Temperature variations of magnetic susceptibility in rocks of the KTB pilot borehole and its vicinity (German part of the Bohemian Massif) and their geological and geophysical implications

Teplotní závislost magnetické susceptibility hornin pilotního vrtu KTB a hornin okolí vrtu (německá část Českého masivu) a její geologické a geofyzikální implikace (Czech summary)

(7 text-figs.)

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The temperature variation of magnetic susceptibility of specimens selected from the KTB pilot borehole (German part of the Bohemian Massif) and sampled in the vicinity of the borehole were investigated by means of the CS-2 Apparatus and KLY-2 Kappabridge. The purpose of this investigation was to identify the minerals that carry the magnetism of the rocks under consideration. In weakly magnetic rocks the rock susceptibility is carried mostly by paramagnetic minerals (biotite in gneisses, hornblende in amphibolites) and only subordinately by magnetite. In strongly magnetic specimens the main contributors to the rock susceptibility are pyrrhotite and magnetite.

Key words: KTB borehole, magnetic susceptibility, magnetic minerals

Introduction

Physical properties of rocks of the superdeep borehole KTB drilled in the westernmost part of the Bohemian Massif and of the rocks exposed close to this borehole are investigated in order to establish data for the interpretation of field geophysical measurements (Soffel et al. 1992). Among the physical properties investigated, the magnetic properties take a prominent position, because they are important not only for the reliable interpretation of ground and airborne magnetometric measurements, but also in palaeomagnetism and the anisotropy of magnetic susceptibility (AMS) which can be applied in solving some problems of structural geology (Tarling - Hrouda 1993).

The purpose of the present paper is to identify magnetic minerals and to reveal their contributions to the rock susceptibility in selected specimens from the KTB pilot borehole and from surface exposures (see Fig. 1) through the investigation of the temperature variation of magnetic susceptibility by means of the CS-2 Apparatus and the KLY-2 Kappabridge.

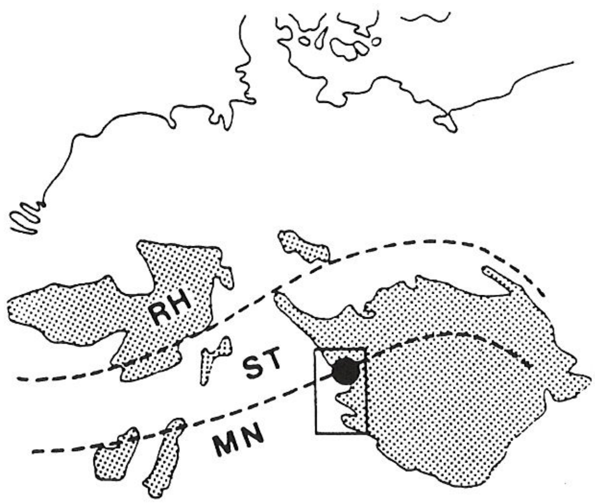

Fig. 1. Location of the study area on the W margin of the Bohemian Massif
RH - Rhenohercynian zone; ST - Saxothuringian zone; MN - Moldanubian zone; *closed circle* - KTB borehole; *oblong* - surface specimens sampling area. Adapted from D. Friedrich (1995)

Measurement technique

The temperature variation of magnetic susceptibility was measured with the CS-2 Apparatus (Parma - Zapletal 1991, Parma et al. 1993) in connection with the KLY-2 Kappabridge (Jelínek 1973, 1980). The CS-2 apparatus consists of a non-magnetic furnace and an electronic control unit. The specimen, 0.3 to 0.5 cm^3 in volume, is heated by a platinum wire. Its temperature is measured using a special platinum wire thermometer. The furnace is cooled by circulating distilled water. The quasi continuous measurement process is automated, being controlled by a personal computer (via RS 232 C serial channel). The measured curve of the temperature variation of susceptibility (henceforth called the thermomagnetic curve, even though this term is more frequently used for the temperature variation of saturation magnetization) is corrected for the susceptibility of the empty furnace and the corrected curve can be, in weakly magnetic specimens, resolved into paramagnetic hyperbola and a complex curve due to ferromagnetic minerals (for details see Hrouda 1994).

Table 1. Location and mineral composition of borehole rocks

Specimen No.	Depth [m]	Rock	Mineral association of dark and ore minerals [petrological pecularities]	Contents of main rock-forming minerals [weight %]
FRI25K	1179.16	Fine up to medium grained, flaser-like garnet amphibolite, rich in mobilized material, altered	Hbl, Bt, Ttn, Grt, Prh	7 % Qtz, 35 % Hbl, 5 % Chl, 2 % Bt, 4 % Ms, 6 % Grt, 40 % Pl
FRI25L	1179.69	Fine up to medium grained, flaser-like garnet amphibolite, rich in mobilized material, altered	Hbl, Bt, Ttn, Grt, Prh	7 % Qtz, 35 % Hbl, 5 % Chl, 2 % Bt, 4 % Ms, 6 % Grt,40 % Pl
KTB1	3508.00	Fine-grained up to medium-grained flaser-like sillimanite -muscovite-biotite gneiss,altered	Bt (Chl), Ms, Sil, Grt, Chl, Tur [Zeo-veinlet]	33 % Qtz, 22 % Chl, 17 % Pl, 29 % Ms (3508 m)
KTB2	3548.91	Fine grained garnet-bearing sillimanite-muscovite-biotite gneiss, altered	Bt (Chl), Ms, Sil, Grt, Chl, Ap [Gr + Py] [leucocratic layer]	49 % Qtz, 7 % Chl, 27 % Pl, 17 % Ms (3548 m)
KTB3	3567.10	Fine-grained flaser-like garnet-bearing sillimanite-muscovite-biotite gneiss,altered	Bt (Chl), Ms, Sil, Grt, Chl [cataclasite, ChlGrt]	46 % Qtz, 12 % Chl, 28 % Pl, 12 % Ms (3566 + 3568 m)
KTB4	3770.55	Fine-grained biotite-garnet-amphibolite, slightly altered	Hbl, Grt, Bt, Prh, Rt [rel Grt, Hbl-symplectite, ZeoPrh veinlet]	8 % Qtz, 47 % Hbl, 12 % Grt, 32 % Pl (3770 + 3772 m)
KTB5	3839.99	Fine up to medium grained garnet-biotite -horblende gneiss, altered, containing amphibolite lenses	Hbl, Bt (Chl), Grt Ttn, Chl, Czo [rel Grt, antiperthit]	-
KTB6	3563.20	Fine-grained flaser-like sillimanite -muscovite-biotite gneiss, altered	Bt (Chl), Bt, Ms, Sil, Grt, Ap, Prh [rel Ky, Mu-blasts]	48 % Qtz, 12 % Chl,3 % Bt, 26 % Pl, 11 % Ms (3562 + 3564 m)
KTB7	3671.70	Medium-grained flaser-like muscovite -biotite gneiss, rich in pyrrhotite, altered	Bt (Chl)+Si, Ms Prh, Sil, Alm [PrhBt, Prh veinlet, recryst. Ms, musc. Sil,Py + Lmt + Gr veinlet]	43 % Qtz, 10 % Chl, 3 % Bt, 29 % Pl, 15 % Ms (3572 m)
KTB8	3775.07	Fine-grained biotite-garnet-amphibolite up to garnet-horblende biotite gneiss	Hbl, Grt, Bt, Chl, Ep, [Hbl sympl., Grt pse PrhBt,leucocratic layer]	8 % Qtz, 33 % Hbl, 16 % Grt, 42 % Pl (3774 + 3776 m)
KTB9	3792.55	Fine-grained faintly foliated epidote amphibolite (metagabbro?) up to epidote-garnet amphibolite	Hbl, Chl, Ep, Grt, Ilm, Ttn [Ep pse Bt, Ep veinlet]	8 % Qtz, 42 % Hbl, 12 % Grt, 38 % Pl (3792 + 3794 m)

Explanation of abbreviations: Ap - apatite, Aln - allanite, Bt - biotite, Chl - chlorite, Bt (Chl) - chloritized biotite, Cpx - Clinopyroxene, Czo - clinozoisite, Ep - epidote, Gr - graphite, Grt - garnet, Hbl - horblende, Ilm - ilmenite, Lmt - laumonite, Mgn - magnetite, Ms - muscovite or light mica specification, Pl - plagioclase, Qtz - Quartz, Prh - pyrrhotite, Py - pyrite, Rt - rutile, Sil - sillimanite, Ttn - titanite, Tur - tourmaline, Zeo - zeolite, ZeoPrh - Zeo + Prh aggregate, ChlGrt - Chl + Grt aggregate, rel Grt - relic garnet, rel Ky - relic kyanite, Prh Bt - Prh in phyllosilicate bands, musc. Sil. - muscovitized sillimanite, Grt pse - pseudomorphoses after Grt, Ep pse Bt - Ep pseudomorphoses after Bt.

Geological and petrographical characteristics, sample preparation

The geological and petrological characteristics of the specimens investigated are summarized in Tables 1 and 2 for the KTB pilot borehole and for the surface rock samples close to borehole, respectively.

Table 2. Location and mineral composition of the borehole vicinity rocks

Specimen No.	Rock	Mineral association of dark and ore minerals	Contents of main rock-forming minerals [volume %]
FRI2	Fine-grained faintly foliated garnet-bearing amphibolite	Hbl, Grt, Ilm, Prh, Ttn	60 % Hbl, 35 % Pl, 3 % Grt, 2 % Ilm
FRI3	Fine-grained faintly foliated garnet-bearing biotite-sillimanite gneiss	Bt, Sil, Grt, Prh, Gr	55 % Qtz, 10 % Pl, 20 % Bt, 13 % Sil,2 % Prh
FRI4	Fine-grained faintly foliated garnet-bearing amphibolite	Hbl, Ttn, Grt, Prh, Ilm	60 % Hbl, 32 % Pl, 6 % Qtz, 1 % Ttn,1% Prh
FRI6	Medium-grained faintly foliated clinopyroxene amphibolite	Hbl, Cpx, Ttn, Prh, Gr	60 % Hbl, 33 % Pl, 6 % Cpx, 1 % Ttn
FRI8	Medium-grained faintly foliated amphibolite	Hbl, Ttn, Ilm, Mgn	60 % Hbl, 39 % Pl, 1% Ttn
FRI16	Medium-grained well foliated amphibolite	Hbl, Czo, Bt, Chl, Ilm	70 % Hbl, 12 % Qtz, 12 % Pl, 3 % Czo, 3% Ilm
FRIW1	Fine-grained well foliated calcite bearing clinozoisite amphibolite	Hbl, Czo, Ttn	80 % Hbl, 10 % Pl, 10 % Czo

For explanations of abbreviations see Table 1

The specimens of the KTB pilot borehole were first crushed using a brass hammer and then powdered using an agate bowl. The resulting grain size ranged approximately from 0.1 mm to 0.4 mm. The surface rocks were milled in an agate mill about 10 minutes so that their grain size was about 0.1 mm.

Thermal susceptibility variation of the rocks investigated

The results of the investigation of temperature changes of magnetic susceptibility are presented in Figs. 2 to 5 and in Table 3. The figures show the heating thermomagnetic curves of individual specimens normalized to the highest susceptibility value. Table 3 presents the specimen name, rock type, rock bulk susceptibility, paramagnetic and ferromagnetic susceptibility components, R_{30} parameter (cooling to heating susceptibility ratio at 30 °C), and abbreviations of the identified magnetic minerals ordered according to their relative contributions to the rock bulk susceptibility.

It can be seen from Figs. 2 to 5 that the thermomagnetic curves measured can be divided into two groups. In the first group, the initial part of each of the thermomagnetic curves is similar to the paramagnetic hyperbola. In some specimens the curve has a small elevation in the vicinity of 300 °C. At temperatures higher than 450 °C the thermomagnetic curve rises conspicuously and around 600 °C it decreases relatively rapidly, indicating probably the presence of magnetite.

As can be seen from Table 3, the susceptibility of the first group of borehole specimens, mostly gneisses, is relatively low, ranging from 246 x 10^{-6} to 641 x 10^{-6} [SI]. In the amphibolites from the surface samples the total susceptibility is slightly higher, reaching up to 3755 x 10^{-6}. The separation of ferromagnetic and paramagnetic susceptibility components, respectively, shows that the paramagnetic components are stronger than the ferromagnetic components in all of the specimens. Paramagnetic components strongly predominate in many specimens. The ferromagnetic minerals are represented mainly by magnetite. Small elevations of some curves in the vicinity of 300 °C may indicate minor amounts of pyrrhotite.

The thermomagnetic curves of the second group of specimens are characterized by conspicuous elevations (followed by relatively rapid decrease) in susceptibility around 300 °C and around 600 °C, indicating the presence of pyrrhotite and magnetite, respectively (Figs. 4, 5).

Table 3. Characteristics of thermal variation of magnetic susceptibility of investigated rocks

Specimen Name	Rock Type	Suceptibility Total	Ferro	Para	R_{30}	Magnetic Minerals
First Group, Borehole Specimens						
KTB1	gneiss	324	64	260	2.8	Bt, Mgn
KTB2	gneiss	406	4	402	2.0	Bt, Mgn
KTB3	gneiss	421	15	406	7.9	Bt, Mgn
KTB5	gneiss	641	251	391	2.0	Bt, Mgn
KTB6	gneiss	246	1	245	8.1	Bt, Mgn
KTB9	amphibolite	619	116	503	2.2	Hbl, Mgn
FRI25L	amphibolite	785	353	432		Hbl, Mgn
First Group, Borehole Vicinity Specimens						
FRI2	amphibolite	2 095	513	582	1.3	Hbl, Mgn
FRI6	amphibolite	779	9	770	1.9	Hbl, Mgn
FRI8NEU	amphibolite	3 755	2 937	818	2.0	Hbl, Mgn
FRI16	amphibolite	1 045	156	889	1.6	Hbl, Mgn
FRIW1	amphibolite	523	24	499	1.7	Hbl, Mgn
Second Group, Borehole Specimens						
KTB4	amphibolite	1 197	875	322	2.1	Mgn, Prh
KTB7	gneiss	4 130	4 130	-	1.2	Mgn, Prh
KTB8	amph. gneiss	930	451	479	1.8	Mgn, Prh
FRI25K	amphibolite	923	423	500	2.4	Mgn, Prh
Second Group, Borehole Vicinity Specimens						
FRI3	amphibolite	9 876	9 876	-	2.4	Mgn, Prh
FRI4	amphibolite	3 986	3 470	516	4.5	Mgn, Prh

Note: The values of the total, ferromagnetic and paramagnetic susceptibilities are given in units of 10^{-6} SI
Explanation of abbreviations: Bt - biotite, Hbl - hornblende, Mgn - magnetite, Prh - pyrrhotite

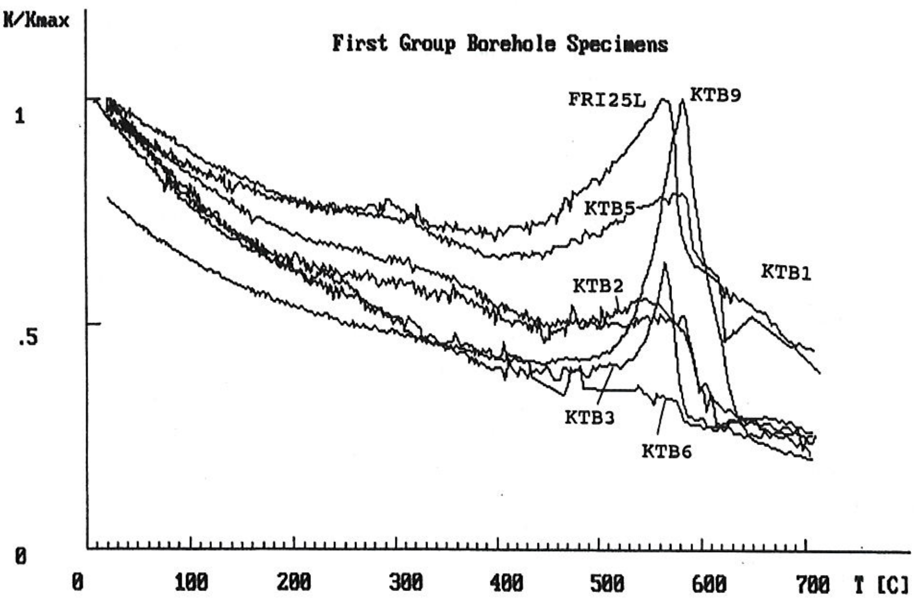

Fig. 2. Heating thermomagnetic curves of the first group specimens (mostly gneisses) from the KTB-1 pilot borehole, Germany

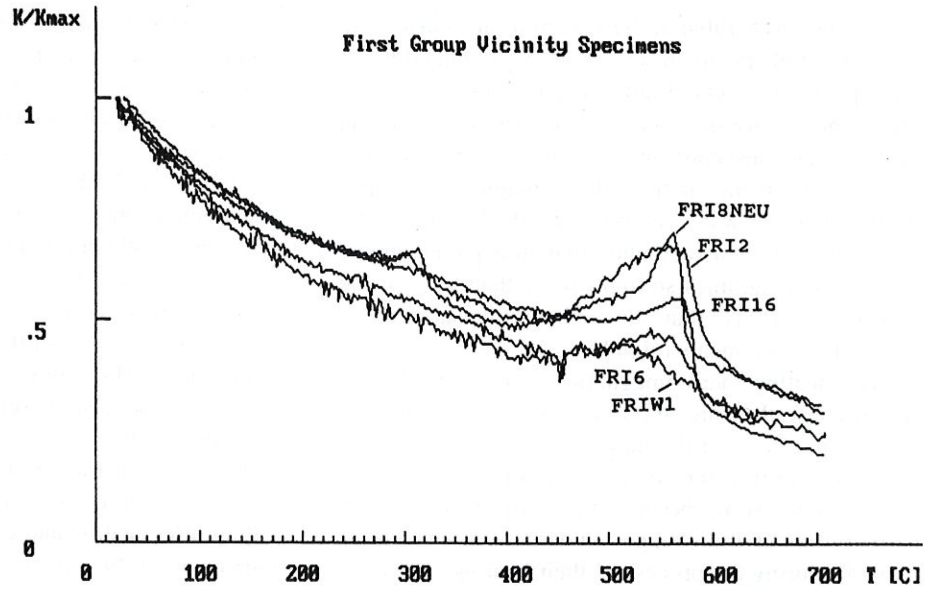

Fig. 3. Heating thermomagnetic curves of the first group specimens (amphibolites) from the vicinity of the KTB-1 pilot borehole, Germany

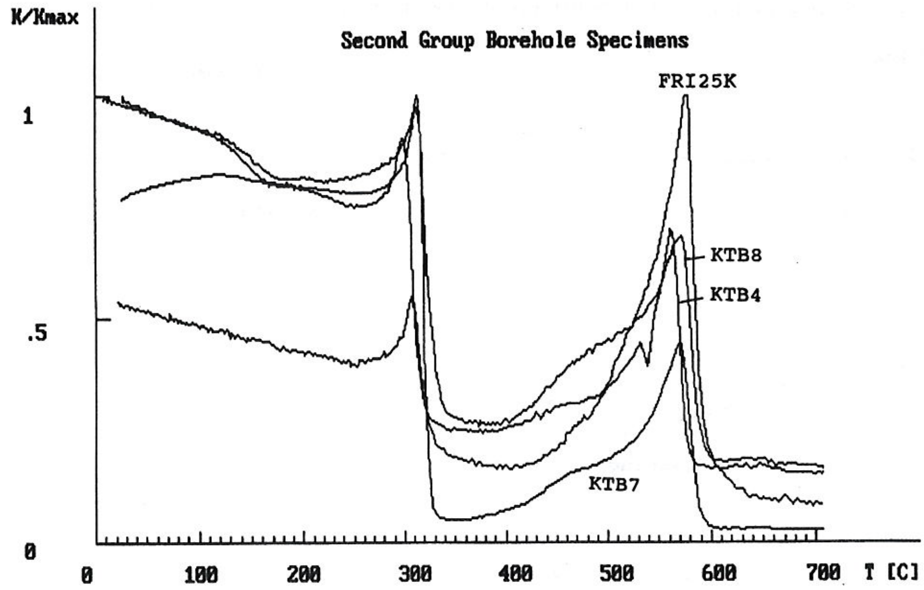

Fig. 4. Heating thermomagnetic curves of the second group specimens from the KTB-1 pilot borehole, Germany

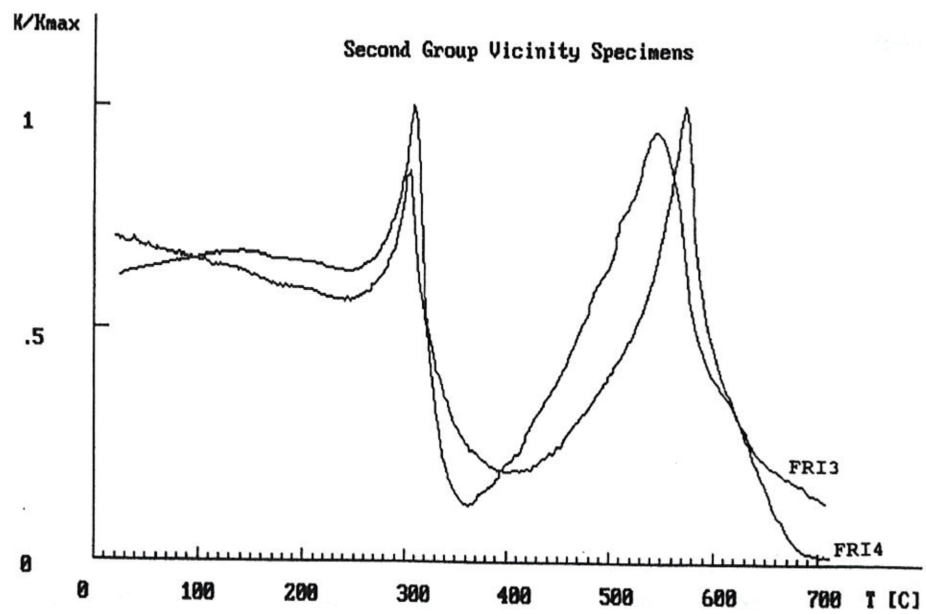

Fig. 5. Heating thermomagnetic curves of the second group specimens (amphibolites) from the vicinity of the KTB-1 pilot borehole, Germany

As shown in Table 3, the susceptibilities of the second group of specimens are relatively high and in some specimens very high, approaching 10 000 x 10^{-6}. The relationship between the ferromagnetic and paramagnetic susceptibilities is variable. In some specimens the ferromagnetic and paramagnetic susceptibilities are comparable, in the others the ferromagnetic component is clearly higher than the paramagnetic one, being sometimes so high (more than 99% of the rock susceptibility) that our method is not able to separate the components reliably.

The heating thermomagnetic curves were discussed, because they are important for the identification of the initial state of the magnetic minerals present in a rock. In addition, the cooling thermomagnetic curves are also interesting, because they inform us, at least partially, about the changes undergone by magnetic minerals during the process of their heating. The thermomagnetic cooling curves are very variable and cannot be presented as comprehensively as the heating curves. Hence, instead of presenting the heating and cooling curves of all the specimens investigated only selected typical examples will be presented.

Fig. 6 shows both the heating and cooling thermomagnetic curves of the specimen FRI8NEU from the vicinity of the KTB borehole. The susceptibility of this specimen is mostly controlled by the paramagnetic fraction (hornblende) and the effect of ferromagnetic minerals (traces of pyrrhotite, small amounts of magnetite) is small. However, the cooling thermomagnetic curve appears to be shifted towards much higher susceptibilities. This can be explained most easily by assuming that new magnetite was created during heating. A similar behaviour is expressed by all the cooling curves of the specimens of the first group. The room temperature susceptibility increases to double values after heating and cooling in the majority of specimens of the first group. It may increase exceptionally up to eight times (see the values of the R_{30} parameter in Table 3).

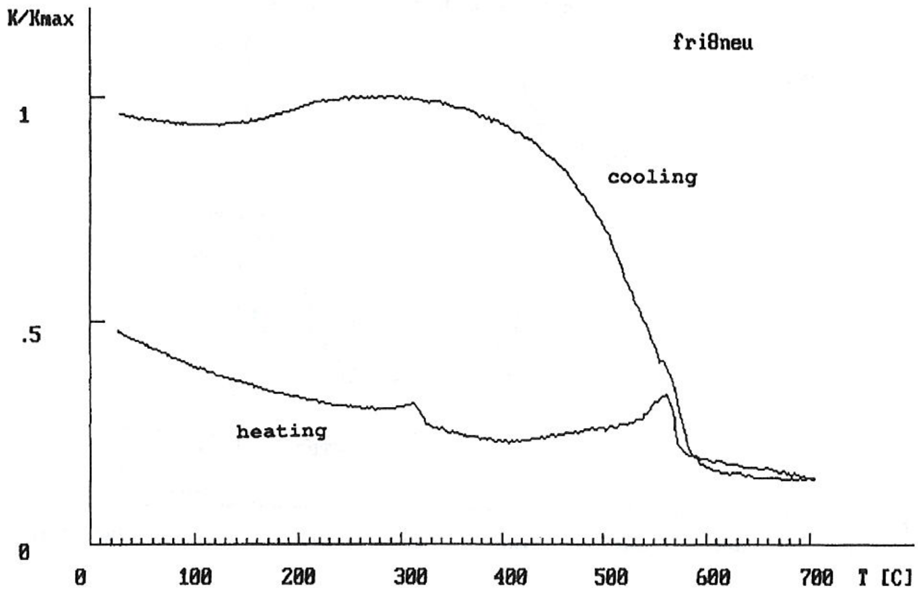

Fig. 6. Heating and cooling thermomagnetic curves of the weakly magnetic FRI8 amphibolite from the vicinity of the KTB-1 pilot borehole, Germany

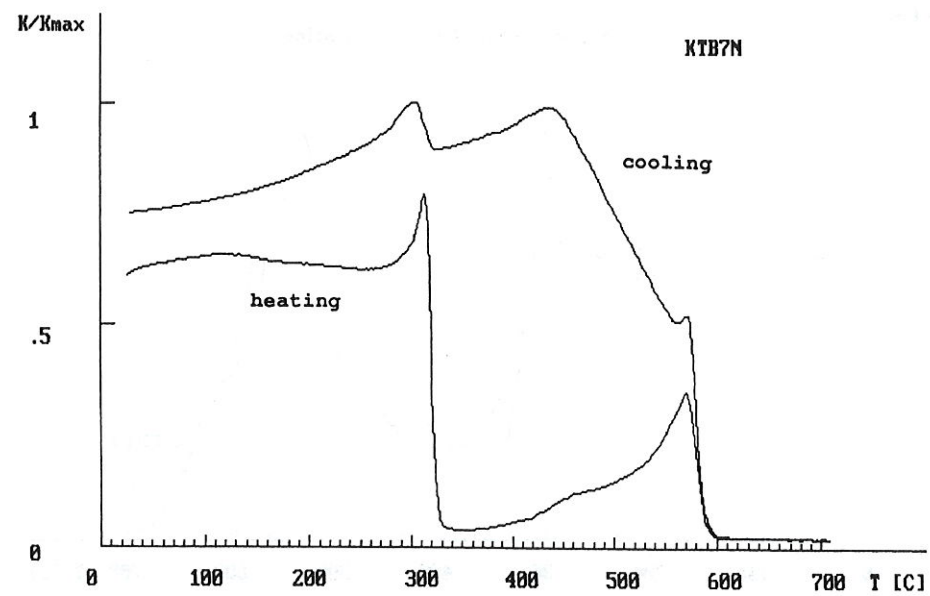

Fig. 7. Heating and cooling thermomagnetic curves of the strongly magnetic gneiss from the KTB-1 pilot borehole, Germany

Fig. 7 shows both heating and cooling curves of the specimen KTB7 (gneiss from the borehole) containing both pyrrhotite and magnetite. At low temperature the predominant mineral is pyrrhotite which shows en elevation between 300 °C and 320 °C and sharp decrease at 320 °C on the heating curve. Above the temperature of 350 °C the susceptibility gradually increases up to 570 °C after which it drops again, because of the Curie temperature of magnetite. The cooling curve shows a relatively high increase of susceptibility in the temperature interval between 590 °C and 580 °C and a small peak around 570 °C. During further cooling, from 580 °C to 430 °C, the susceptibility inreases with decreasing temperature. This suggests that at least part of the indicated magnetite was created during heating, probably due to the oxidation of pyrrhotite. Around 320 °C the cooling curve shows a peak characteristic of pyrrhotite and then it slowly decreases towards the room temperature value which is only slightly higher than the susceptibility before heating. This probably means that the increase in susceptibility due to the creation of new magnetite was partially compensated by lowering the content of pyrrhotite.

Discussion, geological and geophysical implications

Information about the carriers of magnetism in the rocks of the KTB borehole and its vicinity can be obtained from numerous saturation magnetization thermomagnetic curves presented in the KTB-Reports, in thesis works of German universities, and in the paper by de Wall & Worm (1993) and from measurements of the other magnetic parameters (e.g. Soffel et al. 1992).

The present paper adds quantitative data on the susceptibility contributions from paramagnetic and from ferromagnetic minerals. This is important, because the susceptibility is probably the most frequently measured magnetic parameter and quantitative knowledge of its contributors is of vital importance for reliable interpretation of the AMS measurements in terms of the preferred orientation of magnetic minerals (c.f. de Wall 1991).

The results of the present study can be used in palaeomagnetism and AMS, because they not only identify the minerals carrying the magnetism of the rocks investigated, but also inform us quantitatively about the contributions of the ferromagnetic and paramagnetic components to the rock susceptibility. For example, they fully confirm the idea of de Wall (1991) that the AMS of weakly magnetic rocks from the KTB pilot borehole is carried predominantly by paramagnetic minerals. In these rocks, the AMS can be interpreted in terms of the preferred orientation of biotite in gneisses and hornblende in amphibolites, respectively. In strongly magnetic rocks whose magnetism is carried by pyrrhotite and magnetite, the above measurements give us quantitative information about the contributions of these minerals to the rock susceptibility and increase therefore reliability in the AMS interpretation of these rocks (pyrrhotite is an order-of-magnitude more anisotropic than magnetite).

It should be emphasized here that our thermomagnetic curves represent the temperature variation of low-field magnetic susceptibility (measured in the field of 0.38 *mT*). They differ from the more frequently used thermomagnetic curves that represent the temperature variation of the high-field (often saturation) magnetization (for the KTB rocks published for example by de Wall & Worm 1993). While the high-field thermomagnetic curves of ferromagnetic minerals decrease with increasing temperature relatively rapidly (for examples see de Wall & Worm 1993) also at relatively low temperatures, the low-field susceptibility, in the initial part of the thermomagnetic curve (for example, between room temperature and 200 °C), is either more or less constant or increases slowly with increasing temperature; only in the vicinity of the Curie temperature it shows more conspicuous and rapid changes.

The knowledge of the susceptibility variations with temperature is important in the interpretations of magnetic anomalies, in the consideration of possible deep sources of the anomalies. Namely, the induced magnetization is due to the weak Earth's magnetic field and the susceptibility is therefore the controlling factor for this magnetization. From Figs. 2 to 5 it is obvious that in weakly magnetic rocks the susceptibility considerably decreases with increasing temperature (and depth), whereas in strongly magnetic rocks the susceptibility may slowly decrease or remain constant or even increase with increasing temperature, showing considerable increase close to 300 °C followed by rapid and considerable decrease at higher temperatures. Consequently, the susceptibility contrast between weakly and strongly magnetic rocks, which is probably the source of the magnetic anomalies in the area under consideration, can increase with depth, reaching the highest values in the depths of about 10 km where the temperature is about 300 °C.

Conclusions

The following conclusions can be drawn from the investigation of the variations of magnetic susceptibility with temperature of rocks from the KTB pilot borehole and surface rocks cropping out near to the borehole.

1. The thermomagnetic curves of weakly magnetic rocks have in their initial parts a shape similar to the hyperbola characteristic of paramagnetic minerals and show elevations around 600 °C followed by relatively rapid susceptibility decrease. These curves together with petrologic analysis indicate that the magnetic minerals in these rocks are represented predominantly by paramagnetic silicates (biotite in gneisses, hornblende in amphibolites) and by minor amounts of magnetite.

The rock susceptibility is, therefore, carried predominantly by the paramagnetic minerals and subordinately by magnetite (cf. also de Wall 1991, Friedrich et al. 1995).
2. The thermomagnetic curves of medium to strongly magnetic rocks show pronounced peaks characteristic of pyrrhotite and magnetite, respectively, which are the main carriers of magnetism in these rocks. The effect of paramagnetic minerals on the rock susceptibility in these rocks is subordinate or of negligible importance relative to that of pyrrhotite and magnetite. It is pyrrhotite amongst the ferromagnetic minerals that affects the rock susceptibility more significantly.
3. The cooling thermomagnetic curves show generally higher susceptibilities than the heating curves. This is probably due to the fact that new magnetite originated during the heating process.

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Teplotní závislost magnetické susceptibility hornin pilotního vrtu KTB a hornin okolí vrtu (německá část Českého masivu) a její geologické a geofyzikální implikace

Pomocí aparatury CS-2 a střídavého můstku KLY-2 byla měřena teplotní závislost magnetické susceptibility vzorků hornin vybraných z pilotního vrtu KTB a vzorků odebraných na výchozech v okolí vrtu. Cílem práce bylo identifikovat magnetické minerály ve studovaných horninách. Ve slabě magnetických horninách je magnetická susceptibilita určena především obsahem paramagnetických minerálů (biotitu v rulách, amfibolu v amfibolitech) a jen nepatrně je ovlivněna přítomností velmi malého množství magnetitu. V silně magnetických horninách jsou hlavními nositeli magnetismu pyrhotin a magnetit.