The Use of Magnetic Susceptibility of Rocks in Geological Exploration

(case histories study)

by

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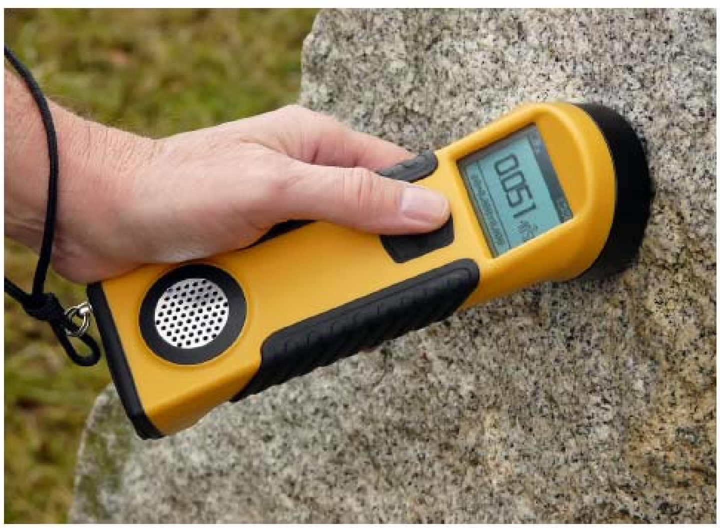

Written to demonstrate the usefulness of Hand-Held Magnetic Susceptibility Meters in solving various geological problems.

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Contents

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1. Introduction

Magnetic susceptibility is probably the most easily measurable petrophysical parameter. It can be measured not only in the laboratory on rock specimens, but also in the field on rock outcrops (see the picture on the frontal page). Various instruments for measurement of magnetic susceptibility in the field on rock outcrops have been developed recently. Among them, the Kappameters of the KT series are probably the most convenient, because they are light and of pocket size (useful in geological mapping), very sensitive (1 x 10^{-6} [SI] in the KT-10 model), measure the susceptibility very rapidly (one measurement takes a few seconds), contain memory for storing large amounts of measured data (up to 500 measurements) *, and possess blue tooth connectivity (for combining susceptibility data with GPS measurements) and USB connectivity (for transferring the measured data into computer).

Magnetic susceptibility of rocks is in principle controlled by the type and amount of magnetic minerals contained in a rock. Sometimes, it is dominantly controlled by paramagnetic minerals (mafic silicates such as olivine, pyroxenes, amphiboles, micas, tourmaline, garnets), often by ferromagnetic minerals (iron oxides or sulphides, represented for instance by magnetite and/or pyrrhotite, respectively) and much less frequently by diamagnetic minerals (calcite, quartz). As the ferromagnetic minerals mostly belong to accessoric minerals that are often sensitive indicators of geological processes, the magnetic susceptibility is a useful parameter in solving some petrologic problems.

Magnetic susceptibility is in general a symmetric second order tensor reflecting not only compositional aspects (as outlined above), but also structural aspects (investigated through the anisotropy of magnetic susceptibility, for details see the book by Tarling & Hrouda, 1993). However, the latter can be studied only using extremely sensitive laboratory instruments and will therefore be avoided in this study.

It is difficult to present the use of magnetic susceptibility in general geological terms, because this is a very complex problem. In our opinion, instead of attempting for generalization, it is more convenient to present a set of case histories of the use of magnetic susceptibility in solving various geological and petrological problems.

2. Several good reasons why to measure magnetic susceptibility in the field on rock outcrops

a) Measurement of susceptibility on rock outcrops is very fast, one measurement taking a few seconds, and one can execute numerous detailed measurements in reasonable time. To do the same amount of measurements through taking samples and their subsequent measurement in laboratory would be impracticable.

b) Kappameter measurement enables us to detect subtle changes in magnetic mineral content within the geological body or outcrop that are not macroscopically observable. In this way, cryptic magnetic and non-magnetic layers, lenses, enclaves and other bodies can be identified as well as gradual changes in the content of magnetic minerals.

c) Magnetic susceptibility cannot be assessed on the basis of external appearance of a rock under interest even though the mafic rocks show in general higher susceptibility than felsic rocks. There are many examples of light granites being both weakly and strongly magnetic. On the other hand, some dark rocks as gabbros and lamprophyres can be weakly magnetic. In addition, Fe ores with magnetite have high susceptibility, while the Fe ores with dominating hemoilmenite and having the same Fe content can show much lower susceptibility. Because of all these phenomena it is recommended to measure the susceptibility in the field on rock outcrops.

d) Susceptibility measurements along the outcrop enable qualified selection of the specimens for following laboratory investigations.

* See Addendum

e) Magnetic susceptibility depends on geochemical or mineralogical composition of the rocks and on later metamorphic processes and alterations. Very important controlling factors are also fugacities of O_2 and S. Magnetic susceptibility provides us with invaluable information in this respect.

3. Physical principles

Magnetic susceptibility characterizes the ability of a substance to be magnetized when exposed to external magnetic field. In magnetically isotropic substances, it is defined as follows

$M = \mathrm{k}\, H\,,$

where M represents the vector of the induced magnetization (in SI of units in A/m), H is the vector of the intensity of magnetic field (also in A/m) and k is the magnetic susceptibility (dimensionless scalar entity). In some substances, the susceptibility is constant, while in the others it is a complex function of the field intensity (see Fig. 1).

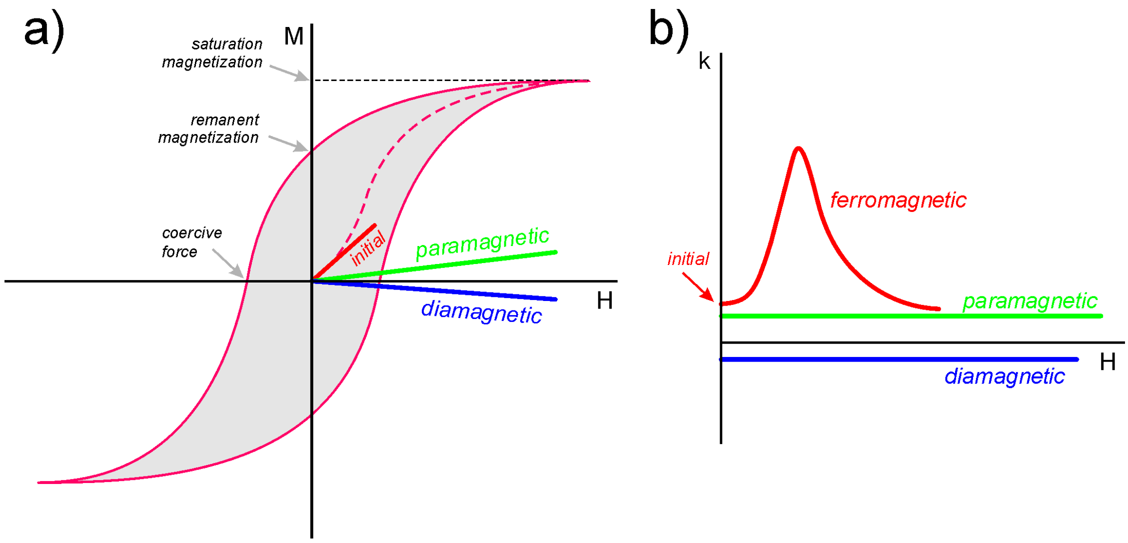

Fig. 1 Relationship between magnetization and intensity of magnetizing field for ferromagnetic, paramagnetic and diamagnetic substances (a) and field variation of susceptibility for the same substances (b).

According to their magnetic structure, materials can be divided into three basic groups; for their magnetization to field intensity relationship and their variation with field see Fig. 1. The first group is represented by *diamagnetic* materials whose magnetic susceptibility is negative, in general low in absolute value and independent of the magnetizing field (k is negative constant). The second group is represented by *paramagnetic* materials whose susceptibility is positive, in general higher than in diamagnetic materials but still relatively low in absolute value and also independent of the magnetizing magnetic field (k is positive constant). The third, and most important group, is represented by the materials with ordered magnetic structure, called the *ferromagnetic materials sensu lato*. These materials are characterized by the existence of spontaneously magnetized sublattices (magnetic domains) even in the absence of external magnetic field. They are extremely important in palaeomagnetism because they can carry remanent magnetism. Their magnetic susceptibility is positive, often very high in absolute value and dependent in a complex way on the magnetizing field (k is a complex function of H as illustrated by the hysteresis loop, see Fig. 1). In the ferromagnetic substance magnetized for the first time the magnetization increases with increasing field intensity along the dashed line; the very beginning part of the dashed line is straight line. If the field intensity reaches certain value, called the saturation field, the susceptibility virtually no longer increases (in fact it increases very slowly due to paramagnetic effect). If the field then decreases, the magnetization also decreases, but not along the dashed line, but along the solid line that crosses the ordinate at zero field value. It means that there is a magnetization even in the absence of the magnetizing field. This magnetization is called the remanent magnetization and represents the basis for palaeomagnetism. If the field intensity increases in the opposite direction, the magnetization decreases reaching zero at the field intensity called the coercive force. Further decreasing field produces saturation again. Reverting field direction and continuing in field changing enables the hysteresis loop to be closed. This cycle can be repeated many times, but the dashed line is never reached.

The ferromagnetic materials *sensu lato* are subdivided into three groups: (1) the *ferromagnetic materials sensu stricto* in which all the atomic magnetic moments are parallel, (2) the *ferrimagnetic materials* in which the atomic magnetic moments create two antiparallel sublattices, one dominating over the other so that the overall material magnetism is strong and (3) the *antiferromagnetic materials* in which the atomic magnetic moments also create two antiparallel sublattices, but these sublattices are roughly balanced and therefore the magnetism of these materials is relatively weak.

The paramagnetic and diamagnetic susceptibilities are field-independent, while the ferromagnetic susceptibility is field-dependent (Fig. 1b). Due to the last effect, the susceptibilities measured in different fields are incomparable and the use of a standard field would be advantageous in comparative studies. This problem is often solved through using the field weak enough in which the magnetization is directly proportional to the field intensity. Then, the corresponding susceptibility is field-independent and called the initial susceptibility. In most ferromagnetic minerals the initial susceptibility is measured in the fields less than 10 A/m, only in the case of pyrrhotite the field should be much lower. As the measuring field in the Kappameters of the KT series is less than 1 A/m, the instruments measure the field-independent susceptibility in all minerals.

The magnetic susceptibility depends not only on the measuring field, but also on the grain size of a ferromagnetic mineral. Namely, when the grain size diminishes from the *multi-domain* grains to the limit of the so-called *single domain* grains (different in different minerals), the susceptibility decreases. If the grain size diminishes even more, to the limit of the so-called *superparamagnetic* grains, the susceptibility increases dramatically. These changes are described in more detail in the section on Environmental Magnetism, where they are used in the so-called magnetic granulometry.

The magnetic susceptibility depends also on temperature. In paramagnetic minerals, the dependence is represented by hyperbola, in ferromagnetic minerals there are acute drops in susceptibility at certain temperatures when magnetic or crystalline states are changed (Curie temperature, Verwey and Morin transitions). These changes play virtually no role at the ambient temperatures in most minerals, only in some titanomagnetites or hemoilmenites they can be important.

The magnetic susceptibility depends obviously on the content of iron in a rock, but this relationship is very complex, depending on minerals in which the Fe is contained.

4. Magnetic susceptibility of minerals

Except for rare monomineralic rocks, rocks consist in general of all three kinds - i.e. diamagnetic, paramagnetic and ferromagnetic - minerals. In order to get an idea of the contribution of individual minerals to the magnetic susceptibility of a rock, Table 1 shows the susceptibility of the most frequent rock-forming and accessoric minerals. For fast information, Fig. 2 shows the contributions of individual minerals to the rock susceptibility as function of the content of the individual minerals in a rock.

From Tab. 1 and Fig. 2 it is clear that in strongly magnetic rocks, i.e. those with susceptibility higher than 5×10^{-3}, the rock susceptibility is controlled mostly by the presence of ferromagnetic minerals. In rocks with the lower susceptibility, the susceptibility may be controlled by both paramagnetic and ferromagnetic minerals, according to the rock mineral composition.

In some almost monomineralic rocks, such as limestone, marble, quartzite, if the content of ferromagnetic and paramagnetic minerals is very low or zero, the susceptibility can be even negative, being controlled by the presence of diamagnetic calcite or quartz.

In many minerals, the susceptibilities presented in Tab. 1 are not single values, but rather wide susceptibility intervals. This reflects variability of susceptibility with chemical composition of the minerals. For example in orthopyroxene, the susceptibility is very low in the member free of iron, while in the member which contains no magnesium, it is relatively high. In general, the susceptibility depends on the ratio of Mg to Fe components (Fig. 2b). Similar situation exists in olivine, garnets and amphiboles. In titanomagnetites, the susceptibility depends on the amount of the titanium in the mineral (generally it decreases with increasing Ti content, see Fig. 2c).

Table 1 Magnetic susceptibility variations in individual minerals (compiled from Bleil & Petersen 1982, Kropáček 1971, Krs & Kropáček 1987). Mass susceptibilities given by Bleil & Petersen were re-calculated into bulk susceptibilities using mineral densities given by Betekhtin (1956).

Mineral	*Susceptibility* [10^{-6}]	*Mineral*	*Susceptibility* [10^{-6}]
forsterite	-12.6	quartz	-15.4
fayalite	4,976	opal	-12.9
olivine	124 to 4,270	orthoclase	-13.7
		halite	-10.3
enstatite	121	apatite	-10.6
ferrosilite	3,670	graphite	-177
orthopyroxene	3,700		
diopside	1,319	aragonite	-15.0
hedenbergite	2,783	calcite	-13.1
augite	555 to 1,111	dolomite	11.3
clinopyroxene	613 to 25	siderite	2,770 to 3,170
actinolite	490	spinel	30
arfvedsonite	3,468	chromite	2,827 to 7,069
riebeckite	3,016	franklinite	5,750 - 3,000,000
hornblende	746 to 1,368	jacobsite	50,000 to 3,000,000
		magnetite	3,000,000
muscovite	36 to 711	maghemite	up to 3,000,000
biotite	873 to 3,040	rutile	107
phlogopite	176 to 281	ilmenite	8,042
lepidolite	136 to 1,560	hematite	1,300 to 7,000
pyrope	502	pyrite	-6.3 to 63
almandine	2,510 to 6,230	marcasite	61 to 245
spessartite	6,780	galena	-33 to 9.3
andradite	2,280 to 4,320	sphalerit	-15 to 2,060
garnet	553 to 6,230	chalcopyrite	308 to 411
		pentlandite-folgerite	100,057
staurolite	790 to 1,590	gersdorffite	214 to 1,571
cordierite	200 to 1,100	cobaltite	553 to 157,892
tourmaline	39 to 1,520	pyrrhotite	see Tab. 1
beryl	23		
epidote	1,010		
orthite	970 to 3,960		
sphene	264		
zircon	-15 to 386		

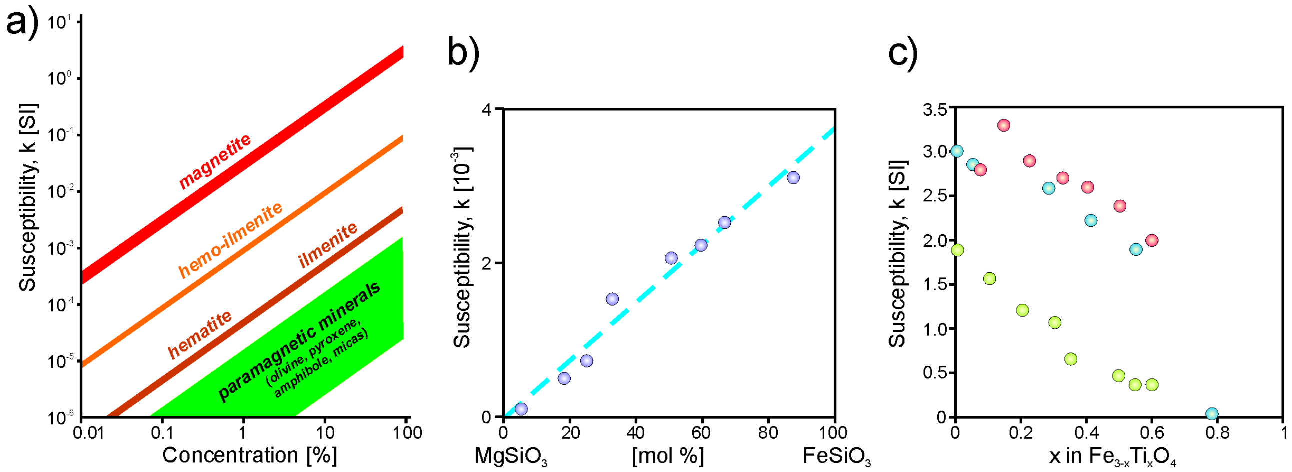

Fig. 2 Magnetic susceptibility of minerals. Adapted from Hrouda & Kahan (1991), Nagata (1961), Jackson et al. (1998).
a – mineral contributions to rock susceptibility, note that 100 % of mafic silicates contribute less than 1% of magnetite
b - susceptibility variation with chemical composition in orthopyroxene
c - susceptibility variation with chemical composition in synthetic titanomagnetite (symbols in different colours denote different experiments producing grains of different sizes)

5. Geological mapping and petrology

5.1 Granitic rocks

Magnetic susceptibility of granitic rocks is very variable, ranging from the order of 10^{-6} in leucocratic granites to the order of 10^{-2} in some granodiorites or tonalites. However, as known since the sixties, the susceptibility is not distributed homogeneously, but displays a roughly bimodal pattern (Fig. 3). One mode corresponds to the orders of 10^{-3} to 10^{-2} and the other one to those of 10^{-5} to 10^{-4}. In the literature, the former mode granites are referred to as magnetic or ferromagnetic, while the latter as weakly magnetic or paramagnetic (e.g. Dortman et al., 1984; Bouchez, 2000).

From the point of view of their composition, granitic rocks do not also create a homogeneous group, but can be divided into different types coming from different tectonic environments. Two types are of particular importance: an *I-type* (igneous), broadly corresponding to the biotite hornblende tonalite association, and an *S-type* (sedimental), broadly corresponding to the two-mica granite association (Pitcher, 1983). These two types, introduced by Chappel and White (1974), were later complemented by two others: an *M-type* (mantle-derived) corresponding to the most calc-alkaline plagiogranites and an *A-type* corresponding to anorogenic alkali granites (see Pitcher, 1983).

From the point of view of magnetic minerals, granitic rocks can be divided basically into two series: (1) the *Magnetite Series* characterized by the occurrence of magnetite and/or magnetite-ilmenite and (2) the *Ilmenite Series* characterized by the occurrence of ilmenite and/or hemo-ilmenite (Ishihara, 1977). Studies of the area distributions of these series show that the Magnetite Series granites roughly coincide spatially with the I-type granites, while the Ilmenite Series granites coincide with the S-type granites (Takahashi et al. 1980, see Figs. 3b,c). One may therefore hypothesize that the magnetic granites correspond basically to the I- and/or A-types, while the weakly magnetic granites correspond to the S-types and the susceptibility can hence be used as first approximation indicator of granite origin (e.g. Ellwood and Wenner, 1981). However, as the occurrence of magnetite or ilmenite is primarily controlled by the oxygen fugacity in the magma source, the correlation between the above granite types and granite series need not be very close.

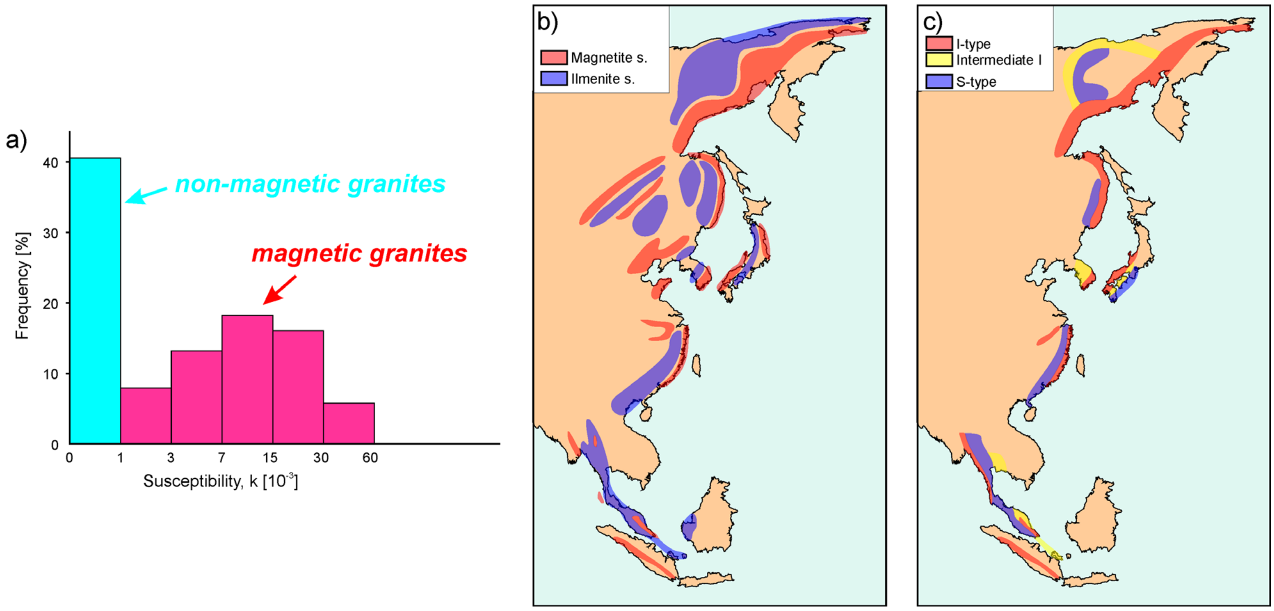

Fig. 3 Bimodal distribution of susceptibility in granitic rocks of the former U.S.S.R (a), inferred distributions of magnetite-series/ilmenite-series rocks (b) and S- and I-types granitoids (c) in eastern Asia. Adapted from Dortman (1984) and Pitcher (1982).

In addition, the magnetic mineral assemblage may reflect not only the conditions of granite formation, but also processes of its later evolution whereby its magnetic mineralogy may change (Kopf, 1966). Consequently, the susceptibility must be used as granite origin indicator with great caution, after a thorough study of the origin of magnetic minerals. Nevertheless, as the susceptibility measurement is much faster and cheaper than the investigation of oxygen and strontium isotopes used for the discrimination of the granite type in geochemistry, the susceptibility survey can be recommended despite all its disadvantages.

An example is presented from the granitoid Brno massif consisting of three principal sectors, the eastern and western granitoid sectors separated by the central meta-basic sector (see Fig. 4). Originally, rocks of all these sectors were regarded as resulting from magmatic differentiation. Nowadays, the order-of-magnitude difference in susceptibility between the eastern and western granitoid sectors suggest, together with new geochemical data, that those sectors originated in different tectonic environments and were later juxtaposed tectonically.

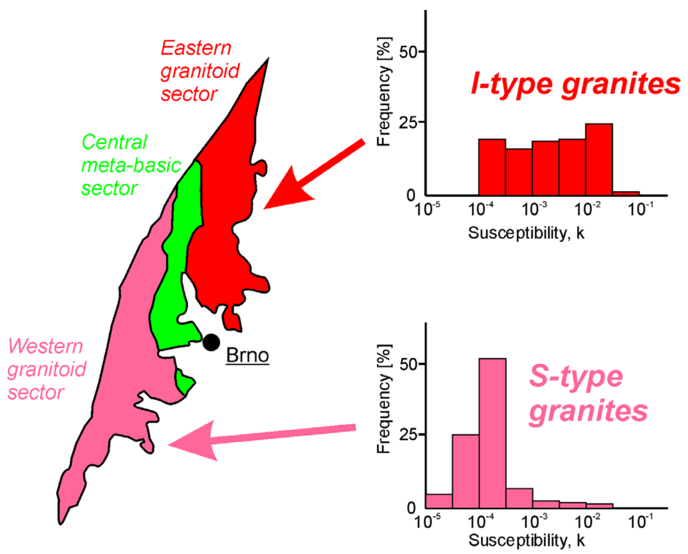

Fig. 4 Geological scheme and frequency histograms in susceptibility in the Brno massif.

Some chemical changes induced by interplay of magmas are manifested in susceptibility values and can be too weak that they are not simply visible in the rock composition. An example will be presented from the Brno massif in Moravia.

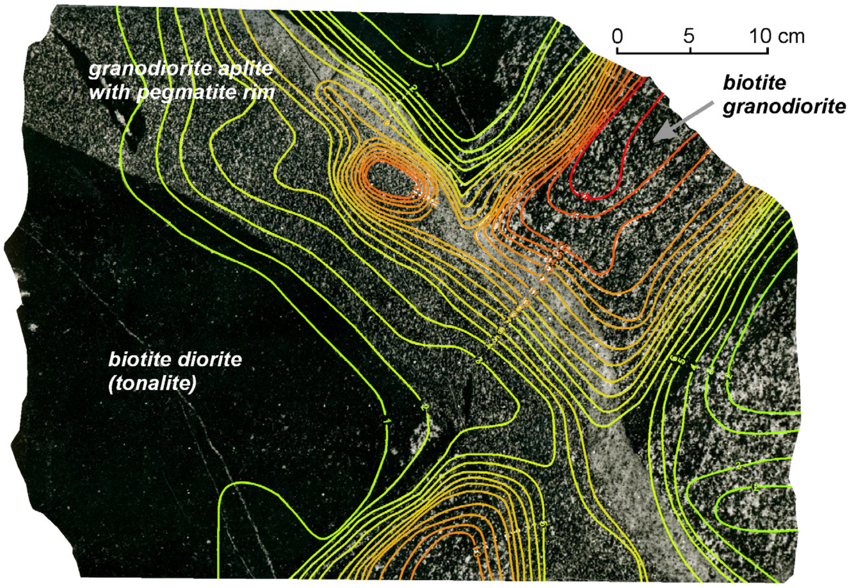

Fig. 5 Polished sample of a contact of diorite, granodiorite, and aplite from the western sector of the Brno massif with contour map of susceptibility (in 10^{-3}). Adapted from Hrouda & Rejl (1982).

The granitoids of the western sector of the Brno massif are characterized by intense hybridization and contamination, syntexis of the rocks of the crystalline mantle, and metasomatic processes manifested in microclinization of potash feldspar. In one quarry, a 5 cm thick slab sample, 50 x 40 cm in size, was taken containing diorite, granodiorite and granodiorite aplite in intimate contact. The sample was polished and its susceptibility was measured using the Kappameter (see Fig. 5). It has been shown that the susceptibility of diorite is low, 1 to 2 x 10^{-3}. The susceptibility of granodiorite is higher, ranging from 3 to 18 x 10^{-3}, the highest values being in the centre of the granodiorite body. The susceptibility of the aplite-pegmatite dike is intermediate between diorite and granodiorite; only where the dike crosses granodiorite the susceptibility increases considerably. This susceptibility pattern can be explained as follows. During metasomatism iron was mobilized from dark silicates (or older Fe oxides), slightly transported and deposited as magnetite. The transport of iron was primarily controlled by the emplacement of the aplite-pegmatite dike and by the assimilation of granodiorite fragments in aplite.

5.2 Volcanic rocks

Volcanic rocks, particularly the young ones (called neo-volcanics), are often strongly magnetic and the variation in their susceptibility can be an important geological indicator. For example, the original titanomagnetites being the carriers of magnetism in these rocks can disintegrate or change in the structure and/or composition during low-temperature oxidation or other changes. These changes manifest significantly in the rock susceptibility and, conversely, can be investigated through the susceptibility measurement. Below, an example will be presented from a Quartenary lava flow from N Moravia.

The Chřibský les lava flow is one of three lava flows of the Velký Roudný volcano in N Moravia (Fig. 6a). In volcano periphery, it has been found that the lava flow consists of two lava subflows separated by a 2 m thick layer of volcanic ash. In the Slezská Harta locality, which is located near the toe of the lava flow, the ash layer is not present and there was a question whether the lava flow in this region is also represented by two subflows or whether only one subflow is present. Namely, in this region a dam was constructed and the answer to the above question was important, because of the strength properties of the rock massif from the point of view of engineering geology.

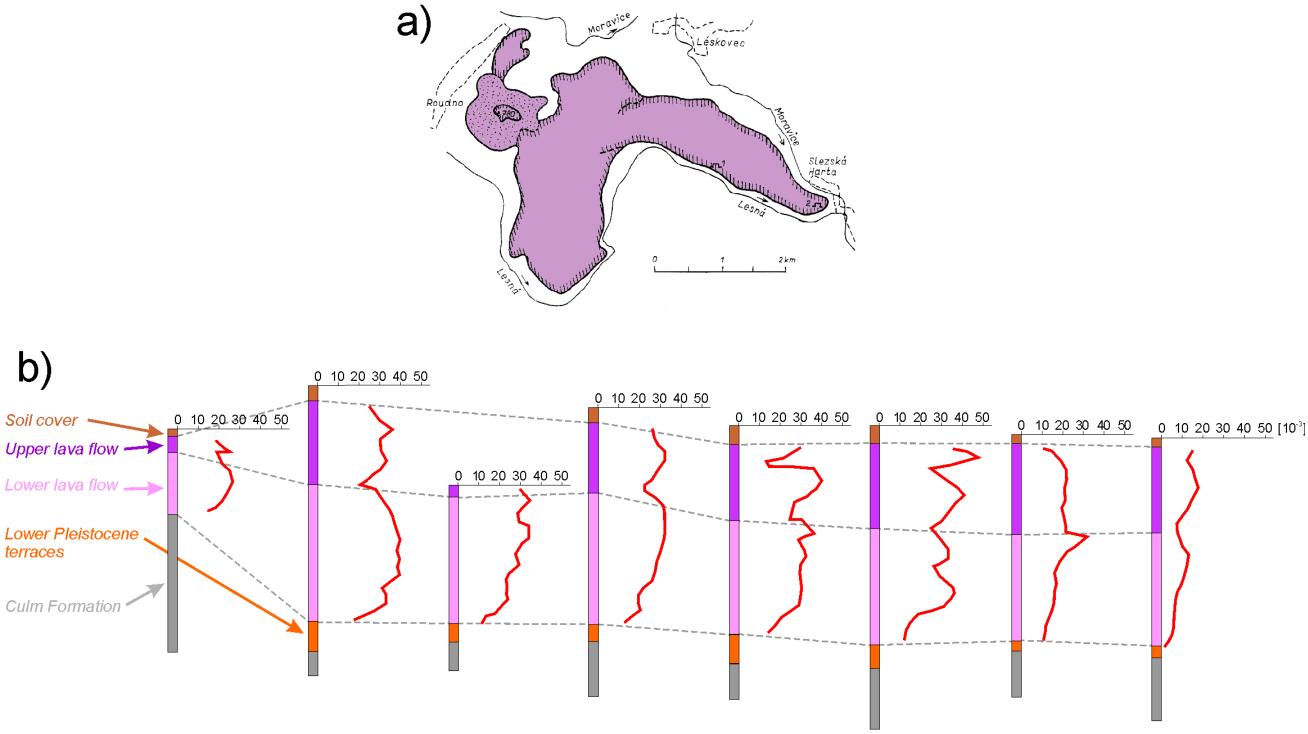

Fig. 6 Geological scheme of the Velký Roudný volcano (a) and the depth variation in magnetic susceptibility in several boreholes drilled through the Chřibský les lava flow at the locality of Slezská Harta (b). Adapted from Kolofíková (1976) and Müllerová & Müller (1972).

The lava flow was drilled through in many places and the magnetic susceptibility was measured by Kappameter on drill cores (Müllerová & Müller 1972). A special behaviour of susceptibility was found, i.e. the susceptibility decreased near the marginal parts of each of the subflows, while in the central areas it was high. Thus, the existence of two subflows manifested very conspicuously in the magnetic susceptibility (Fig. 6b). As this susceptibility behaviour was found also in the region of the Slezská Harta locality, where the ash layer is not present, one could conclude that the two subflows exist also in this region and this must have been taken into account in planning the construction works.

The susceptibility revealed also another interesting phenomenon. The susceptibility is higher (2 times) in the region near the volcano neck than in the Slezská Harta region (near the toe of lava flow). Mössbauer spectroscopy has revealed that in the basalt of the former area well developed titanomagnetites are present, while in the Slezská Harta area the titanomagnetites exhibit lattice structure suggesting extremely fast cooling (chilled margin, for details see Kolofíková 1976).

Another example of the use of magnetic susceptibility in investigating volcanic rocks comes from the Teplice Rhyolite Complex located in the Eastern Krušné Hory Mts., Czech Republic. The complex represents a post-collisional event of the Variscan orogeny and consists of explosive rhyolitic and dacitic piles. The entire piles were drilled through down to the crystalline basement by the Mi-4 drillhole, 924.5 m deep (for its location see Fig. 7a) (Breiter et al. 2000). Classification of the volcanic rocks of the drillhole suggests a rhyolitic to rhyo-dacitic composition (Fig. 7b). Trace element variability patterns, predominantly concentrations of Rb, Sr, Th and Zr enable to distinguish five volcanic units, in accordance with volcanostratigraphy and vertical zoning. The age of the complex is Westphalian C/D.

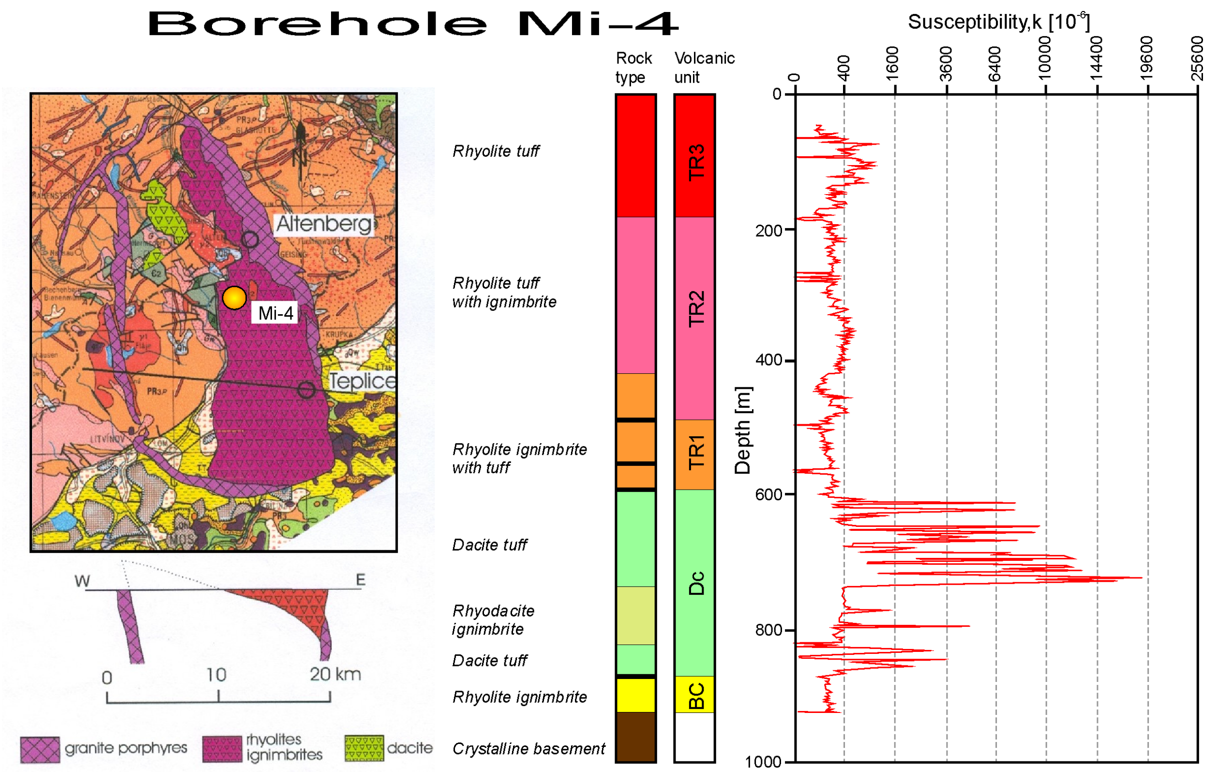

Fig. 7 Relationship between rock types and magnetic susceptibility in volcanic rocks of the Mi-4 borehole. a) – borehole location, b) – susceptibility variation with depth

Magnetic susceptibility was measured by the Kappameter on drillcores (spacing 2-3 determinations per metre). The results showed large difference between rhyolite and dacite to rhyo-dacite volcanics (Fig. 7b). The dacitic tuffs are the only anomalous member of the whole volcanic sequence. Elevated susceptibilities ranging from 1 x 10^{-3} to 19.6 x 10^{-3} were found in the upper part and at the base of the dacitic layer. The susceptibility of subvolcanic rhyolite is in general low containing a few even less magnetic ignimbritic layers (Fig. 7b). The dacitic ignimbrites are also weakly magnetic unlike the strongly magnetic tuffs. The variation of susceptibility within the dacitic rocks may reflect alteration effects on accessory magnetic minerals, likely magnetite.

5.3 Sedimentary rocks

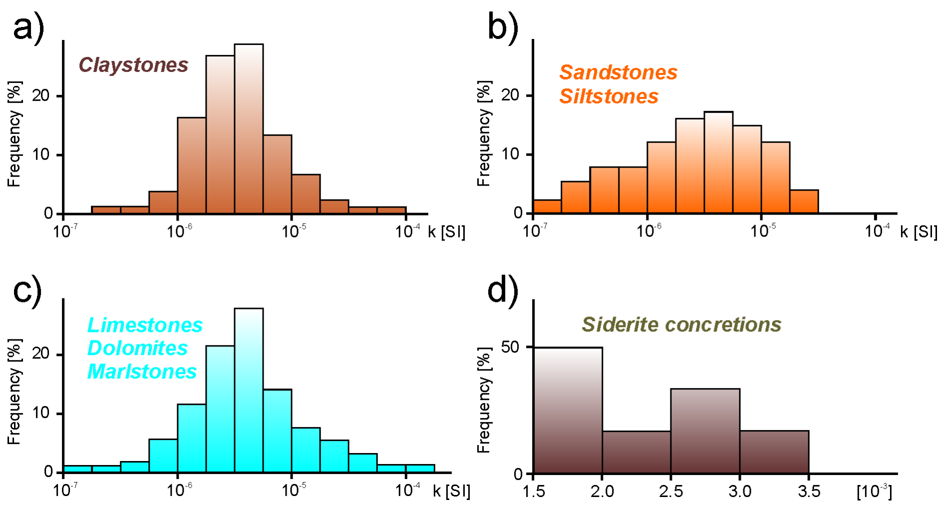

Fig. 8 Histograms of magnetic susceptibility of various sedimentary rocks (a) and siderite concretions (b). Adapted from Dortman (1984) and Hounslow (2001).

Magnetic susceptibility of sedimentary rocks is in general very low (see Fig. 8). The old versions of Kappameters were hardly able to measure it, only the new model (KT-10) has potential to measure with sufficient precision even those weakly magnetic rocks. Higher susceptibilities are possessed by the rocks that were splashed from highly magnetic volcanic rocks (e.g. magnetite bearing sands in some beaches of the Black sea) and by the sediments containing tufitic component. Some sedimentary rocks may contain siderite or ankerite whose susceptibilities are an order-of-magnitude higher (see Fig. 8d). Then, the susceptibility of such rocks can be also relatively high according to the amount of the heavy carbonates contained in the rock. All the above effects on the increased susceptibility values in sedimentary rocks may be indicated by the sensitive KT-10 Kappameter.

5.4 Metamorphic rocks

5.4.1 Indication of some metamorphic zones

An example will be presented from the Swiss Alps, where Rochette (1987b) used Kappameter in the investigation of metamorphic zones. The magnetic susceptibility of Helvetic Jurassic black shales in the Swiss Alps is controlled by iron-bearing silicates, magnetite or pyrrhotite. The susceptibility shows a good correlation with the Alpine metamorphism of the black shales from zeolite to amphibolite facies. In increasing metamorphism, the susceptibility first decreases due to the

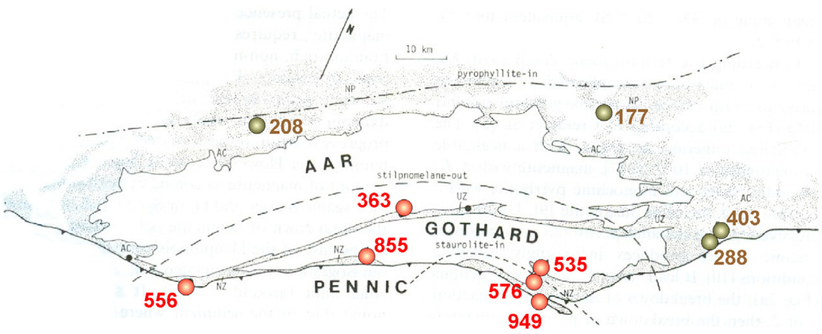

Fig. 9 Susceptibility indication of metamorphic isogrades in black shales of the Swiss Alps. Higher susceptibilities in red indicate appereance of new metamorphic pyrrhotite. Adapted from Rochette (1987b).

breakdown of original magnetite, then sharply increases when pyrite is transformed into monoclinic pyrrhotite. The breakdown of magnetite is located on the anchizone-epizone boundary and the transformation of pyrrhotite corresponds to the middle epizone. The sharp increase of susceptibility due to the formation of new pyrrhotite enables the precise mapping of the pyrrhotite-in isograde to be made, which appears to correspond closely to the stilpnomelan-out isograde.

5.4.2 Metamorphosed sediments of accretionary prisms

A sequence of rocks of the Upper Proterozoic accretionary prism that underwent progressive regional metamorphism was investigated in Central and Western Bohemia (Fig. 10a). The rocks were originally represented by shale and greywacke, being during metamorphism progressively transformed into slate, phyllitic slate, chlorite sericite phyllite, roofing slate, phyllitic schist, two mica schist, garnet two mica schist, two mica gneiss and biotite gneiss.

Fig. 10b shows the mean susceptibilities in individual localities in individual rock groups. There is obviously no trend in changing the susceptibility with progressive regional metamorphism. Increasing temperature and pressure during progressing metamorphism induce neither changing nor creation of new magnetic minerals.

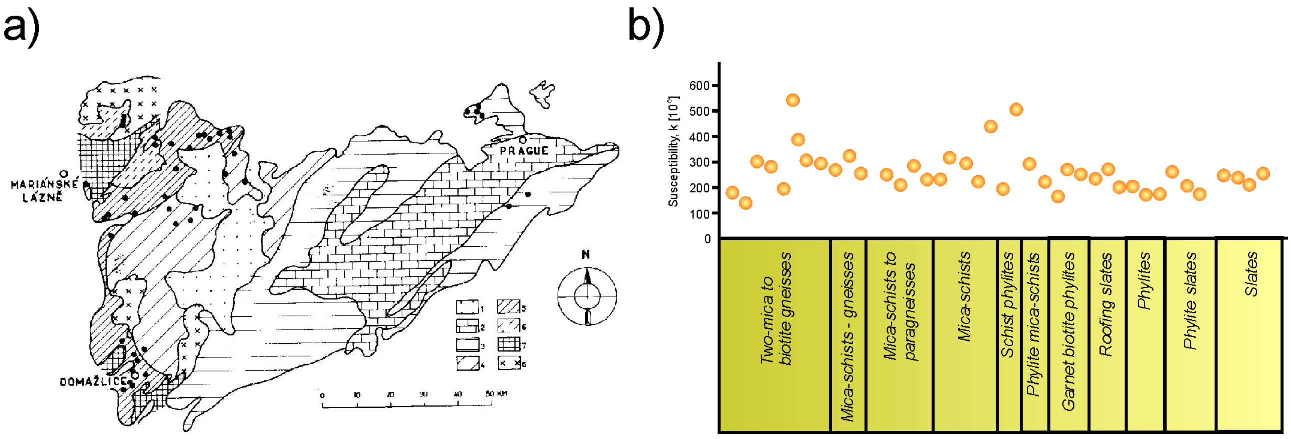

Fig. 10 Geological scheme of the Proterozoic of the Tepla-Barrandian region with the sites where susceptibility was investigated (a) and mean susceptibilities in individual localities (b). Legend: 1 – Permo-Carboniferous, 2 – Palaeozoic of the Barrandian, 3 – slate, 4 – phyllite, 5 – mica-schist, 6 – gneiss, 7 – amphibolite. Adapted from Janák (1972) and Hrouda & Janák (1976).

5.4.3 Metamorphosed igneous rocks

The effect of the metamorphism grade on the susceptibility of the metamorphosed igneous rocks was investigated on example of amphibolites of the West Moravian crystalline complex (Fig. 11a). The study was made in two principal units of the complex, i.e. in the Moldanubian nappe and in the Moravian nappe. Even though the Moldanubian nappe lies over the Moravian nappe, its rocks show higher metamorphism grade than those of the Moravian.

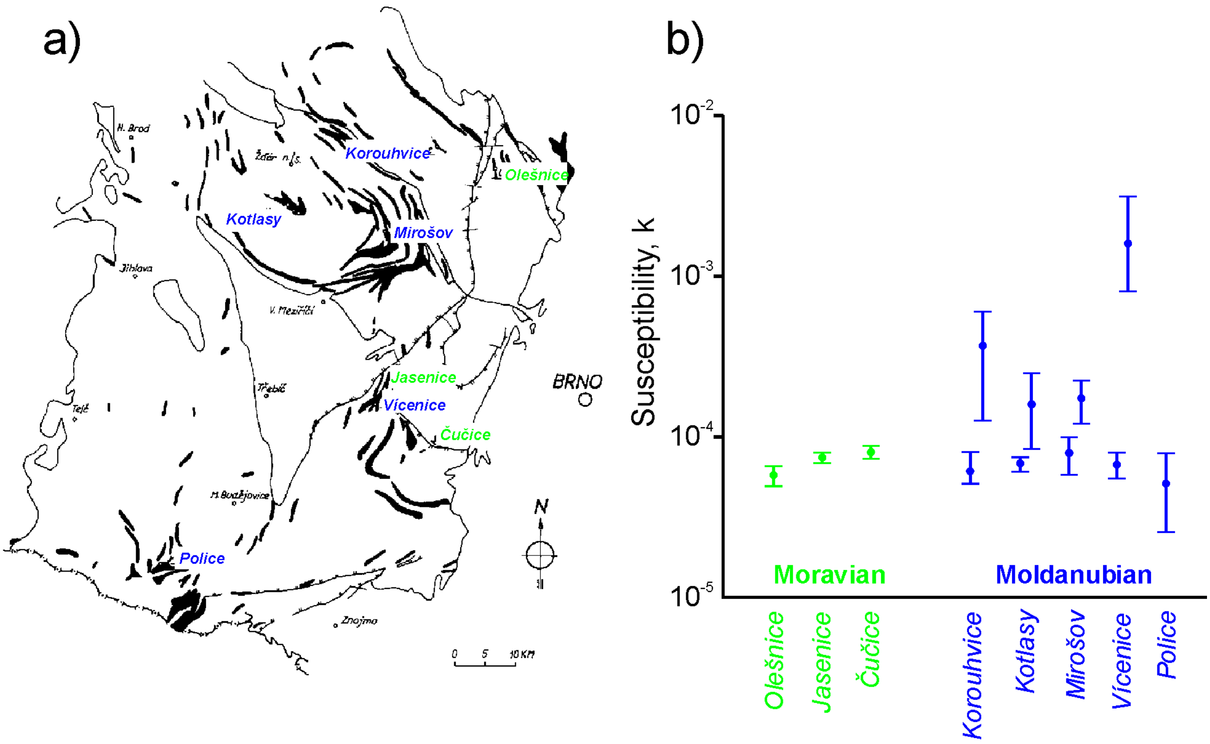

Fig. 11 Amphibolite bodies in the West Moravian Crystalline Complex and susceptibility characteristics for individual localities. Adapted from Hrouda et al. (1971).

The susceptibilities in the investigated localities are shown in Fig. 11b in terms of mean values and error bars characterizing the scatter and corresponding to standard deviations. The susceptibilities of the Moravian amphibolites are in the order of 10^{-4}, showing relatively narrow scatter. For this reason, only one mean value and one error bar are presented for each locality. In the Moldanubian amphibolites, on the other hand, the susceptibilities are very variable, ranging over two orders in magnitude (10^{-4} to 10^{-2}). Frequently, the susceptibility distribution is bi-modal, the first mode comprising values in the order of 10^{-4}, and the other mode values 10^{-3} to 10^{-2}. For this reason, each Moldanubian locality is characterized by two mean values and two error bars, corresponding to the first mode and second mode values, respectively.

Reflected-light microscopical research made by Dr. L. Rejl has shown that the susceptibility of the Moravian amphibolites is dominantly controlled by paramagnetic amphibole and only subordinately by magnetite. In the Moldanubian amphibolites, the same holds for the first mode specimens, while in the strongly magnetic specimens magnetite and sometimes also pyrrhotite were identified. It is obvious that the high grade metamorphism gave rise to development of new ferromagnetic minerals that could be indicated by the susceptibility measurement.

5.5 Delineation of boundaries between magnetically different rocks

Magnetic susceptibility is extremely effective in geological mapping, if macroscopically similar, but magnetically different rocks should be distinguished and delineated. An example is presented from the Čistá - Jesenice granitoid massif in the West Bohemia.

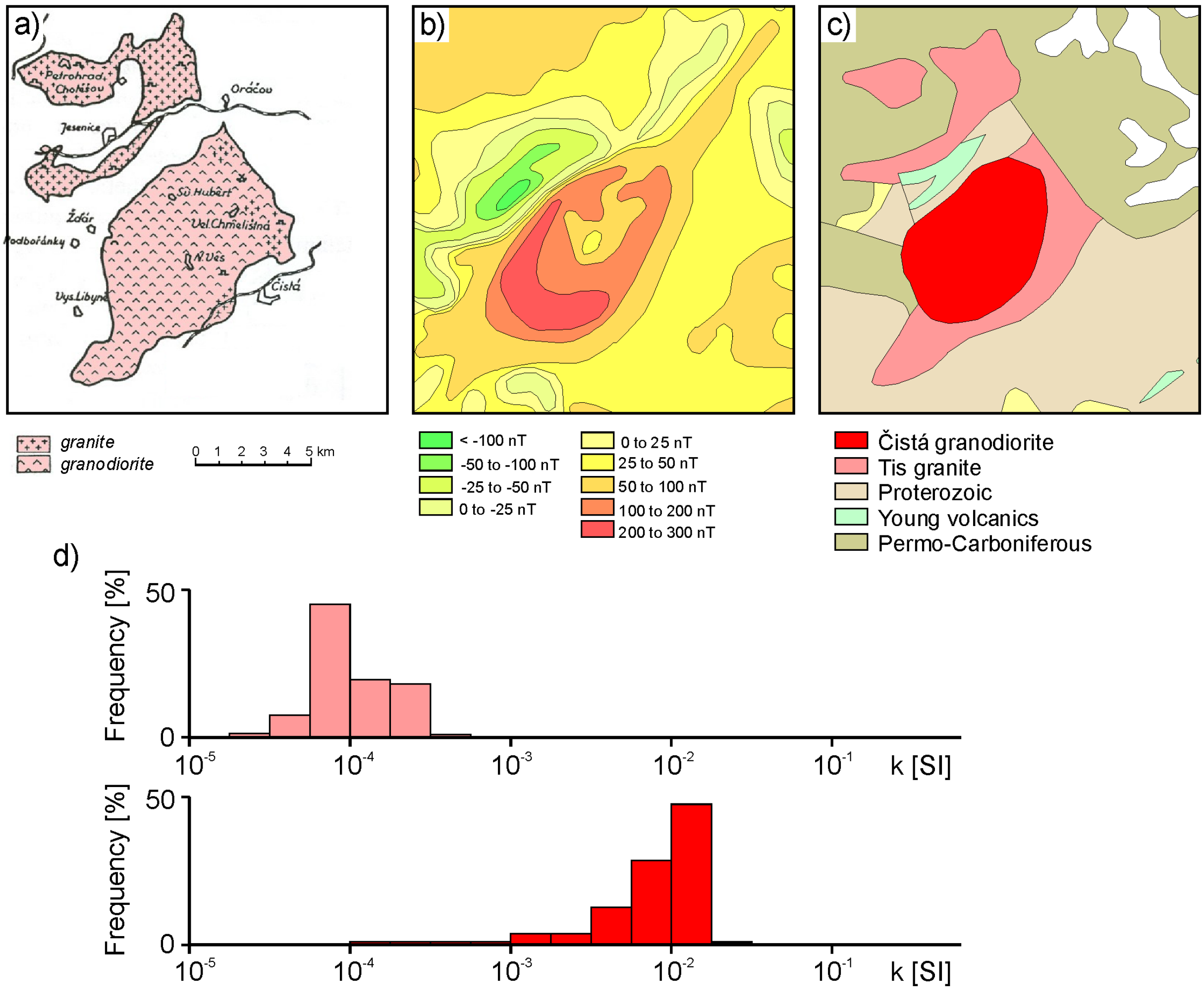

Fig. 12 Geological scheme (a) by Orlov (1933), map of magnetic ΔT anomalies (b), and recent geological scheme (c) of the eastern part of the Čistá - Jesenice massif. Adapted from Chlupáčová et al. (1975) and Šalanský (1995).

The Čistá - Jesenice massif in W. Bohemia consists of granite and granodiorite, originally regarded as differentiated through a magmatic differentiation process (Orlov 1933, see Fig. 12a). However, strong magnetic anomalies occur over a part of the massif (Fig. 12b). Petrographic research revealed that these anomalies are over granodiorite which creates an individual body - the Čistá granodiorite stock - within granite (Klomínský 1961). However, the precise delineation of the stock outcrop was not possible through classical geological mapping, because diorite cannot be simply distinguished macroscopically from granite in the field.

Petrophysical research (Bartošek et al. 1969, Chlupáčová et al. 1975) found that the susceptibility of granite is in the order of 10^{-4}, while that of granodiorite is in the order of 10^{-3} to 10^{-2} (Fig.12d). Then, Kappameter was used to delineate precisely, through measuring susceptibility of rock pieces in the field, the outcrop of the granodiorite stock. Later it was revealed that granite and granodiorite differ also in age and tectonic environment in which they generated. Granite is pre-Cambrian S-type granite, while granodiorite is Variscan, probably A-type granite (Bartošek et al. 1969).

6. Metasomatism, alterations

Some processes of alteration of original rocks are accompanied by changes in rock's magnetic mineralogy, i.e. phase changes or destruction of original magnetic minerals, formation of new magnetic minerals. As these changes are usually reflected in rock's magnetic susceptibility, they are easily detectable by susceptibility measurement.

6.1 Alkaline metasomatism (fenitization)

Metasomatic changes in granitic rocks often comprise changes in magnetic mineralogy and are accompanied by changes in magnetic susceptibility. Granitic rocks of the Čistá - Jesenice massif in the West Bohemia suffered in the Hůrky locality the process of alkaline metasomatism - fenitization (Bartošek et al. 1969). This process progressed in four stages starting with mylonitization of original granitic rocks and ending in complete transformation of granite in the so-called fenite. During this

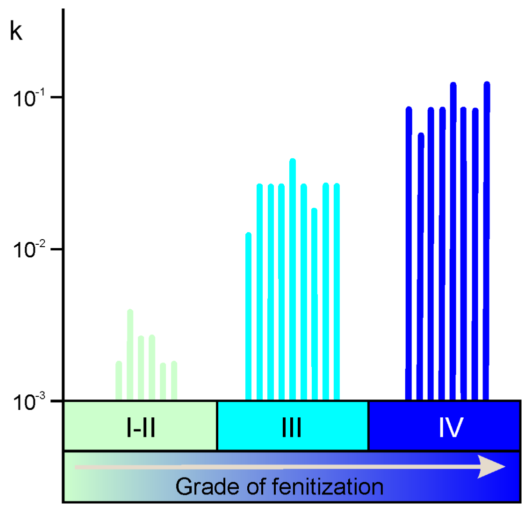

Fig. 13 Variation of susceptibility according to the grade of alkaline metasomatism (fenitization) in the Čistá - Jesenice Massif (W. Bohemia).

process the magnetic susceptibility irregularly increases due to the increase of content of new-formed magnetite; in the most strongly fenitized rocks the susceptibility is two orders of magnitude higher than in one of the original rocks, the Tis granite (see Fig. 13). As fenites in the Hůrky locality bear important mineralizations, the investigation of the intensity of fenitization through the susceptibility measurement is very important for economic geology.

6.2 Serpentinization of ultrabasic rocks

In ultrabasic rocks of ophiolite suites, processes of autometamorphism (serpentinization, amphibolitization, carbonatization) are very frequent. These processes are accompanied by conspicuous changes in susceptibility. Namely, during serpentinization new magnetite creates which is destroyed during subsequent process of carbonatization. (Fig. 14a). As the susceptibility changes range up to three orders, the susceptibility is extremely convenient for the indication of alterations of ultrabasic rocks.

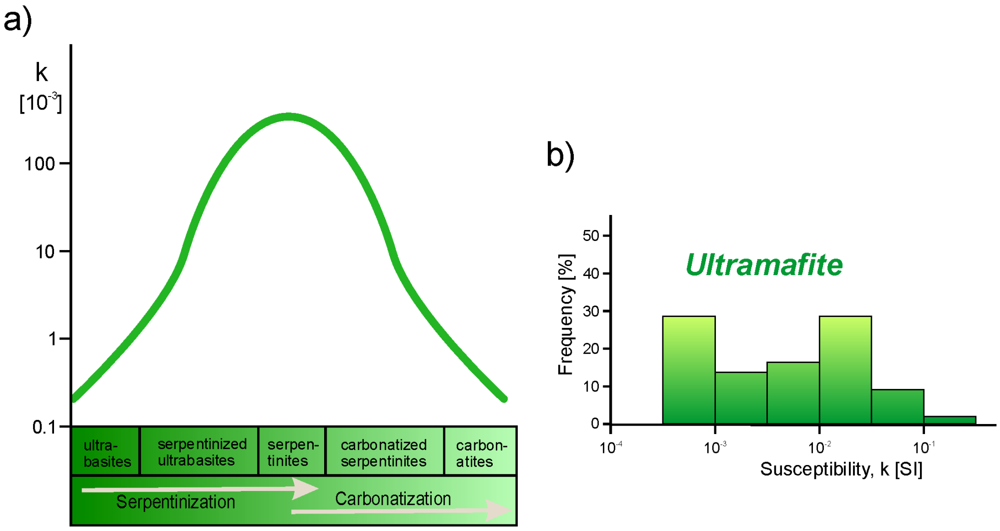

Fig. 14 Susceptibility changes during serpentinization and carbonatization of ultrabasic rocks (a) and susceptibility histogram of ultramafic rocks from the locality of Bory, Western Moravia, Czech Republic (b). Adapted from Dortman (1984) and Hrouda et al. (2008).

Susceptibility of serpentinized ultramafic rocks was investigated in the locality of Bory, Western Moravia, Czech Republic (Hrouda et al. 2008). Histogram of susceptibility data shows two peaks, one in the upper part of the order of 10^{-4}, the other one in the lower part of the order of 10^{-2} (Fig. 14b). Special investigation of the magnetic minerals, using temperature variation of susceptibility has shown that the susceptibility of rocks with $k < 1\text{x } 10^{-3}$ is predominantly controlled by the mafic silicates and the amount of magnetite is very low if any. These rocks, as revealed microscopically, show virtually no signs of serpentinization. On the other hand, the rocks with $k > 1 \text{ x } 10^{-2}$ is predominantly controlled by magnetite. This magnetite is new formed during rock serpentinization. Its grains are mostly located within interfoliation spaces, less frequently in micro-joints and on the foliation/joint crossing. Susceptibility shows as rapid indicator of the degree of serpentinization of ultramafic rocks.

6.3 Propylitization

In large areas of Tertiary volcanic rocks in the West Carpathians the low-temperature alteration, called propyllitization, is characteristic of many localities. This alteration is accompanied by phase change up to destruction of original titanomagnetites or formation of new, but less magnetic minerals. These changes manifest in the decrease of magnetic susceptibility (Fig.15). Through susceptibility measurement the intensity of propyllitization can be well indicated. As the propyllitization is often associated with economically important mineralizations, the possibility of rapid and cheap indication of propyllitization zones is of great significance.

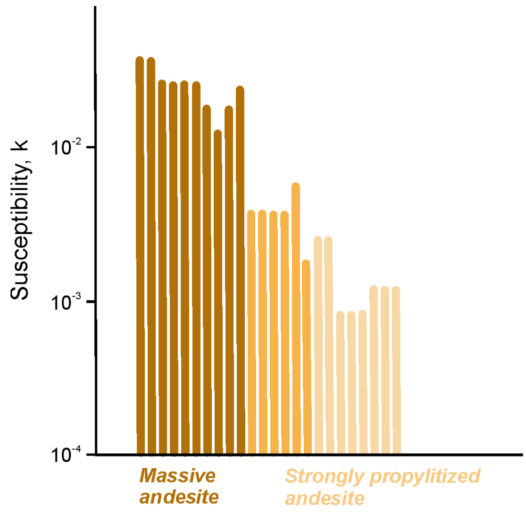

Fig. 15 Magnetic susceptibility in non-altered and altered andesites of the West Carpathians. Compiled from data of Drs. Ondra and Hanák.

6.4 Spilitization

Spilitization belongs to common alterations of basalt submarine see-bottom extrusions. It manifests in nearly total recrystallization of the original mineral composition and formation of new association involving uralite, chlorite, aktinolite, minerals of the zoisite-epidote group, leucoxene, calcite and, which is the most important, sodium plagioclase, albite to oligoclase. Titanomagnetite, which is a common Ti-Fe oxide in basalts, is usually destroyed and transformed into leucoxene, new-formed ilmenite and hematite. As a consequence, magnetic susceptibility of spilitized basalts is much lower compared to basalts not affected by spilitization as illustrated by Fig. 16. Two basaltic suits from West Bohemia were used to demostrate an influence of spilitization on magnetic susceptibility of basic volcanics: a) Upper Proterozoic spilitic basalts of the Barrandian, and b) subaerial Tertiary alkali basalts of the Eger Rift with mineral composition consisting of Ti-augite, Ti-amphibole, olivine, basic plagioclase, titanomagnetite, ilmenite and some glass.

Alterations of dolerites act in a similar way and strongly altered dolerites show only weak magnetic susceptibility, but some of them can contain pyrrhotite and due to its subsequent import can be more magnetic.

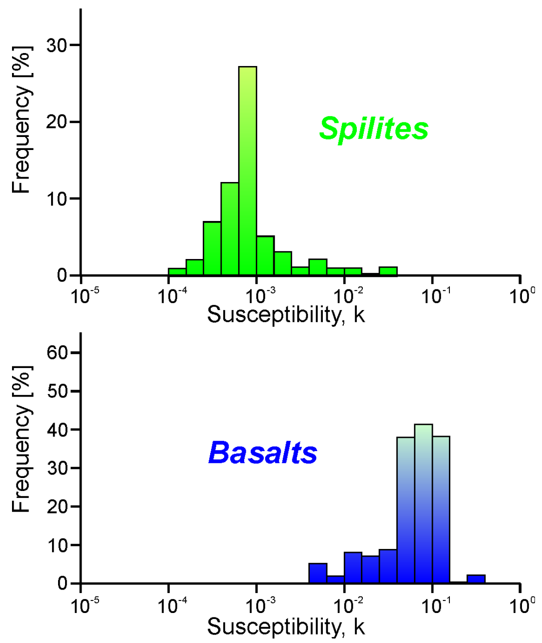

Fig. 16 Susceptibility histograms of spilitized basalts of the Barrandian (West Bohemia) and alkali olivine basalts of the Eger Rift (West Bohemia).

6.5 Cataclasis and mylonitization

The granitoids occurring in the northernmost part of the Brno massif are often strongly cataclased or even mylonitized and one can find succession of rocks ranging from massive granodiorite, through rock cataclased to mylonitized to various degrees, to ultramylonites. A special study was made to find out whether and how the cataclasis and mylonitization manifest in magnetic susceptibility. The susceptibility was investigated in two localities with massive granodiorite and in two localities with cataclased to mylonitized granodiorite (Fig. 17a).

In massive granodiorite, the susceptibility is relatively high, reaching the beginning of the order of 10^{-3}, and being very variable from specimen to specimen. In cataclased to mylonitized granodiorite, the susceptibility is much lower, in the order of 10-4, showing very small variability (Fig. 17b).

The minerals of the ferromagnetic fraction were separated by a permanent magnet from crushed rock up to 0.06 mm in size and then investigated by X-ray analysis. In addition, they were investigated by reflected-light microscopy on polished specimens by Dr. L. Rejl. These investigations have shown that the magnetic minerals are in these rocks represented by magnetite and hematite and hematite originates through martitization from magnetite. It is therefore obvious that cataclasis and mylonitization was accompanied by transformation of magnetite into hematite the intensity of which can be investigated through the susceptibility measurement.

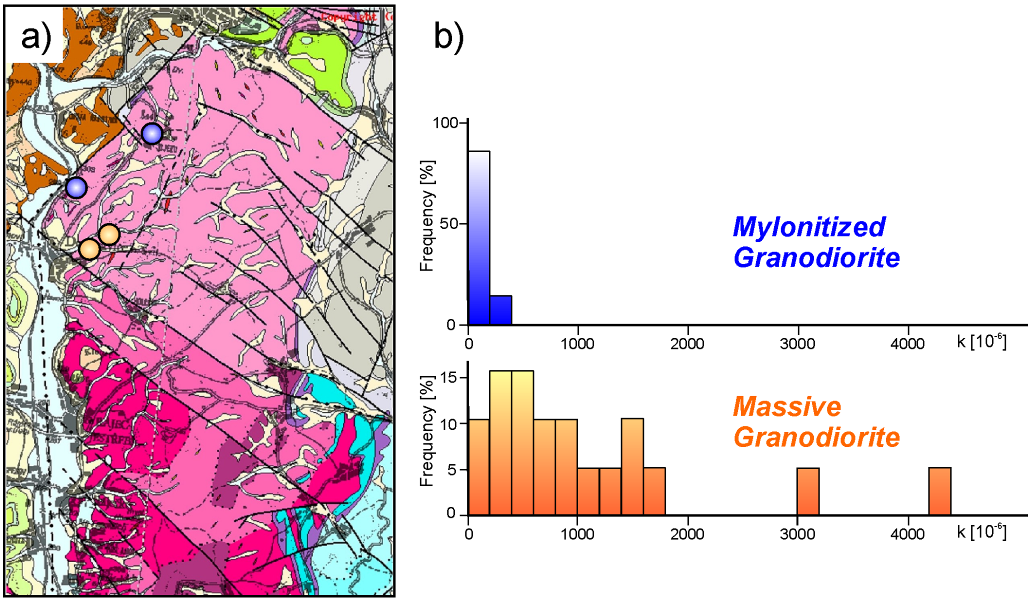

Fig. 17 Geological sketch map of the northernmost part of the Brno massif (a) and frequency histogram of susceptibility in massive and mylonitized granodiorites.

7. Verification of magnetic anomalies

Field susceptibility measurement by the Kappameter can provide rapid data useful in the interpretation of magnetic anomalies. An example will be presented below from the northern part of the Brno massif.

The pattern of the magnetic anomalies ΔT in the N part of the granodiorite Brno massif is very complex (see Fig. 18). In order to interpret this pattern in geological terms, detailed field study of magnetic susceptibility and orientation laboratory study of remanent magnetization were made. It was revealed that the remanent magnetization is much weaker than the induced magnetization due to susceptibility (the q factors are mostly less than 0.1) and the ΔT anomalies in the magnetic map are controlled very likely by the susceptibility distribution.

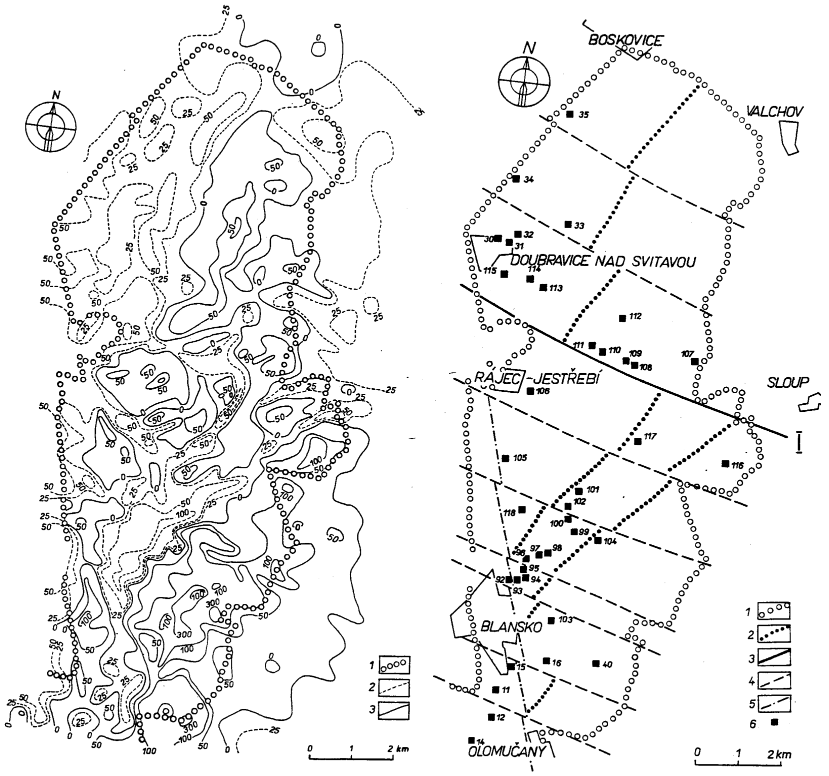

Fig. 18 Map of magnetic anomalies ΔT (left) and geological interpretation scheme (right) of the N part of the Brno massif. After Šalanský (1964, 1970) and Hrouda & Rejl (1974).
Legend: 1 - massif boundary, 2 - mylonitized zones, 3 - main fault, 4,5 - subordinate faults, 6 - measuring site

It has been found that the highest susceptibility is exhibited by the hornblende biotite granodiorite occurring in the S part of the region investigated; the susceptibility is mostly in the order of 10^{-2}. Relatively lower susceptibility is exhibited by the biotite granodiorite occurring in the N part of the area investigated; the susceptibility is in the order of 10^{-3}. The lowest susceptibility is characteristic of mylonitized rocks in which magnetite was partially (and sometimes strongly) destroyed.

The geological interpretation of the magnetic map based on the results of susceptibility investigation is shown in Fig. 18. The area south of the line I is built up of the hornblende biotite granodiorite, while the area north of this line is built up of the biotite granodiorite. The dashed parallel lines denote the narrow mylonitized zones in the vicinity of faults and the dotted lines delineate areas of cataclased up to mylonitized rocks.

8. Economic geology

8.1 Ore deposits

Natural magnetite and pyrrhotite (i.e. mixture of hexagonal and monoclinic phases), or other ferrimagnetic minerals, tend to accumulate in ore deposits (including the non-iron ones) or in their environs. Even though they do not often represent the economic minerals, their magnetic properties can be important in the search for ore deposits, because these minerals often accompany the economic metallizations in various ways.

Thanks to their high susceptibility and remanent magnetization, these minerals can be surveyed not only by geoelectrical methods, like the mineralizations of many other minerals, but also by magnetometric methods. The measured magnetic anomalies can directly indicate those ore deposits in which the distribution of ferrimagnetic minerals conforms to the distribution of the economic mineralization and, of course, those ore deposits in which these minerals represent the economic mineralization. However, in most cases these ferrimagnetic minerals create only haloes in footwall rocks and the magnetometry can indicate the deposit only indirectly. In both cases, it is useful to measure the magnetic susceptibility in situ, in order to get an idea of the spatial relationship between the susceptibility and the economic mineralization, which can be utilized in magnetic survey of the deposits of a similar type.

If a ferrimagnetic mineral creates an economic mineralization, the magnetic susceptibility can be used in the fast control of the searched or exploited ore. This case often takes place in metamorphosed oxidic Fe-ores of the Sydvaranger type, Lahn-Dill type, magnetite skarns and also in bodies of metamorphosed siderite ores, originally metasomatic in origin.

In addition to magnetite and pyrrhotite, other rare magnetic minerals can be interesting from the point of view of economic geology, such as: cassiterite, franklinite, cobaltite, Ni-sulphides, etc. (see Tab. 1). For example, magnetic susceptibility is currently used in the indication of the content of ferrimagnetic cassiterite in deposits of the greisen type in the Erzgebirge Mts. (NW Bohemia). Pyrrhotite and magnetite are often present in the Co, Ni and platinoid deposits. In such deposits the measurement of magnetic susceptibility on drill cores is a good supplement of the susceptibility well-logging, because its results can be used in the correlation of the depth data provided by well-logging and by core measurement. In addition, the susceptibility measurement of cores helps in searching for the relationship of ferrimagnetic minerals and economic ore minerals and/or footwall rocks. The magnetic susceptibility can be also used in the selection of samples for more detailed laboratory study.

In hydrothermal deposits, submarine exhalation deposit as well as in the porphyry-copper type deposits, pyrrhotite and magnetite are often important minerals accompanying the economic minerals. The generation of ferrimagnetic minerals is controlled by many parameters, among which the most important are the temperature, O_2 fugacity, S_2 fugacity, pH factor of the environment, and others.

In higher-temperature hydrothermal deposits with W, Mo and Cu stockworks, the magnetite veinlets, greisens and impregnations represent the initial phase of the ore mineralization process the extent of which can be localized through measurements of susceptibility in situ. Also the Au stockwork mineralization can be sometimes accompanied by pyrrhotite or magnetite, though neither of them carries Au, which often occurs as virgin metal in quartz or tied to pyrite, arsenopyrite or tellurides. In alkaline rocks, magnetite often accompanies REE, Nb, Ta, Zr, Th mineralizations that can therefore be indicated through elevated magnetic susceptibility values.

The magnetic minerals, hematite, pyrrhotite and magnetite, often occur in sulphide ore deposits. Their development in the deposits of the submarine exhalation type is obvious from various T – fO_2 diagrams, such as that shown in Fig. 19. It can be seen in this diagram that sphalerite and chalcopyrite originate under relatively low temperatures (under 300^{o}C) and low fugacities O_2 when magnetite is absent and host rocks are enriched in pyrite and/or pyrrhotite.

Various alterations may give rise to transformation and even destruction and subsequent disappearance of ferrimagnetic minerals from a deposit. For example, the types of alteration haloes recognized in the footwall rock below the Kuroko deposit and some Canadian deposits are very consistent and include alteration mineral assemblages that proceed from the outside toward the ore in the order zeolite-bearing to montmorillonite-bearing and sericite-chlorite assemblages. Major element chemistry reveals decreasing contents of Na and Ca toward fore ore zones accompanied by increasing contents of K and Mg. Trace element contents also vary, with decreasing content of Sr and Cl and increasing contents of S toward the ore while whole-rock Fe^{+2}/Fe^{+3} ratios and magnetic susceptibilities both decrease toward the ore zone (Plimer 1985). Pyrrhotite and/or magnetite can create haloes at the boundary of the ore zone in the places where more suitable conditions existed for the generation of one or both (less frequently) these minerals.

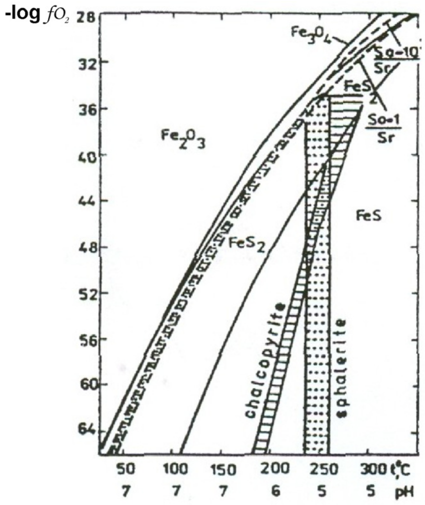

Fig. 19 Creation of volcanic-metasomatic, volcanic-sedimentary sulphide deposits during variable pH factor and temperature and constant concentrations of E = 10^{-2} mol and NaCl = 1 mol. Adapted from Smirnov (1982).

Zonality and existence of haloes in hematite, magnetite, pyrite and pyrrhotite are frequent in volcano-sedimentary ore deposits. Rhyolites with massive sulphide deposits tend to be concentrated in the calc-alkaline sequences. Sedimentary rocks tend to occur either as lateral stratigraphic equivalent to, or stratigraphically above, volcanic strata. Magnetite iron formation occurs in all lithologies, especially in peripheral areas of volcanic complexes.

An example of various magnetic mineral assemblages in volcanic rocks can be the Devonian sequence of the Vrbno Group of the Jeseníky Mts. (N. Moravia) investigated by the borehole JR-10 (Fig. 20). This borehole contains three distinct layers, the uppermost one containing magnetite, the intermediate one containing hematite and the lowermost one containing predominantly pyrrhotite and in the basal parts also hematite. They originated very likely in different parts of the volcano-sedimentary basin and were later thrust one over another. Keratophyre rocks form substantial parts of each layer. Even though their age is more or less the same, they differ in their susceptibility and the kind of ferromagnetic mineral. Trachytes and trachyandesites and their tuffs of the upper layer show anomalous susceptibility. They are rich in magnetite and include a few tiny bands of oxidic Fe ores which suggest that they probably originated in a large distance from the zone bearing polymetallic metallization. Rhyolites and their tuffs of the intermediate layer exhibit only low susceptibility values as they contain only hematite and pyrite and show signs of albitization and silicification. They were very likely nearest the polymetal bearing zone. In the lowermost layer of the volcanics with variable values of susceptibility, pyrrhotite is present in dolerites, trachytes and quartzites. Hematite is also present, but only in trachytic rocks. This lowermost sequence indicates also the narrow vicinity of chalcopyrite and sphalerite deposits. The different nature of individual layers of volcanics and/or sedimentary rocks in the profile of the JR-10 borehole cores was thus indicated by susceptibility measurement and later confirmed by the geochemisty and mineralogy.

Sulphide deposits underwent, together with surrounding rocks, regional metamorphism in some terranes. They occur in rock complexes metamorphosed from zeolite facies to granulite facies. During the process of metamorphism, the ores may have recrystallized and partially mobilized together with quartz, carbonates and baryte. New minerals may have formed, for example, pyrite, pyrrhotite, magnetite, Mg and Fe carbonates.

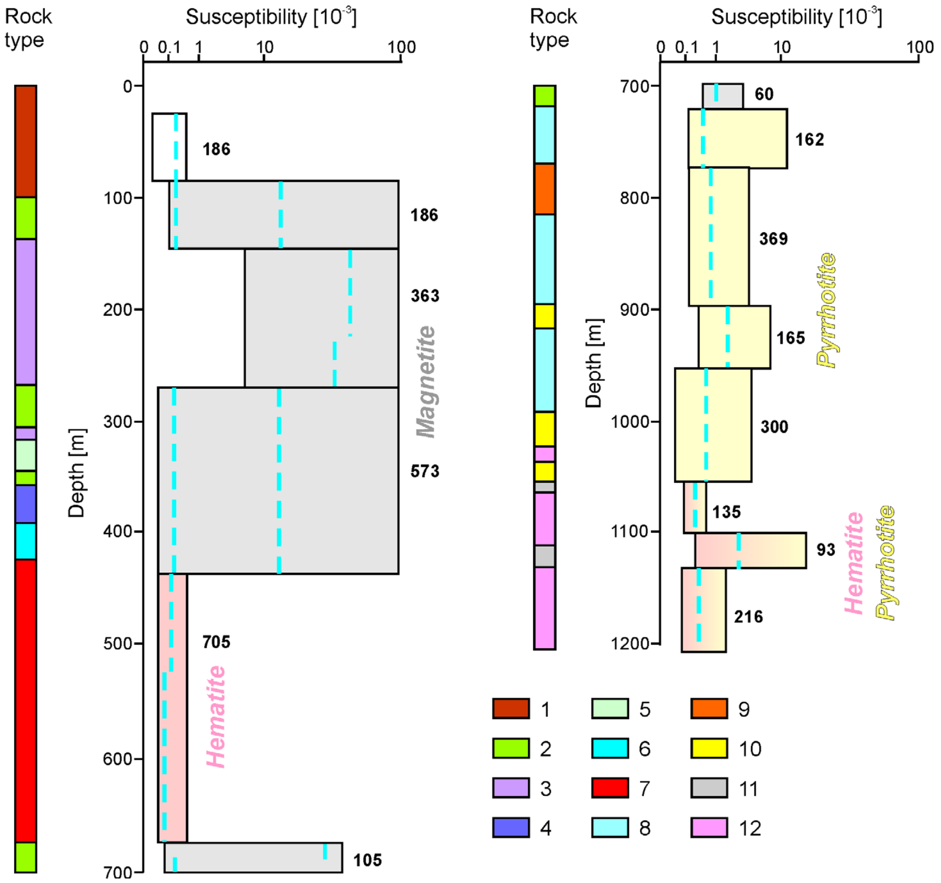

Fig. 20 Depth variation in susceptibility in the JR-10 borehole
Legend: Culm Formation: 1 - psammitic to pelitic rocks (phyllites and meta-greywackes)
Devonian of the Vrbno Group: 2 - chlorite slates and phyllites, 3 - keratophyres s.l. (trachyandesites and their tuffs) with magnetite and hematite, 4 - keratophyre meta-tuffs, mostly with magnetite ± hematite, 5 - sericite slates to phyllites (meta-tuffites and/or strongly altered volcanic rocks), 6 – sericite slates with intercalations of meta-ferolites s.l., 7 – keratophyres s.l. (trachy-rhyolites and their tuffs) with hematite, in places albitized and silicified, 8 - meta-dolerites, 9 - meta-andesite, 10 - psammitic to pelitic meta-sedimentary rocks, in places with pyrrhotite, 11 - quartzites, 12 - keratophyres s.l. (trachytes, trachy-andesites, dacites, etc.) with hematite and pyrrhotite, in places chloritized
Block boundaries delineate minimum and maximum susceptibility values, dashed line indicating median for each block.
Numbers attached to each block represent numbers of susceptibility measurements with kappameter.

The most commonly documented mineral reaction in metamorphosed deposits is the increase in pyrrhotite: pyrite with increasing metamorphic grade. The breakdown of pyrite results from one of the following reactions:

$2FeS_2 = 2FeS + S$

FeS_2 + ferromagnesian silicate = $2FeS$ + magnesian silicate

$3FeS_2 + 2O_2 = Fe_3O_4 + 3S_2$.

The transformation can be often also reversed, mostly in the terminal phase of crystallization when new pyrite is created. The reaction of pyrite to produce pyrrhotite in metamorphosed massive sulphide rock is considered unlikely and much of the data support the pyrite-pyrrhotite conversion is equivocal. The iron sulphides pyrite and pyrrhotite have very extensive stability fields, being stable at all facies of metamorphism. Desulphurization of pyrite is, therefore, a reduction which may take place at low fO_2 and high fS_2 (Plimer 1985). In many deposits, desulphurization and sulphide-silicate mineral reactions are insignificant and pyrrhotite in massive exhalative sulphide ores is primary.

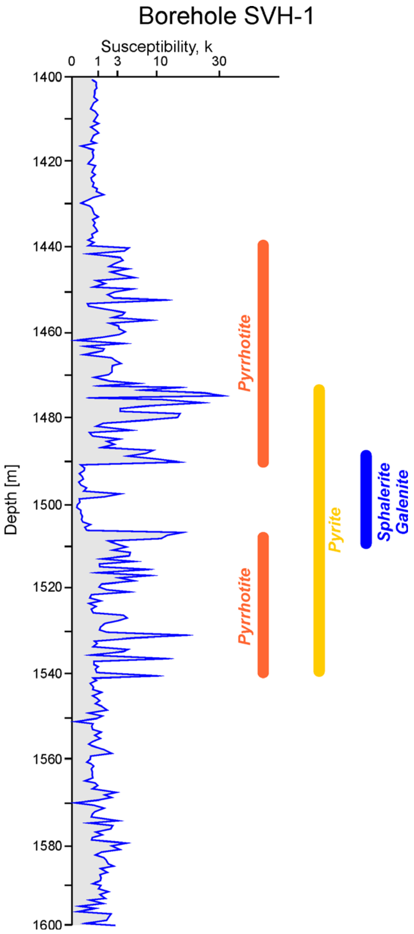

Fig. 21 Depth variation in susceptibility in the SVH-1 borehole drilled at the village of Heřmanovice in the Zlaté Hory ore district, the Jeseníky Mts. In the depth between 1,400 and 1,600 m graphite muscovite phyllite was drilled, carbonate muscovite phyllite with layers of porphyroids and crystalline carbonates. The deposit layer is created by porphyroids and carbonates. The measurement of the drill core was made by the Kappameter (with corrections for core diameter).

Zonality and wide haloes of ferrimagnetic minerals in rocks surrounding the polymetallic sulphide mineralization, indicated by measurement of magnetic susceptibility of drill cores, is shown in graph of the borehole SVH-1 in Fig. 21.This borehole drilled in the N part of the Nízký Jeseník Mts., near the S border of the Zlaté Hory ore district, revealed a volcanic sedimentary complex of the Vrbno Group with polymetallic metallization of the submarine exhalative type under the thick tectonic slices of the Culm formation. The central galenite-sphalerite layer is rimmed on both sides by wide halo of disseminated pyrrhotite. The magnetic susceptibility indicates not only the extent of pyrrhotite mineralization, but also its intensity. Within the ore body, where pyrrhotite is almost absent, only pyrite is present. In the whole space of the pyrrhotite halo, the heavy carbonates occur as well as anomalously concentrated muscovite originated probably through transformation of sericite. The whole rock complex, including the deposit, underwent epizonal regional metamorphism in the chlorite zone. The extent and intensity of magnetic halo was not revealed on the basis of macroscopic description of cores; only magnetic susceptibility indicated them.

It should be noted that pyrrhotite can also occur in the form of hexagonal phase which is antiferromagnetic and displays only relatively low susceptibility. This pyrrhotite can occur in deeper parts of massive sulphide ores, while a mixture of hexagonal and monoclinic pyrrhotite is typical of the near-surface parts. Susceptibility can help us in the delineation of the boundary between these two types.

8.2 Non-ore deposits

In the investigation of non-ore deposits, magnetic susceptibility can help in the lithostratigraphic correlations of the borehole profiles. The localization of leading horizons of volcanic provenance is important in the survey for coal, organic shales, etc.

The measurement of magnetic susceptibility is also useful in the testing of the quality of glass sand where the presence of Fe-oxides is not desirable. In a similar way, susceptibility can be used in testing the quality of other raw materials.

8.3 Oil deposits

If rocks containing oil undergo elevated temperature, some Fe oxides and hydrooxides can transform in the reduction environment due to the presence of the organic substance into ferrimagnetic minerals, which results in the increase of magnetic susceptibility. Particularly obvious is this process in the oil deposits which underwent natural combustion. These are characterized by the existence of intense magnetic anomalies and high susceptibility (see Cisowski and Fuller 1987).

9. **Environmental applications**

Magnetic properties, including susceptibility, has become a subject of growing interest of environmentalists, because they can effectively help us in solving problems of weather changes through the Quaternary in various geographic provinces, correlation of sub-recent seas, lake and cave sediments and, which is most important for environmental consideration, in finding and limiting the heavy metal pollution of soils (Evans & Heller, 2003).

Magnetic susceptibility using sensitive kappameter KT-10 can be effectively used in studying *loess lithological sequences*, where alternating magnetic and non-magnetic layers were formed due to alternating wind blown directions from cool an/or warm climatic regions. Loess is, as mentioned by Evans and Heller (2003), produced in two types of source regions *(a)* by glacial grinding, frost action and fluvioglacial abrasion in glacial areas, *(b)* by frost action and salt weathering in cold dry deserts. During cold, arid glacial periods, the loess builds up steadily, but in interglacial conditions palaeosol horizons develop. Palaeosol horizons from sites located in China show much higher susceptibility than loess horizons (see Fig. 22). On the other hand in Siberia, where palaeosols reveals the similar susceptibility as those from China, the loess susceptibility is clearly higher due to its magnetic rock source.

Nevertheless, magnetic susceptibility is very useful for *lithostratigraphical correlations*, mainly if used together with other magnetic parameters.

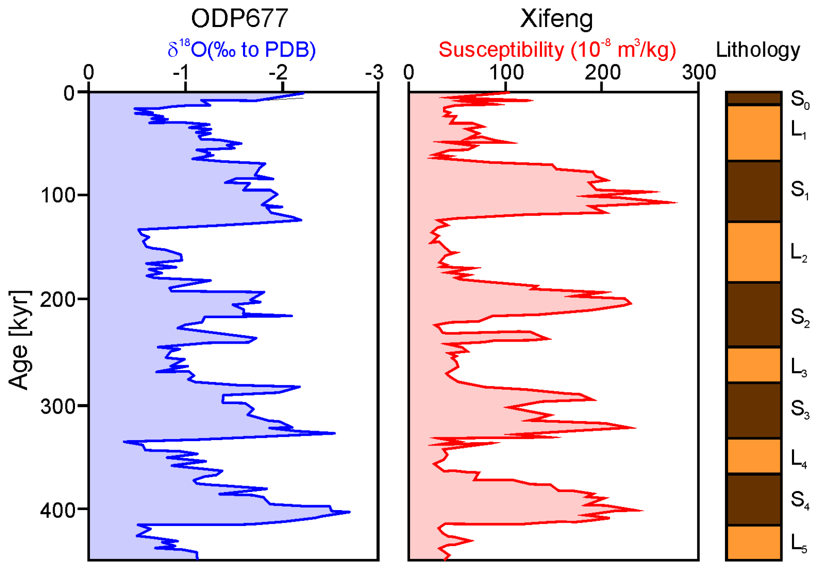

Fig. 22 Magnetic susceptibility profile at Xifeng, China, compared with the oxygen isotope profile at ODP677. The sequence of soil (S) and loess layers (L) at Xifeng is indicated on the right. Adapted from Evans & Heller (2003).

However in environmental studies, the mass susceptibility, which is defined as magnetization per kilogram (or as the bulk susceptibility divided by the bulk density), is more convenient for environmental studies than the bulk susceptibility. For example, consider horizons A, B and O that have more or less the same bulk susceptibilities, but different densities, the density of the horizon O being about 500 - 1000 kg/m^3, that of the horizon A about 1000 – 1500 kg/m^3 and that of the horizon B about 2000 kg/m^3. It is obvious that the mass susceptibilities of the individual horizons will be very different despite similar bulk densities. In addition, the mass susceptibility is very useful in correlation with chemical analyses that are also calculated per mass unit.

However, if the *heavy metal pollution* is strong enough, as for example in Upper Silesia Poland (Heller et al. 1958), even the bulk susceptibility of the uppermost layers of soil is many times higher than that of subsoil and bulk susceptibility operates well and can be used as fast pollution indicator (Fig. 23). The values of bulk susceptibility indicating pollution should exceed 500 x 10^{-6} in the fermentation and humic subhorizons. The reason for soil pollution and susceptibility enhancement is the fall down of dust containing glassy spherules carrying heavy metals and magnetic minerals, mainly magnetite and maghemite. The source of the pollutants may be flying ashes coming from coal-burning power plants, cement producing industry, metallurgical plants and from some other anthropogenic activity.

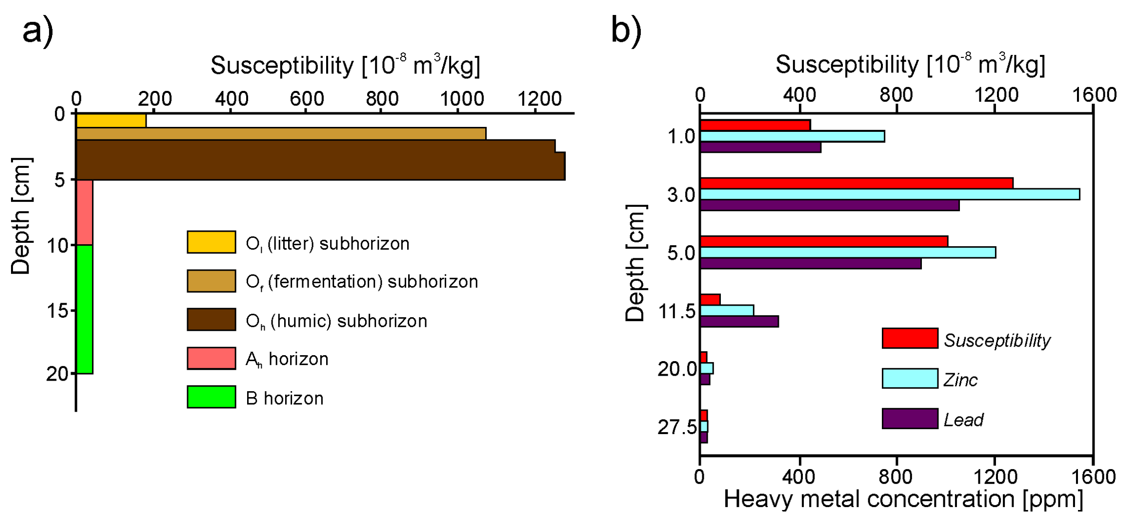

Fig. 23 Depth profile of magnetic susceptibility in a soil pit in Chrzanow forestry area, Poland (a), correlation of magnetic susceptibility with lead and zinc content in a soil pit near Jaworzno power station, Poland (b). Adapted from Evans & Heller 2003.

10. Advices and recommendations

Measurement of bulk susceptibility using a new kappameter enables a wide scale of applications in various geological fields to be made and the instrument will therefore be a useful for both the geologist and the geophysicist. But there are some rules that must be kept by everybody in order to obtain good result and protect the instrument against damages. These are as follows:

- Do not measure with weak batteries (exchange batteries after Low Battery signal appears at your earliest convenience).
- Do not measure in the rain when the surfaces of rocks are very wet.
- The first step and the third step in a measurement (measuring with coil in the air) should not be executed near the metallic earrings, necklaces or any other metallic objects, but in the free air, at least 50 cm in distance from them.
- When measuring the drill cores avoid measuring near the nails of wooden core boxes. Never measure cores placed in metallic boxes. The best way is to take cores from the box away. Do not forget to make the corrections for diameter of the core.
- When measuring on outcrops, care must be taken to finding convenient surfaces in order to eliminate the influence of weathering. Namely, weathering results in susceptibility decrease. The decrease is the more intense the stronger the weathering is. Remember that the kappameter coil is most strongly influenced by the rock nearest to the coil surface, even if one measures using the pin. Remember that magnetic anisotropy exists and measure parallel and perpendicular to the foliation in metamorphic rocks. Make corrections for the unevenness of the rock surfaces. Susceptibility distribution in any outcrop is found relatively reliably if more than 12 measurements are made, one, two or three measurements are insufficient. Take care not to measure near the geological hammer you certainly have with.
- When putting the coil of the kappameter on rock surface, make it gently, beware shocks and pressing on the coil, because it can be damaged by rough handling.
- When you verify magnetic anomalies, you have to measure all kind of stones available, which you may find in the region of interest, even those very small in rock and soil debris. They need not cover all the surface of the coil and may be very thin. But remember, that the value you obtain is informative only. From a collection you gathered you can take the characteristic pieces for the lab measurement, sufficiently big and suitable for cutting the lab specimens. Susceptibility measurement helps you to take representative samples for lab measurement of anisotropy and or remanent magnetization measurement. When measuring small pieces kept in hand, put away the rings from your fingers.

Your kappameter should serve you well and could provide you with much useful information for many years by good handling. Do not forget that among its advantages is the weak magnetic measuring field comparable to the Earth`s field.

References

Betekhtin, A.G., 1956. Course of mineralogy (in Russian). Nedra Moscow, 558 pp.
Bartošek, J., Chlupáčová, M. and Štovíčková, N., 1969. Petrogenesis and structural position of small granitoid intrusions in the aspect of petrophysical data. Sbor. geol. ved, UG, 8, 37-68. Prague.
Bleil, V. and Petersen, N., 1982. Magnetic properties of natural minerals; Paramagnetism. In: Landolt-Boernstein, Numerical data and functional relationships in science and technology, Group V, vol. 1, subvol. b, 312-320. Springer Verlag Berlin.
Chappel, B.W. and White, A.J., 1974. Two contrasting granite types. Pacific. Geol., 8, 173-174.
Chlupáčová, M., Hrouda, F., Janák, F. and Rejl, L., 1975. The fabric, genesis and relative-age relations of the granitic rocks of the Čistá - Jesenice massif (Czechoslovakia), as indicated by magnetic anisotropy. Gerl. Beitr. Geophys., 84, 487-550. Leipzig.
Cisowski, S.M. and Fuller, M.D., 1987. The generation of magnetic anomalies by combustion metamorphism of sedimentary rock, and its significance to hydrocarbon exploration. Geol. Soc. Amer. Bull., 99, 21-29.
Dortman, N.B., 1984. Physical properties of rocks and mineral deposits (in Russian). Nedra, Moscow.
Ellwood, B.B. and Wenner, D.B., 1981. Correlation of magnetic susceptibility with $_{18}0/_{16}0$ data in late orogenic granites of the southern Appalachian Piedmont. Earth Planet. Sci. Lett., 54, 200-202.
Evans M. E., Heller F. (2003): Environmental magnetism. Principles and Applications of Enviromagnetics. – Academic Press, Elsevier, 293 pp.
Heller F., Strzyszcz Z., and T. Magiera (1998): Magnetic record of industrial pollution in forest soils of Upper Silesia. – Jour. Geopfys. Res. 103, 17767-17774.
Hrouda, F. & Rejl, L., 1974. Tectonics of the Brno massif studied by magnetometric methods (in Czech). Věst. Ústř. Úst. geol., 40, 1-9.
Hrouda, F. & Rejl, L., 1982. Small-scale magnetic susceptibility distribution in some plutonic rocks and its geological implications. Věst. Ústř. Úst. geol., 57-69. Prague.
Hrouda, F. & Kahan, Š., (1991). The magnetic fabric relationship between sedimentary and basement nappes in the High Tatra Mountains, N. Slovakia. J. Struct. Geol., 13, 431-442.
Jover, O., Rochette, P., Lorand, J.-P., Maeder, M. and Bouchez, J.-L., 1989. Magnetic anisotropy of some granites from the French Massif Central: origin of their low-field susceptibility. Phys. Earth Planet. Inter., 55, 79-92.
Klomínský, J.,1961. Geological interpretation of geophysical measurement in the Čistá massif (in Czech). Geol. průzkum, p. 341. Prague.
Kolofíková, O., 1976. Geological interpretation of measurements of magnetic properties of basalts on example of the Chřibský les lava flow of the Velký Roudný volcano (Nízký Jeseník, Mts.) (in Czech). Čas. miner. geol., 21, 387-396. Prague.
Krs, M. and Kropáček, V., 1987. A contribution to the magnetic properties of natural cobaltite. Phys. Earth Planet. Inter., 46, 227-232.
Kropáček, V., 1971. Distribution of the values of natural remanent magnetization and magnetic susceptibility of some minerals. Studia geoph. geod., 15, 340-353.
Müllerová, J. and Müller, K., 1972. Demonstration of the existence of two lava flows in the Velký Roudný at Slezská Harta (in Czech). Sbor. věd. prac. VŠB, 18, 97-100. Ostrava.
Nawrocki J., Wojcik A., and A. Bogucki (1996): The magnetic susceptibility record in Polish and Ukrainian loess-palaeosol sequences conditioned by palaeoclimate. Boreas 25, 161-169.
Orlov, A., 1933. Petrography of the Čistá-Jesenice granite massif. Věst. král. spol. nauk., II, 1-29. Prague.
Pitcher, 1979. The nature, ascent and emplacement of granite magmas. Jour. Geol. Soc., 136, 627-662.
Plimer, I.R., 1985. Submarine exhalative ores. Geol. Survey of Czechoslovakia, pp. 394, Prague.
Rochette, P., 1987a. Magnetic susceptibility of the rock matrix related to magnetic fabric studies. J. Struct. Geol., 9, 1015-1020.
Rochette, P., 1987b. Metamorphic control of the magnetic mineralogy of black shales in the Swiss Alps: toward the use of "magnetic isogrades". Earth Planet. Sci. Lett., 84, 446-456.
Smirnov, V., 1982. Geology of mineral deposits. Nedra. Moscow.
Šalanský, K., Krčmář, B., Man, O., Martinec, J., Řeháčková, M. & Weiss, J., 1964. Report on the geophysical mapping in 1963 (region between Brno and Žďár n/S). Report of Geofyzika Brno.
Šalanský, K., Dvořák, J. & Manová, L., 1970. Airborn geophysical mapping. IX Central Moravia (in Czech). Report of Geofyzika Brno.
Zapletal, K. 1989. Low-field susceptibility anisotropy of some pyrrhotite types. In: M. Gadsden (Editor) - IAGA Bull. No. 53, part B, p. 179. Aberdeen.

* Addendum: KT-10's memory has been increased from 500 to 3,000 measurements. /

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