

# Modelling Relationship Between Bulk Susceptibility and AMS in Rocks Consisting of Two Magnetic Fractions Represented by Ferromagnetic and Paramagnetic Minerals – Implications for Understanding Magnetic Fabrics in Deformed Rocks

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**Abstract:** Measurement of Anisotropy of Magnetic Susceptibility (AMS) has become an important tool for Structural Geological analysis in the past few decades. In the past, AMS data have been used for petrofabric analysis of deformed rocks as well as for gauging strain. However, the AMS of some rocks can be carried by both ferromagnetic and paramagnetic minerals. Separating effects of these mineral groups on the rock's AMS is difficult because of expensive and commercially less available instrumentation. On the other hand, instrumentation is available in most rock magnetic and palaeomagnetic laboratories for resolving bulk susceptibility into ferromagnetic and paramagnetic components. Mathematical modelling was made of the relationship between bulk susceptibility and AMS. If the contribution of the ferromagnetic or the paramagnetic fraction to the rock susceptibility is dominant (let us say higher than 80%), the resultant AMS is relatively near to the AMS of the dominating fraction in all aspects, the degree of AMS, shape parameter and orientation of principal susceptibilities. In the interpretation of the AMS of rocks with dominating one fraction, the resolution of the AMS into paramagnetic and ferromagnetic components is not necessary, the resolution of bulk susceptibility into components is sufficient that can be made using the instrumentation available in most rock magnetic and palaeomagnetic laboratories.

**Keywords:** Magnetic anisotropy, Bulk susceptibility, Ferro- and paramagnetic minerals, Mathematical modelling.

## INTRODUCTION

The petrophysical method of the Anisotropy of Magnetic Susceptibility (AMS), which investigates the preferred orientation of magnetic minerals in rocks, is one of the most important techniques of the structural analysis of rocks. This technique is so sensitive that in rocks possessing very weak preferred orientation of minerals it is the only method that gives reasonable results (e.g. Hrouda, 2007; Ciffeli et al. 2009). In addition, it is extremely fast, an order of magnitude faster than classical methods of structural analysis. For all these reasons, it has experienced broad use in many branches of geology and geophysics.

The AMS is in general controlled by all minerals present in a rock. In strongly magnetic rocks, with bulk susceptibility higher than  $5 \times 10^{-3}$  (in the SI of units which is used throughout the paper), the effects of paramagnetic and diamagnetic minerals are negligible and the AMS is

effectively controlled by the ferromagnetic fraction only (e.g. Hrouda and Kahan, 1991). In weakly magnetic rocks, with bulk susceptibility less than  $5 \times 10^{-4}$ , the content of ferromagnetic minerals is often so low that the AMS is effectively controlled by the paramagnetic fraction (e.g. Rochette et al. 1992; Bouchez, 2000) and, if the bulk susceptibility is less than  $5 \times 10^{-5}$ , even the effect of diamagnetic fraction cannot be neglected (e.g. Hrouda, 1986, 2004).

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

or at variable temperatures, preferably between the temperature of liquid nitrogen and room temperature, because in both cases the ferromagnetic and paramagnetic minerals behave in different ways (for review see Martín-Hernández and Ferré, 2007).

The problem of these resolution methods is that they require expensive and commercially less available instrumentation and they are time consuming so that they can hardly be used in a routine way. Fortunately, it is often observed that in rocks, one mineral dominates magnetically. Therefore, for all practical applications, resolution of rock AMS into para- and ferromagnetic components is not necessary as a routine. Nevertheless, it is desirable to know the contributions of the ferromagnetic and paramagnetic minerals to the rock susceptibility. This information can be obtained through calculating paramagnetic susceptibility from rock chemical analysis (e.g. Aydin et al. 2007) and its comparison with measured susceptibility or through investigating the temperature variation of susceptibility (Hrouda, 1994; Hrouda et al. 1997) using the instrumentation available in most rock magnetic and palaeomagnetic laboratories. The disadvantage of these methods is that they investigate only the bulk susceptibility and it is not certain to what extent the results may be applicable to the AMS. There are two possibilities: (a) one may consider the bulk susceptibility and the AMS to be two different things, (b) one may consider that the AMS cannot be totally independent of bulk susceptibility. The purpose of the present paper is to investigate the relationship between the bulk susceptibility and the AMS in rocks consisting of two magnetic fractions represented by ferromagnetic and paramagnetic minerals. The investigation is made on mathematical models based on realistic AMS variations of both fractions obtained through statistical evaluation of magnetically monomineralic rocks.

### CONCEPT OF MAXIMUM THEORETICAL PARAMAGNETIC SUSCEPTIBILITY

#### Principles

This concept, introduced by Aydin et al. (2007) on the basis of works by Syono (1960), Nagata (1961), Collinson (1983) and Rochette et al. (1992), considers all iron and manganese of the rock to be contained in paramagnetic minerals and calculates the Maximum Theoretical Paramagnetic Susceptibility (MTPS) from the Fe and Mn contents in the rock determined through the whole-rock chemical analysis. If the MTPS is comparable to the measured rock susceptibility, the rock susceptibility is obviously carried dominantly by paramagnetic minerals. On

the other hand, if the measured susceptibility is much higher than the MTPS, it is obvious that all iron is not contained in paramagnetic minerals, but at least a part of it is contained in much more susceptible ferromagnetic minerals.

The relationship between bulk paramagnetic susceptibility and contents of iron and manganese can be described as follows (e.g. Rochette et al. 1992; Aydin et al. 2007)

$$K_{MTPS} = -14.6 + d [25.2 c(Fe^{2+}) + 33.4 c(Fe^{3+}) + 33.8 c(Mn^{2+})] 10^{-6} \quad (1)$$

where -14.6 is the rock diamagnetic susceptibility in the order of  $10^{-6}$ ,  $d$  is the rock density (in  $kg\ m^{-3}$ ), and  $c(Fe^{2+})$ ,  $c(Fe^{3+})$ ,  $c(Mn^{2+})$  are concentrations in atomic weight per cent of bivalent iron, trivalent iron and manganese ( $Mn^{2+}$ ), respectively.

Zapletel (1985), considering not only the atomic weight per cent concentrations but also oxide weight per cent concentrations, suggests the following relationships

$$K_{MTPS} = d [2.696 c(Fe^{2+}) + 3.229 c(Fe^{3+}) + 3.282 c(Mn^{2+})] 10^{-8} \quad (2)$$

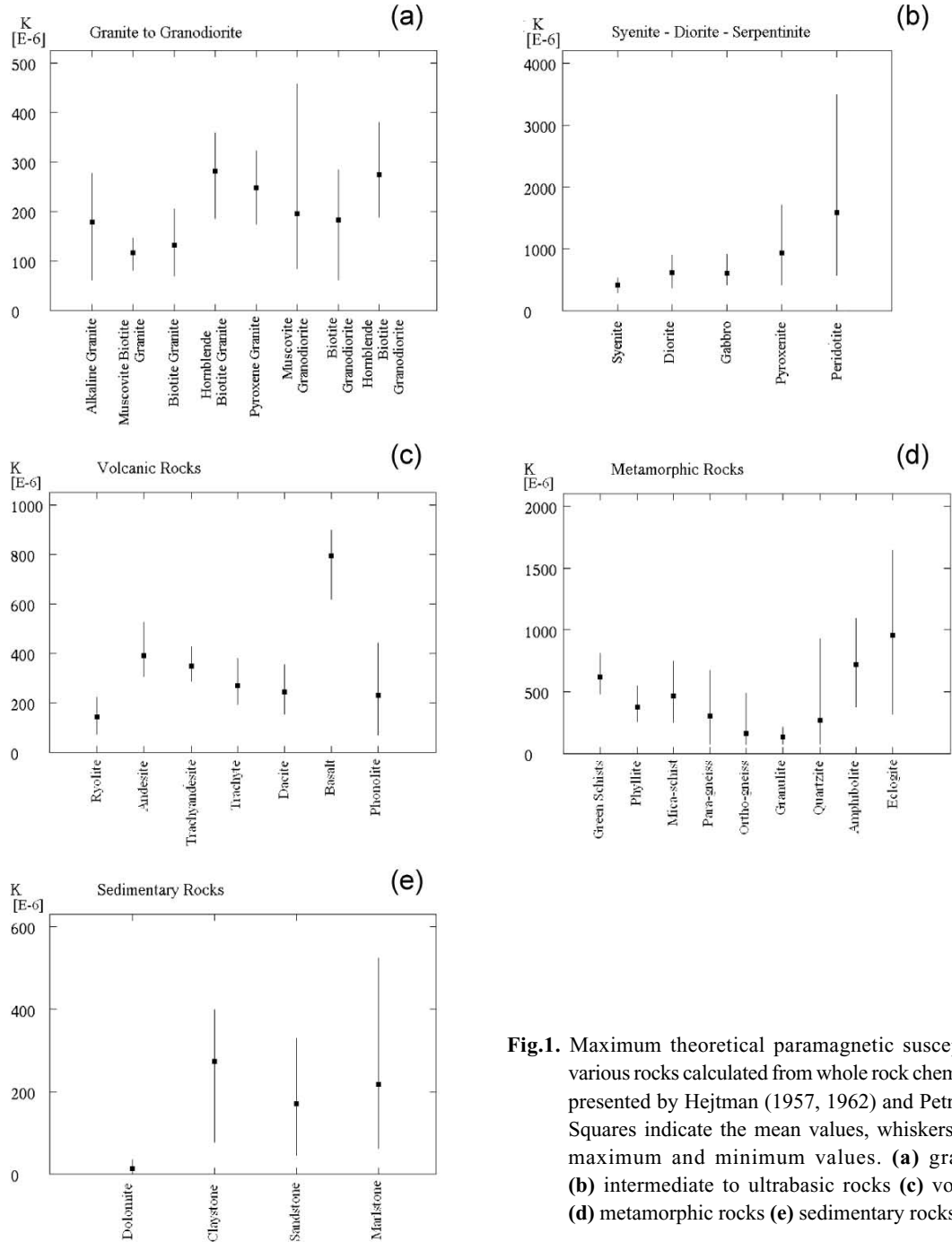
$$K_{MTPS} = d [2.096 c(FeO) + 2.258 c(Fe_2O_3) + 2.542 c(MnO)] 10^{-8} \quad (3)$$

where  $c(FeO)$ ,  $c(Fe_2O_3)$  and  $c(MnO)$  are oxide weight per cent concentrations of bivalent iron, trivalent iron and manganese, respectively.

The constants in the eqs.(1-3) are derived from the Avogadro number and Bohr magneton. As these constants in the individual equations come from different sources, the equations provide us with slightly different values. In the present paper, the MTPS calculation is based on the eq. (3), which uses the constants presented by Collinson (1983) who checked their correctness through measurement of susceptibility of minerals with known chemical composition.

#### Examples

In order to get an idea of paramagnetic susceptibilities of various rocks, the MTPS were calculated using eq. (3) from chemical analyses of various rocks, mostly coming from the Bohemian Massif, presented in text books on petrology of rocks by Hejtman (1957, 1962) and Petránek (1963). The results are presented in Fig.1 in terms of mean, minimum and maximum MTPS values found for each rock type considered. Even though presentation of minimum and maximum values are not recommended to be presented for measured susceptibilities of rocks, because of frequent occurrence of extreme values due to inhomogeneous



**Fig.1.** Maximum theoretical paramagnetic susceptibilities of various rocks calculated from whole rock chemical analyses presented by Hejtman (1957, 1962) and Petránek (1963). Squares indicate the mean values, whiskers indicate the maximum and minimum values. **(a)** granitic rocks **(b)** intermediate to ultrabasic rocks **(c)** volcanic rocks **(d)** metamorphic rocks **(e)** sedimentary rocks

distribution of magnetic minerals in rocks, the above presentation is used, because the chemical analyses come from large amounts of rocks (of the order of kilograms) and the effect of inhomogeneous distribution is effectively attenuated in this case.

Figure 1 shows that the MTPS may range from the order of  $10^{-5}$ , throughout the entire order of  $10^{-4}$ , to the first half of the order of  $10^{-3}$ . The lowest values are found in felsic rocks, while the highest values are found in rocks rich in mafic minerals. In granites and granodiorites, the MTPS

ranges from order of  $10^{-5}$  to almost  $5 \times 10^{-4}$ , with the mean value being about  $2 \times 10^{-4}$  (Fig. 1a). This is in very good agreement with the suggestion by Bouchez (2000) that the upper limit in susceptibility of paramagnetic granites is  $4 \times 10^{-4}$ . However, it should be emphasized that not all granites with susceptibility less than  $4 \times 10^{-4}$  are paramagnetic. There are numerous examples of granites with susceptibility less than  $4 \times 10^{-4}$  whose susceptibility is effectively carried by both paramagnetic and ferromagnetic minerals (e.g. Hrouda et al. 1999). In intermediate, basic and ultrabasic plutonic

rocks, the MTPS is in general higher than in the above granitic rocks (Fig. 1b), increasing with increasing basicity. In ultrabasic rocks, it may be relatively high, reaching  $3.5 \times 10^{-3}$ . Nevertheless, the MTPS may also be low, lower than  $5 \times 10^{-4}$  and this should be taken into the consideration in interpreting magnetic fabrics of such rocks. In volcanic rocks, the MTPS is mostly in the first half of the order of  $10^{-4}$ , only in basalts it is considerably higher, in the upper half of the order of  $10^{-4}$  (Fig. 1c). Nevertheless, the MTPS is mostly much lower than the measured susceptibility which indicates considerable presence of ferromagnetic minerals in volcanic rocks. In metamorphic rocks, the MTPS is mostly in the first half of the order of  $10^{-4}$ , less frequently being in the upper half of the order of  $10^{-4}$  (Fig. 1d). In some amphibolites and eclogites it can be fairly variable, ranging from the order of  $10^{-4}$  to  $10^{-3}$ . In sedimentary rocks, the MTPS can be very low as in some carbonates and can reach the first half of the order of  $10^{-4}$  in clastic sedimentary rocks.

It can be summarized that the MTPS is in the order of  $10^{-4}$  in most rocks, much less frequently reaching the order of  $10^{-3}$ . However, it should be emphasized that not in all rocks with susceptibility in the order of  $10^{-4}$  the susceptibility carriers are solely paramagnetic minerals. It may often happen that the MTPS is in the lower part of the order of  $10^{-4}$ , while the rock susceptibility is in the upper part of the order of  $10^{-4}$  and a ferromagnetic mineral may considerably contribute to the rock susceptibility as well. For this reason, it is recommended to calculate the MTPS for each rock type under study and compare it with measured susceptibilities.

#### SUSCEPTIBILITY RESOLUTION INTO PARAMAGNETIC AND FERROMAGNETIC COMPONENTS

Variation of susceptibility of paramagnetic minerals with temperature is represented by hyperbola, while in ferromagnetic minerals it is a complex curve characterized by acute susceptibility decrease at the Verwey or Morin transition and at the Curie temperature (e.g. Dunlop and Özdemir, 1997). Figure 2a shows the variation of susceptibility with temperature in biotite concentrate separated from granodiorite. The variation curve is obviously represented by hyperbola almost up to the temperature of about 400°C. Above this temperature, the susceptibility rapidly increases, probably due to increasing content of new magnetite created by heating, which is indicated by the cooling curve showing much higher susceptibilities. Figure 2b shows the curve of variation of susceptibility with temperature in magnetite containing both the Verwey transition (at about -150°C) and the Curie temperature (at 581°C). The curve also shows phenomenon usual in

ferromagnetic minerals, that in some temperature intervals, typically between room temperature and 200°C or between -140°C and -50°C, the susceptibility can be roughly considered constant or following gently sloping straight line. This property can be used in the susceptibility resolution into the paramagnetic and ferromagnetic components, the above temperature interval being henceforth called the resolution interval.

There are two models for the susceptibility vs. temperature curve of a rock containing paramagnetic minerals and one ferromagnetic mineral within the resolution interval. The first considers the ferromagnetic susceptibility constant

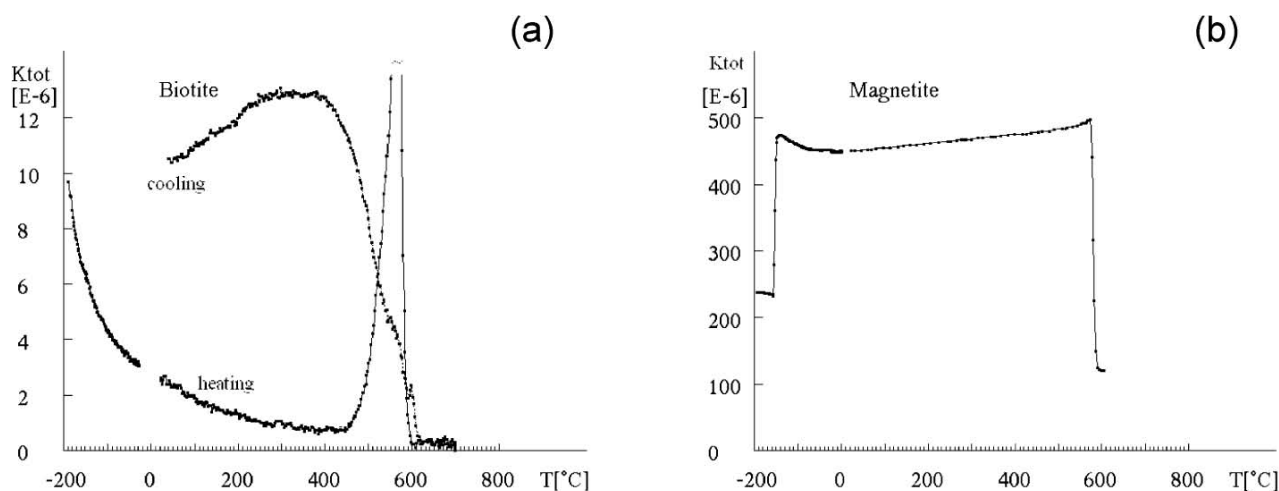
$$k = p_p C/T + p_f k_f \quad (4)$$

The second considers the ferromagnetic susceptibility to be represented by mildly sloped straight line

$$k = p_p C/T + p_f (bT + a) \quad (5)$$

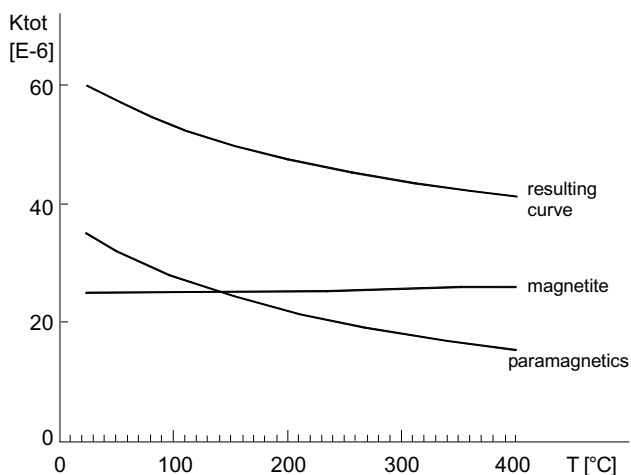
where  $k$  is rock susceptibility,  $k_f$  is ferromagnetic susceptibility,  $p_p$  and  $p_f$  are percentages of paramagnetic and ferromagnetic fractions, respectively,  $C$  is paramagnetic constant and  $T$  is absolute temperature,  $a$  and  $b$  are constants.

Equation (4) is that of hyperbola offset along the susceptibility axis, while equation (5) represents a combination of hyperbola and straight line. By fitting hyperbola and straight line to  $k$  vs.  $T$  curve using least squares method (e.g. Hrouda, 1994; Hrouda et al. 1997) one obtains the paramagnetic susceptibility contribution ( $p_p C/T$ ) and the ferromagnetic susceptibility contribution ( $p_f k_f$  or  $p_f (bT + a)$ ) to the rock susceptibility. The principle of this method for susceptibility resolution into paramagnetic and ferromagnetic component is illustrated in Fig.3, the method being executable by the program CUREVAL, which can be free of charge downloaded at [www.agico.com](http://www.agico.com) (Software Support/Temperature Variation of Susceptibility). However, it should be emphasized that the program does not work automatically without human assistance. Before using it, it is necessary to inspect the curve visually. If neither hyperbola nor its part is recognizable in the susceptibility vs. temperature curve (see Fig. 4a), and Curie temperature and/or Verwey or Morin transition are on the other hand well recognizable, it is highly likely that the susceptibility of such a rock is dominated by ferromagnetic mineral(s) and a possible minor contribution of paramagnetic minerals cannot be enumerated. If a hyperbola and superposed Curie temperature and/or Verwey or Morin transition can be observed (Fig.4b), it is obvious that both paramagnetic and ferromagnetic minerals contribute to the rock



**Fig. 2.** Examples of the variation of magnetic susceptibility with temperature in paramagnetic and ferromagnetic minerals. The susceptibility is in terms of total susceptibility that is proportional to magnetic signal not normalized by specimen volume. **(a)** biotite concentrate from granodiorite. **(b)** magnetite.

susceptibility importantly and contributions of both fractions can be evaluated quantitatively. If only hyperbola is seen on both low temperature and high temperature curve, without any indication of Curie temperature and/or Verwey or Morin transition (Fig.4c) or the indication of Curie temperature and/or Verwey or Morin transition is very weak (Fig.4d), it is highly likely that the susceptibility of such a rock is dominated by paramagnetic mineral(s). Nevertheless, it is recommended to do the susceptibility resolution into paramagnetic and ferromagnetic component using the CUREVAL program, because it may happen that the hyperbola is shifted due to presence of a ferromagnetic mineral whose Curie temperature is weak and almost disappeared in the background of the paramagnetic susceptibility variation. Calculations of paramagnetic and ferromagnetic contributions to the rock susceptibility using

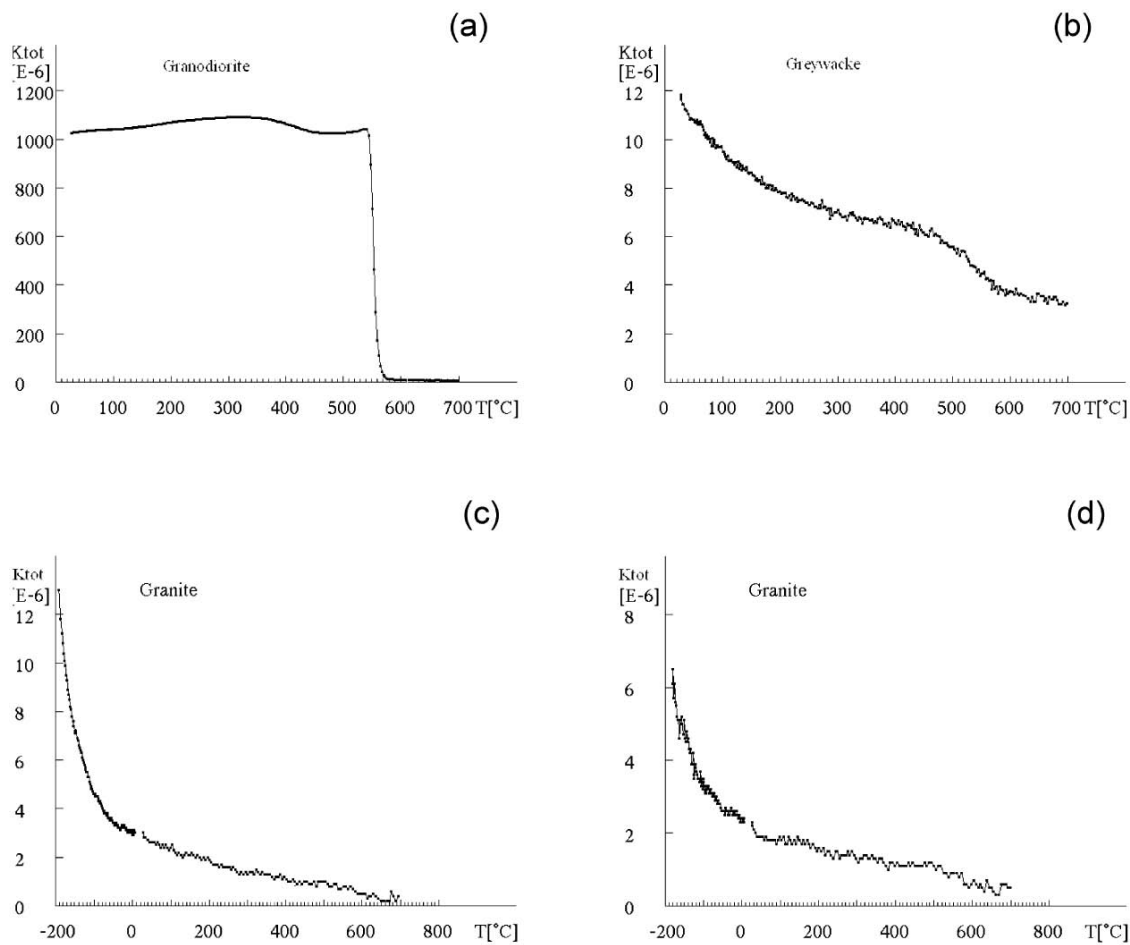


**Fig.3.** Principle of the resolution of magnetic susceptibility of rocks into paramagnetic and ferromagnetic components.

the low temperature and high temperature curves should be comparable, even though the low temperature method may slightly favour the paramagnetic fraction due to its above mentioned hyperbolic course.

It is obvious from eqs. (4) and (5) that the effect of diamagnetic fraction is neglected in both the resolution methods, because diamagnetic susceptibilities are in general much lower than the paramagnetic and ferromagnetic susceptibilities (e.g. Nye, 1957). However, the modern instruments are very sensitive and the effect of diamagnetic minerals can be indicated in some rare cases. The most common diamagnetic minerals are probably quartz and calcite with susceptibilities about  $15 \times 10^{-6}$  and  $13 \times 10^{-6}$ , respectively (e.g. Nye, 1957). Consequently, the effect of diamagnetic fraction can be applicable only to rocks with susceptibility in the order of  $10^{-5}$ . The diamagnetic susceptibility is constant, temperature independent. Then, as obvious from eqs. (4) and (5), the diamagnetic fraction makes underestimation of the ferromagnetic susceptibility. In some extreme cases, if there are almost no ferromagnetic minerals in the rock, this underestimation may result in calculation of negative ferromagnetic susceptibility, which is physically impossible.

The prerequisite of the successful susceptibility resolution into paramagnetic and ferromagnetic components is no mineral changes within the resolution interval. For this reason, the resolution interval is selected at relatively low temperatures, typically between room temperature and 250°C, where the mineral changes are less likely. Or alternatively, low temperature measurement is used that is routinely made between the temperature of liquid nitrogen and room temperature and the resolution interval avoiding



**Fig.4.** Variations of susceptibility with temperature in rocks with variable ratios of paramagnetic to ferromagnetic susceptibilities. **(a)** rock with dominating ferromagnetic fraction. **(b)** rock with dominating paramagnetic fraction. **(c)** rock with roughly balanced paramagnetic and ferromagnetic fractions. **(d)** rock with slightly prevailing paramagnetic fraction

the Verwey and Morin transition temperatures is used (typically between  $-140^{\circ}\text{C}$  and  $-50^{\circ}\text{C}$ ). To be sure of no mineral changes within the resolution interval, a two steps measurement is recommended. The specimen to be measured is divided into two parts. The first step is the standard measurement of one part to  $700^{\circ}\text{C}$  and back. If the cooling curve is virtually the same as the heating curve, it is obvious that there are no observable mineral changes due to heating and the resolution can be made just after this first step without measuring the second part. If the cooling curve is very different from the heating curve, it is likely that heating induces mineral changes within the specimen, but we do not know the temperatures at which these changes take place. In this case, it is recommended to heat the second part of the specimen to the temperature of the upper limit of the resolution interval. Then, if the cooling and heating curves are virtually the same, there are very likely no observable mineral changes due to heating within the resolution interval and the resolution can be made. If the

curves are different, it is likely that heating induces mineral changes within the resolution interval and we have to resign on resolution.

The resolution methods work well if the susceptibility vs. temperature curve is represented either by hyperbola offset along the susceptibility axis (equation 4) or by a combination of hyperbola and straight line (equation 5). Unfortunately, there can be cases when the susceptibility vs. temperature curve is neither of these two. The most typical example is the susceptibility behaviour of ferrimagnetic and antiferromagnetic minerals above their Curie temperature (called the Néel temperature in case of antiferromagnetics) described by the Curie-Weiss law

$$k = C/(T-\Theta) \quad (6)$$

where  $C$  is the paramagnetic constant and  $\Theta$  is the paramagnetic Curie temperature. This is hyperbola shifted along the temperature axis. If the eq. (6) is combined with eq. (4) or (5), the resultant curve is no longer hyperbola,

being more complex curve. Unfortunately, there is no appropriate resolution model for such a case. At the first sight, one could neglect this case, not selecting the resolution interval above the Curie (Néel) temperature of ferrimagnetic and antiferromagnetic minerals. This is the case of magnetite and hematite whose Curie (Néel) temperatures are high, about 580°C and 695°C, respectively, only partially the case of pyrrhotite with the Curie (Néel) temperature about 325°C, but definitively not the case of ilmenite whose Néel temperature ranges from -218°C to -205°C and the paramagnetic Curie temperature is -250°C (Bleil and Petersen, 1982). In the last case, the methods based on eq. (4) and (5) would not work. To be sure that the investigated specimen obeys the condition of eqs. (4) and (5), it is recommended to plot the fit hyperbola and the measured susceptibility points. If the hyperbola fits the measured points well, one can use the method without problems. If it does not, e.g. the points of a part of the curve are above the hyperbola, while those of the other part are under the hyperbola, it is better to avoid the resolution.

### THE MODEL CONSTRUCTION

Theory of the low-field AMS is based on the assumption of the linear relationship between magnetization and magnetizing field, traditionally described as follows

$$\mathbf{M} = \mathbf{K} \mathbf{H} \quad (7)$$

where  $\mathbf{M}$  is the magnetization vector,  $\mathbf{H}$  is the field intensity vector, and  $\mathbf{K}$  is the symmetric second-rank tensor of magnetic susceptibility. It is usual to resolve the susceptibility tensor into the magnitude and orientation components

$$\mathbf{K} = \mathbf{O} \mathbf{K}_d \mathbf{O}' \quad (8)$$

where  $\mathbf{K}_d$  is the magnitude component called the diagonal form susceptibility tensor, and  $\mathbf{O}$  is the orientation matrix ( $\mathbf{O}'$  is its transpose). The  $\mathbf{K}_d$  tensor has zero non-diagonal components and the diagonal components are called the principal susceptibilities. The individual columns of the  $\mathbf{O}$  matrix are the direction cosines of the principal susceptibilities.

It is also usual to represent the susceptibility tensor by convenient parameters derived from the principal susceptibilities (e.g. Nagata 1961; Jelínek 1981), for instance

$$\begin{aligned} K &= (K_1 + K_2 + K_3)/3 \\ P &= K_1 / K_3 \\ T &= (2\eta_2 - \eta_1 - \eta_3) / (\eta_1 - \eta_3) = 2 \ln F / \ln P - 1 \end{aligned} \quad (9)$$

where  $K_1 \geq K_2 \geq K_3$  are the principal susceptibilities,

$\eta_1 = \ln K_1$ ,  $\eta_2 = \ln K_2$ ,  $\eta_3 = \ln K_3$ . The parameter  $K$  is called the mean susceptibility and it characterizes the qualitative and quantitative content of magnetic minerals in a rock. The parameter  $P$ , called the degree of AMS, indicates the intensity of the preferred orientation of magnetic minerals in a rock. The parameter  $T$ , called the shape parameter, characterizes the symmetry or shape of the AMS ellipsoid. If  $0 < T < +1$  the AMS ellipsoid is oblate (the magnetic fabric is planar);  $T = +1$  means that the AMS ellipsoid is rotationally symmetric (uniaxial oblate). If  $-1 < T < 0$  the AMS ellipsoid is prolate (the magnetic fabric is linear);  $T = -1$  means that the AMS ellipsoid is uniaxial prolate. The components of the  $\mathbf{K}_d$  tensor are

$$K_{d11} = 3PK/G, \quad K_{d22} = 3FK/G, \quad K_{d33} = 3K/G \quad (10)$$

$$K_{d12} = K_{d21} = K_{d23} = K_{d32} = K_{d13} = K_{d31} = 0$$

where  $F = \exp[(T \ln P + \ln P)/2]$  and  $G = P + F + 1$ .

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

$$\mathbf{K} = c_f \mathbf{K}_f + c_p \mathbf{K}_p + c_d \mathbf{K}_d = \mathbf{k}_f + \mathbf{k}_p + \mathbf{k}_d \quad (11)$$

where  $\mathbf{K}$  is the rock susceptibility tensor,  $\mathbf{K}_f$ ,  $\mathbf{K}_p$ ,  $\mathbf{K}_d$  are tensors of ferromagnetic, paramagnetic, and diamagnetic susceptibilities, respectively;  $c_f$ ,  $c_p$ ,  $c_d$  are the respective percentages; and  $\mathbf{k}_f$ ,  $\mathbf{k}_p$ ,  $\mathbf{k}_d$  are called the respective susceptibility contribution tensors. Neglecting the contribution of the diamagnetic minerals and realizing that each susceptibility tensor can be resolved into the mean susceptibility and the normed susceptibility tensor, the presented model can be defined as follows

$$\mathbf{k} = K_f \mathbf{k}_f + K_p \mathbf{k}_p \quad (12)$$

where  $K_f$ ,  $K_p$  are mean susceptibilities and  $\mathbf{k}_f$ ,  $\mathbf{k}_p$  are normed susceptibility contribution tensors of the ferromagnetic and paramagnetic fractions, respectively.

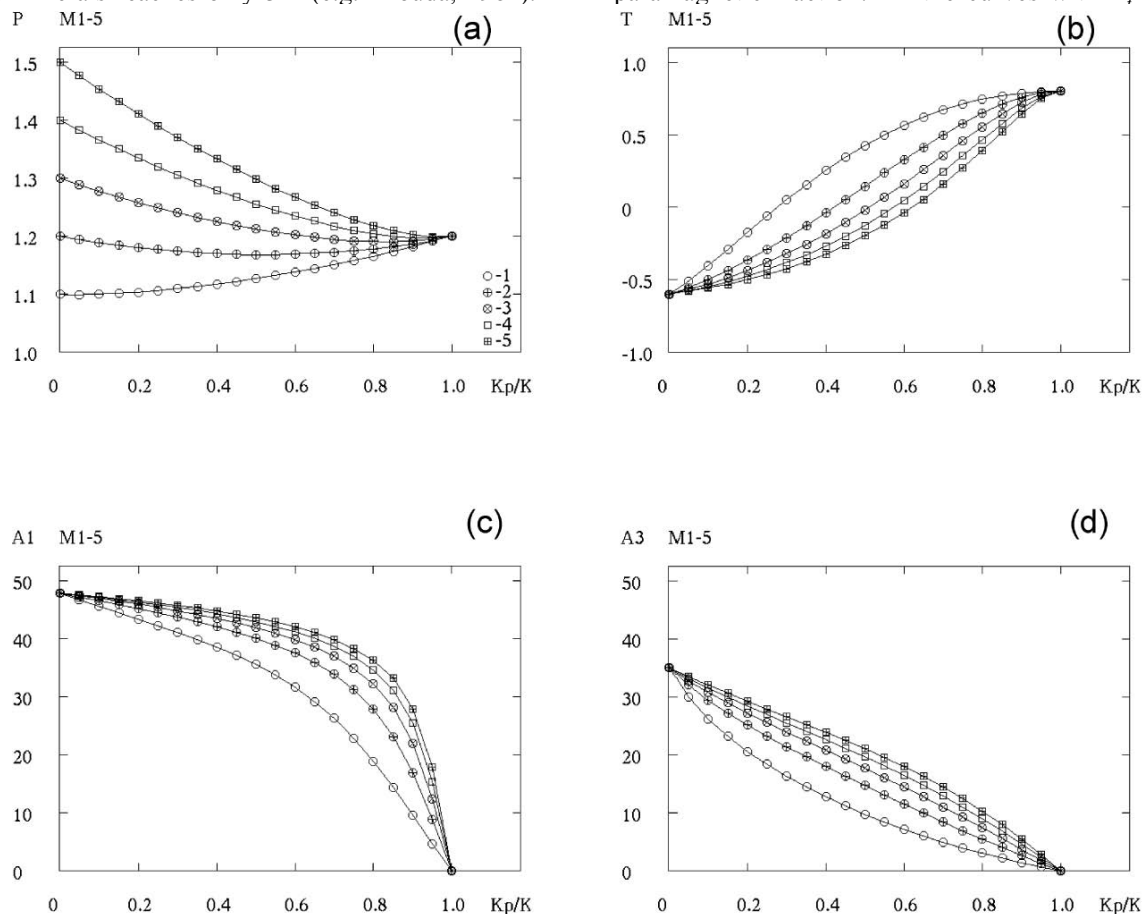
The models are constructed as follows. First, the normed susceptibility contribution tensors are constructed for ferromagnetic and paramagnetic fractions specified by the degree of AMS, shape parameter, and orientations of principal susceptibilities. Second, the mean susceptibilities,  $K_f$ ,  $K_p$ , are varied in such a way that the paramagnetic mean susceptibility to whole rock mean susceptibility ratio ( $K_p/K$ ) ranges from zero to 1. In order to easily identify the effects of the ferromagnetic and paramagnetic fractions on the resultant AMS, the AMS of both the fractions are considered very different, in terms of degree of AMS, shape of the AMS ellipsoid and orientations of the principal susceptibilities.

## MODELLING RESULTS

In the present modelling, it is necessary to consider realistic AMS variations for both paramagnetic and ferromagnetic fractions. The upper limit of the degree of AMS of paramagnetic fraction, whose AMS is magnetocrystalline in origin, is given by the degree of AMS of the single crystals of the mineral considered. These are relatively well known for micaceous minerals such as biotite, muscovite, chlorite (Zapletal, 1990; Borradaile and Werner, 1994; Martin-Hernandez and Hirt, 2003), less well known for amphibole (Friedrich, 1995). The maximum degree of AMS of single crystals of these minerals seems to be  $P = 1.35$ . As in real rocks the minerals never show perfectly coaxial orientation, the maximum degree of AMS of paramagnetic fraction will be considered  $P = 1.25$  in the presented models. As for the ferromagnetic fraction, the situation is more complex. In pyrrhotite and hematite, which have an AMS that is magnetocrystalline in origin, the degree of single crystal AMS may easily be  $P > 100$  (Uyeda et al. 1963; Rochette, 1988). However, the rock AMS carried by these minerals reaches only 3-4 (e.g. Hrouda, 1982). In

addition, in most rocks  $P < 1.5$ . In magnetite, whose AMS is due to shape anisotropy, the degree of AMS depends on grain shape. Even though there are rare magnetite-bearing rocks with  $P \sim 3-4$  (e.g. Greiling et al. 2007), the most magnetite fabrics have  $P$  much less than 1.5. For this reason, the maximum degree of AMS of ferromagnetic fraction will be considered  $P = 1.5$  in the presented models.

Figure 5 contains the results of the first modelling experiment. In this experiment, the AMS of the paramagnetic fraction is considered constant with  $P_p = 1.2$ ,  $T_p = 0.8$ , orientation of  $K_{p1}$  being  $55^\circ/35^\circ$  and of  $K_{p3}$  being  $235^\circ/55^\circ$ . The AMS of the ferromagnetic fraction is considered with variable  $P_f = 1.1 - 1.5$  and constant  $T_f = -0.6$  and orientation of  $K_{f1}$  being  $90^\circ/0^\circ$  and of  $K_{f3}$  being  $0^\circ/90^\circ$ . Figure 5a shows the variation of the resultant degree of AMS according to the varying ratio of paramagnetic to resultant mean susceptibility ( $K_p/K$ ). At  $K_p/K = 0$  (no paramagnetic fraction considered), the resultant degrees of AMS correspond to those of the ferromagnetic fraction. At  $K_p/K = 1$  (no ferromagnetic fraction considered), the resultant degree of AMS corresponds to the constant degree of AMS of paramagnetic fraction. In the curves with  $P_r > P_p$ , the



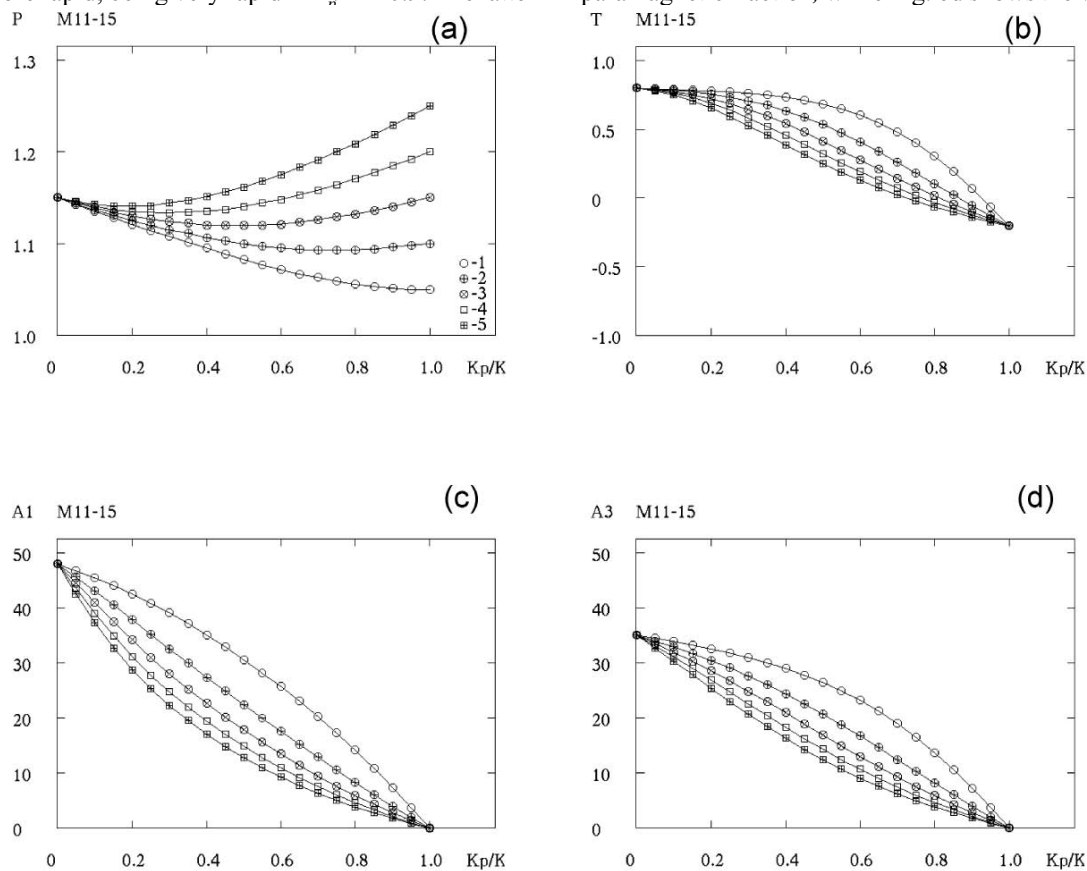
**Fig.5.** Modelling the effect of ferromagnetic and paramagnetic fractions on whole rock AMS. Model with constant paramagnetic and variable ferromagnetic AMS. For more information see the main text. **(a)** degree of AMS. **(b)** shape parameter. **(c)** angle between resultant and paramagnetic magnetic lineations. **(d)** angle between resultant and paramagnetic magnetic foliation poles.



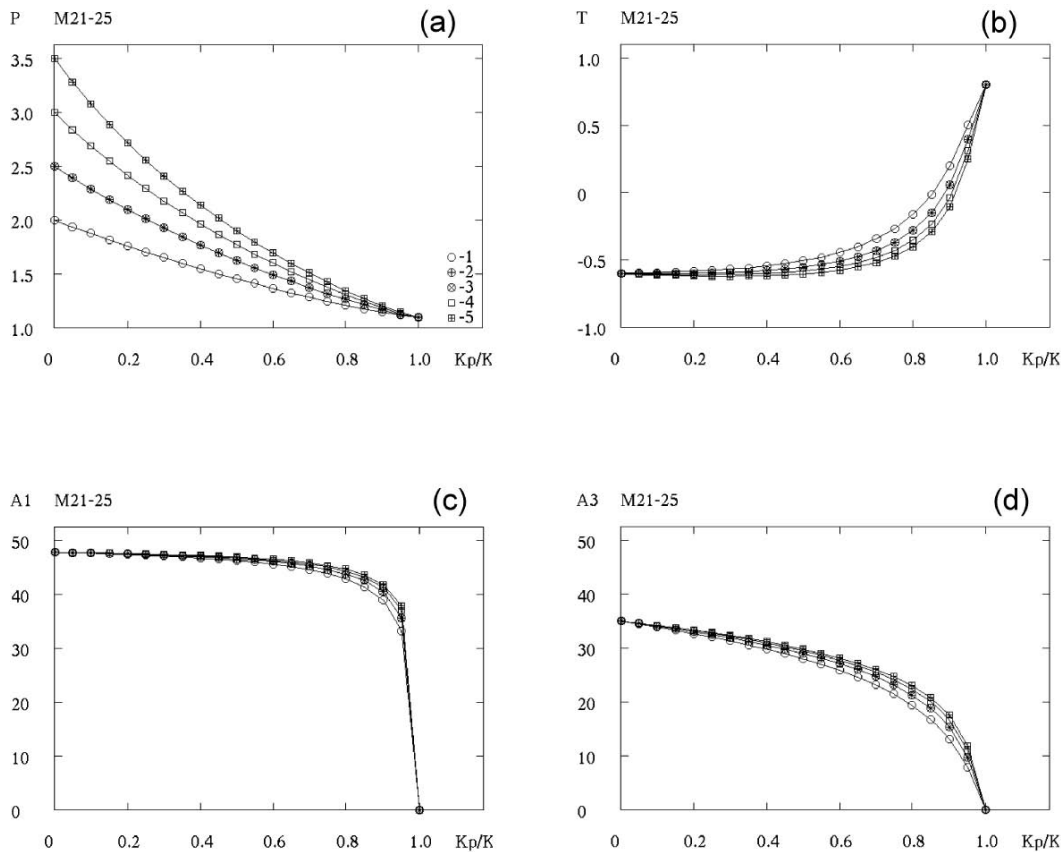
resultant degree of AMS decreases with increasing  $K_p/K$  ratio, while in curve with  $P_f < P_p$ , the resultant degree of AMS increases with increasing  $K_p/K$  ratio. Figure 5b shows the variation of the resultant shape parameter according to  $K_p/K$ . The curves are slightly S shaped, starting at  $T = -0.6$ , which corresponds to the shape parameter of ferromagnetic fraction, and ending at  $T = 0.8$ , which corresponds to that of paramagnetic fraction. Figures 5c, d show the variations of the resultant magnetic lineation and magnetic foliation pole during the experiment. They continuously change from the parallelism to ferromagnetic fraction AMS to that of paramagnetic fraction AMS. Figure 5c shows the variation of the angle between the resultant magnetic lineation and the magnetic lineation of paramagnetic fraction according to  $K_p/K$ , while Fig.5d shows the variation of the angle between the resultant magnetic foliation pole and the magnetic foliation pole of paramagnetic fraction according to  $K_p/K$ . The former angle continuously diminishes with increasing  $K_p/K$  ratio. In the curve with  $P_f = 1.1$  the decrease is relatively rapid, while in the curve with  $P_f = 1.5$  the decrease is relatively slow up to  $K_p/K = 0.6$  then it becomes much more rapid, being very rapid if  $K_p/K > 0.9$ . The latter

angle continuously diminishes with increasing  $K_p/K$  ratio.

Figure 6 contains the results of the second modelling experiment in which the AMS of the ferromagnetic fraction is considered constant with  $P_f = 1.15$ ,  $T_f = 0.8$ , orientation of  $K_{f1}$  being  $90^\circ/0^\circ$  and of  $K_{f3}$  being  $0^\circ/90^\circ$ . The AMS of the paramagnetic fraction is considered with variable  $P_f = 1.05 - 1.25$  and constant  $T_p = -0.2$  and orientation of  $K_{p1}$  being  $55^\circ/35^\circ$  and of  $K_{p3}$  being  $235^\circ/55^\circ$ . Fig. 6a shows the variation of the resultant degree of AMS according to the varying  $K_p/K$  ratio. At  $K_p/K = 0$ , the resultant degree of AMS corresponds to that of the constant ferromagnetic fraction, while at  $K_p/K = 1$ , it corresponds to the considered degrees of AMS of paramagnetic fraction. The curve with  $P_p = 1.05$  continuously decrease, while the other curves initially decrease and then increase. Figure 6b shows the variation of the resultant shape parameter. The curves continuously decrease, starting at  $T = 0.8$ , which corresponds to the shape parameter of ferromagnetic fraction, and ending at  $T = -0.2$ , which corresponds to that of paramagnetic fraction. Figure 6c shows the variation of the angle between the resultant magnetic lineation and the magnetic lineation of paramagnetic fraction, while Fig. 6d shows the variation of



**Fig.6.** Modelling the effect of ferromagnetic and paramagnetic fractions on whole rock AMS. Model with constant ferromagnetic and variable paramagnetic AMS. For more information see the main text. **(a)** degree of AMS. **(b)** shape parameter. **(c)** angle between resultant and paramagnetic magnetic lineations. **(d)** angle between resultant and paramagnetic magnetic foliation poles.



**Fig.7.** Modelling the effect of ferromagnetic and paramagnetic fractions on whole rock AMS. Model with constant paramagnetic and variable and strong ferromagnetic AMS. For more information see the main text. **(a)** degree of AMS. **(b)** shape parameter. **(c)** angle between resultant and paramagnetic magnetic lineations. **(d)** angle between resultant and paramagnetic magnetic foliation poles.

the angle between the resultant magnetic foliation pole and the magnetic foliation pole of paramagnetic fraction. Both angles continuously diminish with increasing  $K_p/K$  ratio.

Figure 7 contains the results of the third modelling experiment. In this experiment, the AMS of the paramagnetic fraction is considered constant with  $P_p = 1.1$ ,  $T_p = 0.8$ , orientation of  $K_{p1}$  being  $55^\circ/35^\circ$  and of  $K_{p3}$  being  $235^\circ/55^\circ$ . The AMS of the ferromagnetic fraction is considered with variable  $P_f = 2.0 - 3.5$  and constant  $T_f = -0.6$  and orientation of  $K_{f1}$  being  $90^\circ/0^\circ$  and of  $K_{f3}$  being  $0^\circ/90^\circ$ . Figure 7a shows the variation of the resultant degree of AMS according to the varying  $K_p/K$  ratio. At  $K_p/K = 0$ , the resultant degrees of AMS correspond to those of the ferromagnetic fraction. At  $K_p/K = 1$  the resultant degree of AMS corresponds to the constant degree of AMS of paramagnetic fraction. In all curves, the resultant degree of AMS decreases with increasing  $K_p/K$  ratio, with the curvatures of all curves being only mild. Figure 7b shows the variation of the resultant shape parameter according to  $K_p/K$ . The curves starting at  $T = -0.6$ , which corresponds to the shape parameter of ferromagnetic fraction, pass more or less parallel to abscissa

up to  $K_p/K = 0.6$  and then they rise up rapidly, ending at  $T = 0.8$ , which corresponds to  $T_p$ . Figure 7c shows the variation of the angle between the resultant magnetic lineation and the magnetic lineation of paramagnetic fraction according to  $K_p/K$ , while Fig. 7d shows the variation of the angle between the resultant magnetic foliation pole and the magnetic foliation pole of paramagnetic fraction according to  $K_p/K$ . The former angle passes more or less parallel to abscissa up to  $K_p/K = 0.8$  and then it decreases rapidly, reaching zero at  $K_p/K = 1$ . The latter angle continuously diminishes with increasing  $K_p/K$  ratio, the decrease being dramatic if  $K_p/K > 0.8$ .

## DISCUSSION

In all the presented models, the AMS of both the fractions were considered very different, in terms of the degree of AMS, shape of the AMS ellipsoid and orientations of the principal susceptibilities in order to easily identify the effects of the ferromagnetic and paramagnetic fractions on the resultant AMS. In two first models that consider comparable

intensities in the ferromagnetic mineral and paramagnetic mineral AMS fabrics, the AMS parameters change continuously with changing proportion of the ferromagnetic to paramagnetic mean susceptibility. Nevertheless, if the contribution of the ferromagnetic or the paramagnetic fraction to the rock susceptibility is let us say higher than 80%, the resultant AMS is relatively near to the AMS of the dominating fraction in all aspects, the degree of AMS, shape parameter and orientation of principal susceptibilities. In such rocks, one can interpret the whole rock AMS data in terms of the dominant fraction without danger of large error. This interpretation can be partially misleading in the case of quantitative fabric interpretation, but it is acceptable in solving most geological problems. If one finds out that the susceptibility of the rock under study is carried by two fractions, one ferromagnetic and one paramagnetic, and the contribution of one fraction to the rock susceptibility is dominant over that of the other fraction, the resultant AMS can be interpreted in terms of the dominant fraction. In the interpretation of the AMS of such rocks, resolution of the AMS into paramagnetic and ferromagnetic components is not necessary that requires expensive and commercially less available instrumentation and being time consuming so that it can hardly be used in a routine way. On the other hand, the information of the contributions of the ferromagnetic and paramagnetic minerals to the rock susceptibility can be obtained relatively easily through calculating MTPS from rock chemical analyses that are often available from other investigations and its comparison with measured susceptibility or through investigating the temperature variation of susceptibility using the instrumentation available in most rock magnetic and palaeomagnetic laboratories.

In the model whose one component is weakly anisotropic and the other component is strongly anisotropic, the resultant AMS is relatively near to the AMS of the dominating fraction as in the previous models, but the effect of the strong fraction is much wider. The strong fraction affects the resultant AMS considerably even in cases if the contribution of this fraction to the mean susceptibility is balanced with contribution of the paramagnetic fraction.

The AMS of paramagnetic minerals, mostly represented by mafic silicates, is relatively low, with  $P < 1.4$  (Borradaile et al. 1987; Zapletal, 1990; Borradaile and Werner, 1994; Rochette et al. 1994; Friedrich, 1995; Martin-Hernandez and Hirt, 2003). In ferromagnetic minerals, the situation is more complex. In pyrrhotite and hematite, the degree of single crystal AMS may easily be  $P > 100$  (Uyeda et al. 1963; Rochette, 1988). In magnetite, the most magnetite fabrics have  $P$  much less than 1.5. Consequently, the degree of AMS of the rock whose AMS is carried dominantly by

paramagnetic minerals is in general lower than that of the rock whose AMS is carried dominantly by ferromagnetic minerals even in cases that both mineral groups show the same intensity of the preferred orientation. The AMS cannot be therefore simply interpreted in terms of mineral preferred orientation without knowing the dominant AMS carrier. The presented modelling shows that resolution of the bulk susceptibility into paramagnetic and ferromagnetic components is sufficient for such purposes.

From time to time a need appears to compare the orientations of minerals deciphered from AMS data with those by a non-magnetic method such as universal stage and/or X-ray goniometry, Electron Back Scattered Diffraction, Shape Preferred Orientation analysis using Digital Image Analysis techniques etc (e.g., Archanjo et al. 1995; Launeau and Cruden, 1998; Sen and Mamtani, 2006). This can be made by means of the orientation tensor introduced by Scheidegger (1965) as purely mathematical tool for characterizing the preferred orientation of minerals, because the relationship between the AMS and the orientation tensor is known (for review see Ježek and Hrouda, 2000). In order to re-calculate the AMS into the orientation tensor, the AMS of the dominant carrier is necessarily to be known. Before doing this re-calculation, one has to be sure that the rock AMS is carried dominantly by one mineral, only. Again, the presented modelling shows that resolution of the bulk susceptibility into paramagnetic and ferromagnetic components is sufficient for such purposes.

Strain analysis is among the most laborious techniques of structural analysis, being confined to rocks containing convenient strain indicators (e.g. oolites, concretions, reduction spots, lapilli, fossils). For this reason, many attempts have been made to use the AMS as a strain gauge, investigating the quantitative relationship between the AMS and strain theoretically through mathematical modelling, empirically through examining the AMS of natural rocks with known strain, and experimentally through investigating the AMS of rocks and rock analogs deformed in the laboratory (e.g., Borradaile and Alford, 1987; Hrouda, 1993; Mukherji et al. 2004; Sen et al. 2005). Ježek and Hrouda (2007) presented a method and software (SUSIE) for determination of strain from the AMS. It is based on direct modelling of the AMS using the March and Jeffery models and their comparison with measured data. Provided that one knows the carrier of the AMS and the mechanism of the reorientation of magnetic minerals in a rock during its straining it is possible to convert the AMS data into the strain data. Even though the method can in principle work even for two or three assemblages of magnetic minerals in a rock,

it is advantageous if the rock AMS is dominantly carried by one magnetic mineral. Whether it is the particular case, it can be checked through the resolution of the bulk susceptibility into paramagnetic and ferromagnetic components.

### CONCLUSIONS

1. In models with comparable intensities in the ferromagnetic mineral and paramagnetic mineral AMS fabrics, the AMS parameters change continuously with changing ratio of ferromagnetic to paramagnetic mean susceptibility. If the contribution of the ferromagnetic or the paramagnetic fraction to the rock susceptibility is dominant (let us say higher than 80%), the resultant AMS is relatively near to the AMS of the dominating fraction in all aspects, the degree of AMS, shape parameter and orientation of principal susceptibilities.
2. In the model whose one component is weakly anisotropic and the other one strongly anisotropic, the resultant AMS is not only relatively near to the AMS

of the dominating fraction as in the previous models, but the strong fraction also affects the resultant AMS considerably even in cases if the contribution of this fraction to the mean susceptibility is balanced with contribution of the paramagnetic fraction.

3. In the interpretation of the AMS of rocks with dominating ferromagnetic or paramagnetic fraction, the resolution of the AMS into paramagnetic and ferromagnetic components is not necessary that requires expensive and commercially less available instrumentation, the information of the contributions of the ferromagnetic and paramagnetic minerals to the rock mean susceptibility is sufficient that can be obtained relatively easily through calculating MTPS from rock chemical analyses or through investigating the temperature variation of susceptibility using the instrumentation available in most rock magnetic and palaeomagnetic laboratories.

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