GEOLOGICA CARPATHICA, 43, 1, BRATISLAVA, FEBRUARY 1992
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MAGNETIC, DENSITY AND RADIOACTIVE PROPERTIES OF ROCHOVCE GRANITES (SLOVENSKÉ RUDOHORIE MTS., WESTERN CARPATHIANS)

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(Manuscript received December 10, 1990; accepted in revised form September 19, 1991)

Abstract: The magnetic anomaly in the Rochovce area is caused by anomalously increased magnetic properties of the hidden Upper Cretaceous granite body. The granites of this body show high values of magnetic susceptibility assigning them to the magnetite series of Ishihara (1977). The analysis of physical properties of the granites points to the existence of three physically differing types (intrusive phases). The inner magnetic fabric of the body is anomalous, being deformed in the near-horizontal direction as established by our study of the magnetic susceptibility anisotropy tenzor.

Key words: Western Carpathians, Rochovce granites, petrophysical properties.

Introduction

The so called "Rochovce anomaly" showing a reversed relation of magnetic and gravimetric anomalies (Filo et al. 1974) has been detected at the boundary zone of the Veporic and Gemeric units.

Evaluation of structural borehole KV-3 situated in the anomaly (Klinec et al. 1977, 1980), showed that at a depth of 700 *m* the granites occur with physical properties that cause both the above-mentioned anomalies (Stránska in Obernauer 1979; Stránska 1989). Since that the whole area is also interesting from a metallogenetic view (Václav et al. 1988a, b) and the granites themselves are connected with W-Mo mineralization (Határ et al. 1989) several additional boreholes (Ni-1, Ro 1-6) were drilled in the vicinity of the KV-3 borehole (Fig. 1).

A more detailed study of the petrophysical properties of the Rochovce granites, anomalous compared with the other (Variscan) Western Carpathian granites, is the objective of the present study.

Methods of work

Since the Rochovce granite body does not outcop and can be sampled only by drilling, we have used only analyses of drill cores. A total of 230 granite samples were analysed (Stránska 1989) for density (volume and mineralogical) and magnetic parameters (magnetic susceptibility and natural remanent magnetic polarization). In addition, radioactive parameters (bulk gamma-activity (Q) and U, Th, K concentrations) were determined using a 4000 channel spectrometer.

Four granites from the KV-3 borehole were analysed in detail. Besides the above determinations, thermal properties (contact - free using laser, MGRI Moscow), Curie temperature and longitudinal and transverse wave velocities (an original instrument at KGU Kiyev) were determined, in relation to sample petrography and geochemistry (Gregor 1988a, b).

Measurement of magnetic susceptibility anisotropy (KLY-10 instrument) were performed on 26 samples and data were recalculated using the program ANISO-14Q written by V. Jelínek. Density and magnetic susceptibility were also measured on these samples.

Density characterization

The mineralogical density of Rochovce granites ranges between 2.57 – 2.69 g/cm^3, and the volume density between 2.56 – 2.67 g/cm^3 (Stránska 1989). These values correspond to published modal composition as given by Klinec et al. (1977, 1980) and Határ et al. (1989).

A certain regularity can be seen if we follow density values in particular boheroles (Figs. 2, 3). The samples from boreholes KV-3, Ni-1, Ro-6 and and Ro-2 (below 579 *m*), Ro-5 (below 635 *m*) show higher average values of mineralogical (2.64 g/cm^3) and volume (2.62 g/cm^3) density to the samples from boreholes Ro-3, Ro-2 (531 – 577 *m*), Ro-5 (559 – 635 *m*) which show lower average values of 2.62 g/cm^3 and 2.60 g/cm^3, respectively. The minimal values 2.59, and 2.58 g/cm^3 were determined in borehole Ro-5 and in vein type of the Ro-2 borehole.

According Határ et al. (1989) the Rochovce granite body is composed of two intrusive phases. The phases can be distinguished relatively well by density properties. The first phase has average mineralogical (2.64 g/cm^3) and volume (2.62 g/cm^3) densities, while the second phase has corresponding values of 2.62 g/cm^3 and 2.60 g/cm^3. The lowest values among our measurements were found in aplitic granites in the Ro-5 borehole and in the vein type from Ro-2 borehole (possibly a third phase?), Table 1.

Radioactive properties

The bulk gamma activity of Rochovce granites is considerably higher compared to other Western Carpathian granites, and it is

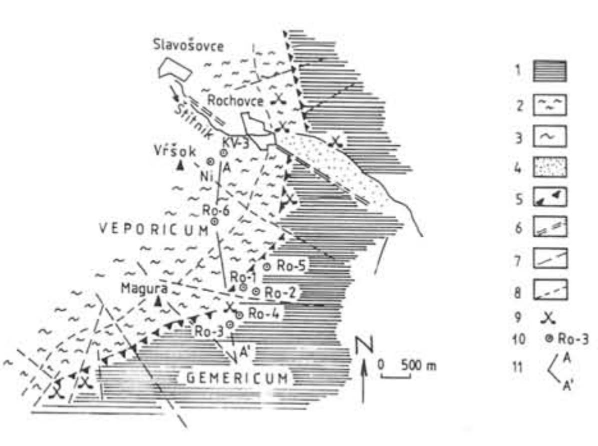

Fig. 1. Schematic geological map and drillhole location.
1 - Gemeric unit, Carboniferous, Ochtiná formation; 2 - Veporic unit, Permian, Rimava formation; 3 - Veporci unit, Carbonifferous, Slativná formation; 4 - alluvium; 5 - Lubeník-Margecany line; 6, 7, 8 - tectonic lines of lower orders; 9 - old mine works for Fe, As, Pb, Zn sulphidic mineralization; 10 - drillhole location and designation; 11 - line of geological section.

comparable to that of Gemeric granites. There are differences in the bulk gamma activity and U, Th, K concentrations among granites of the various intrusive phases (Tab. 2).

Granites of the second phase display the highest values of studied parameters. The average value of gamma activity is 40.8 ppm Ue, while the U, Th and K concentrations are 16.6 ppm, 26.46 ppm and 4.4 %, respectively. Accessory brannerite (UTi_2O_6), as the main U concentrator, occurs in this phase, whereas Th is concentrated mainly in monazite (up to 13 – 14 wt.% Th_2O).

The third phase granites show radiometric values similar to those of the second phase suggesting a close genetic relationship between them. The first phase granites may be distinguished mainly by their values of bulk gamma activity and U concentration (25 ppm and 10.4 ppm, respectively). A considerable part of the U and Th is present in one mineral - uranothorite (Th, U)SiO_4 which contains up to 50 – 60 wt.% Th and 12 – 32 wt.% of UO_2. Both elements are also present in significant amounts in allanite and titanite.

When comparing radioactive properties of granites from particular boreholes (Fig. 2) one can see the increase of radioactive parameters from NW (KV-3) to SE (Ro-3) which is explainable by the volumetric increase of the second phase granites to the southeast.

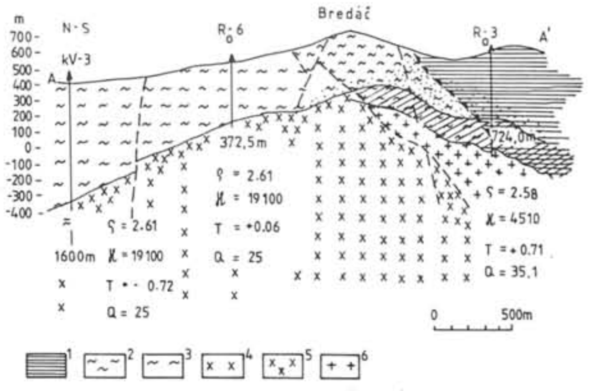

Fig. 2. Schematic section across granite intrusion and its metamorphic mantle (N-S trending, see Fig. 1, A-A').
1 - Gemeric unit, Carboniferous, Ochtiná formation; 2 - Veporic, Permian, Rimava formation; 3 - Veporic, Carboniferous, Slativná formation; 4 - coarse-grained porphyritic biotite granites of 1st intrusive phase; 5 - marginal fine-grained granites of 1st intrusive phase; 6 - granites of 2nd intrusive phase; 8 - intrusive mineralized endo- and exocontact zones with MoS_2; 9, 10 - tectonic lines of lower orders; 11 - Lubeník-Margecany line; 12 - drillhole location and designation.
Mean value of volume density [g/cm^3]; mean value of magnetic susceptibility [$\times 10^{-6}$ SI units]; parameter of magnetic anisotropy; mean value of total radioactivity [ppm U_{ekv}].

Table 1. Density parameters of Rochovce granites.

Rochovce granites	n	Do ($g.cm^{-3}$)				Dm ($g.cm^{-3}$)				P %	Dp
		min	max	$\bar{x}$	ds	min	max	x	ds	$\bar{x}$	$\bar{x}$
Phase I.	185	2.56	2.67	2.61	0.019	2.57	2.69	2.63	0.021	0.73	2.62
Phase II.	25	2.51	2.63	2.58	0.019	2.55	2.65	2.59	0.018	0.62	2.59
Phase III.?	22	2.52	2.62	2.57	0.031	2.54	2.66	2.58	0.033	0.49	2.57

Do - volume density, Dm - mineralogical density, P - porosity, n - number of samples, $\bar{x}$ - mean values, ds - standard deviation.

Table 2. Radioactive parameters of Rochovce granites.

Rochovce granites	n	Q (ppm Uekv)		Th (ppm)		U (ppm)		K (%)		Th/U
		$\bar{x}$	ds	x	ds	$\bar{x}$	ds	$\bar{x}$	ds	$\bar{x}$
Phase I.	110	25.0	5.8	24.5	6.3	10.4	3.7	3.8	0.8	2.5
Phase II.	25	35.1	6.5	26.6	5.1	16.6	4.8	4.4	0.6	1.6
Phase III.	15	34.8	5.8	28.0	7.2	16.3	5.1	3.9	1.4	1.6

Q - total radioactivity, n - number of samples, $\bar{x}$ - mean value, n - standard deviation.

Table 3. Magnetic parameters of Rochovce granites.

Rochovce granites	n	NRMP (nT)				KAPA ($\times 10^{-6} \times$ SI)			
		min	max	$\bar{x}$	ds	min	max	x	ds
Phase I.	129	28.3	1487	230	207	6 218	98 575	19 101	8 840
Phase II.	25	3.2	314.4	42.2	61.51	271.9	13 840	4 510	3 429
Phase III?	22	0	3.8	0.26	0.87	0	405.7	24.7	90.07

NRMP - remanent magnetic polarization, KAPA - magnetic susceptibility, n - number of samples, $\bar{x}$ - mean value, ds - standard deviation.

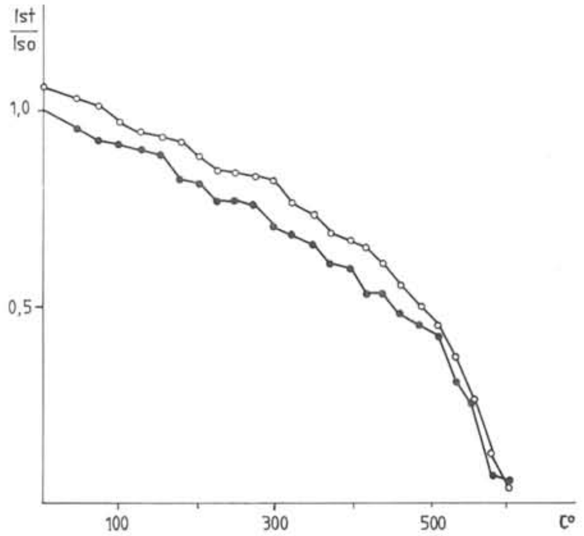

Fig. 4. Thermomagnetic analysis of Rochovce granites. Solid circle - temperature by heating, open circle - temperature by cooling.

Magnetic susceptibility

Magnetic susceptbility values of Rochovce granites (Tab. 3) are 10 – 100 times higher than the majority of other Western Carpathian granitoids. It is interesting to note that Rochovce granites are SiO_2 rich (about 75 %). The main carrier of magnetic properties of Rochovce granites is magnetic, as is confirmed by thermomagnetic measurements (laboratories of KGU Kiyev), Fig. 4, and by discovery of anomalous amounts of magnetite in analysed samples (Klinec et al. 1977, 1980; Határ et al. 1989) where it attains up to 8 *kg/t*.

Reflected light study of these granites has revealed (Klinec et al. 1980; Gregor 1988) the occurrence of magnetite in two generations. The first one is represented by magnetite occurring in fresh biotite grains or accumulations. The grains are minute and inhomogeneously distributed. The second generation of magnetite occurs in chloritised biotites and also in plagioclase, orthoclase and quartz. It also occurs in veinlet infillings. Klinec et al. (1980) report that the rock has experienced a magmatic history which included three stages of crystallization. The first magnetite generation probably formed in the first stage of crystallization, whereas the second one may have originated from biotite, perhaps due to the increase of oxygen fugacity as demonstrated by the experiments of Wones and Eugster (1965):

$$\text{biotite} + O_2 = \text{magnetite} + \text{orthoclase} + H_2O$$

This mechanism would also confirm the relation between Fe/(Fe+Mg) ratio of biotite and magnetic susceptibility presented by Gregor (1990).

Detailed study of magnetic susceptibility in particular boreholes (Figs. 2, 3) revealed a certain regularity. The samples from boreholes KV-3, Ro-6, Ro-2 (below 579 *m*) and Ro-5 (below 635 *m*) show the highest values, which average about 20000×10^{-6} SI units and seldom decline below 10000×10^{-6} SI units. These samples correspond essentially to the first intrusive phase (Határ et al. 1989). Lower values of magnetic susceptibility ranging around 5000×10^{-6} SI units, and only rarely exceeding an upper limit of 10000×10^{-6} SI unites and a lower limit of 1000×10^{-6} SI units are characteristic of boreholes Ro-5, Ro-2 (531 – 577 *m*), corresponding to Határ's second intrusive phase (l.c). The lowest values of about 100×10^{-6} SI units in average and not exceeding 1000×10^{-6} SI units were detected in samples from the Ro-5 boreholes and in vein types of the Ro-2 borehole (third phase).

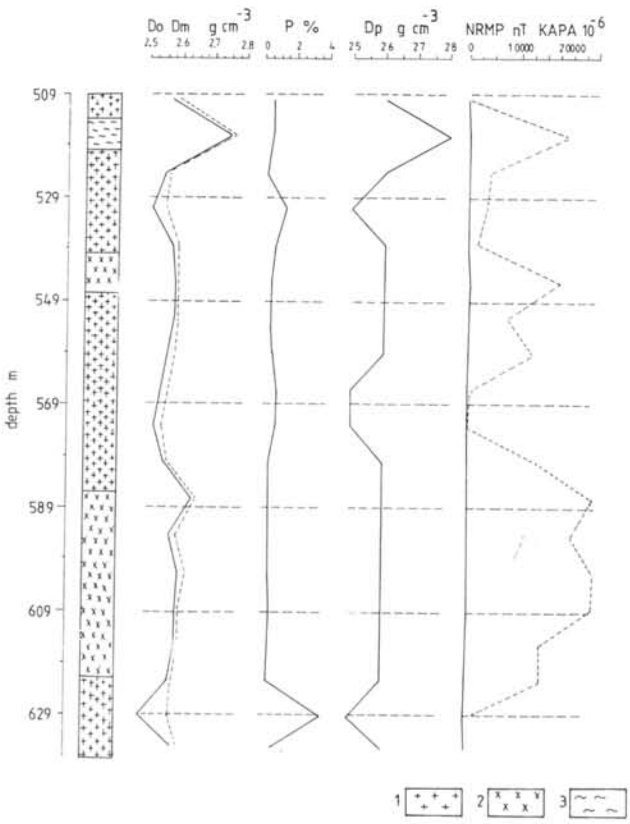

Fig. 3. Physical properties of rocks from the drillhohe Ro-2.
Do - volume density [*g/cm*^{3}]; Dm - mineralogical density [*g/cm*^{3}]; P - porosity [%]; NRMP - remanent magnetic polarization [*nT*]; KAPA - - magnetic susceptibility [$\times 10^{-6} \times$ SI units].

Magnetic susceptibility anisotropy

When analysing the magnetic susceptibility anistotropy we set out from works by Janák and Hrouda (1974), Hrouda (1982) and

Borradaile (1988), where possibilities of using of tensor magnitudes in solving of some genetical problems were demonstrated.

The magnetic anisotropies of Rochovce granites (Tab. 4) are among the higest of Western Carpathian granites. For interpretation we used the susceptibility ellipsoid, a geometric presentation of the susceptibility tensor characterizing the rock magnetic fabric by its shape and orientation. The susceptibility ellipsoid has a shape similar to that of the deformation ellipsoid. The results of study of its shape changes are depicted in Figs. 5, 6, 7. The deformation of the susceptibility ellipsoid (based on lineation and foliation parameters, Fig. 5) shows an increase in body deformation from the KV-3 borehole south- to southeastward. The relation between lineation and foliation parameters and the degree of anisotropy (Figs. 6, 7) is documented by the increased three-axiality of the susceptibility ellipsoid of the first phase granites. Graham (1966) ascribes the formation of such an ellipsoid to shear movements, which are characteristic of the first deformation stage, producing monoclinic symetry of the three-axial ellipsoid.

The deformation ellipsoids, estimated from measurements of magnetic susceptibility, demonstrate greater deformation and increasingly greater flattening. This deformation type leads to the formation of planar structures mostly, in the area of Ro-2, 3, 5 boreholes.

The previous conclusions are well elucidated by using another parameter, Jelinek's (1981)

$$T = 2\,\frac{(\eta_2 - \eta_3)}{(\eta_1 - \eta_3)} - 1$$

to expres the relation of susceptibility anisotropy.

The T parameter of Rochovce granites attains various values in different parts of granite body (Tab. 4, Fig. 2) indicating both different magnetic structure and type of deformation. In the borehole KV-3 the T parameter shows highly negative values which change continuosly to the S-SE through zero (Ro-6) to positive ones of nearly + 1 in the Ro-3 borehole. One can account for this trend in two ways:

Model 1: Differing conditions in the magmatic crystallization stage of the first and second intrusive phases. Under this model, the first phase crystallized in a transtension environment while the second one was emplaced in a transpression environment. The first movement along the Lubeník-Margecany line was accompanied by a perpendicular one to the S and SE during the final thrust movements of the Gemeric over the Veporic unit. This would also account for the emplacement of the second phase products (Mo-W ore-bearing) at the contact between the first phase granite stock and the overthrusted Upper Palaeozoic unit.

Model 2: Different tectonic processes after intrusion and crystallization. In this model, the deformation of the susceptibility ellipsoids in both directions perpendicular to borehole axes represents partitioning of the acting tectonic movements in the intrusive body, in depending on the distance from active fault structures. These sites lokalized transtension and transpression movements in the shearing zone of the contact between Gemeric and Veporic units during Upper Cretaceous orogeny. In this case one can speculate about the possibility of an older age of intrusion and its Alpine rejuvenation.

Our date are consistent with both of the above conclusions the above regarding a possible means of body deformation.

Table 4. Parameters of magnetic anisotropy of Rochovce granites.

Sample No.	L	F	P	T	I_{max}	I_{mid}	I_{min}
Kv-3/723	1.219	1.023	1.247	-0.790	12	33	54
Kv-3/1310	1.148	1.033	1.186	-0.614	13	49	38
Kv-3/1310a	1.183	1.023	1.210	-0.763	17	48	37
Ro-6/370	1.180	1.206	1.423	0.060	0	6	80
Ro-5/509	0.331	0.128	1.164	0.579	20	18	62
Ro-5/558	0.061	0.093	1.099	0.876	7	14	75
Ro-5/622	1.062	1.625	1.726	0.779	20	19	62
Ro-5/635	1.149	1.373	1.577	0.392	4	5	84
Ro-5/649	1.135	1.395	1.583	0.448	0	8	82
Ro-2/531	1.087	1.253	1.362	0.461	38	1	52
Ro-2/542	1.082	1.209	1.308	0.415	30	4	59
Ro-2/560	1.048	1.335	1.399	0.723	11	0	79
Ro-2/577	1.080	1.125	1.214	0.209	9	30	58
Ro-2/578	1.121	1.341	1.503	0.441	26	11	61
Ro-2/586	1.098	1.324	1.454	0.499	20	6	69
Ro-2/587	1.106	1.332	1.473	0.482	26	11	61
Ro-2/587, 8	1.027	1.129	1.160	0.635	1	27	63
Ro-2/593	1.064	1.251	1.333	0.567	22	5	67
Ro-2/600	1.189	1.565	1.862	0.443	5	15	75
Ro-2/601	1.052	1.293	1.360	0.671	20	4	70
Ro-2/616	1.179	1.561	1.841	0.461	13	7	76
Ro-2/624	1.207	1.428	1.723	0.309	38	10	50
Ro-2/622	1.063	1.205	1.281	0.510	20	12	66
Ro-3/673	1.039	1.389	1.444	0.790	19	23	59
Ro-3/699	1.006	1.572	1.581	0.974	16	2	73
Ro-3/723	1.063	1.247	1.326	0.565	0	23	67

L - magnetic lineation, F - magnetic foliation, P - magnitude of magnetic anisotropy, T - parameter of magnetic anisotropy, I - inclination of magnetic anisotropy.

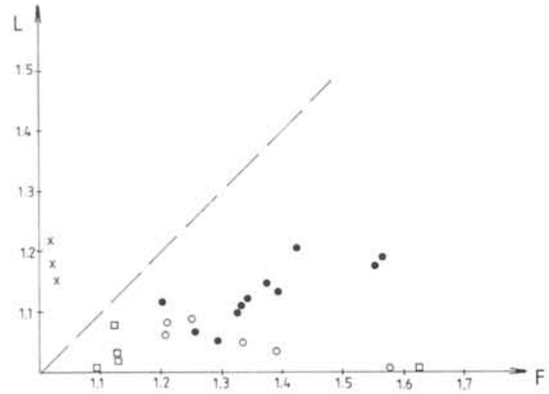

Fig. 5. Relationship between magnetic lineation parameters (L) and magnetic foliation (F).
Solid circle - granites of 1st intrusive phase; open circle - granites of 2nd intrusive phase; open square - granites of 3rd intrusive phase, cross - granites of 1st intrusive phase (borehole Kv - 3).

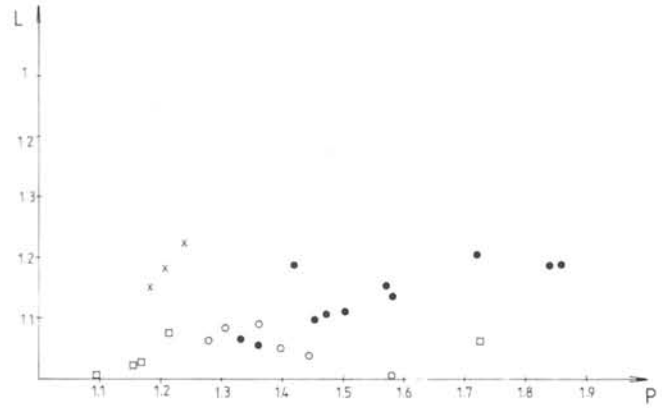

Fig. 6. Relationship between magnetic lineation parameters (L) and the magnitude of magnetic anisotropy (P). Symbols as in Fig. 5.

In addition to the deformation ellipsoid shape we also measured the directions of principal deformations. Since our samples were drill-cores the orientation was determined with respect to the borehole axis. In Figs. 8, 9, 10 this axis goes through the centers of the diagrams, perpendicular to the page. Several important conclusions regarding the inner magnetic fabric of the granite body result from the obtained values. A slight inclination of principal and intermediate susceptibility as well as the concentration of minimal susceptibilities toward the borehole axis suggest a nearly-horizontal trend of the magnetic fabric. It is interesting that such a fabric is observed in both phases though, the causes are obviously different. In the discussion we shall try to account for these differences.

Discussion

The high magnetic susceptibility values of Rochovce granites make it possible to classify them as belonging to the magnetite series of Ishihara (1977). Ishihara (1981) supposes that magnetic series magmas originate in a lower crustal environment from which they rise to higher positions under conditions of tension, high oxygen fugacity, and little contamination by wall rocks.

The Upper Cretaceous age of the Rochovce intrusion correlates with pressure relaxation during the end ceasing of the Alpine orogeny. Under this interpretation, the Rochovce granites can be considered post-kinematic.

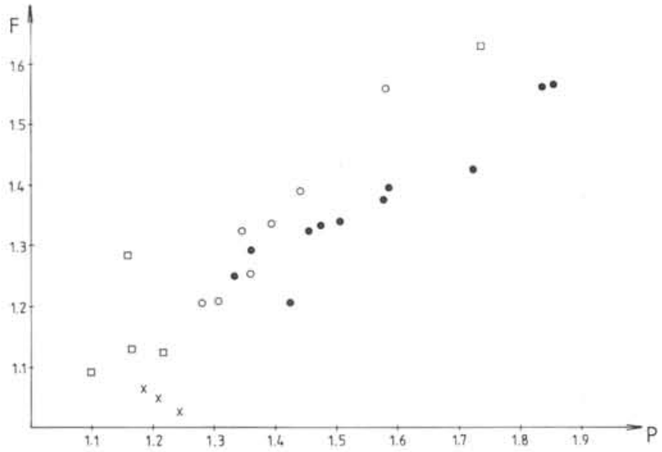

Fig. 7. Relationship between magnetic foliation parameters (F) and the magnitude of magnetic anisotropy (P).Symbols as in Fig. 5.

A possibility remains of Late-Paleozoic (Permian) age of intrusion: after the main volume of syn-tectonic granites had been emplaced in deep-seated tectonic structures, post-kinematic granites rose in a tension environment, similar to the occurrence in the Velence Mts. (Hungary) where the post-kinematic granites are also mineralized (Mo-ores) (Buda 1973).

When analysing the results of magnetic susceptibility anisotropy an important question arises regarding the origin of deformated magnetic rock fabric. Hrouda (1974) considers that such inner fabric can originate basically in three ways:

1) By oriented grain growth, either during recrystallization of magnetice (as in the case of chlorite and sericite), or by new crystallization in sympathy with pre-existing elements.

2) By deformation of magnetic grains shape homogeneously with the deformation of enclosing rock.

3) By re-orientation of magnetite grains without any substantial change of their shape. In this case the magnetite grains behave during deformation as rigid particles enclosed within a plastic mass.

In our opinion the first generation magnetite may have formed in the first crystallization stage defined by Klinec et al. (1980). The second generation magnetite, exhibiting high values of magnetic susceptibility anisotropy, could have then originated in the second stage of syn-kinematic crystallization. In such a way the magnetic susceptibility anisotropy of the first phase granites would be mainly due to the oriented growth of the second generation magnetite crystals at higher oxygen fugacity. The formation of new magnetic fabric would copy in some way pre-existing structures, explaining the elongation of the main susceptibility axis.

The pronounced flattening of the susceptibility ellipsoid of the second and third phase granites, and of the first phase granites from the area of boreholes Ro-2, 3, 5 probably originated in the another way. We propose that this effect is caused by contemporaneous re-orientation of magnetite grains together with the whole rock due to the strong horizontal compression of the entire granite body. Such re-orientation might have occurred at the area either in the time of crystallization of the second intrusive phase with metasomatical influence on the first phase, or less probably, after the intrusion had already been crystallized. An important result is the discovery of the near-horizontal inclination of the main and intermediate susceptibility axes, the minimum susceptiblity direction being near the borehole axis. Is suggests a nearly horizontal inner magnetic fabric of the whole body which originated either by copying of older structures, or by tension move-

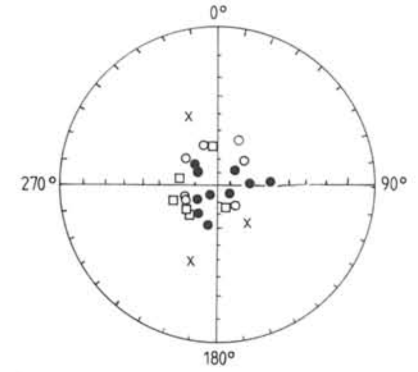

Fig. 8. Projection of minimal susceptibility axis inclination in coordinate system. Symbols as in Fig. 5.

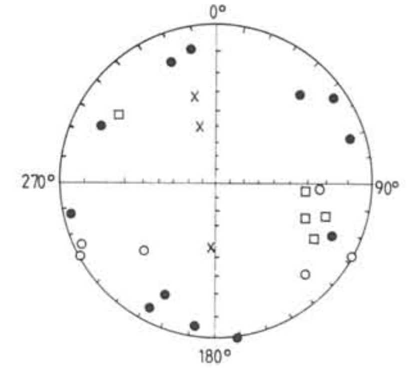

Fig. 9. Projection of mean susceptibility axis inclination in coordinate system. Symbols as in Fig. 5.

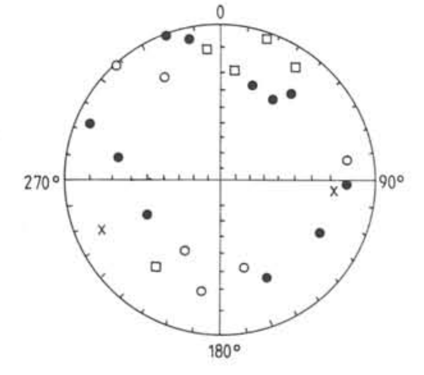

Fig. 10. Projection of maximum susceptibility axis inclination in coordinate system. Symbols as in Fig. 5.

ment in shear zones. Perhaps, in the case of boreholes Ro-2, 3, 5, horizontal compression during transpression movement was important.

Conclusions

The analysis of physical properties of drill-cores from drillings KV-3, Ni-1, Ro-1 – 6 has shown that three physically differing granite types occur here. The existence of two intrusive phases defined by Határ et al. (1989) was unambiguously confirmed by the physical property evidence.

The Rochovce granites display very high values of magnetic properties which appear anomalous in the Western Carpathians, especially in view of their acid character. Having high values of magnetic susceptibility, the Rochovce granites can be classified as examples of the magnetite series of Ishihara (1977). The granites of this series are characterized by specific feature, e.g., the rapid rise from great depth in a tensional environment with no or little contamination by wall rocks. Typical for these granites is Mo-W, or Cu, Pb, Zn and Au, Ag mineralization (Ishihara 1981).

Analysis of the inner magnetic fabric based on magnetic susceptibility anisotropy has shown different causes of its formation in the first and second phase granites as well as differences in the body itself. These differences originated during solidification of body and during later tectonic movements. Orientation directions of inner magnetic fabric which are nearly horizontal probably formed by copying of old structural elements (first phase) as well as by the formation of new structure due to the horizontal compression (area of Ro-2, 3, 5 boreholes).

Acknowledgment: We thank Prof. D. Hovorka and Prof. W. Frangos for stimulating comments when reading the manuscript.

Translated by D. Petríková

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