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TECTONIC AND STRUCTURAL IMPLICATIONS OF PALEOMAGNETIC AND AMS STUDY OF HIGHLY METAMORPHOSED PALEOZOIC ROCKS FROM THE GEMERIC SUPERUNIT, SLOVAKIA

JADWIGA KRUCZYK[1], MAGDALENA KĄDZIAŁKO-HOFMOKL[1], MARIA JELEŃSKA[1], IGOR TÚNYI[2], PAVOL GRECULA[3] and DANIEL NÁVESŇÁK[4]

[1]Institute of Geophysics of the Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warsaw, 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, Mlynská Dolina 1, 817 04 Bratislava, Slovak Republic
[4]Geological Survey of the Slovak Republic, Werferova 1, 040 11 Košice, Slovak Republic

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Abstract: Paleozoic highly metamorphosed rocks were sampled in 4 localities situated along the Košice-Margecany shearing zone (East-Carpathian dextral system), on two sites situated close to the Dobšiná shearing zone (West-Carpathian sinistral system), and on one site situated within the Gemeric Superunit. The West-Carpathian and East-Carpathian shearing systems resulted in the division of Gemeric Superunit into a mosaic of small tectonic blocks. Each site sampled for this study represents one such block. Our paleomagnetic study revealed that the rocks became remagnetized in the Middle Miocene after a regional CCW rotation, probably during the period between anomaly 6 (20 Ma) and anomaly 5 (10 Ma). After the remagnetization episodes the blocks underwent rotations (around their vertical axes) associated with activity of respective dextral or sinistral shearing zones. The results of the AMS study suggest a correlation between the magnetic fabric and the Alpine tectonic deformation episodes.

Key words: Gemeric Superunit, Paleozoic, paleomagnetism, AMS, tectonic deformations.

Introduction

The Gemeric Superunit, which belongs to the Alpine-Carpathian-Pannonian (ALCAPA) block is situated at the southern edge of the Central Western Carpathians, Figs. 1a, 1b. It has a distinct belt structure, often with narrow lithological strips of the length up to several tens of kilometers. The Gemeric Superunit is built by the Early and Late Paleozoic and Triassic rocks. Paleogene and Neogene sediments cover its marginal parts with the exception of the eastern margin, which is in tectonic contact with the crystalline complex of Veporic Superunit (Čierna Hora Mts). The superunit is cut into numerous blocks by two systems of shearing zones trending NW-SE and NE-SW. Rocks building the Gemeric Superunit underwent polyphased deformation and metamorphism that took place during the Variscan movements as well as during the Alpine orogenies. It is supposed, that one deformational episode took place in the Gemeric Superunit during the Variscan Orogeny and that formation of nappe structures marked the end of Variscan events. The present geological frame of the Gemeric Superunit is due to Alpine tectonics (Grecula 1997; Plašienka et al. 1997).

The purpose of this study is twofold:

- to reveal this part of geodynamic history of the Gemeric Superunit that became preserved by paleomagnetic characteristics of its highly metamorphozed Paleozoic rocks;
- to find correlations between the anisotropy of magnetic susceptibility (AMS) and the shearing zones.

Geological setting and sampling

General remarks concerning the geodynamic features

During the Upper Mesozoic and the Tertiary the ALCAPA area was subject to significant tectonic processing. The convergence of the Afroarabian and the Euroasian litospheric plates led to final collision of the Bohemian Massif with the Apulia. This collision resulted in a formation of Alpine nappes and northeastern shifting (escape) of fragments of the Alpine and the Dinaric units, grouped in the Inner Carpathian, Tissia and Dacides terranes. Csontos et al. (1992) and Márton et al. (1995) argue, that the escape was driven from behind by pushing forces caused by the Bohemian Massif- Apulia collision, but influence of pulling forces caused by subduction of the Euroasian Plate under the Inner Carpathians also contributed to this process. The escape movements started after the Cretaceous folding in the Alps; these were most intensive after the pre-Oligocene folding and extinguished during the Early Miocene. The escaping fragments approached European Plate in different periods; for Gemeric Superunit it happened during the Early Eocene (Márton et al. 1995).

According to Peresson & Decker (1996) the Early and Middle Miocene tectonics of the ALCAPA region was dominated by the N-S directed compression and E-W directed extension. During the Late Miocene the direction of the compression changed to an E-W trend. This, and the final oblique collision

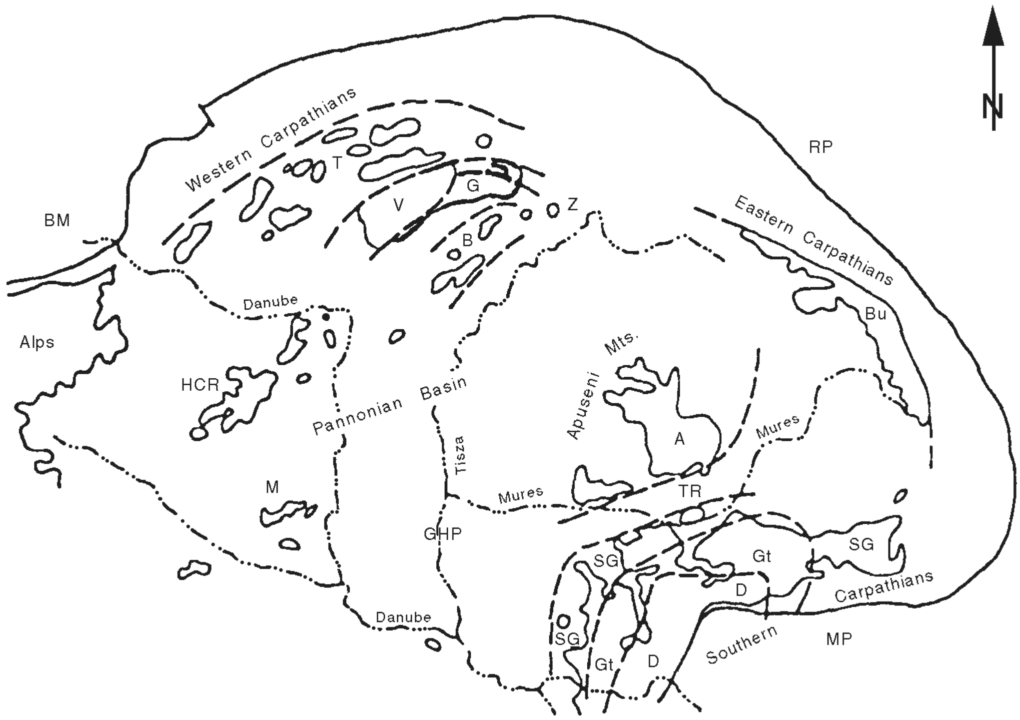

Fig. 1a. Position of the Gemeric Superunit in the frame of the Carpathian mountain system. BM — Bohemian Massif, RP — Russian Platform, MP — Moesian Plate, HCR — Hungarian Central Range, GHP — Great Hungarian Plane, T — Tatric Superunit, V — Veporic Superunit, G — Gemeric Superunit, B — Bükkic units, Bu — Bucovinian units, Z — Zemplín units, SG — Supragetic units, Gt — Getic units, D — Danubian units, TR — Transsylvanides, A — Apuseni Mts., M — Mecsek Mts. (From Grecula et al. 1995, reprinted with permission of Geocomplex Bratislava).

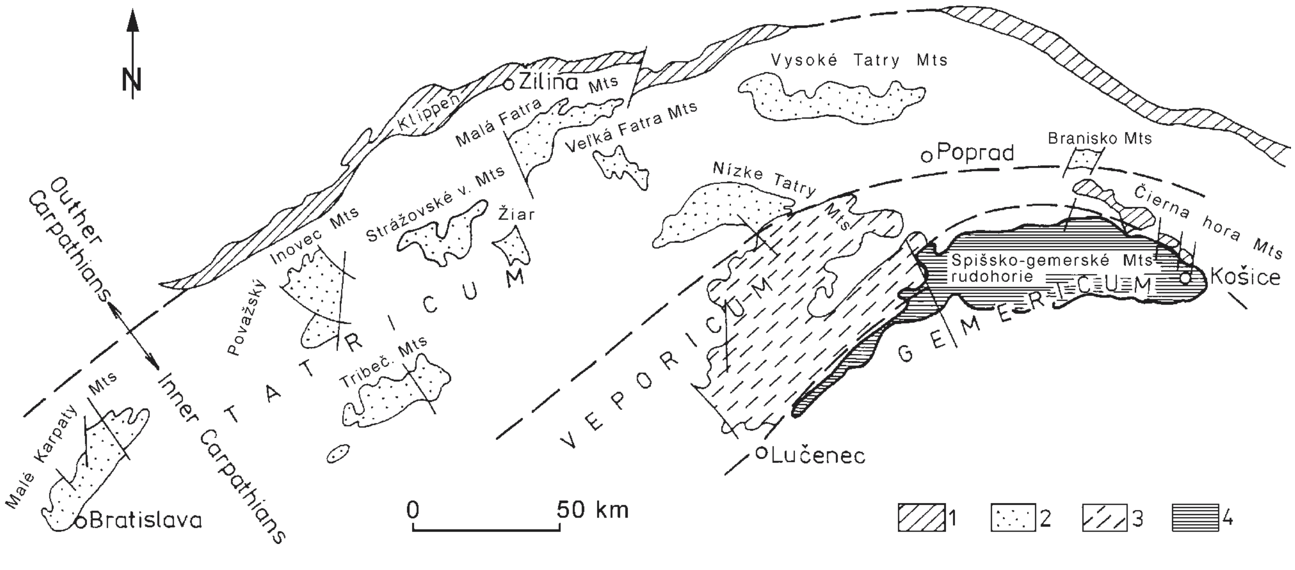

Fig. 1b. Position of the Gemeric Superunit in the West-Carpathian mountain system. 1 — Klippen belt, 2 — Tatric Superunit, 3 — Veporic Superunit, 4 — Gemeric Superunit. (From Grecula et al. 1995, reprinted with permission of Geocomplex Bratislava).

of the escaping Inner Carpathian units with the North European Platform, caused their counterclockwise rotation and uplift of the rigid basement rocks (Plašienka et al. 1997; Peresson & Decker 1996). The paleomagnetic study by Márton et al. (1995) and Márton & Márton (1996) performed in Southern Slovakia and North Hungarian Central Range suggest, that this rotation of the whole region ended at the Early-Middle Miocene boundary (Karpatian-Badenian). In the present study we show that the Middle and Late Miocene kinematics caused local rotations of blocks comprising the Gemeric Superunit.

Along with the processes leading to the northeastward escape, the above mentioned compressional stresses were com-

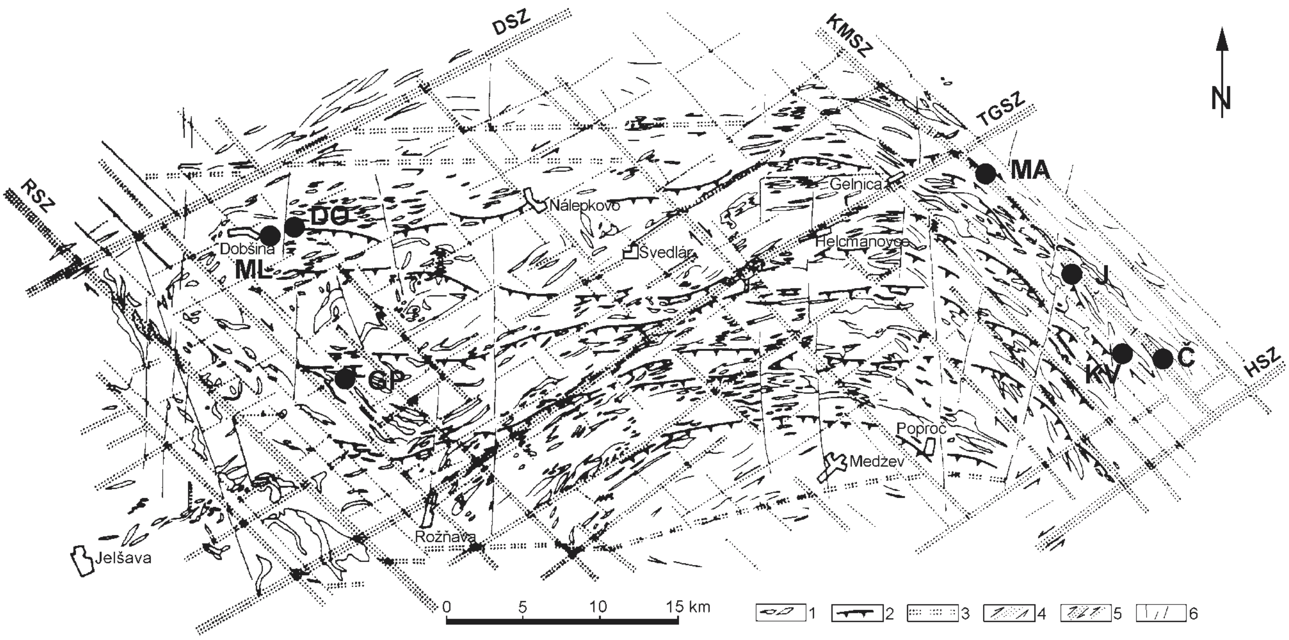

Fig. 2. Map of the shear zones of the Gemerides. RSZ — the Rejdová shear zone, DSZ — the Dobšiná shear zone, KMSZ — the Košice-Margecany shear zone, TGSZ — the Transgemeric shear zone, HSZ — the Hodkovce shear zone. 1 — course of lithological units, 2 — Variscan nappes, 3 — Alpine rejuvenated Variscan (?) shear zones, 4 — principal shear zones (Alpine), 5 — shear zones of lower order, 6 — faults with a character of pure shear (the youngest ones), black circles — sampling localities: Č — Črmeľ, KV — Vyšný Klátov, J — Jahodná, MA — Margecany, DO — Dobšinská Priehrada, ML — Mlynky, GP — Gemerská Poloma. (From Grecula et al. 1990, reprinted with permission).

pensated along the wedge system by paired shear zones, one trending NW-SE (the Košice-Margecany shearing zone (KMSZ), the dextral strike-slip fault, the East-Carpathian system), and the second shear zone trending NE-SW (the Transgemeric shear zone (TGSZ), the sinistral strike-slip fault, the West-Carpathian system). These paired zones resulted in creating an arc structure of the Gemeric Superunit and its division into a mosaic of blocks that could have been subjected to local rotations, Fig. 2 (Grecula et al. 1990). In the megascale the shear zones are demonstrated by the change of the course of rock complexes, by retraction, as well as destruction of the Variscan veins and the stratiform mineralization (Návesňák 1993). The deformation of the Paleozoic rocks associated with these events is of a brittle–ductile character.

The age of the shear zones is estimated on the basis of geological features as well as the Rb/Sr isotopic dating. As this research was not performed specifically for the dating of the shear zones, we may only assume that movements on them started before the Cretaceous and ended during the Styrian phase (the Middle Miocene) — Grecula et al. (1990), Návesňák (1993).

Návesňák (1993) distinguishes within the Gemeric Paleozoic rocks three systems of mylonitic schistosity (S2, S3, S4) and two lineations (L2, L3) caused by the Alpine tectonics. The S1 and L1 systems linked with the Variscan deformation stage are visible only within large blocks that were not influenced by the Alpine shearing. The E-W trend of lineation L1 indicates the direction of an old shear system, the foliation S1 indicates surfaces of metamorphic schistosity corresponding to L1. The most characteristic lineation L2 (azimuth of 230°–240° or 60° with a low dip) associated with the TGSZ and LSSZ, mylonitic foliation S2 (azimuth of about 165°, dip of about 40° with scatter from 0° to 70°) and foliation S3 (azimuth of 293°–335°, shallow dip) are due to a compression linked with the TGSZ and LSSZ (the Lacemberská dolina Valley-the Stará Voda shearing zone, parallel to the TGSZ zone) shear zones. The L3 lineation trends to 290° or 100° with a shallow dip. The S4 foliation (azimuth of 230°–235°, dip of about 45°) is associated with the KMSZ zone.

Metamorphism

The mineral association of the majority of rocks of the Gemeric Superunit corresponds to the metamorphic facies of green shists. In several zones of the Gemeric Superunit, also in the enclaves of high pressure and middle temperature, metamorphites and rocks of amphibolite facies (Grecula 1997; Radvanec 1994, 1997) with important retrograde metamorphic reworking have been preserved.

These processes, as well as strong folding, granitization, local granite intrusions and ore mineralizations begun during the Variscan orogeny. During the Alpine orogeny metamorphic and tectonic processes continued. The Variscan and Alpine metamorphic events resulted in well-developed blastesis of magnetite, hematite and chlorite. The presence of martite within magnetite grains, as well as transformation of sulphides into Fe-hydroxides indicate that blastesis took place during a retrograde phase. The influence of tectonic factors is reflected in the general presence of the mylonitic foliation. Márton et al. (1995) argue, that the activation of astenosphere associated with the tectonic escape caused reheating of crust. This assumption is supported by Peresson & Decker (1996) who show the uplift of the astenosphere under the Pannonian Basin caused by extension tectonics during the Middle Miocene. We believe that this process induced physico-chemical conditions suitable for the Middle Miocen remagnetizations of older rocks.

Sampling

62 hand samples were collected for the present study. The sampling was carried out in the following areas: along the KMSZ shear zone forming the eastern border of the Gemeric Superunit (exposures KV, Č, J, MA), in the vicinity of the Dobšiná shear zone (DSZ — one of shear zones belonging to TGSZ system) in the western part of the Gemeric Superunit close to its northern border (exposures DO, ML) and one exposure (GP) lying in the middle part of the unit, see Fig. 2. The rocks represent strongly metamorphosed and mylonitized sericitic schists (Č, J), cataclasites (MA, KV), phyllites and schists rich in carbonates (ML, DO, GP). Oriented hand samples taken in the field were drilled into standard paleomagnetic specimens in the laboratory.

Experimental procedure

All experimental work was performed in the Paleomagnetic Laboratory of the Institute of Geophysics of the Polish Academy of Sciences in Warsaw. Natural remanent magnetization (NRM) was measured with a cryogenic magnetometer of 2G, specimens were demagnetized thermally with the Magnetic Measurements non-magnetic furnace or with a 2G alternating field device. All apparatuses are installed within the Magnetic Measurements compensating cage. The magnetic susceptibility and its anisotropy was measured with the KLY-2 Geofyzika Brno bridge before the demagnetization procedure. The obtained parameters (Tarling & Hrouda 1993) that will be discussed later comprise:

— mean low field magnetic susceptibility

$K_m = 1/3(K_{max} + K_{int} + K_{min})$ where

$K_{max}, K_{int}, K_{min}$ — the maximum, intermediate and minimum susceptibilities, respectively

— anisotropy parameter

$$P' = \exp\sqrt{2((\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2)}, \text{ where}$$

$\eta_1 = \ln(K_{max})$, $\eta_2 = \ln(K_{int})$, $\eta_3 = \ln(K_{min})$, $\eta_m = \sqrt{\eta_1\eta_2\eta_3}$

— shape parameter $T = (2\eta_2 - \eta_1 - \eta_3)/(\eta_1 - \eta_3)$; the anisotropy ellipsoid is prolate (prevailing lineation) if $T < 0$, the anisotropy ellipsoid is oblate (prevaling foliation) if $T > 0$

— directions of K_{max} and K_{min} axes of the susceptibility elipsoid.

Mean magnetic susceptibility was measured also after consecutive heating steps in order to monitor mineralogical changes caused by heating. Results of paleomagnetic experiments were analyzed with the program package PDA of Lewandowski et al. (1997), results of the AMS study — with the ANISO 11 program of Jelínek (1977) and Spheristat 2 program of Pangea Scientific.

The identification of magnetic minerals was done through a microscopic examination of polished sections (performed by Siemiatkowski from the State Geological Institute, Wroclaw), a thermomagnetic analysis, and a study of hysteresis parameters. The thermomagnetic analysis consisted of studying the thermal decay of isothermal remanence Ir acquired in 1 T field during the heating to 700 °C in the air with the use of the TUS Warsaw device. The blocking temperatures Tb obtained here indicate that magnetic minerals are present in the rock. The hysteresis parameters were measured with the vibrating magnetometer VSM of Molspin with the highest available field of 1 T.

General characteristics of sampled rocks and their magnetic mineralogy

Sites situated along the KMSZ shear zone:

Čermeľ (Č) — schistosity (azimuth/dip) 245/50, mylonitic schists, 8 hand-samples. Paleontologic age is supposed to be the Tournaisian–Viséan; according to Grecula et al. (1990) they became modified due to the Late Variscan shearing, but mylonitisation originated during the Alpine tectonics. The microscopic study reveals parallel texture manifested by mylonitic smears, calcite veins cutting the rock were also visible. Fe-hydroxides, pyrrhotite and chalcopyrite in clasts of 0.1 mm represent opaque minerals. Rocks are magnetically weak — isothermal remanence Ir of fresh specimens was too low for a thermomagnetic analysis. Heating to 600 °C resulted in increase of Ir by about 30 times due to formation of new magnetite. The hysteresis parameters (see Table 1) indicate the presence of magnetic material with low and intermediate coercive force. The mean magnetic susceptibility Km ranged between 400 and 800×10^{-6} SI and increased after heating to 500 °C.

Vyšný Klátov (KV) — no tectonic parameters, amphibolite schists (cataclasites) belonging to the gneissic amphibolite Klátov complex, 12 hand samples. The tectonic position is ambiguous, the complex may be treated either as a small nappe, or as a highly metamorphosed part of the Rakovec nappe. The radiometric age (K-Ar and Ar-Ar) spans the time from 448 to 383 Ma (the Upper Ordovician, Lower Devonian). The metamorphic processes perhaps underwent here in the amphibolite facies conditions which are indicated by the presence of chloritized amphiboles with magnetites and post-plagioclase smears composed of epidote–albite–calcite. The microscopic study reveals the presence of automorphic magnetite with martite lamellae of 0.03–0.3 mm. Hematite forms smears of 0.1 mm, tablets of 0.001–0.1 mm and flakes. Single sulphides are present within the hematite grains as well as clusters of Fe-hydroxides with relicts of pyrites. Automorphic and framboidal pyrites are also visible. The thermomagnetic analysis shows the presence of magnetite with Tb 560–575 °C, accompanied in some specimens with phase with Tb of about 200 °C (goethite?) and hematite with Tb of about 650 °C (Fig. 3a,b). The hysteresis parameters (see Table 1), despite the presence of hematite and perhaps goethite visible in polished sections, are characteristic for multidomain magnetite (Day et al. 1977). The magnetic susceptibility Km is high and ranges from 3200 to 22000×10^{-6} SI, it increases after heating to temperatures exceeding 600 °C in all specimens.

Jahodná (J) — schistosity 220/55, very fine-grained sericitic schists (mylonites) with quarz lens, 5 hand samples.

Table 1: Hysteresis parameters measured for particular specimens.

Locality	Specimen	Ms $\mu A.m^2$	Mr $\mu A.m^2$	Hc mT	Hcr mT
Č	105 –1	0.6	0.3	19	43
	107 –1	0.7	0.1	4	47
KV	134 – 1	443	25	7.5	35
	135 – 1	272	11	5	30
	138 – 2	239	9.5	5	30
J	113	2.7	0.8	44	310
	114	3.9	0.7	29	280
MA schist	124 –1	260	17	7	27
sandstone	132 – 1	0.2	0.06	24	62
sandstone	133 –1	0.2	0.08	20	70
DO	174 – 1	0.5	0.2	28	160
	174 – 2	1.23	0.24	41	65
	175	0.3	0.09	8	48
	176 – 1	0.5	0.17	12	30
	176 – 2	0.35	0.09	3	35
ML	157 –1	15	13	312	330
	160 -1	?	0.7	175	330
	161 –1	?	0.3	127	170
	162 –1	2.1	1.9	237	250
	163	6.4	5.0	108	115
	167	?	0.4	52	230
GP	179 –1	0.35	0.27	29	65
	181	0.21	0.06	13	65
	182	0.24	0.06	22	60
	185 – 2	0.21	0.06	16	55

Ms – saturation magnetization, Mr – saturation remanence, Hc – coercivity, Hcr – remanence coercivity

The paleontologic age of the rocks is supposed to be the Lower Permian, whereas the radiometric K-Ar dating gives 126 Ma (the Lower Cretaceous) as the age of the metamorphic changes. The microscopic analysis reveals the presence of automorphic hematites with sulphide grains, spherical agglomerates of hematite grains probably of a post-pyrite origin, and single hematite tablets. Ilmeno-magnetite pseudomorphs were also visible. The thermomagnetic analysis indicates hematite as the only magnetic mineral, the curves of Ir vs. T are very similar to those shown in Fig. 3c. This conclusion is supported by the hysteresis parameters (cf. Table 1) revealing high values of coercivity, and by the saturation field exceeding the maximum field of the experiment. The Km values were low and ranged from 200 to 250×10^{-6} SI. Heating to 600 °C resulted in a significant increase of the Km.

Margecany (MA) — schistosity 190/40, chlorite-sericite schists, and polymict sandstones, both highly mylonitized. Some 10 hand samples were taken from 3 sites, but only 8 samples from 2 sites (one site containing schists and the second — sandstones) were suitable for measurements. This locality is situated at the crossing of two shear zones: KMSZ and TGSZ. The radiometric (Ar-Ar) unpublished age is 329.6 Ma, placing the rocks in the Upper Carboniferous. The microscopic analysis was performed only for one specimen representing polimict sandstones and did not reveal the presence of magnetic minerals. The thermomagnetic analysis that was performed on several specimens shows the presence of magnetite and goethite in schists and magnetite in sandstones — the Ir vs. T curves are similar to the one shown in Fig. 3a. The study on hysteresis parameters suggests the dominance of multidomain magnetite in sericitic schists and SD and PSD magnetite in sandstones (Day et al. 1977) — see Table 1. The obtained values of the Km for schists were very high ($6500–70000 \times 10^{-6}$ SI) for sandstones — low ($190–220 \times 10^{-6}$ SI), after heating to 550–600 °C the Km increases.

Localities situated at the DSZ shear zone:

Dobšinská Priehrada (DO) — bedding 180/34, chlorite schists (mylonites) with calcite smeared veins, 11 hand samples. The assumed age is the Upper Carboniferous. Within the veins plagioclases in clasts, epidotes, chlorites, albites are encountered. The age of metamorphism is uncertain, likely occurring during the large time span from the Neovariscan to the Jurassic or even the Cretaceous. The microscopic analysis reveals the presence of post-pyrite Fe-hydroxides with pyrite relicts. The thermomagnetic study supports this result revealing various Ir vs. T curves showing the presence of phase with Tb of 200 °C, hematite and low amounts of magnetite (the Ir-T curves are similar to those shown in Figs. 3a and 3c). After the heating new magnetite appears. The Km ranges from 400 to 750×10^{-6} SI and increases after heating to 600 °C. The values of hysteresis parameters (Table 1) should be regarded only as estimates because the rocks here are too weak for reliable measurements with our VSM.

Mlynky (ML) — bedding 320/65, 12 hand samples, strongly carbonatized pyroclastic phyllites belonging to the diabase series of the Rakovec Nappe. Their estimated age is the Upper Devonian–Lower Carboniferous, they became metamorphosed during the Variscan orogeny in the greenschist facies conditions, but the Alpine events erased the Variscan features. The microscopic analysis revealed hematite in tablets of 0.01–0.03 mm and less than 0.001 mm as the main magnetic mineral. The thermomagnetic analysis supports this conclusion (Fig. 3c), the hysteresis parameters attain values characteristic for hematite (Table 1) as well. The Km ranges from 190 to 750×10^{-6} SI and increases after heating.

Locality siutated outside the main shear zones:

Gemerská Poloma (GP) — bedding 350/51, 9 hand samples, ankeritic carbonaceous beds cut by calcite veins, product of regional metasomatosis. The assumed age of the rocks is Upper Silurian–Lower Devonian, the age of metasomatic alteration is supposed to be either Variscan, or Alpine. The polished sections have intensive brownish colouring characteristic for fine Fe-hydroxides. The thermomagnetic analysis reveals the presence of goethite and, perhaps, a small amount of magnetite. Pyrite is probably also present, because after the heating pyrrhotite appears on the Ir vs. T curves. Heating to 650 °C results in a thousandsfold increase of Ir due to the appearance of pyrrhotite and magnetite. Here, as in DO, results of measurements of the hysteresis parameters are only estimations. The Km ranges from 230 to 600×10^{-6} SI and in-

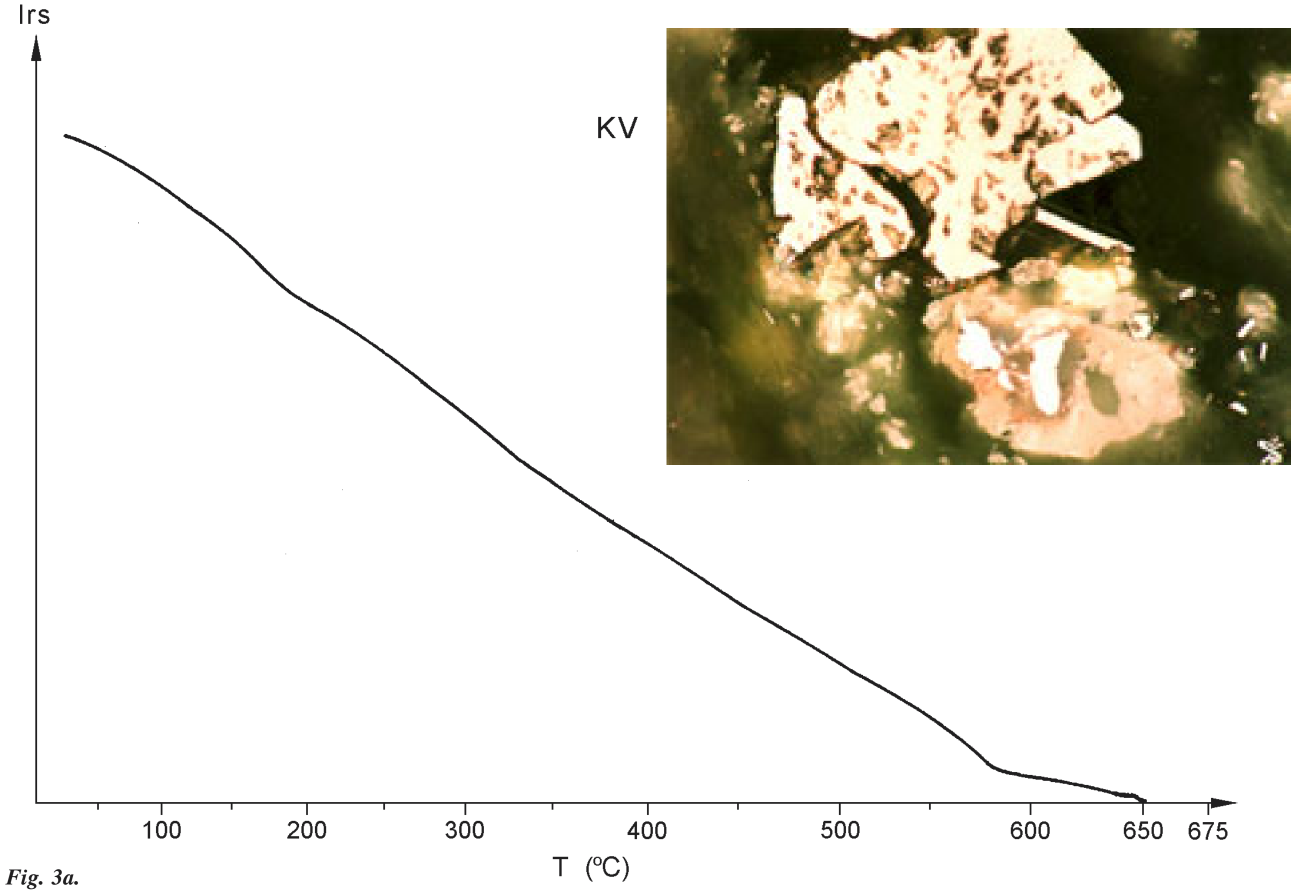
Irs
KV
100
200
300
400
500
600
650
675
T (ºC)

Fig. 3a.

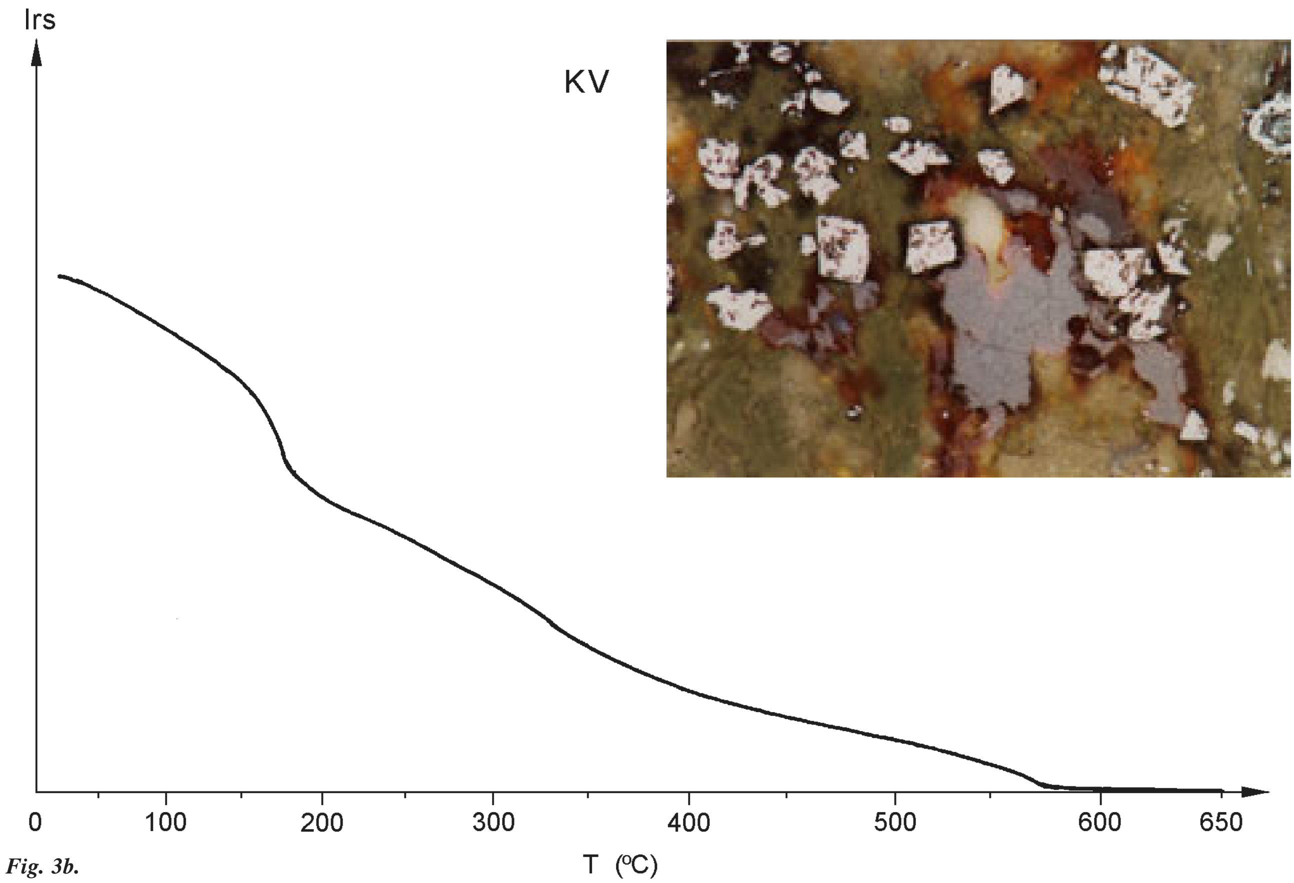
Irs
KV
0
100
200
300
400
500
600
650
T (ºC)

Fig. 3b.

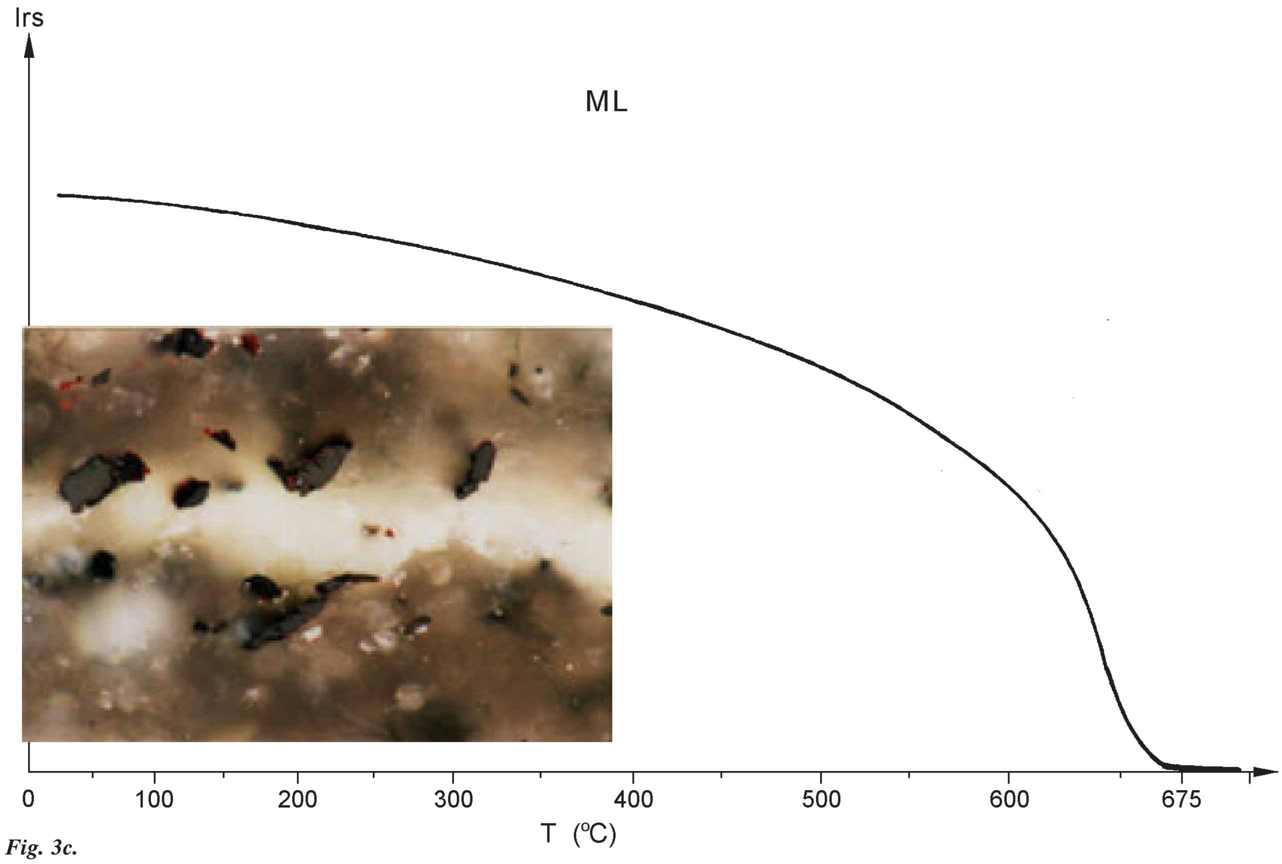

Fig. 3c.

Fig. 3. Results of the thermomagnetic analysis along with corresponding polished sections. a — specimen from KV containing magnetite ×500 and hematite lamelae and post-pyrite + hydro-Fe-oxydes ×200, b — specimen from KV containing goethite, c — specimen from Mlynky containing hematite ×500. Irs — isothermal remanence acquired in the field of 1 T.

creases considerably after heating to 450 °C; at this temperature pyrite transforms into pyrrhotite.

Paleomagnetic results and discussion

The pilot specimens were demagnetized thermally and with an alternating field (AF). As the thermal demagnetization was much more effective than the AF, the bulk of the collection was demagnetized thermally (to temperatures 500 –675 °C) and results of this procedure were taken for interpretation. The isolation of the characteristic (CHRM) components of the NRM was performed by the program package of Lewandowski et al. (1997) based on the principal component analysis of Kirschvink (1980). The previous section shows that the studied rocks have various lithologies, are highly metamorphosed and contain inhomogeneously distributed and varied magnetic minerals of secondary origin occurring in various forms. Hence, the demagnetization curves are complicated and difficult to resolve. Nevertheless, we were able to isolate the CHRM in six localities in sufficient amount of specimens for mean directions to be calculated for each of them. The analysis of the demagetization results of majority of specimens reveals the presence of more than one component of the NRM. We tried to find among them the components with relatively high unblocking temperatures (Tub) appropriate to the magnetic mineralogy of specimens ignoring the components appearing in temperatures lower than 200 °C. The mean directions in situ and after tectonic correction together with the parameters of the Fisher's statistics are summarized in Table 2.

Localities situated along the KMSZ shear zone:

Črmeľ (Č) — intensity of the NRM ranges from 0.7 to 3.5 mA/m. There is no data for this locality because we were not been able to isolate any characteristic component of the NRM.

Vyšný Klátov (KV) — intensity of the NRM is in the range 12–300 mA/m. The CHRM found in 7 specimens from 6 hand samples in the Tub range of 475 to 575 °C is carried by magnetite. An example of demagnetization results is shown in Fig. 4a.

Jahodná (J) — intensity of the NRM ranging from 0.1 to 0.6 mA/m is carried by hematite grains of various generations. The thermal treatment does not demagnetize it fully, beacuse the remanence remaining after annealing in 550–600 °C becomes unstable — it changes in intensity and direction during the measurement procedure. Nevertheless we

Table 2: Directions of the characteristic CHRM component for the Gemerides. Geographic position: 20.5°E, 48°N. Reference data after Besse & Courtillot (1991) for Middle Miocene D = 6, I = 62.

Loc.	N N/n	D/I *In situ*	D/I f.cor.	D/I p.cor.	α_{95}	k	plat	pol	ΔD=Do–Dref
KMSZ									
KV	6/7	**313/-60**	-	-	13	21	41	R	127 CW
J	3/6	**190/-65**	-	-	18	18	47	R	92 CCW
MA	3/5	**275/65**	-	-	20	16	47	N	4 CW
DSZ									
DO	9/12	320/51	265/66	**303/61 45%**	13	11	42	N	63 CCW
ML	5/8	68/70	342/30	**2/61 45%**	9	42	42	N	4 CCW
Outside main shearing zones									
GP	5/8	109/72	13/46	**25/62 65%**	6	98	43	N	17 CW

Loc. — locality; N/n — number of hand samples in which this CHRM was found/number of specimens taken for calculations; D/I *in situ* — declination/inclination before tectonic correction; D/I corrected — declination/inclination after correction; f.cor. — full correction; p.cor. — partial correction; 45% (65%) untilt. — 45% (65%) untilting; α_{95}, k — parameters of Fisher's statistics; plat — paleolatitude; pol — polarity of CHRM; CW — clockwise; CCW — counterclockwise; Do — declination obtained in this study; Dref — reference declination; R — angle of local rotation. KMSZ — Košice-Margecany shearing zone; DSZ — Dobšiná shearing zone. The directions taken for interpretation are in bold letters.

isolated the CHRM in 6 specimens from 3 hand samples in the Tub range of 250–450 °C. An example of demagnetization result is shown in Fig. 4b.

Margecany (MA) — intensity of the NRM in schists is 27-300 mA/m and about 0.2 mA/m in sandstones. The demagnetization results indicate that the NRM is carried mainly by magnetite, small components carried by goethite demagnetize very quickly. The directions of the CHRM isolated in specimens from both lithologies have normal and reversed directions and are highly scattered. Only in five specimens (from 1 sandstone and 2 schists samples) we were able to isolate the group of similar CHRM directions. Its Tub did not exceed 400 °C. Fig. 4c presents an example of the demagnetization results.

Localities situated along the DSZ schear zone:

Dobšiná (DO) — intensities of the NRM range from 0.2 to 3 mA/m. The remanence is carrried mainly by magnetite and hematite present in various ratios. Fig. 4d shows an example of the demagnetizing curve for specimen with predominance of magnetite, the NRM for specimens with hematite predominance did not demagnetize during the thermal treatment but became unstable after the heating to 600 °C. The CHRM was isolated in 12 specimens from 9 hand samples in Tub of 575 °C (only in one specimen this component had Tub of about 200 °C).

Mlynky (ML) — intensity of the NRM ranges from 0.8 to 40 mA/m. The NRM is carried by magnetite and hematite of various generations. In some specimens remanence, after heating to 600 °C became unstable. The CHRM was isolated in 8 specimens from 5 hand samples in Tub ranges 500–550 °C or 625–675 °C. An example of the demagnetization results for specimen with NRM carried by hematite is shown in Fig. 4e.

Locality situated outside main shear zones:

Gemerská Poloma (GP) — intensities of the NRM range from 0.1 to 0.4 mA/m. The natural remanence demagnetized completely or in great percent in the temperatures 300–350 °C (see Fig. 4f) indicating that it is carried mainly by pyrrhotite. As this mineral was identified neither by the microscopic analysis nor by the thermomagnetic analysis we suppose that it appears as very fine (submicroscopic) grains, probably due to alterations of pyrite which is present here in abundance. In temperatures exceeding 400 °C the remanence increases very quickly. The CHRM was isolated in 8 specimens from 5 samples in the Tub range of 300–350 °C.

The plot of the mean directions obtained for investigated localities in situ are presented in Fig. 5a. This plot and the data in Table 2 show that the in situ directions for KV, J and MA differ in declinations, but their inclinations are similar to each other. Lack of bedding parameters enables tectonic correction of them, but the similarity of inclinations suggests the post-folding origin of the CHRM and mutual rotations of the blocks represented by the exposures. The mean directions obtained for the three remaining localities differ in declinations and inclinations from each other both in situ and after full correction and differ from the in situ directions of the KV, J and MA (Table 2, Fig. 5b). In order to see whether part untilting of the DO, ML and GP will move their inclinations closer to the other three we performed the inclination-only fold test of Enkin (1994), Enkin & Watson (1996). This test is used for finding the degree of untilting that gives minimum dispersion of inclinations. This degree is indicated by the maximum of the plot of the Fisher's precision parameter k versus degree of untilting. In this way we may answer the question of whether the remanence studied is pre-tilting, post-tilting or was aquired at some intermediate stage. The result of this test performed for the directions of all six localities shows that the best fit would be obtained by 50% untilting of the DO, ML and GP, the value of k attains here maximum of 221. Another trial performed for 45% untilting of DO nad ML and 65% of untilting of the GP gave better estimate: the maximum of k increased to 572 — Fig. 6. The results of this test for all six exposures combined are presented in Fig. 5c. The mean directions calculated for the

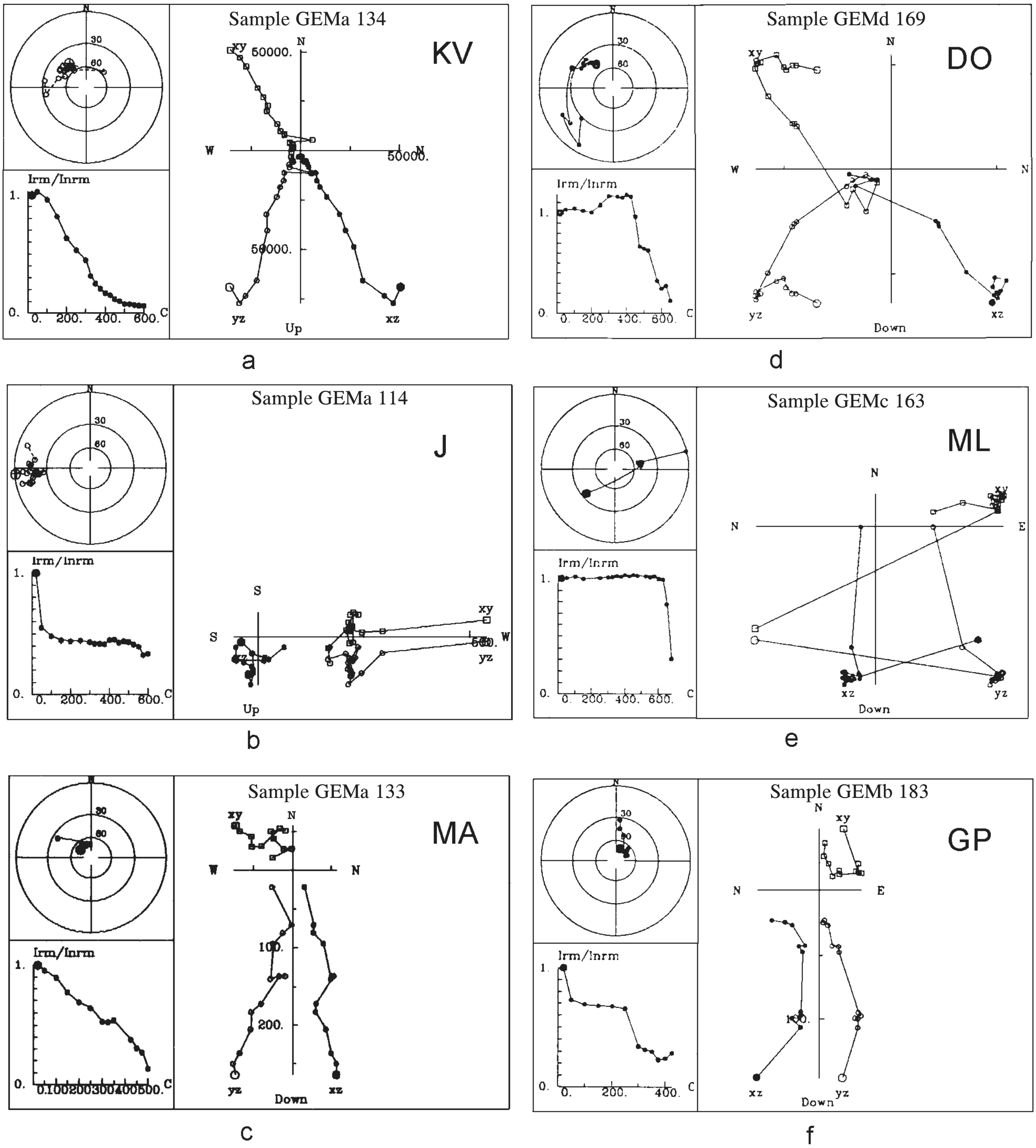

Fig. 4a-f. Examples of the thermal demagnetization experiments. (The names of localities in abbreviated form are assigned to respective figures).

appropriate unfolding ratios are summarized in Table 2 and shown in Fig. 5c together with the in situ directions of the KV, J and MA. Their inclinations remain in the narrow range of 60–65° but declinations differ considerably. We believe that each locality is situated within an individual small tectonic block and explain the differences in declinations as result of local rotations of the blocks connected with the shearing zones.

The inclinations obtained here are close to the inclinations calculated for the Gemeric Superunit for the Middle Miocene (10–20 Ma) after the European reference data of Besse & Courtillot (1991): D_{ref} =6, I_{ref} = 62. The observed differences between the final declinations Do and the Dref reflect the amount and sense of local rotations of blocks that took place after their remagnetization. Angles and sense of rotations are summarized in the respective column in Table 2 as $\Delta D = D_o - D_{ref}$.

The presented results show that according to paleomagnetic data blocks situated along the dextral KMSZ zone (KV and J) rotated clockwise, the block represented by MA situated at the crossing of KMSZ (dextral) and TGSZ (sinistral) zones rotated counterclockwise as well as those situated along the sinis-

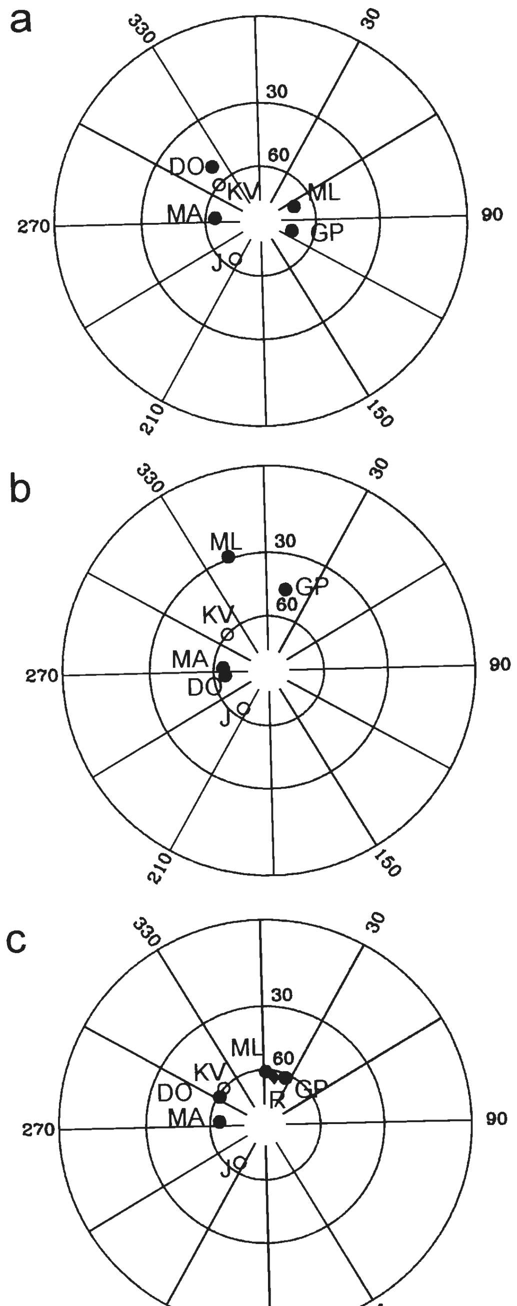

Fig. 5. Mean directions of the characteristic component of remanence (CHRM) isolated in HT range in studied localities. **a** — in situ, **b** — KV, J, MA — in situ, DO, ML, GP — after full tectonic correction, **c** — the best fit: KV, J, MA — in situ , DO and ML — after 45% untilting, GP — after 65% untilting. Diamond R denotes the reference field.

tral DSZ (DO, ML) zone. The block represented by GP situated within the unit rotated clockwise. The senses of rotations agree with character of respective shearing zones.

The first paleomagnetic research in the area of the Gemeric Superunit was performed by Hanuš & Krs (1963). They studied problems of hydrothermal mineralization on metasomatic sideritic deposits in the region of Dobšiná, Mlynky, Rožňava and others, and metasomatic magnesitic deposits in

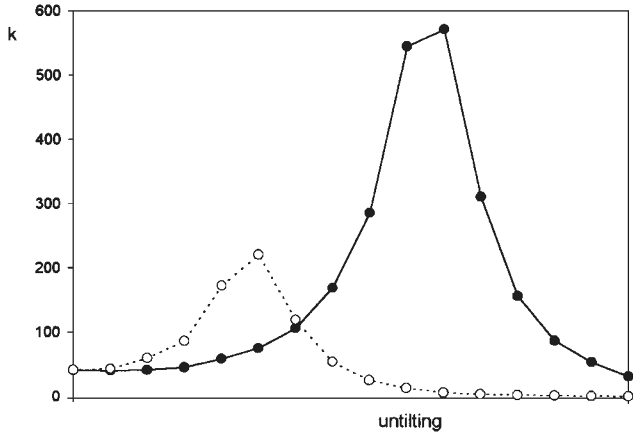

Fig. 6. The results of the inclination-only test, Enkin (1994) for KV, J, MA in situ , DO, ML, GP — after 50% untilting (open symbols) and KV, J, MA in situ, DO and MA — after 45% untilting, GP — after 65% untilting (full symbols). k — Fisher's precision parameter.

Bankov nearby Košice. On the basis of the study performed on undemagnetized rocks containing hematite they concluded, that there were no rotations in the region of the post-dating mineralization study. The interesting thing is, that their mean paleomagnetic direction in situ of undemagnetized NRM specimens sampled in the siderite vein-filling in the mine in Mlynky (D = 77°, I = 56°, α_{95} = 13°) is very close to the Mlynky in situ result of the present paper for which the CCW rotation is very small. The same is true for their result from the magnesite at Bankov near Košice (D = 198°, I = –70°, α_{95} = 4°40') and Jahodná of the present study — both results suggest the CW rotation (29° in Jahodná and 12° in Bankov).

The timing of events suggested by paleomagnetic study seems to be as follows: the Middle Miocene remagnetization of rocks — postfolding along the KMSZ zone, synfolding along the DSZ zone and in the GP locality. The magnetization in GP seems to be acquired during a stage of folding later than that along the DSZ. The presence of both normal and reversed polarity remanences suggests, that remagnetization processes were not synchroneous, but took place in the Gemeric Superunit during respective periods of reversed and normal polarity. The time span of remagnetization episodes is limited by the tectonic events that took place in the Gemeric Superunit to the period between the end of regional rotation (Karpatian–Badenian according to Márton et al. 1995 and Márton & Márton 1996) and extinction of activity along the shear zones (the Styrian phase, end of the Middle Miocene). Taking these constraints into account we believe that remagnetization processes took place during the time span between anomalies 6 (20 Ma) and 5 (10 Ma), when, according to the geomagnetic polarity time scale of Merril et al. (1996), the polarity of the geomagnetic field changed many times.

AMS study

The measurements of the anisotropy of magnetic susceptibility show that in all studied localities the values of the anisotropy parameter remain in a broad range (Table 3). The directions of the maximum and minimum anisotropy ellipsoid cluster reasonably well everywhere with the exception of the GP. The mean directions of Kmax and Kmin axes in situ and that of tectonic lineations L and foliations S (Návesňák 1993) corresponding to the magnetic anisotropy directions in respective localities are summarized in Table 3. Fig. 7 presents mean directions of Kmax and Kmin and the magnetic foliation planes together with the corresponding tectonic lineations and foliation planes. In the localities from the KMSZ zone there are no correlations of the magnetic and tectonic lineations, with the exception of MA where the Kmax direction is close to the L3. The magnetic foliation (Kmin) corresponds to the tectonic (mylonitic) foliation S4 in three localities from the KMSZ zone (C, J, MA) whereas in the KV which is perhaps situated within an independent tectonic unit (see chapter Geological setting and sampling) the magnetic foliation does not correspond to any tectonic one. The situation in MA suggests, that magnetic fabric reflects both shearing systems: East-Carpathian through magnetic foliation and West-Carpathian through magnetic lineation. In the DSZ zone the situation is different: in the chlorite schists of DO magnetic foliation corresponds with the S2 and the magnetic lineation with the L2 , whereas in the phyllites of the ML — with S3 and L3 systems, respectively. Systems L2, S2 are related to the TGSZ zone, systems S3, L3 — to the LSSZ zone, both belonging to the same West-Carpathian system. Figure 8 summarizes the magnetic foliation planes (with the exception of the result for KV) and the tectonic foliation planes. The presented pattern shows distinct relations between the magnetic foliation in localities from the KMSZ zone and the tectonic foliation S4 associated with this zone (East-Carpathian shearing system). Magnetic foliations in localities from the DSZ zone are close to both tectonic foliations linked with the West-Carpathian shearing system proving that the magnetic anisotropy originated due to the Alpine deformations. The rotations suggested by the paleomagnetic research (see chapter Paleomagnetic results and discussion) agree with the sense of shearing.

Table 3: The characteristics of the anisotropy of magnetic susceptibility together with the corresponding directions of the tectonic lineation L and the foliation planes S after Návesňák (1993).

Locality	Kmax *in situ*	Kmin *in situ*	P'	L	S
KMSZ					
Č	257/53	38/29	1.08–1.17	-	S4
KV	354/70	250/7	1.04–1.21	-	-
J	196/46	32/23	1.03–1.10	-	S4
MA	295/9	45/57	1.10–1.28	L3	S4
DSZ					
DO	66/24	320/31	1.06 – 1.13	L2	S2
ML	258/22	135/51	1.03 – 1.6	L3	S3
Outside Main Shearing Zones					
GP	scattered results		1.03 – 1.10	-	-

P' — anisotropy parameter, for formulas see text; L — mineral lineation; S — mineral foliation; KMSZ — Košice-Margecany shearing zone; DSZ — Dobšiná shearing zone.

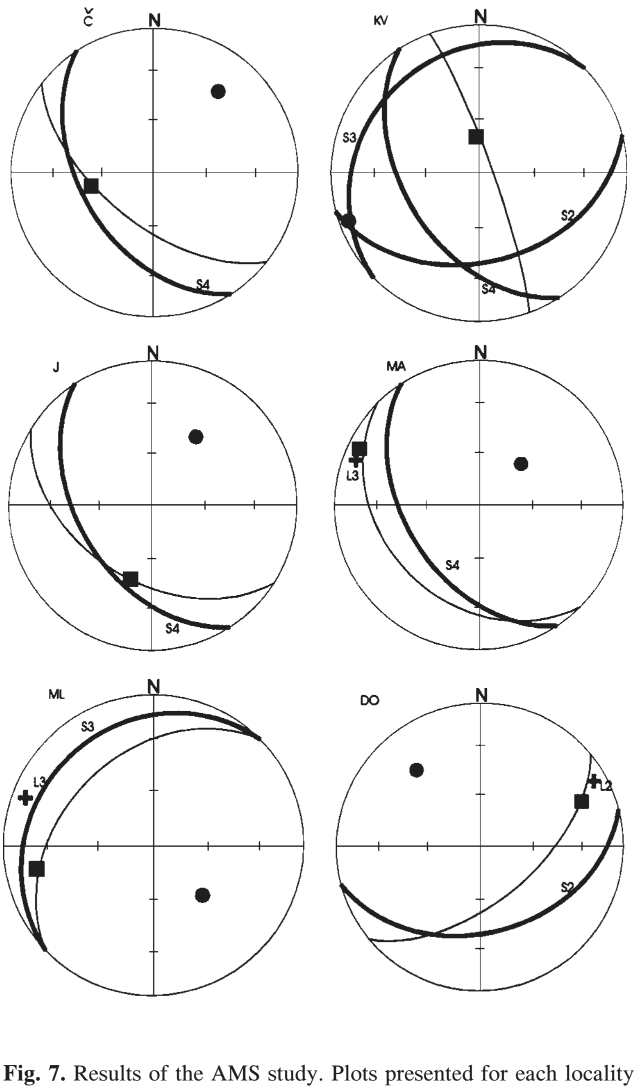

Fig. 7. Results of the AMS study. Plots presented for each locality show mean direction of the magnetic lineation Kmax (**solid square**), mean direction of Kmin (**solid circle**), magnetic foliation plane (**thin line**), direction of tectonic lineation fitting best magnetic lineation (**cross**), tectonic foliation plane fitting best magnetic foliation (**bold line**). Appropriate labels denoting the tectonic lineations and foliations systems are also included. Abbreviations denoting the localities are the same as in Fig. 3.

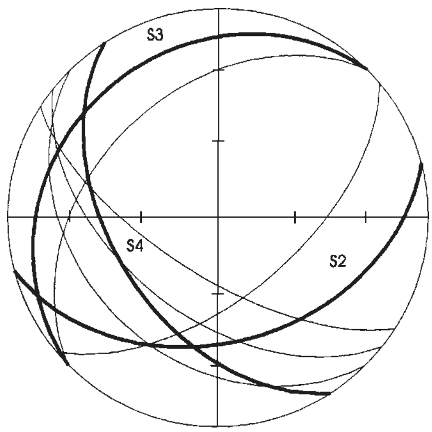

Fig. 8. Plot of the magnetic foliation planes obtained in this study with the exception of KV together with the corresponding tectonic foliation planes.

Conclusions

1 — The NRM of the studied rocks is carried by secondary magnetic minerals and represents secondary overprinting.

2 — The presence of reversed polarity of CHRM in KV and J and normal polarity in remaining localities indicates that remagnetization was not synchronous.

3 — In the localities situated along the KMSZ zone the remagnetization took place after folding, in the localities situated along the DSZ zone and within the unit — during folding.

4 — All the studied Paleozoic metamorphic rocks of the Gemeric Superunit became remagnetized during the Middle Miocene probably between anomaly 6 (20 Ma) and anomaly 5 (10 Ma).

5 — After the remagnetization episodes the particular tectonic blocks became rotated due to the activity of the shearing systems, blocks lying close to the dextral KMSZ zone rotated clockwise (with the exception of MA that was influenced by both systems), blocks lying close to the sinistral DSZ zone rotated counterclockwise.

6 — The AMS originated due to the activity of the shearing zones, the magnetic fabric agrees with the tectonic fabric: S4 fits the magnetic foliation in the KMSZ localities, S2 and S3 fit the magnetic foliation in the DSZ localities.

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MULTIPLE SOURCES OF THE WEST-CARPATHIAN VARISCAN GRANITOIDS: A REVIEW OF Rb/Sr AND Sm/Nd DATA

IGOR PETRÍK

Geological Institute, Slovak Academy of Sciences, Dúbravská 9, 842 26 Bratislava, Slovak Republic; geolpetr@savba.savba.sk

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Abstract: Detailed reviewing of several existing Rb/Sr datings from the West-Carpathian granitic massifs shows that the Rb/Sr dates older than U/Pb zircon data are possibly caused by inclusion of high Rb/Sr samples in the sample collections. Such samples, usually occurring as leucocratic veins in metamorphic complexes, usually have higher initial $^{87}Sr/^{86}Sr$ ratios which results in generating pseudo-isochrons. Therefore, there is no need for an initial mixing line as suggested earlier. Some samples outlying both above and below isochrons may be interpreted in terms of system opening at a time different from the initial closure. Depending on reconstructed Rb/Sr ratios late Variscan to Early Alpine ages are obtained for the opening. In contrast to Rb/Sr, previously published Sm/Nd data show that the initial $^{143}Nd/^{144}Nd$ ratios were not homogenized making it possible to suggest end-members responsible for the observed variation. Such end-members are sought in (1) the peraluminous (leuco)granites that originated through dehydration melting of gneisses with fairly high I_{Sr} and (2) gabbro/dioritic rocks occurring within granite massifs or as mafic enclaves. Assimilation of supracrustal rocks by the mafic magma could have produced either sub- to metaluminous I-type granitoids or peraluminous S-type granites depending on proportions of the end-members. The varying proportions may also have been responsible for the mineralogical and petrological differences observed between the two groups. Seven different sources are suggested for all the Variscan granitoids in the Western Carpathians.

Key words: Western Carpathians, open system, source rock, end-member, granitoids, leucogranite, diorite, assimilation, Rb/Sr, Sm/Nd, pseudoisochron.

Introduction

The problem of the source rocks of the West-Carpathian Variscan granitoids (Fig. 1) has been addressed several times mainly on isotopic grounds discussing the possible role of a mantle component. Less frequently, the probable protolith was characterized by petrological considerations. While early researchers preferred a metasedimentary source and palingenetic origin of granitoids (Cambel 1980; Hovorka 1980), later, mainly due to accumulating Rb/Sr data, the role of „mantle component“ has been increasingly emphasized (Cambel & Petrík 1982; Kráľ 1994). The recognition of S-, I- and A-type features borne by these granitoids enabled different source lithologies to be assumed (Cambel & Vilinovič 1987; Petrík et al. 1994; Uher & Broska 1996; Petrík & Kohút 1997).

Recently, the existing body of Rb/Sr data was complemented by new Sm/Nd determinations (Kohút et al. 1999). The authors found in contrast to the Rb/Sr system, that the Sm/Nd system was not homogenized and samples do not generate isochrons. To explain the heterogeneity in $^{143}Nd/^{144}Nd$ ratios they also invoked processes of contamination and/or magma mixing. Based on depleted mantle Nd model ages, the role of a Middle Proterozoic component recycling was stressed (l.c.).

All the isotopic data clearly preclude a single source for the West-Carpathian granitoids. Although this was concluded by all authors, the lithological character of possible precursors was mentioned only in a general way, mainly in the isotopic context. The aim of the present work is to confront the available data with actual, granite-related rocks found in outcrops, and to suggest probable protoliths.

Geological setting

The West-Carpathian Variscan granitoids comprise considerable parts of the Variscan crystalline terranes imbricated in the Alpine structural edifice (Fig. 1). The edifice was formed by contraction of the Variscan continental crust disintegrated by Early Jurassic rifting and Early Cretaceous extension. Three main megaunits were thrust one over another during the Late Cretaceous: the Tatric Superunit, Veporic Superunit and Gemeric Superunit (Plašienka et al. 1997). The bulk of granitoids were emplaced during the Carboniferous (350–300 Ma B.P.) when they intruded the thickened Early Paleozoic basement, and after initial uplift and erosion in the Early Triassic, they were submerged and remained buried until the Tertiary. Then, in the Paleogene, first the Vepor pluton was exhumed along normal faults, followed in the Neogene by Tatric plutons (Kováč et al. 1994) to form the characteristic present day core-and-cover structure. The granitoids in the Tatric Superunit crop out in eleven “core” mountains. In the Veporic Superunit the largest and most complex Vepor pluton has been uncovered. All the Tatric and Veporic granitoid plutons intruded high-grade metamorphic rocks: migmatites, gneisses and amphibolites. By contrast, in the Gemeric Superunit small bodies of Permian Gemeric granites intruded low

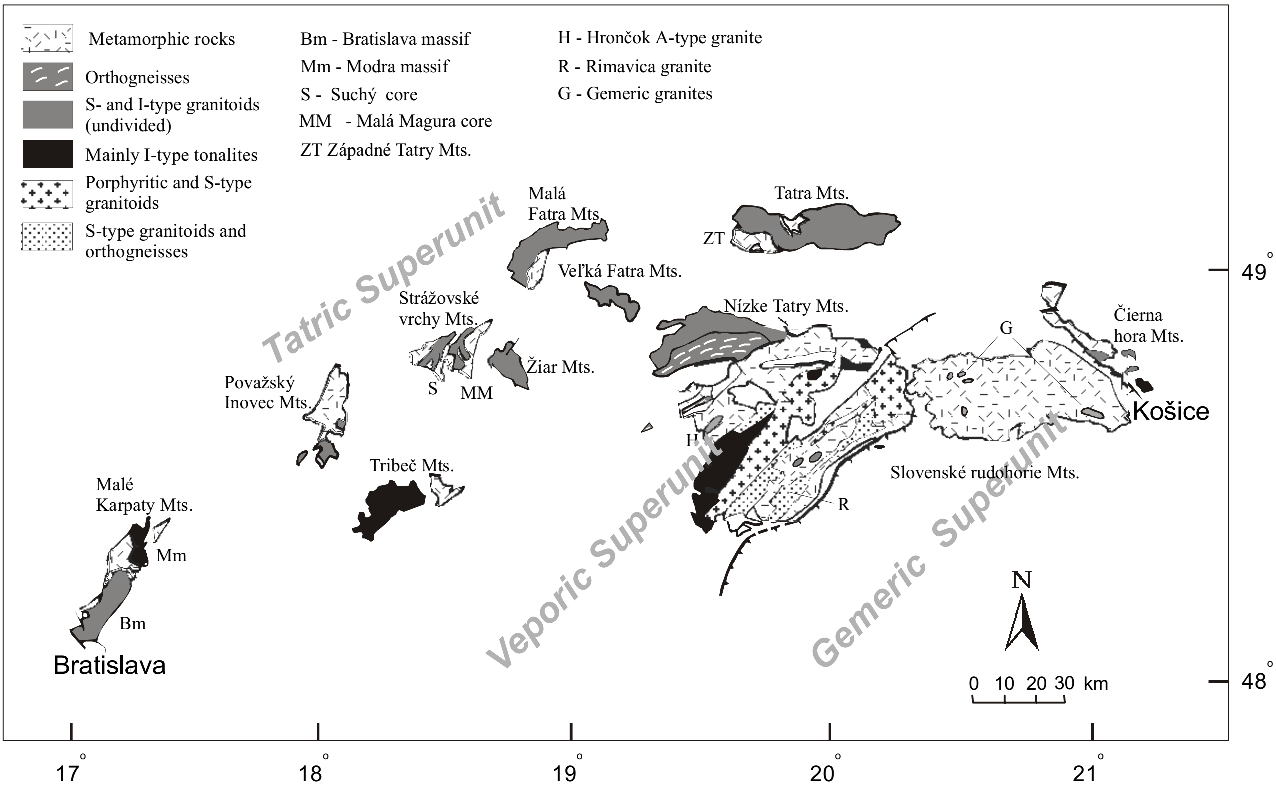

Fig. 1. Crystalline basement outcrops in the Western Carpathians showing main granitoid types and mountain ranges.

grade metapelites and now occur in the form of tectonic slices. While Tatric granitoids bear mostly primary, Variscan features, the Veporic and Gemeric granitoids are often sheared and strongly reworked due to the Alpine burial resetting their K/Ar and $^{40}Ar/^{39}Ar$ ages (Dallmayer et al. 1996; Kováčik et al. 1996).

The isotopic evidence

A major part of the granitoids with a peraluminous, commonly leucocratic, character and a more or less obvious relationship to metasedimentary wall rocks (migmatite belts, paragneiss xenoliths) was included in the S-type group. Some of them have slightly increased initial Sr isotope ratios (Rimavica Granite in the Veporic Superunit or Malé Karpaty granitoids), or very high ratios (Kralička Granite of the Nízke Tatry Mts., Gemeric granites), while others do not (Strážovské vrchy or Vysoké Tatry Mts.), Table 1. A minor part of the biotite-rich granitoids (granodiorites and tonalites), showing sub- to metaluminous natures, and scattered mafic microgranular enclaves (MME) form the I-type group. They mostly have low Sr initial ratios around 0.705 (Tribeč Mts., Sihla tonalite) however, a significant exception is represented by the Prašivá/Ďumbier granodiorite of the Nízke Tatry Mts. with $I_{Sr} = 0.7078$, Table 1. The A-type group represented by the Hrončok Granite also shows a high I_{Sr} (0.7114). Based on detailed discussion of the Rb/Sr data, Kráľ (1994) distinguished two groups of granitoids with $I_{Sr} > 0.707$ and = 0.706 (approximating the S- and I-type group) and suggested wall rock assimilation to explain the higher I_{Sr} values.

Rb/Sr systematics

The accumulated Rb/Sr whole rock and U/Pb zircon data showed that a discordancy exists between them, the former giving higher dates. Kráľ (1994) and Petrík et al. (1994) discussed the discordancy, speculated about a possible lack of homogenization and postulated an inherited $^{87}Sr/^{86}Sr$ mixing line of the source rock. If so, the Rb/Sr data should help to identify possible end-members. However, a closer inspection of several published Rb/Sr data sets shows that at least some of the published dates are based on pseudoisochrons constructed using unrelated or altered rocks. [All the following age calculations were performed by Isoplot (Ludwig 1994), using the errors given by authors, and results are at 95% probability level (2σ), see Table 1].

Strážovské vrchy Mts. (Suchý granitic core)

The original Rb/Sr age (Kráľ et al. 1987, recalculated as 392 ± 17 Ma, Table 1), based on four selected samples (SR-3, 4, 5, 6), exceeds the zircon age (356 ± 9 Ma, Kráľ et al. 1997) by 36 Ma. The original slope is rather steep owing to the exclusion of a low Sr sample SR-2, and accepting a high Rb/Sr sample SR-6 (Fig. 2A). The latter sample is a leucocratic sill (one of several) alternating with paragneisses in the Suchý core. The sills occur within a gneiss belt 500 m wide steeply dipping into the main granitic body and showing no transition to it. The sample was included because of its high Rb/Sr ratio, being considered a leucocratic off-spring of the main body. A view that such aplitic leucocratic veins are products of the dehydration melting of the metapelitic

Table 1: Rb/Sr isochron ages of selected West-Carpathian granite cores recalculated at 95% probability level (Isoplot & Ludwig 1994). *Notes:* Errors are those given by authors ($^{87}Rb/^{86}Sr$, $^{87}Sr/^{86}Sr$): 2 %, 0.02 % (1σ) by Bagdasaryan, Cambel and co-workers; 0.25 %, 0.005 % (1σ) by Kráľ and co-workers; 1%, 0.03% (2σ) by Kohút and co-workers. For samples with MSWD>1 also magnified errors 2σ*√MSWD are given. n^{1-16} refer to the following samples: n^1 — SR-3A, 3B, 4, 5, 6; n^2— as for n^1 with SR-2, without SR-6; n^3— T-18, 50, 25, 87, 27; n^4— as for n^3 without T-27; n^5— T-22, 36, 37, 62, 63, 70; n^6: as for n^5 without T-37; n^7— ZK-14, 24, 92, 117, 120, J-3, 5, 16; n^8— ZK-68, Kr-1, 2, 3, 2/83, 3/83; n^9— as for n^8 with ZK-3; n^{10}— VF-356, 135, 639, 612, 695, 40, 43, 45, 385, 229, VFMa-1, 2a, 2b, 3, 4, 6; n^{11} as for n^{10} without VFMa-1, 2a, 2b, 6; n^{12}— ZK-28, 118, 121, 83, 57, 58; n^{13}— as for n^{12} without ZK-58 with ZK-76, 66, 9; n^{14}— ZK-26, 27, 69, 122; n^{15}— ZK-72, 67, 56, 19, KV-1, 2, 3, 4; n^{16}— as for n^{15} without KV-2 and with D-1, 2, 3.

Massif Granite type	Age (Ma) ±2σ	MSWD ±2σ √MSWD	Isr	Age (Ma) ±2σ	MSWD ±2σ √MSWD	Isr
Tatric massifs	**isochron variant**			**isochron variant**		
Suchý Mts.	n^1= 5 392 ± 17	13.5 392 ± 62	0.70596 ± 0.00027	n^2= 5 353 ± 34	19.4 353±150	0.70616 ± 0.00037
Tribeč Mts. Monazite series	n^3= 5 337 ± 33	4.94 337 ± 73	0.70594 ± 0.00079	n^4= 4 349 ± 12	0.55	0.70586 ± 0.00023
Tribeč Mts. Allanite series	n^5= 6 432 ± 69	2.06 432 ± 99	0.70522 ± 0.00046	n^6= 5 305 ± 125	1.39 305±147	0.70579 ± 0.00059
Nízke Tatry Mts. Kralička type	n^8= 6 361 ± 40	0.305	0.71601 ± 0.00144	n^9= 7 361 ± 40	0.307	0.71596 ± 0.00143
Veľká Fatra Mts.	n^{10}= 16 359 ± 47	53.6 359 ± 344	0.70631 ± 0.00069	n^{11}= 12 422 ± 77	34.9 422±455	0.70570 ± 0.00087
Nízke Tatry Mts. Ďumbier & Prašivá	n^7= 8 369 ± 122	0.115	0.70782 ± 0.00135			
Veporic massifs	**isochron variant**			**isochron variant**		
Sihla type	n^{12}= 6 373 ± 163	0.129	0.70537 ± 0.00101	n^{13}= 8 298 ± 79	0.056	0.70563 ± 0.00078
Rimavica type	n^{15}= 8 393 ± 24	0.48	0.70771 ± 0.00071	n^{16}= 10 385 ± 47	0.55	0.70766 ± 0.00087
Hrončok type	n^{14}= 4 247 ± 8	0.952	0.71140 ± 0.00099			

source (paragneisses) rather than late differentiates of the main body is now considered more probable. The SR-2 sample with no signs of postmagmatic alteration or contamination was reconsidered and included into a new set. The new arrray including five samples gives 353 ± 34 Ma, a value concordant with the zircon dating, although with larger error and MSWD = 19.4 (Table 1).

Rb and Sr mobility. For one of the originally excluded samples (SR-1) Kráľ et al. (1987) suggested a possible Rb mobility. The sample with the lowest Rb (40 ppm, compared to the typical range of 70–100 ppm) contains abundant late sillimanite (3.5 vol. %) accompanied by minor muscovite (3.7 %). Various sillimanite-bearing granitoids were found along a belt at least 5 km long containing up to 7 % sillimanite and 6 % muscovite. The assemblage is thought to have formed at a high-temperature subsolidus stage in a low pH environment (acid leaching, Korikovsky et al. 1987; Burnham 1979). The decrease of the Rb/Sr ratio at a time significantly different from that of the initial system closure may result in an outlying position of the altered sample — above the isochron, and vice versa. The distance from the isochron (defined by non-altered samples) will be proportional to the Rb/Sr decrease and the time elapsed since the initial closure (i.e. the greater and younger the Rb escape, the greater the deviation). Provided that we are able to reconstruct the original Rb/Sr ratio, the time elapsed between the initial closure and system opening can be calculated [see Fig. A1 and equations (A1, A2) in Appendix].

Hradetzky & Lippolt (1993) discussed in detail the Rb/Sr system and concluded that in superficial conditions it is the Sr mobility which causes the system opening. The example of Suchý sillimanite granitoids suggests that in high-temperature, acid hydrothermal solutions, Rb may become more mobile than Sr. Marquer & Peuqat (1994) found that in granites deformed in ductile shear zones the Rb/Sr ratio increases in greenschist facies and decreases in amphibolite facies conditions. Moreover, the greenschist facies mylonites fall below and the amphibolite facies mylonites above the intrusive Rb/Sr isochron.

In the given example, the Rb/Sr values prior to alteration were derived assuming various degrees of the Rb escape (Table 2). For the Suchý sillimanite granitoids, t_1 = 51–102 Ma and t_c = 302 – 251 Ma [eq. (A1), (A2), Appendix], assuming the intrusive age of 353 Ma (Table 2).

It is realized that the derived ages depend on the method of Rb and Sr reconstructions (by inspection of outliers in variations diagrams, Fig. 2B,C,D) and are based on one sample. Therefore, special research is needed to confirm the open system interpretation of anomalous areas in granitic massifs. However, if real, the obtained Permian age data would coincide with the Permian to Lower Triassic post-collisional transtension and rifting in the West-Carpathian basement. Increased heat flow could have initiated circulation of high temperature fluids along weakened zones of the northern Tatra basement complex (Tatra — Fatra Belt, Plašienka et al. 1997). A parallel, much more pronounced process, is recorded in the southern Vepor Belt where significant Permian to Lower Triassic magmatism and volcanism occurred (Uher & Broska 1996; Kotov et al. 1996; Putiš et al 2000). Two additional cases are shown below where outliers below the isochron correlate well with apparent Rb/Sr increases (Table 2).

Tribeč Mts.

The Tribeč tonalites dated by the Rb/Sr method (Bagdasaryan et al. 1990) yielded 362 ± 27 Ma (recalculated at

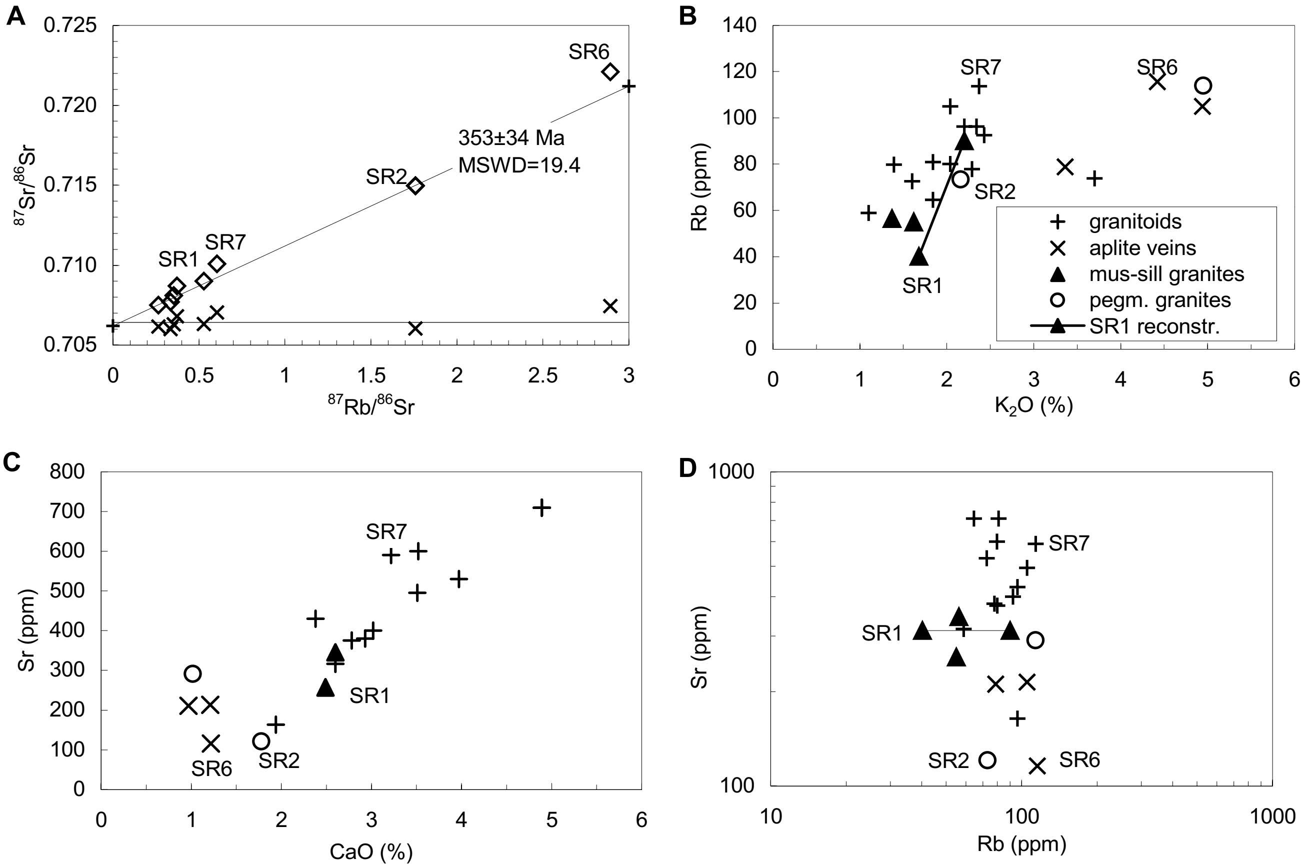

Fig. 2. Rb/Sr system in the Suchý granitoid core: (**A**) Isochron with outlying samples SR-1, 6, 7. $^{87}Sr/^{86}Sr_{(350)}$ ratios of the samples are also shown; (**B, C, D**) Correlations between Rb, Sr, K_2O and CaO. Reconstructed SR-1 position (90 ppm Rb) is shown in B, D.

Table 2: Calculations of the age of system opening using the examples of the Suchý, Veľká Fatra and Tribeč granitoids using equations (A1, A2). See Appendix for details.

Massif Sample	Intrusive age (Ma)	I_{Sr}	Rb ppm Measured	Sr ppm Measured	Rb ppm Reconstructed	Sr ppm Reconstructed	$^{87}Sr/^{86}Sr$ Measured S_m	$^{87}Sr/^{86}Sr$ Recon. S_r	$^{87}Rb/^{86}Sr$ Measured R_m	$^{87}Rb/^{86}Sr$ Recon. R_r	Age (Ma) t_c
Suchý	353	0.70616	40.22	312.2	90	312.2	0.7087	0.70803	0.3728	0.8341	251
SR-1					140					1.2976	302
Veľká Fatra	340	0.70649	99.77	148	99.77	200	0.71512	0.71594	1.9518	1.4443	227
VFMa-2	350							0.71622			198
Tribeč	350	0.70586	153.71	60.45	153.71	100	0.7391	0.74263	7.3795	4.4610	265
T-27						200				2.2304	302

2σ) contrasting with the U/Pb age of 306 ± 10 Ma (Broska et al. 1990). After subdividing the sample set according to criteria based on the allanite and monazite dichotomy (Broska & Gregor 1992; Petrík & Broska 1994) broadly corresponding to I- and S-type subgroups, respectively, two slopes are obtained in the Nicolaysen diagram. The monazite-bearing group yields 337 Ma ± 33 Ma with one outlying sample T-27 (a leucocratic vein) below the isochron (Fig. 3A). This sample has a significantly decreased Sr content (60 ppm, compared to the observed range of 600–70 ppm) allowing us to presume that the original Rb/Sr was lower (Table 1). Using equations (A1, A2) for the age of system opening the values of 265–302 Ma are obtained for estimated Sr 100 and 200 ppm (Table 2). Excluding this sample from the monazite group improves the isochron statistics to 349 ± 12 Ma and MSWD = 0.55 (Table 1).

The allanite-bearing group with very low Rb/Sr ratios yields 432 ± 69 Ma with one sample T-37 (leucocratic vein) steepening the slope. Unfortunately, in the absence of chemical data for this sample there is no possibility to evaluate its chemistry. Again, the main granitoid body supplies only tonalites with low, tightly grouped Rb/Sr ratios which produce isochrons with very high errors. For example, excluding T-37 would give 305 ± 125 Ma (Table 1).

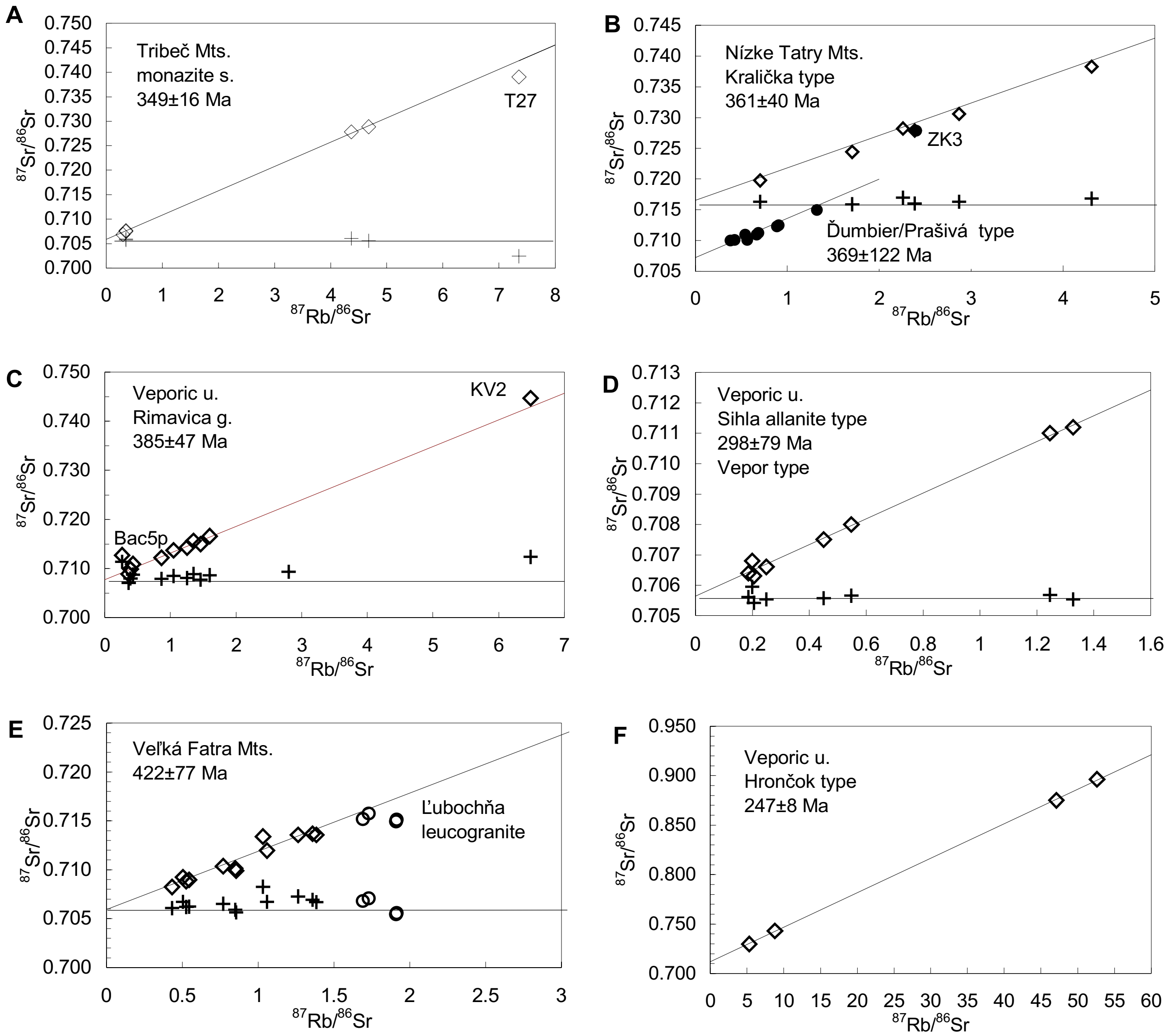

Fig. 3. Rb/Sr isochrons for granitic rocks of the Tribeč Mts (**A**), Nízke Tatry Mts. (**B**), Rimavica Granite (**C**), Sihla type tonalite (**D**), Veľká Fatra Mts. (**E**) and Hrončok type granite (**F**). Crosses: samples age-corrected to 350 Ma.

The Nízke Tatry pluton

The Nízke Tatry granitoid pluton belongs to a petrologically key area with various granitoid types dated by the Rb/Sr method (Bagdasaryan et al. 1985). No high precision zircon data are available at present from the area. While the southern slopes of the Nízke Tatry consist of orthogneisses (mainly ductilely deformed S-type granitoids, Petrík et al. 1998) the ridge and northern slopes are formed by the postkinematic, undeformed Ďumbier tonalite/granodiorite and the Prašivá Granite. The specific, leucocratic Kralička Granite crops out within the orthogneiss belt. It is believed to have been formed by partial melting of the orthogneisses (Zoubek 1951). The Ďumbier/Prašivá granitoids form a tight array corresponding to 369 ± 122 Ma, I_{Sr} = 0.70782 and MSWD = 0.115, whereas the Kralička type yields 361 ± 40 Ma with the high I_{Sr} = 0.71601, MSWD = 0.305 (Fig. 3B, Table 1). There is one obvious outlier in the Ďumbier/Prašivá sample set (ZK-3), a sample discussed already by Kráľ (in Cambel et al. 1990a) who hypothesized its possible high age (with the Ďumbier/Prašivá initial Sr ratio of 0.716 it gives 595 Ma). It is argued here that ZK-3 belongs to a different granite type, possibly akin to the Kralička Granite rather than to the Ďumbier/Prašivá type (as all the rocks on the main ridge between Chopok and Ďereše peaks) thus having the same age. The Kralička granite isochron including ZK-3 gives an age identical to Ďumbier/Prašivá age (361 ± 40 Ma). The Rb and Sr chemistry of the Kralička granites is compared with other Nízke Tatry granitoid types in Fig. 4. Also shown is a newly analysed set of samples (labeled Chopok) from the area between Chopok and Ďereše. The Kralička type granitoids differ by their much lower Sr contents overlapping with the Chopok type and orthogneisses.

The Ďumbier/Prašivá granitoid samples come from localities which are more than 40 km apart implying Sr isotopic inhomogeneity. They include both monazite and allanite-bear-

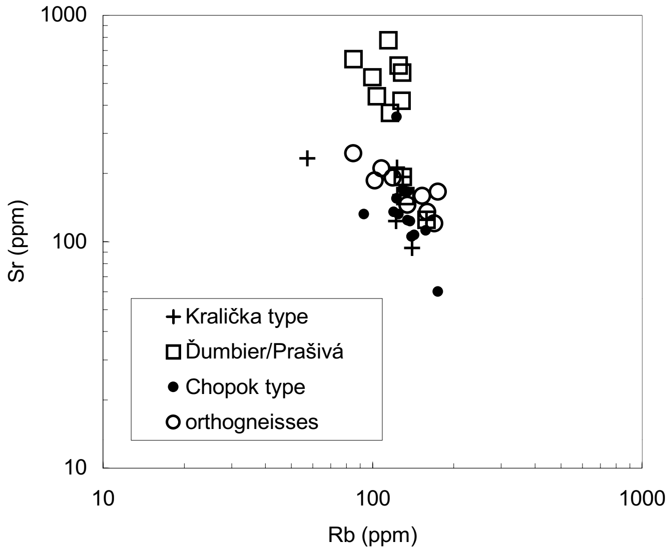

Fig. 4. Rb vs. Sr in the Nízke Tatry Mts.: Kralička, Ďumbier/Prašivá type granitoids and orthogneisses. The Kralička type and "Chopok" type are identical in terms of Rb/Sr ratios.

ing rocks with subaluminous nature showing one of the highest I_{Sr} within I- and S-type granitoids (except the Kralička type). Their close association with orthogneisses and their presumed derivatives (Kralička and Chopok granite?) having extremely high I_{Sr}, is considered significant for explaining this anomaly.

Veľká Fatra Mts.

The granitoids of the Veľká Fatra Mts. are the only ones in the Western Carpathians where Rb/Sr and Sm/Nd systematics are available (in addition to K/Ar and $^{40}Ar/^{39}Ar$ data) through the comprehensive work by Kohút (1992) and Kohút et al. (1996, 1998, 1999). Mainly for geological reasons, Kohút (1992) treated the groups of main pluton granitoids separately from the leucocratic Ľubochňa granites, showing cutting contacts with the zoned pluton. While all the samples give 359 ± 47 Ma (Table 1), the main granitoids yields 422 ± 77 Ma and the Ľubochňa granite samples fail to form an isochron at all (Fig. 3E). Although the author accepts the high age interpreting it as that of a „pre-existing pluton" he also discusses the possibility of pseudoisochron due to the inhomogeneity of source(s). Considering the U/Pb zircon age of 356 ± 25 Ma obtained from the main pluton (Kohút et al. 1997), the latter interpretation seems to be more probable in explaining different initial ratios of the main petrographic types. The Ľubochňa leucogranites form a negative slope, the sample with apparently lower $^{87}Sr/^{86}Sr$ (VFMa-2) also having the lowest concentration of Sr (148 ppm). The possible increase of the Rb/Sr ratio allows us to try an open system interpretation. The ages of 227 Ma for the system opening are obtained assuming original Sr 200 ppm and the intrusive age of 340 Ma, and 198 Ma for the intrusive age of 350 Ma (Table 2). Similarly, anomalous Veľká Fatra orthogneiss samples (5, 44 in Bagdasaryan et al. 1992) may be explained by a Sr loss (not shown).

Vepor pluton (the Sihla and Rimavica granitoids)

In their original work Bagdasaryan et al. (1986) interpreted the Rb/Sr data obtained on Sihla I-type tonalites as an isochron giving (as recalculated in Table 1) 373 ± 163 Ma and data on Vepor/Ipeľ granodiorites as isochron 254 ± 150 Ma. By redefining the granitoids after the allanite/monazite dichotomy criterion, as in the case of the Tribeč tonalites, a new array (8 allanite-bearing samples) is obtained corresponding to 298 ± 79 Ma (MSWD = 0.056) concordant with the U/Pb age 304 ± 3 Ma (Bibikova et al. 1990), Fig. 3D. The monazite-bearing samples are apparently disturbed and their increased $^{87}Sr/^{86}Sr$ ratios indicate different source(s). The samples age-corrected to 300 Ma do not form any mixing line, rather than two „plateaus" of the Sihla and Vepor/Ipeľ groups (not shown in Fig. 3).

Rimming the southeastern boundary of the Vepor pluton, the Rimavica S-type granitoids represent a rather inhomogenous group with strong Alpine overprint. Their Rb/Sr age claimed by the authors (Cambel et al. 1988) is 393 ± 24 (as recalculated in Table 1) based on eight samples taken as much as 22 km apart. A constant Sr isotope ratio can hardly be expected over such an area. Actually, twelve samples were measured from five localities, two of them, Krokava and Chyžné (KV and D in Notes to Table 1) covered by five and four samples, respectively. The Chyžné Group yields 316 ± 111 Ma, the Krokava group yields 394±195 Ma. The Krokava samples also supplied zircons for the U/Pb dating (350 ± 5 Ma, Bibikova et al. 1990). Other samples (leucocratic veins of muscovite granitoids Bac-5p and KV-2, Fig. 3C) have apparently increased Sr initial ratios of 0.71138 and 0.71238 respectively (age-corrected to 350 Ma, further on denoted by subscript $_{350}$). Thus, the S-type granitoids of the SE Veporic Superunit seem to comprise several granite types (intrusions?) with Rb/Sr ages overlapping the zircon age.

Sm/Nd systematics

In contrast to Rb and Sr, typically dispersed elements, Sm and Nd reside mainly in accessory minerals. In the West-Carpathian granitoids where hornblende is rare, the relevant accessories are monazite in the S-type, and allanite and titanite in the I-type rocks. As the Sm/Nd ratio changes only slightly during partial melting, the Nd evolution line of a granite may be extrapolated into the past where, at the intersection with the depleted mantle (DM) evolution line, it provides the crustal residence age (T_{DM}). Due to much slower diffusivity of rare earth elements (REE), the Nd isotopes do not homogenize and may preserve source characteristics (e.g. Pin & Duthou 1990). An attempt to identify these source(s) is made below using both Sm/Nd and Rb/Sr data.

The bulk of the Sm/Nd data comes from Kohút et al. (1999) who provided twenty-one samples covering all main granite occurrences (one sample per massif except the Veľká Fatra Mts. with five samples). The authors found that the granitoids lack homogenization of $^{143}Nd/^{144}Nd$ isotopes, which is also expressed by their model ages (two stage T_{DM}, $^{147}Sm/^{144}Nd$, and $^{143}Nd/^{144}Nd$ values for depleted mantle are after Liew & Hofmann 1988) in the range of 1.6–0.62 Ga. This range was interpreted analogically with other workers on the European Variscides as resulting from source inhomogeneities. The sources are regarded as mixtures of at least two end members (Liew & Hofmann 1988; Pin & Duthou 1990; Janoušek et al. 1995). Kohút et al. (1999) also identified a gabbro from the Veporic Superunit and the Kralička Granite from the Nízke Tatry Mts. as samples with the highest $^{143}Nd/^{144}Nd_{(350)}$ = 0.511834 and lowest $^{143}Nd/^{144}Nd_{(350)}$ = 0.512474 ratios, respectively with corresponding T_{DM2st} = 1.6 and 0.62 Ga [DM2st refers to two-stage mantle melting according to Liew & Hoffman (1988)]. The bulk of granitoids shows a lesser $Nd_{(350)}$ isotopic range between 0.51215 (Tribeč tonalite) and 0.51197 (Považský Inovec leucogranite) with corresponding T_{DM2st} = 1.11–1.4 Ga. This range most probably reflects variable proportions of (at least) two contrasting sources of the granitoid magma.

Summary of the isotope systematics

The detailed inspection of the Rb/Sr systematics of the most important granitoid massifs showed that (1) the main body tonalites and granodiorites if subdivided according to the allanite /monazite criterion yield dates within error concordant with U/Pb zircon ages. However, due to the small ranges of the Rb/Sr ratios they show too large errors (Tribeč, Ďumbier/ Prašivá type, Sihla type). (2) The incorporation of high Rb/Sr samples occurring often only as leucocratic veins or sills results in the increase of the presumably apparent age since the veins arising from a different (metapelitic) protolith (e.g. Suchý, Tribeč Mts., Veporic Superunit) have higher initial $^{87}Sr/^{86}Sr$ ratios. (3) Although an initial slope may form due to higher I_{Sr} of the leucocratic melts, the hypothesis of a „source mixing line“ existing in the initial $^{87}Sr/^{86}Sr$ ratios of the main granitoid groups does not seem to be confirmed. (4) Correlation between the distances of outliers above the isochron and their anomalously low Rb/Sr ratios (and vice versa) may be interpreted in terms of the Rb/Sr system opening at a time different from the initial closure time. Using the equations (A1, A2) and good guesses for the original Rb/Sr ratios, late Variscan to early Alpine ages are obtained for this opening.

Interpretation of the isotope systematics

The need for differing precursors

The Sm/Nd data show that the most radiogenic samples have the lowest Sm/Nd ratios. Such rocks (gabbro, tonalites) have steep light rare earth element patterns, but flat Nd evolution lines which intersect the DM evolution line at the youngest ages (Fig. 5A). In contrast, the samples with the highest Sm/Nd ratios (flat light rare earth element patterns characteristic mainly of leucogranites) are least radiogenic, which means that they must have started their crustal history at a very low Nd isotopic ratio, that is they have high DM model ages. Lithological and model age contrasts exist between the end-members as is confirmed by a negative correlation between $^{143}Nd/^{144}Nd_{(350)}$ and SiO_2 shown in Fig. 5B. Thus, a young mafic, infracrustal end member (IC_m) is required to mix with an old, felsic supracrustal end member (SC_f) to give the observed span in $^{143}Nd/^{144}Nd_{(350)}$ ratios. The requirement of a low Sm/Nd ratio for the IC_m end member precludes a mid ocean ridge type basalt with Sm/Nd 0.33 (e.g. Jenner et al. 1987), and points rather to light rare earth element enriched gabbros and diorites. The SC_f end member best correlates with peraluminous leucocratic melts formed by metapelite/metagreywacke dehydration melting in upper crustal conditions.

The end-members

IC_m end-member. The only known basic rocks with low Sm/Nd ratios found in a close relation to granitoids are dioritic rocks. They are known from many West-Carpathian basement massifs, where they form small-sized bodies within granitoids commonly too small to be shown on geological maps. Diorites, as known from the Malé Karpaty Mts. (Cam-

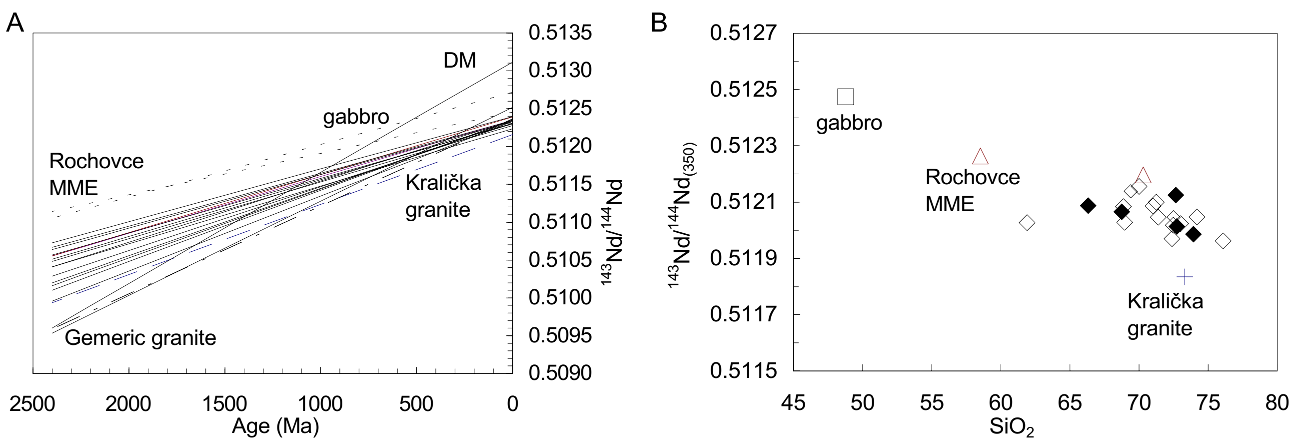

Fig. 5. (A) Nd evolution diagram, dotted: gabbro and diorite mafic enclave, dashed: felsic rocks (Kralička type), thin lines: Tatric and Veporic granitoids; Depleted mantle (DM) evolution after Liew & Hofmann (1988). (B) $^{143}Nd/^{144}Nd_{(350)}$ vs. SiO_2; gabbro: KV-3 from the contact zone of the Veporic and Gemeric superunits (Kohút et al. 1999); enclave: from the Rochovce Granite (Hraško et al. 1999); closed symbols: Veľká Fatra granitoids.

bel & Pitoňák 1980; Cambel & Vilinovič 1987), are fine- to medium-grained plagioclase- and hornblende-dominated rocks with SiO_2 ranging from 54 to 63 % and steep rare earth element patterns (Sm/Nd = 0.12–0.18). The main carrier of light rare earth elements, besides hornblende, is allanite. Cambel & Vilinovič (1987) showed that major and minor elements of these diorites are found along trends defined by granitoids in Harker diagrams (Fig. 6). Since much of the granite variation may be interpreted by a magma differentiation process, such as crystal fractionation (Vilinovič & Petrík 1984), the observed trends may coincide just because the compositions of cumulates and diorites are similar. This would preclude simple mixing relations, as indicated in the diagram Zr vs. SiO_2 (Fig. 6D), but it does not rule out the diorite magma playing a role in granite genesis. Even more indicative, that mafic magmas are involved, is the presence of mafic microgranular enclaves (MME) in I-type tonalites (Petrík & Broska 1989). The Tribeč MME with dioritic to tonalitic compositions lie on linear trends with host tonalites in both major and trace element variations, Figs. 7A,B. The compositional range of the enclaves is best explained by their mixing with granitoid magma before being individualized into enclaves. The fact that the MME occur only in the most mafic varieties of host tonalites implies an interaction (mixing) of both magmas which has shifted the host granitoid magma toward a more mafic composition. Thus, the diorites, occurring either as individual bodies or as MME, appear a suitable IC_m candidate in the granite magma genesis. They themselves appear to be products of the hybridization of a mantle-derived gabbroic (basaltic) precursor by a felsic magma.

SC_f end member. Felsic rocks with high Sm/Nd ratios are typically represented by leucogranites occurring within para- and orthogneiss complexes. They commonly show flat rare earth elements patterns often with increased heavy rare earth elements. Peraluminous leucogranites are considered to be typical products of partial dehydratration melting of metapelite precursors (Montel & Vielzeuf 1997; Stevens et al. 1997; Patino-Douce & Harris 1998). Their light REE depleted nature is known from the geochemical studies of granites of collisional orogenic belts (Dietrich & Gansser 1981; Nabelek & Glascock 1995) which showed that they had Sm/Nd ratios typically between 0.2–0.4. The strongly peraluminous Kralička Granite with the lowest $^{143}Nd/^{144}Nd_{(350)}$ and highest $^{87}Sr/^{86}Sr_{(350)}$ ratios is considered to be a melting product of the Nízke Tatry orthogneisses which also have flat REE patterns (Sm/Nd = 0.2–0.3). The orthogneisses were interpreted as ductilely deformed S-type granitoids (Petrík et al. 1998). Thus both para- and orthogneisses may produce characteristic leucogranites when being melted. They have the properties of the SC_f end-member which escaped Sr isotopic homogenization common in main granite bodies, and reflect the $^{87}Sr/^{86}Sr$ ratio of their source. The high $^{87}Sr/^{86}Sr$ value indicates a recycled crustal material. This is, in the case of orthogneisses, confirmed by the high Nd T_{DM2st} age

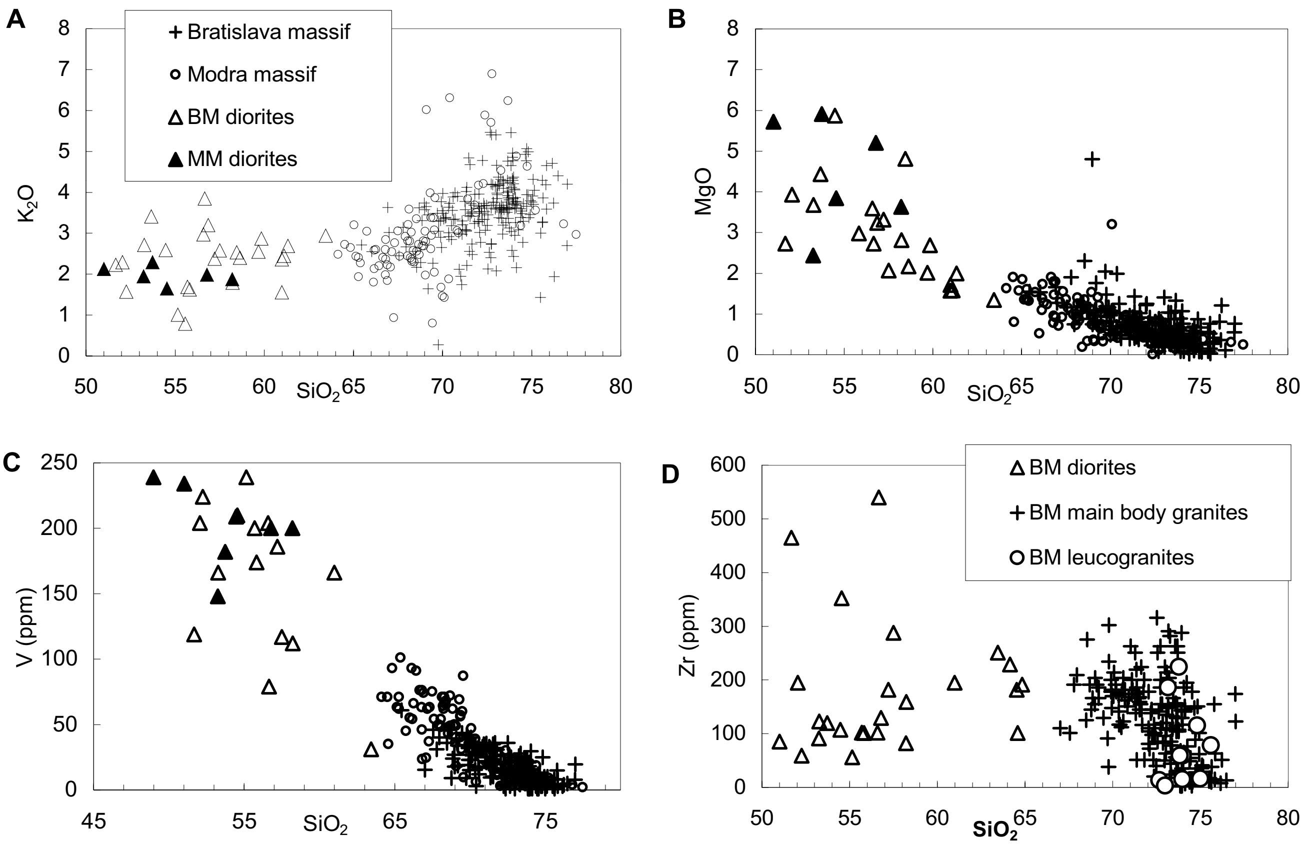

Fig. 6. Harker diagrams for K_2O (**A**), MgO (**B**), V (**C**) and Zr (**D**) in the Malé Karpaty granitoids and diorites. (A–C) data from both Bratislava and Modra massifs, (D) the Bratislava Massif only (source data Cambel & Vilinovič 1987).

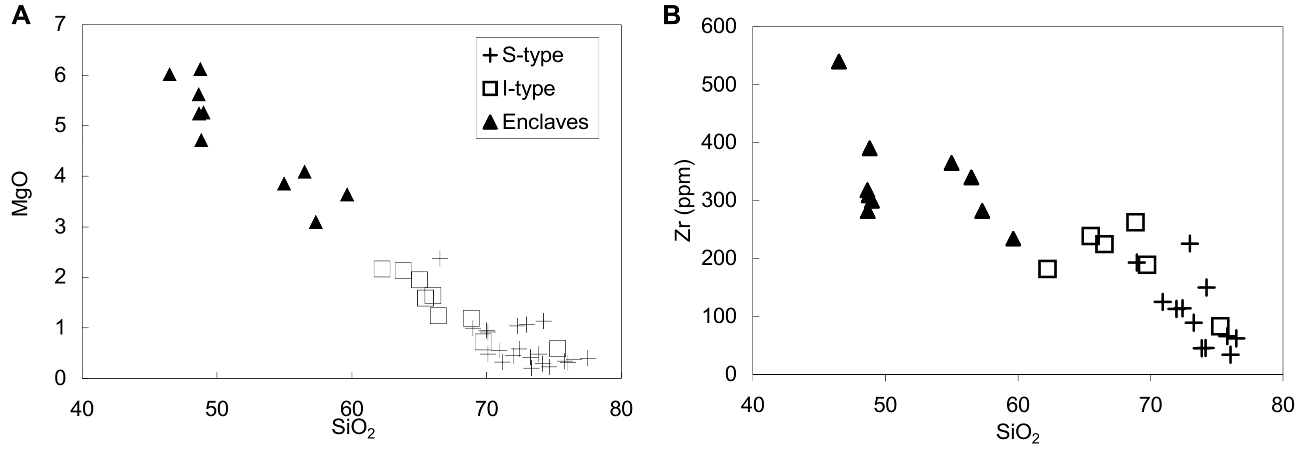

Fig. 7. Harker diagrams of MgO (**A**) and Zr (**B**) in granitoids and mafic microgranular enclaves in the Tribeč Mts. (source data Petrík & Broska 1989). Formed presumably from the same magma as diorites, the enclaves show mixing relations with I-type tonalites.

(1.6 Ga) and the upper intercept zircon age (for the Western Tatra orthogneiss >1.6 Ga, Poller et al. 1999a). The metagreywackes (gneisses) have not yet been dated by high precision methods, however earlier zircon datings for the Tatra paragneiss range between 620–700 Ma (Cambel et al. 1990).

Mixing of the end-members

The relationship between the end-members characterized above and the whole group of granitoids is shown in diagram Sm/Nd vs. $^{143}Nd/^{144}Nd$ (Fig. 8A). Diorites, spatially and genetically related to granitoids, are preferred to the gabbro which is tectonically sandwiched between metapelites and the Alpine Rochovce Granite (Krist et al. 1988) with no apparent relationship to them. The end members are bounded using the following data.The Sm/Nd data for diorites (IC_m end member) come from the Tatry Mts. Poller et al. (1999b) found $\varepsilon_{Nd(330)}$ values of 0–2 which correspond to $^{143}Nd/^{144}Nd_{(330)}$ = 0.512213–0.512315 [initial $\varepsilon_{Nd(330)}$ calculated using magmatic zircon age]. The value of 0.51228 within the range given above was used for the mixing model. The range of Sm/Nd ratios (0.12–0.19) is taken mainly from the Malé Karpaty diorites. The SC_f end member is bounded by the Sm/Nd ratios of leucogranites (Suchý and Považský Inovec garnet aplites, Kralička Granite) ranging from 0.16 to 0.29, and the $^{143}Nd/^{144}Nd$ ratios of the Western Tatra micaschists (Poller et al. 1999b) ranging from 0.51162 to 0.5118. The outlined fields with the joining mixing line (calculated according to Faure 1989) cover the observed scatter of granitoids. The two outliers are the Veporic two-pyroxene gabbro, apparently a pure mantle-derived rock with $\varepsilon_{ND(350)}$ = 5.6 and the Gemeric Granite with extremely high Sm/Nd and $^{87}Sr/^{86}Sr_{(350)}$ ratios (0.29–0.31, 0.720–0.734 respectively) suggesting a different supracrustal source.

Sr vs. Nd isotopes

The mixing relations of IC_m and SC_f end-members are also illustrated in a $(^{87}Sr/^{86}Sr)_{350}$ vs. $(^{143}Nd/^{144}Nd)_{350}$ diagram (Fig. 8B). Two mixing lines are shown between the same IC_m end-

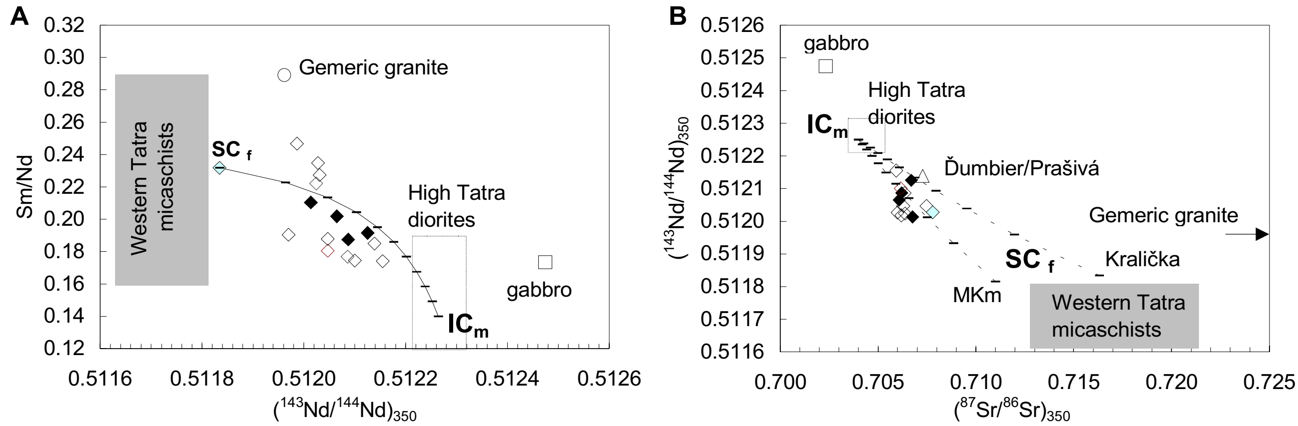

Fig. 8. (A) Mixing in $^{143}Nd/^{144}Nd$ vs. Sm/Nd plot (Nd IC ppm: 60, SC: 15). (B) $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ plot with mixing line [Sr used in mixing (ppm): IC_m 600, SC_f 122/150, Nd SC_f 15/18]. Tick marks at 10 %. MKm — Malé Karpaty gneisses. Source data: Kohút et al. (1999) — individual points (closed symbols — Veľká Fatra granitoids), Poller et al. (1999b) — the fields of micaschists and diorites.

member as in Fig. 8A and two SC_f end-members with different $^{87}Sr/^{86}Sr$ ratios, 0.710 and 0.716. They represent the I_{Sr} values of the Malé Karpaty gneisses (Bagdasaryan et al. 1983) and the Kralička Granite (Kohút et al. 1999), respectively. The $^{143}Nd/^{144}Nd$ ratio of the first SC end-member is assumed to be the same as for orthogneisses, at the upper limit of the Tatra micaschist range (Poller et al. 1999b). The mixing range covers the observed field of granitoids which are spread mainly between diorite and gneiss end-members. However, some of them with relatively high $^{143}Nd/^{144}Nd$ ratios are shifted to higher $^{87}Sr/^{86}Sr$ values (Ďumbier tonalite) thus lying on the other line, diorite — Kralička Granite. An end-member with such a high $^{87}Sr/^{86}Sr$ ratio seems to be necessary to explain the relatively increased I_{Sr} (0.706–0.708) of some more mafic types (Ďumbier/Prašivá): a smaller SC_f end-member proportion (60 % in this model) is sufficient to increase the I_{Sr} while keeping the high Nd isotopic ratio and the more mafic composition of the tonalites. The S-type granitoids with $^{87}Sr/^{86}Sr_{(350)}$ around 0.706–0.707 would require 60–80 % of the gneissic end-member which is in agreement with their more felsic nature.

The mechanism of mixing

The mechanism of mixing can hardly be traced unambiguously. In principle three processes are conceivable: (1) melting of a mixed source rock, (2) mixing of contrasting magmas and (3) assimilation of a felsic rock by a mafic magma. All of them have been invoked in literature. On the basis of Sm/Nd data from lower crustal xenoliths, Pin & Duthou (1990) preferred a composite source mixed on a small-scale. However, the potential source rocks in the Western Carpathians (paragneisses, orthogneisses) do not show a mixed character and actually they were treated as end-members. Therefore, melting and assimilation of a metagreywacke precursor by the hybrid gabbro-diorite magma and subsequent mixing and mingling are considered more likely.

An important result of melting experiments with various metasedimentary rocks is that they can produce only peraluminous and mostly leucocratic melts (Vielzeuf & Montel 1994; Montel & Vielzeuf 1997). Slightly more mafic peraluminous melts originate by melting of a metagreywacke protolith as demonstrated by Montel & Vielzeuf (1997). Such melts resemble the compositions of typical two-mica S-type granitoids which form bulk massifs in the Western Carpathians. Montel and Vielzeuf's results are shown in an A–B plot (after Debon & Le Fort 1983) and compared with Malé Karpaty granitoids and metamorphic rocks (Fig. 9). The greywacke starting compositions are matched by less peraluminous and less mafic varieties of Malé Karpaty gneisses. The more mafic greywacke-derived experimental melts (circles), straddle the boundary of leucogranites and overlap the peraluminous part of the Malé Karpaty monzogranites. However, they do not cover minor subaluminous and metaluminous granodiorites. Therefore, the input of a mafic end-member is necessary to get the more mafic, metaluminous granodiorites and tonalites (Patino-Douce 1995; Castro et al. 1999). This is also supported by the lower I_{Sr} of the Malé Karpaty granitoids (0.707; Cambel et al. 1982) compared to that of gneisses (0.710; Bagdasaryan et al. 1986).

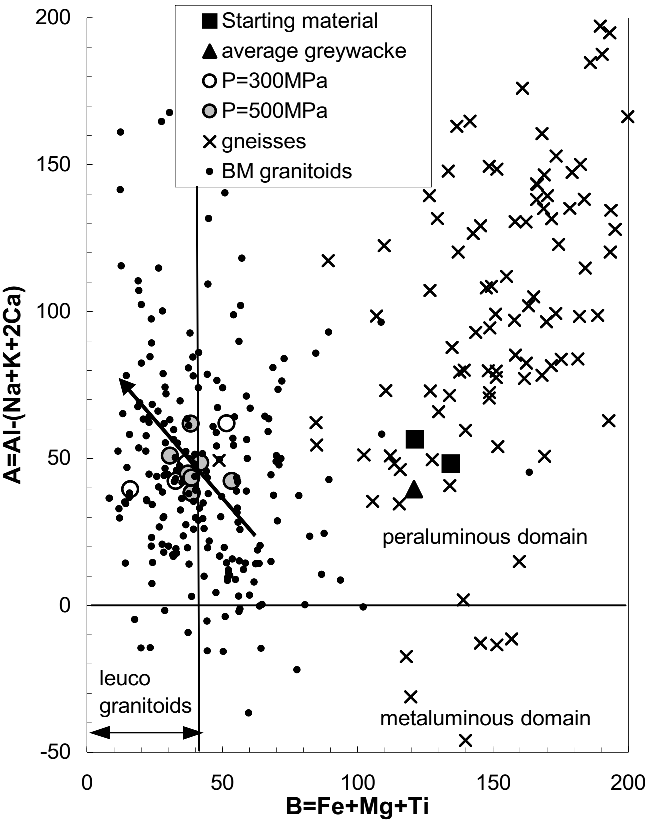

Fig. 9. Malé Karpaty granitoids and metamorphic rocks in the A–B plot (Debon & Le Fort 1983) compared with experimental melts (Montel & Vielzeuf 1997). Evolution trend of granitoids is shown by the arrow. Source data Cambel & Vilinovič (1987) and Cambel et al. (1990).

Generally, the input appears to have been more pronounced in I-type granitoids with I_{Sr} between 0.706 and 0.705. The contrasting mineralogical composition and petrological properties of the S- and I-type granitoids, as inferred by Petrík & Broska (1994), may thus reflect varying proportions of the mafic gabbroic infracrustal end-member, rich in water and rare earth elements. Such magmas originate above a subducting slab (Peacock 1993). The melting of deeply buried metapelites in the course of Variscan thrusting is documented by extensive migmatization. Janák et al. (1999) estimated the melting conditions of the Tatra migmatites at 700–750 °C, 1100–1200 MPa (kyanite zone) and 680–825 °C, 530–800 MPa (sillimanite zone). The peak temperatures seem to require a mantle-derived heat source. The hybrid diorite zone present in the area (Kohút & Janák 1994) supports the role of infracrustal magmas both as suppliers of heat and material.

Other granitoid types

Besides the common S- and I-type granitoids discussed above, the A-type granites of the Veporic Superunit, and specialized granites of the Gemeric Superunit are treated separately.

The Rb/Sr age of the Hrončok A-type granite is 247 ± 8 Ma as recalculated according to the data of Cambel et al. (1989) and redefinition by Petrík et al. (1995), Fig. 3F, Table 1. It is concordant with the zircon dating which yielded the lower and upper intercept ages of 238.6 ± 1.4 Ma and 1096 Ma ± 44, respectively (Putiš et al. 2000). The I_{Sr} (= 0.7114), the second highest after the Kralička Granite, and mildly alkalic chemistry with high Rb/Sr ratios (2–18) point to a mature source, possibly older biotite granites. The intersection of the Hrončok protolith Sr evolution (I_{Sr} = 0.7114 at 240 Ma) with the mantle value at 1 Ga gives the Rb/Sr ratio about 0.32, a value typical of granites. This, and the high I_{Sr}, precludes the Sihla tonalite as a potential precursor as suggested by Petrík & Kohút (1997).

The Gemeric granites with I_{Sr} 0.720–0.734 (after Cambel et al. 1990) also show the most extreme Rb/Sr and Sm/Nd ratios (>10 and 0.29 respectively). They also have the highest single stage Nd age = 2.4 Ga, Fig. 5A (two stage Nd age is 1.3 Ga at t = 280 Ma). In the absence of high precision zircon data no protolith age constraints can be made. The Permian age appears most probable for an event when a muscovite and quartz rich source (recycled metapelite) underwent melting to produce the observed highly specialized Rb, Li, F, B, Sn, Mo enriched melts.

Conclusions

Existing Rb/Sr data from several Western Carpathians granite massifs were re-interpreted after a detailed inspection of outlying samples. It appears that a mixing line in source $^{87}Sr/^{86}Sr$ ratios is not neccessary to explain higher Rb/Sr ages from these massifs. The high Rb/Sr samples (vein leucogranites) are often unrelated to other granitoids and, with their increased I_{Sr}, generally reflect heterogeneous sources of S-type granitoids. Some individual samples lying above and below the isochron may be interpreted in terms of the Rb/Sr system opening at a time different from the initial closure. The samples from the Tatra belt granitoids indicate Permian to Triassic ages for this event, coeval with extensional magmatism in the Vepor Belt.

While being homogenous in terms of I_{Sr}, the main body granitoids still preserve a range of initial $^{143}Nd/^{144}Nd$ ratios reflecting various proportions of at least two contrasting source components. The components were identified with old supracrustal metasediments producing peraluminous leucogranitoids and young basaltic (gabbroic) producing diorites. The assimilation of the supracrustal component by the diorite magma may have produced observed isotopic, trace and major element variations of both S- and I-type granitoids.

The following source rocks, arranged with decreasing proportions of the supracrustal component, are recognized among the West-Carpathian granitoids: (1) Gemeric granites derived from a several times recycled crustal material with extreme Sr initials (I_{Sr} > 0.720), possibly muscovite metapelite. (2) The Kralička type granite (I_{Sr} = 0.715) and its equivalents derived from a recycled crustal complex dominated by older S-type granitoids (orthogneisses). (3) The Hrončok A-type granite (I_{Sr} = 0.7114) derived from a mature high Rb/Sr, probably granitic source. (4) Peraluminous leucocratic aplitic veins, migmatite related in metamorphic complexes, the products of gneiss dehydration melting (Strážovské vrchy, Považský Inovec, Malé Karpaty Mts.). (5) Undeformed, peraluminous, mainly S-type granitoids with I_{Sr} = 0.708–0.706 showing transitional characteristics, derived from a metagreywacke (gneissic) protolith with minor infracrustal contribution (Bratislava type granitoids). (6) Sub- to metaluminous I-type granodiorites and tonalites (I_{Sr} = 0.705) with moderate infracrustal contribution. (7) Dioritic rocks and MME probably themselves products of crustal contamination of mantle-derived gabbroic melts.

The variable proportions of H_2O and REE-rich IC_m end-member (7) and H_2O and LREE-poor SC_f end-member (4) may explain the contrasting mineralogical and petrological properties observed and inferred for the major (5, 6) groups of S- and I-type granitoids (Petrík & Broska 1994) which follow mainly from contrasting water contents.

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Appendix

System opening

The time elapsed since the system opening (t_1) is given by:

$$t_1 = 1/\lambda \ln[(S_m - S_r)/(R_r - R_m) + 1] \quad \text{(A1)}$$

where S_m, R_m and S_r, R_r are measured and reconstructed $^{87}Sr/^{86}Sr$ and $^{87}Rb/^{86}Sr$ ratios, respectively and λ is the ^{87}Rb decay constant. The age of the Rb/Sr change (t_c) is then:

$$t_c = t_2 - t_1 \quad \text{(A2)}$$

where t_2 is intrusive age of the sequence. The reconstructions of SR-1 and T-27 samples are shown in Fig. A1. A series of samples with the same t_c and various degrees of Rb/Sr change would form an isochron corresponding to the t_c. It is noted that the equation (A1) neglects the decrease of $^{87}Rb/^{86}Sr$ ratios with time, but the error so introduced is much smaller than the uncertainty due to the Rb/Sr ratio reconstruction. There is also an implicit assumption that the Rb escape (sample SR-1) was not accompanied by a change in the $^{87}Sr/^{86}Sr$ ratio. This seems unrealistic when we realize that the ^{87}Sr resides precisely at the sites of its formation, i.e. in the Rb^+ positions of K-rich minerals. However, the change of $^{87}Sr/^{86}Sr$ ratio requires decoupling of radiogenic and common Sr. This may occur when the rock is thermally overprinted and the biotite-produced ^{87}Sr escapes to plagioclase until a new whole rock $^{87}Sr/^{86}Sr$ ratio is established. In the case of biotite to sillimanite breakdown, interlayer cations including Rb, and Sr (common and

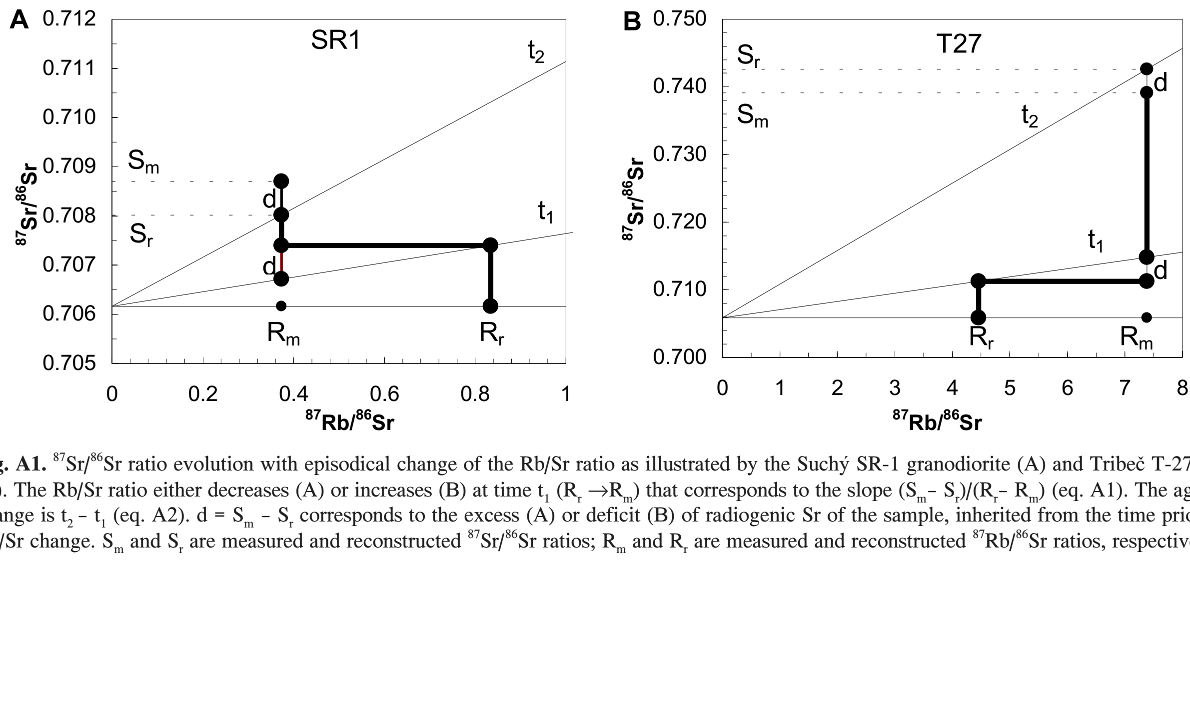

Fig. A1. $^{87}Sr/^{86}Sr$ ratio evolution with episodical change of the Rb/Sr ratio as illustrated by the Suchý SR-1 granodiorite (A) and Tribeč T-27 granite (B). The Rb/Sr ratio either decreases (A) or increases (B) at time t_1 ($R_r \rightarrow R_m$) that corresponds to the slope $(S_m - S_r)/(R_r - R_m)$ (eq. A1). The age of the change is $t_2 - t_1$ (eq. A2). $d = S_m - S_r$ corresponds to the excess (A) or deficit (B) of radiogenic Sr of the sample, inherited from the time prior to the Rb/Sr change. S_m and S_r are measured and reconstructed $^{87}Sr/^{86}Sr$ ratios; R_m and R_r are measured and reconstructed $^{87}Rb/^{86}Sr$ ratios, respectively.

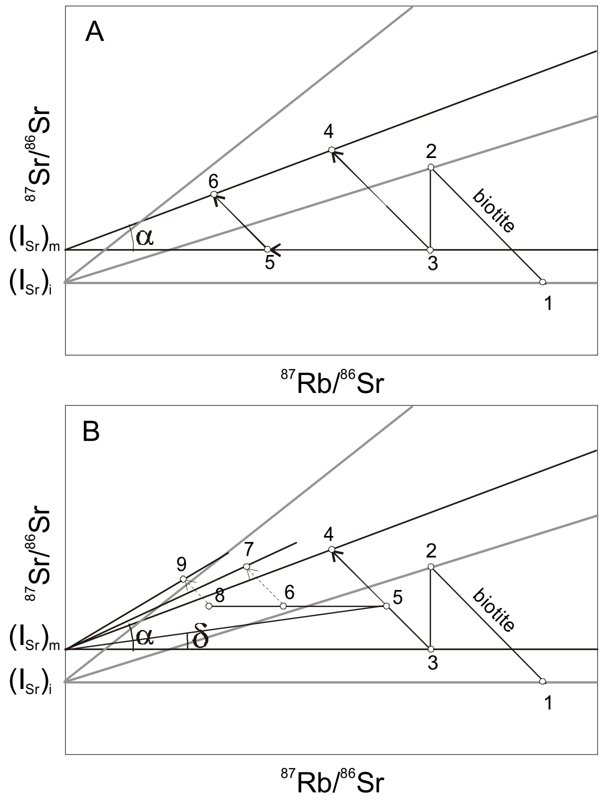

Fig. A2. $^{87}Sr/^{86}Sr$ mineral evolution: (A) A metamorphic event occurring at the time corresponding to the angle α (path 1–3), is immediately followed by various decreases of Rb/Sr ratio (paths 3–4, 3–5–6). (B) The metamorphic event is followed by various degrees of the Rb escape after a time delay (angle δ, paths 3–5–7 and 3–5–9). In this case the $^{87}Sr/^{86}Sr$ evolution produces mineral pseudoisochrons with higher "age" than that of the metamorphic event. $(I_{Sr})_i$ and $(I_{Sr})_m$ are intrusive and metamorphic Sr initial ratios, respectively.

radiogenic) are likely to escape together without the change of $^{87}Sr/^{86}Sr$ ratio. The ^{87}Sr excess in the SR-1 sample seems to be preserved from an earlier history confirming that the $^{87}Sr/^{86}Sr$ ratio does not change in the course of the reaction. However, as pointed by Hradetzky & Lippolt (1993) if Sr is emitted mainly from plagioclase, the $^{87}Sr/^{86}Sr$ increases, because it is common Sr that escapes. If so, the data obtained for low Sr outliers (VMFa-2, T-27 in Table 2) represent upper limits for the age of system opening possibly indicating rather an Alpine than a late Variscan event.

Mineral isochron

While Sr mobility is typical of weathering products, Rb escaped during high temperature acid leaching (above 600 °C, Korikovsky et al. 1987) implying a thermal overprint, redistribution and homogenization of ^{87}Sr between minerals (Fig. A2a, path 1–2–3). The new whole rock $^{87}Sr/^{86}Sr$ ratio $(I_{Sr})_m$ is not influenced by the subsequent Rb or Sr escape because biotite undergoing the breakdown releases both radiogenic and common Sr. Therefore, the high-temperature system opening has no effect on the mineral isochron age provided that the Rb escape occurred simultaneously with mineral ^{87}Sr homogenization (path 1–2–3–5–6). Actually, Kráľ (2000, personal comm.) obtained a mineral isochron for SR-1 biotite corresponding to approximately 300 Ma. Such an age (t_c) for the system opening would require a reconstructed Rb value of 140 ppm (Table 2). This seems too high a value compared to the observed range (40.2–115.6 ppm). A delay between the metamorphism and Rb/Sr change would, however, raise the biotite $^{87}Sr/^{86}Sr$ ratio above mineral isochron (Fig. A2b, path 1–2–3–5–6–7 or –8–9) and generate an apparent biotite mineral age. The neccessary delay (angle δ) is strongly dependent on the biotite Rb/Sr change (path 5–6–8), for example at t_c = 251 Ma the apparent biotite age of 300 Ma is produced at 75 % Rb/Sr ratio drop and the delay of 12 Ma, or at 50 % drop and the delay of 24 Ma. The geological relevance of the delay between metamorphism and system opening is not discussed here mainly because of the lack of the neccessary high-precision mineral trace element data.

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159–168

COUNTERCLOCKWISE ROTATIONS OF THE NEOGENE ROCKS IN THE EAST SLOVAK BASIN

EMÖ MÁRTON[1], DIONÝZ VASS[2] and IGOR TÚNYI[3]

[1]ELGI, Columbus u. 17-23, 1145 Budapest, Hungary
[2]Technical University, Department of Environmental Studies, T.G. Masaryka 24, 960 53 Zvolen, Slovak Republic
[3]Geophysical Institute of the SAS, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic

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Abstract: Paleomagnetic investigation of sedimentary and volcanic rocks of the East Slovak Basin gave information about the counterclockwise (CCW) rotation of the Neogene units of Eggenburgian to Middle Sarmatian age. The Eggenburgian sediments (1 loc. 20 spec.) show about 80° CCW rotation, the zeolitized rhyolite tuffs of Lower Badenian age (2 loc. 19 spec.) show a 40°–60° CCW rotation, the rhyolites (1 loc. 3 spec.) of Upper Badenian age about 50° CCW rotation, the sediments of Lower-Middle Sarmatian age (1 loc. 6 spec.) gave CCW rotation of about 20° and the youngest post-Sarmatian rhyolite (1 loc. 9 spec.) did not yield any rotation. The rotation was preceded by left lateral penetration of the Tissia units into the West- and East-Carpathian boundary zone.

Key words: Western Carpathians, East Slovak Basin, Neogene sedimentary and volcanic rocks, paleomagnetism, counterclockwise rotation.

Introduction

Recent communications, concerning paleomagnetism (Orlický 1996) and paleomagnetism plus isotope dating (Márton & Pécskay 1995) of the north-eastern corner of the Inner Carpathians suggest that the counterclockwise declination rotations observed on late Badenian-Sarmatian volcanics might be of tectonic significance.

Orlický interpreted observations from the East Slovak Basin (ESB) in terms of fault-related small-scale block movements, while Márton and Pécskay envisage a kind of triangle, bordered by the Hornád/Hernád-line, the Szolnok-Maramures flysch belt and the NE Outer Carpathians, which could have rotated as a unit in late Sarmatian–early Pannonian times. This rotation would be about 4–5 Ma younger than the final counterclockwise rotation of the central part of the Inner Western Carpathians (Márton & Márton 1996; Márton et al. 1996).

The aim of the present study is to seek support for the counterclockwise rotation in the East Slovak Basin also from sediments or volcano-sedimentary rocks and constrain the timing. The sampling sites and localities of the present study are shown on a schematic geological map in Fig. 1, and on a schematic geological map of the pre-Tertiary basement (Fig. 2).

Geology and tectonics

The ESB started to open as a shear basin in the early Miocene (Eggenburgian, about 22 Ma B.P.). At the beginning, a narrow furrow opened along the Pieniny Klippen Belt. The marine transgression reached the basin from the remnant flysch basins of the Outer Carpathians. At the end of the Eggenburgian, prograding deltas (Čelovce, Lada) entered the basin, marking its temporary closure. Deposits of Ottnangian age (19–17.5 Ma B.P.) are missing (Fig. 3).

The ESB started to re-open in the early Karpatian (17.5 Ma B.P.), by extension (Kováč et al. 1994a). Later, the character of the paleostress field progressively changed, and shear became the dominant factor in the evolution of the ESB. Shear controlled basin evolution (Fig. 3) characterizes the late Karpatian through late Sarmatian period (17–11.5 Ma B.P.). During this period, the basin had the features of a typical pull-apart basin, including the migration of subsidence centres (from NW to SE, in recent coordinates) and rapid subsidence (Vass et al. 1988). The thickness of the deposits during this period is more than a thousand metres and the whole basin fill is 8000–9000 m thick in the centre. Other pull-apart features of the basin are the "en echelon" arrangement of faults, flower structures on major fault zones, and dismatch between units of the basement.

The basement of the ESB is built of very different tectonic units (Fig. 2). These are the Veporic Superunit represented by the Krížna Nappe, Humenné Mesozoic Horst and Veporic Superunit of the Čierna Hora Mts. partly covered by Central Carpathian Paleogene. The Kritchevo-Iňačovce Unit formed by metamorphic rocks, including slightly metamorphosed Eocene marine deposits considered by Soták et al. (1993) to be equivalent of the Vahic/Penninic Superunit. This superunit may correspond to the Nádudvar Formation, or the Szolnok-Maramures Flysch; the Zemplinic (Zemplén) Unit, which probably belongs to the Tisza (Tissia) Superunit (Körössy 1963; Grecula & Együd 1977); the Gemeric Superunit, Bükk Unit and Meliatic Unit (which may represent the NE promontory of the Pelsó Megaunit which escaped from the Central Alpine and NW Dinarides area (Kázmér & Kovács 1985; Haas et al. 1995).

By the end of the pull-apart evolution of the ESB, a strong andesite volcanic activity started. This volcanic activity is considered as subduction related and during the Sarmatian the basin was in an interarc position (Vass et al. 1988).

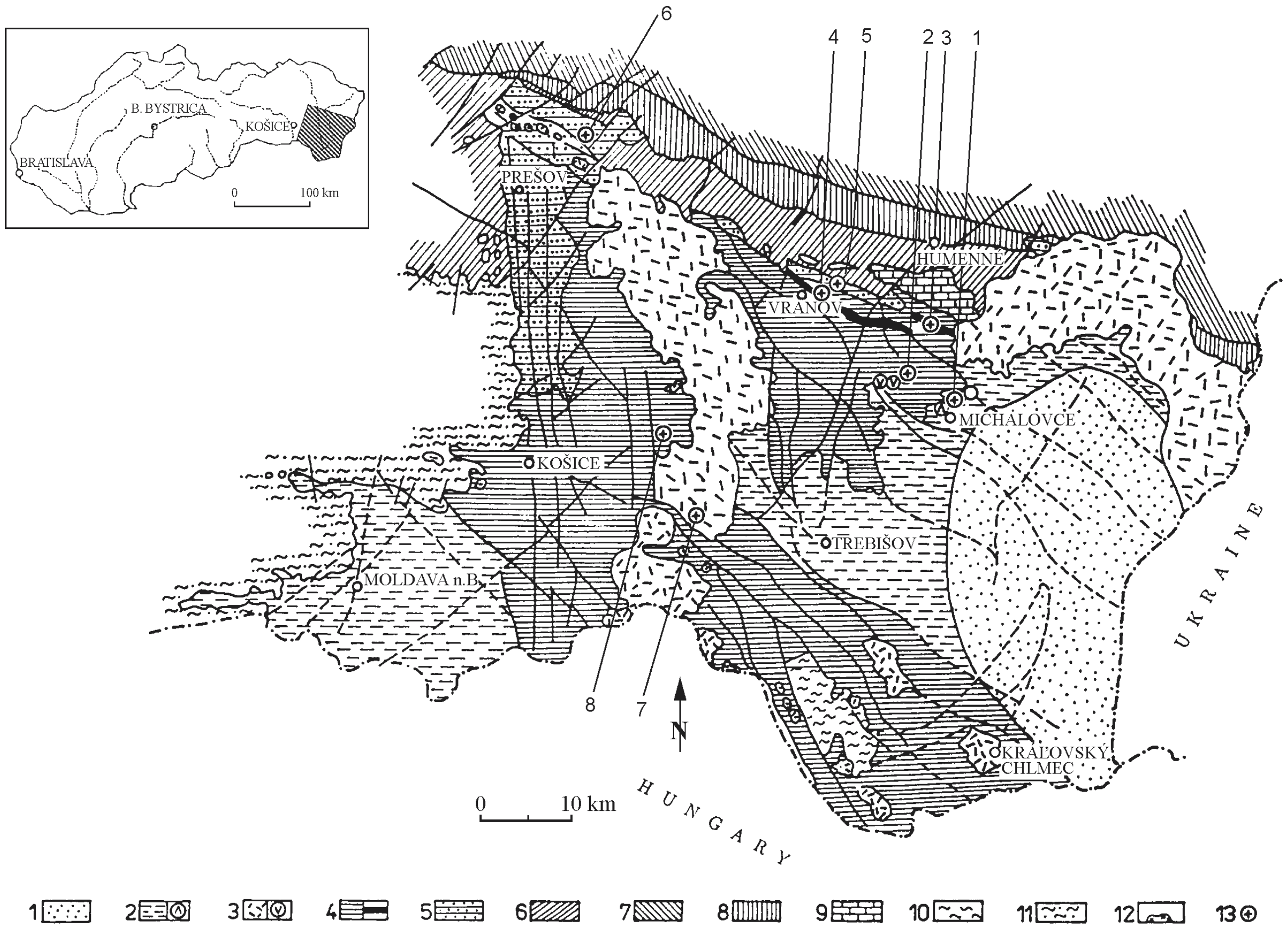

Fig. 1. Simplified geological map of the East Slovak Basin and sampled sites. *Explanation*: 1–5: Neogene sedimentary basin fill and neovolcanics. 1 — Pliocene; 2 — Late Miocene, a — sediments, b — rhyolite; 3 — neovolcanics Middle and Late Miocene in age, a — predominantly andesites and andesite volcano-clastics, b — rhyolite; 4 — Middle Miocene, a — sediments, b — zeolitized tuff (Hrabovec Tuff); 5 — Early Miocene (Karpatian); 6 — Central Carpathian Paleogene; 7 — Outer Carpathian Flysch; 8 — Klippen Belt; 9 — Mesozoic of Krížna Nappe Unit; 10 — Paleozoic and Mesozoic of Zemplinic Unit; 11 — Peleozoic and Mesozoic of Silicic Superunit, Meliatic Unit and Veporic Superunit undivided; 12 — Proterozoic of Zemplinic Unit; 13 — sample sites, see Fig. 2 and Table 1.

The recent geophysical evidence of the former pull-apart character of the basin is the thin continental crust in the south (including 8–9 km of basin fill deposits 27 km) which becomes thicker (32 km) in the North-Northwest (Šefara et al. 1987), the high heat flow (more than 110 Wm^{-2}) and the high geothermal gradient (53 °C/km, Král et al. 1985).

The pull-apart history of the basin ended with the Sarmatian. During the Pannonian the subsidence significantly slowed down and the Pannonian deposits are only a few hundred metres thick.

During or after the Pontian, basin inversion took place. Pliocene deposits are fluvio-lacustrinal and are restricted to the SE corner of the basin.

Sampling and laboratory measurements

We drilled the Eggenburgian sediment at one, and the zeolitized tuff of Badenian age at three localities. All these are in well-controlled tectonic positions. Sarmatian volcanosedimentary rocks and andesite were collected at three localities.

In addition to the sediments and sediment-like deposits, two rhyolite domes were also sampled. At one of them, which was earlier sampled by one of the authors (I. Túnyi) hand samples were taken and subsequently drilled in the laboratory, the other was drilled in the field. A total of 92 independently and magnetically oriented samples were taken.

Standard-size cylinders were cut from the drill-cores, measured and stepwise demagnetized by the thermal and AF methods or by combining the AF and thermal methods, IRM and low susceptibility versus temperature experiments were also carried out to help the identification of the magnetic minerals. Stepwise thermal demagnetization was carried out in Bratislava, the other experiments in Budapest.

Results and assessment of data

The samples from the two rhyolite domes yielded excellent paleomagnetic directions. The NRMs are in both cases single-component (Fig. 4), the carrier of the remanence is magnetite (Figs. 5a and 6a) and the site mean directions are statistically very well defined (Table 1).

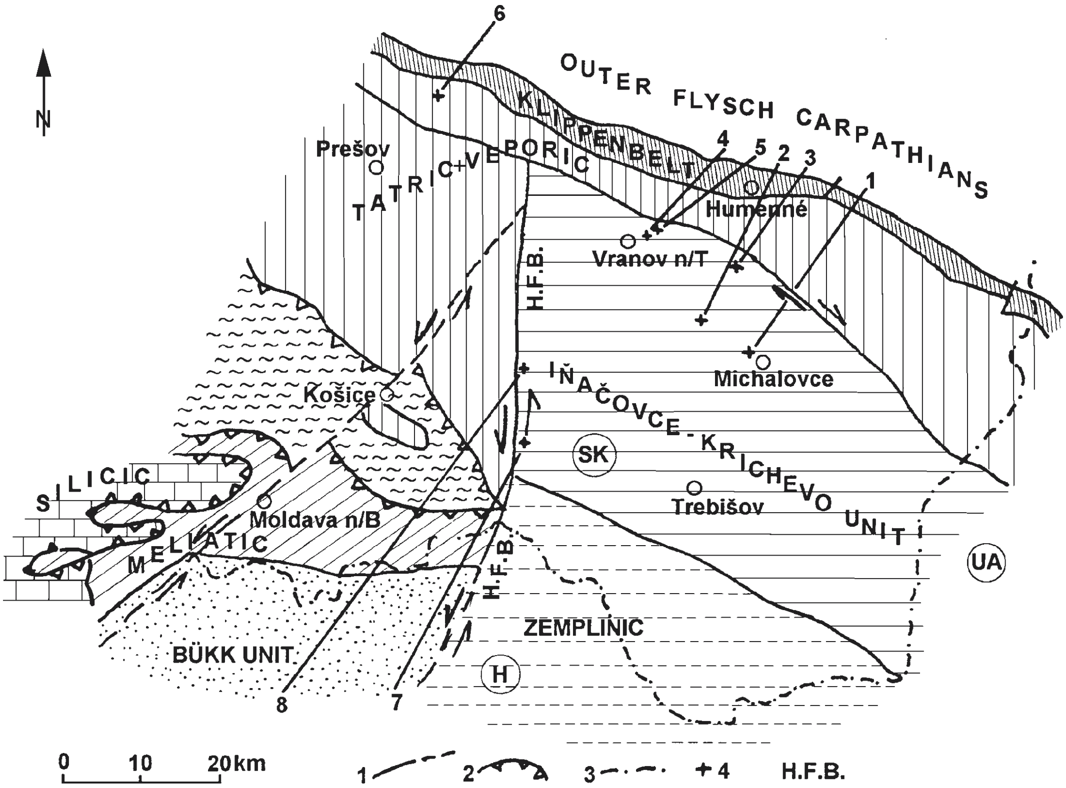

Fig. 2. Recent situation of the pre-Tertiary units in the East Slovak Basin basement and in its surroundings. 1 — faults or unspecified boundaries of tectonic unit; 2 — overthrust lines; 3 — state boundaries; 4 — sample sites, loc. Nos. (see Table 1); H.F.B. — Hornád/Hernád fault belt.

Table 1: East Slovak Basin site and locality mean paleomagnetic directions of the present study.

loc. no.	locality/site	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	age	dip°
1	**Hrádok** *rhyolite* SM 1111–19	9/9	183	–53	363	3	**183**	**–53**	10.5–13.2 Ma	-
2a	**Lesné** *rhyolite* SM 1131–32	3/4	312	63	249	8	**312**	**63**	late Badenian	-
2b*	**Lesné** *rhyolite* SM 1133	16/2	311	66	1080	3	**311**	**66**	late Badenian	-
3	**Oreské** *zeolitized tuff* SM 1120–30	11/11	2	44	28	9	**319**	**60**	early Badenian	226/35
4	**Kučín** *zeolitized tuff* SM 1134–42	8/9	8	24	61	17	**304**	**75**	early Badenian	200/55
5	**Nižný Hrabovec** *zeolitized tuff* SM 1192–1203	6/12	**95**	**–54**	34	12	63	–20	middle Badenian	208/50
6	**Lada** *claystone* SM 1143–69	20/21	**289**	**57**	14	9	281	30	Eggenburgian	269/28
7	**Slančík** *andesite* SM 1176–83	6/8	**338**	**56**	24	14	338	46	middle Sarmatian	336/10
8*	**Svinica** *tuff* SM 1184–91	11/8	17	61	50	6	0	62	late Sarmatian	272/9

n/no — numbers used/collected samples; D°,I° (D_C°, I_C°) — declination, inclination before (after) tilt correction; k and α_{95}° — statistical parameters (Fisher 1953);
* — statistics is based on number of speciment (n).

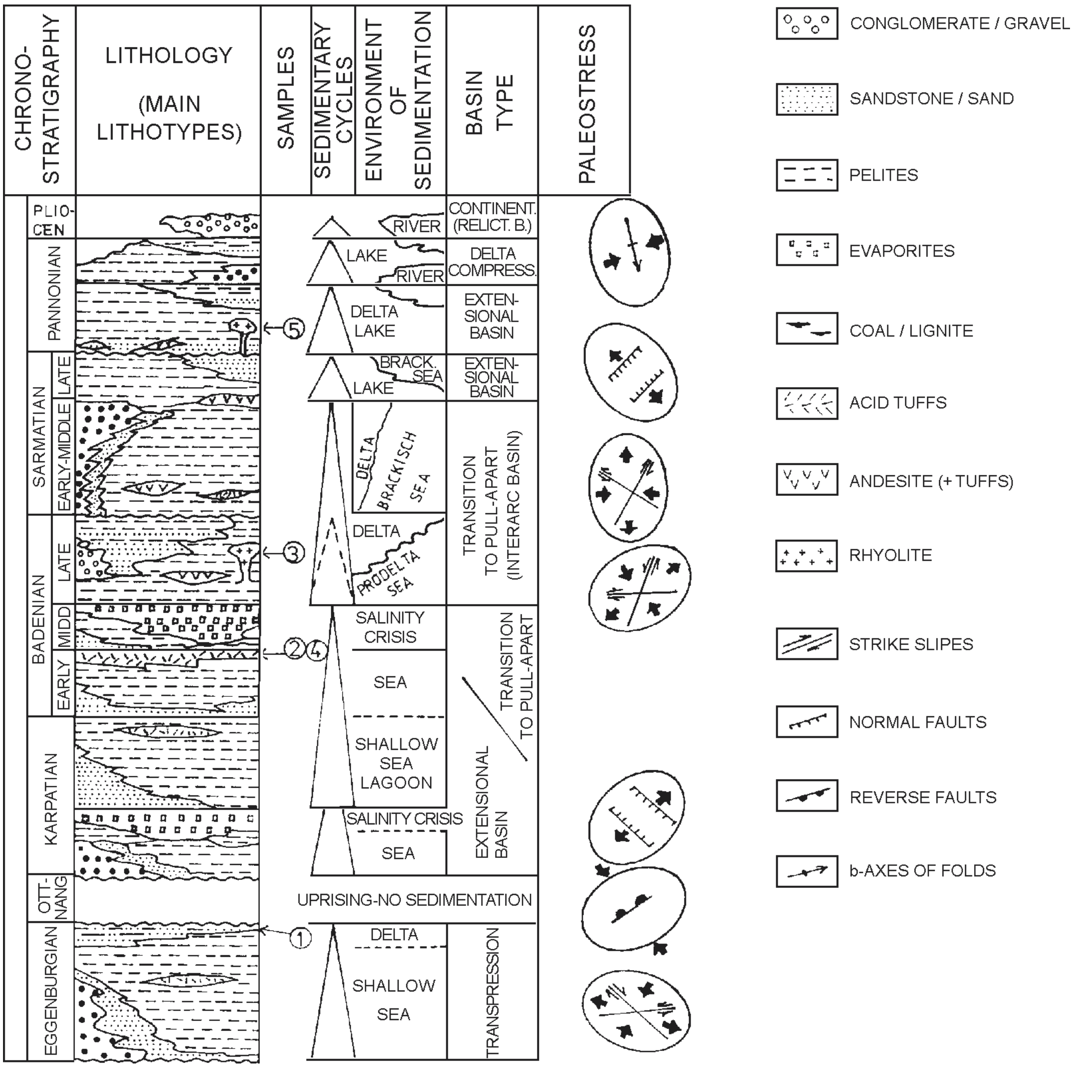

Fig. 3. Schematic lithology, sedimentary cycles and paleostress diagrams of the East Slovak Basin (according to Kováč 1994a, modified).

The zeolitized rhyolite tuffs are weakly magnetic. This explaines that the demagnetization curves of the NRM are less smooth than those of the rhyolites. Nevertheless, the components of the NRM are well defined (Fig. 7). The IRM acquisition curves suggest that the magnetic mineral is soft (Fig. 6b), and this combined with the stability (Fig. 5b) or moderate increase (Fig. 7) of the susceptibility on heating, suggest that the NRM is most likely residing in magnetite. The site mean paleomagnetic directions are statistically fairly well defined and depart significantly from that of the local direction of the present Earth's magnetic field (Table 1).

The sediments are of different ages and of different lithologies. The Eggenburgian locality, Lada, where several horizons of the clay stone intercalations in the thick sandstone sequence were sampled, yield a good paleomagnetic direction. The Zijderveld diagrams reveal that the NRM is practically single-component (Fig. 8), the main carrier of the magnetization is magnetite (Fig 8a, Fig. 6b), though sometimes goethite may also contribute to the NRM (Fig. 8b). At Lada, the majority of the samples carry characteristic remanence, with direction significantly different from that of the Earth's present field at the sampling area (Table 1). Of the sediments collected at other localities, Nižná Myšľa was unstable, while Svinica yielded a mean direction which is interpreted as a recent overprint (Table 1 and Fig. 9). At Slančík, 6 samples of the collected 8 are clustered away from the present field direction (Table 1 and Fig. 10), while two are aligned with the present field (rejected when computing the locality mean direction).

Discussion

The East Slovak Basin is situated on the ALCAPA (and Tissia) overriding plate of a subduction/collision zone, close to the inner margin of the accretionary prism. The present (assumed) configuration of the flysch accretionary prism (Outer Carpathians and the arcuate shape of the Carpathians) suggests that the collision between the subducting North European and the overriding Carpathian-Pannonian plates was oblique. The oblique collision, proceeded by oblique subduction resulted in

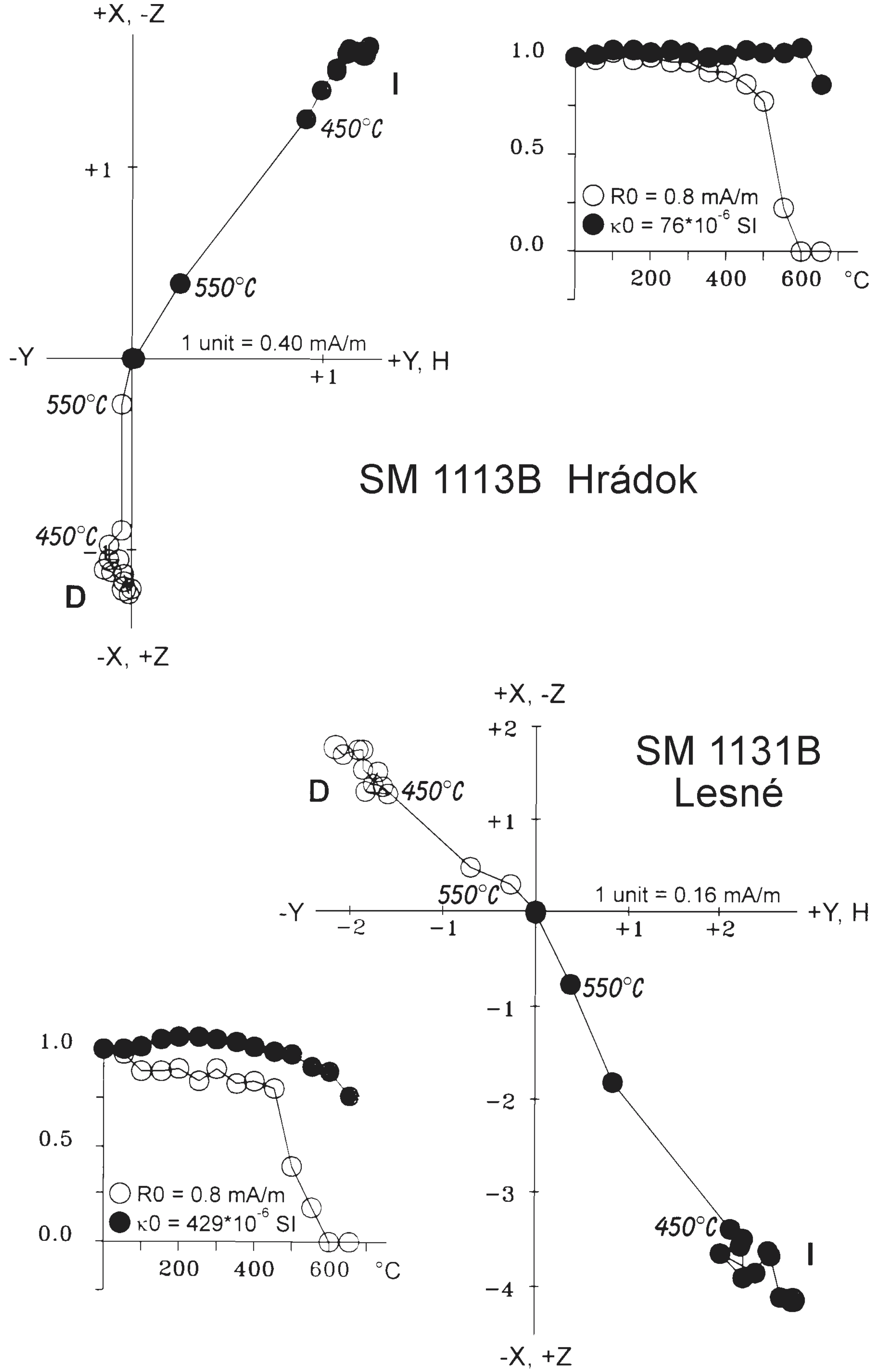

Fig. 4. Typical behaviour of the rhyolites on thermal demagnetization. Modified Zijderveld diagrams and normalized intensity/susceptibility (circles/dots) curves.

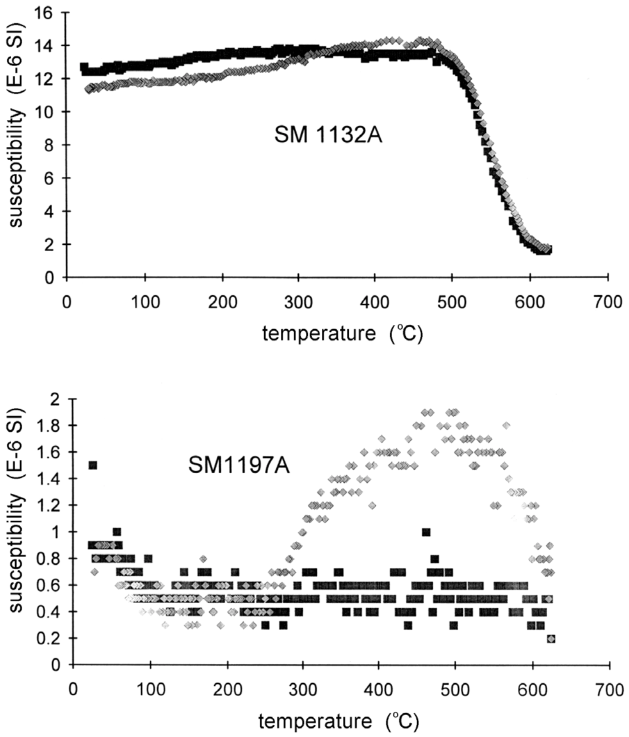

Fig. 5. Low-field susceptibility versus temperature curves for Lesné (upper diagram) and Nižný Hrabovec (lower diagram). Heating curves are of darker, cooling curves are of lighter colour.

compression oblique to the convergence zone, and produced shear stress along it. It is generally accepted that in the Carpathians the oblique convergence led to bending and final formation of the accretionary prism, i.e. to the whole arcuate shape of the Outer Carpathians. Along and near the convergent margin, pull-apart or shear basins were generated. Such basins connected to the Western Carpathians are the Vienna Basin, the narrow furrows along the inner side of the Pieniny Klippen Belt in NW Slovakia, the Transcarpathian Basin, including its autonomous western part, the ESB.

The ESB was regarded as a pull-apart basin opened by a major right-lateral strike-slip fault of NW-SE direction (Royden & Báldi 1988; Vass et al. 1988). The lateral displacement or wrench faulting caused the breaking up of the area into elongated blocks by "en echelon" faults and the blocks moved relative to each other along faults, corresponding to Riedel Shears of the strain ellipsoid. The elongated blocks, termed "Riedel Flakes" (Dewey 1982) when generated by right lateral strike slip, are expected to suffer clockwise rotation. Contrary to the prediction of the model by Royden & Báldi (1988), the paleomagnetic results from the ESB suggest counterclockwise rotation.

The oldest rock where we observed CCW rotation is Eggenburgian. The angle is about 80°. This locality (Lada) is in the transition zone between the Central Carpathian flysch basin and the ESB (in fact, it is lying on the Central Carpathian Paleogene).

East of this locality, in the ESB proper, the angle of rotations is smaller at the same time, the rocks studied here are also younger. The oldest of them are the zeolitized rhyolite tuff, which yields an overall mean direction of D = 297° I = 64°, k = 28, α_{95} = 24° (the statistics are based on the number of sites, which is 3) when sites 3 and 4 are corrected, site 5 is not corrected for the local tilts (in all other combinations the tilt test is negative, tilt test by Watson & Enkin 1993). Among the younger rocks, sampling points 2 and 8 are characterized by moderate CCW declination deviation and point 1 shows no deviation from the present North (Fig. 10).

Orlický (1996) and Nairn (1967) observed similar rotations on late Badenian-Sarmatian igneous rocks in the southern margin of the basin. Thus we can conclude that with the exception of 1 site, i.e. the youngest one, all observations suggest that the major part of the ESB basin (i.e. the part that started to open after the Ottnangian, and subsided most intensively in the Sarmatian) rotated in a CCW sense by an average angle of about 45°. The rotation observed at Lada seems to be larger and is difficult to relate to the history of the major part of the ESB. Perhaps it characterizes the movements of the Central Carpathian area more than that of the ESB.

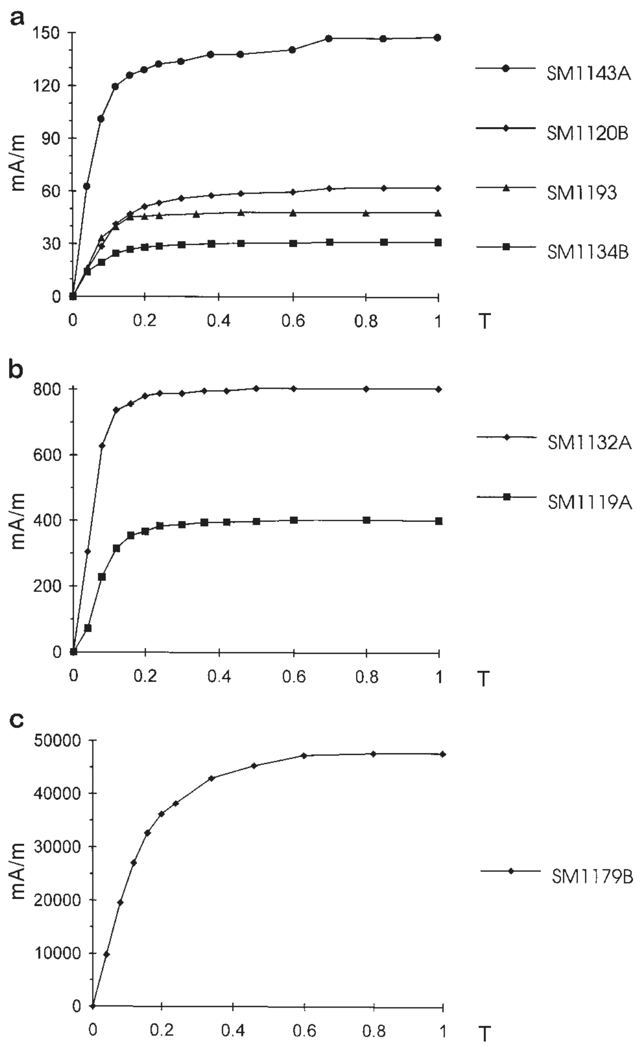

Fig. 6. IRM acquisition curves. **a** — Lada (SM1143A) and examples for zeolitized rhyolite tuffs; **b** — rhyolite doms; **c** — Sarmatian sediment Slančík.

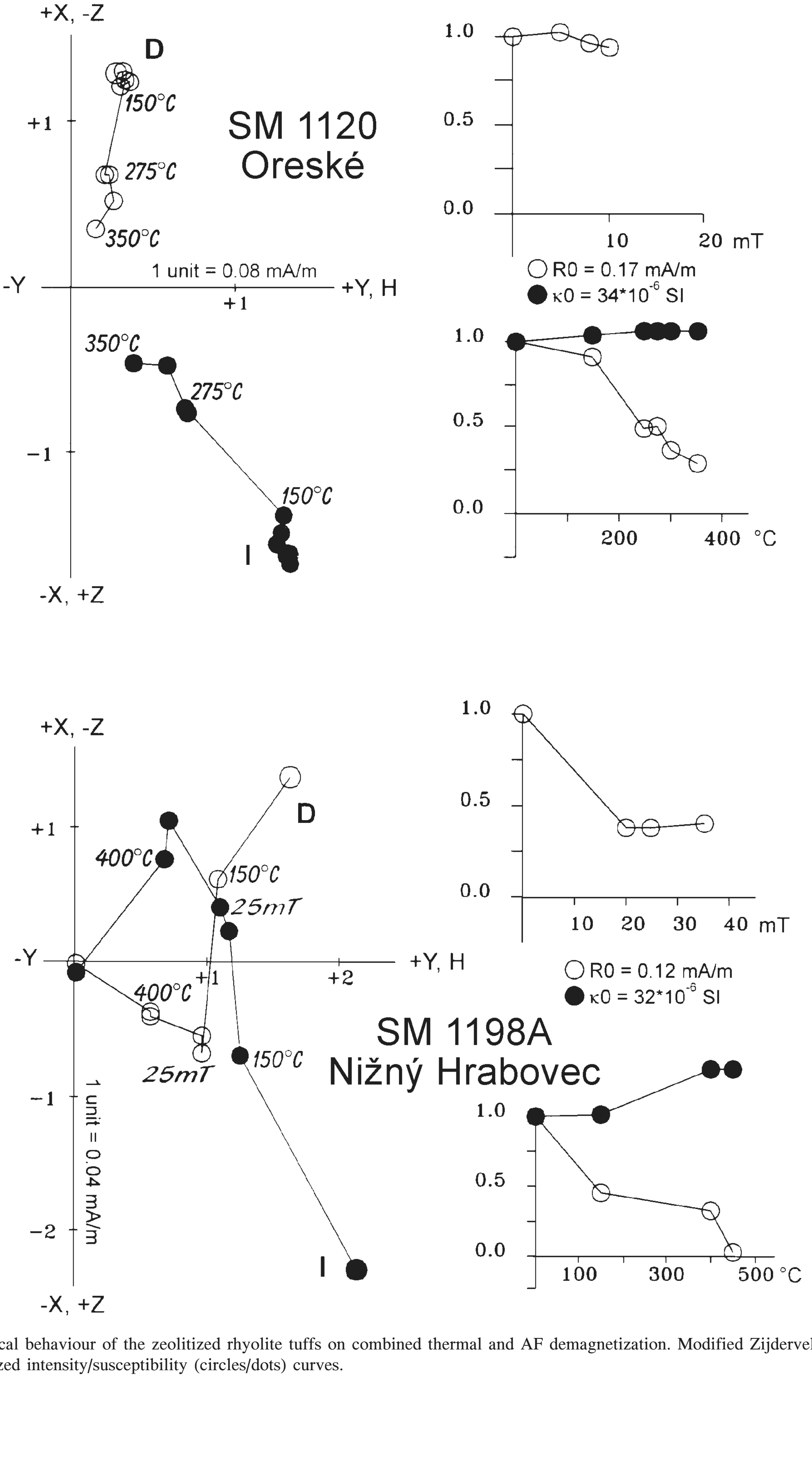

Fig. 7. Typical behaviour of the zeolitized rhyolite tuffs on combined thermal and AF demagnetization. Modified Zijderveld diagrams and normalized intensity/susceptibility (circles/dots) curves.

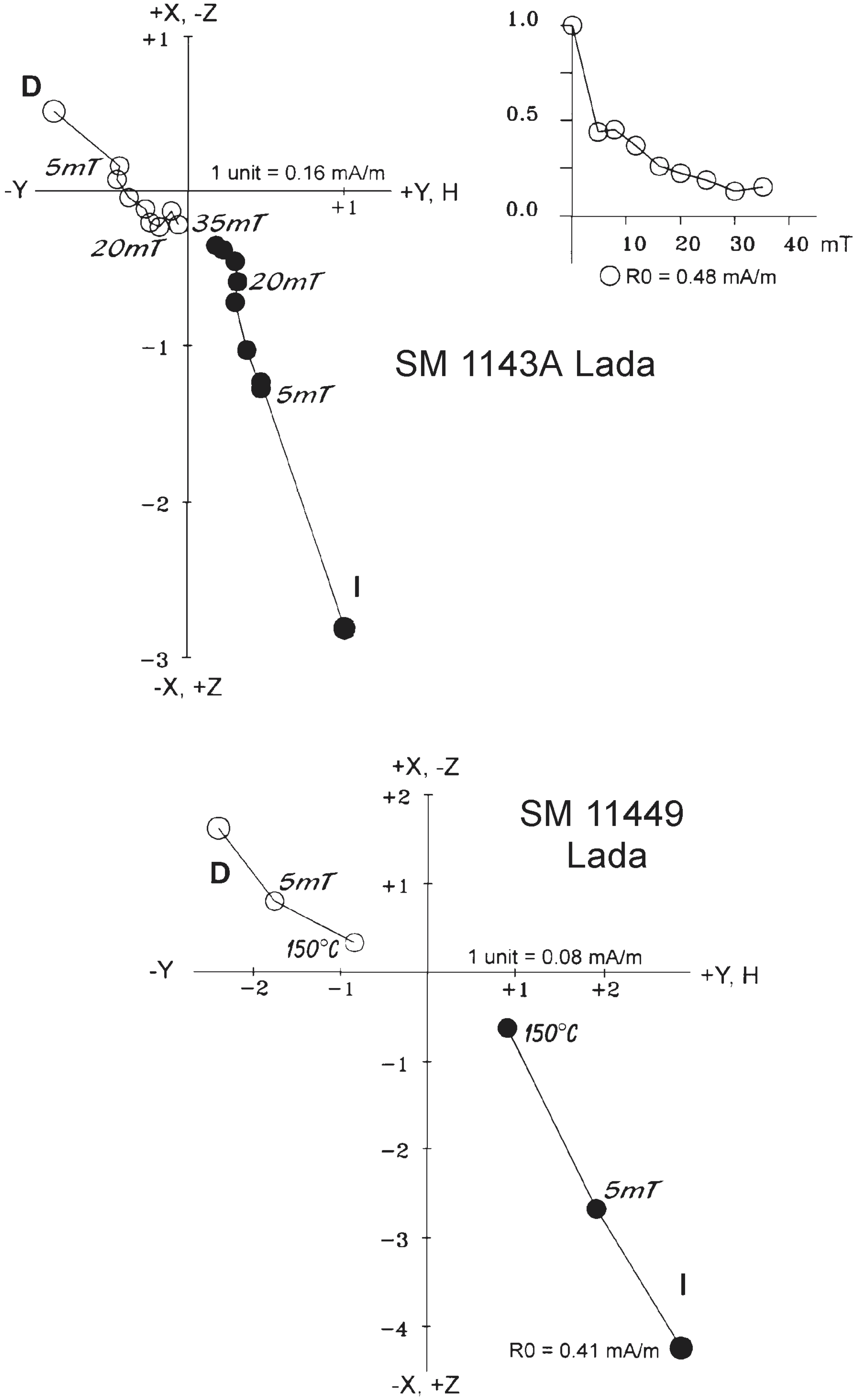

Fig. 8. Typical behaviour of samples from Lada on AF (upper diagram) and combined thermal and AF (lower diagram) demagnetization. Modified Zijderveld diagrams and normalized intensity (circles) curves.

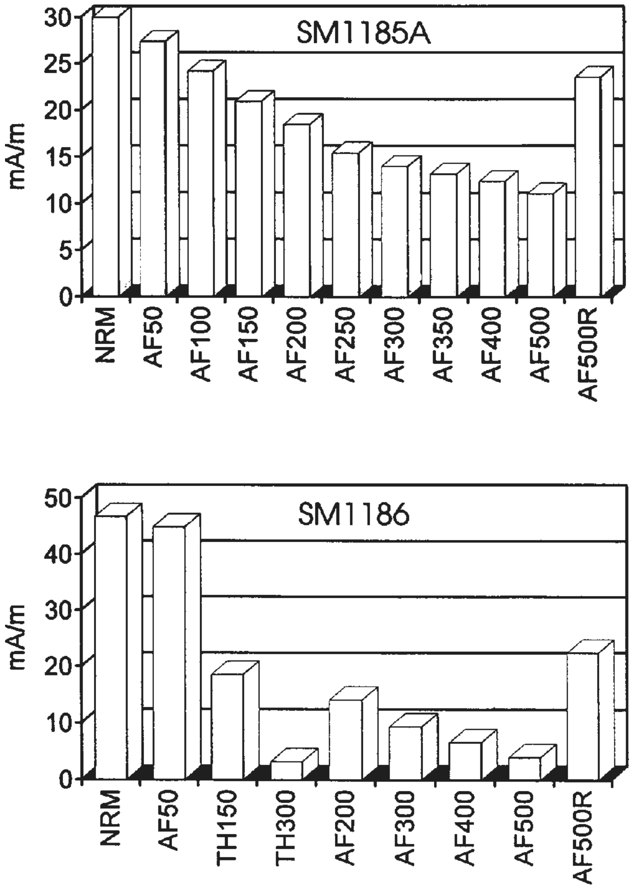

Fig. 9. Svinica. Two examples showing the viscous character of the remanence. Upper diagram: the Z component of the NRM on AF demagnetization up to 50 mT (AF500), stored in the laboratory in a vertical position for 3 weeks and measured again (AF500R). Lower diagram: the Z component of the NRM on combined AF and thermal demagnetization up to 300 °C, stored in the laboratory in a vertical position for two months, demagnetized in an AF field of 20 mT (AF200) measured and demagnetized up to 50 mT (AF500). Stored for another 3 weeks in the lab with Z in the same vertical position and remeasured (AF500R). It is important to note that when the specimens are stored in the laboratory field between demagnetization runs, the original NRM directions, which were close to the present field, are not recovered during the new demagnetization run.

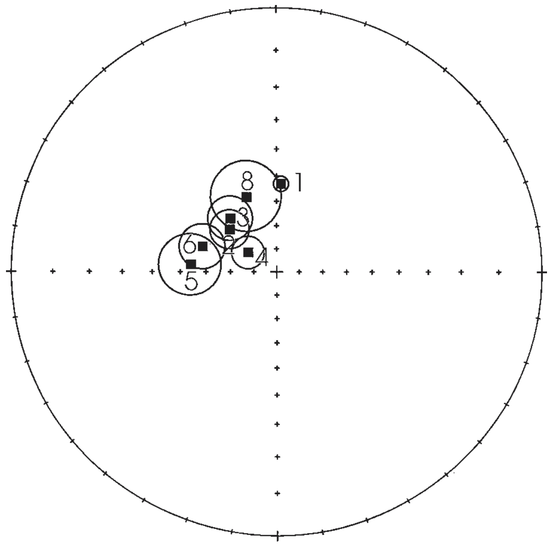

Fig. 10. Site and locality mean paleomagnetic direction with confidence circles. The numbers refer to Table 1 (data in heavy print). Stereographic projection. All inclinations are positive on the plot, i.e. site mean directions with reversed polarity (1 and 5) are shown as equivalent normal polarity directions.

However, the rotation of the ESB may be connected to that of the Tokaj Mts., due to the similar angle and timing of the rotation (Márton & Pécskay 1995). Concerning the exact timing of the rotation, the CCW rotation of the mid-late Sarmatian Slančík, in addition to the previously existing indications obtained on igneous rocks of Sarmatian age, points to the late Sarmatian–early Pannonian time. We cannot be more precise, since the only reliable paleomagnetic result in our data set, showing affinity to stable European directions, is Hrádok at Michalovce, (rhyolite extrusion) with K/Ar ages ranging from 10.9 to 14.3 Ma B.P. (Merlich & Spitkovskaya 1974; Vass et al. 1978)

Nevertheless, the constraint on timing is precise enough to suggest that the major part of the ESB together with the Tokaj area must have been emplaced 4–5 Ma later than the Central Carpathian-North Hungarian block, with the North-South running zone as the best candidate for a boundary between them in the area of the present Slánské vrchy Mts. in the Hornád/Hernád fault zone. The structural unroofing of the basement of the East Slovak Basin (in the sense of Soták et al. 1993), when the Iňačovce-Krichevo Unit was exhumed during the Miocene extension can be corelated with the above mentioned CCW rotation of the basin sedimentary fill contemporaneus with volcanics.

The origin of the CCW rotation in the area of the East Slovak Basin may also be explained in another way. At least two basement units, the Zemplinic Unit and Iňačovce-Kritchevo Unit, have affinities to the Tissia Superunit. The Zemplinic Unit was correlated with the Tissia and/or Mecsek Mts. (Körössy 1963; Grecula & Együd 1977 and others). The Iňačovce-Kritchevo Unit and especially its Iňačovce part, i.e. the unit directly proved by wells as the ESB basement, according to Vozár et al. (1993) may belong to the Szolnok-Maramures Flysch and/or Nádudvar Formation. The Fig. 2 shows that both units could come to present position by left lateral strike-slip from the SW. This left lateral motion preceded the left that is CCW rotation of the ESB. The relation between sens of the strike-slip motion and the following block rotation is documented by Torres & Slivester and Sengör, Gorur & Saroglu (in Allen & Allen 1992).

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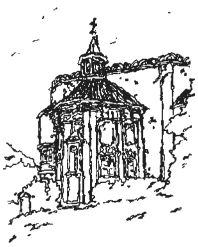
NEW TRENDS IN GEOMAGNETISM VII, PALAEO, ROCK AND ENVIRONMENTAL MAGNETISM

7th Castle Meeting

O. Orlický, I. Túnyi and E. Petrovský (Eds.)



Moravany Castle Meeting, Slovak Republic
June 19–25, 2000

Foreword

The 7th scientific meeting ***New Trends in Geomagnetism*** follows the previous six meetings, focused on the recent progress in paleomagnetism, rock magnetism and environmental magnetism, held in 1988 at Liblice, in 1990 at Bechyně, in 1992 at Smolenice, in 1994 at Třešť, in 1996 at Topoľčianky and in 1998 at Hrubá Skála. This biennial meeting was organized by the Academies of Sciences of the Czech and Slovak Republics and held at the beautiful Slovak castle of Moravany. The meeting is traditionally a suitable place for informal discussions and exchange of the latest knowledge among scientists from many European and non European countries. The general topics are: paleomagnetism and tectonics, archeomagnetism, assessment of the quality of palaeomagnetic and rock-magnetic data, general rock magnetism and its physical background, magnetostratigraphy, environmental magnetism, relations between palaeomagnetism and global changes as well as new techniques and approaches.

About 70 participants from some 26 countries were registered for the Moravany Castle Meeting. The Local Organizing Committee appreciate the offer of the *GEOLOGICA CARPATHICA* Editorial Board to publish the short contributions of the meeting in this journal. They are ordered and grouped according to their link to individual topics. The papers are in alphabetical order according to the name of the first author within the following topics: 1) Palaeomagnetism and Tectonics; 2) Archeomagnetism; 3) General Rock Magnetism and its Physical Background; 4) Magnetostratigraphy; 5) Environmental Magnetism; 6) New Techniques and Approaches.

We believe that this is an excellent opportunity to extend the scope of the rock-magnetic, environmental magnetic and paleomagnetic research to the scientific community engaged in geological research. On the other hand, the participants of the meeting can learn more about the geological studies and find it useful to publish some of their own results with geologically oriented outputs in this journal. The organizers would like to express their thanks to *Jozef Michalík*, Chief Editor and *Eva Chorvátová*, Managing Editor, for their helpful activity.

1. PALEOMAGNETISM AND TECTONICS

1.1 IMPLICATIONS OF SECONDARY PYRRHOTITE REMANENCES IN METASEDIMENTS OF THE TETHYAN HIMALAYA: TECTONICS, COOLING HISTORY, AND EARTH FIELD REVERSALS

E. APPEL, C. CROUZET and E. SCHILL

Institut für Geologie und Paläontologie, Universität Tübingen, Sigwartstrasse 10, 72076 Tübingen, Germany; erwin.appel@uni-tuebingen.de

Key words: Pyrrhotite, secondary magnetization, thermoremanence, reversal record, continental tectonic, cooling history.

It is known that in low metamorphic marly carbonates, pyrrhotite is formed at elevated temperatures (anchimetamorphic to greenschist zone) by the breakdown of primary magnetite and pyrite. Assuming a homogeneous initial rock facies the pyrrhotite to magnetite content can used for geothermometry in a temperature range where other thermometers are rare. During cooling pyrrhotite acquires a (p)TRM. The dominance of ferrimagnetic pyrrhotite is clearly indicated by thermal demagnetisation of NRM and SIRM and also from high temperature runs of susceptibility.

Secondary pyrrhotite remanences are found to be generally very stable in Mesozoic low grade metamorphic marly limestones of the Tethyan Himalaya. They occur all along the Himalayan arc and provide valuable data to test models of block rotation, i.e. oroclinal bending and rotational underthrusting. Also they reveal information about the thermotectonic history, i.e. the sequence of cooling, main Himalayan deformation and "long wave" folding. Many demagnetisation paths show nearly antiparallel components unblocked in different temperature intervals, both carried by pyrrhotite. We interpret this as the record of polarity transitions by pTRMs in single specimens. A polarity sequence comparable to magnetostratigraphy can be established. This constrains implications on cooling rates, ages of cooling and palaeotemperatures.

The age of remanence acquisition is a matter of debate but can be related to the last cooling event and exhumation. There are only very few geochronological studies available in the Tethyan Himalaya. However, cooling ages in the Higher Himalaya clustering around 20 Ma may give an indication. If cooling rates have exceeded about 1 °C/kyr, even the Earth magnetic field behaviour during polarity transitions may be resolved.

The possibility in retrieving this record through thermal demagnetisation in the laboratory requires the independence of successive pTRMs and the equality of blocking and unblocking temperatures (for similar cooling rates), which is valid only for single-domain particles. Laboratory unblocking temperatures can be corrected into blocking temperatures for field cooling, based on the relaxation law and temperature dependent mineral magnetic properties. No pyrrhotite particles could be identified in Tethyan Himalayan metacarbonates by optical microscopy. This suggests that the grain size is submicroscopic and thus below the SD-MD transition.

In the talk we present examples from Tethyan metacarbonates all along the Himalayan arc, sampled so far during the past 12 years, to address the potential use of the different aspects mentioned above.

1.2 PALAEOMAGNETIC INVESTIGATIONS OF SEDIMENTS FROM LAMA LAKE, NORTHERN CENTRAL SIBERIA

U. FRANK and N.R. NOWACZYK

GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany; ufrank@gfz-potsdam.de

Key words: Lacustrine sediments, paleomagnetism, Late Quaternary, Northern Central Siberia.

Two cores from Lama Lake, Northern Central Siberia, which were recovered within the scope of the German-Russian research project Taymir, were subjected to detailed paleomagnetic studies. According to pollen stratigraphy the 11 m long core PG1111 comprises the last 17 ka whereas Core PG1341 with 19 m length probably extends to the past 30 ka. Subsampling of the piston cores, seperated by about 20 km, was carried out quasi-continuously with cubic plastic boxes (20×20×18 mm). The palaeomagnetic investigation comprises the measurement of low field magnetic susceptibility κ_{LF} and natural remanent magnetization (NRM) including stepwise AF demagnetization. The directions of the characteristic remanent magnetization (ChRM) were derived from vector analysis of the results of sucsessive demagnetization steps. Further rock magnetic investigations yielded magnetite as the dominant carrier of the magnetic signal (Nowaczyk et al. 2000).

In order to test the reliability of the reconstructed signal by intralake comparison of the records, both cores were correlated. This was done on base of all parameters available including the median destructive field of the NRM and the Q-Ratio. Due to highly scattered signal in PG1111 and PG1341 no correlation could be achieved for the lowermost 2 and 8 m of the cores, respectively. But there is a good agreement between the NRM-intensity, susceptibility and Q-Ratio records obtained from the uppermost 9 m, indicating that the sediment sequences of both cores are incomplete. The similarities between the inclination and declination records are limited, although the inclination and declination records of the single cores could partly be correlated with records from Lake Baikal and Lake Aslikul.

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1.3 PALEOMAGNETISM OF UKRAINIAN CARPATHIAN NEOGENE VOLCANITES AND LOCAL TECTONICS

A. GLEVASSKAYA

Institute of Geophysics, National Ukrainian Academy of Sciences, Palladin av. 32, 0380 Kiev-142, Ukraine

Key words: Neogene volcanites, paleomagnetism, paleotectonics, Ukrainian Carpathians.

Recent paleomagnetic studies in Western Carpathians have revealed large Paleogene and Lower Miocene rocks rotations. Paleomagnetic results from Eastern Ukrainian Carpathians (Mikhailova et al. 1974; Glevasskaya 1985) have been analysed to estimate if similar rotations and other postvolcanic tectonics occurred in this territory.

Western neovolcanic Carpathians region is known as central part of Vigorlat-Gutin andesitis-basaltic ridge, which trasses Transcarpathian deep fault zone; burial andesitic-dacitic ridge directed along Peripannonian fault and rhyolitic Beregovo-Muzhievo paleovolcanic structures belonging to the Pannonian massif periphery. According to regional magnetostratigraphical cross-section (Glevasskaya 1996), time of volcanic activity coincides with normal Transcarpathian (12.4–8 Ma) and prevailing reversal Uzhgorod (16–12.4 Ma) geomagnetic superchrons subdivided on several magnetic N and R orthochrons with inversion borders. Paleomagnetic data show that each volcanic structure is unhomogenous and consists of some volcanic buildings, whose age becomes younger from NW to SE and from S to N. The NRM polarity and directions of original magnetization have been obtained after T and AF demagnetization the Tellier method has been applied to paleointensity indications, magnetic-mineralogical data have been received too (Mikhailova, Glevasskaya & Tsykora 1974; Glevasskaya 1996). All these data have been used for determining of paleomagnetic markers and its applications to geological correlation of separate volcanic bodies and massifs. It is important, that paleomagnetic parameters of stable, anomalous and inversion zones of paleomagnetic cross-sections were determined. Available D and J values of the stable polarity zones are typical for Later Neogene APW coordinates are (ϕ = 74–80° N, Λ = 178–220° E). Anomalous paleomagnetic directions in these sections are interpreted as paleocentury variations and near inversion zones and have not any tectonic information (in some massifs of Makovitsa, Dehmanov Vrh and other in Vigorlat-Gutin ridge). Significant and steady D-variations may be connected with more scale tectonics in eastern part of burial ridge, Oash massif and the most ancient part of Sarmathian volcanic and hypabissal intrusive bodies of Viskovo region. Possibilities of scale tectonic rotation in these region are studying.

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1.4 PALAEOMAGNETISM OF A TRIASSIC-JURASSIC BOUNDARY SECTION: CSŐVÁR, HUNGARY

D. HALÁSZ[1], E. MÁRTON[2], J. HAAS[3] and J. PÁLFY[4]

[1]Eötvös Loránd University, Faculty of Sciences, Dept. of Geology, Múzeum krt. 4/a, H-1088 Budapest, Hungary
Eötvös Loránd Geophysical Institute, Paleomagnetic Laboratory, Columbus u. 17-23, H-1145 Budapest, Hungary; bodorka@ludens.elte.hu
[2]Eötvös Loránd Geophysical Institute, Paleomagnetic Laboratory, Columbus u. 17-23, H-1145 Budapest, Hungary; paleo@elgi.hu
[3]MTA Research Team, Dept. of Geology, Eötvös Loránd University, Múzeum krt. 4/a, H-1088 Budapest, Hungary; haas@ludens.elte.hu
4Hungarian Natural History Museum, PO Box. 137, H-1431 Budapest, Hungary; palfy@paleo.nhmus.hu

Key words: Triassic-Jurasic boundary, magnetostratigraphy, overprint.

The upper Triassic-lower Jurassic section at the Castle Hill of Csővár is one of the few marine sections in the world which, based on paleontological data and sedimentological observations seems to be continuous across the Triassic-Jurassic boundary. That is why we decided to study this section for magnetostratigraphy.

Apart from the favourable circumstances like the good condition of the section for paleomagnetic sampling, current complex sedimentological, paleontological, and stable isotope investigations of the profile, there was a particular reason for our interest. Namely that a detailed magnetostratigraphy profile of lacustrine sediments in the Newark Basin (eastern North America) revealed a short reversed polarity zone at the uppermost Rhaetian (Kent et al. 1995), which promised an excellent tool in world-wide definition of the Triassic-Jurassic boundary.

We collected 54 independently orientated samples representing 44 m of the 60 m long section, which contains the boundary. This segment of the section contained also some allodapic layers and slumps.

Paleomagnetic measurements of the samples were carried out in the Paleomagnetic Laboratory of ELGI. As a result of AF, thermal or combined demagnetization and the study of the magnetic mineralogy we achieved the following results: 25 samples are very likely to possess primary remanence. These are all of normal polarity. Their mean direction is D = 289°, I = 38°, k = 16, $\alpha 95$ = 7° in geographic system, Dc = 300°, Ic = 43°, k = 18, $\alpha 95$ = 7° in tectonic system. These directions fit well an earlier defined direction for a locality of similar age nearby (Dc = 291°, Ic = 49°, k = 20, $\alpha 95$ = 10° (Márton 1998).

There are samples collected from the "transition zone" between the biostratigraphically constrained highest Triassic and lowest Jurassic strata, which are indeed of reversed polarity. However, the remanence in this case is secondary, clearly post-dating the last significant horizontal movement of the area (probably 14.5 Ma — Márton & Pécskay 1998). The mean direction of this group is D = 189°, I = –65°, k = 165, $\alpha 95$ = 5° in the geographic system. The secondary remanence is residing in goethite that appears under the microscope as the alteration product of pyrite. The NRM of the rest of the samples is exhibiting great circle distribution of the directions on demagnetization. Most of these samples are inside or close to the "transition zone".

As it is clear from both the declination and inclination, the reversed polarity observed in the Csővár section cannot be due to a field reversal in the Mesozoic. Moreover the overprint of reversed polarity causing great circle distribution observed in the "transition zone" is also likely to be due to Cenozoic processes. Thus, our results are in favour of an uninterrupted normal polarity chron across the Triassic-Jurassic boundary.

Finally, we emphasise that we were able to distinguish between Mesozoic and Neogene remanences because the Csővár section belongs to a terrain, which rotated significantly after the Mesozoic. Otherwise the reversed magnetization could have easily been regarded as a result of a field reversal at the Triassic-Jurassic boundary, i.e. could have lead to a total misinterpretation of the data.

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1.5 "SYNTECTONIC" REMAGNETIZATION

B. HENRY

Géomagnétisme et Paléomagnétisme, IPGP and CNRS, 4 avenue de Neptune, 94107 Saint-Maur cedex, France; henry@ipgp.jussieu.fr

Key words: Paleomagnetism, statistics, tectonics.

Determination of the direction of "syntectonic" (for paleomagnetists, this word means acquired during a tilting or between two periods of deformation) remagnetization is generally made using progressive unfolding. However such an unfolding is mostly based on a wrong hypothesis, i.e. that the folding percentage is the same at the same time in all the parts of a studied area. Surmont et al. (1990) and Shipunov (1997) proposed another approach, where the determination of the direction of the syntectonic magnetization is independent of the unfolding percentage. This approach is based on the fact that, during progressive unfolding, the paleomagnetic direction evolves on the projection sphere along an arc of small circle. The intersection of the small circles associated with the different sites thus corresponds to the single common direction of magnetization in these different sites during the whole deformation. It therefore represents the syntectonic remagnetization direction and also yields the unfolding percentage in each site during the remagnetization. In order to obtain the best estimate of this intersection, least squares method can be applied. Shipunov (1997) proposed to use a clever vertical projection, but unfortunately such a projection does not keep the angle value and the obtained results are sometimes biased. The best approach remains that by iterative calculation used by Surmont et al. (1990).

This small circle method is however not always wholly satisfying. In fact, it happens that the result is strongly constrained by a single data, for example in case of almost parallel small circles except for one circle, which has a very different orientation. If this last circle is badly determined, the result can be biased. Badly determined small circle can be first related with an imprecisely specified paleomagnetic direction. In order to reduce this problem, it is proposed to apply, for the least-squares calculation, a weighting for each small circle by a precision parameter (for example Fisher's k or $\sqrt{k}$) associated with its paleomagnetic direction. For another hand, dip azimuth generally cannot be always very precisely measured. For strongly dipping or overturned formations, that can give a very large error in small circle determination. The best way to have actual meaning of a syntectonic remagnetization direction is then to determine the confidence zone, associated with this direction and integrating the uncertainty on dip measurement. For this, the parametric bootstrap is particularly convenient. For each site, the uncertainty on the dip can be determined for example by repetitive measurements on the field. During the bootstrapping, the resampling is applied on the different small circles, but each small circle at each resampling is itself determined by bootstrapping the dip value within its uncertainty window (or directly the dip measurements on the field). Using both weighting by precision parameter and parametric bootstrap, the syntectonic remagnetizations with their confidence zone are therefore accurately determined. Some examples are presented.

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1.6 PALEOMAGNETIC AND ROCK MAGNETIC STUDY OF THE EARLY PALEOZOIC METAMORPHIC COMPLEX OF RUDAWY JANOWICKIE (WEST SUDETES, POLAND)

M. JELEŃSKA[1], T. WERNER[1] and S. MAZUR[2]

[1]Institute of Geophysics, Pol. Acad. Sci., Ks. Janusza 64, 01-452 Warsaw, Poland; bogna@igf.edu.pl
[2]Institute of Geological Sciences, Uniwersity of Wrocław, Pl. M. Borna 9, 50-250 Wrocław, Poland

Key words: Paleomagnetism, rock magnetism, metamorphic complex, Paleozoic deformation.

Rudawy Janowickie Mts. are the part of the Karkonosze-Izera Massif which crops out in the West Sudetes on the NE margin of Bohemian Massif. This is a fragment of the Variscan crystalline basement which comprises the Early Carboniferous Karkonosze granite pluton surrounded by its Neoproterozoic–Paleozoic metamorphic envelope. The latter can be subdivided into three major tectonic units (Mazur & Kryza 1996; Mazur et al. 1998): (1) the Izera-Karkonosze unit consists of gneisses and mica schists and experienced MP metamorphism, generally below the amphibolite facies, followed by a relatively HT and LP event. (2) the South Karkonosze unit consists of phyllites and metabasites. It underwent HP/LT blue-schists facies metamorphism overprinted by a MP greenschist facies episode. (3) the Leszczyniec unit comprises metabasites and gneisses which underwent relatively HP metamorphism reaching up the epidote-amphibolite facies. The protolith ages and the age of metamorphism are poorly constrained. Recent U-Pb dating gave ages of ca. 500 Ma for the gneisses of the Izera-Karkonosze unit and for metabasites of the Leszczyniec unit (Kroner et al. 1994; Oliver et al. 1993). The Karkonosze granite has been dated, using Rb-Sr whole rock method, at 329 Ma (Duthou et al. 1991). The South Karkonosze unit and the Leszczyniec unit are interpreted as nappes that emplaced ocean floor and sediments on a top of a continental passive margin. They were thrusted towards NW on an autochthonous pre-Variscan basement of the Saxothuringian basin, and modified by the Early Carboniferous SE- extentional collapse. Finally they were intruded by Karkonosze granite. A total of 145 hand samples and 52 drilled cores were collected in 12 localities (8 within the Leszczyniec unit, 4 within the Izera-Karkonosze unit (Kowary formation) and 1 within the South Karkonosze unit (Niedamirów formation)). Thermal demagnetization of saturation remanence and hysteresis parameters were used to identification of magnetic minerals. Magnetite in PSD state is the main magnetic carrier, sometimes associated with goethite. In two localities hematite was found. In 5 localities represented by schist and metabasite susceptibility was carried by ferromagnetic minerals. The structural and AMS data revealed that the Leszczyniec nappe shows a different structural pattern in comparison to the underlying tectonic units. The structural stretching lineation L1 and magnetic lineation Kmax are mostly WNW–ESE oriented over the majority of the Karkonosze-Izera massif and nearly perpendicular to the general trend of L1 and Kmax within the Leszczyniec unit. The AMS data revealed the important discrepancy between the orientation of L1 and Kmax in metabasites and gneisses within the Leszczyniec unit itself. This discrepancy seems to preclude the simultaneous deformation of metabasites and gneisses. It indicates rather different metamorphic. A sinistral shear of the metabasites, coeval with the progressive metamorphism of these rocks, was probably connected with underthrusting beneath the active plate margin. In contrast, the opposite dextral shear of the gneisses, accompanied by the retrogressive metamorphism, was related to the subsequent exhumation of the Leszczyniec unit. Consequently, it seems that the deformation of the metabasites preceded the emplacement of the gneisses. It seems that the deformation of the metabasites preceded the emplacement of the gneisses. Demagnetization of NRM was made applying AF treatment. Thermal demagnetization was not possible for the majority of samples because heating caused chemical changes of magnetic minerals and an increase of remanence. Three groups of high stability characteristic remanence directions were isolated. Providing that Kmin distribution is uniform for the area we applied correction for tilting different for each locality. The amount of tilting was deduced from Kmin distribution. The paleopoles derived from these directions are placed in Carboniferous segment of APWP for Baltica (Torsvik et al. 1992) for group 3, in the vicinity of Silurian-Ordovician boundary (group 2), and not far from the Early Ordovician poles for Baltica (group 1). Group 3 of ChRM directions is easy to interpret as Carboniferous overprint. Group 2 can represent remagnetization at Silurian-Ordovician boundary. However, the oldest deformation event D1 commanced not late than Silurian. So, the cause of remagnetization is unknown. Group 1 can represent magnetization acquired during or close to the emplacement of rocks. The position of paleopoles to the north from the Baltica poles of ca. 500 Ma age corresponds well with the age of rocks. The direction was found in the rocks of different lithology: metabasites, gneisses and limestones within the Leszczyniec unit. However, the structural and AMS data allow us to conclude that the gneisses of the Leszczyniec unit are younger than the metabasites and were emplaced after metabasites deformation. This conclusion contradicts the assumption that the group 1 of the ChRM directions represent Early Ordovician magnetization. On the other hand close position of the plate of Kmax distribution and the plane of ChRM distribution allow to suspect that the magnetic anisotropy have influenced the NRM directions. This ambiguity can be solved by determination of the age of gneisses of the Leszczyniec unit and more careful examination of connection between NRM and AMS such as unstraining the NRM vectors etc.

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1.7 A METHOD FOR ANALYSING THE SHAPE, ORIENTATION AND DISTRIBUTION OF MAGNETIC GRAINS IN ROCKS: MONCHIQUE MASSIF REVISITED

A. KEATING

Instituto Geofísico da Universidade do Porto Serra do Pilar 4430
Vila Nova de Gaia Portugal; anakeating@yahoo.com

Key words: AMS, magnetic fabric, method.

The anisotropy of magnetic susceptibility (AMS) is a measure of the magnetic fabric in rocks that is easy to obtain in laboratory, and that gives a finite strain measurement. The study of finite and incremental strain on structures, ranging from the micro scale to the macro scale, plays an important role in the understanding and quantification of the structural history and it can have very important technological applications. In this work the sample AMS and the ellipsoid shape and orientation are presented in the geographical referential of the Monchique Massif.

1.8 PALAEOMAGNETIC WORK ON CAPE VERDE ISLANDS

M. F. KNUDSEN and N. ABRAHAMSEN

Department of Earth Sciences, Aarhus University, Finlandsgade 8,
DK-8200 Aarhus N, Denmark; madsfk@geo.aau.dk; abraham@geo.aau.dk

Key words: Paleomagnetism, magnetostratigraphy, Cape Verde Islands, Escabecada, volcanics, eruption frequency, hotspot.

The Cape Verde Rise and hotspot with the Cape Verde Islands (Fig. 1, left) are situated in the North Atlantic some 600–800 km West of Dakar, Senegal. There is still active and historic volcanism on two of the southern islands (Islands of Fogo and Brava). The oceanic islands are situated over the Mesozoic marine magnetic anomalies M2–M16, and the oceanic crust thus have ages between ca. 122 and 140 Ma (Hayes & Rabinowitz 1975; Stillman et al. 1982).

The Cape Verde archipelago is believed to be the result of the eastward movement of the Atlantic oceanic lithosphere over two hotspots, or two active centers in one hotspot, resulting in the horseshoe-shaped configuration of the Cape Verde Islands (Bebiano 1932; Plesner 1998). The hotspot area has caused a large crustal structure forming a topographic dome 500 km in diameter, called the Cape Verde Rise, on which the islands are placed. Since the direction of motion of the Atlantic plate is eastward the islands placed to the west in the archipelago are youngest, which is also evident from the low degree of erosion of these westernmost islands in comparison to the easternmost islands. The island of Maio is believed to be the oldest in the Cape Verde archipelago because of the presence of up-thrusted MORB and Mesozoic sediments. The island has extinct volcanism, which dates between 113 ± 8 Ma and 6.5 ± 0.6 Ma. The younger volcanic activity in the archipelago began in the Tertiary and continued to the present whereas historic activity only has taken place on the islands of Fogo and Brava. So far only a few palaeomagnetic results of the islands have been published (Watkins et al. 1968; Storetvedt & Løvlie 1983; Abranches et al. 1990; Knudsen & Abrahamsen 2000).

During two campaigns (Aug. 1998 and Jan. 2000) we sampled 625 oriented palaeomagnetic cores and hand samples from 5 of the islands, the sites of which are shown in the figure (indicated by an asterisk). The sites cover historic lava flows from the very impressive active volcano of Fogo, Miocene to Pliocene volcanics of Santo Antão and Santiago, and Mesozoic limestones on Maio. The sampling is summarised and the magnetostratigraphic result obtained from a profile at Escabecada in SW Santo Antão is shown (E in the figure). The magnetic polarity was investigated in order to establish a magnetostratigraphic correlation of the lava series and to give an estimate of the ages of the lava flows in the different profiles, using the magnetic polarity in combination with the absolute $^{40}Ar/^{39}Ar$-age.

From Santo Antão palaeomagnetic hand samples were measured in detail from the profile at Escabecada (Fig. 1, right). They belong to the older lava sequences, with an estimated age of 2.71 ± 0.03 Ma. The Escabecada Profile is dominated by thin lava flows alternating with pyroclastic layers, which are cut by numerous dykes.

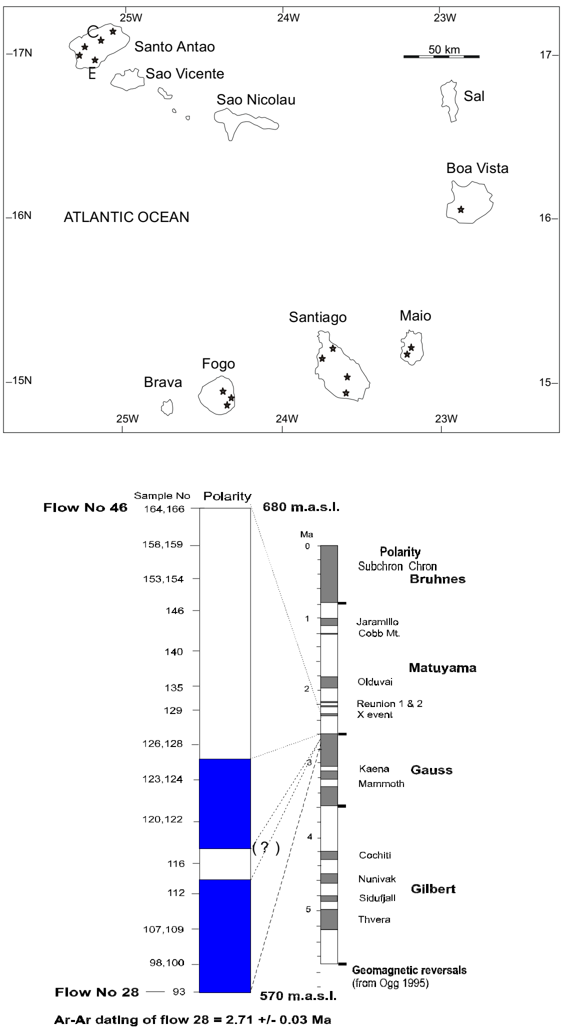

Fig. 1. Cape Verde Islands (up) and Escabecada profile (down).

Directions of the principal components were plotted in stereograms showing the best fits of each flow in the profile. All samples turned out to have fairly high remanent intensities and directionally stable primary magnetizations due to their content of magnetic minerals (magnetite), the primary component being of thermoremanent origin. A number of 22 drill cores from 15 flows have been analysed from ca. 110 m of the profile. All samples show a stable primary magnetization with well-determined best fits. The mean of all the normal polarity samples yields I_m = 25.3°, D_m = 352.9° and α_{95} = 13.4° (N_1 = 10), while the mean of all the reversed polarity samples is I_m = –27.6°, D_m = 191.2° and α_{95} = 12.0° (N_2 = 13). In the figure a tentative correlation between the polarity of the profile and the global polarity scale is suggested. The $^{40}Ar/^{39}Ar$ age of the bottom flow is 2.71 ± 0.03 Ma (Plesner 1998) which constrains this flow to the top part of the Gauss Chron (Marine anomaly C2An.1n). This is in agreement with the normal polarity found in the bottom four flows.

To estimate a minimum frequency of the eruptions we assume the top of the normal polarity interval in the Escabecada Profile to coincide with the end of the Gauss Chron. In this estimate we also assume that the Gauss Chron ends at our stratigraphic highest flow of normal polarity, providing us with a minimum estimate of the eruption frequency. We find that during the time interval 2.71 ± 0.03 Ma to 2.60 Ma seven lava flows erupted. This gives a minimum estimate of the eruption frequency as one flow every 15,000 years with an uncertainty of ~4.3 Ka. The uncertainty corresponds to ca. 30 %, originating from the uncertainty of the $^{40}Ar/^{39}Ar$ dating.

Based upon the palaeomagnetic investigations until now of the lava flows in two series on the island of Santo Antão we may conclude, that the 290 m Cha de Morte-Profile (C in Fig. 1) is dominantly of reverse polarity, equivalent to a Lower Matuyama age (between 2.1 and 2.6 Ma), and the slightly older Escabecada Profile (E in Fig. 1) shows reverse polarity in the top flows and a dominant normal polarity in the lower flows, suggesting an age between 2.5 to 3 Ma (the younger part of Gauss and the older part of Matuyama). At Escabecada an estimate of the minimum eruption frequency is found to be one flow every 15,000 years ± ca. 5 Ka.

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1.9 THE NRM ORIGIN AND MAGNETIC MINERALOGY OF SOME PRECAMBRIAN DYKES OF THE VOLYNIAN MEGABLOCK (UKRAINIAN SHIELD) AND ITS GEOLOGICAL APPLICATIONS

S. KRAVCHENKO* and A. GLEVASSKAYA

*Institute Geophysics, National Academy of Sciences, Palladin av. 32, 03680 Kiev-142, Ukraine; svetak@igph.kiev.ua

Key words: Precambrian dykes, paleomagnetism, magnetic mineralogy, Ukrainian Shield.

Among numerous paleomagnetic data of magnetic rocks of the Volynian megablock of the Ukrainian Shield two poles are distinguished that may be considered the reference ones for the time interval including the Early-to-Middle Proterozoic boundary: for gabbro-monzonites of the Bukie massif (D = 35°, J = 32.5°), with isochronous U-Pb age of 2010 ± 50 Ma for zircon (Elming et al. 1998) and 1758.1 ± 1.0 Ma for the R-anorthosites of the Korosten pluton (D = 211°, J = 13°) (Mikhailova et al. 1994). It is assumed that such antiparallel directions of the remanent magnetization evidence the geomagnetic field inversion at that time.

Besides large magmatic bodies, dykes of different age and composition cutting the volcanic-sedimentary rocks of the early-Proterozoic Osnitsky Complex widely occur in the Volynian megablock. However, even reliable paleomagnetic data of these dykes cannot place them reliably in a paleomagnetic series since no isotopic age determinations have been made. We attempted determination of the age of rock from its paleomagnetic and magneto-mineralogical characteristic by using the reference poles in the region.

In paleomagnetic studies of many dykes of gabbro-diabases, diabase porphyrites, lamprophyres, dykes with different direction of ancient magnetization including the ones similar to those corresponding with the said reference poles are distinguished. The magnetization carriers in these rocks are mainly high-temperature oxidation titanomagnetites. Often one-component magnetization is seen whose orientation is similar to that of R-anorthosites of the Korosten Complex or N-gabbroids of the Bukie massif, which suggest magnetization of the least two stages of dyke formation after the Osnitsky Granitoid Formation.

To precise the time of dyke magnetization formation magneto-mineralogical studies are sometimes of some help. E.g. in parallel dykes of cenotypal lamprophyres with similar composition, strike and dip, but two different paleomagnetic orientations, both directions have been separated in NRM of one of the dykes in thermomagnetic studies. The first component has the orientation of D = 228°, J = 36° and the second direction is D = 19°, J = 35°.

A magneto-mineralogical analysis shows that the carriers of the first of them is titanomagnetite (TM) with Curie temperature of ≈300 °C and that TM is a product of magnetic crystallization. The Tellier method study confirms the TRM origin of this component. The paleomagnetite orientation of the first component is similar to that of Korosten'time.

The second component is associated with magnetite ($T_c \cong 580$ °C) which is a product of magnetic amphibole transformation. So, the second component is younger then the first one and it can not be analogues of Bukie'time. It is assumed that it may be associated with tectonic activization presumably in the Middle Riphean and similar-age N-magnetization of the andesite porphyrites of the Emilchyno area (D = 23°, J = 18°) (Kravchenko et al. 1991).

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1.10 PALAEOMAGNETISM, PALAEOTECTONICS AND PALAEOGEOGRAPHY OF CRETACEOUS AND CENOZOIC ROCKS OF THE WESTERN CARPATHIANS

M. KRS[1], P. PRUNER[1] and I. TÚNYI[2]

[1]Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, 165 02 Prague 6-Lysolaje, Czech Republic; inst@gli.cas.cz
[2]Geophysical Institute of the SAS, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic; geoftuny@savba.savba.sk

Key words: Western Carpathians, Cretaceous and Cenozoic rocks, palaeomagnetism, palaeotectonic rotations, palaeogeographic affinity.

To contribute to elaboration of a geodynamic model for the Western Carpathians, in reference to global-tectonics interpretation, evaluation of palaeomagnetic data so far inferred was required from volcanic (teschenite) and sedimentary rocks of the Outer Carpathian flysch belt, from carbonates of the Klippen Belt and from volcanic (prevalently melaphyres) and sedimentary rocks of the Inner W. Carpathians. The interpretation was based on the analysis of the mean palaeomagnetic pole positions (Krs, Krsová & Pruner 1996). The data from the Outer Carpathians indicated pronounced horizontal tectonic rotations of an anticlokwise sense; they refer to rocks of Eocene to Early Cretaceous ages of the Dukla, Magura, White Carpathians (Biele Karpaty) and Silesian tectonic units. The above cited paper also comprises interpretation of palaeomagnetic directions for Jurassic-Cretaceous carbonates of heavily tectonically exposed Klippen Belt and for different nappes of Permian to Cretaceous rocks in the Inner Carpathians. Carbonates of the Klippen Belt showed palaeotectonic rotations of an anticlokwise as well as clokwise sense, while volcanic and sedimentary rocks studied from several nappes in the Inner Carpathians showed horizontal rotations exclusively of anticlokwise sense (Krs 1982; Pruner, Venhodová & Slepičková 1998).

Palaeotectonic rotations around a vertical axis are characteristic for the W. Carpathians indicating marked tectonic deformations of larger rock units. Palaeotectonic rotations lead to the formation of a specific pole distribution which runs across the apparent polar wandering path, in this case for the African Plate. Besides palaeotectonic rotations, palaeogeographic latitudes have been derived and compared with palaeolatitudes in other regions of the Tethyan realm, namely the Iberian Meseta and ajacent mobile belts, Corsica and Sardinia, Italy including Sicily and the adjacent parts of the Alps, Greece and Southern Bulgaria, the Transdanubian Mountains in Hungary, and Turkey including the eastern Aegean territory and Cyprus (cf. Van der Voo 1993). The most pronounced palaeolatitudinal drift occurred in the Permian and the Triassic, and the drift began decelerating from the Jurassic until the Neogene. The differences in

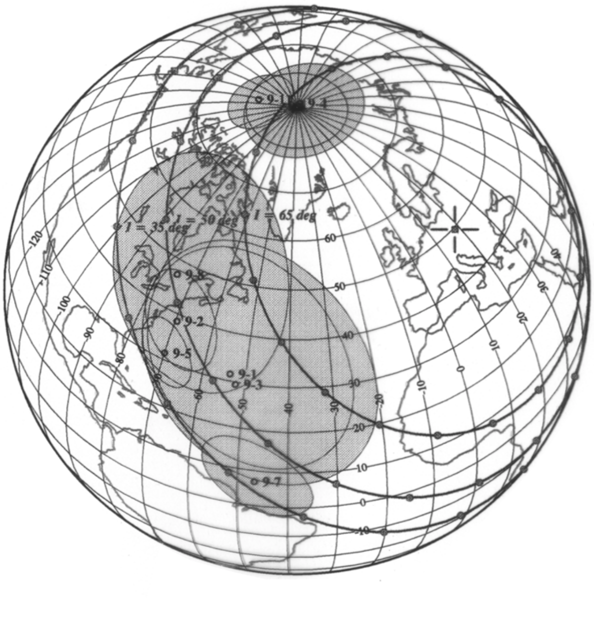

Fig. Silesian Unit, rocks of the teschenite association of the Hauterivian–Barremian age. Distribution of virtual pole positions calculated from site means published in (M. Krs & B. Šmíd 1997).

the magnitude of pole movement reflect two types of rotation, i.e. those around proximal poles of rotation (palaeotectonic rotations) and distanced poles of rotation (continental drift). These two movements may be simulated by theoretical models (Krs, Pruner & Potfaj 1992).

To judge the possibility of palaeotectonic rotation within smaller areas and to judge the waning of the Alpine tectonism in the whole region of the W. Carpathians, virtual pole positions were calculated for the Early Cretaceous to Eocene rocks of the Outer W. Carpathians and for the Cenozoic rocks of the Inner W. Carpathians using previously and recently derived palaeomagnetic data. A typical example of two movements of poles may be demonstrated on palaeomagnetic results from the rocks of the teschenite association of the Silesian Unit. The virtual pole positions lie close to the small circle corresponding to the palaeomagnetic inclination Ip = 55° (due to continental drift), and are distributed along the circle as a result of small-scale tectonic rotations (around proximal pole of rotation). Similar analysis was done for the Dukla, Magura, White Carpathian units and for sedimentary rocks of the Silesian unit.

Palaeomagnetic data recently published for the Cenozoic (prevalently Miocene) rocks from three distinct basins in the Inner W. Carpathians were also analyzed (data of Márton, Vass & Túnyi 1996; Vass, Túnyi & Márton 1996; Túnyi & Márton 1996). Similar palaeotectonic rotations as for the Outer W. Carpathians were also interpreted for sedimentary rocks of the Cenozoic age in the basins of the Inner W. Carpathians. Prevalent anti-clokwise rotations interpreted palaeomagnetically both in the Outer W. Carpathians as well as in the Cenozoic sedimentary rocks in the basins of the Inner W. Carpathians are subject for global-tectonics consideration. The rotations are similar in magnitude in both the zones, but generally waining towards the Karpatian age. Palaeotectonic rotations suggesting both small-scale and large-scale movements were found even within single sampled nappes and basins containing horizontally or subhorizontally layered beds. The above briefly discussed palaeomagnetic data from the Permian to the Karpatian, interpreted in global-tectonics terms, indicate palaeogeographic affinity of the whole region of the W. Carpathians to the African Plate.

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1.11 PALEOMAGNETIC STUDY OF THE PALEOZOIC ROCK TYPES OF THE GEMERIC SUPERUNIT — CENTRAL WESTERN CARPATHIANS (SLOVAKIA)

J. KRUCZYK[1], M. KĄDZIAŁKO-HOFMOKL[1], M. JELEŃSKA[1], I. TÚNYI[2], D. GREGOROVÁ[2], L. GAZDAČKO[3] and J. GRABOWSKI[4]

[1]Institute of Geophysics, Polish Acad. of Sciences, Ks. Janusza 64, 01-452 Warszawa, Poland
[2]Geophysical Institute of the SAS, 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; jgra@pgi.waw.pl

Key words: Central Western Carpathians, Pleozoic Rocks of the Gemeric Superunit, palaeomagnetism, magnetic minerals, magnetic lineation, magnetic foliation.

Introduction

The Gemeric Superunit constitutes one of three major tectonic units of the pre-Mesozoic basement of the Central West Carpathians. It is composed predominantly of variegated epimetamorphic rocks (metavolcanics and metasediments) of the Early Paleozoic up to the Devonian age (the Gelnica and Rakovec groups). They are covered by weakly metamorphosed Late Paleozoic formations and the Alpine Meliata unit, where ophiolitic sequences of Triassic age were preserved.

Table 1:

Component	rock/tectonic unit	age	D	I	α_{95}	k	N/n
J1	metabasalts/ Meliata unit	Triassic	320	43	3.6	637	1/4
J2	metabasalts/ Meliata unit	Triassic	18	63	7.4	278	3/10
HD	metadiabases, Gelnica unit	Lower Paleozoic	347	71	13.8	81	3/17

N — number of hand samples, n — number of specimens

The selected localities of the Gelnica and Rakovec groups and the Meliata unit were subject of our paleomagnetic study.

Rock magnetic properties and paleomagnetic results

Magnetite is the only magnetic mineral in the Triassic metabasalts of the Meliata unit (locality Jaklovce). Two components of magnetisations were revealed. The first, J1, with moderate inclinations and north-westerly declination and the second, J2, with northerly declination and quite steep inclination (Table 1). Both components occur in discrete hand samples and reveal the same unblocking temperature spectra 150–550 °C.

Magnetite occurs also in the only investigated locality of the Gelnica unit (Hajdova Dolina). It is most probably of post-pyrite origin which is evidenced by the sulphur content within the magnetite grains. All samples from Hajdova Dolina revealed mostly one component (HD) with NNW declination and steep inclination (Table 1).

Hematite is the dominant magnetic mineral in the investigated greenstones and phyllites of the Rakovec Group. In all three investigated localities the magnetisations were very stable, however their directions were considerably spread, therefore it was impossible to establish any characteristic component. However well defined magnetic fabric was revealed which is consistent within the entire Rakovec Group, with ENE directed lineations and subhorizontal foliations.

Discussion and conclusions

The ENE lineation of the Rakovec Group matches very well the strike of the Transgemeric shear zone, which is a prominent strike slip fault of Tertiary age.

Components J2 and HD (Table 1) must be interpreted as Tertiary remagnetisation, as is inferred from their steep inclinations. Such interpretation is confirmed by previous paleomagnetic results from the Gemeric Paleozoic (Kruczyk et al. 1999), where the late Tertiary remagnetisations (Middle Miocene) were also reported. Component J1 might be a primary Triassic component, because its inclination matches the Middle Triassic inclinations from the Silica nappe of northern Hungary (Márton et al. 1988). However it might also represent a Cretaceous remagnetisation, since it is very similar to the synfolding Cretaceous direction from the Silica nappe in the southern margin of the Gemeric Superunit (Márton et al. 1991).

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1.12 THE HISTORY OF THE URALS PALEOOCEAN ACCORDING TO THE NEW PALEOMAGNETIC DATA

N. LUBNINA[1] and A. DIDENKO[2]

[1]Department of Geology, Moscow State University, Vorobjevy Gory, 119899 Moscow, Russia; lub@dynamo.geol.msu.ru

[2]Institute Physics of the Earth RAS, Bolshaya Gruzinskaya 10, 123810 Moscow, Russia; didenko@uipe-ras.scgis.ru

Key wods: Ural, paleomagnetic data, geodynamic reconstruction, ophiolites.

The main debated problem of the Urals tectonic is the problem of time-dimensional relations between proto- and paleoUralian structural-formational complexes. According to the first model, the Urals paleoocean basin is a neogenetic structure, which was formed as a result of a destruction of the Carelian or the protoUrals (Cadomian) basement of the East-European continent. The alternative model supposes these complexes are defined as inherited from the protoUrals one. Both of them had “through” evolution.

Based on the new paleomagnetic data, the history of the Urals paleoocean have been quantitatively refined:

1—New paleomagnetic data for the island-arc formation of the Bedamelsk suite of the Polar Urals is obtained (Didenko et al. 2000). According to the Sm/Nd and Rb/Sr dating, the age of these rocks is defined as 670–650 Ma (Khain et al. 1999). New paleomagnetic pole position for the Upper Riphean-Vendian boundary is F = 19.9° N, L = 20.4° E, dp = 6.3°, dm = 9.0°. It is very close to the pole of the East European continent (Fig. a). Hence, during the Late Riphean-Vendian time the East-European continent was located at the mid-southern latitudes. The island-arc formation of the Bedamelsk suite was formed at 35° ± 7° S. The strike of the Late Riphean-Vendian island-arc is close to sublatitudional and similar to the orientation of the Uralian margin of the East European continent. By 600 Ma the East European continent was located at southern high latitudes (Fig. b).

2—During the latter part of the Early Ordovician along the northwestern (Uralian) border of the East European continent, active continental margin have been formed. The Lemva rift foredeep was located to the north. According to the new paleomagnetic data, the Lemva zone was located at northern equatorial latitudes, not far from the East European continental margin (Lubnina et al. 1998).

3—The Middle-Late Ordovician is the time of the Ural paleoocean having a maximum opening. The paleospreading zone had a NNW-SSE strike. The ophiolite complexes (dykes and gabbroids of the Voikar-Synia and the Syum-Key ophiolites massifs) formed at 6.8° ± 4° N. The Island-arc formation of the Polar Urals (the Voikar island-arc) was formed at 22° ± 4° S, not far from south-western active margin of the Kazakhstan-Siberian paleocontinent. Later, in the Silurian-Devonian differential rotation of the East European and Kazakhstan-Siberian continents caused “oblique” collision and closing of Urals paleo-ocean (Lubnina et al. 1998).

4—There is a small difference in Late Paleozoic latitudes of Voikar island-arc and East European continent. The Voikar island-arc was located at 5° N. This circumstance contradicts the final collision between the East European and Siberian continents during the Permian.

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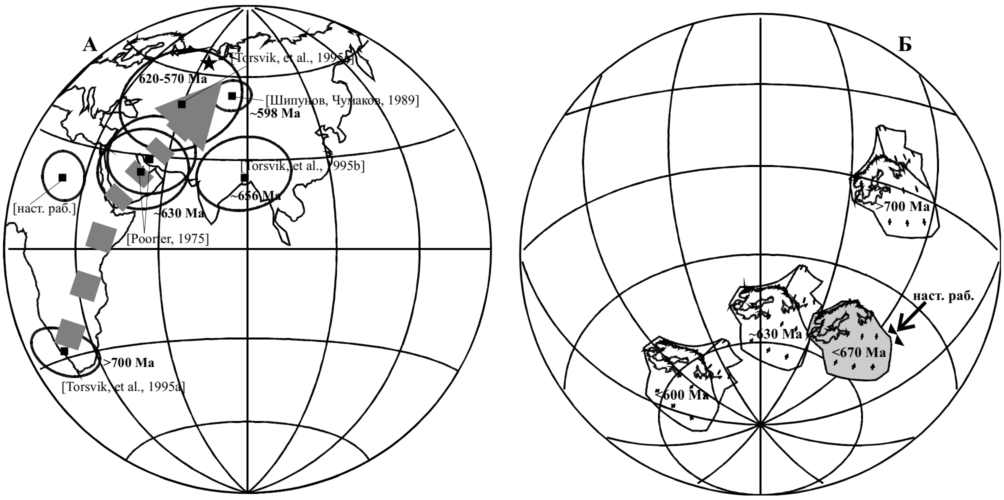

Fig. *(To the contribution 1.12)* Late Riphean-Vendian pole positions for the East European Platform (a) and it's possible position at this time (b). The mean pole position were derived by means of Fischer (1953) at the 95% probability level. Dotted pointer — Apparent Polar Wander Path (APWP) for Baltica during 700–600 Ma, based on (4, 5, 6, 7).

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1.13 THE CAUSE OF THE OVERPRINT REMANENCE OBSERVED IN THE LATE JURASSIC-CRETACEOUS SEDIMENTS FROM PORTUGAL

E. MÁRTON[1], C.M. ABRANCHES[2] and J.C. PAIS[3]

[1]Eötvös Loránd Geophysical Institute, Paleomagnetic Laboratory, Columbus u. 17-23, H-1145 Budapest, Hungary; paleo@elgi.hu
[2]Geophysical Centre, University of Lisbon, Campo Grande, Ed. C1, Piso 4, 1700 Lisboa, Portugal
[3]Center of Geological Studies, Faculty of Sciences and Technology, Quinta da Torre, 2825 Monte da Caparica, Portugal; jjp@mail.fct.unl.pt

Key words: Jurasic-Cretaceous, Portugal.

Late Jurassic-Cretaceous sediments from the Lusitanian Basin and Algarve (12 localities) are characterized by single or two-component NRM. In the latter case one component is aligned with the direction of the present Earth magnetic field (component “B”), the other exhibits CCW rotation (component “A”) In the first case only component “A” is observed. The inclination of component “A” is somewhat shallower than the present one. The polarity is always normal, except for a single site at one Berriasian locality.

During the Jurassic and the Cretaceous, the Earth magnetic field changed polarity quite frequently, and neither the normal, nor the reversed polarity periods were dominant except in the upper Barremian, Aptian and lower Albian (Cretaceous quiet interval), where the normal polarity field is rarely disturbed. The rather uniform directions of the “A” components combined with the nearly always normal polarity was the reason why the possibility of regional overprint of the original remanence had to be considered.

In the Lusitanian Basin as well as near Algarve, igneous activity was intensive in the late Cretaceous (Paleocene?). Comparing the direction and the polarity of the igneous complexes with that of component “A”, we came to the conclusion that if component “A” is an overprint remanence, it is not likely connected to the igneous activity.

Sediments may acquire overprint remanent magnetization as a consequence of tectonic processes. Therefore, disconformity bounded stratigraphic sequences could have been remagnetized in connection with the tectonic phase responsible for the disconformity. Thus we subdivided our sedimentary localities into three groups: 1. Oxfordian–Berriasian, 2. Aptian, 3. Albian–Cenomanian and carried out between-locality tilt tests for each of the groups. The conclusion is that the remanence of group 1 and 3 must be of post-tilting age (corroborated by the negative result of a within-locality fold test for an Oxfordian locality, while there is a significant improvement in the clustering for group 2 when tilt corrections are applied. The same conclusion is valid if we include in the above three groups data published by Galdeano et al. 1989. It stands to reason to assume that the age of the overprint for group 1 is of Valanginian–Hauterivian for group 3 is of Campanian age. This way the three paleomagnetic groups may represent Iberia at 130, 110 and 80 Ma, respectively.

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1.14 PALEOMAGNETISM OF THE PERMIAN SERIES OF THE MEZARIF BASIN (ALGERIA)

N. MERABET[1], A. KHERROUBI[1], S. MAOUCHE[1] and B. HENRY[2]

[1]CRAAG, BP 63, 16340 Bouzaréah, Algiers, Algeria; merabetn@hotmail.com
[2]Paléomagnétisme et Géomagnétisme, CNRS and IPGP, 4 avenue de Neptune, 94107 Saint-Maur cedex, France; henry@ipgp.jussieu.fr

Key words: Paleomagnetism, Permian, Africa, fold test.

For ten years, an appreciable number of Permo-Carboniferous poles had been determined in the Saharan basins in Algeria. Recently, the primary character of the magnetization of Carboniferous formations was confirmed by paleomagnetic tests. On the contrary, the age for the magnetization obtained in Permian units is still not constrained by any paleomagnetic test. For another hand, our knowledge of Africa kinematics evolution, which is the key of the Pangea configuration during this period, is still not precise enough and requires more investigations. For this purpose, paleomagnetic sampling had been done in the Autunian red series of Nekheila (Mezarif basin, Algeria) located in the northern side of the stable West-African craton, not far from the Abadla basin where paleomagnetic data were obtained in a previous study previous study (Merabet et al. 1998).

The scarcity of outcrops did not permit to sample more than 7 sites. The ChRM was thermally isolated after the removal of a viscous component in 117 specimens containing hematite as main carrier of magnetization. This ChRM mean direction is defined by D = 128.6°, I = 26.4°, k = 178, α_{95} = 4.0°, and D = 131.8°, I = 15.7°, k = 196, α_{95} = 3.8° respectively before and after dip correction. The dip variation from one site to another are weak, and the fold test is not significant. However, the mean direction, for the ChRM from Nekheila combined with that from the unit of the same age in the neighboring Abadla basin, changes during dip correction from D = 128.3°, I = 20.9°, k = 101, α_{95} = 3.3°, and D = 130.7°, I = 14.0°, k = 155, α_{95} = 2.7°. This shows the ante-deformation character of the ChRM of Nekheila and Abadla Autunian formation. At least part of the deformation in this area occurred relatively early after the Autunian, and that argues for paleomagnetic directions significant of the Autunian times.

The paleomagnetic pole associated to the ChRM of Nekheila is situated at 29.3° S and 56.4° E (K = 310 and A95 = 3.0°). It is very close to that (29.1° S and 57.8° E) of Abadla. It is also close to the Stephano-Autunian one (33.8° S and 61.4° E) of the lower Tiguentourine formations belonging to the stable Eastern Saharan craton. Our new datum confirms thus the reliability of the Autunian African paleomagnetic poles obtained these last years in the Algerian Saharan craton. It represents a new contribution for a better comprehension of the geodynamic evolution of the Pangea during the Paleozoic times.

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1.15 PALAEOMAGNETISM OF RECENT RUSSIAN LAKE SEDIMENTS

D. NOURGALIEV, F. HELLER, A. BORISSOV, P. IASSONOV, D. KHASSANOV and B. BOUROV

Kazan State University, Kazan, Russia
ETH Zurich, Switzerland

Key words: Secular variation, lake sediments, Holocene, Russia.

Since Mackereth's first work [1] on the paleo-secular variation (PSV) recorded by sediments of lake Windermere, a globally distributed set of lacustrine PSV records has been evolving which extends back several tens of thousands of years. Further progress in understanding the changes of the geomagnetic field and the processes in the Earth's core is connected with the analysis of changes of the space-time structure of the field during the last 10^4 years and longer periods. In the present paper we are discussing preliminary data obtained from sediment cores from Lake Aslikul (54°25' N, 54°07' E) [2], Lake Plescheevo (56°46' E, 38°45' E) and Lake Naroch (54°50' N, 26°40' E) in the European part of NIS.

These lakes have been investigated in 1995–1999 using a corer based on the design of Mackereth [3] for the acquisition of lake sediment cores up to 6.5 m in length in water depths up to 100 m. In contrast to the Mackereth corer, however, our device enables collection of 6.5 m cores even in shallow water depths of 1–2 m. We have taken up to 6 vertical cores, each 70 mm in diameter and variable in length from 3.0 to 6.4 m from various parts in each lake. The core locations have been selected according to preceding high-frequency seismic studies. The natural (NRM) and the characteristic remanent magnetization (ChRM) of samples was measured using a JR-4 spinner magnetometer and a ScT cryogenic magnetometer. Pilot alternating field (AF) demagnetization was conducted on samples from different parts of all cores. C^{14} ages of the sediments were determined by Drs. G.Bonany and I.Hajdas using AMS at ETH Zurich.

The declination and inclination data of these lakes for the last 4000 years can be compared with lake records from Great Britain [4], with archaeomagnetic data from England and Paris [5] and with the record from Lake Kinneret, Israel [6]. These records cover an area from 5° W to 54° E longitude and from about 30° N to 55° N latitude thus enabling analysis of global and regional sources of PSV. The major swings but also finer details of the paleosecular inclination variations repeat well between all these records with low shift (Figure on page 206). Comparison of the declination records is more complicated. Secular variations of declination on the same latitude are much more sensitive to changes of regional (non-dipole) sources of the geomagnetic field. We can see clear negative correlation of major swings and finer details of declination between west and east European records. It is caused by different but clearly correlated sources of PSV for west and east Europe.

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1.16 KINEMATIC ASPECTS OF CRYSTALLINE BLOCKS OF THE MIDDLE JURASSIC-EARLY CRETACEOUS INTRUSIVE–VOLCANIC FORMATION OF THE ANTARCTIC PENINSULA AND ARGENTINE ISLANDS

M. ORLOVA

Institute of Geophysics of National Academy of Sciences, Palladin av. 32, 252680 Kiev 142, Ukraine; earth@igph.kiev.ua

Key words: Antarctic Peninsula, local tectonic deformations, paleo- magnetic analysis, horizontal displacements, turns of blocks.

The investigation deals with local tectonic deformations in order to reconstruct the scheme of vector displacements from paleomagnetic analysis of specimens in blocks of crystalline rocks of sea-coast of the AP and neighboring islands. The region of our research is located at (64°–64°21' W and 65°10'–65°20' S). Here the Middle Jurassic to Early Cretaceous intrusive–volcanogenic of formation are distributed (Grikurov 1993; Elliot 1962; Curtis 1994). Oriented samples for paleomagnetic researches were taken from several outcrops in order to describe rocks at the time of the Middle Jurassic to Lower Cretaceous, represented within the limits of each site. Samples were taken manually, the measurements were made with the help of geological compass with an accuracy of 1–2 deg. Along with sampling, measurements of strike and dip of zones of jointing and faults with horizontal component of displacement have been performed. The collection of specimens was treated thermally (up to 600 °C with steps 25–50 °C). The NRM components are the C component, directed along the present local geomagnetic field and the characteristic component A(B)–N(R) polarity (Orlova 1999).

The average directions of the NRM distributions of intrusive–volcanogenic rocks of the region *before* and ***after*** tilt correction are follows: *I — (Demaria), N/n = 2/19, D/J = 350/–67, K = 52.0, L95 = 4.7;* ***Dt/Jt = 82/–73, Kt = 53.0, L95 = 4.7.*** *II — (Rasmussen), N/n = 3/20, D/J = 355/–74, K = 83.4, L95 = 3.6;* ***Dt/Jt = 84/–65, Kt = 82.7, L95t = 3.6.*** *III — (Pitermen), N/n = 3/12, D/J = 24/–72, K = 90.1, L95 = 4.6;* ***Dt/Jt = 71/–82, Kt = 92.3, Lt = 4.5.*** *IV — (The Barchans), N/n = 3/13, D/J = 78/88, K = 6.0, L95 = 18.5;* ***Dt/Jt = 98/65, Kt = 17.6, L95t = 10.6.*** *Va — (Winter), N/n = 3/10, D/J = 96/2, K = 21.9, L95 = 12.1;* ***Middle****(a, b)* ***Dt/Jt = 80/68, Kt = 41.7, L95t = 7.6,*** were N/n — number of sites/ number of samples in the outcrops; K and L95 — Fisher's statistic.

Based on the conducted analysis of the NRM distributions of the Middle Jurassic to Lower Cretaceous intrusive–volcanogenic rocks of the region, corrected for dip and strike of bedding, we can assume, that they are synchronous. Then the true direction of the NRM ancient component for these rocks can be found from direct methods consisting of a determination of a cross point of remagnatization circles (Paleomagnitology 1982). The plane of each circle is determined by ancient directions (Dt/Jt) and modern magnetic meridians (Nt) in samples corrected for dip and strike of bedding. Remagnatization circles of samples from outcrops Demaria (Dt/Jt = 82/–73, Nt = 66/–58), Rasmussen (Dt/Jt = 84/–65, Nt = 59/–51) and Winter (Dt/Jt = 247/–69, Nt =76/–16) intersect in a point with co-ordinates Do/Jo = 79/–67. Co-ordinates of paleomagnetic pole Lat.= 48° S and Long.= 224° E correspond to this direction. Almost the same results have been reported by Longshaw & Griffiths (1983) [175 Ma. Lat.= 46° S, Long. 237° E] (Grunow 1993) on lavas, granites and dikes at east part of the Graham Land.

The average NRM directions for outcrops of the region are distributed along a certain large circle and naturally are displaced from the Do/Jo point westward. The subsequent stage of research consisted of evaluating turns of blocks, turns round the vertical axes. The turn angle was determined by a comparison of average NRM direction of rocks of the block with Do/Jo. This is similar to the method of Rzhevsky (1977), permitting to evaluate as well amplitude of a horizontal displacement $L = 2l \sin(a/2)$, where l — a distance of a site from an axes of a turn. The spin axes was found by a graphic method, and is considered to be located in a place with co-ordinates 65°4' S and 64°20' W.

The minimum turn of angle in 2 degrees and displacement for 800 meters was determined for rocks in site Rasmussen. Taking into account, that an accuracy of determination exceeds obtained angle we can suppose that Rasmussen outcrops did not have horizontal displacements. The turn of the block including outcrops in site Demaria was 6 degrees and was displaced to SW on 1488 m, that approximately corresponds to a wide of a Waddingtin bay. The block including outcrops of an island Pitermen has moved 3013 meters from the sea-coast line of the AP in SW direction and turned clockwise by 15 degrees. The group of the Barchans islands, according to the scheme took a position close to the Moot point at sea-coast of AP and underwent a significant displacement of 10,988 meters to the west, and also a clockwise rotation of 47 degrees. The Winter islands, and likely the nearby Galindes and Skua islands also were along a modern line of sea-coast of the AP, and then were displaced to SW by 12,100 meters and were turned by 47 degrees.

Thus, the scheme of reconstruction as a result of conducted research, allows to assume, that the blocks of the Middle Jurassic to Lower Cretaceous intrusive–volcanic rock outcrops within the limits of the considered sea-coast of the Antarctic Peninsula have experinced rotations clockwise from 6 up to 47 degrees as well as horizontal displacements in SW direction of 1488 up to 12,100 meters.

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1.17 PALEO, ROCK, MAGNETIC AND MINERALOGICAL CHARACTERISTICS OF BAKED CLAYS ASSOCIATED WITH BURNT COAL SEAMS IN THE DACIC BASIN (ROMANIA)

S. C. RĂDAN[1], M. RĂDAN[1] and S. RĂDAN[2]

[1]Geological Institute of Romania, 1 Caransebes Str., 79678 Bucharest, Romania; mms.radan@fx.ro

[2]GeoEcoMar, 23-25 Dimitre Onciul Str., 70318 Bucharest, Romania; mms.radan@fx.ro

Key word: Magnetic study, magnetostratigraphy, lignite-clay sequence.

Introduction

An integrated rock magnetic and magnetostratigraphic study has been carried out on Pliocene rhythmically bedded lignite-clay sequences in 9 quarries in the western Dacic Basin (Romania).

In two of them (i.e., Jilţ Sud and Lupoaia quarries), some occurrences of baked clays (porcelanites/clinkers) generated by natural spontaneous burning of lignite seams were investigated, as well.

The main results related to the porcelanite deposits are presented in this paper.

Sampling, laboratory methods and field measurements

It is worthily to be mentioned that in several cases, oriented monolit-blocks, subsequently cut at 2–5 levels, and each subsample cut further into cubic specimens, were used in the study. So the rock-/(paleo) magnetic and mineralogical changes by the clay – porcelanite-like clay — porcelanite succession were minutely investigated.

Some clinkers were sampled, too.

The magnetic susceptibility (MS) and its anisotropy (AMS) were measured on a KLY-2 Kappabridge, and the natural remanent magnetization (NRM) on a JR-4 spinner magnetometer.

The porcelanite samples were thermally demagnetised using a TSD-1 Schonstedt equipment. The AMS stability was also tested.

To evaluate the capability of the porcelanite deposits to be detected by measurements with a Geometrics G-826 portable proton magnetometer, a series of magnetic profiles were carried out in zones where the baked clays are visibly (surface exposure), as well as where they are situated under the ground surface (an area checked by drilling works).

Selected results and remarks

It can be pointed out that the appearance of the porcelanites within the lignite-clay sequence from the mentioned area represents — through their magnetochronological characteristics — a **noise** for the elaborated magnetostratigraphic scales. This assertion is based on the fact that it has been identified a normal polarity of the characteristic remanent magnetization (ChRM) of the porcelanites, assigned to the Brunhes Chron (the last 0.78 Ma), while the coal seams (X, X-XI), which have mainly generated the clay baking, are placed within the deposits calibrated — inside of the magnetostratigraphic patterns — at the C2Ar Chron level (4.18–3.58 Ma; Cande & Kent 1995) in the Gilbert Chron.

Of course, this **noise** is easily avoided in the magnetostratigraphic interpretation of the respective sections. Instead, the **signal** quality of the magnetic properties of porcelaniates is drawing attention by its geophysical contend and the various geological significances.

All these aspects are illustrated and discussed in an ample unpublished work (Rădan 1998). From the multitude of existent rock-, paleo-, magnetic images, we have selected here two ilustrations.

So, in Fig. 1 are presented two magnetic profiles recorded in the southem vicinity of Lupoaia lignite quarry. They show significant ΔT anomalies (490–600 nT), produced by porcelanite deposits located by exploration wells at depths ranging between 9–33.5 m. Some MS measurements on porcelanite core samples were done.

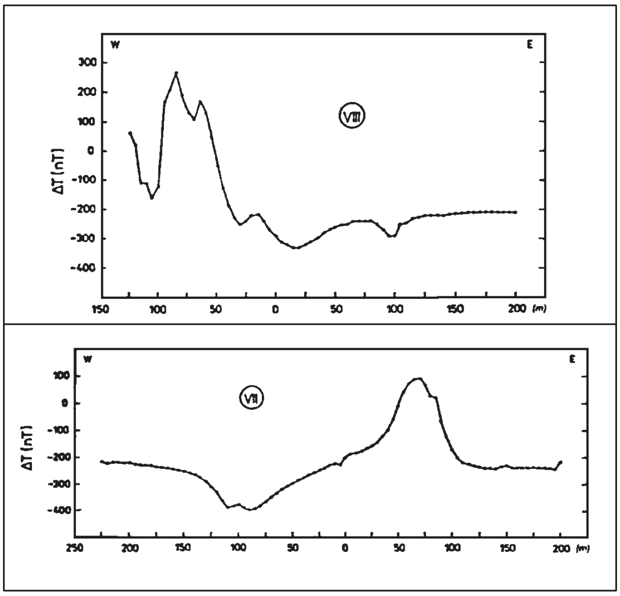

Fig. 1. Magnetic profiles (ΔT) in zones with porcelanite deposits located under the ground surface (southward of Lupoaia lignite quarry, Dacic Basin, Romania).

Relating to the AMS, in Fig. 2 are presented the stereograms the distribution of the principal magnetic susceptibility (k_1, ▲ — maximum; k_2, ■ — intermediate; k_3, ● — minimum) obtained for each sample/monolith-block collected a minisection in Lupoia quarry consisting of clays, coaly clays, porcelanite-like clays (separated by coal banks). As a general remark, the k_1 and k_2 axes are placed in a (quasi) horizontal plane (the bedding plane), and the k_3 axes are situated in a (near) vertical direction. Similar results were obtained for other cases studied in the western Dacic Basin (e.g., Rădan 1998; Rădan & Rădan 1999), and their significance was revealed.

It seems reasonable to conclude, that the integrated rock, paleo, magnetic and mineralogical study, performed on porcelanite samplex, and particularly, on oriented monolith-blocks of porcelanite-like clays, has resulted in the quasi-instantaneous sampling of a magnetic recording fragment of the post-depositional thermally disturbed history which has been printed in the coal bearing formations.

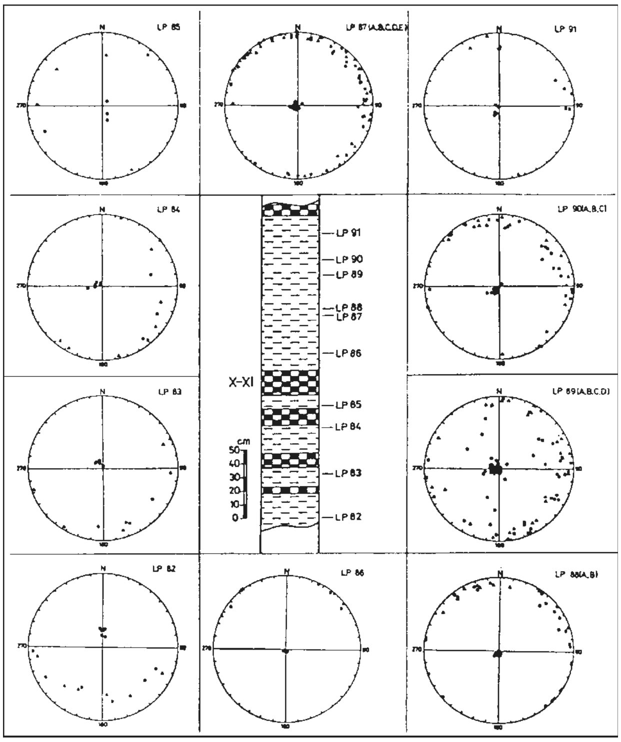

Fig. 2. Directions of principal magnetic susceptibilities (minisection in an area with thermaky affected clays; Lupoaia lignite quarr, Dacic Basin, Romania).

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1.18 COUPLING OF LATE-OROGENIC TECTONICS AND SECONDARY REMANENCE DIRECTIONS IN THE HIMALAYAS

E. SCHILL and E. APPEL

Institut für Geologie und Paläontologie, Universität Tübingen, Sigwartstraße 10, 72076 Tübingen, Germany; evaschill@uni-tuebingen.de

Key words: Paleomagnetism, Himalays, block rotation, crustal shortening.

The northern margin of India has undergone a crustal deformation of enormous magnitude during the collision with Eurasia. An extent of about 1500 km of the northern margin of "Greater India" prior to the collision (compare to the present outline at 89° E) is proposed by Patzelt et al. (1996). The crustal shortening between India and Eurasia is controlled by straight forward shortening in N-S direction and shortening due to rotational underthrusting. The amount of the rotational shortening between the stable Indian plate and the Tethyan Himalayas (distal shelf of India) can be quantified using the angle between the expected palaeo-declinations (calculated from the APWP) and the observed declinations (Klootwijk et al. 1985; Appel et al. 1991; Patzelt et al. 1996). This angle appears to be influenced also by other processes. The most obvious is the oroclinal bending of the whole Himalayas parallel to a small-circle around an Euler pole at the locality Turfan (42.49° N, 91.1° E, radius: 1695 km; Klootwijk et al. 1985). This combination of rotational underthrusting and oroclinal bending is modulated by tectonic rotations on smaller scales (~100 km and ~10 km). Steep inclinations have been interpreted in terms of "MCT-ramping" (Appel et al. 1991; Rochette et al. 1994). The aim of this study is to quantify the amount of the different block rotations. Therefore, palaeomagnetic sampling was carried out in different localities and distances over an area of about 1000 km.

All along the Himalayan Arc secondary remanences carried by pyrrhotite are found in the Sedimentary Series of the Tethyan Himalayas. Pyrrhotite is formed in marly carbonates during low-grade metamorphism on the expense of magnetite. The age of remanence acquisition can be related to exhumation and last cooling below 320–200 °C. Negative foldtests from different areas confirm the secondary origin of the remanences.

In most of the areas well grouping site-mean directions are found. The overall all mean directions are statistically significant, although the mean directions from different sites of the same location (ten-kilometre scale) seem to be more random distributed.

In the easternmost sampling area S_1 (28.6° N, 85.1° E) the remanence directions (along a 10 km E-W profile) are 1D-distributed along a small-circle parallel the N-S direction (Fig. 1a). This distribution is interpreted as a late-orogenic long-wave folding (Schill et al. subm.). This N-S tilting is partly reflected also in the bedding data (Fig. 1b). Both, dip values and inclination vary systematically with the distance.

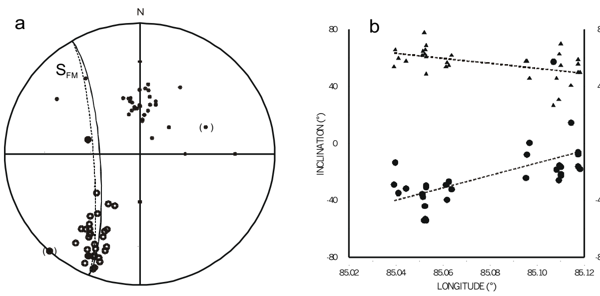

Fig. 1a. Small-circle distribution of the remanence directions of the pyrrhotite component (sampling area S1). Large symbols: remanence directions in the upper/lower (open/full symbols) hemisphere. Small symbols: bedding. Full (dashed) line: best-fitting small-circle in the upper (lower) hemisphere. **Fig. 1b.** Correlation between the inclination of remanence (circles) and the dip of bedding (triangles) respectively with the distance along the E-W profile. Dashed lines: linear fit.

This coupling between palaeomagnetic remanence directions and late-orogenic structures seem to be valid along the entire Himalayas and also on larger scales. In the westernmost sampling area S_2 (33.9° N, 76.5° E) the deviation of the declination of the remanence direction from the calculated mean follows the deviation of the strike from its mean over an area of several tens of kilometres (Fig. 2).

Considering tectonic features like fold axes and strike, this behaviour allows the separation of block rotations on different

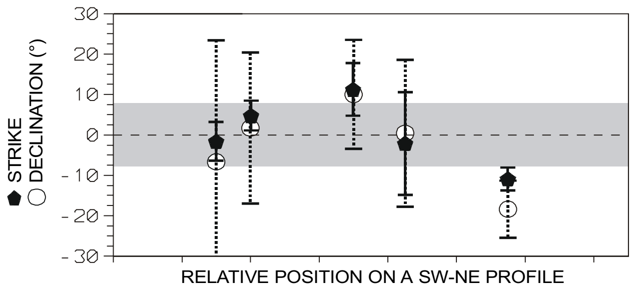

Fig. 2. Comparison of block rotations recorded by palaeomagnetic declination and tectonic strike along a SW-NE profile. Full/dashed lines: confidence angle of declination/standard deviation of strike.

scales. Local and meso-scale effects can be subtracted from the total angle of block rotation between the Tethyan Himalayas and the stable Indian plate. The remaining angle represents only the oroclinal bending and rotational underthrusting.

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2. ARCHEOMAGNETISM

2.1 A FIRST SECULAR VARIATION CURVE FOR SPAIN FROM ARCHAEOMAGNETIC DATA

J.I. NÚÑEZ[1], M.L. OSETE[1], D. BERNAL[2] and D.H. TARLING[3]

[1]Dept. of Geophysics and Meteorology, Universidad Complutense de Madrid, Madrid 28040, Spain; juanig@eucmos.sim.ucm.es
[2]Dept. of History, Geography and Philosophy, Archaeological area, Facultad de Filosofía y Letras, Universidad de Cadiz, 11003Cádiz, Spain; dario.bernal@uca.es
[3]Dept. of Geological Sciencies, Plymouth Polytechnic, Drake Circus, Plymouth, Devon PL4 8AA, England; d.tarling@plymouth.uk

Key words: Archaeomagnetism, Secular Variation Curve, Spain.

Introduction and methodology

Archaeomagnetism is the thermoremanent magnetization study of archaeological material: this technique of recovering information about the Earth's Magnetic Field (E.M.F.) preserved by the material at some moment in the past. Archaeomagnetic studies (of well-dated sites) have yielded a history of E.M.F. over the past few millennia (Secular Variation Curves, S.V.C). The principal use of SVC's is as archaeological dating tools, by comparing the palaeomagnetic direction from a particular site with the S.V.C defined for the area in which the site is located.

In Spain few archaeological studies have been carried out in comparison with Occidental Europe. In this way, in France and Great Britain work has been ongoing over the last few decades and their S.V.C's are very well defined. The objective of this study is to make the first S.V.C. (with reference to Madrid) with new results from Spain and existing data from the South of France and Northern Morocco.

For each structure 15–20 samples should be taken, to allow meaningful statistical analyses. In most cases, the samples had to be drilled (1" diameter cylindrical cores). Where material was not consolidated, hand specimens were taken. The samples were oriented by means of a magnetic or sun compass.

Palaeomagnetic results

Samples from 18 sites (kilns, baths and fires), with a chronological range between 100 BC and 1500 AC, have been taken and their characteristic directions determined using AF and thermal methods (Fig. 1). In the vast majority of samples, the demagnetization of NRMs revealed a single component of magnetization (on removal of a small viscous overprint). In these cases AF demagnetization was used, yielding well-defined characteristic directions which were calculated using least-squares line-fitting. The only

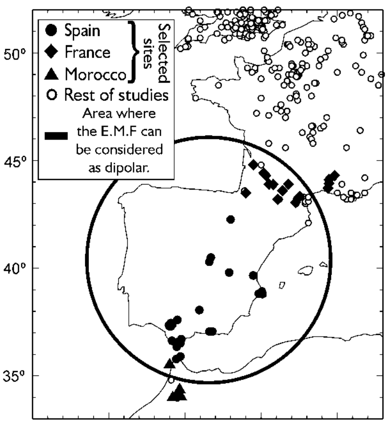

Fig. 1. Localization of sampled sites in Spain and sites selection of South France and North Morocco.

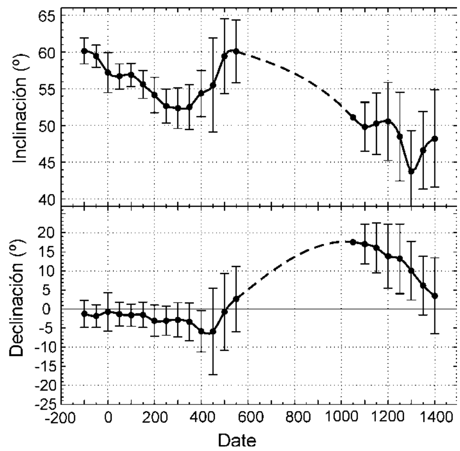

Fig. 2. A first Secular Variation Curve for Spain (with reference to Madrid).

sites which gave problems were those from thermal baths and fires. In these cases a mixture of 2 components was observed. Here the TH demagnetization and remagnetization circles analysis (Collinson 1983) was used to determine the characteristic direction.

The first secular variation curve for Spain

For regions less that 1 million km^2 in area the Earth's Magnetic Field can be considered dipolar (Tarling 1983). In this study Madrid is used as the reference point, and the analyzed area includes data from the South of France and Northern Morocco (Fig. 1). The data were selected from the Archaeomagnetic Database compiled by the Dept. of Geological Sciences, University of Plymouth, UK (D. Tarling, personal communication). The following criteria were adopted:

Dating errors < 50 years; Number of samples > 5; $\alpha_{95} < 3$. Data has been selected from neighboring countries, resulting in a total of 28 points with ages ranging between 200 B.C. And 1500 A.D. There is a time gap in the data between the 7th and 10th centuries A.D. Combining these with data from this study and previous work gives a total of 45 data points for construction of a preliminary Secular Variation Curve for the Iberian Peninsula, albeit with a gap between the 7th and 10th centuries.

To construct the Secular Variation Curve, the palaeomagnetic directions were corrected so that they corresponded to a geographical point coinciding with Madrid, using the Via-Pole Conversion method (Noel & Batt 1990). Next, following the statistical treatment described by Sternberg & McGuire (1990), a 100 year smoothing window moving in 50 years increments, was applied to the data (Fig. 2).

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2.2 THE GERMAN ARCHAEOMAGNETIC SECULAR VARIATION CURVE

E. SCHNEPP[1] and R. PUCHER[2]

[1]Institut für Geophysik, Herzberger Landstr. 180, 37075 Göttingen, Germany, eschnepp@foni.net
[2]GGA-Institut, Stilleweg 2, 30655 Hannover, Germany, r.pucher@gga-hannover.de

Key words: Archaeomagnetism, Secular variation, Germany.

The archaeomagnetic secular variation (SV) curve for Germany is based on recent palaeomagnetic measurements carried out on archaeological sites in Germany and on a collection of published and unpublished archaeodirections also from the neighbouring countries. All sites are located in an area ranging from 3° to 15° E in geographical longitude and 47° to 57° N in latitude. During the past two years 13 new sites have been sampled mainly from the epoch between the early middle age and the 18th century, but also from the stone age, bronze age and the roman epoch. They are dated mainly with the radiocarbon method. At these 13 sites 22 archaeological structures were sampled as pottery kilns, smelting ovens, kilns for quicklime, oven heatings, fire places, a bread oven, a pile and two places with burnt soils. Oriented handsamples were taken from the burnt clay of the floors and also from the walls, if present. Many of the ovens had walls sometimes floors stonewalled with bricks, limestone or graywackes. This material was also taken as oriented handsamples.

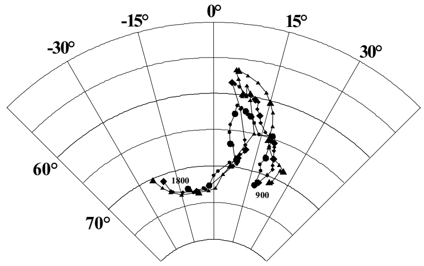

Fig. 1. The archaeomagnetic secular variation curve of Germany (●) is shown together with the master curves of France (→) and England (▲) (Daly & LeGoff, Phys. Earth Planet. Int., 93, 159–190, 1996) in equal area projection for the time interval 900 to 1800 AD. All data are reduced to Hannover (9.77° E/52.37° N) using the virtual geomagnetic pole. The curves are calculated every 25 years for a symmetric 80 years interval, larger symbols indicate the centuries.

All blocks were cut into cubes of 25×25×25 mm^3 for the palaeomagnetic laboratory procedures, as measurement of natural remanent magnetisation (NRM) and susceptibility, alternating field and thermal demagnetisation, acquisition curves of isothermal remanent magnetisation, Curie temperature and Thellier tests. If the direction of NRM was not well grouped near the present field direction, there was a strong correlation between low Koenigsberger ratios and arbitrary NRM directions. In most cases demagnetisation behaviour of the samples was not complicated and it was possible to determine a stable direction using principal component analysis. The directions of the characteristic remanent magnetisations were well clustered and the α_{95} confidence limits ranged from 2.5° to 5.3°.

The data set for calculating the German archaeomagnetic secular variation curve consists now of 145 archaeodirections with age ranging from 750 BC to 1800 AD. Although, geographical and age distribution of the data set is still uneven, for the time interval 900 to 1800 AD at least six data points per 80 year interval can be used to calculate an average secular variation value each 25 years. The obtained curve clearly deviates from the neighboured French or British archaeomagnetic secular variation master curves (Fig. 1), although all data are reduced to the same place (Hannover, 9.77° E/ 52.37° N). The German curve shows a delay in time of up to 100 years. For times before 1200 AD and after 1600 AD curves match well and there is only a shift in declination. Around 1300 AD also the inclination was about 5° higher than in France and Britain and the curves show significant differences. This means that the nondipole field changed during these 100 years. Further five ovens with ages younger than 900 AD are under investigation. The results may hopefully allow to remove data of the western part and discard the overlap with the French and British data sets to obtain independent SV curves. For times before 900 AD the data set is too small for calculation of reasonable mean values, or the deviation from the French or British curve is insignificant, because the data sets overlap strongly.

3. GENERAL ROCK MAGNETISM AND ITS PHYSICAL BACKGROUND

3.1 MAGNETIC PROPERTIES OF NATURAL AND SYNTHETIC HEMATITE

C.B. DE BOER and M.J. DEKKERS

Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands; dekkers@geo.uu.nl

Key words: Hematite, rock-magnetic properties, canted and defect movement, Morin transition, transdomain changes.

The magnetic properties of hematite are relatively poorly known despite its importance for paleomagnetism, in particular when dealing with sedimentary rocks. They are often quoted as 'highly variable because of the complex interplay of the canted and defect moment'. In the present contribution some recent mineral-magnetic data of hematite will be examined to provide a method to distinguish between the various hematite types. The canted and defect moment can be distinguished by cycling through the Morin transition: the canted moment disappears but the defect moment persists, enabling distinction. Because the magnetic structure is changing, also remanent magnetizations drop considerably on cooling through the Morin transition. Well crystalline hematite has a sharp (<10 °C) Morin transition with increasing impurity content, decreasing crystallinity and/or grain size the Morin transition becomes more smeared (>50 °C). In finely crystalline hematite the Morin transition can be suppressed completely. Cycling in zero fields yields the well-known partial remanence recovery on warming back to room temperature. Cycling of the low-field magnetic susceptibility yields higher values when back at room temperature than before cycling. This behaviour is more prominent in large grains than in small grains and inferred to be caused by a new domain configuration in the hematite. The new structure remains on heating to the Néel temperature but is magnetically soft. Cyling in fields of a milliTesla's adds magnetization that appears to be remanence. Possible paleomagnetic implications will be discussed. Alternating field demagnetization before thermal treatment is suggested to avoid erroneous interpretation of geologically irrelevant NRM components.

Analysis of thermomagnetic curves shows that the canted and defect magnetic moments are additive, variations in the saturation magnetization of hematite could well be due to variations in the defect moment. To discriminate between changes in magnetic moment of a sample due to chemical or structural changes and those due to increased aligning of magnetic domains, redispersion of the sample between subsequent thermomagnetic runs is recommended. On warming to elevated temperatures (>800 °C) a new highly magnetic phase may be produced, shown to be special variety of maghemite.

3.2 THE INVERSE MAGNETIC FABRIC IN THE LOCALITY OF CHORYNĚ (FLYSCH BELT OF THE WESTERN CARPATHIANS) AND ITS ORIGIN

F. HROUDA

AGICO Inc., Ječná 29a, CZ-621 00 Brno, Czech Republic

Key words: Inverse magnetic fabric, single domain magnetite, anisotrophy of susceptibility, anisotrophy of remanence.

The anisotropy of magnetic susceptibility (AMS) in rocks of the Flysch Belt of the Western Carpathians is mostly sedimentary in origin, i.e. the susceptibility ellipsoid is predominantly oblate, the magnetic foliation is parallel to the bedding, and the magnetic lineation is parallel to the near-bottom water current direction. In some places where the flysch rocks were affected by ductile deformation, the susceptibility ellipsoids can be on the transition between oblate and prolate or even prolate and the magnetic foliation may deviate (sometimes strongly) from the bedding.

In the locality of Choryně, the magnetic fabric is very different from the above magnetic fabrics characteristic of the most Flysch Belt. The susceptibility ellipsoids are clearly prolate and both the magnetic foliation and magnetic lineation are perpendicular to the bedding. This magnetic fabric cannot be explained as originated through simple sedimentary or tectonic processes. In order to better understand the origin of this magnetic fabric, the anisotropy of magnetic remanence (AMR) was also investigated; the rocks were magnetized anhysteretically using the AMU-1 Anhysterectic Magnetizer in conjunction with the LDA-3 AF Demagnetizer, their remanent magnetization was measured by the JR-5A Spinner Magnetometer and the AMR was evaluated by the program AREF. The AMR fabric is very different from the AMS fabric. Though relatively scattered, the AMR magnetic foliation poles are in average near the bedding poles and the magnetic lineations are near the bedding. The AMR ellipsoids range from moderately prolate to moderately oblate.

The magnetic minerals were investigated through the measurement of the temperature variation of bulk susceptibility. The heating theromomagnetic curve slowly increases with increasing temperature and in the vicinity of 500 °C it decreases relatively rapidly. This may indicate presence of very small grains of titanomagnetite.

The unusual AMS can be explained as the inverse fabric resulting from very small grain size of magnetic minerals. In these very small grains, which are evidently single domain magnetic particles, the easy magnetization direction is along the shortest grain dimension, while the difficult magnetization direction is along the longest grain dimension. If the magnetic particles show sedimentary fabric, i.e. they are deposited with their larger surfaces on the bedding planes, then both the magnetic foliation and lineation are perpendicular to the bedding.

3.3 THE EFFECT OF MODERATE HEATING ON ROCK MAGNETIC PROPERTIES OF LOESS-PALAEOSOL SEQUENCES AND ITS IMPLICATION ON MAGNETIC PALAEO CLIMATE PROXIES

J. HUS[1] and D. JORDANOVA[2]

[1]Centre de Physique du Globe, 5670-Dourbes, Belgium; jhus@kmi-irm.oma.be
[2]Geophysical Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. bl. 3, 1113 Sofia, Bulgaria; vanedi@geophys.bas.bg

Key words: Loes/soil sediments, hysteresis parameters, magnetic susceptibility.

Loess/palaeosol sequences formed during the Quaternary over large areas in Asia, Central and Eastern Europe are land manifestations of alternating cold and warm climatic periods. Physical and chemical processes play an important role during formation of each loess and palaeosol horizon and afterwards in exposures and will determine their specific properties, including mineral magnetic characteristics. The variations of magnetic susceptibility and other structural sensitive magnetic parameters, which are widely used as palaeoclimate proxies, inevitably are influenced by the weathering regimes acting during loess accumulation and/or soil formation. Common impact of weathering on ferrimagnetic minerals is low-temperature oxidation. Iron oxides, in particular magnetite, are prone to surface oxidation which can result in building up of stresses between the core and maghemitized shell. The stress-release origin, proposed by van Velzen & Zijderveld (1995) has been tested on a collection of loess/palaeosol samples from loess sequences of different areas.

The effect of moderate heating at 150 °C on magnetic susceptibility and hysteresis parameters was examined on 41 powder samples from different loess and soil horizons in the sections Huangling and Baoji (China), Tajijar (Tadjikistan), Viatovo (Bulgaria), Kurtak (Siberia), Kesselt and Rocourt (Belguim). The changes in the hysteresis parameters, after heating at 150 °C in air indicate that both loess and soil samples became magnetically softer after heating as is witnessed by decreases of coercivity parameters Hc and Hcr, as well as a decrease of saturation remanence Jrs. The most significant changes (in percent) are observed for loess and soil samples from Kurtak (Siberia). With this exception, changes are higher in the loess compared to the soils. Another important observation, which broadens possible interpretations of the experimental observations, is the increase of saturation magnetization Js after heating. In contrast to the structure-sensitive parameters, the most significant increase of Js is observed in the upper part of the sequences in Tadjijar (>10 %), Viatovo and Baoji.

Several processes can be put forward to explain the observed changes in magnetic characteristics of loess/palaeosol samples after heating at 150 °C:

— mineralogical changes: initial stages of dehydroxylation of Fe oxyhydroxides and phyllosilicates; laboratory oxidation with increasing temperature

— structural changes: loss of physically adsorbed or intercalated water; stress release of partially oxidized SD/PSD magnetite grains; grain-growth of nanoparticles of Fe oxides.

The effect of the above mentioned factors will be discussed.

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3.4 MAGNETIC CHARACTERIZATION OF SYNTHETIC MAGHEMITES

N. JORDANOVA and D. JORDANOVA

Geophysical Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. bl.3, 1113 Sofia, Bulgaria; vanedi@geophys.bas.bg

Key words: Maghemite, inversion temperature, magnetic susceptibility.

Maghemite is a strongly magnetic mineral which is wide-spread in natural environments — in soils, sediments, igneous and metamorphic rocks. Therefore, its magnetic characterization is of practical interest for palaeomagnetism and environmental magnetism. The main difficulty in magnetic investigation of maghemite arises from its thermal metastability — it inverts to hematite in the temperature interval between ca. 350–600 °C before reaching the Curie point (Cornel & Schwertmann 1996; Dunlop & Ozdemir 1997). We have studied magnetic properties of four synthetic maghemites, kindly provided by Dr. O. Ozdemir.

High-temperature behaviour of magnetic susceptibility was measured on KLY-3 Kappabridge (Agico, Brno), equipped with CS-3 furnace. Thermomagnetic runs, done in air, show rapid susceptibility decrease at temperatures, varying between 490 to 600 °C for different samples, which indicate inversion to hematite. A moderate decrease in magnetic susceptibility is also observed at ~350 °C for all the samples. After heating to 700 °C, well pronounced hematite peak suggests almost complete inversion of the starting material, since the room-temperature susceptibility value after cooling is near zero.

Thermomagnetic K(T) curves, measured in Ar-atmosphere for the studied maghemites show different features. The small decrease at ~350 °C is missing, inversion occurs at lower temperatures between ca. 460–535 °C, very well pronounced magnetite phase with T_c = 580 °C appeared after the main inversion temperature and again hematite is the ultimate final product. The presence of magnetite detected on the thermomagnetic curves measured in Ar is striking and one possible explanation could be that the original material is not pure maghemite, but mixture of maghemite and magnetite. However, this is not confirmed by the results from low-temperature K(T) measurements since no one of the samples show indication of Verwey transition.

Hysteresis measurements suggest that the studied maghemites are of SD sizes. Js values obtained in a maximum field of 1 T are slightly higher (75–79 Am^2/kg) than usually reported, doubting some traces of magnetite present.

The thermomagnetic analyses performed in air and an inert atmosphere show that the high-temperature behaviour of susceptibility and especially inversion of the studied synthetic maghemites depend on the quantity of available oxygen.

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3.5 INTENSE REMANENCE OF HEMATITE-ILMENITE SOLID SOLUTION

G. KLETETSCHKA

NRC — Goddard Space Flight Center/NASA, Code 691, Greenbelt, MD 20771, U.S.A.; gunther.kletetschka@gsfc.nasa.gov

Key words: Hematite-Ilmenite solid solution, intense magnetic signature.

When interpreting magnetic anomalies of planetary bodies a contributing factor is remanent magnetization. The potential to acquire an intense thermoremanent magnetization (TRM) can be characterized by ratio (REM) between Natural Remanent Magnetization (NRM) and Saturation Isothermal Remanent Magnetization (SIRM). Magnetite-bearing crustal material has low potential to acquire magnetic remanence (REM < 0.05). However, Kletetschka et al. (2000) showed that the Ti-free end member of hematite ilmenite solid solution has REM > 0.1. Rocks, containing hematite-ilmenite solid solution series minerals, were studied from two locations. Wilson lake granulite terrane, Labrador, contains titanohematite with exsolved ferrian ilmenite lamellae. Allard lake anorthosite terrane contains ferrian ilmenite with exsolved titanohematite lamellae. In both cases titanohematite carries the dominant magnetic remanence. Magnetic measurements of these rocks indicate large remanence acquisition potential (REM > 0.1). We interpret this effect as evidence that titanohematite acquired its intense TRM as a fairly large homogeneous grain where the low demagnetizing energy allows for a large remanence acquisition potential. However, TRM re-acquisition experiments with titanohematite samples do not re-produce the initial intense magnetization and thus have low REM (< 0.05). Original rocks with large REM possess large coercivity and large resistance against alternating field (AF) demagnetization. This is in contrast with the low coercivities of pure coarse-grained hematite and its moderate AF resistance (Kletetschka et al. 2000). Furthermore different grain sizes of titanohematite have identical resistance against AF demagnetization, and TRM and IRM acquisitions. Thus magnetic remanence acquisition in massive "titanohematite" resembles fine-grained hematite rather than the coarse grained one. We propose that the reason for the large coercivity, and negligible grain size dependence, is related to exsolution of ferrian ilmenite lamellae. The titanohematite likely acquired the intense remanence when it was still an unmixed pre-exsolved ilmeno-hematite homogeneous phase (> 0.1 mm in size). Later ferrian ilmenite exsolution divided the magnetic grain into smaller segments increasing the coercivity and decreasing the remanence acquisition potential. This segmentation magnetically hardened the grain and caused large coercivities and low REM values obtained in TRM re-acquisition experiments. This observation indicates, that the magnetism of the ilmeno-hematite and disordered hematite ilmenite solid solution phases is not significantly perturbed by the continuous reaction: ilmeno-hematite > titanohematite and the discontinuous reaction: disordered hematite ilmenite solid solution > titanohematite, respectively. Thus we conclude that any occurrence of hematite-ilmenite solid solution in a rock cooled in a low intensity magnetic field will produce what would be considered an intense magnetic signature.

3.6 MAGNETIC HYSTERESIS OF PSEUDO-SINGLE-DOMAIN AND MULTIDOMAIN MAGNETITE BELOW VERWEY TRANSITION

A. KOSTEROV

Marine Geology Department, Geological Survey of Japan, 1-1-3 Higashi, Tsukuba 305-8567, Japan; kosterov@gsj.go.jp

Key words: Magnetite, magnetic hysteresis, Wervey transition, pseudo-single-domain particles, multidomain particles.

Magnetite has been extensively studied since it is the most abundant magnetic mineral in nature, and also because of its widespread applications in industry. It is therefore surprising to recognize how little is known about the magnetic hysteresis properties of its low-temperature phase, existing below Verwey transition (119–123 K in stoichiometric material). Until now, only the behavior at Verwey transition and immediately below it, down to 77 K, has been studied in some detail (see Muxworthy & McClelland [2000a, b] for a review). For small PSD grains 60 to 250 nm in size a very limited set of hysteresis data is available for the temperature range below 77 K (Schmidbauer & Schembera 1987; Schmidbauer & Keller 1996).

I therefore carried out hysteresis measurements from 10 K to room temperature on one multidomain (MD) and three pseudo-single-domain (PSD) magnetite samples, using a Princeton Measurements vibrating sample magnetometer equipped with a cryostat (Institute for Rock Magnetism, Minneapolis). Multidomain sample was crushed magnetite with the grainsize 100–150 μm, fully described by Hartstra (1982) (fraction of his sample HM4, hereafter referred as HM4L). Both SIRM warming and κ(T) curves of this sample display sharp Verwey transition at 117.5 K suggesting a relatively small non-stoichiometry. One of the PSD samples was also a <5 μm fraction of HM4 (referred hereafter as HM4S; note in passing that room temperature hysteresis parameters suggest even smaller mean grainsize). Another two were the commercial magnetites from Wright (3006) and Pfizer (BK5099) companies with the mean grainsize around 1 μm. Verwey temperatures for these samples were found to be 122 K for HM4S, 110 K for 3006, and 95 K for BK5099 showing that the two latter samples have been noticeably oxidized. Hysteresis measurements have been performed after cooling down to 10 K either in zero magnetic field or in 1.5 T field. Maximal field of the hysteresis loop was 1.4 T; this was not quite sufficient to saturate the low-temperature phase of magnetite, but higher fields could not be used because of the electromagnet pole saturation.

Hysteresis properties below Verwey transition were found to depend strongly on the cooling history for both PSD and MD samples. For PSD samples M_{rs}/M_s ratios are lower after zero field cooling, similar to that observed by Schmidbauer & Keller (1996). However, in contrast to the latter study, M_{rs}/M_s ratios for field-cooled samples show relatively strong decrease between 15 and 80 K. After zero field coolings M_{rs}/M_s does not vary much in this temperature range for samples HM4S and 3006, while for the sample BK5099 it has a distinct maximum at 30–35 K. Behavior of the coercive force in this temperature range is altogether dissimilar to that of Schmidbauer and Keller's sample, zero field coolings resulting in higher coercive forces than field coolings. Temperature dependences of coercive force show a trend opposite to that for M_{rs}/M_s: it decreases strongly for zero-field-cooled samples remaining almost constant for the field-cooled ones. Moreover, coercive force of the three PSD samples was found to depend on whether the sample had been zero-field-cooled from magnetized

(SIRM at room T) or from demagnetized state. Taken together, these results strongly suggest that below Verwey transition a multitude of magnetic states may be available to PSD magnetite grains, and neither shape nor magnetocrystalline anisotropy exert full control over the hysteresis properties in this temperature range. Close to Verwey transition both M_{rs}/M_s and H_c decrease significantly; curves corresponding to different cooling histories converge. Samples HM4S and 3006 show minima in both M_{rs}/M_s and H_c at 132–134 K and 122–124 K respectively, and for sample BK5099 M_{rs}/M_s and H_c flatten out at about 110 K. Bearing in mind that the isotropic point of magnetite does not shift down much with the increase of non-stoichiometry (Kąkol & Honig 1989; Aragón 1992), previous identification of this anomaly with the isotropic point seems doubtful.

For the multidomain sample HM4L both M_{rs}/M_s ratio and coercive force are significantly higher after zero field cooling. This effect is most likely due to the fact that cooling in a strong magnetic field renders easy magnetization axes to be as close to the cooling field direction as possible. It is worth noting however that zero-field- and field-cooled states display the same temperature dependence of hysteresis parameters only below ~60 K. At higher temperatures, but below the Verwey transition itself, for the zero field cooling decrease quite significantly, and for field cooling slightly increase. This may indicate that from the point of view of magnetism, low-temperature structure formed on cooling through Verwey transition is in fact fully stable only well below the transition temperature. At the same time, the transition itself, as shown in hysteresis properties, is quite sharp and extends for 3–4 K at the most. Above the transition, zero-field- and field-cooled curves of both M_{rs}/M_s and H_c converge perfectly. Minimum of M_{rs}/M_s and H_c occurs at 124–126 K again suggesting that it may not be directly related to the isotropic point.

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3.7 AN ALTERNATIVE WAY TO INTERPRET IRM ACQUISITION CURVES

P.P. KRUIVER and M.J. DEKKERS

Paleomagnetic laboratory Fort Hoofddijk, Budapestlaan 17, 3584CD Utrecht, The Netherlands; kruvier@geo.uu.nl

Key words: Isothermal remanent magnetization, multimodal coercivity distribution.

In general, isothermal remanent magnetisation (IRM) acquisition follows a cumulative log-normal distribution as a function of the magnetising field (Robertson & France 1994). They characterise an IRM acquisition curve by i) the saturation magnetisation M_{ri}; ii) the applied field at which half of the saturation IRM is achieved, $B_{1/2}$ and iii) the dispersion parameter DP, which reflects the dispersion of apparent coercivities. In a plot of IRM acquisition intensity versus the logarithm of the applied field, the curve has a sigmoid shape for a single magnetic phase. If more than one magnetic phase is present (e.g. different magnetic minerals or a multimodal grain size population), their IRM acquisition curves combine linearly, provided that no magnetic interactions occur. Then the shape of the curve is sigmoid with inflections, which correspond to the onset of SIRM of the different phases. Robertson & France (1994) proposed a method to resolve the different contributions in the IRM acquisition curve by a technique of curve fitting, so that the type, grain size and magnetic concentration of each magnetic phase may be estimated separately. Stockhausen (1998) refined this technique by introducing three goodness-of-fit parameters.

As an IRM acquisition curve generally behaves conform a cumulative log-normal distribution, a straight line results in a plot of IRM acquisition with a cumulative probability scale on the y-axis versus the logarithm of the field on the x-axis. A bimodal (or multimodal) distribution will appear as two (or more) straight line segments separated by curved parts. This way of plotting the data is visually more appealing than a sigmoid curve. In one glimpse it is possible to see how many coercivity populations are expected to be present in the sample. A computer program can be used to discriminate between the phases, as in the methods of Robertson & France (1994) and Stockhausen (1998). An estimate of goodness-of-fit will be provided as well.

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3.8 A NEW APPROACH TO THE COMPONENT ANALYSIS OF THE NATURAL REMANENT MAGNETIZATION

E. MÁRTON[1] and P. MÁRTON[2]

[1]Eötvös Loránd Geophysical Institute, Paleomagnetic Laboratory, Columbus u. 17-23, H-1145 Budapest, Hungary; paleo@elgi.hu
[2]Eötvös Loránd University, Geophysics Department, Ludovika tér 2., H-1083 Budapest, Hungary; martonp@ludens.elte.hu

Key words: Component analysis, magnetite, iron sulphides.

The component analysis of the natural remanent magnetization (NRM) searches for linear segments in the sequence of several vector observations in the three-dimensional space: the components recognized are statistically significant lines. The geological problem of sorting out components in order of age and identifying which mineral phases carry each component is beyond the scope of the analysis.

Even the most sophisticated algorithm (Kent et al. 1983) has a definite preference for long lines over short lines, when automatically employed. Thus, inspection of the orthogonal projection is recommended and the user may introduce explicit break point, i.e.

forced end points of segments. When doing this, he may be entirely subjective in his choice.

When the NRM is thermally demagnetized, it is useful to monitor susceptibility. The susceptibility/NRM intensity versus temperature curves may be smooth but may as well exhibit abrupt changes, especially when the carrier of the NRM is maghemite, or iron sulphides. When goethite contributes to the NRM, the intensity will dramatically drop, often between two steps of demagnetization.

We shall present examples which illustrate that the classical statistical component analysis in combination with the inspection of the susceptibility/NRM intensity versus temperature curves (indicating phase transition or important unblocking of the magnetic minerals) is more efficient in recognizing and separating components of different ages than the statistical analysis by itself.

This work was supported by the Hungarian Science Research Found (OTKA), Project Numbers: T022119, T029805.

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3.9 ASSESSING THE SUPERPARAMAGNETIC CONTRIBUTION TO THE MAGNETIC SIGNAL IN A DUNE SOIL FROM CENTRAL SPAIN

G. McINTOSH[1], M.L. OSETE[1] and A. PEREZ-GONZALEZ[2]

[1]Depto de Geofisica, Facultad de CC Fisicas, Universidad Complutense de Madrid Avda Complutense s/n, 28040 Madrid, España; gregc@eucmos.sim.ucm.es

[2]Depto de Geodinamica, Facultad de Geologia, Universidad Complutense de Madrid Avda Complutense s/n, 28040 Madrid, España

Key words: Spain, dune soil, magnetic susceptibility.

The mineral magnetic properties of a suite of soils have been studied. The soils have developed on dunes that have formed on the alluvial plain of the Rio Zancara, in La Mancha, south of Madrid in central Spain. In general the younger soils, developed on dunes approximately 3–5 Ka old, are weakly developed, and show moderate physical and magnetic horizons. For the older soils, approximately 20–30 Ka in age, the physical horizons become clearer, as does the magnetic zonation.

One interesting characteristic shared by all of the studied soils is a high and constant value of the frequency dependence of magnetic susceptibility. Expressed as a percentage, this value varies between 10–16 % and in profile extends to depths of > 50 cm in each soil. On first appearances this would seem to imply a rapidly developed and pervasive magnetic mineral population spanning the stable single domain–superparamagnetic boundary.

Measurements were made using a Bartington dual frequency susceptibility meter, and because of the low susceptibility values of many of the soil samples there is considerable doubt over the quality of the data. However, in the most strongly developed soil values of susceptibility where sufficient to place some confidence in the results.

In order to test the validity of the frequency dependent susceptibility results, further samples from the magnetically strongest soils were subjected to low temperature experiments. These concentrated on the acquisition and decay of isothermal remanent magnetisations at room and liquid nitrogen temperatures. Two procedures were followed. An isothermal remanence was imparted at low temperature and measured during warm-up. Secondly, isothermal remanence acquisition curves were measured at room and low temperatures. By combining these two approaches some information about the super-paramagnetic grains and their coercivities might be obtained. These results may shed some light on the earlier data, either supporting the "interesting hypothesis" of rapid formation of ultrafine-grained material, or reinforcing the "boring hypothesis" of instrumental/methodological error.

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3.10 ROCK-MAGNETIC PROPERTIES, GEOCHEMISTRY AND DIAGENESIS OF EASTERN MEDITERRANEAN SURFACE SEDIMENTS

H.F. PASSIER[1], M.J. DEKKERS[1] and G.J. DE LANGE[2]

[1]Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands; hpassier@geo.uu.nl, dekkers@geo.uu.nl

[2]Department of geochemistry, Faculty of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands; gdelange@geo.uu.nl

Key words: Rock-magnetic properties, geochemistry, diagenesis, sapropel.

Rock-magnetic properties (IRM, ARM, χ_{in}, S-ratio at 0.3 T, RT hysteresis and thermo-magnetic curves) and geochemical data (contents of Fe, S, Mn, Al, Ti, and organic C) were studied in Holocene sediments of two eastern Mediterranean boxcores (ABC26 and BC19), sampled at a resolution of 3 to 5 mm. These sediments contain the most recent sapropel S1 or Si2 (organic-rich sediment layer; maximum C_{org} = 3.9 wt. % for BC19 and 2.6 wt. % for ABC26) at a few decimeters below the sediment-water interface. The original sapropel was thicker than the currently visible sapropel: the upper ~5 cm have been oxidized. The top of the visible sapropel forms the active oxidation front.

There are three main sources of magnetic particles in the sediments: 1) eolian Saharan dust, 2) volcanic ash (core BC19), and 3) diagenetic Fe oxides. The eolian and volcanic magnetic fractions consist of SD to PSD (titano)magnetite. The volcanic magnetite (concentrated in ash layers) has the largest grain size. The eolian magnetite content correlates with eolian dust-input proxies, such as the Ti/Al ratio. The upper 10 to 15 centimeters of the cores consist of sediments that are unaffected by suboxic/anoxic diagenesis.

The oxidized sapropel is enriched in diagenetic Fe oxides (Fe in oxides is up to 3 wt. % in BC19 and 2 wt. % in ABC26). The coercivity is high in this entire zone, the maximum coercivity is found in a distinct sediment layer of about 1 cm thickness in between the Fe and Mn redox boundaries at the top of the remaining sapropel. Extreme values in this zone are: B_c = 61 mT, MDF_{ARM} = 64 m, MDF_{IRM} = 97 mT, S-ratio = $(1-(IRM_{-0.3T}/IRM_{1T}))/2$ = 0.8. Wasp-waisted hysteresis loops are typical of this zone. It appears that between the Fe and Mn redox boundaries, SP grains as well as extremely coercive magnetite are formed. We propose that this highly coercive magnetite consists of elongated SD magnetosomes produced by magnetotactic bacteria. Higher up in the Fe-rich zone this mixture of SP and SD grains is not present and SD maghemitized magnetite appears dominant.

The sapropel and the underlying pyritized sediment (syn-sapropel) are both characterized by reductive dissolution and pyritization features. Two types of pyrite occur; one oxidizes below 450 °C and the other above 450 °C. The higher oxidation temperature is predominantly found below the sapropel. This may be related to the microtexture of pyrite, which is euhedral below sapropels and mainly framboidal within sapropels.

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3.11 MAGNETIC MINERALOGY–ORE MICROSCOPY AND ROCK MAGNETIC TESTS — ARE THEY ENOUGH?

G. J. SHERWOOD[1], J-P. J. POLLARD[1] and H. BÖHNEL[2]

[1]School of Biological & Earth Sciences, Liverpool John Moores University, Byrom St., Liverpool L3 3AF, UK; besgsher@livjm.ac.uk
[2]Instituto de Geofisica — UNICIT, Juriquilla, Qto. 76226, Mexico; harald@tonatiuh.igeofcu.unam.mx

Key words: Magnetic mineralogy, titanomagnetites, rock magnetism, reflected light microscopy, igneous petrology.

In a palaeomagnetic study a thorough knowledge of the magnetic mineralogy will allow conclusions to be drawn about the origin of the magnetic remanence. Rock magnetic tests — thermomagnetic curves, hysteresis loops, low temperature susceptibility, etc. — are often used as a proxy for direct observation of magnetic mineralogy using reflected light microscopy.

The resolution of the optical microscope is such that it is impossible to observe the very small PSD & SD grains (< 1 μm) which hold the more stable parts of the remanence. A similar problem may arise with some rock magnetic tests — thermomagnetic curves and low temperature susceptibility behaviour will also tend to be dominated by the larger grains. Hysteresis loops, however, are sensitive to the presence of PSD & SD grains.

When attempting to use igneous rocks for palaeointensity work, it is even more important to determine the origin of the remanence in the sample. It is essential to prove that the rocks are preserving an original thermoremanence and have not been influenced by later events such as hydrothermal alteration which may have caused the growth of new magnetic phases.

In this study we look at lavas and other igneous rocks from various parts of the world and pose the following questions:

1. How effective are reflected light microscopy and rock magnetic tests for determining the origin of the remanence?

2. Should we only be looking at the magnetic minerals, or should we look at the whole rock?

We assess the value to the palaeomagnetist of traditional petrographic study using thin sections, looking particularly at its ability to detect signs of hydrothermal alteration which may have produced secondary chemical remanences.

3.12 MAGNETIC PROPERTIES OF SILICICLASTIC ROCKS IN THE BALTIC CAMBRIAN SEDIMENTARY BASIN

A. SHOGENOVA[1], L. BITJUKOVA[1], S. SLIAUPA[2], V. RASTENIENE[2], L. LASHKOVA[2] and A. ZABELE[3]

[1]Institute of Geology at TTU, 7 Estonia Ave., Tallinn 10143, Estonia; alla@gi.ee
[2]Institute of Geology, Sevcenkos 13, LT-2600 Vilnius, Lithuania; sliaupa@geologin.lt
[3]University of Latvia, Alberta st.10, Riga LV-1010, Latvia; azabele@popohost.lanet.lv

Key words: Magnetic susceptibility, saturation isothermal, remanent magnetization, natural remanent, magnetization, siliclastic rocks, Baltic Cambrian basin.

Magnetic properties of Cambrian siliciclastic succession were studied in Estonia, Latvia and Lithuania covering the flank and central parts of the intracratonic Baltic basin. Cambrian deposits compose the basal portion of the sedimentary infill of the Baltic basin, the thickness ranging from a few dozens of meters in the east and north-east to more than 500 m in the western part of the Baltic sea. The depth systematically increases from several meters in Estonia (NE flank of the Baltic basin) to more than 2 km in western Lithuania. This is associated to significant sin-depositional and essentially diagenetic variations across the basin. Two sedimentation focuses are recognised in the Baltic area. The pre-trilobitic Cambrian is restricted in the east of Lithuania and Latvia and in Estonia, it occurs at shallow depths and is dominated by clayey lithologies except the western near-shore facies. The tidal and shallow marine trilobitic Lower-Middle Cambrian sediments cover the whole territory of the Baltic basin extending further west. They are represented by triple alternation of sandstone, siltstone and claystone, which show different proportions across the basin. Magnetic properties of the Cambrian rocks depend on their lithology and cementation, represented by secondary quartz, clay and carbonates. These cements were formed at different stages of early- and late diagenesis, strongly depended on burial depth, temperature and primary composition. Main iron-bearing minerals in the studied rocks are represented by iron hydroxides (goethite) and glauconite, formed during sedimentation, early diagenetic pyrite and siderite and post-sedimentary iron oxides (hematite) and sulphides (pyrite). Iron, calcium and magnesium oxides compose carbonate cement mainly represented by iron-bearing dolomite. Iron also enter into the clay minerals represented by illite, illite-smectite, kaolinite and chlorite, a part of illite systematically growing with burial depth to the west.

33 wells located in Estonia, Latvia and Lithuania were sampled for the petrophysical and geochemical studies. 269 samples of Cambrian sandstones, siltstones and claystones represented shallow (Estonia — 80–600 m), central (Latvia, C.Lithuania — depths of 1–1.6 km) and western (W. Lithuania, 1.8–2.3 km) parts of the basin. Magnetic susceptibility (κ), saturation isothermal remanent magnetization (SIRM), natural remanent magnetization (NRM) were measured along with estimation of abundance of bulk geochemical elements and iron form.

Magnetic properties in different parts of the basin are controlled by various factors. In the shallow part of the basin the iron-bearing dolomite cementation of siltstones significantly influenced magnetic properties. In the central part of the basin the iron minerals entering into the clay minerals are more significant. And in the deepest (western Lithuanian) part of the basin the ferric iron minerals factor is the dominant. There is a high correlation of total iron content with *magnetic susceptibility* (κ) of Cambrian rocks (Fig. 1a). Claystones and siltstones show slight paramagnetic properties (κ is $1-39*10^{-5}$ SI) with total iron content in the limits of 1–10 %. Sandstones are both diamagnetic and low-intensity paramagnetic. Majority of western Lithuanian (deep) sandstones are diamagnetic ($-0.5-3*10^{-5}$ SI) with total iron content up to 0.6 %. Here, only sandstones containing increased amount of clay- and dolomite-related elements and iron minerals show paramagnetic features. By contrast, all the sandstones from the other parts of the basin (central and northern) are paramagnetic. This associates with slight enrichment in iron content (up to 1.5 %) of central and northern sandstones by comparison to western ones. Sandstones from the central part have κ up to $10*10^{-5}$ SI. In the northern shallow part of the basin (Estonia) the total iron content in sandstones is in the range of 0.1–0.7 % and it causes κ in the range of $(0.1-5.8)*10^{-5}$ SI. The highest values of κ $(105-128)*10^{-5}$ SI were determined in the iron-bearing cores (total iron is about 50 %).

Saturation isotermal remanent magnetisation (SIRM) in the deep (western Lithuanian) zone is higher in siltstones $(85-450)*10^{-3}$ A/M than in sandstones $(35-170)*10^{-3}$ A/M, and it is hundred times higher in the samples of iron-bearing cores. In the central part of the basin SIRM of sandstones is in the same limits as for sandstones $(90-450)*10^{-3}$ A/M and it is some times higher only in several clayer siltstones from Latvia. In the northern part of basin (Estonia) SIRM of sandstones and most siltsones is generaly in the same limits as for Lithuanian siltstones and Latvian sandstones and siltstones $(90-400)*10^{-3}$ A/M (Fig. 1b).

Natural remanent magnetization (NRM) showed various behaviour in the different parts of the basin. It does not depend on total

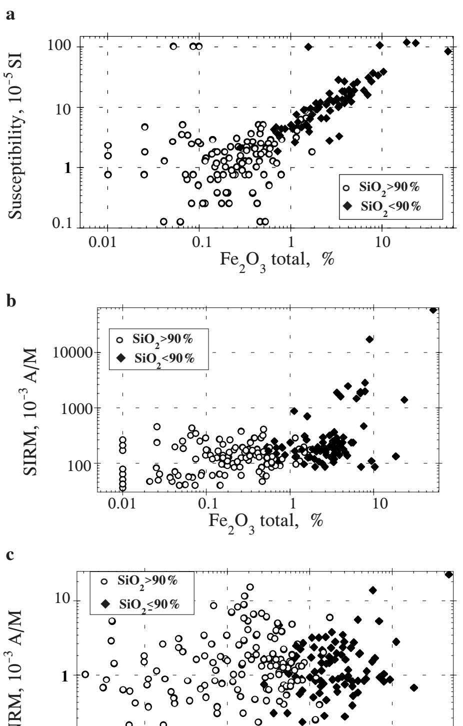

Fig. 1. a) Magnetic susceptibility, b) Saturation isothermal remanent magnetization and c) Natural remanent magnetization versus total iron content in the Baltic Cambrian rocks.

iron content in the shallow Estonian part of the basin $(0.3-4.82)*10^{-3}$ A/M. NRM is higher in sandstones $(0.23-15.8)*10^{-3}$ A/M, than in siltstones $(0.07-5.3)*10^{-3}$ A/M in the central part. But NRM is higher in siltstones $(0.3-22.7)*10^{-3}$ A/M than in sandstones $(0.12-8.6)*10^{-3}$ A/M in the deep Lithuanian part of the basin (Fig. 1c).

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3.13 MINERAL MAGNETIC STUDY OF THE CHINESE LOESS AND ITS SOURCE MATERIAL

M. TORII

Department of Biosphere-Geosphere System Science, Okayama University of Science, Okayama 700-0005, Japan; torii@big.ous.ac.jp

Key words: Chinese loess, desert sand, magnetic mineralogy, magnetic granulometry.

We report mineral magnetic study of the Chinese loess and its potential source material, desert sands. We have collected modern desert sand samples from the Taklimakan desert, northwest China. Magnetically dominant mineral is found to be almost stoichiometric magnetite, i.e., without oxidation and titanium substitution. Although hematite exists as magnetically less dominant mineral, its volumetric content is about ten times higher than that of magnetite (Torii et al. submitted).

Then we made a comparison between the Taklimakan magnetic mineral and those from two typical loess/paleosol sections, Shajinping (western Loess Plateau) and Luochuan (central Loess Plateau). The former features pristine loess without distinct susceptibility enhancement (Mishima et al. submitted). On the other hand, loess/paleosol from Luochuan is typical, well-matured loess with strong magnetic enhancement at each paleosol layer (Torii & Fukuma 1998; Fukuma & Torii 1998).

Magnetic minerals are examined in terms of mineralogy and grain-size distribution on the samples exclusively from the loess layers of the above two localities. Dominant magnetic mineral from both sites is magnetite that is oxidized into some extent but not totally as evidenced by the variously smeared Verwey transition. Magnetic grain-size is examined on the basis of magnetic hysteresis data. It is notable that the all hysteresis data are approximately on a straight on the bilogarithmic Day-plot. However hysteresis data of Luochuan paleosol do not lie on the same line. Taklimakan samples occupy lower right-hand corner of the Day-plot. Then the samples of Shajinping take middle position and those of Luochuan distribute on the upper left-hand corner. These lines of evidence suggest decreasing trend in grain-size from Taklimakan to Luochuan through Shajinping. We believe that the grain-size decreasing pattern of magnetite in the loess is implying the aeolian origin of those magnetite grains. Such aeolian magnetite grains could be transported as dust input to the Loess Plateau from the north or northwest arid areas. Although Taklimakan is one of the most distal source areas, its potential as the aeolian source is possible on the basis of mineral magnetic study.

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3.14 APPLICATION OF THE HIGHER HARMONIC METHOD TO THERMOMAGNETIC ANALYSIS OF FERRIMAGNETIC MINERALS OF ROCKS

V.S. VETCHFINSKII[1] and V.A. TSELMOVITCH[2]

[1]Rybinsk Aviation Technology Academy, Pushkina 53, Rybinsk, Russia; root@rgata.adm.yar.ru
[2]Geophysical Observatory, Borok, Yaroslavskya obl., Russia; tselm@borok.adm.yar.ru

Key words: hysteresis loop, method of high harmonics, domain structure, induced magnetic anisotropy.

One of the fundamental characteristics of ferro- and ferrimagnetic materials is the hysteresis loop. In the range of weak magnetic fields, the hysteresis loop is described by the Rayleigh formula. Its parameters are closely connected with the composition and structure of magnetic material. However, it is difficult to judge about characteristics of ferrimagnetic minerals of rocks from the common loop shape. At the same time, one can expand the signal forming the hysteresis loop measured in an alternate magnetic field into harmonic components. Moreover, higher harmonics of the secondary emf are very sensitive to the variation of the composition and structure of magnetic material. Thus, spectral analysis of the hysteresis loop can give a lot of information about magnetic properties of ferrimagnetic minerals. The method of high harmonic analysis (MHH) may be applied to investigations of induced magnetic anisotropy in rocks, to determination of magnetic field intensity and temperature of thermomagnetic treatment of rocks, and to estimation of domain structure of ferrimagnetic minerals.

Higher harmonic methods of thermomagnetic analysis imply constructively simpler instruments of lower material consumption. These instruments do not need a sample to be rotated or translated, i.e., there are no mechanical components in them at all. Moreover, the MHH methods are distinguished by higher selectivity and sensitivity to various magnetic parameters as compared with thermomagnetic analysis.

3.15 HIGH RESOLUTION ROCK-MAGNETIC RECORD FOR THE TIME INTERVAL 15–6 KA FROM LAKE HUGUANG MAAR, SE CHINA

G. YANCHEVA[1], N.R. NOWACZYK[1], J. MINGRAM[1], G. SCHETTLER[1], J.F.W. NEGENDANK[1] and J. LIU[2]

[1]GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany; gergana@gfz-potsdam.de
[2]Chinese Academy of Science, Beijing, China

Key words: SE China, Holocene, rock magnetism, diagenesis and lake sediments.

The East Asian monsoon winds were the dominant controlling factor of the climate in SE China region during the whole Quaternary. Information about the prevailing direction and strength of the monsoon is thought to be preserved in sedimentary sequences of tropical lakes. High-resolution susceptibility logs revealed short-wave signals in the Early Holocene susceptibility records of seven parallel sediment cores recovered from lake Huguang Maar in SE China (21°N, 110°E). A 4 m section from a shallow water core location has been sampled in 4 mm intervals for detailed rock-magnetic studies. The section spans the time interval between 15000 and 6000 years cal BP and three different climatic events are clearly distinguishable in the rock-magnetic record. A depth interval with a corresponding age of 13–11 Ka can be matched to the European Younger Dryas. Observed high values of magnetic susceptibility κ_{LF}, anhysteretic remanent magnetization (ARM) and saturation remanent magnetization (SIRM) for this interval are associated with enhanced terrigenous input of fine and magnetically soft particles. Two warming stages between 15–13 Ka and after 11 Ka respectively, are characterized by high organic production and dilution process in the lake. The magnetic carriers are predominantly of high coercivity type with greater stability against AF-demagnetization and relatively low susceptibility.

4. MAGNETOSTRATIGRAPHY

4.1 MAGNETIC INVESTIGATION OF WELL CORES FROM THE NORTH SEA BASIN; AN IMPORTANT CONTRIBUTION TO THE GLOBAL POLARITY SCALE FOR THE TRIASSIC

C. BEYER

CB-Magneto, POB 7015, 4004 Stavanger, Norway

Key words: Triassic, magnetostratigraphy, Snore Oil Field.

A magnetostratigraphic study of several long well cores through a 400 m thick red bed sequence in the Norwegian North Sea has revealed a detailed polarity stratigraphy which corresponds well with the scale established by Kent and Olsen on the North-eastern American Newark basin. A similar good correlation is not easily achieved when trying to match it with the Triassic polarity scale established in SE-Turkey.

A total of 13 polarity zones were determined. These corresponds swell with the E13 to E19 of the Newark scale. Based on the magnetostratigraphy a rather constant accumulation rate of 0.04 mm/a could be determined.

The previously not easily resolvable homogeneous sequence could be dated by the correlation to the Newark scale to represent the time from Early Norian to Early Rhaetian which is considerably longer than what was previously thought.

4.2 ARE THE 24R CRYPTOCHRONES NOISE, INTENSITY VARIATIONS OR REAL REVERSALS?

C. BEYER

CB-Magneto, POB 7015, 4004 Stavanger, Norway

Key words: Paleocene, cryptochron, chron 24, magnetostratigraphy, Denmark.

The interpretation of ocean floor anomalies provides the basic reference scale for the global magnetostratigraphic polarity scale for the late Mesozoic to recent sedimentary sequences. Cande and Kents revised interpretation from 1995 indicates that as many as 11 normal polarity anomalies are present in 24r. Whether these should be determined as true reversals is not obvious as an alternative possible interpretation is that they represents intensity variations in the oceanfloor basalt caused by the changes in mineralogy. One possible way to clarify this would be to find these anomalies in two contemporary Paleocen-Eocene sedimentary sequences of different facies. In Denmark the transitional Paleocene/Eocene volcanic ash sequence is accessible in a number of outcrops across Denmark. Their geographical locations were determined by the Neogene uplift of Fennoscandia and the subsequent Quaternary glacial erosion which removed progressively older sediments northward in Jylland (Jutland) with the result that the succession constitutes the pre-Quaternary surface in a zone stretching from the South East to the North West of Denmark. The sedimentary fa-

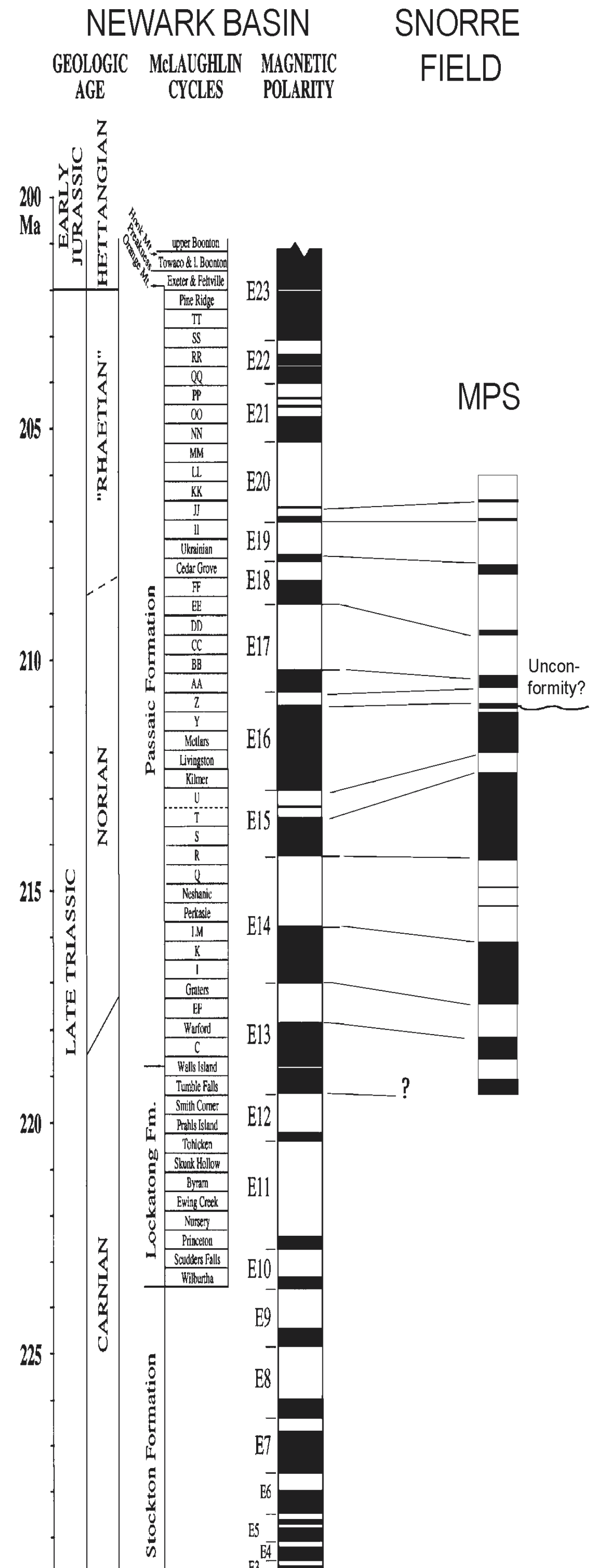

Fig. *To the contribution No. 4.1.*

cies change from a clayey, mainly tuffaceous facies in the South East to a silty, tuffaceous diatomite in the North West. This has given rise to the establishment of two partially time-equivalent formations: The clayey Ølst Formation and the diatomitic Fur Formation. The tephrastratigraphy enables a high resolution chronostratigraphic correlation between these two formations.

This presentation reports the result of a detailed palaeomagnetic analysis of these formations in a stratigraphic interval including the upper part of the Holmehus Formation (25r) up to the uppermost part of the Ølst Formation (24r), corresponding to almost 5 million years of sedimentation. Outcrop samples are from the diatomitic facies in NW Jutland and from two large clay pits at Ølst ca. 20 km north of Århus. Samples in the Ølst Formation were registered with respect to numbered ash beds so that the same stratigraphical level could later be sampled in the Fur Formation for comparison of the magnetic properties.

A cored borehole (DGI83101) from Østerrenden, Store Bælt was also studied. This borehole is stratigraphically more complete than the clay pits at Ølst and include a transitional sequence between the top of the Holmehus Formation and the overlying Ølst Formation. Four short normal anomalies occurring in the Ølst sequence may be recordings of cryptochrons. One of them is present at the same stratigraphic level in both the Østerrende core and at Ølst. The study of the diatomitic facies is not yet completed. It is hoped that it will reveal anomalies which may or may not be correlatable with the ones from the Ølst.

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4.3 A SUMMARY OF RESULTS OF MAGNETOSTRATIGRAPHIC AND MICROPALAEONTOLOGICAL INVESTIGATIONS OF THE J/K BOUNDARY STRATA IN THE TETHYAN REALM

V. HOUŠA, M. KRS, P. PRUNER and D. VENHODOVÁ

Institute of Geology, Academy of Sciences Prague, Rozvojová 135, 165 02 Prague 6-Lysolaje, Czech Republic; inst@gli.cas.cz

Key words: Tethyan realm, Jurasic/Cretaceous boundary, petromagnetism, magnetostratigraphy, calpionellid zonation.

The aim of this study is to summarize principal results hitherto obtained during combined detailed magnetostratigraphic and micropalaeontological investigations of the Jurassic/Cretaceous (J/K) boundary strata at three localities yielding reliable interpretation results. The localities in the Tethyan realm include the J/K sections at Brodno near Žilina (Western Carpathians, W Slovakia), the Bosso Valley (Umbria, central Italy) and at Puerto Escaño (Province of Cordóba, S Spain). These localities provided very detailed to high-resolution magnetostratigraphic data across the J/K boundary.

Originally, two additional localities were magnetostratigraphically studied: Štramberk (Western Carpathians, N Moravia) and the Río Argos (Province of Murcia, SE Spain). Although 540 orientated samples were studied from the locality of Štramberk, only an approximate pattern of magnetozones and subzones was obtained. This was due to the deposition of the Tithonian/Berriasian limestones in a peri-reef zone, in a dynamic depositional environment unfavourable for a precise record of the palaeomagnetic field. A different problem appeared during magnetostratigraphic investigations at the locality of the Río Argos. Good knowledge of geology and palaeontology of well accessible limestone beds, ranging from the latest Tithonian to the early Aptian in age, were basic prerequisites for successful investigations. In total, 361 orientated samples were collected and subjected to combined or thermal progressive demagnetization, using the Schonstedt GSD-1 and the MAVACS demagnetizers. The samples were progressively demagnetized at dense steps up to the temperature of 590 °C, even up to 690 °C. Multi-component analysis of remanence and subsequent studies of the data resulted into conclusion that the Río Argos section was syn-tectonically and/or post-tectonically remagnetized during the Neogene. Similar Neogene remagnetization of Mesozoic limestones was also observed in other parts of the Tethyan realm.

All the localities with the J/K boundary strata were carefully investigated palaeontologically before the acquisition of samples for magnetostratigraphic studies. The three most suitable localities, namely Brodno, the Bosso Valley and Puerto Escaño, are characterized by favourable depositional setting, rich calpionellid associations and favourable petrophysical properties of limestones. The intensities of natural remanent magnetization (Jn) vary considerably at these localities, usually within the range of hundreds of 10^{-6} Am^{-1} to thousands of 10^{-6} Am^{-1}. Very rarely, low intensities of the order of tens of 10^{-6} Am^{-1} were recorded, and quite exceptionally also values higher than ten thousand of 10^{-6} Am^{-1}. Table reviews basic magnetic properties of the Tithonian and Berriasian samples with either normal or reverse palaeomagnetic directions (revealed after multi-component analysis of remanence and subsequent studies of the origin of the C-components). Suitable physical properties of the limestones investigated were of key importance for accurate derivation of detailed to high-resolution magnetostratigraphic profiles. Samples of the studied upper Tithonian and lower Berriasian limestones are characterized exclusively by three-components remanence: by A-, B- and C-components. The A-component of remanence usually constitutes a significant portion of the Jn, frequently reaching 40 to 60 % of its value. This component of normal polarity is prevalently of viscous origin, it is totally unstable and was separated after demagnetization within the temperature interval of 20 to 100 (150, 200) °C. The B-component of remanence, characterized by single or two polarities, is secondary and usually of syn-tectonic origin. The B-components were separated after demagnetization within the temperature range of 100 (150, 200) °C to 420 (400, 440) °C. Some of the samples from the Bosso Valley locality showed signs of the Neogene imprint in the B-components. However, no signs of the Neogene imprint were recorded in samples from the Brodno and Puerto Escaño localities. The C-components of remanence were reliably inferred for most of the studied limestone samples, after thermal demagnetization in the range of 420 (400, 440) °C to 540 (560, 580, even 590) °C. Much like C-components at other localities of the Mesozoic limestones in the Tethyan realm, the C-components of remanence are carriers of palaeomagnetic directions. Magnetism of the studied limestones is generally characterized by the unblocking temperature of magnetite. A decrease in the values of volume magnetic susceptibility (k_n) from the Tithonian to the Berriasian was recorded in all three sections, aspects of utilization of this parameter for a possible correlation was also pointed out, but not yet studied in detail.

At the locality of Brodno near Žilina, altogether 368 orientated samples were collected and studied. Originally, only a synoptic profile was derived at Brodno, ranging between magnetozones M21r and M17r. This profile was futher logged by additional data and has now the character of a high-resolution profile across the J/K boundary. Two narrow subzones with reverse polarity were detected within magnetozones M20n and M19n, which were proposed to be named „Kysuca Subzone“ and „Brodno Subzone“.

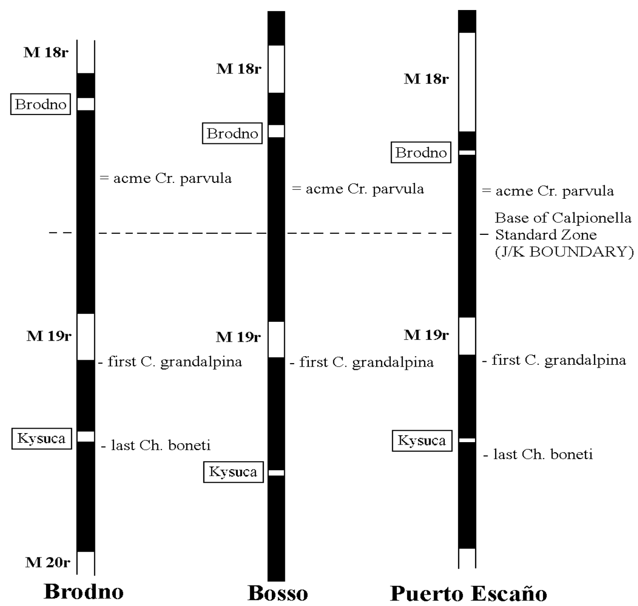
In the Bosso Valley section, we concentrated on the 40-m thick portion of the whole section studied synoptically by W. Lowrie and J.E.T. Channell in 1983. Intensities of magnetization of the limestone samples were similar to those from the Brodno locality, see Table. Magnetozones in the range M20n to M17r were detected in detail. Two reverse subzones were precisely localized in the magnetozones M20n and M19n in an analogous relative position as in the Brodno section.

At Puerto Escaño, altogether 194 orientated samples were collected along a relative short section across the J/K limestone strata, 5.0 m in true thickness (condensed sedimentation). Magnetozones were delineated from M20r to M17r, including the “Kysuca Subzone“ and the “Brodno Subzone“.

Principal results

The hitherto inferred magnetozones and subzones are schematically shown on Figure. The reverse subzones proposed to be named „Kysuca Subzone“ and „Brodno Subzone“ were precisely localized in all the sections in analogous relative positions in magnetozones M20n and M19n, respectively. The inferred magnetozones and subzones are well correlable with the M-sequence of marine magnetic anomalies. At the locality of Brodno, the transition from N (R) to R (N) polarity of the Earth's palaeomagnetic field was inferred indicating the duration of transition within a time interval of about ± 5 ka.

Locality	Age	Magnetozone	Number of samples	J_n [10^{-6} A/m]		k_n [10^{-6} SI]	
				Mean value	Standard deviation	Mean value	Standard deviation
BRODNO	Early Berriasian	N	50	678	343	9.8	4.2
		R	71	452	386	5.5	8.9
	Late Tithonian	N	159	1068	474	19.5	8.7
		R	88	1274	791	22.0	10.0
BOSSO VALLEY	Early Berriasian	N	51	311	212	-1.1	2.4
		R	29	418	411	-2.4	2.6
	Late Tithonian	N	112	1062	1514	16.6	19.5
		R	20	192	73	7.8	5.9
PUERTO ESCANO	Early Berriasian	N	45	3805	1411	25.4	9.4
		R	42	2538	711	20.8	4.6
	Late Tithonian	N	109	7145	2620	35.0	13.2
		R	31	5809	1761	35.4	9.4



Correlation of magnetozones with calpionellid events

Stratigraphically significant calpionellid events occupy an identical position in relation to magnetozones and subzones inferred in all the three sections. The base of the calpionellid zone Crassicolaria coincides with the base of the „Kysuca Subzone“. Appearance of the species *Calpionella grandalpina* represents a significant horizon: it lies immediately below the base of the magnetozone M19r in all sections investigated. The base of the standard zone Calpionella, used for the definition of the Jurassic/Cretaceous boundary in calpionellid stratigraphy, was detected in magnetozone M19n in all sections investigated: it lies approximately at 35 % of the local thickness of M19n at Brodno and the Bosso Valley, and at 46 % of the local thickness at Puerto Escaño. (However, a hiatus was detected close to the J/K boundary at Puerto Escaño).

4.4 MAGNETOSTRATIGRAPHY OF THE LATE MIOCENE MARINE-LAND DEPOSITS OF EASTERN PARATETHYS (BEREZNEGOVATOE PROFILE, NIKOLAEV REGION, S. UKRAINE)

E. KRÓL[1] and G. SLIVINSKAYA[2],

[1]Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warsaw, Poland
[2]Institute of Geophysics, National Academy of Sciences of Ukraine, Palladin av. 32, 252680 Kiev, Ukraine

Key words: Magnetostratigraphy, Late Miocene, eastern Paratethys deposits.

The stratotype, complex profile Bereznegovatoe (lat. 47.2° N, long. 32.5° E) of Late Miocene marine/land sediments from the bottom part of the northern slope of the In-Black Sea Depression (southern Ukraine) has been studied to obtain the local magnetostratigraphic scale.

This profile of the total thickness of more than 12 m consists of clays, sandy clays, alleurites and is intercalated by tiny layers of marls and limestones. It has been subdivided lithologically into 26 different layers from the bottom to the top, starting from the Sarmatian/Meotian boundary (Prisjazhnuk 1995). The estimation of the age of this boundary 9.3 Ma (optionally 9.6 Ma) is cited after Chumakov (1999).

Owing the detailed biostratigraphical indexes, lithology and palaeontology of the profile is presented as follows: the Meotian sediments with the total thickness 6.5 m are dated mainly from Lower Meotian and they cover time span from 9.3 to 8.2 Ma BP. Layers 2–7 are represented as sandy clays and clays intercalated by marls, rich in freshwater molluscs, land molluscs, abundant subsaline-water ostracods, remnants of small mammals, bones of fish, dolphins and turtles. These deposits provide the subcontinental Early Meotian rhythm.

The overlying beds with thickness of about 2.5 m represent the second rhythm of sedimentation of Early Meotian of lagoon — marine character (layers 8–15). This packet includes marine forms together with freshwater and subsaline — water fauna.

The next, 16 layer has no paleontologic data — so it can be interpreted as either Upper Meotian or Lower Pontian. This means there is no representation of Upper Meotian sediments, so in this locality there was a deposition gap, which continued around 1 Ma. The Meotian-Pontian boundary is fixed at the depth 5.2 m from the top of the profile (the basal layer 17). The upper part (clays of layers 17–20) and limestones of layers 21–26 are of Early Pontian age from about 7.2 till 6.5 Ma.

The representative collection of specimens for paleomagnetic measurements has been gathered from deposits covered layers 2 till 20 (from 3.8 to 12 m of studied sequence). The specimens were collected from 114 levels situated in the distance from 3 cm till 5 cm (along the profile) in its upper part, but enlarged to more than 50 cm in the lower part of it, from the reason dependent of mechanical properties of sediments. Not less than 2, 3 small specimens, but usually 6 represented one level.

The profile is relatively well situated on the time scale thanks the radiometric data for the main stratigraphic boundaries of Eastern Paratethys deposits obtained for volcanic ashes.

The standard paleomagnetic and rock-magnetic methods applied to this collection indicate magnetite as the main carrier of NRM.

These weakly magnetized rocks (intensity of NRM between 0.03 and 0.67 mA/m per 1 cm^3) indicated a relatively stable primary component of the RM extracted thanks to AF or thermal cleaning and thanks to the application of the Kirchvink method.

Both methods of demagnetization appeared effective for the studied sediments. The respective isolated components are characterised as follows: the soft, contemporary component with close to N or S declination and with the middle and high positive or negative inclination has been removed easily by low AF field or low unblocking temperature. The decrease of intensity of reached usually not less than 50 % of its initial value, sometimes up to 80 % of it during the first 3–4 steps of demagnetization procedure. As the average initial intensity of NRM was very low it stressed us to provide the measurements with special care, checking the noise level and diminishing the influence of spurious magnetization of holders for specimens after each demagnetization step. For the weakest specimens the empty holder had been additionally demagnetized by AF field between the following steps of demagnetization procedure. This elaborateness technique of measurements on SQUID cryomagnetometer let to isolate the second-characteristic component of NRM along the profile and to reconstruct the pattern of Earth's magnetic field polarity for Bereznegovatoe section. The isolated ChRM component is characterised by close to N or S magnetic declination and middle, only occasionally high inclination (positive and negative). The average value of inclination close to maximum 50° for ChRM component repeats for the following zones of normal or reversed polarities. It indicates on the presence of so called „inclination error" of NRM described by King & Rees (1966). This error diminishes to the expected for the specific paleogeographic latitude (magnetic inclination angle from 10° up to 25°).

The local pattern of normal and reversed polarities for Bereznegovatoe section was confirmed by the statistical reversal test. The six changes of magnetic polarity are observed for the Early Meotian and one reversed period (with the short anomaly interval) for the Early Pontian.

This local magnetostratigraphy correlates with the according part of the GPTS (Cande & Kent 1995) in the time span 6.5 to 9.3 (or optionally 9.6) Ma.

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4.5 NEOGENE MAGNETIC IMPRINT DETECTED IN THE JURASSIC-CRETACEOUS LIMESTONE STRATA IN THE TETHYAN REALM

M. KRS, P. PRUNER and D. VENHODOVÁ

Institute of Geology, Academy of Sciences Prague, Rozvojová 135, 165 02 Prague 6 – Lysolaje, Czech Republic; inst@gli.cas.cz

Key words: S. Spain, Río Argos, central Italy-Bosso Valley, Jurassic-Cretaceous limestones, Neogene imprint.

Magnetostratigraphic investigations of Jurassic/Cretaceous (J/K) boundary limestone strata carried out in detail at several localities in the Tethyan realm resulted in the determination of normal and reverse magnetozones and subzones well correlable with the M-sequence of marine magnetic anomalies. The globally-based events of the reversals of the Earth´s palaeomagnetic field are applicable to correlation with biozones determined palaeontologically. However, the methodology of investigations had to be considerably modified according to varying physical properties of rocks. At the locality of Río Argos (Province of Murcia, SE Spain) the limestones carry components of partial syn-tectonic and total post-tectonic remagnetization; at the locality of Bosso Valley (Umbria, central Italy) the limestones carry components of partial syn-tectonic and partial post-tectonic remagnetization; at the localities of Brodno (Western Carpathians, W Slovakia), Štramberk (Western Carpathians, N Moravia) and Puerto Escaño (Province of Cordóba, S Spain), besides secondary components, the limestones proved to be carriers of palaeomagnetic directions. In this presentation, we would like to draw attention to the Neogene remagnetization, which was also found by some researchers in other parts of the Tethyan realm (J.J. Villalaín, M.L. Osete, R. Vegas, V. García-Dueñas, F. Heller in the western Betics and J.M. Parés, E. Roca in the Valencia Trough).

At the Río Argos (φ = 38.1° N; λ =1.9° W), we collected altogether 361 oriented samples of limestones covering the period from the Late Tithonian to the Early Aptian. Such laboratory procedures were selected which allowed separation of the respective remanence components and the determination of their geological-historical origin. The samples generally showed three remanence components: A-, B- and C-components. The A-components are of viscous or chemoremanent origin and were inferred after the progressive thermal demagnetization procedure in the temperature interval below 100 °C, the B-components were mostly derived in the temperature interval of 100 to 400 °C, and the C-components were inferred in the temperature interval of 400 to 580 °C for a considerable number of samples. From the whole set of samples, 84 were found totally remagnetized, few samples were found weathered, and the remaining samples from the whole Río Argos section indicated syn-tectonic remagnetization. This finding was interpreted from the study of precision parameter k or semi-vertical angle of the confidence cone α_{95} in dependence on the dip angles of the strata. The total remagnetization of some limestone strata occurred during the Neogene, after termination of tectonic movements, while the most intense remagnetization was imprinted in the limestones during the reverse polarity of palaeomagnetic field. The epicentre of processes causing total remagnetization of the limestone strata was also determined using magnetic and palaeomagnetic data along the whole Río Argos section.

At the Bosso Valley (φ= 43.52° N; λ = 12.57° E), the magnetostratigraphic and micropalaeontological studies were focused on the basal, 40-m thick portion of the whole section comprising Tithonian and lower Berriasian limestones. This locality was subjected to a synoptic study already in 1983 by W. Lowrie and J.E.T. Channell, who derived the essential pattern of the magnetozones. In 1998 and 1999, we collected altogether 260 oriented samples with high sampling density and subjected them to progressive thermal demagnetization and subsequent multi-component analysis of remanence at simultaneous logging of magnetic susceptibility vs. temperature. The A-component of remanence separated within the temperature interval of 20 to 100 (150) °C constitutes a significant part of the natural remanent magnetization modulus. Another two components B and B1 are characterized by single polarities, reverse and normal ones, respectively. The B-component, oriented vertically, when related to the limestone strata corrected for tectonic dip, were separated within the temperature interval of 100 (150) to (200) 250 °C, see Fig. Inclination of the present teoretical geocentric dipole field for the Bosso Valley locality is 62.2°. This inclination is very close to the mean inclination (64.3°) of the B-components not corrected for dip of strata (in-situ directions) and transformed to normal polarity. The B-components were undoubtedly imprinted in the near past, obviously in the Neogene, after the rocks had been folded.

Post-tectonic components of remanence, so far inferred in several magnetostratigraphic profiles, originating most probably from the Neogene period, were well documented in the Río Argos and Bosso Valley J/K limestone sections. The events responsible for partial and/or total Neogene remagnetization, detected during magnetostratigraphic investigations or during regular palaeomagnetic investigations of Mesozoic rocks in the Tethyan realm, are undoubtedly worth further studies.

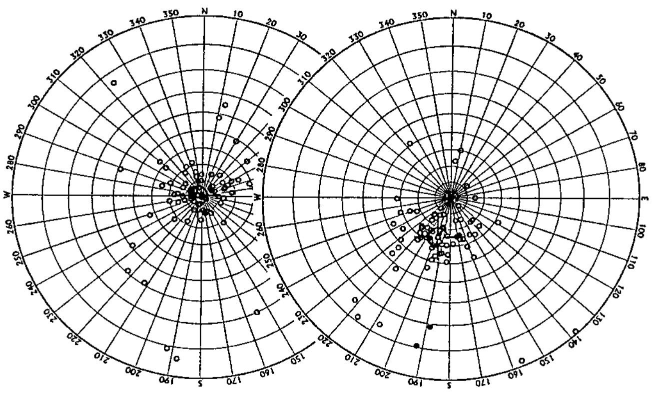

Fig. The Bosso Valley, Late Tithonian and Early Berriasian limestone. Directions of B-components of remanence corrected (left) and not corrected (right) for dip of strata. Stereographic projection, open (full) small circles represent projection onto the lower (upper) henisphere. The confidence circle at the 95 % probability level is circumscribed about the mean direction.

4.6 GEOMAGNETIC REVERSALS IN THE SEDIMENTS OF THE CENTRAL CHINESE LOESS PLATEAU

S. SPASSOV[1], F. HELLER[1], M.E. EVANS[2], L.P. YUE[3] and Z.L. DING[4]

[1]Institut für Geophysik, ETH Zürich, CH-8093, Switzerland
[2]Institute for Geophysical Research, University of Alberta Edmonton, Canada T6G 2J1
[3]Institute of Geology, North-West University, Xi'an 710069, China
[4]Institute of Geology, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China

Key words: Loess, rock magnetism, geomagnetic reversals.

Despite many years of investigation, the actual process by which the Chinese loess was magnetized is still poorly understood. The major normal and reversed polarity chrons are almost always recognizable, but there are serious conflicts over shorter intervals. In an effort to shed some light on this problem, we have investigated in detail a number of stratigraphic intervals where polarity transitions occur. Samples were collected to provide continuous coverage spanning several polarity boundaries within the Matuyama and Brunhes Chron. The Matuyama/Brunhes boundary (MBB) at two sites in the Central Chinese Loess Plateau where relatively warm and humid climate conditions prevailed during the Quaternary, is characterized by a narrow zone of mixed polarities, but with no systematic transitional paths evident. The transitional behaviour may be caused by complex remanent magnetization lock-in of fine grained particles present and their chemical growth. Published Blake Event records are possibly also affected by such magnetization parameters. The Jaramillo/Matuyama Boundary (JMB) observed at one site, is much simpler. A rapid shift from normal to reversed polarity takes place over about 8 cm (≈1000 years) with one or two transitional directions being measured.

5. ENVIRONMENTAL MAGNETISM

5.1 ANALYSIS OF HEAVY METAL POLLUTION IN SOILS BY MEANS OF NON LINEAR MAPPING AND FUZZY C-MEANS CLUSTER ANALYSIS

M. HANESCH[1], R. SCHOLGER[1] and M. J. DEKKERS[2]

[1]Institute of Geophysics, University of Leoben, Peter-Tunner-Str. 25-27, A-8700 Leoben, Austria; hanesch@unileoben.ac.at; cholger@unileoben.ac.at
[2]Paleomagnetic Laboratory 'Fort Hoofddijk', Faculty of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands; dekkers@geo.uu.nl

Key words: Environmental magnetism, magnetic susceptibility, multivariate, statistics, soil contamination.

Soil quality is a factor of utmost importance in food production. Potential health hazard by contaminated food has led to growing awareness of this fact particularly over the last decade. Soils have a high filter and buffer capacity. Contaminants that were accumulated in the soil during a certain period a long time ago still present a hazard because the pollution may persist for a long time. Therefore, soil monitoring survey programs have been started in many countries. The aim of these programs is to recognize existing and threatening contaminations and, where possible, to counteract them when the hazard is still manageable. It is comparatively laborious and time-consuming to accomplish this aim because geochemical analyses of many elements (and occasionally organic compounds) have to be performed for a reasonably dense grid of soil samples. It would be desirable to find a straightforward and relatively inexpensive method that complements the traditional methods. More samples could then be analysed in shorter duration and the use of the comparatively laborious traditional methods could be restricted to areas where potential pollution has been delineated.

Measurement of the magnetic susceptibility could provide this additional information. It has been shown that susceptibility tends to correlate with anthropogenic heavy metal pollution. In the framework of the MagNet project (EU FMRX980247), it is tested to what extent susceptibility measurements can yield reliable information for pollution control.

The soil data we report on here were collected by the Styrian Research Centre for Agriculture. The dataset comprises the variables usually determined in soil science, including heavy metals. We added susceptibility values by measuring the soil samples with a Bartington MS2C sensor. A mass specific susceptibility can be calculated from this volume susceptibility with the help of the calibration curve shown in Figure 1. It was found by linear regression of the logarithmic values from the measurements with both a Bartington susceptometer with a MS2C sensor and an AGICO KLY2 susceptibility bridge. For the measurements with the KLY2, dried and sieved samples of a defined weight were used. This calibration procedure will be repeated for soil samples in the soil archives of the other Austrian provinces. Thus, we will be able to analyse samples from different provinces together.

We aim to test to what extent susceptibility can be used to monitor pollution and for which pollution types the method yields satisfactory results. Therefore it is required to distinguish between groups of soils representing different types of polluted and unpolluted areas in a dataset. Fuzzy c-means cluster analyses and non linear mapping were employed to define these groups. The fuzzy method was chosen because it allows for the detection of gradual changes in the dataset. When analysing soil data those gradual changes are expected rather than well-defined 'crisp' boundaries between the different groups.

The first results lead to two main conclusions. First: when a large number of variables is used, any distinction between the soil samples gets blurred by 'over-information'. The allocation of groups becomes difficult and mathematically unstable. Second: the main influences are the geological background and the land use (Figures 2 and 3). These are interrelated.

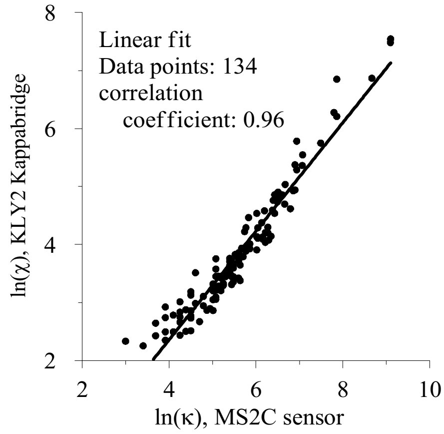

Fig. 1. Calibration curve for the calculation of mass specific susceptibility.

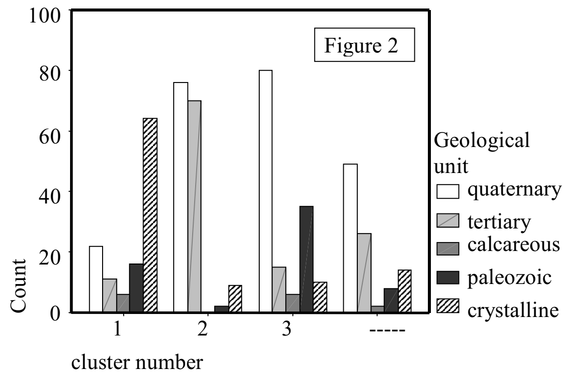

Fig. 2. Results of the c-means cluster analysis. Relation between geological unit and cluster assignment.

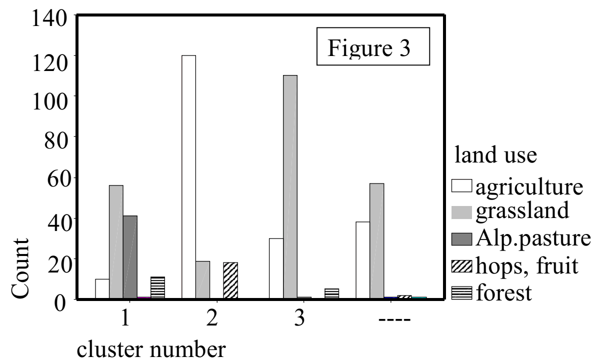

Fig. 3. Results of the c-means cluster analysis. Relation between land use and cluster assignment.

The lack of well-defined boundaries between the groups can be avoided if the variables are chosen according to the problem that has to be solved. In this study, we have to choose variables that help to find the relations between susceptibility and heavy metals. In addition, it should be possible to discriminate between geogenic anomalies and anthropogenic pollution. Therefore, susceptibility is selected as variable as well as some heavy metals which are known to be typically geogenic (Cr, Ni, Co, Cu) and some which are typically anthropogenic (Pb, Cd) in the study area.

The second problem is more difficult to solve. There are two possibilities to take the geological background into account. We could use background values existing in literature for the different geological units. This undoubtedly bears the risk to overlook local aspects of the dataset. Alternatively, we may use the subsoil data to either calculate a local background value or to perform partial least squares regression analysis which helps to separate measured values into a background part and an anthropogenic part.

During the presentation, these different strategies will be compared and first results will be presented which show possible applications of susceptibility in pollution control.

5.2 PALAEOCLIMATE VARIABILITY IN SOUTH-EASTERN EUROPE DEDUCED FROM MAGNETIC SUSCEPTIBILITY RECORDS OF LOESS/SOIL SEDIMENTS

D. JORDANOVA and G. YANCHEVA

Geophysical Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str. bl.3, 1113 Sofia, Bulgaria; vanedi@geophys.bas.bg

Key words: Loes/paleosol sequences, magnetic susceptility, paleoclimate.

The palaeoclimatic history of the Earth is an important key for understanding the present and forecasting the evolution of the Earth's ecosystems. However, one general question concerns the problem whether terrestrial and oceanic palaeoclimate proxy records are influenced and respond in the same manner to the factors which determine global climate. On the other hand, evaluation of local and regional impacts on the climate's characteristics is also an important task.

In the present study, palaeoclimatic significance of magnetic susceptibility records from three loess/palaeosol sequences in North Bulgaria is considered. Located at different palaeogeomorphological forms, different positions relative to the dust source area and the main wind direction, susceptibility variations along the sequences at Koriten (27°7', 43°9'); Viatovo (26°2', 43°7') and Lubenovo (24°9', 43°6') show remarkably similar behaviour both in loess and palaeosol horizons. Comparison with the astronomically tuned $\delta^{18}O$ record from North Atlantic (ODP site 677) allow refinement of time scale for the loess/palaeosol records, initially based on M/B boundary found in the last loess horizon. Predominance of the 100 Ky. periodicity is evident from the carried out spectral analysis. Impressing similarity in the shape of magnetic susceptibility variations of the three records and the Chinese loess suggest that it is an excellent proxy of subsequently occurring climatic oscilations during Quaternary. On the other hand, significant differences of the absolute values of magnetic enhancement among different sites, probably is a reflection of local/regional peculiarities of the climate.

5.3 MAGNETIC SUSCEPTIBILITY AS A PROXY FOR HEAVY METAL CONTAMINATION IN ROADSIDE SOILS

M. KNAB, V. HOFFMANN and E. APPEL

Institut und Museum für Geologie und Paläontologie, Sigwartstraße 10, 72076 Tübingen, Germany; mathis.knab@uni-tuebingen.de

Key words: Environmental magnetism, pollution, magnetic susceptibility, heavy metal, magnetic proxies.

Magnetic susceptibility (χ), and the content of heavy metals as well, are enhanced in roadside areas. Soil samples of the highway B27 near Tübingen (Germany) was investigated in different distances to the road and depths. A significant positive correlation between χ and certain heavy metals was found. Using Principal Component Analysis (PCA) it is possible to discriminate groups of same behaviour. One of these groups show the same trend of χ and Pb, Zn, Cd, Cu. One group is formed from Mn and Fe showing a negative behaviour to χ. However in some correlation diagrams it can be recognized that the data plots could be caused by different sources. Neither correlation analysis nor PCA are sensitive to this case.

Soils have a geogenic/pedogentic background signal and we know that the soil in our case is urban or at least reworked during the construction of the road. So we have to expect that there could be a former increase of magnetic susceptibility and/or heavy metals in this background signal. For estimating the increase caused by traffic it is no use taking into account only the information about the background of the geological layer.

A pedo-/geogenic (background) and an anthropogenic cluster can be separated by using fuzzy C-means cluster analysis. It is possible to discriminate up to 4 clusters. Each of them represent a different status of pollution.

The anthropogenic cluster contains higher correlation coefficients between χ and the most of heavy metals. A negative correlation of Fe versus χ appears in the background cluster. Whilst a positive correlation can be found between them in the anthropogenic cluster. However the content of Fe is very low in the anthropogenic cluster. This could be caused by dissolution of the pedogenic Fe in the closest part to the road.

5.4 FERRIMAGNETIC MINERALS OF ANTHROPOGENIC ORIGIN IN HIGHLAND PEATS IN SOUTH-WESTERN POLAND AND NORTHERN BOHEMIA

T. MAGIERA[1], Z. STRZYSZCZ[1], A. KAPIČKA[2] and E. PETROVSKÝ[2]

[1] Institute of Environmental Engineering, Polish Academy of Sciences, Zabrze, Poland
[2] Geophysical Institute, Academy of Sciences, Prague, Czech Republic

Key words: Peat bog, magnetic susceptibility, magnetite-like spinels.

Highland peats (ombrotrophic) and bogs are suitable collectors of dust pollution. They are built up above the groundwater table and therefore all non-atmospheric input pollution may be exclud-

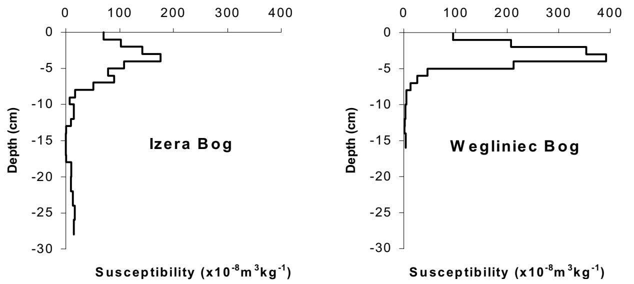

Fig. 1. Magnetic susceptibility in peat profiles from Izera Mts. and Wegliniec area.

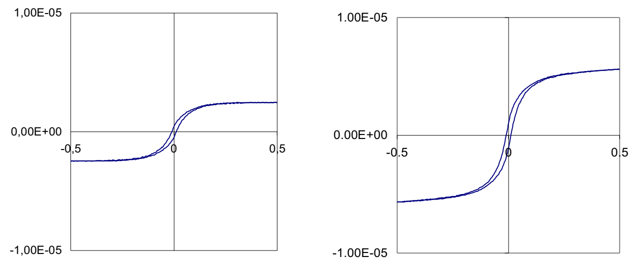

Fig. 2. Hysteresis loop of samples from most magneticaly enhanced peat layers from a) Izera Bog, b) Wegliniec Bog.

Table 1: Magnetic characteristic of anthropogenic particles present in peats.

Study area	χ ($10^{-8}m^3kg^{-1}$)	χ_{fd} (%)	Hc (mT)	H_{CR} (mT)	Ms (mAm^2kg^{-1})	Mr (mAm^2kg^{-1})	Mr/Ms
Izera Bog	117	4.0	10.29	-	40.06	9.59	0.2395
	136	3.3	10.80	26.22	114.35	21.74	0.1901
	32	2.1	14.76	-	36.76	7.07	0.1924
	175	2.0	10.56	26.33	110.36	19.50	0.1707
	17	2.3	11.30	-	41.77	6.17	0.1477
Wegliniec Bog	190	2.3	8.10	-	125.36	20.66	0.1648
	350	2.1	9.17	23.34	239.48	41.58	0.1736
	390	2.6	10.47	25.20	190.61	35.71	0.1874
	51	2.9	10.76	-	49.42	9.31	0.1884
	45	2.7	9.97	-	14.74	2.64	0.1788

ed. In result the dust deposition including magnetic particle accumulation may be preserved "in situ" for long time. Additionally very low or even negative magnetic susceptibility of organic matter is helpful to notice even small occurrence of particulate magnetic pollutants being the result of increased immisson.

Highland peats located in Western Sudeten (Karkonosze and Izera Mts.) and its foreland in range of emission from Turow Power Plant and smaller power plants located in Northern Bohemia, Easter Saxony and Brandenburg in area called Black Triangle. The study was performed in peat profiles from Izera Mts. (about 20 km E from Turow Power Plant), and Sudeten Foreland (Wegliniec — about 50 km NE from Turow Power Plant).

In both places the susceptibility increases in the top of peat profile with the maximum in about 4–6 cm below the surface (Fig. 1). The identical behaviour of susceptibility is observed in peat profiles from Czech part of Krkonoše mountains (Kapička et al. 2000). In Wegliniec area the susceptibility value is even higher then in Izera Mts. It is probably the result of combination of local immissions influx with long distance pollution influx connected with Turow, Saxonian and Brandenburg power plants emission. The Izera bog is remote from any local emission sources. The radiometric data based on C^{14} analysis suggests that the instant increase of magnetic dust deposition started about 1950 what coincide with starting the Turow power plant. The decrease in the youngest peat layers is probably result of starting to use electrofilters in Turow and other plants since a middle of 1970's and closing down some of old plants in former East Germany.

The shape of hysteresis loop (Fig. 2) suggests that magnetic material derived from studied peats is relatively fine-grain magnetite-like spinels. In both cases the material is almost saturated in 300 mT. With one exception the frequency dependence of magnetic susceptibility is between 2.0 and 3.3 %, what is characteristic for anthropogenic magnetic particles derived from fly ashes (Strzyszcz et al. 1996; Magiera & Strzyszcz 2000). The coercivity (HC) in Izera peats is between 10.29 and 14.76 mT (average 11.5 mT) whereas in Wegliniec peats between 8.10 and 10.76 mT (average 9.7 mT) (Tab. 1). It confirms the Flanders (1994) observations that Hc decreases with increase the distance from the source of fly ash emission. On the base of saturation remanence (Mr) to susceptibility (χ) ratio (Thompson & Oldfield 1986) it may be estimate that diameters of anthropogenic magnetic particles are between 20 and 60 μm. Both coercivity and magnetisation ratios are typical for pseudo-single domain (PSD) to multi-domain (MD) grains.

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5.5 APPLICATION OF THE ACID AMMONIUM OXALATE METHOD TO SAMPLES FROM A LOESS-PALEOSOL SITE NEAR BORETICE (CZECH REPUBLIC)

I.H.M VAN OORSCHOT and M.J. DEKKERS

Paleomagnetic Laboratory 'Fort Hoofddijk', Budapestlaan 17, 3584 CD Utrecht, the Netherlands; oorschot@geo.uu.nl

Key words: Selective dissolution, loess, paleosol, oxalic acid, carbonate.

Selective extraction techniques are used in environmental magnetism to constrain paleoclimate proxies as determined by rock magnetic measurements. These techniques are intended to preferentially dissolve a specific mineral phase. A selective extraction technique that is frequently applied in soil science is the acid ammonium oxalate technique [1]. It is used to determine non-crystalline iron(hydr)oxides in soils and it may be applied in environmental magnetism.

Several studies have contradicted the dissolution method and have shown that also crystalline iron oxides can be dissolved [e.g. 2]. To verify the extraction mechanism and reproducibility of the AAO-method we performed extraction experiments on synthetic samples [3]. Preliminary results indicate that the method dissolves crystalline magnetite as well as crystalline maghemite. Grain size mainly determined the dissolution behaviour, but mineral-specific dissolution occurred as well in the larger grain-size range. Furthermore, the presence of calcium carbonate in the synthetic samples strongly influenced the iron oxide dissolution.

Subsequently we compared the findings from the synthetic samples with extractions of samples from a loess-paleosol section near Boretice in South Moravia (Czech Republic). The profile consisted of a Lower Pleistocene loess with high carbonate content (10–13 %) overlain by a Braunlehm B Horizon and a Rotlehm from the Middle Pleistocene.

Preliminary results of the extractions indicate a loss of magnetic signal within the soil samples, but hardly any change in magnetic signal of the loess samples. This would suggest a preference for pedogenic iron oxide dissolution with the AAO method.

However, again we found that the high carbonate content of the loess samples caused problems during extraction. The pH increase during extraction caused changes in the chemical reactions in the loess samples and even caused changes in the magnetic signal of the extracted loess samples. The lack of dissolution of iron oxides in the loess samples can therefore be caused by changes in the chemical system during extraction, rather than by selective dissolution of the extraction method.

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5.6 MAGNETIC SUSCEPTIBILITY CHARACTERIZATION OF SEDIMENTARY ENVIRONMENTS WITHIN THE DANUBE DELTA–BLACK SEA SYSTEM

S. C. RĂDAN[1], M. RĂDAN[1], S. RĂDAN[2] and A. GANCIU[2],

[1]Geological Institute of Romania, 1 Caransebes, Str., 79678 Bucharest, Romania; mms.radan@.fx.ro

[2]GeoEcoMar, 23-25 Dimitrie Onciul Str., 70318 Bucharest, Romania

Key words: Danube Delta, lake sediments, magnetic susceptibility, monitoring.

Introduction

The Danube Delta (DD), a very important natural wetland in Europe, is working as a buffering interface between the River Danube (RD) supplies and the western Black Sea (BS).

A geological monitoring (GEM) has started in the RD–DD–BS macrosystem, in 1992. In this context, a study of dynamics and deposition precesses of sediments in fluvial, deltaic and marine environments was necessary.

In addition to the geological, geochemical and biological methods, the magnetic susceptibility (MS) monitoring has been introduced as a GEM tool, as well.

Actually, our first MS measurements on DD lake sediments were done in 1997, and they have continued until today, but a long time the study has been classified as environmental magnetism (see also Verosub & Roberts 1995).

Since 1992, the old and new MS data are compared and integrated in an explicit environmental framework.

Results and discussion

As regards the Danube Delta, five k classes have been used for MS calibration of lake sediments (see Fig. 1; Rădan et al. 1998a,b). Good correlations with various deltaic environments are identified, and a case study of anthropis influence on the DD ecosystem is developed.

The lowest magnetic susceptibilities (Ist class; even negative k values) were provided by bottom sediments from lakes (e.g., in the Matita-Merhei and Raducu-Raduculet Depressions; Fig. 1) which show more confined environments (with a large development of the organic sediments).

The bottom sediments sampled from the lakes which are generally characterized by restricted water circulation conditions and by the absence of an important influence of the Danubian supplies are defined by k values included in the IInd class on the proposed MS scale (Fig. 1).

High and very high k values (placed in the last two classes, IV, V) were recorded on bottom sediments sampled in lakes strongly influenced by the Danube water and sediment supplies. These lakes are connected to the Danube River by short channels (e.g., L. Uzlina, in the Gorgova-Uzlina Depression: Fig. 1).

Based on MS data obtained during several investigation phases (i.e., in 1980, 1987, 1992–1999), there have been pointed out changes in sedimentary environments within the Mesteru–Fortuna Depression, as result of digging a new channel in the area, in 1982.

As regard the sedimentary environments relating to the fluvial-marine interaction zone, particularly in the *Danube–Black Sea* area, some interesting magnetic signatures have been deciphered.

In the northwestern Black Sea, the *area directly influenced by the Danube River sediment discharge* (i.e., *Danube Delta front* and

Location	Monitoring phase 1995	1996	1997
1. *Meşteru-Fortuna Depression*			
L. Cuteţchi	II	II	II
L. Lungu	V	IV	IV
			V
L. Meşteru	V		
	V	IV	
L. Tătaru	II	II	III
	III		
L. Durnoi	II	II	
L. Băclăneşti	I	I	I
L. Fortuna		III	III
	IV		IV
			V
			V
			V
2. *Matiţa-Merhei Depression*			
L. Trei Ozere	I	I	I
		I	I
			II
L. Bogdaproste	I	I	II
			III
L. Matiţa	II	II	II
			II
L. Babina	I	I	II
			III
			II
L. Merhei	I	I	I
	II		I
			I

Location	Monitoring phase 1995	1996	1997
3. *Gorgova-Uzlina Depression*			
L. Gorgova		II	III
L. Uzlina	V	V	V
L. Isacova	II	II	II
4. *Dranov Depression*			
L. Dranov	III	III	III
	III		III
			III
5. *Răducu-Răduculeţ Depression*			
L. Răducu	I	I	
6. *Lumina-Roşu Depression*			
L. Iacub	III		II
			III
		V	V
L. Puiu	II		III
			II
			III
			III
L. Roşu	III	IV	IV
	I	I	I
		I	
L. Roşuleţ			II

Legend:
Magnetic susceptibility (in *SIu.*)

V	$> 275 \times 10^{-6}$
IV	$175 \times 10^{-6} - 275 \times 10^{-6}$
III	$75 \times 10^{-6} - 175 \times 10^{-6}$
II	$10 \times 10^{-6} - 75 \times 10^{-6}$
I	$< 10 \times 10^{-6}$

Fig. 1. Magnetic susceptibility characterization of lake sediments from the Danube Delta (as resulted from monitoring phases 1995, 1996, 1997).

Danube prodelta areas, according to Panin et al. 1999), as well as the *area under the influence of the Danube originated sediment flux* are suggestively shown by *k* anomalies observed in two ***MS*** maps (with a maximum contour od 400×10^{-6} SI.) (Rădan et al. 1998c,d,).

Concluding remarks

The magnetic susceptibility data, obtained on bottom sediments sampled and investigated during a long period of time (more than two decades), demonstrate the feasibility and the reliability of the applied technique to characterize various sedimentary environments within *Danube Delta*, and equally in the *Danube–Black Sea interaction zone* (where the method has been used only in the last 5 years).

The abilities of the ***MS*** monitoring to identify the preservation of the environmental magnetic signature (EMS) printed in bottom sediments, or on the contrary, ***where***, ***when*** and ***why*** the *EMS* has been changed, are exemplified by several convincing cases analysed for lakes from the *fluvial delta plain* and the *marine delta plain* of the *Danube Delta*.

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6. NEW TECHNIQUES AND APPROACHES

6.1 A NEW ASTRONOMICAL TIMESCALE FOR THE LOESS DEPOSITS OF NORTHERN CHINA

D. HESLOP, C.G. LANGEREIS and M.J. DEKKERS

Palaeomagnetic Laboratory "Fort Hoofddijk", Faculty of Earth Sciences, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands; heslop@geo.uu.nl

Key words: China, loess, orbital, lock-in depth.

The loess and palaeosol deposits of Northern China act as a key archive in the study of Quaternary palaeoclimatic change. Detailed research of the loess sequences has led to the development of a number of continuous records of palaeoclimatic change through the utilisation of physical parameters demonstrated to be accurate proxies for variations in the Southeast Asian monsoon system over the past 2.6 Ma.

In recent years a number of proxy-parameters have been developed in an effort to extract climatically sensitive data from loess sequences across the Chinese plateau. Of the wide variety of loess proxy-parameters proposed as suitable for the reconstruction of past monsoonal activity, most palaeoclimatic investigations have concentrated on the analysis of variations in magnetic susceptibility (χ). Zhou et al. (1990) proposed that the increases in magnetic susceptibility detected in palaeosol units could be (at least partially) attributed to the formation of fine-grained magnetic minerals (magnetite and/or maghaemite) as a product of the pedogenic process. A number of studies have demonstrated a close correspondence in the variations of magnetic susceptibility recorded within Chinese loess sequences to signatures of past global climatic change derived from alternative environmental archives, e.g. oceanic and ice-core $\delta^{18}O$ profiles (Heller & Liu 1984; Kukla et al. 1990; Chen et al. 1991; Bloemendal et al. 1995; Chen et al. 1997; Chen et al. 1999). The demonstrated empirical link between the magnetic parameters of the loess sequences and climate has led to the acceptance of magnetic susceptibility (and therefore pedogenesis) as a primary indicator of past summer monsoon activity.

Previous attempts to formulate chronological schemes for the loess sequences have relied upon linear interpolation between palaeomagnetic markers or, alternatively, by the tuning of quasi-cyclical signals observed in the proxy climate records to Earth orbital periodicities. Here, we present a refined timescale for the entire sequence of Quaternary Chinese loess, which relies upon the correlation of detailed monsoon records to the astronomical solution of Laskar (1990) and the oceanic ODP677 $\delta^{18}O$ records of Shackleton et al. (1990). Analysis of the resulting chronological framework demonstrates downward displacement of the identified palaeomagnetic horizons with respect to the climatic record. Such a temporal disparity in the palaeomagnetic and palaeoclimatic archives reveals serious flaws in the underlying assumptions of previously proposed solutions for the loess timescale. The presented chronological scheme considers in detail the relative structures of the palaeoclimatic and palaeomagnetic records to produce an accurate timescale that is consistent with the current understanding of loess depositional and post-depositional processes.

Investigation of the resulting chronological framework in the frequency domain using evolutive spectral and cross-spectral analysis techniques indicates the robustness of the proposed age model, and illustrates the presence of a number of apparent shifts in the fundamental cycles driving the Southeast Asia monsoon mechanism.

6.2 SELECTIVE DISSOLUTION OF MAGNETIC IRON OXIDES BY THE ACID AMMONIUM OXALATE METHOD

I.H.M VAN OORSCHOT and M.J. DEKKERS

Paleomagnetic Laboratory Fort Hoofddijk, Budapestlaan 17, 3584 CD Utrecht, the Netherlands; oorschot@geo.uu.nl

Key words: Selective extraction, iron oxides, synthetic samples, oxalic acid, dissolution mechanism.

A selective extraction technique that is frequently applied in soil science is the acid ammonium oxalate technique [1]. It is used to determine amorphous iron(hydr)oxides in samples and this makes it interesting for application in environmental magnetism.

In the original method of Schwertmann [1] the dissolution rate varies with time, because the dissolution mechanism changes during extraction [2, 3]. In the initial mechanism, the complex of oxalate and surface-iron is slowly released into solution. When dissolved ferrous iron is available, the fast second mechanism becomes dominant, usually after ~1 hour of extraction time. Addition of ferrous iron to the extraction solution at the start of the experiment favours the second mechanism and ensures constant dissolution rate [3, 4]. When ferrous iron is added to the extraction solution in advance, the method is referred to as the AAO-Fe(II) method.

Extraction experiments were performed on synthetic samples containing magnetite (Fe_3O_4) and/or maghemite (α-Fe_2O_3) of different grain-size ranges. Two batches of samples were extracted: in batch 1 the iron oxides were dispersed in calcium carbonate, in batch 2 quartz was used instead of calcite. The samples were extracted with a mixture of acid ammonium oxalate (0.02 M) and ferrous iron (2 mM) at pH 3. Each extraction step lasts 30 minutes, with a maximum of two extraction steps per sample. Dissolution was monitored by analysis of the changes in the initial susceptibility as well as the hysteresis parameters after each extraction step.

At pH > 4 the required iron-oxalate complex of the second mechanism, FeC_2O_4, is unstable and fast dissolution is inhibited. The calcite in the samples of batch 1 increased the pH to 5–8, thus decreasing the dissolution rate and at the same time initiating precipitation of a yellow crystalline solid. The precipitate was analysed by XRD and identified as humboldtine ($FeC_2O_4.2H_2O$). To avoid increase of pH by calcite, only samples of batch 2 have been used in further tests.

The results indicate that extraction with the AAO-Fe(II) method is influenced by grain size rather than mineralogy, with the largest grain size dissolving more slowly. Within the larger grain-size fraction distinction between the two different iron oxides is possible. Furthermore, the hysteresis parameters show an increased contribution of SP grains after extraction.

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6.3 AN ORIGIN AND MECHANISM OF THE SELF-REVERSAL TRM OR PTRM OF ROCKS: A STUDY OF THE RHYODACITE FROM THE HARUNA LOCALITY (JAPAN)

O. ORLICKÝ[1] and M. FUNAKI[2]

[1]Geophysical Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 842 28 Bratislava, Slovak Republic, E-mail: geoforky@savba.sk
[2]National Institute of Polar Research, Tokyo, Japan; funaki@nipr.ac.jp

Key words: Titanomagnetite, magnetic moments and spin rotation, origin and mechanism of self-reversal.

In routine paleomagnetic investigations the field reversal hypothesis is frequently accepted in accounting for essentially most of the observed reversals of rocks. However, in many cases volcanic rocks have been revealed which are able to acquire reverse TRM or PTRM by the so call self-reversal process (self-reversed RM is opposite in the direction to the inducing magnetic field). The self-reversed thermoremanent magnetization (TRM) was first discovered on the rhyodacite from the Haruna locality by Nagata et al. (1952). We have followed with an investigation of these dacite pumices. The rocks were erupted about six hundred years ago. Results of the electron microprobe analysis of the two samples have proved the titanomagnetites (TM; composition: x ≈ 0.1) in these rocks. Ilmenite-hematites have not been detected. Curie temperature (T_C) of these TM is about 490-510 °C; NRM ≈ 3,000 to 12,000 nT, $\kappa \approx 12{,}000$ to $18{,}000\times10^{-6}$ SI units. Most samples have shown the reverse NRM. Very large dispersion of the direction of NRM was detected during the thermal demagnetization in fully compensated external field (all procedures were arranged in such a way to protect the samples against the influence of an external field during the thermal demagnetization). In most samples the reverse RM occurred within the 450-630 °C temperature interval (over the T_C) during the thermal demagnetization. After annealing of samples at 650–700 °C, in fully compensated field (duration of about 90 min.), and successive cooling within the laboratory field (H = 0.480 Oe), the reverse TRM of samples was acquired (30 samples from 3 individual outcrops were tested). The peculiar behaviour of the TRM was registered after annealing of samples at 650-700 °C in compensated field (duration of 90 min.) and their successive cooling within the laboratory field (in the individual 40 °C intervals, started from 630 °C down to the room temperature, or in all 630-20 °C interval, started from 630 to 590 °C, in the second run from 630 °C to 550 °C, in the each successive run the 40 °C interval was added, to verify an aditivity of the PTRM). Zigzag behaviour (from reverse to normal and opposite of the TRM of samples was registered over 200 °C during thermal demagnetization of rocks, in which the TRM was previously laboratory induced. Three temperature intervals were selected for the laboratory magnetization of rocks: 470–430 °C, 340–200 °C, 190–150 °C and for successive demagnetization. The following was concluded:

— the carriers of the self-reversed TRM of dacite pumices are the TM, which are supposed to be very resistant to thermal effect;

— the relatively high residual RM detected after thermal demagnetization has shown that there is a high spontaneous magnetization of domains in the magnetic minerals;

— the process of the self-reversal of the TRM of rock is conspicuously affected by the magnetostatic interaction among the mineral grains, except for an exchange interaction between the magnetic particles;

— magnetic and directional stability of the TRM of the respective rocks with respect to the thermal demagnetization is comparable for three selected temperature intervals (previous laboratory magnetization in intervals 470–430, 340–200, 190–150 °C);

— very conspicuous change from normal to reverse PTRM was detected during the laboratory magnetization of rocks in the interval 340–200 °C, stable reverse PTRM was detected also during laboratory magnetization of rocks in the interval 190–150 °C;

— the shape of the laboratory induced PTRM curve of rocks (inducing of the PTRM in H = 0.48 Oe within the temperatures started from 630–590 °C, successively to 630–30° interval), has shown that the rotation of the magnetic moments on macroscopic scale (or progressive rotation of spins on microscopic scale) has taken place. This being the dominant mechanism of acquisition of the self-reversed TRM, or PTRM of the Haruna dacite rocks.

Discussion

Nagata et al. (1959) found that the reversal was the result of the Ilmenite-Hematite (Ilm-Hem) phase acquiring a self-reversed TRM. The Magnetite-Ulvospinel (Mag-Usp) phase was also detected in these rocks. The ratio of the Mag-Usp phase to the Ilm-

Hem phase in the Haruna rocks was approximately 100 to 1 (Nagata et al. 1953; Uyeda 1958). However, the authors ascribed the dominant remanence signal to the Ilm-Hem phase. Uyeda (1955) ascribed acquiring of the self-reversed TRM of the rhyodacite to a magnetic interaction between two phases of differing Curie temperatures both with intermediate compositions in the Ilm-Hem solid solution series. They proposed that true mechanism of the reversed TRM should be closely related to the order-disorder phenomenon. Uyeda (1958), Ishikawa & Syono (1963) found that acquisition of the self-reversed TRM requires not only that the bulk of the sample be ordered and ferrimagnetic but also that it contains a second phase (x phase) that needs to have some specific properties, which have been described in detail. They suggested that the reverse TRM is found to be the result of an antiparallel superexchange interaction between the magnetic moments of an Fe-rich metastable phase which is created around the ordered structure in the process of development of the order. The striking result is that the reverse TRM exists only in the intermediate state and is not found in either the fully ordered or fully disordered state. Many authors have engaged with the self-reversal problem of rocks and the Ilm-Hem magnetic minerals (see in References). Most of authors have believed that TRM or PTRM have been acquired in the Ilm-Hem solid solutions during the cooling of two interacting phases with different compositions and therefore different Curie temperatures. The exact mechanism of the spin alignment between two interacting phases is not well understood.

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6.4 A NUMERICAL SOLUTION FOR ELECTROMAGNETIC SCATTERING BY A PLATE IN CONDUCTIVE MEDIA

V. SEDLÁK

Technical University of Košice, Department of Geodesy & Geophysics, Park Komenského 19, SK-043 84 Košice, Slovak Republic; sedlak@tuke.sk

Key words: Electromagnetic scattering, numerical solution.

A new integral solution formulated with the Galerkin method is derived and applied to model the electromagnetic (EM) response of a thin conducting plate in a stratified medium. The solution is expressed as two coupled integral equations, one for the scalar potential of the equivalent current density and the other for the corresponding magnetic field. The solution adopts the form of a single equation plus a constraint on the current density in two limiting cases. Where the host medium is resistive, the scalar potential equation forces the current to be divergence free. This property of the solution is responsible for the robustness of the method for a wide range of model parameters. Parametric scaling arguments are used to determine when it is necessary to compute the EM response with a solution accounting for both galvanic and inductive effects. The paper presents some theoretical knowledge on the numerical solution for electromagnetic scattering by a plate in conductive media without practical exits.

Much of the Earth is inaccessible to direct observation, its composition and structure must be inferred from remote measurements of its physical properties. Lithological and structural variations may be detected electromagnetically because they are often associated with changes in electrical conductivity and magnetic permeability. Local variation in conductivity can be diagnostic of structures such as faults, fractures and shear zones which are of interest in geological mapping, or of mineral deposits and aquifers which are of direct economic interest. Regional variation in conductivity may be used to delineate formations having different porosity and fluid permeability. Although the electromagnetic method has also been used to map formations based on their magnetic permeability, its major role is to detect conductivity variation.

Computer models are by nature more widely usable than are scale models as suitable computer facilities are wide spread whereas modelling facilities are relatively specialised and rare. One natural application of computer modelling is in the development of inversion and imaging algorithms. Although inversion algorithms could be extremely useful for data interpretation, they require very fast forward models to be practical. Currently these only exist for simple geological structures such as a plane layer earth. In this paper, the electromagnetic response of a thin conducting plate in a stratified conducting medium (conductive medium) is modelled. The plate is a gross simplification of geological structure, but in many cases it is a sufficient one. It is useful both for representing planar geological structures and as a conceptual model when current flow in a three dimensional structure is dominantly two-dimensional.

6.5 MAGNETOMINERALOGICAL DETERMINATION OF BONE

B.A. SJÖBERG

The Swedish Museum of Natural History, dept PZ, Box 50007, SE-104 05 Stockholm, Sweden

Key words: Magnetic susceptibility, bone, diamagnetic and ferromagnetic components.

Limb bones of *Homo* and a selection of other vertebrates and birds were studied with rock magnetic methods. The low field susceptibility and the isothermal remanent magnetization indicate ferromagnetic particles in a diamagnetic matrix. Thermal changes of the organic constituents of the bone have a minor impact on the magnetic susceptibility during heating, suggesting the presence of a magnetic monomineral. Thermomagnetic changes of the low field susceptibility applied to one sample of humerus *(Homo)* indicate a Curie temperature equal to that of magnetite. Lower disintegration temperatures for the middle sections than for the ends of humerus of *Lutra* and ulna of *Homo* point to structural differences between these two parts of the bone. Higher values of the magnetic susceptibility and the saturation remanent magnetization in the ends suggest a lower amount of ferrimagnetic minerals in the middle sections of their thicker walls. The high field measurements of other bones support the presence of a diamagnetic and a strong ferromagnetic component at the end of the bones compared to the middle sections.

6.6 WHAT'S TYPE OF PLATE MOVEMENT?

V.N. VADKOVSKY

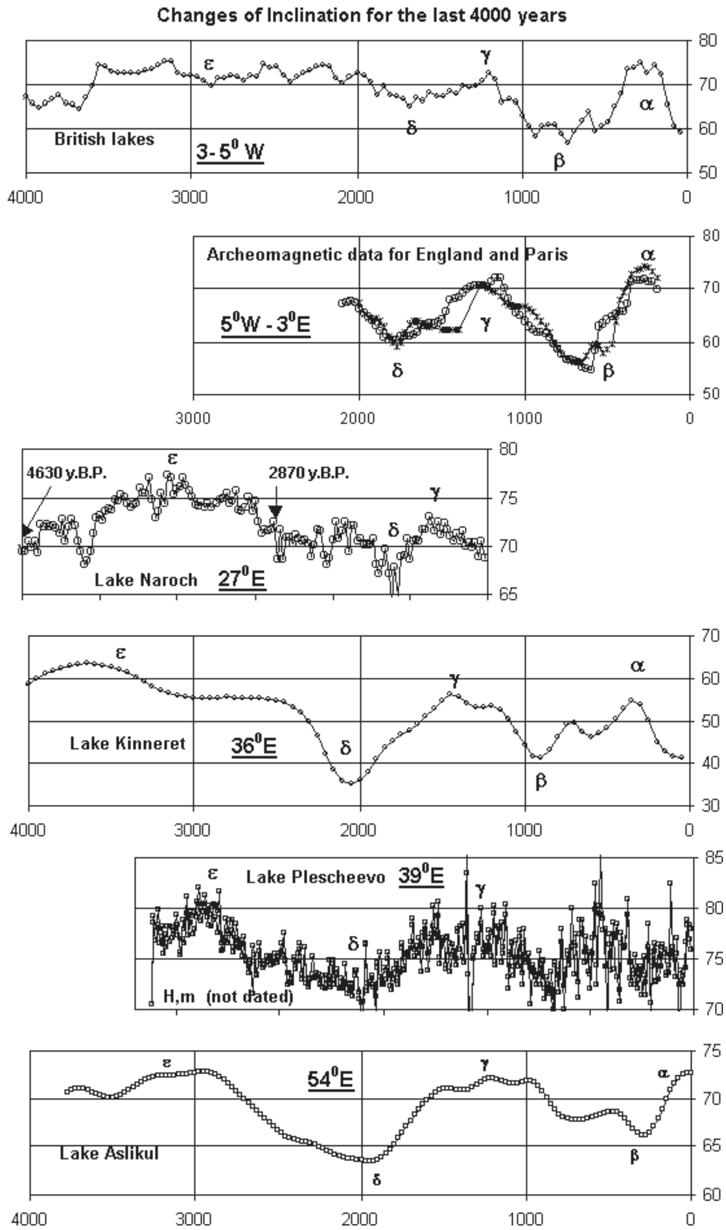
Department of Geology, Moscow State University, 119899 Vorobjevi Gory, Moscow, Russia; vad@dynamo.geol.msu.ru

Key words: Plate movements, Brownian.

Do any estimates of random wandering of litosheric plates exist? The characteristic of random (brownian) wandering of the classic particle is a root-mean displacement z which depends on time as a square root: $z = \sqrt{(2*D*t)}$, where D is the diffusion coefficient (or mobility) of particle in the enviroment. This Einstein relation is true for Brownian wandering on a sphere surface too (Mardia1972), but the displacement is an angle distance f between the start-point and a point in any time. The analog of the root-mean displacement on a sphere is $v = 1 - \cos(f)$ (Fisher 1953). There are analysed non-smoothed data of time-series of apparent palaeomagnetic pole positions for different plates on different time intervals. It has been found that non-smoothed palaeomagnetic data on Baltic shield for the period from 2850 to 600 Ma interval (Elming 1993) and the same data on East-European plate for the period from 430 to 34 Ma interval (Khramov 1991) correspond to Brownian behaviour due to its v(t) dependences.

The Global Palaeomagnetic Database (McElhinny & Lock 1998) was used for the study of joint motion of the plates ensemble. The time period under study (2800 Ma – 0) was divided into non-overlapping intervals of different length (10, 20, 50, 100 Ma). The empiric paleolatitude distributions of all continents were calculated for every temporal-window. This distributions were compared with theoretical distributions on base of the Fokker-Plank-equation. The comparison of these distributions leads to the conclusion that plate motions are of the Brownian type.

Figure to the contribution No. 1.15 *(Nourgaliev et al.: Palaeomagnetism of recent Russian lake sediments)*. Text see on page 179.



Contents of contributions

GEOLOGICA CARPATHICA, 51, 3, BRATISLAVA, JUNE 2000
209–214

DISCUSSION

ILLITE CRYSTALLINITY AND VITRINITE REFLECTANCE IN PALEOZOIC SILICICLASTICS IN THE SE BOHEMIAN MASSIF AS EVIDENCE OF THERMAL HISTORY— DISCUSSION

The relationship between illite crystallinity and vitrinite reflectance: what is behind it?

VÁCLAV SUCHÝ

Institute of Geology, Academy of Sciences of Czech Republic, Rozvojová 135, 165 00 Praha 6 - Suchdol, Czech Republic; sediment@gli.cas.cz

Discussion of the paper by Francå E., Francå J. & Kalvoda J., published in *Geologica Carpathica* 50, 5, 365-372, 1999

Francå E., Francå J. & Kalvoda J. (1999) must be congratulated on their initiative in applying illite crystallinity and vitrinite reflectance techniques in order to prise yet more information on thermal history from the Variscan sediments of the SE Bohemian Massif. Beside new regional data, their paper also contains important discussion about the general relationship between illite crystallinity (IC) and vitrinite reflectance (VR) which should have wider implications for other terrains. In particular, the authors claim that both IC and VR are primarily controlled by the paleotemperatures and thus, can be correlated. Moreover, they argue that "the examination of a mutual correlation of the two parameters is an important step in the data reliability assessment". The authors also claim that "the vitrinite reflectance and/or illite crystallinity data which would plot above the trend" shown in their Fig. 8 and Fig. 9, "do not represent consistent evidence of thermal history."

I believe that there are a number of facts and interpretations surrounding this conclusion that would benefit from further discussion. Although I have no doubt that the regional data presented in the given paper (their Fig. 10) are correct, the general relationship between IC and VR (as shown in their Figs. 8 and 9) is clearly a matter of a far-extending oversimplification and, possibly, some misunderstanding. The analysis of the data available, based on both published studies and my own research, now in progress, show that the statistical link between IC and VR is generally rather weak and subject to severe variations. Because of this, I have serious reservations about whether the relationship between the two parameters could be actually interpreted in terms of "data reliability assessment". In the following text I will endeavour to clarify my scepticism in detail.

In their Fig. 8, Francå et al. (1999) compile IC and VR data published on various localities by a number of earlier writers in order to demonstrate that there is a systematic relationship between the two variables. Upon a closer examination of that figure, however, one can note that the diagram represents a mixture of rather inconsistent data acquired by different analytical techniques, the comparison and/or conversion of which remains problematic. In particular, the illite crystallinity measurements adopted from both studies by Underwood (Underwood et al. 1992; Underwood et al. 1993) were obtained using ethylene glycol-solvated samples, whereas some other data shown in the same Fig. 8 represent IC values obtained from air-dried samples (e.g. Duba & Williams-Jones 1983). As has been shown by a number of studies (Kisch & Frey 1987; Frey et al. 1980), depending on the degree of diagenesis of a given sediment, the IC indices measured in air-dried samples may differ significantly from those measured in glycolated ones. Similarly, organic matter-reflectance values taken from Duba & Williams-Jones (1983) and used in Fig. 8 of Francå et al. represent, at least in part, asphaltic pyrobitumen reflectance that is not equivalent to vitrinite reflectance (see Landis & Castaño 1995 and the discussion therein). My further critical comment concerning the Fig. 8 is that the number of data included in the diagram is relatively limited and the selection of localities presented is clearly biased in favour of the sedimentary basins of active continental margins. The latter point is of a particular importance since the relationship between organic matter and clay mineral diagenesis appears to be different in contrasting tectonic types of sedimentary basins (see below).

The matter of fact is that the correlation between clay mineral (illite, chlorite) crystallinity and organic matter reflectance has recently been demonstrated in many regional studies (Reinhardt 1991; Rahn et al. 1995; Geng et al. 1996; Suchý & Rozkošný 1996; Mählmann 1996; Akande & Erdtmann 1998; Sachsenhofer et al. 1998, among many others).

Nevertheless, on an absolute basis there is not a close correspondence between coal rank and IC grade. Rather, it appears that each region is characterized by its own relationship (Wolf 1975; Teichmüller et al. 1979; Frey et al. 1980). This is because changes in both materials are influenced by a number of factors other than paleotemperature (Kisch 1987; Krumm et al. 1988; Weaver 1989; Rantitsch 1997; Taylor et al. 1998). In particular, a correlation between IC and VR is strongly influenced by the chemical sensitivity of these parameters and by different kinetic parameters (Velde & Vasseur 1992; Essene & Peacor 1995; Schegg & Leu 1996; Sachsenhofer et al. 1998). **Illite crystallinity**, for example, has been found especially sensitive to the availability of K^+ sources in pore waters (Krumm et al. 1988; Pearce et al. 1991) as well as to the overprints by fluids with temperature less than those of peak metamorphism (Zhao et al. 1999). Several authors have also discussed the sensitivity of the IC to kinetic influences, such as tectonic shearing (Kisch 1989; Árkai et al.1997; Frings et al. 1999; Árkai et al. 2000). The importance of synkinematic deformations for IC development has been described by Teichmüller et al. (1979). **Vitrinite reflectance**, unlike illite crystallinity, has been shown to react quickly to very short-term thermal pulses (Barker 1991; Sweeney & Burnham 1990). In addition, vitrinite reflectance may substantially increase in response to localized tectonic shearing (Suchý et al. 1997) whereas simply applied pressure may suppress the VR values (Dalla Torre et al. 1997). A number of researchers have also reported that the maturity of organic matter can be elevated through the effects of hot fluids (Daniels et al. 1990; Schegg 1992; Lünenschloss et al. 1997; Gayer et al. 1998) and these phenomena have been widely recognized in the orogenic belts (Walton et al. 1995; Parnell et al. 1996).

To compare the clay mineral diagenesis with the organic parameters of maturation, their different reaction rates are also of great importance. Organic matter is generally much more sensitive to temperature rise than illite crystallinity, which usually requires a substantially longer time to increase (Teichmüller et al. 1979; Hillier & Clayton 1989; Barker 1991). Consequently, in regional metamorphic terrains and in some sedimentary basins which were overprinted by a short thermal event with a high heat flow, a delay of the mineral reactions behind the reactions of coalification has been commonly encountered (Wolf 1975; Kisch 1987; Robert 1988; Miki et al. 1991 and many others). A characteristic "lag" of clay diagenesis with respect to organic matter maturation has now been detected also in the 2712 m deep Tobolka-1 borehole of the Barrandian Basin (Ordovician-Devonian), Czech Republic. In that borehole, elevated organic matter reflectances (2.27–3.91 R_r; Franců et al. 1998) coexist with much less advanced IC values (0.94–0.54 $\Delta°2\Theta$; Suchý et al., paper in progress). A minor "lag" of the IC with respect to the VR is a characteristic feature of first-cycle sedimentary basins that experienced long-term subsidence at moderate heat flow (Robert 1988). On the contrary, a great delay of IC values behind the VR is likely to occur in many extensional (rift-related) basins with elevated and relatively short-lived heat flow (diastathermal tectonic regime of very low-grade

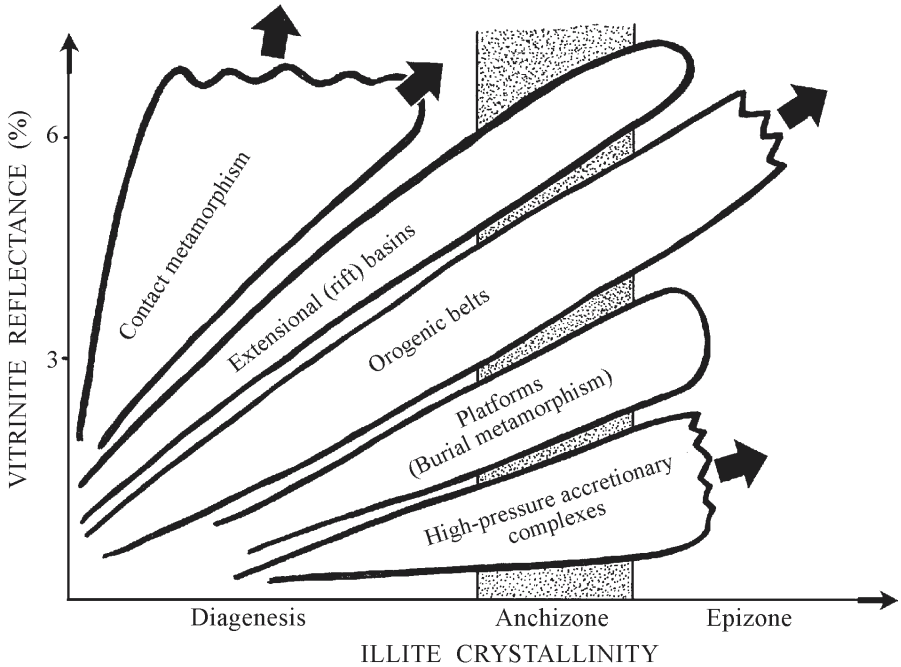


Fig. 1. Conceptual diagram showing variations of illite crystallinity and vitrinite reflectance values in various tectonic settings (modified after Robert 1988 and more recent studies listed in the text). Note that there is no general relation between IC and VR and the fields characteristic of individual tectonothermal environments may actually overlap, especially in complex terrains that experienced multiple tectonic cycles. Diagenetic to low-grade metamorphic rocks developed in contact-metamorphic, orogenic and/or high-pressure settings commonly form the lowest members of prograde metamorphic sequences that turn into epizonal (or higher) facies of "true" metamorphism (arrows). On the other hand, very-low to low-grade metamorphic rocks in platform (burial-metamorphic) and rift settings, typically do not grade into the facies of a "true" regional metamorphism (Robinson & Bevins 1989).

metamorphism of Robinson & Bevins 1989) and, of course, in contact metamorphic environments. Eventually, a very specific relation between IC and VR has been reported from some high-pressure terrains, such as the Franciscan Complex of California where both IC and VR data indicate surprisingly low metamorphic conditions when compared with the observed mineral assemblages (Kisch 1987). Both parameters appear to be retarded to a different degree, possibly because of a pressure effect on IC and/or VR (Dalla Torre et al. 1996a; 1996b). The above reviewed studies clearly show that, at the present stage of knowledge, one can hardly speak about any general or universal relationship between IC and VR. Instead of any "generalized relationship" it appears that there are many correlations possible that involve a range of linear and/or exponential (?) trends. The slopes of individual IC versus VR regressions, however, may substantially differ at various localities which probably mirror, at least in part, differences in their tectonothermal settings (Fig. 1).

What follows from these examples is that both IC and VR are clearly influenced by a number of internal and external variables. Although paleotemperature influence is probably the most important external factor, a complex interplay with other variables (pressure, deformations, fluids, pre-metamorphic experience of organic matter and/or clay minerals) is also essential (Essene & Peacor 1995; Jiang et al. 1997). Much of the differences in IC vs. VR relationship reported in the literature can presumably be ascribed to synergetic effects of the above agents although insufficient standardization in the determination of both parameters can also contribute (Kisch 1990; Dembicki 1984). Clearly, the comparability of IC/VR correlations is only limited to results from similar tectonothermal settings that experienced comparable evolution with respect to time-temperature, fluid, and deformation aspects.

It is quite likely that in the future, a number of other workers will attempt to further refine these relationships in the light of the incoming amount of data that recently have been, and still are forthcoming, particularly through the widespread application of the IC method. Better understanding of the nature of the IC/VR relation may also come from more specific studies on clay mineral transformation process and new reliable kinetic data (c.f. Elliot et al. 1999). It is to be expected that various time-temperature controls on both parameters will also be substantially constrained when, along with IC and VR measurements, an innovative technique of fission track analysis in apatite and especially sphene and zircon is widely applied. The latter techniques enable paleotemperatures well above 250–300 °C to be tracked through geological time, thus providing a sort of "tectonothermal fingerprint" for individual rock samples (Tagami et al. 1998; Jonckheere & Wagner 1999).

In summary, I welcome Francŭ et al.'s stimulating account of the thermal history of the Variscan sediments of the Bohemian Massif but I would urge caution when extrapolating their regional results to the other terrains and vice versa. My feeling is that at the given stage of knowledge the generalizations concerning the IC/VR relationship as presented by Francŭ et al. (1999) are not adequately supported by internally consistent data and may be flawed. On a global plane, further understanding of mineral versus organic diagenesis will clearly require more background data and integrative effort.

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ILLITE CRYSTALLINITY AND VITRINITE REFLECTANCE IN RELATION TO THE THERMAL HISTORY OF PALEOZOIC SILICICLASTICS IN THE SE BOHEMIAN MASSIF: REPLY

EVA FRANCŮ[1], JURAJ FRANCŮ[1] and JIŘÍ KALVODA[2]

[1]Czech Geological Survey, Leitnerova 22, 658 69 Brno, Czech Republic; francu@cgu.cz
[2]Dept. of Geology, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic; dino@sci.muni.cz

Reply to the discussion of V. Suchý

We welcome the critical discussion by V. Suchý (2000) who addressed several very important aspects of the application of the illite crystallinity index (IC), vitrinite reflectance (VR or R_r), and their mutual relationships in respect to thermal history. We agree with the author that "the paleotemperature influence is probably the most important external factor" and that it is also necessary to take into consideration other agents, such as laboratory conditions, chemistry of pore fluids, tectonic setting, etc. Quantitative evaluation of these effects on IC and R_r values is very desirable and in many papers the reader still finds rather theoretical considerations.

The existence of R_r and IC correlation has been documented by the data from the Paleozoic in the eastern Bohemian Massif (Franců et al. 1999, Fig. 10). This chart shows some similarities with the earlier published trends (Franců et al. 1999, Figs. 8 and 9) even though the reviewed IC data show rather a broad scatter and partial inconsistency (criticized by Suchý 2000). The interlaboratory standardization and calibration introduced by Warr & Rice (1994) gives much better chances for evaluations of the organic–clay relationships in future studies.

Robert (1988, Fig. 199) presented a chart showing R_r-IC trends with different "delay of illite evolution in relation to that of OM reflectance" in alternative tectonic settings. The data used in his diagram were not made in a single laboratory, which might have affected the differences in the trends (Robert 1988). Suchý (2000, Fig. 1) further developed this chart and added other tectono-thermal environments. His work would benefit from explanation of why the trend of "Platforms (Burial metamorphism)" lies between those of the "Orogenic belts" and the "High-pressure accretionary complexes". The interplay of heat flow and metamorphic effective time does not change in such order.

The boundaries of the shaded "anchizone" area in Fig. 1 of Suchý (2000) seem to be independent of the vitrinite reflectance (R_r ranging from 0.2 to 6 %). This is not in full agreement with the general characteristics of the diagenesis to very low-grade metamorphism transition (Robert 1988; Árkai 1991; Taylor et al. 1998).

In spite of the comments given above the diagram of Suchý (2000) will certainly attract the attention of many readers, especially when supported by measured standardized data.

Suchý (2000) made an extensive review of the papers dealing with this topic. Several of these papers deal more with the expandability of illite-smectite (%S in I-S) than the illite crystallinity index (IC), e.g. Hillier & Clayton (1989), Velde & Vasseur (1992), Sachsenhofer et al. (1998), Elliot et al. (1999). The IC index measured in samples with expandable component is extremely sensitive to the grain-size fraction analysed. Illitic material with expandable (smectite) layers is concentrated in the very fine (< 0.2 μm) clay fraction (Środoń & Eberl 1984). Smectite makes the 001 basal reflection of illite broader and the IC value higher. This is evident in many XRD patterns where IC > 1 (or 0.7) $\Delta°2\Theta$. It seems to be very important to measure the expandability of the newly formed illite-smectite and distinguish this phase from the detrital illite (muscovite). The analysis of the crystallite size distribution and strain from the X-ray diffraction peaks using the Baertaut-Warren-Averbach technique (Eberl et al. 1996) outlines a promising way to deal with this difficult task.

Finally, we would like to thank Suchý (2000) for many stimulative suggestions and for his urging for caution when using the observed relationship of R_r and IC mechanically in other terrains.

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Contents

Articles

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