GEOLOGICA CARPATHICA, 53, 1, BRATISLAVA, FEBRUARY 2002
15–25

PALEOMAGNETISM OF METAMORPHIC ROCKS FROM THE GEMERIDES (WESTERN CARPATHIANS)

JADWIGA KRUCZYK[1], MAGDALENA KĄDZIAŁKO-HOFMOKL[1], MARIA JELEŃSKA[1],
IGOR TÚNYI[2], ĽUBOMÍR GAZDAČKO[3] and JACEK GRABOWSKI[4]

[1]Institute of Geophysics of the Polish Academy of Sciences, Ks. Janusza 64, 01 452 Warszawa, Poland
[2]Geophysical Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic
[3]Geological Survey of the Slovak Republic, Werferova 1, 040 01 Košice, Slovak Republic
[4]Polish Geological Institute, Rakowiecka 4, 00 975 Warszawa, Poland

(Manuscript received February 20, 2001; accepted in revised form June 13, 2001)

Abstract: The paper extends our previous study of metamorphosed Paleozoic rocks of the Gemeric Superunit (Kruczyk et al. 2000) on four exposures of Paleozoic and two exposures of Triassic rocks. The anisotropy of magnetic susceptibility (AMS) results support the conclusion of previous study of its strong correlation with the tectonic Alpine fabric. Paleomagnetic data, obtained here only for two exposures (one Paleozoic and one Triassic) fit the previous results which indicate Middle Miocene remagnetization and subsequent rotations of respective tectonic blocks around local vertical axes.

Key words: Gemeric Superunit, Paleozoic, Triassic, AMS, remagnetization, tectonic deformation.

Introduction

Our study of rock magnetism, AMS and paleomagnetic characteristics of the Gemeric Superunit began with research on Paleozoic strongly metamorphosed rocks (Kruczyk et al. 2000) from several chosen exposures: four of them lie along the KMSZ (Košice-Margecany Shear Zone with character of strike-slip dextral fault), two — close to the DSZ (Dobšiná Shear Zone parallel to the Transgemeric Shear Zone (TGSZ) with character of strike-slip sinistral fault) and one — in the middle of the unit. Each exposure represents a separate tectonic block with specific succession of rotations. The results show evident correlation of the AMS with corresponding shear zones and remagnetization of rocks during the Middle Miocene, followed by rotations of each tectonic fragment around local vertical axes. The senses of rotations fit the character of shear zones close to the respective exposure: clockwise (CW) rotations were observed in the exposures close to the dextral KMSZ and counterclockwise (CCW) — for exposures close to the sinistral DSZ. The present paper extends field of our study on Lower Paleozoic greenschists, phyllites and metadiabases (four exposures) as well as Triassic metadiabases (one exposure) and marbles (one exposure).

The present paper finishes our study of Gemeric rocks, so we will not only discuss the results of the second group of exposures, but also compare them with that of the first group (Kruczyk et al. 2000). At the end we will show our conclusions concerning the paleomagnetic and tectonic implications of our study.

Geological setting

Gemeric Superunit, being a part of the Inner Western Carpathians, is built up with Lower and Upper Paleozoic rocks as well as Triassic rocks affiliated and divided according to individual authors into various lithotectonic units.

Lower Paleozoic rocks are metamorphosed by regional metamorphism into greenschist and amphibolite (Grecula 1973; Dianiška & Grecula 1979; Hovorka et al. 1979; Faryad 1986; Radvanec 1992) facies. They suffered ductile, brittle-ductile and brittle tectonization in shear zones trending NW-SE and NE-SW. Ductile deformation during the Variscan orogeny was documented with the foliation planes trending NE-SW with moderate dips to the NW and N and brittle-ductile close folds of south-vergence, while Alpine overprint is characterized by fold-overthrust structures of NW vergency and dips to the SE, representing the system of half-open to isoclinal folds with axial plane cleavage. Alpine structures originated in transpressional–transtensional shear zones with sinistral shearing in the direction SW-NE and dextral shearing in zones trending SE-NW (Grecula et al. 1991, Fig. 1). Shearing caused mylonitization of rocks as well as their tectonic transport and reduction. According to geological and geochronological data the described shear zones have Alpine age 135 Ma (Ar/Ar data from muscovite taken from the KMSZ; Maluski et al. (1993) as well as Dallmeyer (1994)). The last tectonic record is characterized with brittle kink-folds having axes of NW-SE and N-S directions as well as the joint systems.

The North Gemeric Upper Carboniferous formations (Vozárová & Vozár 1988) are located in transgressive position directly either on Rakovec Group (Bajaník 1962; Bajaník et al. 1981) or Klátov gneiss-amphibolite complex. The latter represents the tectonic overlier of the Rakovec Group, the ductile shear zone of lower crust level. The transgressive Upper Paleozoic sequences on the South of the Gemeric Superunit (Máška 1957; Fusán 1959; Bajaník et al. 1981; Vozárová & Vozár 1988) are overlain by the higher pressure Bôrka Nappe (Leško & Varga 1980; Mello et al. 1983) affiliated to the Meliatic Unit.

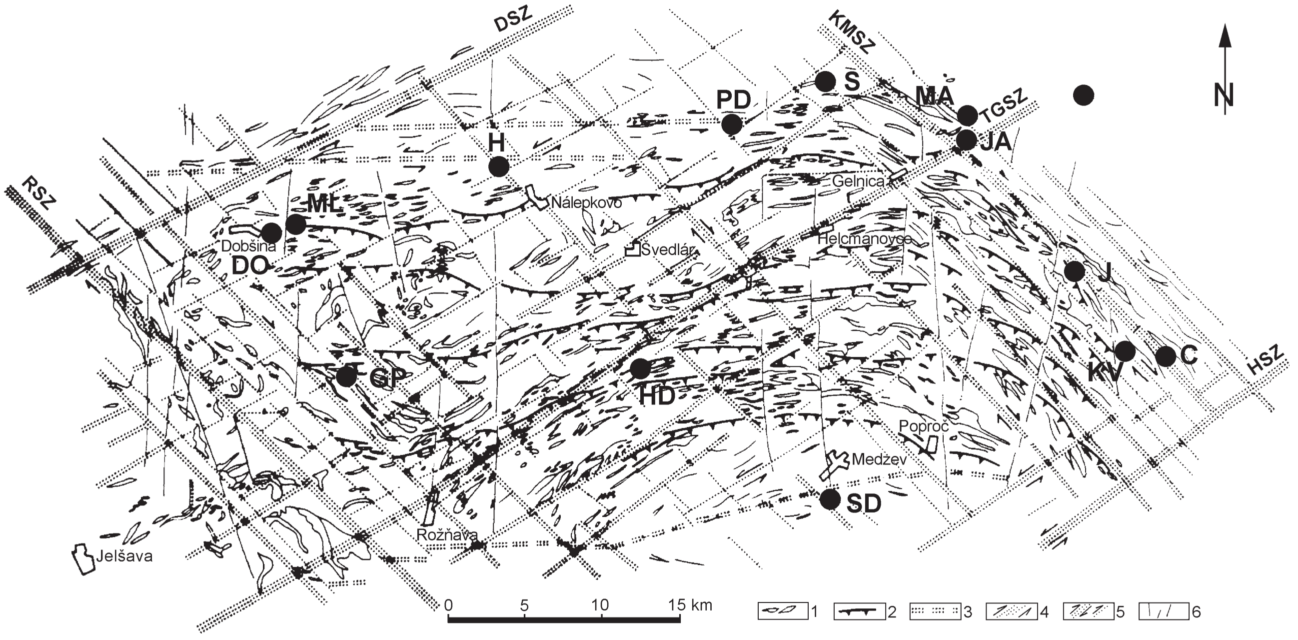

Fig. 1. Map of the shear zones of the Gemerides. RSZ — the Rejdová Shear Zone, DSZ — the Dobšiná Shear Zone, KMSZ — the Košice-Margecany Shear Zone, TGSZ — the Transgemeric Shear Zone, HSZ — the Hodkovce Shear Zone. 1 — course of lithological units, 2 — Variscan nappes, 3 — Alpine rejuvenated Variscan (?) shear zones, 4 — principal shear zones (Alpine), 5 — shear zones of lower order, 6 — faults with the character of pure shear (the youngest ones), black circles — sampling localities: C — Črmel, KV — Vyšný Klátov, J — Jahodná, MA — Margecany, JA — Jaklovce, S — Slovinky, PD — Poráčska Dolina, H — Hnilčík, DO — Dobšinská Priehrada, ML — Mlynky, GP — Gemerská Poloma, HD — Hajdova Dolina, SD — Šugovská Dolina (from Grecula et al. 1990, reprinted with permission).

Locality: Hnilčík (**H**) — quarry (Fig. 1)

Rocks of the Rakovec Group are represented by yellow-green to violet-green phyllites with intercalations of dark-green metabasalt pyroclastics, often with calcite veinlets and mineral assemblage chlorite, epidote, calcite, zoisite, hematite and rutile. The foliation planes 310/30 are accentuated by quartzy shear veins thick to 10 cm with local boudinage. Intercalation of greenish and violet lamina is a characteristic feature, similarly is their folding into open folds with b-axis 30/10. The system of cleavage planes and joints has directions 195/85 and 250/90.

Locality: Poráčska Dolina (**PD**) — Čierny bocian (Fig. 1)

Outcrop of strongly recrystallized metabasites of dark-green to black-green colour with distinct block jointing 0/20 to 350/20. They represent the tight overlier of strongly mylonitized black phyllites. According to the amount of Fe-carbonates, the metabasites are locally strongly weathered and have a brownish appearance. They belong in all probability to the Zlatník Formation of the North Gemeric Upper Carboniferous.

Locality: Slovinky (**S**) — quarry (Fig. 1)

The abandoned quarry contains laminated green-yellow to violet-yellow phyllites with basalt pyroclastic bodies up to several metres thick. They are representatives of the Rakovec Group. Phyllites suffered brittle-ductile mylonitization in planes 156/60 and are penetrated with the Riedel shears trending NW-SE to N-S, usually mineralized with quartz in thin veinlets.

Locality: Hajdova Dolina (**HD**) — Smolník, 400 m to NE of the agricultural cooperative farm

An outcrop of coarse-grained dark-green dolerites to basalt metapyroclastics is present in a tight overlier of graphitic-sericitic phyllites with intercalations of psammites and lydites. They are a constituent of a variegated volcanic complex (sensu Grecula 1982). The mineral assemblage is chlorite, actinolite, calcite, epidote, zoisite, albite ± pyroxene. In mesoscale only a joint system of N-S trend with an inclination to both sides is observable. In the tight overlier, graphitic-sericitic phyllites, the schistosity 156/56 is developed with the b-axis of the isoclinal fold 254/24. Outcrop is located in the Transgemeric Shear Zone.

Locality: Jaklovce (**JA**) — cut of railroad westwards from the Jaklovce lime-kiln (Fig. 1)

Dark-green to black-green ultrabasic rocks, associated with red-violet radiolarites of Ladinian age, outcrop in the railroad cut. They have blocky disintegration. Their joints are filled with chrysotile asbestos. The metamorphic schistosity is 328/48. Their mineral composition is plagioclase, clinopyroxene (augite), magnetite and ilmenite. The red radiolarites often contain joints healed with specularite. The rocks are a representantive of a Jurassic mélange belonging to the Meliatic Unit. The outcrop is located on the crossing of the Transgemeric and Košice-Margecany Shear Zones.

Locality: Šugovská Dolina (**SD**) — abandoned quarry in the valley termination (Fig. 1)

Quarry contains coarse-crystalline grey-white to brownish-white limestones. They often outcrop with metabasic rocks (glaucophanites) and black schists. The rocks are affiliated to the Bôrka Nappe, to the Meliatic Unit of Triassic–Jurassic age. The carbonates are penetrated with the following system of planes and joints: 130/80 with striations 85/70, and 40/76 with striations 8/70 and 300/70. Discontinuities are often healed with calcite veinlets.

Experimental procedure

Experimental study was done in the three laboratories: the Geophysical Institute of the SAS (GPI SAS) in Bratislava, the Institute of Geophysics of the PAS in Warsaw (IGP PAS) and the Polish Geological Institute in Warsaw (PGI). The natural remanent magnetization (NRM) was measured with the JR5 spinner magnetometer of Agico and demagnetized thermally with a non-magnetic oven in Bratislava (MAVACS — system of Geophysics Brno). The demagnetization results were analysed in the IGP PAS and in PGI in Warsaw with the PDA-program package (Lewandowski et al. 1997). The measurements of the magnetic susceptibility and its anisotropy (AMS) were performed with the KLY-2 susceptibility bridge of Geophysics Brno in Bratislava and Warsaw, the monitoring of magnetic mean susceptibility during the procedure of thermal demagnetization of NRM was done in Bratislava. For calculation of anisotropy parameters the ANISO 11 program (Jelínek 1977) has been used, the results were further analysed in the IGP PAS with the Spheristat 2.0 program of Pangea Scientific.

The anisotropy parameters that will be discussed later comprise (Tarling & Hrouda 1993):

— mean low-field susceptibility

Km = 1/3(Kmax + Kint + Kmin), where Kmax, Kint, Kmin are the maximum, intermediate and minimum susceptibilities, respectively.

— anisotropy parameter

$P' = \exp \sqrt{2} \left[(\eta_1 - \eta_m)^2 + (\eta_2 - \eta_m)^2 + (\eta_3 - \eta_m)^2 \right]$ where $\eta_1 = \ln Kmax$, $\eta_2 = \ln Kint$, $\eta_3 = \ln Kmin$, $\eta_m = \sqrt{\eta_1 \eta_2 \eta_3}$

— shape parameter $T = (2\eta_2 - \eta_3 - \eta_1)/(\eta_1 - \eta_3)$

the anisotropy ellipsoid is prolate (lineation prevails) if $T<0$, and oblate (foliation prevails) if $T>0$.

— direction of the axis of maximum susceptibility Kmax: pole to magnetic lineation:,

— direction of the axis of minimum susceptibility Kmin: pole to magnetic foliation

Mean magnetic susceptibility was measured in GPI SAS after each heating step during the thermal demagnetization procedure in order to monitor mineralogical changes caused by heating.

The identification of magnetic minerals was done through the magnetic and non-magnetic methods. Magnetic methods comprised: measurements of hysteresis parameters (Hc — coercive force, Hcr — remanent coercivity, Ms — saturation magnetization, Mr — saturation remanence) with the vibration magnetometer VSM of Molyneaux (done in IGP PAS) and two thermomagnetic methods. One, consisting of thermal decay in a non-magnetic space of the isothermal remanence Ir acquired in the field of 1 T during heating to 700 °C in air was done in the IGP PAS with the non-commercial TUS device. This method gives values of blocking temperatures Tb's of magnetic minerals present in the rock, observed on Ir-T curves. Another one, called the Lowrie method consists of thermal demagnetization of three components implied in the specimen in three mutually perpendicular directions in fields of 0.1 T, 0.4 T and 1.3 T. Each component is carried by a mineral fraction of different coercivity. Temperatures unblocking the respective component indicate the appropriate mineral — carrier of this component (Lowrie 1990). This analysis, which is accompanied by the IRM (isothermal remanent magnetization) acquisition curves, was performed in the PGI in Warsaw with the MMPM1 pulse magnetizer.

The non-magnetic methods comprised the optical microscopy and scanning electron microscopy (SEM) with microprobe. The former was carried for the IGP PAS by J. Siemiątkowski (PGI, Wrocław, Poland), the latter — by E. Starnawska (PGI in Warsaw).

General characteristics of rocks

Exposures situated within the Rakovec Group

Hnilčík (H) — diabase pyroclastics and chloritic-sericitic phyllites. Seven hand samples coming from two sides of the quarry with different schistosity groups H1 and H2. The supposed age of these rocks is Upper Devonian–Lower Carboniferous (?). All methods of identification of magnetic carriers indicate the presence of hematite: Tb temperatures observed on Ir-T curves range between 650 and 690 °C (Fig. 2A), the results of the Lowrie method show that the same temperatures of about 690 °C unblock the soft, medium and high coercivity fractions, IRM acquisition curves do not saturate in the highest field of the experiment, although the 90 % of saturation is reached in the field of 0.4–0.6 mT (Fig. 3A), hysteresis curves show the presence of high coercivity material (Table 1). The presence of low coercivity fraction acquired in the 0.1 T, and the dominance of the medium coercivity fraction acquired in the 0.4 T suggests that the hematite grains are rather large.

Analysis of polished sections revealed the presence hematite crystals of 2–18 μm and grains of pyrite of about 10 μm. This was supported by the SEM and microprobe results.

Poráčska Dolina (PD) — greenschists. Five hand samples of supposed Lower Paleozoic age (?). Thermomagnetic analyses in zero field show the presence of hematite only, with Tb of about 650–690 °C, Ir-T curves look identical as those for Hnilčík (Fig. 2a). The three axis Lowrie thermal analysis reveals the presence of hard, medium and soft coercivity fractions, all with blocking temperatures of 690 °C characteristic for hematite, as it was observed in Hnilčík. In several samples the low and medium coercivity fractions dominate over the hard one. The presence of hematite components of varying hardness is also reflected on the IRM acquisition curves (Fig. 3B,C). In specimens with prevailing soft and medium compo-

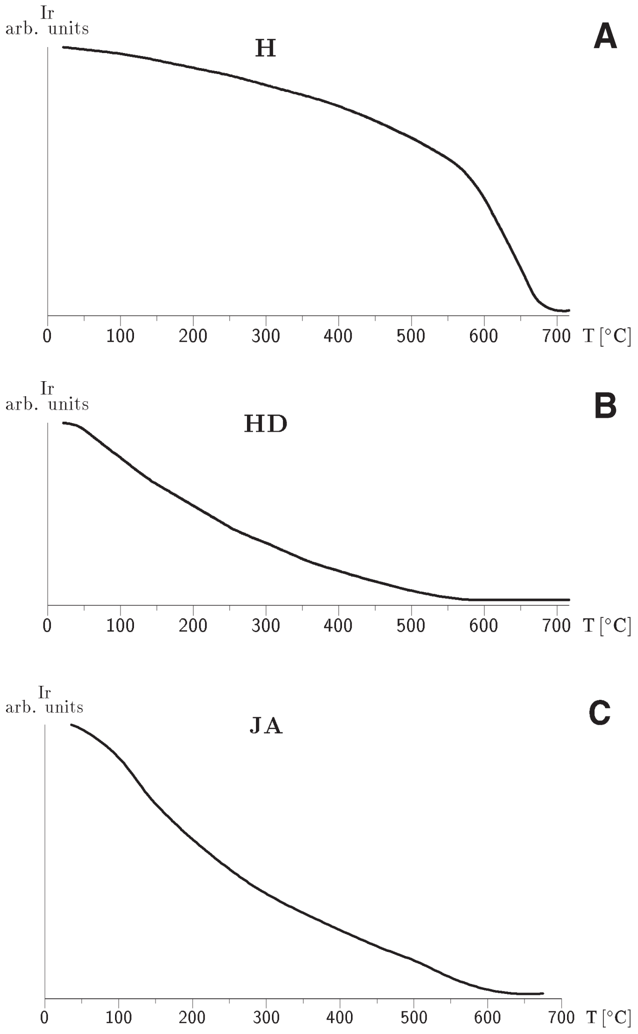

Fig. 2. Results of thermomagnetic analysis performed in the non-magnetic field. Ir — remanence acquired in the field of 1 T in arbitrary units, T — temperature in °C. **A** — Ir-T curve for H; **B** — Ir-T curve for HD; **C** — Ir-T curve for JA.

nents the saturation is nearly reached at 0.8 T, in specimens where the hard component dominates, the saturation is not reached even in the highest field of the experiment (1.4 T). The values of coercivity and coercivity of remanence obtained due to hysteresis measurements acquire intermediate values (Table 1). These results imply presence of hematite in grains of various sizes distributed within the rock.

Microscopic study reveal presence of post-ilmenite and post-ilmenomagnetite leukoxen pseudomorphs with distinct traces of tectonic deformations indicating that the mineral changes took place at temperatures of 250–300 °C (Dunlop & Özdemir 1998). Optically identified hematite grains have lengths of 7–10 μm, and the SEM results confirm the presence of large Fe-oxide grains with the Fe/O ratio of 69–71%/27–30% given by the microprobe.

Slovinky (S) — phyllite greenschists. Nine hand samples of supposed Lower Paleozoic age. Thermal analyses show presence of hematite with Tb's of 650–690 °C, with the thermomagnetic Ir-T curves similar to that for Hnilčík (Fig. 2A). According to the Lowrie method the hard coercivity fraction prevails in all specimens, in some of them the hard and medium coercivity fractions is accompanied by the low coercivity fraction with much lower intensity and unblocking temperature of about 350 °C (Fig. 3D). Dominance of the high coercivity component is reflected on the curves of the IRM acquisition that do not reach saturation in the highest fields available (same Figure). Hysteresis parameters (Table 1) are characteristic for hematite.

According to the microscopic study hematite occurs mainly within the laminae in the form of pallets of 5–21 μm — Fig. 4A — lower part. The elongated grains of Fe-oxides are also revealed by the SEM, their Fe/O ratio being 70–71%/29–30%. Fig. 4A — upper part shows the SEM image of tabular and elongated grains of hematite present in the K rocks.

Exposure situated within the Gelnica Group

Hajdova Dolina (HD) — metadiabases and schists. Four hand samples of supposed Lower Paleozoic age. Both thermomagnetic analyses show the presence of magnetite with Tb's of about 580 °C and mineral with Tb's of 350–400 °C, perhaps post-pyrite Fe-oxide or Fe-sulphide sometimes accompanied by goethite with Tb of 150–200 °C (Fig. 2B and Fig. 3E). According to the IRM acquisition curves the prevailing low coercivity mineral reaches saturation in the fields of 0.2–0.3 T (Fig. 3E). Hysteresis parameters for metadiabases (samples 34 and 35) are characteristic for magnetite, those for schists (sample 32) indicate the presence of maghemite (Table 1).

The results of optical microscopy indicate presence of post-ilmenomagnetite pseudomorphs of 100–500 μm. The SEM analysis indicates presence of titanite, small grains of Fe-oxides with the Fe/O ratio obtained through the microprobe being 58%/38% and also presence of sulphur. It suggests that the magnetite identified through magnetic methods may be of post-pyrite origin.

Exposures situated within the Meliatic Unit

Jaklovce (JA) — metadiabases, six hand samples, supposed age — Lower and Middle Triassic. For the JA specimens only thermomagnetic analysis in the compensated magnetic field was performed because their remanences acquired in consecutive external fields according to the Lowrie method were too high to be measured. The Ir-T curves show the presence of magnetite with Tb's of about 570–580 °C, Fig. 2C. Values of hysteresis parameters (Table 1) support this conclusion.

According to the optical microscopy the metadiabases are only weakly metamorphosed — the fine albite and chlorite-epidote veins implicate the beginning of metamorphic processes. Skeletal magnetites characteristic of deep oceanic basalts (Freeman 1986) occur in grains of 7–17 μm, in some of them processes of oxidation into maghemite have begun (Fig. 4B — lower part). The SEM results show the presence of skeletal as well as dendritic magnetite or maghemite grains (Fig. 4B — upper part) with Fe/0 ratio 66–69%/28–31%.

Table 1: Hysteresis parameters of rocks from this study.

Exposure	Sample number	Ms (μA.m^2)	Mr (μA.m^2)	Hc (mT)	Hcr (mT)	magnetic mineral
H1+H2	40	1.49	0.47	69	95	hematite
	41	5.55	4.72	127	180	
	42	9.98	9.04	140	175	
PD	7	1.76	1.15	75	100	hematite
	7A	1.36	0.96	73	95	
	10	1.30	0.73	71	110	
	11	0.45	0.13	29	75	
S	12	7.03	6.54	256	325	hematite
	14	0.97	0.67	287	450	
	20	10.58	8.51	384	375	
HD	32	0.21	0.06	21.5	200	magnetite/maghemite
	34	1.18	0.20	6.5	38	
	35	1.24	0.42	16.5	50	
JA	4	2440.8	151.0	4	15	magnetite/maghemite
	5	3861.7	367.8	9	55	
SD	27	0.34	0.04	17.5	130	goethite and magnetite/maghemite
	28	0.18	0.04	26.5	200	
	29	0.23	0.05	34	200	

Šugovská Dolina (SD) — metamorphosed carbonates (marbles). Four hand samples with assumed age of Middle Triassic. Specimens were too weak for thermomagnetic analysis in the non-magnetic field to be done therefore only the Lowrie method was applied to them. The results indicate the presence of two minerals: goethite with Tb of about 100 °C and a mineral with Tb of about 400 °C, probably fine-grained magnetite or maghemite (Fig. 3F), the same is seen on the IRM acquisition curves showing its increase in the whole range of available fields. Hysteresis parameters (Table 1) support the conclusion about the presence of high coercivity minerals in the studied rocks. The mean susceptibility Km is very low ranging from -10 to 11×10^{-6} SI. Negative Km values observed in several specimens indicate the dominance of diamagnetic minerals in them.

The pigment with cherry red colouring, identified as Fe-hydroxides is visible in the optical microscope.

Summary: The magnetic properties of the Paleozoic rocks from the Rakovec Group are connected mainly with hematite, whereas in the Gelnica rocks magnetite/maghemite probably of post-pyrite origin, pyrrhotite and goethite were identified. The Triassic rocks from the Meliata Group carry magnetite/maghemite (JA) and goethite accompanied by magnetite or maghemite (SD).

AMS study

The magnetic low field susceptibility of the studied rocks show differences corresponding to the different lithologies: from diamagnetic marbles from SD to strongly ferrimagnetic ultrabasic rocks from JA. The appropriate ranges of the Km are cited in Table 2 together with values of anisotropy parameter P'. The lowest values of P' are to be find in HD where it ranges from about 1.005 to 1.02. The anisotropy ellipsoids are rather oblate, although some manifest weak prolateness (see Fig. 5A). The prevailing P' values for the Rakovec and Meliata localities are situated between 1.002 and 1.15, the less numerous group has P' between 1.25 and 1.32 in Rakovec and 1.20 and 1.30 in Meliata. Anisotropy ellipses are prolate in PD, prolateness prevails also in JA. In the SD rocks of both shapes occur in similar proportions and in H and S rocks, oblate ellipsoids are in the majority (Fig. 5B,C).

The directions of Kmax and Kmin axes are shown in Table 2 together with tectonic lineations (L) and foliations (S) which correspond to the magnetic fabric. According to Návesňák (1993) there are in the Gemerides three systems of mylonitic schistosity S2, S3, S4 and two lineations L2 and L3, caused by the Alpine tectonics. The most characteristic lineation L2 (azimuth 230–240° or 60° with a low dip) is associated with the TGSZ zone, mylonitic foliation S2 (azimuth of about 165° and dip of about 40° with a scatter from 0° to 70°) and foliation S3 (azimuth of 293°–335° and low dip) are due to compression linked with the TGSZ and other, parallel shearing zones. The lineation L3 reflecting the East Carpathian system trends to 290° or 100° with a shallow dip. The foliation S4 (azimuth of 230°–235° and dip of about 45°) is associated with the KMSZ zone (see also Kruczyk et al. 2000). Fig. 6 and Fig. 7A,B show the magnetic lineations and foliations compared with the tectonic ones. These figures include, apart of the results from the present study, the appropriate results of the previous investigations (Kruczyk et al. 2000) as well. The correspondence between the magnetic and tectonic lineations (L2 and L3 shown as crosses on Fig. 6) is clear: magnetic lineation remains very close to the L2 in five localities (both wings of H: H1 and H2, PD, S, DO, ML) in one (MA) it is close to the L3, in one (JA) the magnetic lineation lies between the two tectonic ones. In

Table 2: Susceptibility and AMS results compared with tectonic data.

Locality	Km × 10^{-6} SI	Kmax magnetic lineation D/I	Kmin pole to magn. fol D/I	P'	Tectonic lineation L corresponding to magnetic lineation	Tectonic foliation S corresponding to magnetic foliation
RAKOVEC GROUP (Paleozoic)						
H1	300–560	249/13	15/61	1.10–1.22	L2	S3
H2	290–740	56/8	163/65	1.10–1.29	L2	S2
PD	660–780	61/7	168/58	1.05–1.13	L2	S2
S	130–470	50/29	177/39	1.01–1.08	L2	?
GELNICA GROUP (Paleozoic)						
HD	100–850	103/63 scattered	248/22-scattered	1.004–1.02	?	none
MELIATA GROUP (Triassic)						
SD	–11–11	scattered		1.03–1.13	none	S2 (?)
JA	25000–96000	87/4	358/15	1.04–1.09	L2–L3	none

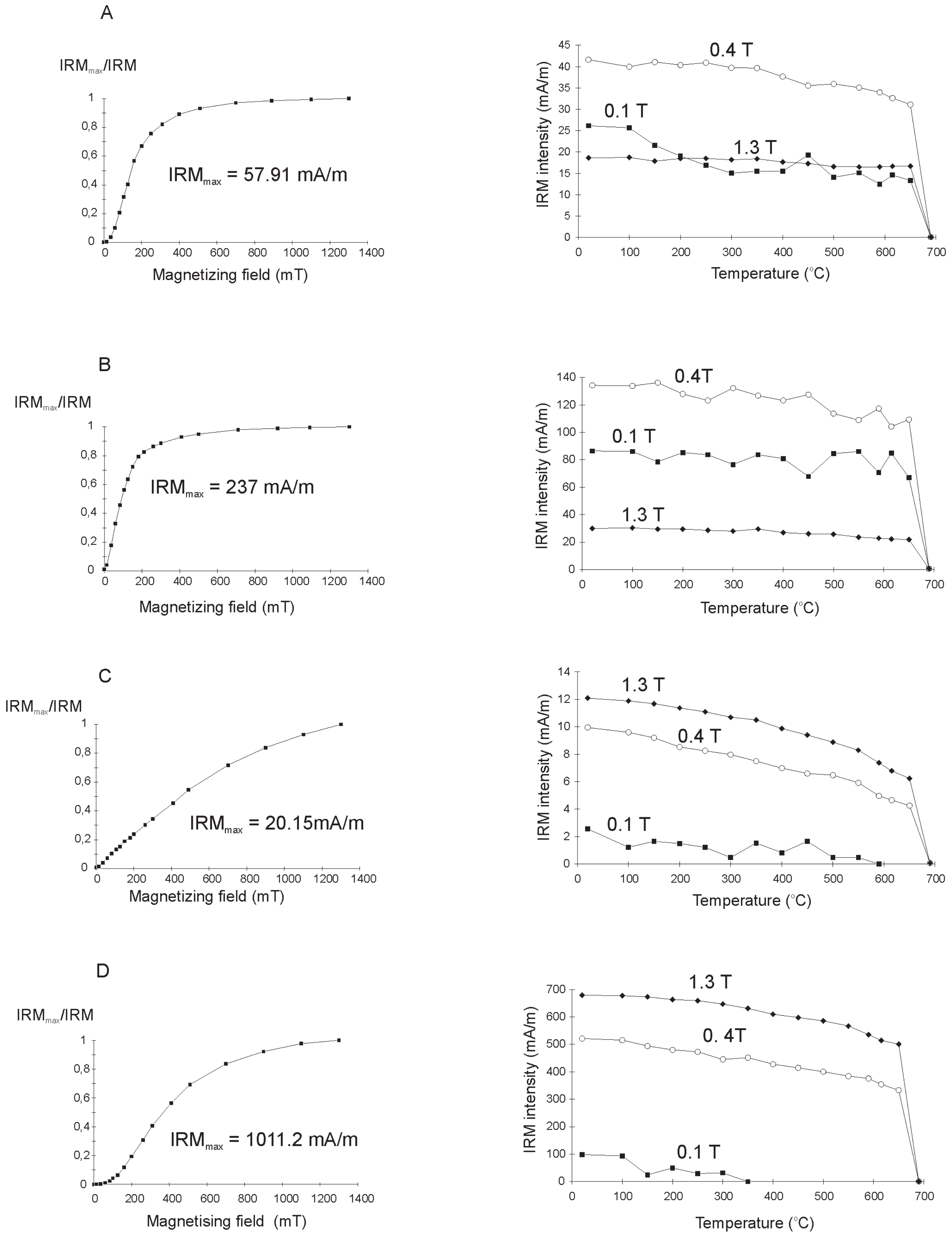

Fig. 3. IRM acquisition curves (left) and thermal demagnetization of the three axes IRM (right). **A** — Hnilčík; **B** and **C** — Poráčska Dolina; **D** — Slovinky; **E** — Hajdova Dolina; **F** — Šugovská Dolina.

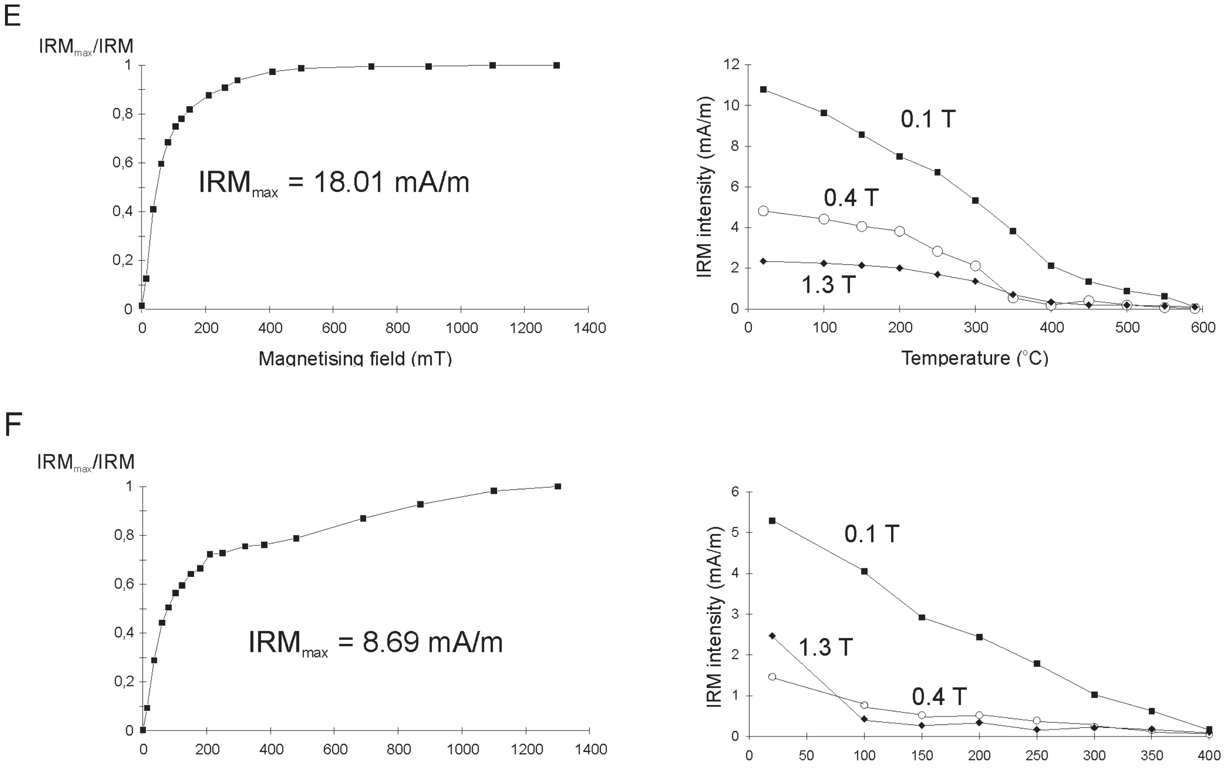

Fig. 3. *Continued.*

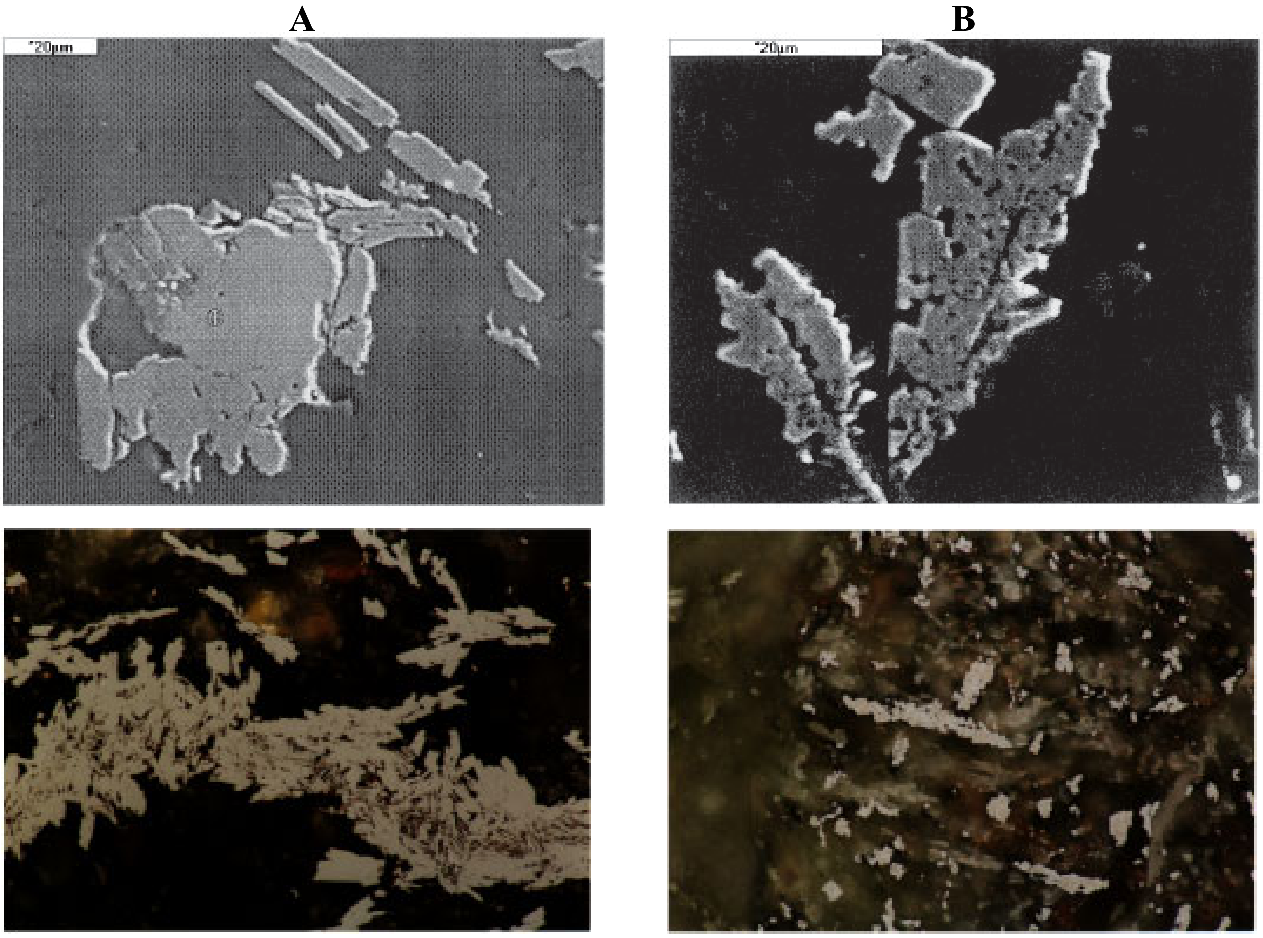

Fig. 4. A — SEM (upper) and optical microscopy (lower) images of the hematite grains in the Slovinky rock. Hematite appears in mylonitized vein and as allongated tablets. **B** — SEM (upper) and optical microscopy (lower) images of dendritic magnetite grains in Jaklovce.

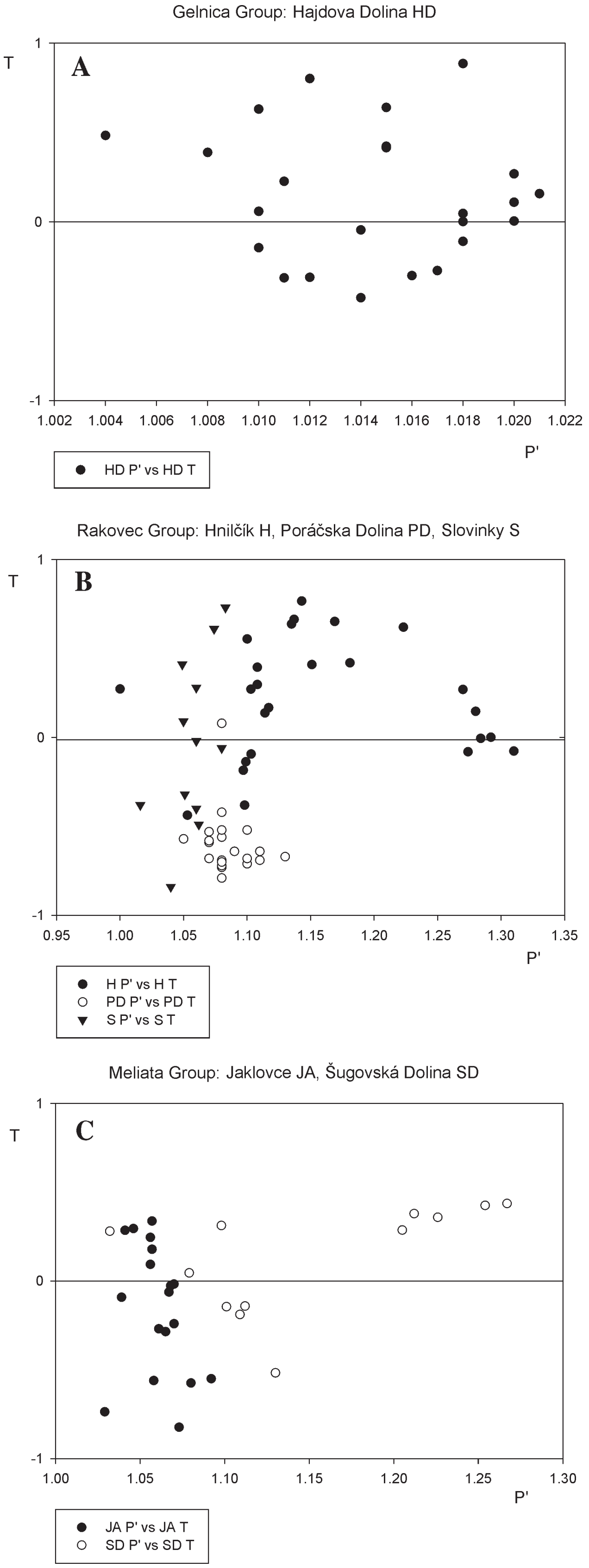

Fig. 5. Parameter of anisotropy P' plotted against the shape parameter T. **A** — Hajdova Dolina; **B** — Hnilčík, Poráčska Dolina and Slovinky; **C** — Jaklovce and Šugovská Dolina.

four localities (C, KV, HD, J) two of which (HD and J) are characterized by low anisotropy (see Table 3 in Kruczyk et al. 2000 and Table 2 of this study) Kmax directions have intermediate-high inclinations and do not show a straightforward relationship either with the L2 or with L3 lineations. The magnetic foliation planes for the rocks of this study (Fig. 7A) correspond to the tectonic foliation S2 (H1) or S3 (H2, PD). In S and JA — the magnetic foliation does not correlate with any of the tectonic ones, which corresponds to their relatively low anisotropy suggesting a low degree of deformation. No correlation of magnetic and tectonic fabrics was observed in HD which has very low P' values indicating that the HD rocks are hardly deformed. Fig. 7B shows the relations of magnetic and tectonic foliations obtained in the previous study (Kruczyk et al. 2000). It implies relations of magnetic foliations of localities situated along the KMSZ (C, J, MA) with the S4 foliation, which does not appear in the present study, and relation of the magnetic foliations of other localities with S2 and S3 as is observed here.

Paleomagnetic results, discussion and summary

The specimens were demagnetized thermally. The majority of them responded well to the treatment (Fig. 8) giving Zijderveld diagrams approaching origin. The principal component analysis revealed that the NRM is either single component or composed of two. Unfortunately, the obtained characteristic directions are highly scattered and only in two cases (HD and JA) have we been able to calculate the mean exposure directions with reasonable confidence parameters, (see Table 3). The directions obtained (*in situ* in both cases) differ in declina-

Table 3: Mean directions for Gemerides with rotation angles Geographic position: 20.5°E, 48°N.

Loc.	N/n	D/I [°] *In situ*	D/I [°] *corr.*	α_{95} [°]	K	pol	ΔD=Do-Dr [°]
localities influenced by the dextral East-Carpathian shearing system							
KV	6/7	**313/-60**		13	21	R	127 CW
J	3/6	**190/-65**		18	18	R	4 CW
GP	5/8	109/72	**25/62 65%**	6	98	N	19 CW
localities influenced by the sinistral West-Carpathian shearing system							
DO	9/12	320/51	**303/61 45%**	13	11	N	63 CCW
ML	5/8	68/70	**2/61 45%**	9	42	N	4 CCW
HD	3/17	**347/71**		14	81	N	19 CCW
localities influenced by both shearing systems							
MA	3/5	**275/65**		20	16	N	92 CCW
JA	3/10	**18/63**		7	278	N	12 CW
mean inclination calculated for Gemerides							
G	8	**64**					

Reference data:
E after Besse & Courtillot (1991) for Stable Europe, 10–20 Ma D = 6, I = 62.
CS after Balla (1987) for Central Slovakia, rad. age 11–17 Ma D = 10, I = 64
Loc. — locality, N/n — number of hand samples/number of specimens taken for calculations, D/I in situ — declination/inclination before tectonic correction for bedding or schistosity, D/I corrected — declination/inclination after tectonic correction (45% or 65% untilting) α_{95} , K — parameters of Fisher statistics, pol — polarity of specimnes taken for calculations (N — normal, R — reverse), CW — clockwise, CCW — counterclockwise, Do — declination obtained in this study, Dr — reference declination, ΔD — angle of local rotation.

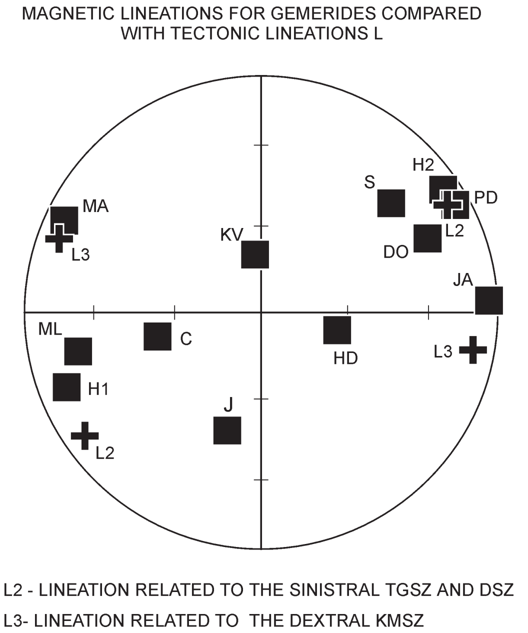

Fig. 6. Results of the AMS analysis: comparison of directions of magnetic (black squares) and tectonic (crosses) lineations for all exposures combined. L2 and L3 — appropriate directions of tectonic lineations (see text), remaining letters denote respective exposures as in Fig. 1.

tions and have inclinations of 63° with α_{95} of 7° for JA, and 71° with α_{95} of 14° for HD indicating the Tertiary age of remagnetization. They are shown in Table 3 and Fig. 9 together with the results obtained in our previous study (Kruczyk et al. 2000) in order to enable the wholesome paleomagnetic analysis for the region. As is easily seen, the new results follow the pattern observed previously. The mean inclination calculated from means for all exposures combined, labeled G in Table 3, is 64°. Very similar values are found for the Neogene volcanic Middle Miocene rocks from Central Slovakia (Balla 1987) and Neogene rocks from the East Slovak Basin (Márton et al. 2000): mean inclination calculated for the purpose of this paper from data of the cited paper of Balla for Central Slovakia (CS) is 64°, and declination 10°, the results of the study by Márton et al. (2000) gave inclination of 63° and different declinations for different localities. These values agree well with the reference data for the Stable Europe Middle Miocene rocks (E) (Besse & Courtillot 1991) with the inclination of 62° and declination of 6°. The E and CS data are included in Table 3 and Fig. 9. Repeating the procedure applied in Kruczyk et al. (2000) we tried to fit the results obtained for HD and J to the E result. It may be done rotating independently both fragments represented by our exposures respectively by 12° CW (JA) and 19° CCW (HD) — see Table 3.

Table 3 presents, apart of paleomagnetic directions, also the rotation angles for all the exposures. They are grouped according to their situation against the main shearing zones. The paleomagnetic declinations in the exposures KV, J and GP reveal clockwise rotations suggesting the influence of the dextral East-Carpathian system. The AMS results confirm this conclusion in the case of J (Fig. 7A, Table 3 in Kruczyk et al. 2000). The paleomagnetic declination of the exposures DO, ML, HD and MA were rotated anticlockwise (CCW) suggesting that they were influenced by the sinistral West-Carpathian system. This conclusion is supported by the AMS results obtained for ML and DO, whereas in the case of MA the AMS shows distinct correlation with the dextral East-Carpathian system (Fig. 6, Fig. 7A and Table 2). The declination of the exposure JA is rotated clockwise (CW), whereas the direction of its lineation lies between tectonic lineations of both systems and magnetic foliation does not correlate with any of the tectonic ones (Fig. 6, Fig. 7B and Table 2). We therefore suppose that MA and JA are influenced by both shearing systems. The results of AMS study obtained for KV, GP and HD, despite their either clockwise (KV and GP) or anticlockwise (HD) rotations, do not show any distinct correspondence with the tectonic fabric.

The above discussion proves that the studied Gemeric rocks of various ages, at least those that give reasonably grouped directions of characteristic remanence, became remagnetized during the Middle Miocene, prior to the rotations of individual fragments of the unit. The rotations were due to the tectonic

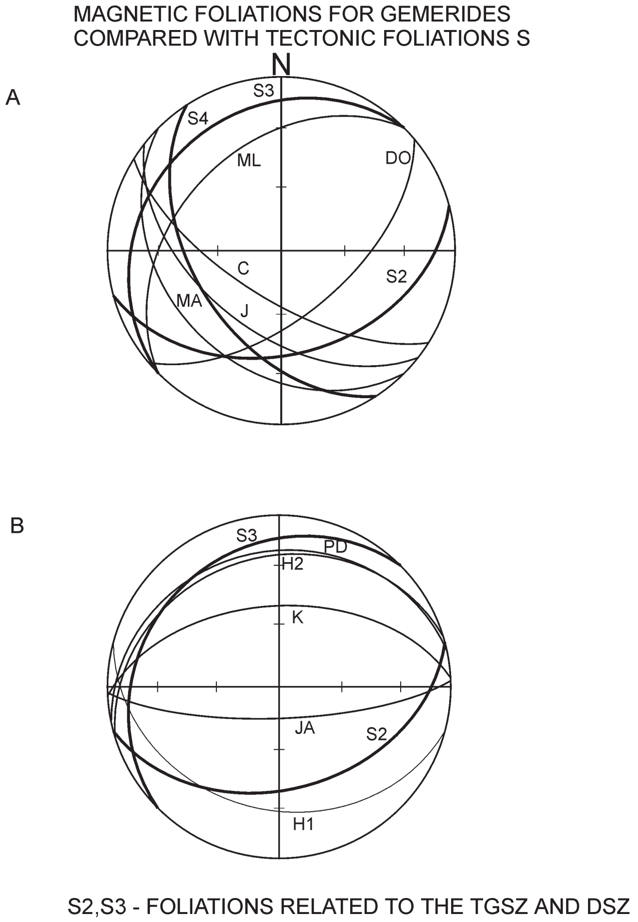

Fig. 7. Results of AMS analysis: comparison of magnetic foliation planes (thin lines) with tectonic foliation planes (thick lines). **A** — for the exposures of the previous study; **B** — for the exposures of this study. S2, S3, S4 — tectonic foliation planes (see text), remaining letters denote respective exposures as in Fig.1.

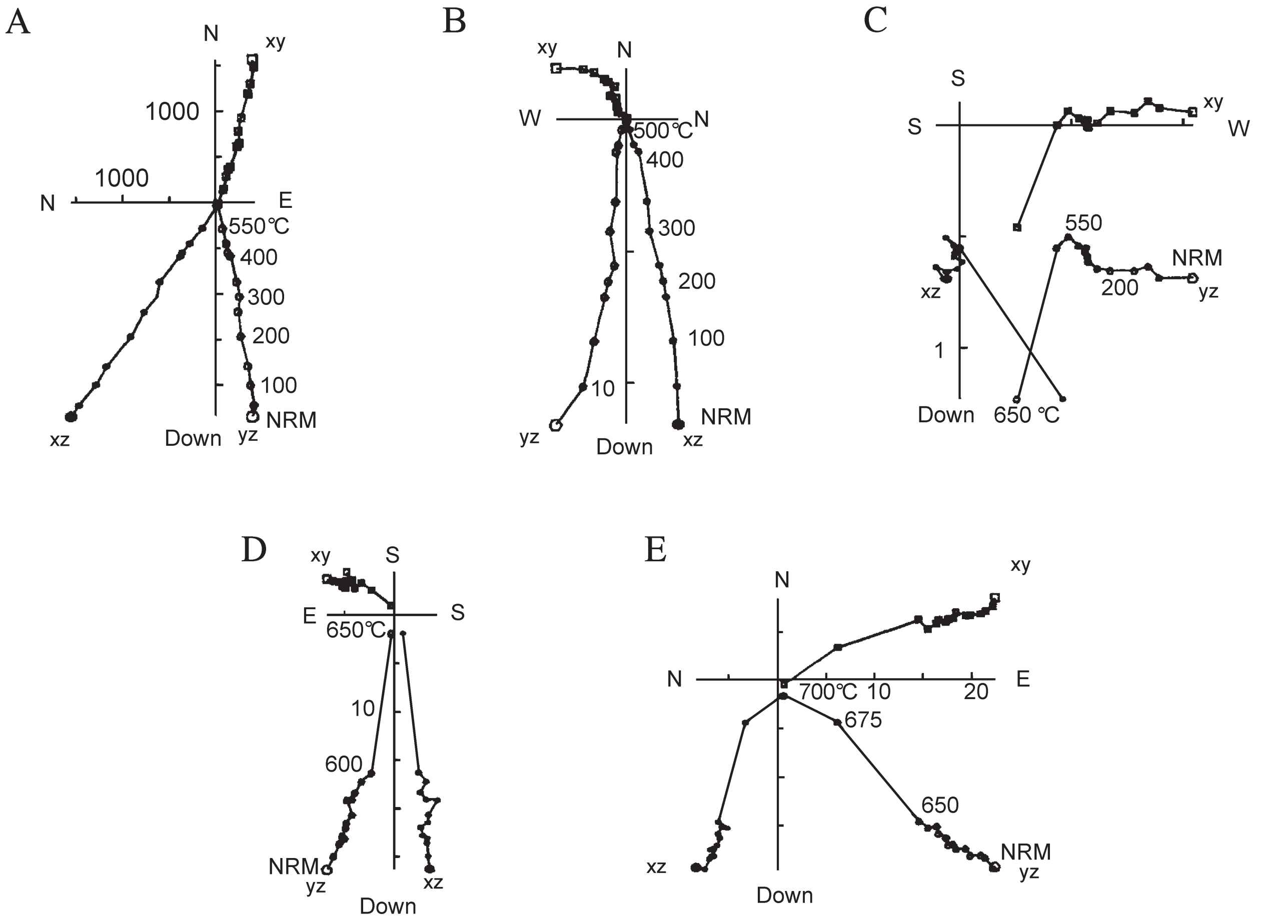

Fig. 8. Examples of Zijderveld diagrams obtained for rocks of this study demagnetized thermally. **A** — Jaklovce; **B** — Hajdova Dolina; **C** — Hnilčík; **D** — Poráčska Dolina; **E** — Slovinky.

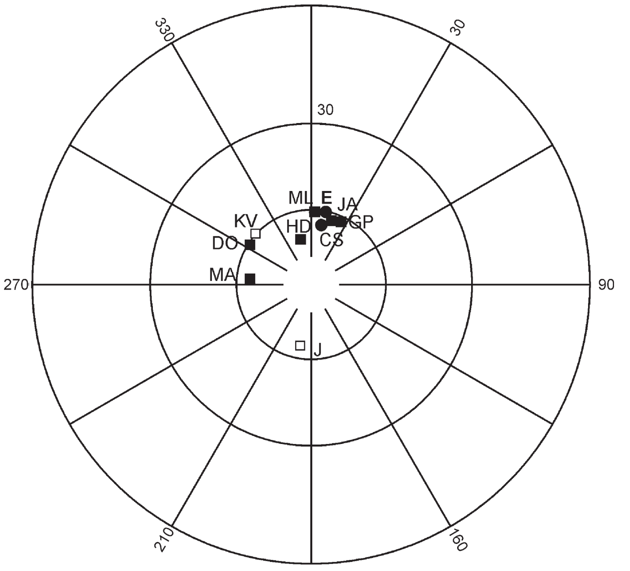

Fig. 9. Mean directions of characteristic remanence obtained for exposures of this and previous study together with reference direction for Stable Europe E (after Besse & Courtillot (1991) and mean direction for Central Slovakia CS (after Balla 1987). Exposures labeled as in Fig. 1. Full squares — normal polarity, empty squares — reversed polarity.

activity related to the East- and West-Carpathian shearing systems.

Conclusions

Our final conclusions summarized below concern all the studied Gemeric exposures.

1. AMS study shows that the anisotropy parameters of rocks remain in a very broad range. In the majority of exposures there is distinct correlation of magnetic and tectonic fabrics, with prevailing influence of magnetic lineations related mainly to the TGSZ system and magnetic foliation — to both systems. Exposures where no or only weak correlation was found have low magnetic anisotropy as at Šugovská Dolina, Hajdova Dolina and Jaklovce, or very scattered directions of susceptibility axes, perhaps due to complicated tectono-metamorphic history as at Vyšný Klátov. Possible superposition of magnetic fabrics related to several deformation events may result in the non-paralelism of resultant magnetic fabric with any of the tectonic ones. In such case it is not possible to separate the respective components of AMS. It may also have caused the great scatter of AMS data.

2. In seven out of eleven Paleozoic and in one out of two Triassic exposures, we were able to isolate reasonably well

grouped characteristic components of NRM. The mean exposure inclinations lie between 61° and 71° and differ in declinations. The NRM has normal polarity in all except two exposures, in two exposures demagnetization took place during folding (see Kruczyk et al. 2000) which shows that remagnetization was not synchroneous in all places.

3. Mean inclination for Gemerides calculated from the exposure means labeled G is 64° and agrees with reference data for the Stable Europe and data from other Slovak regions for the Middle Miocene meaning that all the studied rocks became remagnetized in this period.

4. After remagnetization the tectonic blocks represented by the respective exposures were rotated due to the Alpine tectonic activity: blocks related to KMSZ rotated clockwise, blocks related to TGSZ rotated anticlockwise, in two cases the influence of both systems is observed.

Acknowledgments: The work was done in the frame of the scientific cooperation between the Slovak Academy of Sciences, Polish Academy of Sciences and Polish Geological Institute, with the support of the Institute of Geophysics of the Polish Academy of Sciences, Project 5/2000 as well as Project 6.20.1225.00.0 of the Polish Geological Institute and Project VEGA No. 5136/98 of the Geophysical Institute of the Slovak Academy of Sciences. The authors thank Mgr. D. Gregorová for performing measurements of anisotropy of susceptibility.

References

Bajaník Š. 1962: Several remarks about stratigraphy, magnetism and tectonic of the Rakovec Series between Čierna Hora Mts. and Hnilec river. *Geol. Práce, Zoš.* 64, (in Slovak).

Bajaník Š. et al. 1981: Lithostratigraphical classification of the Rakovec Group and late Paleozoic of the Spiš-Gemer Rudohorie Mts. *Geol. Práce, Spr.* 75, 27-56 (in Slovak).

Balla Z. 1987: Tertiary paleomagnetic data for the Carpatho-Pannonian region in the light of Miocene rotation kinematic analysis. *Tectonophysics* 139, 67-98.

Besse J. & Courtillot V. 1991: Revised and Synthetic Apparent Polar Wander Paths of the African, Eurasian, North American and Indian Plates, and True Polar Wander since 200 Ma. *J. Geophys. Res.* 96, 4029-4050.

Dallmeyer R.D. 1994: Some results of the ^{40}Ar/^{39}Ar measurements on sample from Gemericum. *MS-Geocomplex,* Bratislava.

Dianiška I. & Grecula P. 1979: Amphibolite-gneisse complex as a component of ophiolite suite of the Rakovec nappe. *Miner. Slovaca* 11, 405-425 (in Slovak, English summary).

Dunlop D.J. & Özdemir O. 1998: Rock magnetism. Fundamentals and frontiers. *Cambridge Univ. Press*, 1-573

Faryad S.W. 1986: Metamorphic evolution of paragenesses of Klátov region (Lower Paleozoic of Gemericum). *Geol. Zbor. Geol. Carpath.* 37, 729-746.

Freeman R. 1986: Magnetic mineralogy of pelagic limestones. *Geophys. J.R.A.S.* 85, 433-452

Faryad S.W. 1986: Metamorphic evolution of paragenesses of Klátov region (Lower Paleozoic of Gemericum). *Geol. Zbor. Geol. Carpath.* 37, 729-746.

Fusán O. 1959: Remarks on the Upper Paleozoic of Gemerides. *Geol. Práce, Zoš.* 55, 171-181(in Slovak).

Grecula P. 1973: Home area of Gemericum and its metallogenesis. *Miner. Slovaca*, 5, 3, 221-245 (in Slovak).

Grecula P. et al. 1991: Shear zones and arc structure of Gemericum, the Western Carpatians. *Miner. Slovaca* 22, 97-110.

Grecula P., Návesňák D., Bartalský B., Gazdačko L., Németh Z., Ištván J. & Vrbatovic P. 1990: Shear zones and arc structures of Gemericum, the Western Carpathians. *Miner. Slovaca* 22, 97-100.

Hovorka D. et al. 1979: The metamorphytes of amphybolite facies from Rudňany. *Miner. Slovaca,* 11, 481-504 (in Slovak).

Jelinek V. 1977: The statistical theory of measuring anisotropy of magnetic susceptibility and its application. *Geofyzika*, Brno, 5-88.

Kruczyk J., Kądziałko-Hofmokl M., Jeleńska M., Tůnyi I., Grecula P. & Návesňák D. 2000: Tectonic and structural implications of paleomagnetic and AMS study of highly metamorphosed Paleozoic rocks from the Gemeric Superunit, Slovakia. *Geologica Carpathica* 51, 3, 133-144.

Leško B. & Varga I. 1980: Alpine elements in the West Carpathian structure and their significance. *Miner. Slovaca* 12, 2, 97-130.

Lewandowski M., Nowożyński K. & Werner T. 1997: PDA-package of FORTRAN programs for paleomagnetic data analysis. *Unpublished.*

Lowrie W. 1990: Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. *Geophys. Res. Letters* 17, 2, 159-162.

Maluski H., Rajlich P. & Matte P. 1993: ^{40}Ar-^{39}Ar dating of the Inner Carpathians Variscan basement and Alpine mylonitic overprinting. *Tectonophysics* 223, 313-337.

Máška M. 1957: The report on an investigation of the Paleozoic of Spiš-Gemer Rudohorie Mts. (1. Permian). *Správy o geol. výskumoch,* 1956 (in Slovak).

Márton E., Vass D. & Túnyi I. 2000: Counterclockwise rotations of the Neogene rocks in the East Slovak Basin. *Geol. Carpathica* 51, 3, 159-168.

Mello et al. 1983: The new stratigraphic knowledge about the Meliata group. *Geol. Práce, Spr.* 79, 55-81(in Slovak).

Návesňák D. 1993: Manifestation of shear zones in the north-eastern part of Gemeric Unit, Western Carpathians. *Miner. Slovaca*, 25 263-273 (in Slovak, English summary).

Radvanec M. 1992: Zonality of low-pressure and polyphase metamorphism in open system for the fluid phase in the gneiss-amphibolite complex of Gemeric unit. *Miner. Slovaca* 24, 175-196 (in Slovak, English summary).

Tarling D.H. & Hrouda F. 1993: The Magnetic Anisotropy of Rocks. *Chapman and Hall,* London, 1-217.

Vozárová A. & Vozár J. 1988: Late Paleozoic in West Carpathians. *GS SR*, Bratislava, 1-314.