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The use of the anisotropy of magnetic remanence in the resolution of the anisotropy of magnetic susceptibility into its ferromagnetic and paramagnetic components

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Abstract

The anisotropy of magnetic susceptibility (AMS) is often controlled by both ferromagnetic (sensu lato) and paramagnetic minerals. The anisotropy of magnetic remanence (AMR) is solely controlled by ferromagnetic minerals. Jelínek (Trav. Geophys. 37 (1993)) introduced a tensor derived from the isothermal AMR whose normalized form equals the normalized susceptibility tensor provided that the ferromagnetic fraction is represented by multi-domain magnetite. The present paper shows the close correlation between these tensors for a collection of strongly magnetic specimens containing multi-domain magnetite. In addition, acceptable correlation between the tensors was also found for a collection of specimens containing single-domain magnetite. A new method is developed for the AMS resolution into ferromagnetic and paramagnetic components using the AMR. Some examples are presented of this resolution in mafic microgranular enclaves in granodiorite and in gneisses of the KTB borehole.

Keywords: Anisotropy; Susceptibility; Remanence; Component resolution

1. Introduction

The anisotropy of magnetic susceptibility (AMS) is mainly controlled by the preferred orientation of ferromagnetic (sensu lato), paramagnetic, and diamagnetic minerals in a rock. In strongly magnetic rocks, with bulk susceptibility higher than 5×10^{-3} [SI], the effects of paramagnetic and diamagnetic minerals are negligible and the AMS is effectively controlled by the ferromagnetic fraction only. In weakly magnetic rocks, with bulk susceptibility less than 5×10^{-4}, the content of ferromagnetic minerals is often so low that the AMS is effectively controlled by the paramagnetic fraction (the effect of the diamagnetic fraction can still be neglected) (Rochette, 1987; Hrouda and Jelínek, 1990). In very weakly magnetic rocks, with bulk susceptibility less than 5×10^{-5}, the effect of diamagnetic fraction cannot be, in general, neglected (Owens and Rutter, 1978; Hrouda, 1986).

In rocks with the bulk susceptibility between 5×10^{-4} and 5×10^{-3}, the AMS is generally controlled by both ferromagnetic and paramagnetic minerals. As these mineral groups may behave differently

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in various geological situations, it is desirable to resolve the rock AMS into its ferromagnetic and paramagnetic components. This resolution is usually made through measuring the AMS in magnetic fields of various intensities of the order of Tesla in which the ferromagnetic and paramagnetic minerals behave differently (e.g., Rochette and Fillion, 1988; Owens and Bamford, 1976; Hrouda and Jelínek, 1990) or at low temperature, below 118 K, the Verwey transition of magnetite (Richter and van der Pluijm, 1994). Unfortunately, the instruments for the former investigation are expensive and currently they are not commercially available and the latter method has still technical problems; the component resolution of the AMS is therefore not a routine technique. On the other hand, there is a method of the anisotropy of magnetic remanence (AMR) that is solely controlled by the ferromagnetic minerals and can advantageously be used to investigate their preferred orientation. The orientations of the principal directions of the AMR are virtually the same as those of the AMS. Unfortunately, the anisotropy magnitudes of the AMR are usually much higher than those of the AMS (e.g., Stephenson et al., 1986; Jackson, 1991), which makes use of AMR in the resolution of the AMS into ferromagnetic and paramagnetic components very difficult to impossible. In order to overcome this problem, Jelínek (1993) derived a special tensor from the AMR and called it the remanebility tensor of the second kind. If the ferromagnetic fraction is represented by multi-domain magnetite, the normalized remanebility tensor of the second kind equals the normalized susceptibility tensor. As Jelínek's (1993) paper was published in a less available journal, this technique remained virtually unknown and its potential has not been explored. The purpose of the present paper is to investigate the properties of the remanebility tensor of the second kind on real rocks and to develop a method of the resolution of the AMS into its ferromagnetic and paramagnetic components using the AMR. In addition, some examples of the practical application of the method are presented.

2. Definitions

The *anisotropy of magnetic susceptibility*, characterizing directional variability in low-field magnetic susceptibility, is usually represented by the susceptibility tensor linearly relating the induced magnetization to the magnetizing field. It is defined as follows

$$\mathbf{M} = \mathbf{k}\mathbf{H} \tag{1}$$

where $\mathbf{M}$ is column matrix representing the induced magnetization vector, $\mathbf{H}$ is column matrix representing the magnetizing field intensity vector, and $\mathbf{k}$ is square matrix representing the symmetric second-rank susceptibility tensor.

The *anisotropy of magnetic remanence* is defined analogously (e.g., Jackson, 1991) as

$$\mathbf{M}_\mathrm{R} = \mathbf{k}_\mathrm{R}\mathbf{H} \tag{2}$$

where $\mathbf{M}_\mathrm{R}$ matrix represents the remanent magnetization vector, $\mathbf{H}$ matrix represents the magnetizing field intensity vector, and $\mathbf{k}_\mathrm{R}$ matrix represents the *remanence susceptibility* tensor.

Where remanence is a non-linear function of the large field, $\mathbf{M}_\mathrm{R}$ and $\mathbf{H}$ are not related by a second-rank tensor. Nevertheless, the AMR can still, in many cases, be described by a symmetric second-rank tensor

$$\mathbf{M}_\mathrm{R} = \mathbf{k}_\mathrm{R}\mathbf{H}_\mathrm{u} f(H) \tag{3}$$

where $f(H)$ describes the non-linear field-dependence of $\mathbf{M}_\mathrm{R}$ ($\mathbf{H}_\mathrm{u}$ is the unity vector parallel to the field vector) (Cox and Doell, 1967; Daly and Zinsser, 1973; Stephenson et al., 1986; Jelínek, 1993).

For the case of quadratic relationship between the field and isothermal remanent magnetization (as in the Rayleigh region of the hysteresis loop)

$$\mathbf{M}_\mathrm{R} = \mathbf{R}\mathbf{H}_\mathrm{u} H^2 \tag{4}$$

Jelínek (1993) introduced for the tensor $\mathbf{R}$ the term *remanebility tensor of the first kind* as a remanence analogue of the susceptibility tensor (see also Daly and Zinsser, 1973).

For the special case when the mineral grains carrying the remanence are multi-domain and show shape anisotropy, Jelínek (1993) introduced *the remanebility tensor of the second kind* ($\mathbf{T}$) relating the AMR and AMS (Jelínek's, 1993 derivation of the remanebility tensor of the second kind is presented in the Appendix A). The principal directions of the remanebility tensor of the second kind have the same orientations as those of the remanebility tensor of the first kind and the principal remanebilities are related as follows

$$T_i = R_i^{1/3} \quad (i = 1,2,3) \tag{5}$$

where $T_1 \geq T_2 \geq T_3$ are the principal values of the remanebility tensor of the second kind and $R_1 \geq R_2 \geq R_3$ are the principal values of the remanebility tensor of the first kind. The remanebility tensor of the second kind normed by the mean remanebility is equal the susceptibility tensor normed by the mean susceptibility.

3. Theoretical considerations

The rock susceptibility can be described, with sufficient accuracy, by the following model (Henry, 1983; Henry and Daly, 1983)

$$\mathbf{k} = c_f\mathbf{K}_f + c_p\mathbf{K}_p + c_d\mathbf{K}_d = \mathbf{k}_f + \mathbf{k}_p + \mathbf{k}_d \tag{6}$$

where $\mathbf{k}$ is the rock susceptibility tensor, $\mathbf{K}_f$, $\mathbf{K}_p$, $\mathbf{K}_d$ are tensors of ferromagnetic (sensu lato), paramagnetic, and diamagnetic susceptibilities, respectively, and c_f, c_p, c_d are the respective percentages; $\mathbf{k}_f$, $\mathbf{k}_p$, $\mathbf{k}_d$ are called the respective susceptibility contribution tensors. If the diamagnetic susceptibility can be neglected and the ferromagnetic susceptibility contribution can be measured, then the paramagnetic susceptibility contribution tensor is

$$\mathbf{k}_p = \mathbf{k} - \mathbf{k}_f = \mathbf{k} - k_f\boldsymbol{\kappa}_f \tag{7}$$

where $\boldsymbol{k}_f$ is the mean susceptibility and $\boldsymbol{\kappa}_f$ the normed susceptibility tensor of the ferromagnetic component. Unfortunately, there is no simple method for determining the $\mathbf{k}_f$ or $\boldsymbol{\kappa}_f$ tensor, the existing methods being either expensive or too laborious. Inspired by Borradaile et al. (1999) who used the AMR in isolating the diamagnetic AMS components and using the normed remanebility tensor of the second kind ($\boldsymbol{\tau}$) we may write

$$\mathbf{k}_p = \mathbf{k} - k_f\boldsymbol{\tau}\,. \tag{8}$$

As the whole-rock AMS and isothermal AMR are measured and the mean susceptibility of the ferromagnetic fraction can be determined through the investigation of the temperature variation of the susceptibility (Hrouda, 1994; Hrouda et al., 1997), Eq. (8) can be used in the component resolution.

4. Empirical relationship between the AMR and AMS in multi-domain magnetite bearing rocks

To test the quantitative relationship between the AMR and AMS, a collection of specimens of granodiorite were investigated which have high bulk susceptibility (in the order of 10^{-2}) and their exclusive carrier of AMS is multi-domain magnetite whose relatively large grains can easily be observed under both transmitted-light and reflected-light microscope (Hrouda et al., 1971, 1972; Chlupáčová et al., 1975). The collection was selected in such a way that the range of the degree of AMS was relatively wide to enable easy investigation of the quantitative relationship between the AMR and AMS. In each specimen, the AMS and isothermal AMR (using the magnetizing field of 20 mT) were measured. The AMS was measured by the KLY-3S Kappabridge (Jelínek and Pokorný, 1997), the remanent magnetization was measured by the JR-5A Spinner Magnetometer, the specimens were magnetized isothermally by the PUM-1 Pulse Magnetizer and the measured AMR data were evaluated by the AREF program (based on Jelínek's, 1993 theory). The results are presented in Fig. 1 in terms of the orientations of the principal directions and values of the degree of anisotropy and magnetic fabric shape parameter defined as follows

$$P = k_1/k_3, \tag{9}$$

$$T = 2\ln(k_2/k_3)/\ln(k_1/k_3) - 1 \tag{10}$$

where $k_1 \geq k_2 \geq k_3$ are the principal values. The degree of anisotropy characterizes the intensity of the preferred orientation of magnetic minerals in a rock, the shape parameter, introduced by Jelínek (1981), indicates the character of the magnetic fabric. If $0 \leq T \leq 1$, the magnetic fabric is planar, if $1 \leq T \leq 0$, the magnetic fabric is linear.

Fig. 1a shows the orientations of magnetic lineations and magnetic foliation poles of AMR in the coordinate system of the principal directions of AMS. It is clear from the figure that in most specimens only

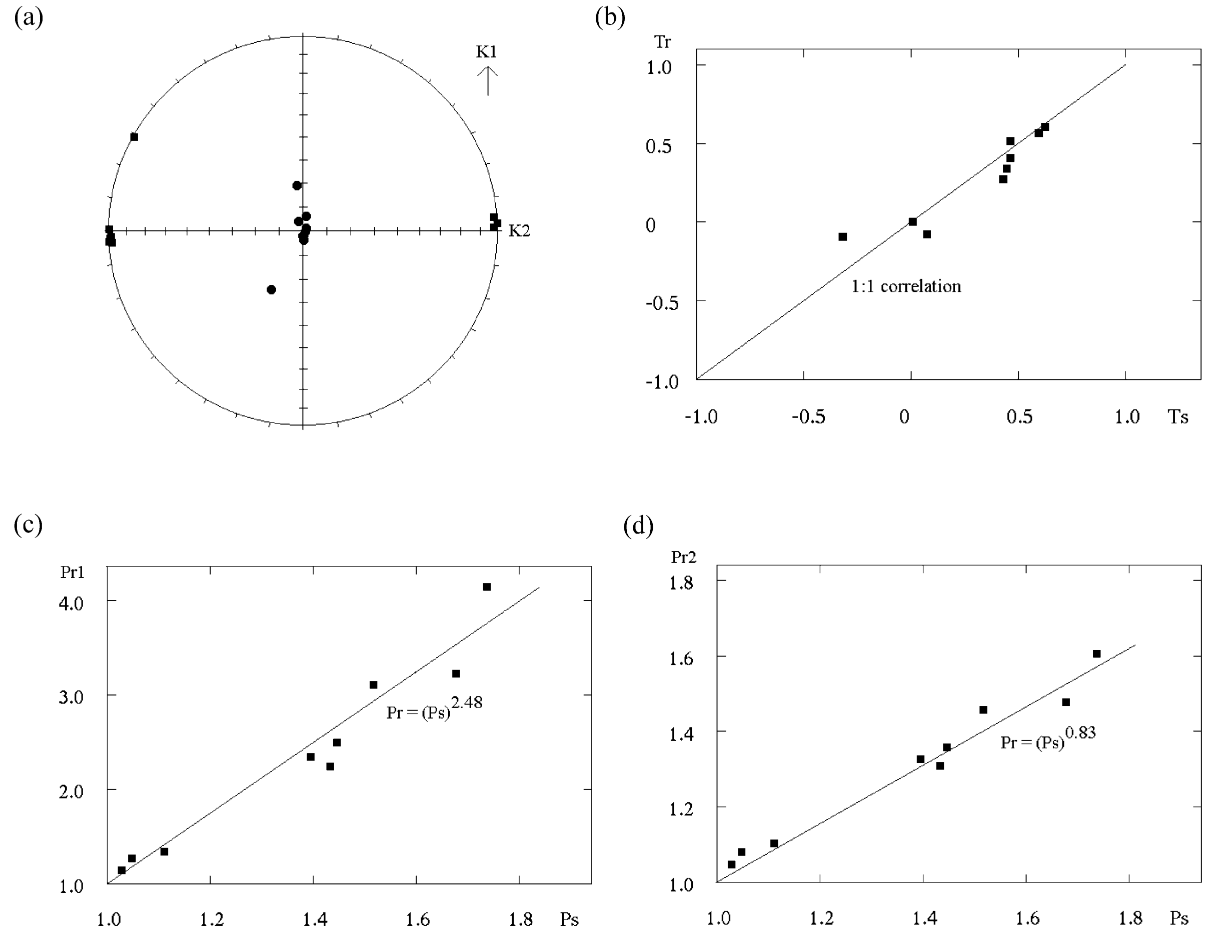


Fig. 1. AMR and AMS in granodiorites with multi-domain magnetite (the Čistá Massif, West Bohemia). (a) Orientations of AMR magnetic lineations (closed squares) and AMR magnetic foliation poles (closed circles). Coordinate system of the principal directions of AMS, K1 is the maximum susceptibility direction in AMS, center of the net indicates the minimum susceptibility direction. Equal-area projection on lower hemisphere. (b) Correlation between the shape parameters for AMR (T_r) and AMS (T_s), straight line of unity slope represents the 1:1 correlation. (c) Correlation between the degree of AMR calculated from the remanebility tensor of the first kind (P_{r1}) and that of AMS (P_s). (d) Correlation between the degree of AMR calculated from the remanebility tensor of the second kind (P_{r2}) and that of AMS (P_s).

very small differences in the orientations of the principal directions of AMS and AMR exist; in two specimens, the differences are larger but still relatively small.

Fig. 1b shows the correlation between the shape parameters from AMS and AMR. The individual plots lie near the line representing the 1:1 correlation, the correlation coefficient being $r = 0.93$. Even though the correlation is not very close, it is clear that the shapes of the AMR ellipsoids can be regarded for the first approximation as virtually the same as those of the AMS for practical purposes.

Fig. 1c shows the relationship between the degree of AMS (P_s) and the degree of AMR calculated from the remanebility tensor of the first kind (P_{r1}). It is obvious from the figure that a relatively close correlation between the degree of AMR and that of AMS exists ($r = 0.97$), but for all specimens the degree of AMR is much higher than that of AMS. According to Stephenson et al. (1986), this behaviour occurs, because it is

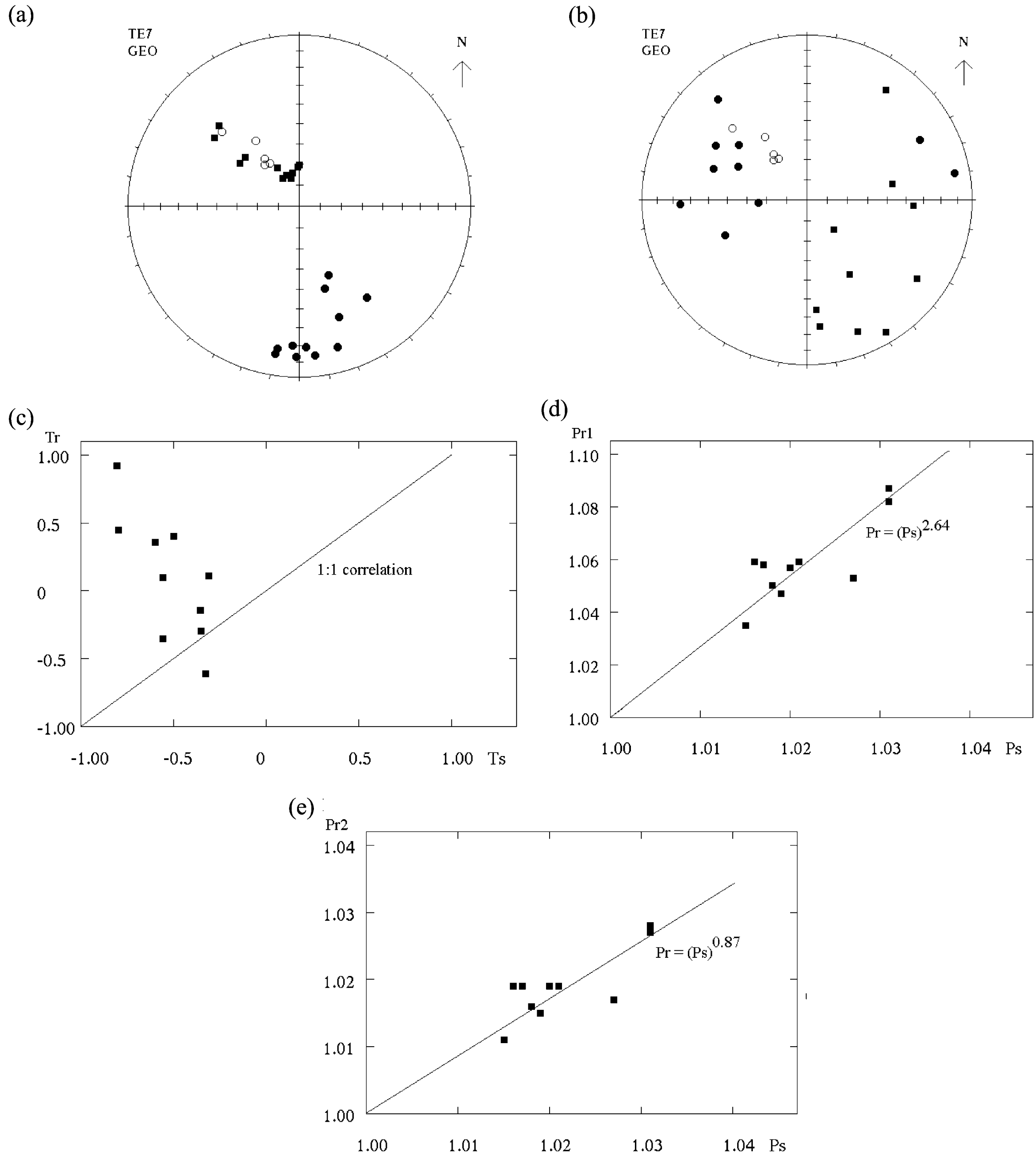


Fig. 2. AMR and AMS in siltstone with single-domain magnetite (locality of Choryně in the Flysch Belt of the West Carpathians). All stereoplots are in geographic coordinate system, equal-area projection on lower hemisphere. (a) Orientations of magnetic lineations (closed squares) and magnetic foliation poles (closed circles) of AMS as well as of bedding poles (open circles). (b) Orientations of magnetic lineations (closed squares) and magnetic foliation poles (closed circles) of AMR as well as of bedding poles (open circles). (c) Correlation between the shapes of AMR (T_r) and AMS ellipsoids (T_s). (d) Correlation between the degree of AMR calculated from the remanebility tensor of the first kind (P_{r1}) and that of AMS (P_s). (e) Correlation between the degree of AMR calculated from the remanebility tensor of the second kind (P_{r2}) and that of AMS (P_s).

easier to induce a reversible magnetization in an energetically unfavourable orientation than to impart a remanent magnetization. Therefore, remanence is by nature more anisotropic than susceptibility.

Combining Eqs. (A12), (5) and (9) yields the theoretical relationship between the degree of AMR calculated from the remanebility tensor of the first kind and the degree of AMS, $P_{r1} = P_s^3$. The same empirical relationship was calculated through least squares fitting the regression straight line to the $\ln P_{r1}$ and $\ln P_s$ data. The result was $\ln P_{r1}=(2.48 \pm 0.08) \ln P_s$, which can also be written as $P_{r1} = P_s^{(2.48 \pm 0.08)}$.

Fig. 1d shows the correlation between the degree of AMS (P_s) and that of AMR calculated from the remanebility tensor of the second kind (P_{r2}). It is clear from the figure that the correlation is very close ($r=0.99$). The regression straight line, calculated in the same way as in the previous case, is slightly less steep ($P_{r2} = P_s^{(0.83 \pm 0.03)}$) than expected from the theory and the normed remanebility tensor of the second kind cannot therefore be regarded as precisely equaling the normed susceptibility tensor. Nevertheless, the differences are not large and the remanebility tensor of the second kind can be, as the first approximation, used as an estimate of the ferromagnetic contribution to the AMS.

5. Empirical relationship between the AMR and AMS in single-domain magnetite bearing rocks

Even though the remanebility tensor of the second kind was derived for the multi-domain magnetite bearing rocks, it is interesting to know the effect of single-domain particles on it. To study this effect, we investigated specimens from the locality of Choryně in the Flysch Belt of the West Carpathians whose magnetism is carried by predominantly single-domain magnetite.

The AMS of rocks of the Flysch Belt of the West Carpathians is mostly sedimentary in origin, i.e. the susceptibility ellipsoids are predominantly oblate and the magnetic foliation is parallel to the bedding. However, in the locality of Choryně the susceptibility ellipsoids are clearly prolate and both the magnetic foliation and magnetic lineation are perpendicular to the bedding (Fig. 2a). This unusual AMS is explained as the inverse magnetic fabric sensu Rochette (1988) resulting from single-domain magnetite grains of very small size (Hrouda, 2000).

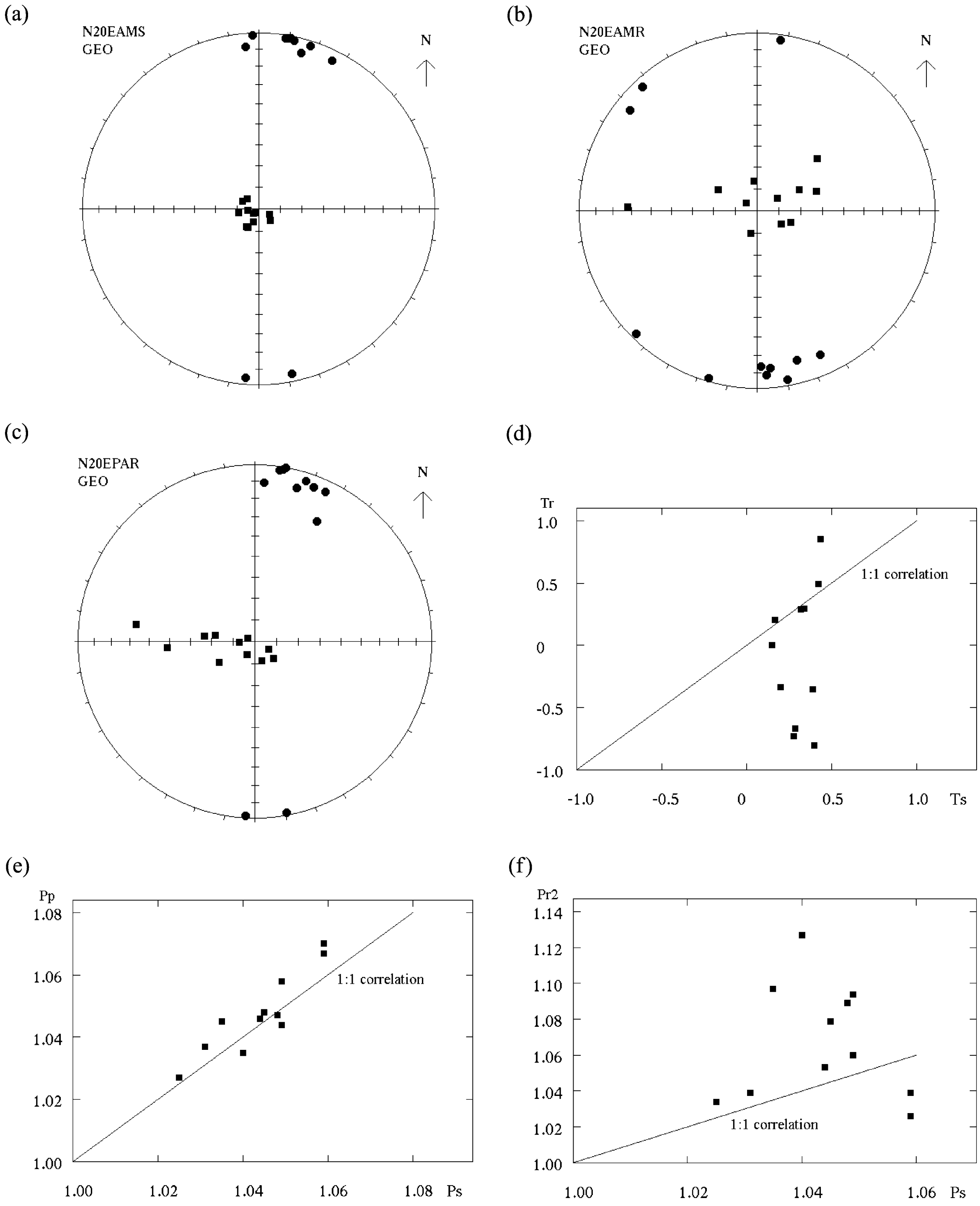
The AMR fabric is very different from the AMS fabric. Though largely scattered, the AMR magnetic foliation poles are in average near the bedding poles and the magnetic lineations are near the bedding (Fig. 2b). The AMR ellipsoids range from moderately prolate to strongly oblate (Fig. 2c).

The degree of AMR calculated from the remanebility tensor of the first kind correlates reasonably well with the degree of AMS ($r=0.81$), with the former being significantly higher ($P_{r1} = P_s^{(2.64 \pm 0.14)}$, see Fig. 2d). The degree of AMR calculated from the remanebility tensor of the second kind correlate well with the degree of AMS in a similar way ($r=0.80$), and the correlation is near the theoretical one ($P_{r2} = P_s^{(0.87 \pm 0.05)}$, see Fig. 2e). Consequently, the effect of single-domain state is not large and the remanebility tensor of the second kind can be also (even though with less accuracy) used in the AMS component analysis. However, one has to respect the differences in the ellipsoid shape and orientation.

6. Examples

The need of resolving the AMS into its ferromagnetic s.l. and paramagnetic components appeared in the investigation of mafic microgranular enclaves in granodiorite to tonalite of the Nasavrky massif (E. Bohemia). The emplacement of these rocks was modeled quantitatively and, for correct modelling, it was necessary to know the quantitative contributions of individual minerals to the rock AMS (Hrouda et al., 1999).

Fig. 3. AMR and AMS in microgranitic enclaves of the locality of Švihov in the Nasavrky Plutonic Complex (East Bohemia). All stereoplots are in geographic coordinate system, equal-area projection on lower hemisphere. (a) Orientations of magnetic lineations (closed squares) and magnetic foliation poles (closed circles) of AMS. (b) Orientations of magnetic lineations (closed squares) and magnetic foliation poles (closed circles) of AMR. (c) Orientations of magnetic lineations (closed squares) and magnetic foliation poles (closed circles) of paramagnetic component calculated by the present method. (d) Relationship between the shapes of AMR (T_r) and whole rock AMS (T_s) ellipsoids. (e) Correlation between the degree of paramagnetic (P_p) and whole rock AMS (P_s). (f) Relationship between the degree of ferromagnetic (P_{r2}) and whole rock AMS (P_s).


(a)
N20EAMS
GEO
N
(b)
N20EAMR
GEO
N
(c)
N20EPAR
GEO
N
(d)
Tr
1.0
0.5
0
-0.5
-1.0
-1.0
-0.5
0
0.5
1.0
Ts
1:1 correlation
(e)
Pp
1.08
1.06
1.04
1.02
1.00
1.00
1.02
1.04
1.06
1.08
Ps
1:1 correlation
(f)
Pr2
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
1.00
1.02
1.04
1.06
Ps
1:1 correlation

For this reason, a relatively extensive investigation of the temperature variation of the rock bulk susceptibility was made, using the technique by Hrouda (1994), which enables the rock bulk susceptibility into ferromagnetic and paramagnetic components to be resolved. It was shown that the bulk susceptibility is carried by both ferromagnetic (represented by magnetite) and paramagnetic (represented by amphibole and biotite) minerals whose contributions to susceptibility are more or less equal, even though in some specimens the former minerals can contribute more strongly than the latter and vice versa. It was hypothesized that similar situation is also observed for the AMS, even though it is not necessarily so. Particularly in very weakly anisotropic rocks, the magnetite grains may be nearly spherical and their grain AMS much lower than the magnetocrystalline AMS of amphibole and biotite. On the contrary, in strongly deformed rocks, the magnetite grains may become, due to progressing deformation, strongly anisometric and their AMS much stronger than that of amphibole and biotite. Let us test our case to determine as to which one it follows.

The enclaves are weakly magnetic, with bulk susceptibility being in the order of 10^{-4}. Their AMS was resolved into components using Eq. (8). The results are summarized in Fig. 3. The magnetic foliation poles and the magnetic lineations of the paramagnetic component are much less scattered than those of the ferromagnetic component and are oriented almost identically as those of the whole-rock AMS (Fig. 3a,b,c). The shapes of the susceptibility ellipsoids of the paramagnetic fraction correlate very well with those of the whole-rock AMS (with correlation coefficient of $r = 0.80$), while the shapes of the susceptibility ellipsoids of the ferromagnetic component do not correlate with those of the whole-rock AMS at all (Fig. 3d). The degree of AMS of the paramagnetic fraction correlates well with that of the whole rock ($r = 0.90$, Fig. 3e), while the degree of AMS of the ferromagnetic component does not correlate with that of the whole rock at all ($r = -0.1$, Fig. 3f). It is clear from the above data that the paramagnetic fraction affects the whole-rock AMS more strongly than the ferromagnetic fraction.

The other example comes from the rocks of the KTB super-deep borehole (Germany). On a small collection of gneisses from this borehole, low field AMS, high field magnetic anisotropy (using torque magnetometer), and temperature variation of bulk susceptibility were investigated (Friedrich et al., 1995; Hrouda et al., 1996). The AMS and bulk susceptibility resolutions into paramagnetic and ferromagnetic components were made using the Hrouda and Jelínek (1990) and the Hrouda (1994) techniques, respectively. In addition, the isothermal AMR induced in the DC field of 20 mT was investigated and the resolution was made using the technique proposed in the present paper. Below, the results of the resolution made by both the techniques are presented for the specimens containing magnetite.

The susceptibility resolution into paramagnetic and ferromagnetic components has shown that the former

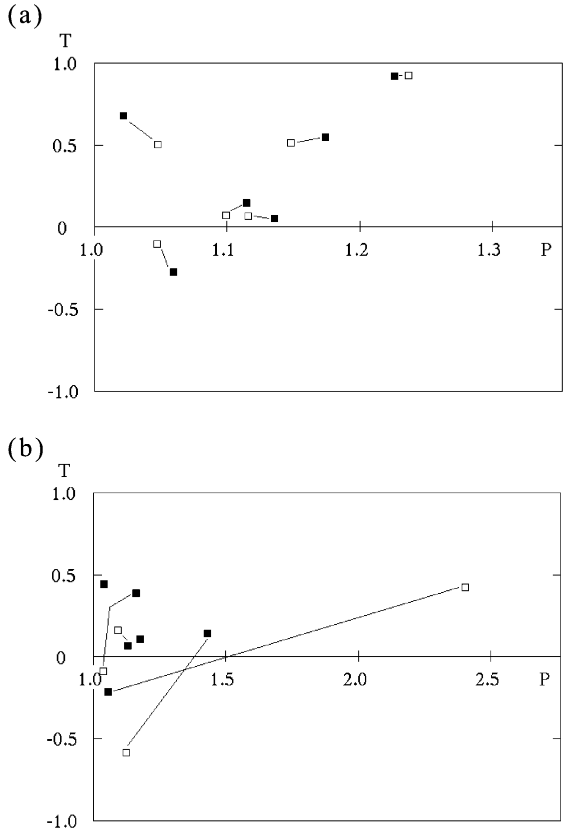


Fig. 4. Resolution of the AMS of the specimens of the KTB borehole into paramagnetic and ferromagnetic components using the present method (closed symbols) and the Hrouda and Jelínek (1990) method (open symbols). (a) AMS parameters for the paramagnetic component. (b) AMS parameters for the ferromagnetic component.

component is much stronger than the latter. The orientations of magnetic lineation and magnetic foliation pole of the paramagnetic component calculated using both methods are very near to those of the whole-rock AMS. The same AMS axes for the ferromagnetic component differ from the whole-rock AMS axes, probably because of low accuracy in the determination of ferromagnetic anisotropy components in weakly magnetic rocks. Nevertheless, the magnetic foliation poles, though with larger scatter, concentrate in the vicinity of the AMS magnetic foliation pole; the magnetic lineations are orientated, though relatively scattered, in the vicinity of the AMS magnetic lineation axes. Consequently, these orientations probably indicate coaxial orientations of the whole-rock, paramagnetic and ferromagnetic fabric elements (Friedrich et al., 1995).

Fig. 4a shows the magnetic anisotropy plot for the separated paramagnetic components determined by the torque magnetometer method (open symbols) and by the present method (closed symbols). It can be seen in the figure that the open and closed symbols corresponding to individual specimens are relatively close each to the other, thus indicating that the paramagnetic component calculated by the two above methods give similar results. Fig. 4b shows the same plots for the ferromagnetic components. Here the anisotropy parameters determined by both the methods are different. In addition, the open symbols are only four, because the calculation of the ferromagnetic component using torque method failed in two specimens, probably because of too weak ferromagnetic component.

7. Discussion

The main problem of the AMR measurement is that a relatively strong magnetizing field must be used to reach an acceptable precision in the AMR determination. This field is only rarely weak enough for a linear relationship to exist between the field and isothermal remanent magnetization enabling the AMR to be treated correctly from the physical point of view. In the most cases, the field must be stronger resulting either in quadratic or even more complex relationship. In this case, the linear relationship between the function of the field and remanent magnetization (Eq. (3)) can still exist, but often, it is not the case. Testing validity of Eq. (3) is very simple, though laborious and time-consuming, through measuring the AMR in several magnetizing fields. If the orientations of the principal directions are more or less constant in all the fields, Eq. (3) can be considered to be valid. An example is presented in Fig. 5a, which shows the variations in orientations of principal directions of a granodiorite specimen whose isothermal AMR was measured using the magnetizing fields of 3, 5, 8, 10, 15, 20 mT. It is clear from the figure that the orientations of the principal directions measured in all fields are virtually coaxial. On the other hand, if the orientations of the principal directions vary systematically with field, Eq. (3) is no longer valid and using the linear theory can result in introducing relatively large errors. An example is shown in Fig. 5c where maximum and minimum axes are plotted according to field for a sample of serpentinized peridotite. The directions strongly vary with field and Eq. (3) is therefore no longer valid.

The present method is based on quantitative subtraction of the AMR tensor from the rock AMS tensor and in this process the assumptions defined not only by Eq. (3), but also by Eq. (4) must be valid. The validity of Eq. (4) can be easily tested through investigating the variation of amplitude of the remanent magnetization with field.

After determining that Eqs. (3) and (4) are valid, the remanebility tensor of the second kind is a useful tool for estimation of the ferromagnetic component of the AMS. However, in this use one has to keep in mind the fact that the normed remanebility tensor does not equal the susceptibility tensor precisely and the estimate of the ferromagnetic component of the AMS by the AMR is only approximate. Nevertheless, the estimate is sufficiently precise for many purposes. Its main advantage lies in the fact that the AMR method, in contrary to high field anisotropy method, which requires expensive instrumentation, is relatively inexpensive, because the isothermal magnetizer is relatively cheap and the AF demagnetizer and remanence meter are the standard equipment of palaeomagnetic laboratories.

Even though the anhysteretic AMR is usually preferred for the isothermal AMR because of its presumed higher precision, the component analysis of magnetic anisotropy introduced in the present paper prefers the isothermal AMR for which the remanebility tensor of the second kind was developed. Namely, the micro-mechanisms of the anhysteretic magnetizing

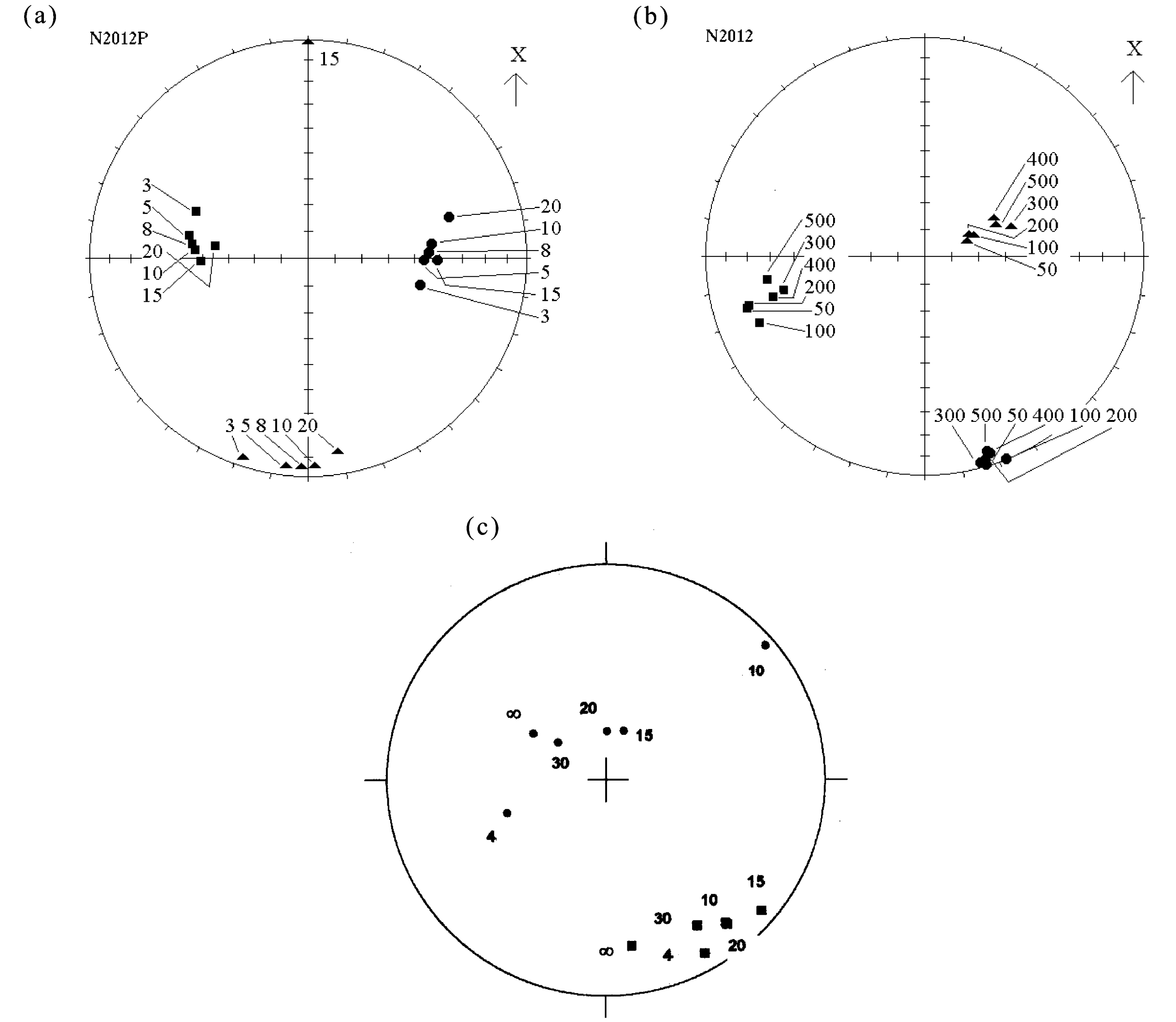


Fig. 5. Variation of the orientations of the principal directions of the AMR with magnetizing field. All plots are in equal-area projection on lower hemisphere. (a) Specimen No. N2012 of granodiorite from the Nasavrky massif. Isothermal AMR acquired in the fields of 3, 5, 8, 10 15, 20 mT (indicated at individual points). Small variations of orientations of the principal directions (square—maximum, triangle—intermediate, circle—minimum axes) with field. Specimen coordinate system. (b) Specimen No. N2012 of granodiorite from the Nasavrky massif. Anhysteretic magnetizations acquired in the AF field of 100 mT and in bias fields of 50, 100, 200, 300, 400, 500 μT (indicated at individual points). Note that the maximum directions are oriented in a similar way as those in isothermal AMR (panel (a)), while the intermediate and minimum directions interchange. Specimen coordinate system. (c) Maximum (square) and minimum (circle) axes of AMR fabric as a function of AF intensity (in mT, written at individual points) in sample of serpentinized peridotite. Adapted from Bina and Henry (1990).

can be different, which can result in imprecise resolution. This is well illustrated in Fig. 5b, which shows the anhysteretic AMR directions of the same specimen as presented in Fig. 5a. The anhysteretic AMR was acquired in the AF field of 100 mT and bias DC fields of 50,100, 200, 300, 400, and 500 μT. It is clear from Fig. 5a,b that only the maximum directions show similar orientations for isothermal and anhysteretic AMR, while the intermediate and minimum directions are evidently interchanged. Our experiments show that having a good instrument for isothermal magnetizing (e.g., the PUM-1 Pulse Magnetizer), the precision in determining the isothermal AMR is comparable to that in determining the anhysteretic AMR.

8. Conclusions

(1) The anisotropy of magnetic remanence (both isothermal and anhysteretic) is significantly stronger than the anisotropy of magnetic susceptibility.

(2) The normed tensor of remanebility of the second kind, derived from the AMR measured in the Raleigh region for the multi-domain magnetite and introduced by Jelínek (1993), theoretically equals the normed susceptibility tensor.

(3) The normed tensors of remanebility of the second kind measured for strongly magnetic rocks in which both AMR and AMS are carried by multi-domain magnetite are very similar to the normed susceptibility tensors even though the differences are slightly higher than the measuring errors.

(4) The normed tensor of remanebility of the second kind may be, with acceptable error, used to quantitatively estimate the normed tensor of susceptibility provided that the magnetism carrier is multi-domain magnetite. Then, knowing the ferromagnetic and paramagnetic components of the mean susceptibility (obtained, for example, through the investigation of the temperature variation of susceptibility), the whole-rock susceptibility tensor can be resolved into its paramagnetic and ferromagnetic components.

(5) Although the estimation of the ferromagnetic susceptibility tensor through the remanebility tensor of the second kind is less precise than the direct measurement, it is very practical, because the equipment for measuring the anisotropy of remanence is available in almost each rock magnetism laboratory, while the equipment for direct measurement is very expensive and only rarely available.

(6) In AMR studies, the anhysteretic AMR is often preferred for the isothermal AMR, because of its presumed higher precision. However, the component analysis of magnetic anisotropy introduced in the present paper prefers the isothermal AMR for which the remanebility tensor of the second kind was developed. Our experiments show that, having a good instrument for isothermal magnetizing (e.g., the PUM-1 Pulse Magnetizer), the precision in determining the isothermal AMR is comparable to that in determining the anhysteretic AMR.

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Appendix A. Introduction of the tensor of remanebility of the second kind (slightly adapted from Jelínek, 1993)

Let us consider the behaviour of a single magnetic grain. The demagnetized grain is commutatively magnetized with an external field of maximum intensity **H**. The intensity **h** inside the grain

$$\mathbf{h} = \mathbf{H} + \mathbf{h}_{\mathrm{dem}} = \mathbf{H} - \mathbf{N}\mathbf{m} \tag{A1}$$

where $\mathbf{h}_{\mathrm{dem}}$ is the intensity of the so-called demagnetizing field, **m** denotes the magnetization vector of the grain, and **N** is the demagnetizing factor. (The demagnetizing factor of an ellipsoid is a symmetric second-order tensor, see Coe, 1966.) The magnetization

$$\mathbf{m} = æ\mathbf{h} \tag{A2}$$

where $æ$ is the internal susceptibility of the grain.

Eqs. (A1) and (A2) yield

$$\mathbf{h} = \mathbf{A}\mathbf{H}, \tag{A3}$$

where $\mathbf{A}=(\mathbf{I}+æ\mathbf{N})^{-1}$ and **I** is the identity matrix.

Now, we shall decrease the external field so that the intensity inside the grain drops to zero. The grain retains magnetization $\mathbf{m}_{\mathrm{o}}$, for which

$$\mathbf{m}_{\mathrm{o}} = \alpha\langle\mathbf{h}\rangle^2 = \alpha\langle\mathbf{A}\mathbf{H}\rangle^2 \tag{A4}$$

where **H** and **h** are the values during magnetization, α is the Rayleigh constant. The expression $\langle\mathbf{h}\rangle^2$ denotes a vector which is parallel to **h** and whose modulus is h^2. The meaning of the expression $\langle\mathbf{A}\mathbf{H}\rangle^2$ is analogous.

Now, when the external field is totally removed, the magnetization drops to the remanent value, again denoted **m**. Without the external field

$$\mathbf{h} = -\mathbf{N}\mathbf{m} \tag{A5}$$

Further

$$\mathbf{m} = \mathbf{m}_o + æ\mathbf{h} \tag{A6}$$

Removing **h** from Eqs. (A5) and (A6) and using Eq. (A4), we get the resultant relation

$$\mathbf{M} = \alpha\mathbf{A}\langle\mathbf{AH}\rangle^2 \tag{A7}$$

Then, the resultant (average) magnetization of the specimen

$$\mathbf{M} = \varphi\alpha\mathbf{A}\langle\mathbf{AH}\rangle^2 \tag{A8}$$

where φ is the volume concentration of the ferromagnetic fraction. The equation can be simplified to

$$\mathbf{M} = v_o H^2\mathbf{T}\langle\mathbf{Td}\rangle^2 \tag{A9}$$

where **T** is a suitable scalar multiple of tensor **A**.

Tensor **T** will be called the remanebility tensor of the second kind. We may also introduce derived quantities of the second kind, namely principal remanebilities, principal directions and anisotropy factors. To a certain degree, Eq. (A9) is analogous to Eq. (4). However, in case of shape anisotropy it is on a better physical basis.

Tensor **T** is closely related to the magnetic susceptibility tensor **k** which expresses the relationship between "soft" magnetization and the external field (see Eq. (1)). If the susceptibility of matrix can be neglected, it can easily be derived from Eq. (2)

$$\mathbf{M} = \varphi\, æ\mathbf{AH}. \tag{A10}$$

Comparison of Eqs. (1) and (A10) yields

$$\mathbf{k} = \varphi æ\mathbf{A}. \tag{A11}$$

Therefore, tensor **k** is a scalar multiple of tensor **A** as well as of tensor **T**. This implies that tensor **k** is also a multiple of tensor **T**. Then the normed tensors

$$\mathbf{k}_n = \mathbf{T}_n \tag{A12}$$

This result is of crucial importance as it directly relates susceptibility anisotropy to remanebility anisotropy. The validity of Eq. (A12) is only approximate as in real cases, as a rule, the assumptions on which it was derived are approximate.

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