabric (permutation between K1 and K3), or related to petrostructural elements other than those dominating in the initial magnetic fabric (see Henry *et al.* 2003, and references herein). The pioneer works of Bathal & Stacey (1969) and Violat & Daly (1971) showed that application of alternating fields (AF) (Stacey 1961, 1963) also introduces a modification of the initial magnetic fabric. Jordanova & Hus (unpublished DWTC report, 1999) showed that strong changes affected shape and orientation of the magnetic fabric and bulk susceptibility in weakly anisotropic loess and palaeosols samples. Recently, Jordanova *et al.* (2007) pointed out that stepwise AF demagnetization mostly gives an increase of the susceptibility and of its anisotropy in rocks mainly due to the presence of large multidomain (MD) grains. The aim of this work is to reveal better the directional changes in order to look for possible implications of AF demagnetization (see Liu *et al.* 2005).

During heat treatment, AMS changes are mainly due to mineralogical alteration, the effect of variation of the 'magnetic structure' having a minor role. That is not so for AF demagnetization because in this case no mineralogical alteration occurs. The non-reversible variation of magnetic susceptibility and of its anisotropy during alternating field demagnetization is not related to the demagnetization of a resultant remanent component because Jordanova *et al.* (2007) obtained the same result during stepwise acquisition of a saturation isothermal remanent magnetization (SIRM). For both AF-demagnetization and SIRM acquisition, elementary moments are concentrated around the field direction, but they are all in the same sense for SIRM acquisition and distributed half-and-half along each sense for AF-demagnetization. In addition, thermal treatment in zero magnetic field removes the AF effect (Bathal *et al.* 1969; Violat & Daly 1971). Jordanova *et al.* (2007) interpreted the AF effect in large MD grains as related to this polarization of elementary moments along the field direction by displacement of domain walls. They also suggested that magnetic interaction may play a significant role.

PREVIOUS STUDIES AND ANALYSIS METHODS

Potter & Stephenson (1990a,b) and Kapicka (1981) studied in detail the effect of AF and DC fields on AMS of weakly anisotropic samples. They confirmed that the field application significantly altered the measured AMS. The same authors computed the additional AMS ellipsoid impressed by the applied field, by using difference ellipsoid from AMS after and before field application. This additional acquired AMS had the form of an ellipsoid of revolution with a unique axis aligned along the applied field direction. For MD grains, this ellipsoid was prolate (maximum susceptibility axis along the field direction), while it was oblate (minimum susceptibility axis along the field direction) for uniaxial single domain (SD) grains. Plénier & Glen (2004) obtained similar results also in weakly anisotropic igneous rocks. Therefore, the initial magnetic fabric should have negligible effect on the field-impressed magnetic fabric, at least in weakly anisotropic rocks.

In order to verify and possibly extend this assumption, two different approaches have been followed here:

– To compare AF effects obtained on weakly anisotropic samples and on more anisotropic ones.

– To analyse in detail the variation, during stepwise AF demagnetization, of the AMS measured tensor and of the difference ellipsoid (Potter & Stephenson 1990a,b).

Studied samples were chosen with moderate to very high magnetic anisotropy (P' from 1.018 to 2.385) in collections from two areas in Antarctica: Livingston Island (62°36′S, 60°30′W) and Terre Adélie in East Antarctica (66°40′S, 140°–143°E). We also analysed in detail the results obtained by Jordanova & Hus (unpublished DWTC report, 1999) on sediment samples, mostly with weak magnetic anisotropy ($P' = 1.002$–1.024), from different loess-palaeosol sections: Rocourt in Belgium, Viatovo in Bulgaria, Huangling and Jiachun in China, Kurtak in Russian Siberia and Tadjijar in Tadjikistan. Measurements of AMS were done in a KLY3 Kappabridge (AGICO, Brno). Because difference ellipsoids can have diagonal terms of unlike sign, the classical shape parameter T cannot be always represented as defined by Jelinek (1981) and the parameter: $U = \{2[(K_2 - K_3)/(K_1 - K_3)]\} - 1$, where K_1, K_2 and K_3 are the principal susceptibilities ($K_1 \geq K_2 \geq K_3$), was used (Jelinek 1981). For this parameter, -1 corresponds to a prolate shape, 0 to a neutral ellipsoid [$K_2 = (K_1 + K_3)/2$] and 1 to an oblate fabric. For samples with only positive diagonal terms, T and U parameters have neighbouring values. Jordanova *et al.* (2007) introduced a new parameter to characterize the intensity of anisotropy: $S_{\mathrm{AMS}} = |K_1 - Km| + |K_2 - Km| + |K_3 - Km|$ were Km is the mean susceptibility [$Km = (K_1 + K_2 + K_3)/3$]. This parameter gives the sum of the deviations of the principal susceptibilities from the Km value. To have easily comparable results in the different samples, we determined $d_{\mathrm{AMS}} = S_{\mathrm{AMS}} - S_{\mathrm{AMS0}}$ (where S_{AMS0} is the value before AF demagnetization). Similarly, d_{Km} is the difference between the value of the mean susceptibility Km after and the value Km_0 before AF demagnetization.

Jordanova *et al.* (2007) showed that the AF effect is an increase of both d_{Km} and d_{AMS} (except for the diorite sample KD2c that shows weak decrease of both values). The total AMS variation can, therefore, be considered as a variation of isotropic (d_{Km}) and anisotropic (d_{AMS}) parts of the susceptibility ellipsoid. Difference ellipsoids correspond to this total variation, but the orientation of their principal axes and their U parameter values reflect their anisotropic part.

AF was applied using the classical procedure for AF demagnetization with progressive decrease of the AF intensity from a chosen maximum field amplitude. Results are presented in samples coordinates (trihedron X, Y and Z). After measurement of the initial AMS, AF of maximum amplitude a was applied along the X direction of the samples and AMS determined; then similarly two other AMS data were obtained after application of AF with the same amplitude a along Y and Z directions, respectively. The same procedure was repeated for different increasing maximum values of the applied AF, up to 100 mT. However, such a procedure may affect the results. Indeed, before AF application along the X direction, only lower AF amplitudes were applied to the sample. On the contrary, for AF application along the Y and later in the Z direction, the same AF amplitude was already applied before along the X direction for the first and along the X and Y directions for the second. For comparison, for four samples (Table 1), AF was applied only along the Z direction. The same is true for the loess and palaeosols samples studied by Jordanova & Hus (unpublished DWTC report, 1999). For these samples, the maximum AF amplitude of 200 mT was applied only along the X direction. The Z direction is in geographical coordinates vertical and perpendicular to the stratification plane.

The difference ellipsoids were computed taking the difference of the tensor terms (Henry *et al.* 2003). They were determined relatively to the initial magnetic fabric. We also tried to determine difference ellipsoids using measured AMS after two successive steps of AF demagnetization. Unfortunately, these ellipsoids are generally badly defined, because the difference between tensor terms is weak. Uncertainty on each term of the difference ellipsoid results from uncertainties of both the measured AMS and is relatively high. A too weak difference between AMS tensor terms does not allow obtaining a reliable difference ellipsoid and consequently only difference ellipsoids relative to the initial magnetic fabric were retained (and only when the difference of tensor terms is large enough).

For clarity, principal axis names and parameters will be indicated by bold characters for the measured AMS and by italics for the difference ellipsoids.

RESULTS

Loess and palaeosol samples

The 12 studied samples but one (TAG54) are characterized by weak to moderate oblate magnetic anisotropy, related to the stratification plane. Their mean susceptibility *Km* is relatively high for sediments. Sample TAG54 has strong prolate magnetic fabric, independent from the stratification plane. The main magnetic minerals in these samples are magnetite, oxidized magnetite, hematite and goethite. The palaeosols contain more oxidized magnetite and maghemite compared to the parent loess (Jordanova *et al.* 2007). The maximum AF amplitudes used were 0.5, 1, 2, 4, 6, 10, 15, 30, 40, 50, 65, 80, 100, 125, 150 and 200 mT. The variation of the mean susceptibility *Km* as a function of the intensity of the applied AF is moderate (Jordanova *et al.* 2007). Most of this variation occurred for AF amplitudes lower than 40 mT.

Measured AMS

Except for TAG54, the behaviour of the AMS principal axes during stepwise AF demagnetization was almost the same (Fig. 1a). Principal maximum axis $\mathbf{K}_1$ evolves towards the direction X of the applied field. Principal minimum axis $\mathbf{K}_3$ remains vertical. On a $\mathbf{P}' - \mathbf{U}$ diagram (derived from Jelinek 1981), evolution is always an increase of $\mathbf{P}'$. When $\mathbf{K}_1$ before AF application is closer to the X direction than to the Y direction then $\mathbf{U}$ decreases. On the other hand, if $\mathbf{K}_1$ before AF application is closer to the Y direction than to the X direction, $\mathbf{U}$ first increases before a decrease occurs (Figs 1b and c).

Table 1. AMS characteristics of investigated samples before AF demagnetization (mean susceptibility **Km** and parameters **P**′ and $\mathbf{U}_{in}$), the direction(s) of AF application and the value of the shape parameter U_{dt} of the difference ellipsoid after applying the highest AF amplitude (along direction X when AF was applied along three directions).

Sample	Rock	Locality	**Km** (SI)	**P**′	$\mathbf{U}_{in}$	AF	U_{dt}
Hua323	Palaeosol	China	0.0015	1.002	0.90	X	−0.93
Hua349	Loess	China	0.0004	1.005	0.89	X	−0.85
Jia450	Loess	China	0.0003	1.002	0.75	X	−0.98
Kur28	Palaeosol	Russia	0.0018	1.024	0.92	X	−0.82
Kur34	Loess	Russia	0.0011	1.019	0.77	X	−0.81
Kur51	Loess	Russia	0.0012	1.021	0.87	X	−0.77
Kur76	Loess	Russia	0.0009	1.012	0.90	X	−0.91
Roc030	Loess	Belgium	0.0001	1.016	0.61	X	−0.93
Roc250	Palaeosol	Belgium	0.0001	1.006	0.61	X	−0.77
Tag50	Palaeosol	Tadjikistan	0.0009	1.003	0.99	X	−0.95
Tag54	Loess	Tadjikistan	0.0002	1.268	−0.64	X	0.48
Via295	Palaeosol	Bulgaria	0.0004	1.002	0.39	X	−0.83
Via455	Loess	Bulgaria	0.0002	1.005	0.54	X	−0.66
DD1c	Diorite	Livingstone	0.039	1.018	−0.31	X, Y, Z	−0.62
KD2c	Diorite	Livingstone	0.050	1.039	0.32	X, Y, Z	−0.68
ND031d	Diorite	Livingstone	0.037	1.019	−0.16	X, Y, Z	−0.39
AP85c	Gneiss	Terre Adélie	0.020	2.385	0.08	X, Y, Z	−0.02
DDU19	Gneiss	Terre Adélie	0.830	1.390	0.67	X, Y, Z	0.83
DDU29	Gneiss	Terre Adélie	0.910	1.465	0.06	Z	0.36
DDU30	Gneiss	Terre Adélie	0.508	1.396	0.20	X, Y, Z	0.45
DDU39	Gneiss	Terre Adélie	0.125	1.202	0.21	X, Y, Z	0.20
DDU46	Granite	Terre Adélie	0.117	1.179	−0.05	X, Y, Z	−0.03
DDU93	Granite	Terre Adélie	0.032	1.269	0.41	Z	0.08
DDU344	Gneiss	Terre Adélie	1.055	1.838	0.40	Z	0.46
DDU361	Gneiss	Terre Adélie	1.756	1.355	0.24	Z	0.26

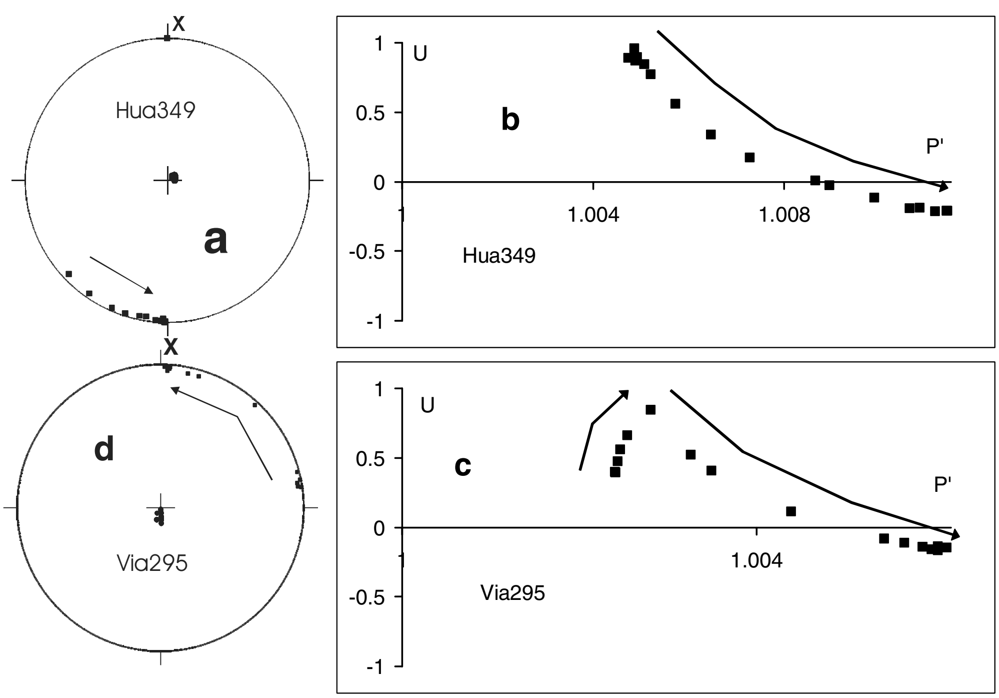

Figure 1. Variation of direction of maximum $\mathbf{K}_1$ (squares) and minimum $\mathbf{K}_3$ (circles) principal AMS axes during stepwise AF demagnetization in the sample Hua349 (a) for AF applied along X direction (stereographic projection in the lower hemisphere) $\mathbf{P}' - \mathbf{U}$ diagram showing change of shape during this treatment in samples Hua349 (b) and Via295 (c).

Sample TAG54 has strong ($\mathbf{P}' = 1.268$) prolate ($\mathbf{U} = -0.64$) initial magnetic anisotropy with $\mathbf{K}_1$ close to the X direction. During stepwise treatment up to 10 mT, orientation of this principal maximum axis slightly evolves towards the Y direction, and principal minimum axis to the initial orientation of the $\mathbf{K}_2$ principal axis. In higher fields, $\mathbf{K}_1$ moves towards its initial orientation and $\mathbf{K}_3$ remains stable. The corrected degree of anisotropy $\mathbf{P}'$ slightly increases while $\mathbf{U}$ is almost stable.

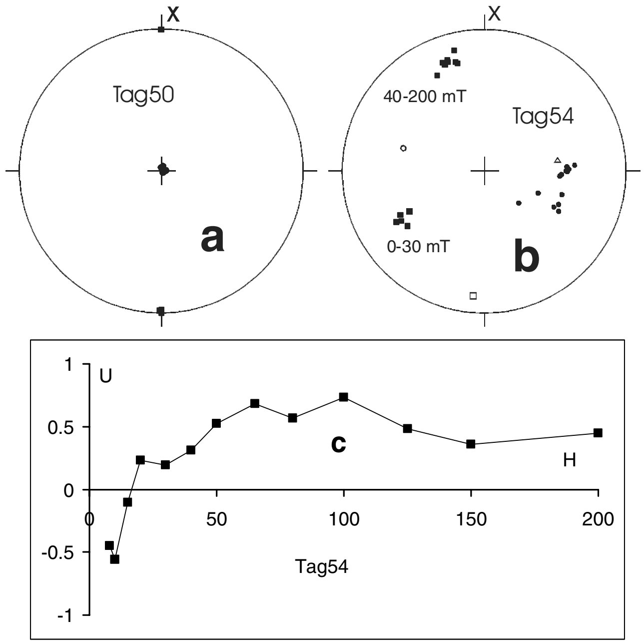

Figure 2. Maximum K_1 (full squares) and minimum K_3 (full circles) principal axes of the difference ellipsoids during stepwise AF demagnetization in the samples Tag50 (a) and Tag54 (b) for AF applied along X direction. For sample TAG54, maximum K1 (open square), intermediate K2 (open triangle) and minimum K3 (open circle) principal axes of the initial fabric (stereographic projection in the lower hemisphere). Evolution of the shape parameter **U** during this treatment for the sample Tag54 (c).

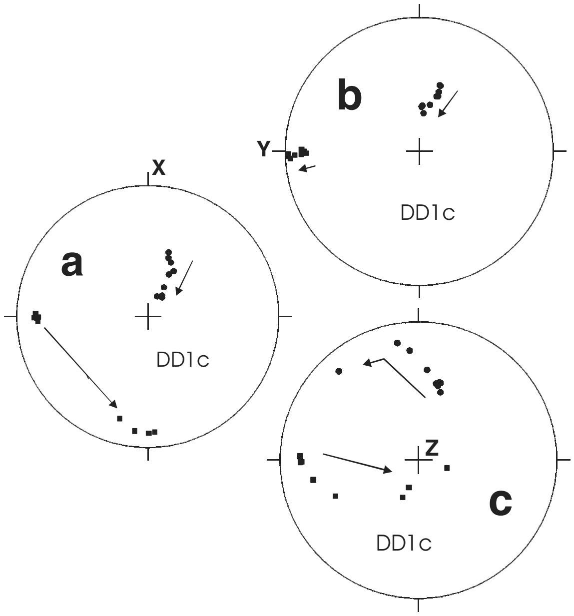

Figure 3. Variation of direction of maximum $\mathbf{K}_1$ (squares) and minimum $\mathbf{K}_3$ (circles) principal AMS axes during stepwise AF demagnetization in the sample DD1c for AF applied along X (a), Y (b) and Z (c) directions (stereographic projection in the lower hemisphere)

Difference ellipsoids

For the lowest AF amplitudes ($<$10 mT), difference of tensor terms relative to their initial value is too weak for difference ellipsoids to be significant. We therefore, only considered difference ellipsoids for AF amplitudes from 10 to 200 mT. For all samples except TAG54, the difference ellipsoids are very similar. K_1 is along the X direction and K_3 along the Z direction (Fig. 2a). The U parameter indicates a prolate magnetic fabric with small flattening. The U value after 200 mT AF demagnetization varies between -0.66 and -0.98 (average -0.90). This small flattening is not related to a measurement uncertainty because the U value is remarkably constant for all the difference ellipsoids for a same sample.

Difference ellipsoids for sample TAG54 present entirely different characteristics (Fig. 2b). K_3 is mostly close to the intermediate principal axis $\mathbf{K}_2$ of the initial magnetic fabric. K_1 is included in the plane containing $\mathbf{K}_1$ and $\mathbf{K}_3$ principal axes of the initial magnetic fabric, but is different from these two axes. During stepwise AF demagnetization, its orientation is stable until amplitude of 30 mT but, for higher amplitudes, it evolves to another direction, perpendicular to its previous orientation and closer to the X direction of the applied AF. The U parameter indicates shape variation from prolate to oblate for 20 mT amplitude (Fig. 2c).

Diorite samples

The three samples collected in different dykes at Livingston Island are characterized (Table 1) by moderate magnetic anisotropy with a rather neutral shape of the susceptibility ellipsoid. Their mean susceptibility *Km* (Table 1) is relatively high. In diorite samples from these dykes, thermomagnetic curves (magnetic susceptibility in low field as a function of temperature) point to the presence of Ti-poor titanomaghemite (Henry *et al.* 2005) and the hysteresis parameters suggest large grain sizes (H_{cr}/H_c between 2.7 and 16.4 and J_{rs}/J_s between 0.08 and 0.11). In thin sections, opaque minerals appear mainly as relatively large irregularly distributed inclusions.

Applied maximum amplitudes during stepwise AF demagnetization were 2.5, 4, 7, 10, 20, 40, 70 and 100 mT. The variation of the mean susceptibility *Km* as a function of the amplitude of the applied AF is moderate (Jordanova *et al.* 2007). Most of the variation occurred for AF amplitudes lower than 40 mT.

Measured AMS

For the three samples, the behaviour of the AMS principal axes during AF stepwise treatment was almost the same (Fig. 3). Principal maximum axis $\mathbf{K}_1$ evolves towards the direction of the applied field, with no relation to the initial direction. It even becomes very close to this direction for the less anisotropic sample DD1c ($\mathbf{P}' = 1.018$). Principal minimum axis $\mathbf{K}_3$ mostly evolves towards the Z direction when the field is applied along X or Y directions, and towards X direction when the field is applied along the Z direction. On $\mathbf{P}' - \mathbf{U}$ diagram, evolution depends on the direction of the applied field relative to the initial magnetic fabric. For a same direction of field application, it is regular in samples with only partial evolution of $\mathbf{K}_1$ towards the AF direction, and shows two different evolutions for low and high AF amplitudes for sample DD1c. The $\mathbf{P}'$ value and prolateness increase when the field direction is closest to the initial $\mathbf{K}_1$ principal axis. The relationship between $\mathbf{d}_{\mathrm{AMS}}$ and $\mathbf{d}_{Km}$ (Jordanova *et al.* 2007) appears to be different according to the direction of AF application (Fig. 4a).

Difference ellipsoids

For the three samples, difference ellipsoids have variable shape, mostly neither totally oblate nor completely prolate (Table 1). They show mostly relatively well grouped principal axes. For DD1c

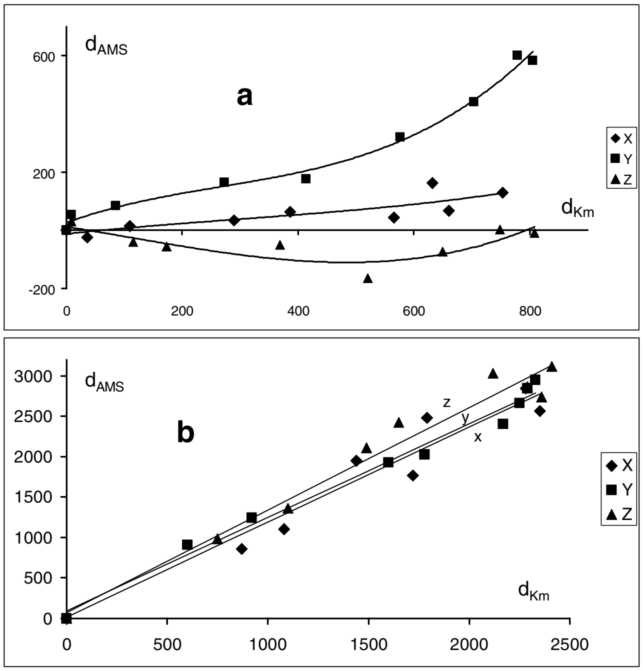

Figure 4. $\mathbf{d}_{AMS}$ as a function of $\mathbf{d}_{Km}$ for AF applied along directions X, Y and Z of the samples ND031d (a) and AP85c (b) - scales in 10^{-6} SI. Lines are only indicated to underline the main variation.

(Figs 5a–c), K_1 principal axes are close to the direction of the applied field, but present a small systematic angular deviation relative to this direction. This deviation is much higher in sample KD2c (Figs 5d–f), while sample ND031d presents an intermediate case. Principal minimum axes K_3 orientation is different according to the samples and to the direction of the applied field. In sample DD1c (Fig. 5a), K_3 principal axes are close to the principal maximum axis

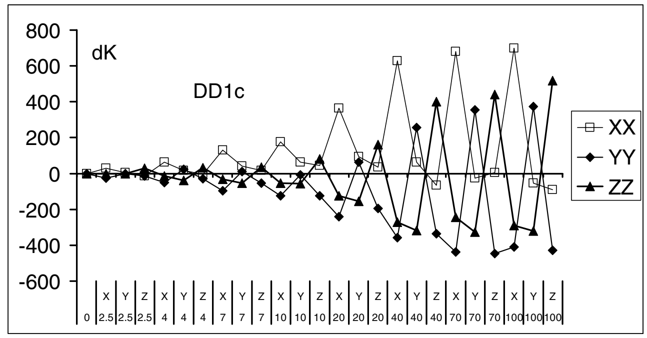

Figure 6. Variation of the deviation **dK** to the mean susceptibility (in 10^{-6} SI) of each diagonal term **XX** (open squares), **YY** (full diamonds) and **ZZ** (full triangles) of the tensor in the sample DD1c as a function of the applied AF (field direction and amplitude in mT).

$\mathbf{K}_1$ of the initial magnetic fabric, except for AF applied along a direction close to this principal axis $\mathbf{K}_1$.

Tensor terms

The effect of AF clearly appears when considering the diagonal terms **XX**, **YY** and **ZZ** of the measured AMS tensor (corresponding here to the directions X, Y and Z, respectively). To visualize this effect, the deviation of each term from the mean susceptibility was determined and the variation of this deviation was plotted on Fig. 6 as a function of the AF direction and amplitude. For a same tensor term (for example **XX**, related to X direction) and for a same AF amplitude applied along the two directions associated to the other diagonal terms (Y and Z directions in the example), the value of this deviation is slightly different. Increase of each diagonal tensor term is maximum when the field is applied along its corresponding direction. However, this maximum increase is different according to the diagonal term for a same field value. That points to an

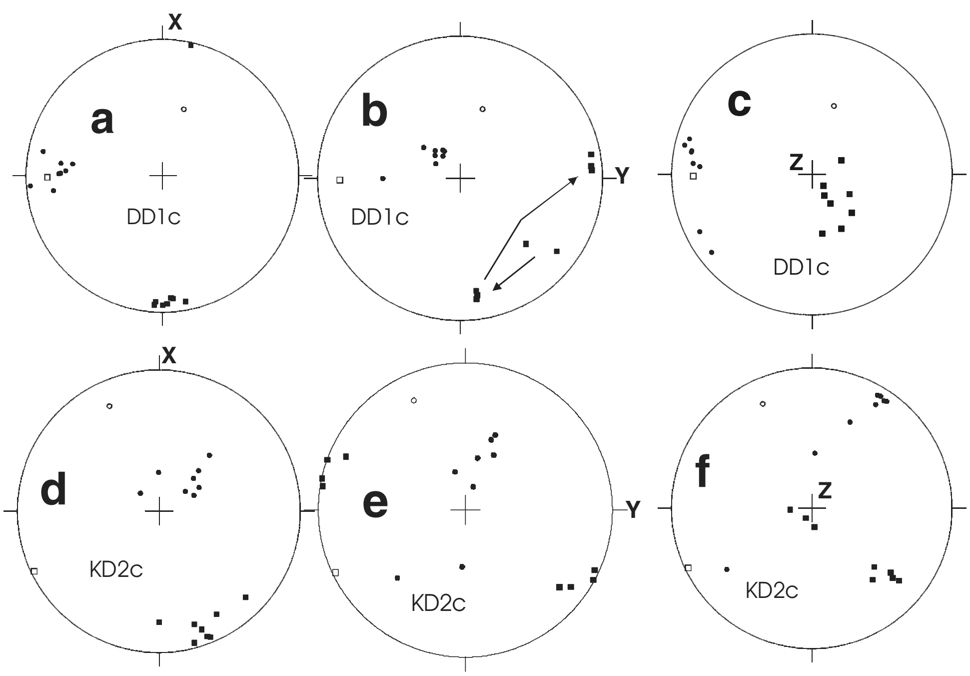

Figure 5. Maximum $\mathbf{K}_1$ (open square) and minimum $\mathbf{K}_3$ (open circle) principal AMS axes of the initial fabric and maximum K_1 (full squares) and minimum K_3 (full circles) principal axes of the difference ellipsoids during stepwise AF demagnetization in the samples DD1c (a, b, c) and KD2c (d, e, f) for AF applied along X (a, d), Y (b, e) and Z (c, f) directions (stereographic projection in the lower hemisphere).

asymmetry of the AF effect. Such an asymmetry cannot be due to the field itself, but indicates an effect of the used procedure or/and of the sample characteristics. In different samples from the same unit, the procedure being the same, its effect should be also the same, and that is not the case in our three samples: the maximum variation of the diagonal terms of the tensor for a same AF applied along its associated direction corresponds to either the X or Y direction. Hence, the procedure followed cannot be the only mechanism explaining the asymmetry of the AF effect on AMS.

Granite and gneiss samples

Nine samples (Table 1) with high magnetic anisotropy have been selected in gneiss and granite collected in the Pointe Géologie area (66°40S; 140°00E) of Terre Adélie, (Monnier *et al.* 1996). They possess high susceptibility and have susceptibility ellipsoids of various shapes. Microscopic observations under reflected light, thermomagnetic curves and microprobe analysis (Jordanova *et al.* 2007) clearly indicate the presence of magnetite, of Ti-poor titanohematite and of Ti-poor titanomaghemite. Hysteresis measurements indicate large effective magnetic grain sizes (H_{cr}/H_c between 5.5 and 26.9 and J_{rs}/J_s between 0.01 and 0.02). Observations of thin sections show concentrations of opaque minerals in narrow strips, and AMS in these rocks is probably partly a distribution anisotropy (Hargraves *et al.* 1991). Gneiss of sedimentary protolith (mainly pelitic) is characterized by the presence of ilmenite–hematite solid solutions with a mean composition close to Ilm_{15}-Hem_{85}. Some samples as AP85c show opaque fractions with a titanohematite content larger that the magnetite one, and AMS could thus result from both shape preferred orientation of the whole magnetic grains and lattice preferred orientation of titanohematite. The increase of the mean susceptibility **Km** as a function of the amplitude of the applied AF is in general important (Jordanova *et al.* 2007) and mainly occurs in low AF amplitude. The **Km** variation appears to be different according to the direction of AF application for amplitudes up to 40 mT. Fig. 7 presents the example of sample AP85c: the **Km** increase is minimum for the AF direction along X (i.e. the direction the closest to $\mathbf{K}_1$) and maximum for the AF direction along Y (i.e. the direction the closest to $\mathbf{K}_3$). There is, therefore, another magnetic anisotropy, related to the variation of **Km**, which appears only for the lowest AF amplitudes and seems to be inverse compared to the initial AMS.

Measured AMS

The principal axes orientation is hardly affected during stepwise AF demagnetization. For the two samples with the highest susceptibility (DDU344 and DDU361—AF applied only along Z direction), the principal maximum axis evolves first of about 10° towards the Z direction for AF up to 7 mT, and back towards its initial position for higher fields. Parameter $\mathbf{P}'$ increases in all the samples, from 2.1 to 16.3 per cent according to the samples. The $\mathbf{P}'$ increase in percentage seems to be partly related to the initial $\mathbf{P}'$ value (Fig. 8). This increase mostly corresponds to a weak variation of the shape parameter **U**. For three samples with AF applied only along a single direction (DDU29, DDU344 and DDU361), the variation of **U** during stepwise AF demagnetization is an increase followed by a decrease. The relationship between $\mathbf{d}_{AMS}$ and $\mathbf{d}_{Km}$ (Jordanova *et al.* 2007) is similar, whatever the direction of AF application (Fig. 4b).

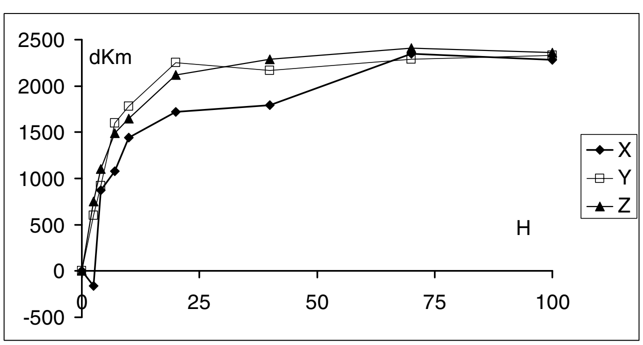

Figure 7. Variation of d_{Km} (in 10^{-6} SI) as a function of AF amplitude (in mT) according to the direction of AF application for sample AP85c.

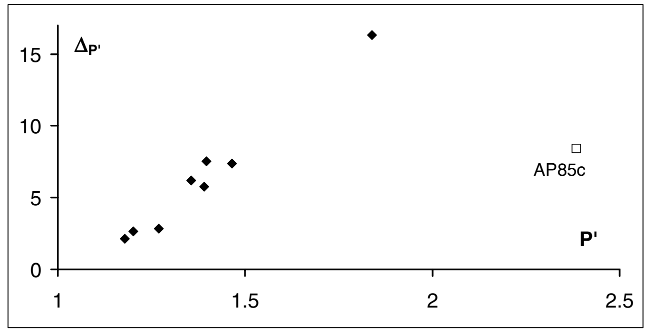

Figure 8. Variation ($\Delta P'$) in percentage of P' relative to the initial P' value, after the highest stepwise AF demagnetization, as a function of P' of the initial AMS.

Difference ellipsoids

Sample AP85c has very high initial magnetic anisotropy ($\mathbf{P}' = 2.385$). Its difference ellipsoids have principal axes close to those of the initial magnetic fabric. The higher the AF amplitude the closer is K_1 of the difference ellipsoid to the initial principal maximum axis $\mathbf{K}_1$. This evolution of the principal axes during stepwise treatment is independent from the direction of the AF applied field. The same observation can be made for U parameter that shows an increase for low AF amplitude and, after 25 mT AF demagnetization, a stable neutral value similar to that of the initial magnetic fabric.

The other samples show K_1 principal axes of the difference ellipsoids that are relatively well grouped in a girdle (Fig. 9). Some similar characteristics can be observed:

– K_1 of the difference ellipsoids are always near to the magnetic foliation plane $\mathbf{K}_1 - \mathbf{K}_2$ of the initial fabric.

– If the direction of AF application is very different from this plane, K_1 principal axes of the difference ellipsoids are close to $\mathbf{K}_1$ of the initial magnetic fabric.

– During stepwise AF demagnetization, K_1 principal axes of the difference ellipsoids always evolve towards $\mathbf{K}_1$ of the initial magnetic fabric.

– U values for the difference ellipsoids show variation for the lowest AF amplitudes but become stable for higher amplitudes, generally with values similar to that of **U** for the initial magnetic fabric (Table 1).

Tensor terms

Contrary to the case of the diorite samples, the diagonal terms **XX**, **YY** and **ZZ** of the AMS tensor do not show significantly different

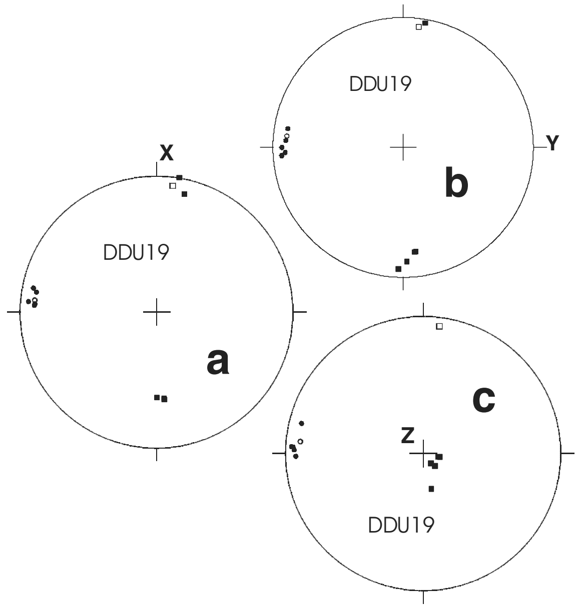

Figure 9. Maximum $\mathbf{K}_1$ (open square) and minimum $\mathbf{K}_3$ (open circle) principal AMS axes of the initial fabric and maximum K_1 (full squares) and minimum K_3 (full circles) principal axes of the difference ellipsoids during stepwise AF demagnetization in the sample DDU19 for AF applied along X (a), Y (b) and Z (c) directions (stereographic projection in the lower hemisphere).

values when AF was applied along their corresponding direction or along perpendicular directions.

DISCUSSION

Difference ellipsoids, independent from samples characteristics and with uniaxial prolate shape along the direction of the applied AF, were expected according to the results obtained by Potter & Stephenson (1990a,b). In the weakly anisotropic loess and palaeosols, the difference ellipsoids have K_1 along the direction of the applied AF and a prolate shape, only slightly different from an uniaxial ellipsoid (Table 1). But they always present K_3 parallel to the principal minimum axis $\mathbf{K}_3$ of the initial magnetic fabric. They, therefore, result from two different origins, the direction of the applied AF and the initial magnetic fabric, the first one being largely dominant.

In sample AP85c with very high magnetic anisotropy, the effect of the direction of the AF applied seems on the contrary to be negligible. That is not the case in the other samples of granite and gneiss with high magnetic anisotropy, where K_1 of the difference ellipsoids does not always corresponds to the principal maximum axis $\mathbf{K}_1$ of the initial magnetic fabric and can be different according to the direction of the applied field. The effect of the direction of the applied AF does not appear in the variation of the diagonal tensor terms and remains, therefore, low compared to that of the initial magnetic fabric. Variation of the U parameter of the difference ellipsoids during stepwise AF demagnetization indicates that this effect is probably stronger for the lowest AF amplitudes. This is confirmed by the evolution of K_1 of the difference ellipsoid towards $\mathbf{K}_1$ of the initial magnetic fabric during stepwise AF demagnetization.

The diorite samples, moderately anisotropic, represent an intermediate case for the AF effects. In these samples the direction of AF has the major role in the evolution of the magnetic fabric during AF demagnetization. But the effect of the initial magnetic fabric is more important than in the weakly anisotropic loess and palaeosols, K_1 for difference ellipsoids being slightly deviated relative to the direction of the applied field.

The behaviour of sample TAG54 is entirely different from that of the other strongly anisotropic samples. For difference ellipsoids, K_3 coincides with the principal intermediate axis $\mathbf{K}_2$ of the initial magnetic fabric and K_1 corresponds neither to the principal minimum axis $\mathbf{K}_3$ nor to the principal maximum axis $\mathbf{K}_1$ of this initial fabric. After AF demagnetization at 40 mT, permutation $K_1 - K_2$ occurs for the difference ellipsoids with K_1 becoming closer to direction of the applied AF. This could indicate an increase for the highest AF amplitudes of the effect of the AF direction relative to that of an 'initial magnetic fabric' which remains dominant (in this case the effect would be opposite to that observed in the other highly anisotropic samples). The interesting question concerns this 'initial magnetic fabric': what do the principal axes of the difference ellipsoid represent in this sample? That is the magnetic fabric of ferrimagnetic minerals. The latter can be either all ferrimagnetics (thus implying very strong magnetic fabric of the paramagnetics, the initial AMS being different from that one of the ferrimagnetics) or part of them that are more affected by AF than the other ones.

The fabric from difference ellipsoids represents one of the components of a composite initial magnetic fabric. The surprising characteristics for undeformed sediment (no relation with stratification, very high anisotropy) of the initial magnetic fabric of this sample could be partly explained by its composite character.

AF demagnetization effects are a polarization of the magnetic moment of the grains along the direction of field application. For MD grains, Jordanova *et al.* (2007) suggested that these AF effects on susceptibility and on its anisotropy are due to 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 that ones at the initial state. They also showed that the higher the magnetic anisotropy, the stronger is the variation of *Km* due to AF demagnetization.

In an isotropic grain, none of the easy magnetization axis is favoured and domains could have equal repartition of the different domains with elementary magnetic moments of different orientation. When submitted to AF, the magnetic moment of the grain tilts towards the easy magnetization axis closest to the AF direction and a new configuration of domain wall is reached. This configuration partly depends on the unpinning of domain walls and may correspond to a local energy minimum different from the global energy minimum. However, because it was possible for the magnetic moment to tilt, the difference in energy level mostly remains moderate.

In a strongly anisotropic grain, the initial domain wall configuration is totally different. For example, in a prolate very elongated grain with shape anisotropy, domain walls and elementary magnetic moments are mainly perpendicular to the long axis of the grain. Only small closure domains exist on the grain borders. To tilt the magnetic moment of the grain in a direction parallel to its lengthening needs a large amount of energy supplied by AF, but the reached domain wall configuration generally is unstable as soon as the field is switched off. Effect of AF in such a case is then a limited change, caused by unpinning and bending of domain walls. Local minimum energy could be probably more different from global minimum energy than for an isotropic grain. An increase of the closure domains gives a change of the magnetic anisotropy, but also of the domain wall area and of the mean susceptibility. It is clear that all these changes are strongly related to the initial magnetic fabric of the rock.

Moderate to high magnetic anisotropy represents an intermediate case resulting from both isotropic and strongly anisotropic behaviours.

CONCLUSION

For MD grains, the effect of AF demagnetization on AMS described by Potter & Stephenson (1990a,b) is probably only observable in isotropic rocks. Though largely dominant in weakly anisotropic samples, it is combined with an effect of the initial magnetic anisotropy in all the anisotropic rocks examined in the present study.

In particular cases, difference ellipsoids obtained by AF demagnetization in general reveal a composite magnetic fabric. Enhancing of the initial magnetic fabric (Liu *et al.* 2005) by AF application could have significant results only in case of non-composite fabric; the increase of the susceptibility and its anisotropy being then only related to AF field direction (isotropic effect) and to the initial magnetic anisotropy. Actual interest of such a method concerns only weak magnetic fabric, determined with high uncertainty. The main problem will be then to determine if the initial magnetic fabric is composite or not, the differences between tensor terms used to obtain the difference ellipsoids being mostly too small in such a case of weak initial magnetic fabric.

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