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PALEOMAGNETISM OF NEOVOLCANICS OF THE EAST-SLOVAK LOWLANDS AND ZEMPLÍNSKE VRCHY MTS.: A STUDY OF THE TECTONICS APPLYING THE PALEOMAGNETIC DATA (WESTERN CARPATHIANS)

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Abstract: Middle-Late Badenian to Late Sarmatian neovolcanics were investigated. They have been included in the areal type of the andesite, as well as dacite and rhyolite activity (Lexa et al. 1993). The thermal and AF tests of the samples revealed stable remanent magnetic polarization (RMP) in the andesites, rhyolites and rhyodacites. The carriers of magnetic properties in the rocks are oxidized Fe-Ti oxides. While the values of inclinations of stable RMP (both — normal and reversed) of the rocks are variable, the declinations of RMP are quite uniform. The declinations of RMP of volcanics (besides the Late Badenian /LB/ pyroxene andesites) are D = 323–328 (localities of normal polarity of RMP) and D = 139–145 (localities of reversed polarity of RMP), regardless of the petrographical type or time origin of rocks. All tectonic structures are bounded by faults of the NW-SE directions. We prefer the idea, that these declinations reflect the tectonic movements which were active in a post-magmatic period. The most probable explanation is that there was a counter-clockwise rotation (CCR 32° on average) of geological units in the past. However, no correction for post-volcanic tilting has been applied, so part of the variations may be attributed to this phenomenon. The first version of the explanation of the CCR of the neotectonic structures is, that this probably took place in the Pliocene-Quaternary period (as a result of a general subsidence of the area). The second idea has considered the fact, that the same age volcanic rocks in the Central Slovak volcanic area (Orlický 1992), in the northern part of the Slanské vrchy Mountains (Nairn et al. 1967; Orlický et al. 1974; Orlický 1993), as well as in the Tokaji Mountains (Nairn et al. 1971) do not show rotation. This may be explained by the fact, that during the Badenian-Sarmatian time, the western part of the Carpathian Arc was no longer active while in the eastern part the final stage of arc-continent collision and related subduction continued.

Key words: Neogene volcanics, paleomagnetism, counter-clockwise rotations.

Introduction

The neovolcanics of Eastern Slovakia were recently investigated by Nairn et al. 1967, Orlický et al. 1974 and Orlický 1993. Paleomagnetic results were originally used for their basic correlations with geological knowledge as well as for a suggestion of a more precise succession of neovolcanic activity. Because most results of rocks from the East-Slovak Lowlands, Zemplínske vrchy Mts., and Veľký Milič Mts. have outlined a preferable trend of declinations of remanent magnetic polarization (RMP), (the results have outlined a counter-clockwise rotation of geological units), an additional collection of samples from further volcanic bodies was assembled and investigated. New geological knowledge of the area (Baňacký et al. 1989) and all hitherto obtained paleomagnetic data have been used to contribute to the solution of some tectonic or neotectonic problems in the East-Slovak Lowlands and Zemplínske vrchy Mts.

Short outline of geology and tectonics

The investigated neovolcanics are situated in Eastern Slovakia, among other neovolcanic bodies in the north-eastern part of the Carpatho-Pannonian region (see in Fig. 1).

Lexa et al. (1993) have distinguished four essential groupings of the Neogene-Quaternary volcanic rocks, according to their compositional characteristics and spatial distribution in the Carpatho-Pannonian region: — Areal type dacite to rhyolite volcanic activity (Eggenburgian to Sarmatian time). Volcanic rocks of this type are dominantly of crustal origin and associated with the initial stages of backarc extension in the Carpatho-Pannonian region. — Areal type andesite volcanic activity including differentiated rocks (Early Badenian until Early Pannonian time). Its spatial distribution is influenced strongly by backarc extension tectonics associating with diapiric uprising of the mantle. Geochemistry indicates mantle source magmas with variable crustal components. — Arc type basaltic andesite/andesite volcanic activity (Middle Sarmatian to the Pliocene/Quaternary age (evolved island type of associations dominate). — Alkali olivine basalts/nepheline basanite volcanic activity in the northwestern part of the Pannonian Basin as well as in the southern part of Slovakia (Pannonian to Quaternary time). Basalts of this type indicate continuing extension accompanied by diapiric uprising in the mantle, which has not been affected by subduction.

The neovolcanics of the East-Slovak Lowlands and Zemplínske vrchy Mts. have been included in the areal type of the andesite as well as dacite and rhyolite volcanic activity. An evolution of the neovolcanic activity proceeded in several stages

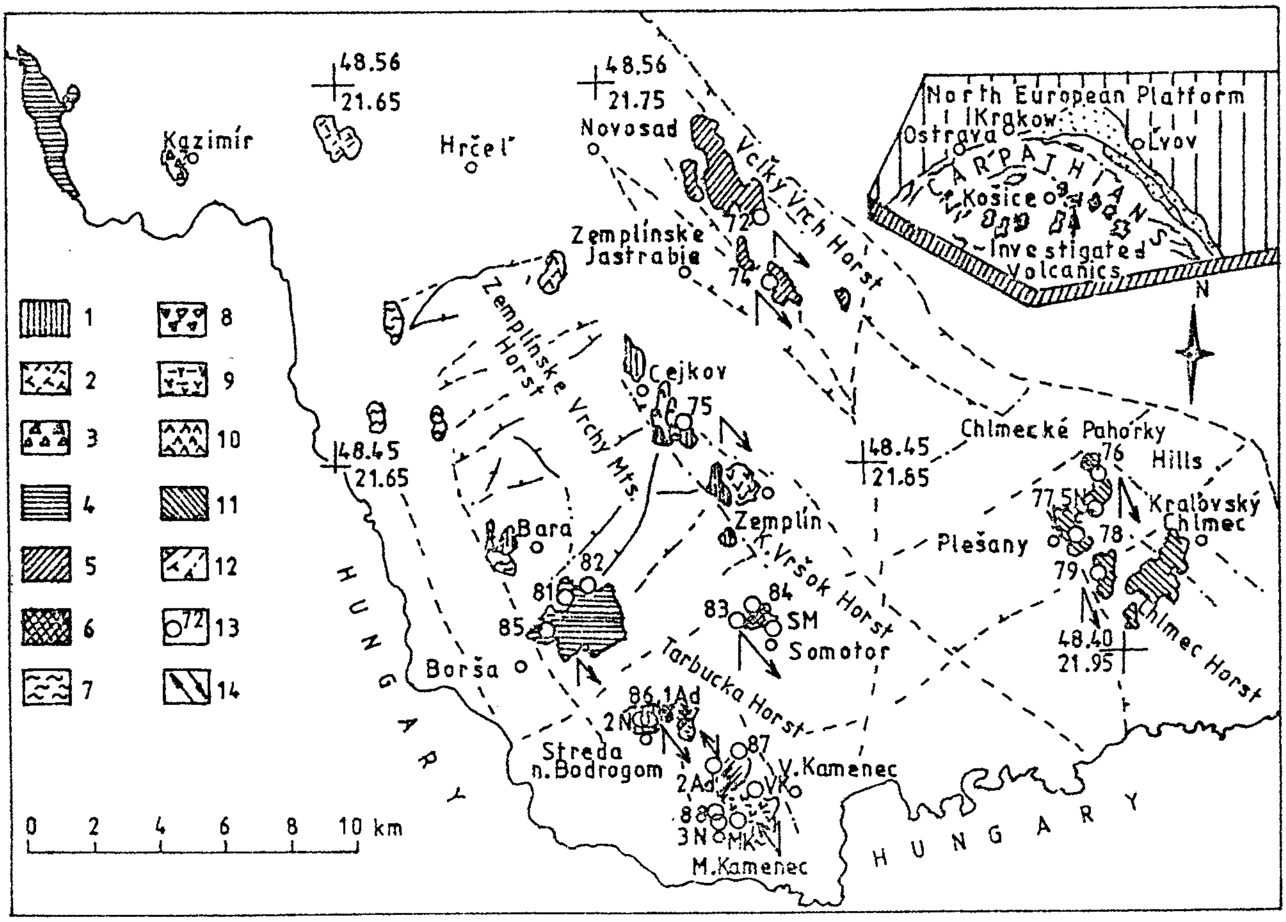

Fig. 1. Sketch map: neovolcanic rocks, tectonics and declinations of the remanent magnetic polarization (RMP) of volcanic bodies of the East-Slovak Lowlands and Zemplínske vrchy Mts. (geology and tectonics, according to Baňacký et al. 1989). *Late Sarmatian*: **1** — Lava flows of basaltic andesites. *Middle Sarmatian*: **2** — Bentonitized rhyolite tuffs, **3** — Rhyolite epiclastics and tuffs, **4** — Rhyolite extrusions and lava flows. *Early Sarmatian*: **5** — Lava flows of pyroxene andesites, **6** — Extrusive bodies of pyroxene andesites. *Late Badenian*: **7** — Undifferentiated rhyodacite pumiceous tuffs, **8** — Rhyodacite volcanoclastics, **9** — Extrusions of coarse-porphyric rhyodacites, **10** — Extrusions and lava flows of finely granular rhyodacites. *Middle-Late Badenian*: **11** — Lava flows of pyroxene andesites. **12** — Faults, **13** — Number of locality, **14** — Declinations of the remanent magnetic polarization (RMP) of neovolcanic bodies, -normal, - reversed polarity of the RMP.

in the course of the Middle-Late Badenian to the Late Sarmatian period (15–12 Ma). During the Middle-Late Badenian time an explosive/extrusive rhyodacite/rhyolite and effusive pyroxene andesite activity took place. The Early Sarmatian period is characterized by an origin of lava flows and domes of pyroxene andesites. Some rhyolite extrusive domes and lava flows, including rhyolite pyroclastic rocks originated during the Middle to Late Sarmatian time. The youngest volcanic products are thought to be lava flows of basaltic andesites and their breccias, which probably originated in the course of the Late Sarmatian time. These stratigraphic positions are supported by biostratigraphic evidence and radiometric dating (Pecskay et al. in press).

The Neogene is disturbed by faults of two main generation (Baňacký et al. 1989). The first generation faults were active in the Early Miocene time, the younger faults — mostly in the Badenian and Sarmatian times. Earlier faults obscured by younger tectonics are likely to have controlled the extent and the intensiveness of subsidence during the Early Miocene period. The younger faults are more conspicuous and divide the East-Slovak Neogene Basin into horsts and grabens (Fig. 1) forming the present morphology of the basin. The southern part of the East-Slovak Lowlands and Zemplínske vrchy Mts. is disturbed by faults of three strike systems. The main NW-SE striking fault system divided the area into blocks. The less significant fault system is NE-SW striking. There are also sporadic N-S faults. Horsts and grabens are often asymmetrical (tilted) as it is indicated by the present strike and depth of bedding.

Sampling and laboratory methods

Original paleomagnetic data were recently presented by Orlický et al. 1974, Orlický 1993, several of them by Nairn et al. 1967 (results gained by Nairn et al. 1967 are indicated by N, e.g. N5 in this contribution). Samples of rocks were also collected from seven further localities (from quarries) loc. 1Ad, 2Ad, SM, MK, VK, 77, 78, (see Fig. 1 and Tab. 1). Hand sampling was carried out. The geological compass was used for orientation of samples of rocks.

Study of the magnetic minerals of the rocks was performed employing the method of measurements of the change of magnetic susceptibility (κ) of magnetic fraction induced by temperature (the thermomagnetic curves are in Fig. 2), as well

Table 1: Paleomagnetic characteristics of neovolcanic rocks.

Age and type of rock	Number of loc.	Geographic coordinates		n N	I°	D°	k	α_{95}	Coordinates of virtual pole		δ_m	δ_p
		φ_L	λ_L						$\varphi_{p(N)}$	$\lambda_{p(E)}$		
Middle-Late Badenien (MLB): Lava flows of pyroxene andesites	76	48.44	21.94	3	-40	168	2253	3	62	228	3	2
	77	48.43	21.94	6	-28	162	108	6	53	232	7	4
	78	48.43	21.93	15	-29	160	126	4	54	233	4	2
	79	48.43	21.93	6	-19	162	171	6	47	230	6	3
	5N	48.44	21.94	6	-24	168		10	52	222		
	SD	48.43	21.94	5	-28	164	93	8	54	229	9	5
Late Badenian (LB): Extrusions and lava flows of rhyodacites and rhyodacite tuffs	87	48.37	21.79	6	76	322	100	8	64	341	14	13
	88	48.36	21.79	9	65	331	110	5	71	295	9	7
	3N	48.36	21.79	6	60	334		4	69	283		
	MK	48.36	21.79	19	67	323	153	3	66	308	5	4
	VK	48.37	21.79	8	66	327	1954	1	68	306	2	2
	SD	48.36	21.79	5	67	328	175	6	69	307	10	8
	75	48.47	21.77	7	-46	145	26	12	55	264	15	9
Early Sarmatian (ES): Extrusive bodies of pyroxene andesites	72	48.51	21.80	6	-78	147	215	5	66	350	9	8
	74	48.49	21.82	2	-36	139	68	31	46	264	36	21
	83	48.41	21.80	7	-69	141	23	13	64	314	22	18
	84	48.41	21.81	6	-52	137	69	8	53	280	11	8
	SM	48.41	21.81	15	-50	152	65	5	62	262	6	4
	SD	48.44	21.81	5	-57	143	23	16	61	284	24	17
Middle Sarmatian (MS): Rhyolite extrusions and lava flows	2Ad	48.37	21.79	6	75	323	596	3	65	338	5	5
	81	48.41	21.73	8	-45	163	31	4	71	257	40	25
	82	48.42	21.74	8	-40	142	113	6	49	266	8	5
	85	48.41	21.72	6	-42	113	82	14	33	291	17	10
	SD	48.41	21.73	3	-44	139	20	29	51	271	36	23
Late Sarmatian (LS): Basaltic andesites	86	48.38	21.77	9	-37	137	20	14	46	268	17	10
	2N	48.38	21.77	5	-54	141		16	57	282		
	1Ad	48.38	21.76	8	-53	157	119	5	67	259	7	5
	SD	48.38	21.77	3	-48	144	47	18	57	270	24	16

I°, D° - inclination, declination of RMP of rocks, respectively
k - precision parameter, α_{95} - semiangle of cone confidence for P=0.05, δ_m, δ_p - dimensions of the reliability oval for pole position, n - number of samples of rocks, N - number of localities, SD - summarized data

as the Mössbauer spectroscopy of powdered samples (Lipka et al. 1987, the Mössbauer spectra of selected samples are in Fig. 3). We see on Fig. 2 that the shapes of thermomagnetic curves of selected samples of andesites, as well as rhyodacites are little different. There are mostly Fe-Ti oxides with one Curie temperature ($T_C \approx 600^o$) in the measured samples. Some samples of andesites (loc. 74, 84), rarely also rhyodacites show two magnetic phases. For example in the sample 74/3 (Fig. 2) one magnetic phase has $T_{C1} \approx 475$ °C, the second one $T_{C2} \approx 575$ °C. Decreasing magnetic susceptibility down to liquid nitrogen temperature corresponds to the presence of titanomagnetite (probably with low oxidation). Most of the studied samples also contain more oxidized Fe-Ti oxides with a presence of hematite, in spite of that it has not been detected by the Curie temperature measurements. For example magnetic fraction of the sample 81 (Fig. 3) contains 17.5 % of the hematite, according to Mössbauer's results.

We know that magnetic susceptibility (κ) is a reflection not only of the qualitative and quantitative composition of magnetic materials, but it strictly depends on the sizes of magnetic particles. We can say that though the investigated volcanic rock is thought to be petrographically uniform it may be different in the qualitative and quantitative composition of its Fe-Ti oxides. The size of the magnetic particles may also be inhomogeneous. For example the increasing magnetic susceptibility of samples 1Ad/4, 2Ad/2, VK/1 in the interval 450–550 °C (Fig. 2) may be a reflection of the presence of pseudosingle-domain magnetic particles in the rocks. Generally, rhyolites as well as rhyodacites contain more oxidized Fe-Ti oxides, with higher content of maghemite and hematite. We see in Fig. 2 that samples 85/2, MK/3, VK/1 (rhyodacites) have Curie temperatures $T_C \approx 600$ °C. There is no presence of titanomagnetites in these samples. The main carriers of RMP in all the studied rocks are oxidized Fe-Ti oxides.

In andesitic rocks the NRM intensities vary from about 65 nT to 1200 nT, with volume susceptibility values 18×10^{-4} to 125×10^{-4} SI units. In rhyolites and rhyodacites NRM intensities vary from about 201 nT to 3944 nT, with volume susceptibility values 13×10^{-4} to 138×10^{-4} SI units. It is remarkable that their NRM intensities are conspicuously higher (1936 or 3944 nT) comparable to those of basaltic andesites (112 or 284 nT). We can assume that the RMP most of the rocks is thought to be of chemical origin, considering the magnetic characteristics of the rocks, the results of Curie temperature measurements, and the results of the progressive thermal demagnetization of rocks. I think that thermoremanent magnetization (TRM) has been preserved very rarely in the rocks under consideration.

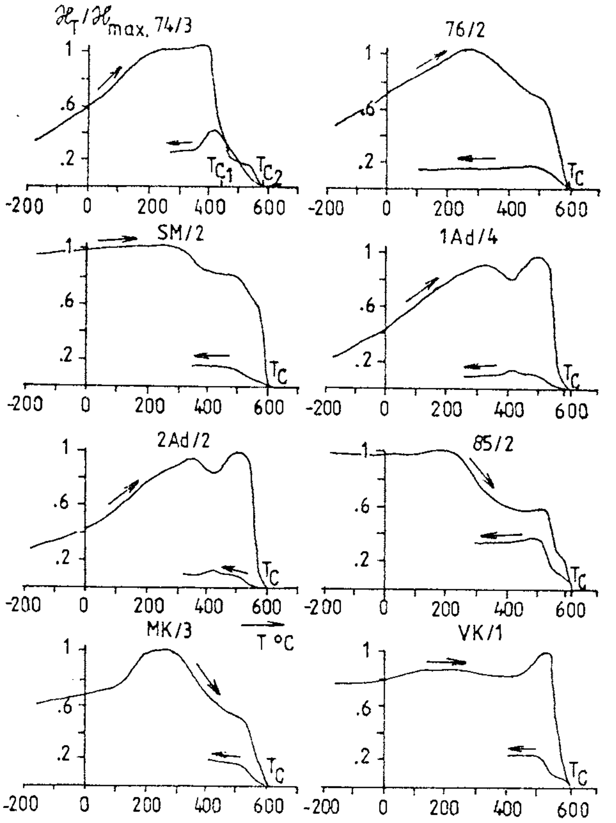

Fig. 2. Thermomagnetic curves of magnetic fraction of volcanic rocks. κ_T/κ_{Max} — magnetic susceptibility at the temperature T (κ_T), and maximal value of susceptibility of the sample from the set of measurements (κ_T).

As has been mentioned above, the original paleomagnetic data, as well as all recently obtained results of laboratory procedures were presented by Orlický et al. 1974. Remanent magnetization measurements were performed on JR-4 spinner magnetometer. (The pick-up unit of the spinner magnetometer has been permanently placed in the centre of Helmholtz's coils.) Rock samples studied by Nairn et al. 1967 and by Orlický et al. 1974 were originally demagnetized by means of alternating field (AF). The most effective field was in the interval 15-30 mT. In additional the investigated rocks were subjected to the progressive thermal demagnetization with the use of MAVACS system. The latter procedure turned out to be more efficient and therefore was used as the standard method for a stepwise demagnetization. (Precise results of the thermal demagnetization of rocks could be obtained by using a special arrangement of laboratory procedures. The pick-up unit of the magnetometer must be placed in the magnetic vacuum. All operations with rock samples must be shielded against any influence of an external magnetic field.) Possible alterations of magnetic minerals due to heating of samples were controlled by measuring after each thermal step (characteristic thermal demagnetization curves, Zijderveld diagrams and stereographic projections of RMP directions after each thermal step are in Figs. 4, 5, 6). The direction of the RMP of basaltic andesites is most stable in the interval 100-450 °C (Fig. 4, 1Ad-41), of pyroxene andesite of SM locality in the interval 50-400 °C (Fig. 4, SM 1-1). We can notice that all magnetic characteristics of andesites from locality Somotor (SM) are very similar to those of basaltic andesites from Streda nad Bodrogom — 1Ad. I think that the RMP of both types of andesites is probably linked with more oxidized magnetic phase, though there is a clear

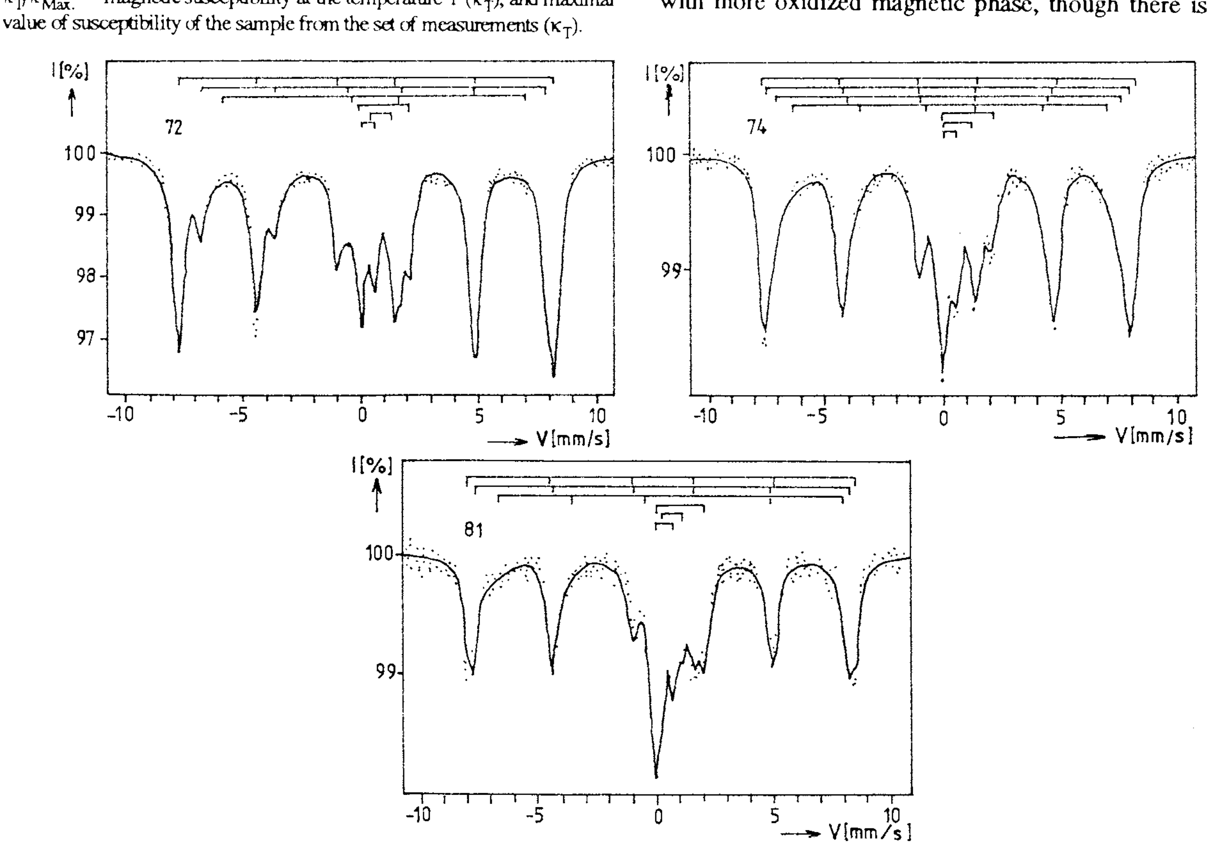

Fig. 3. Mössbauer spectra of magnetic fraction of the pyroxene andesites (72, 74) and rhyolites (81). **72**: gamma-Fe_2O_3 — 58 %, Fe_3O_4 — 23 %; **74**: α-Fe_2O_3 — 10.5 %, gamma-Fe_2O_3 — 42.5 %, Fe_3O_4 — 24.3 %; **81**: α-Fe_2O_3 — 17.5 %, gamma-Fe_2O_3 — 33.3 %, Fe_3O_4 — 10.6 %. (There are of course Fe-Ti oxides in magnetic fractions, but their precise composition has not been determined.)

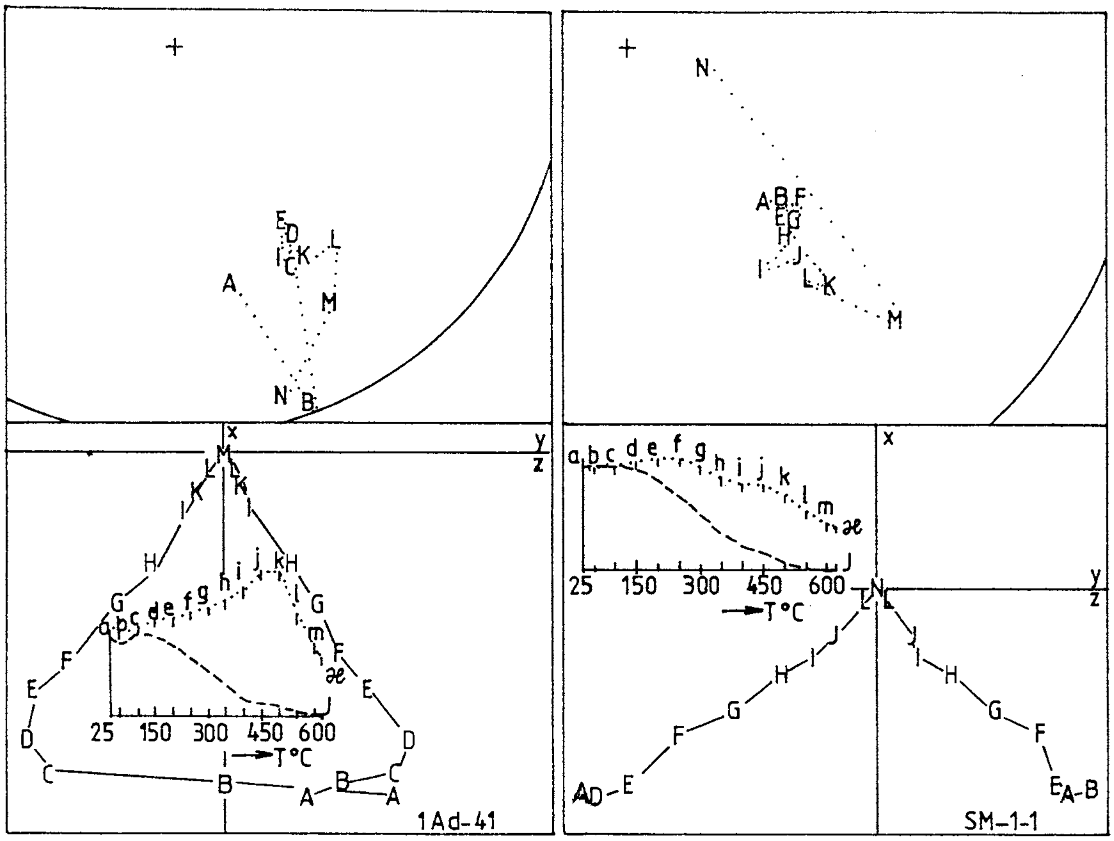

Fig. 4. Thermal demagnetization, Zijderveld diagrams, and stereographic projections of the RMP of basaltic andesite (1Ad-41) and pyroxene andesite (SM-1-1).

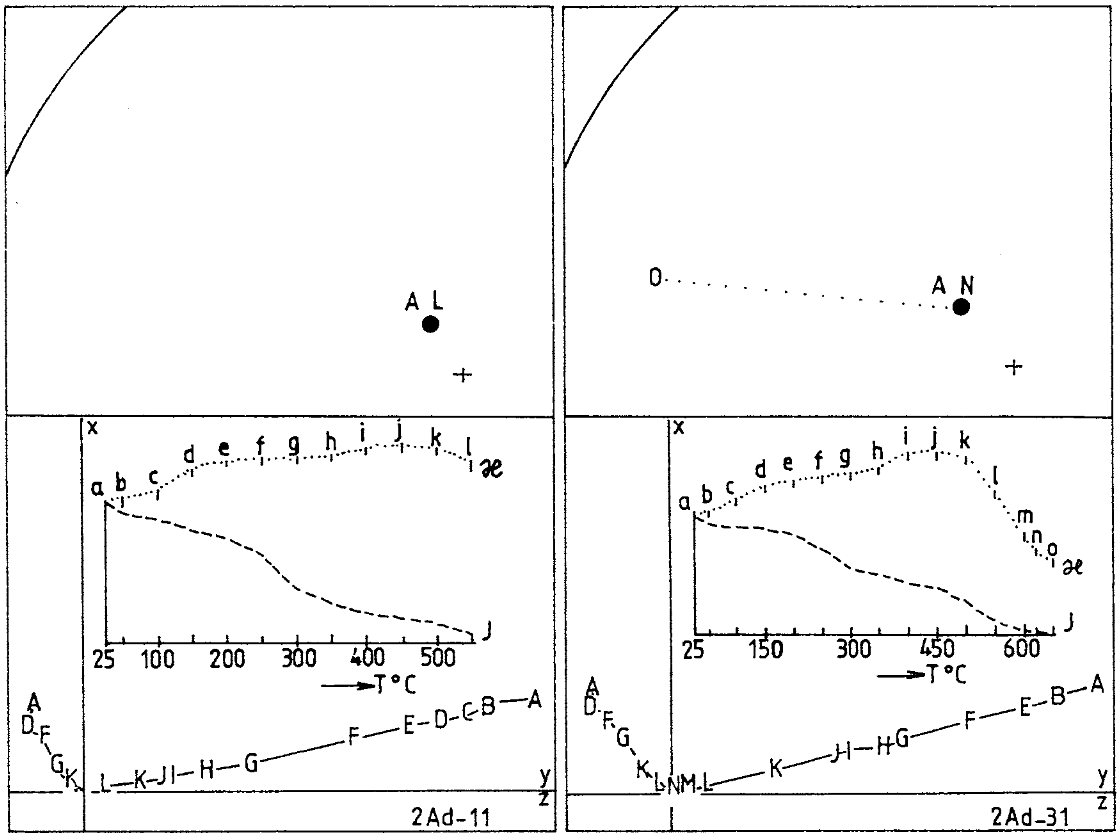

Fig. 5. Thermal demagnetization, Zijderveld diagrams, and stereographic projections of the RMP of pyroxene andesites.

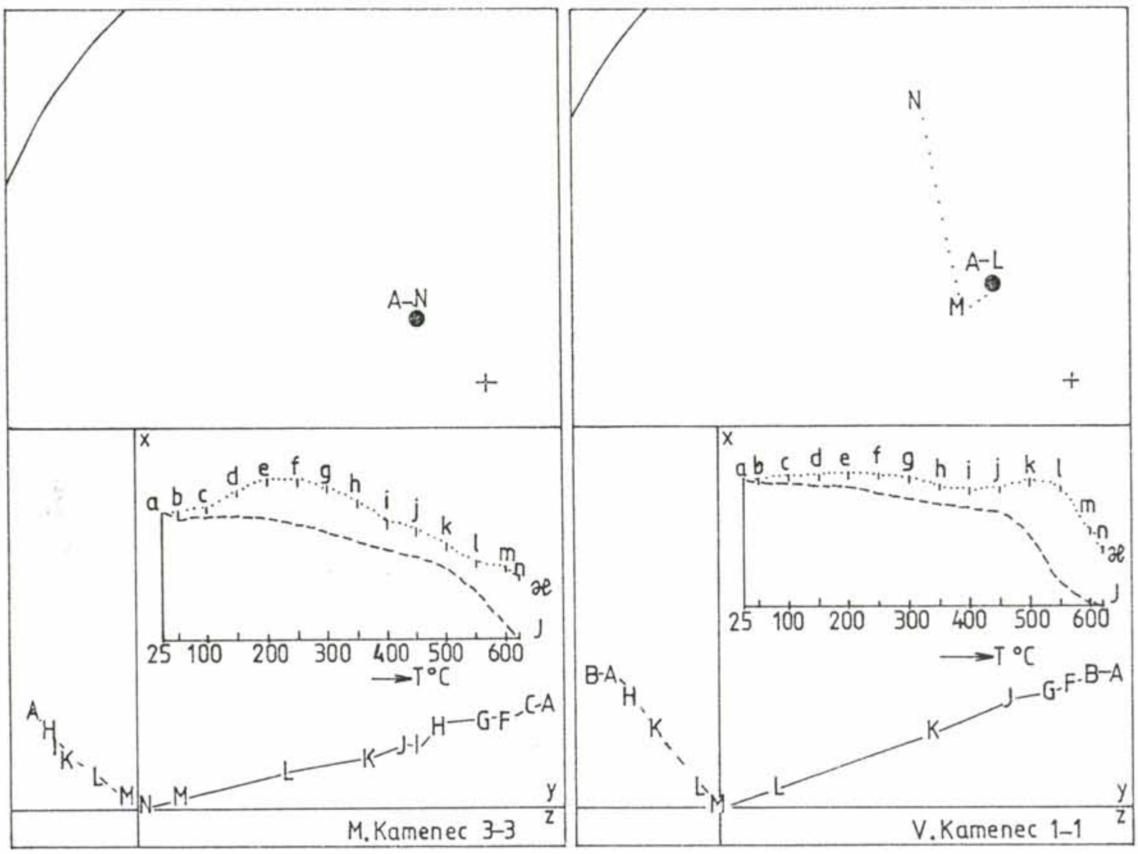

Fig. 6. Thermal demagnetization, Zijderveld diagrams, and stereographic projections of the RMP of rhyodacites.

dispersion of directions of the RMP of rocks at higher temperatures (Fig. 4). The interval 100-400 °C was chosen as the most efficient for thermal cleaning of all samples of the above mentioned localities. The directions of the RMP of pyroxene andesites of locality 2Ad (Fig. 5), as well as rhyodacites of localities Malý and Veľký Kamenec (Fig. 6, M. Kamenec 3-3, V. Kamenec 1-1) are very stable in the interval 25-600 °C. This leads to the interpretation that RMP is linked with the Fe-Ti oxides of the high Curie temperatures ($T_C \approx 600$-620 °C) of the rhyodacites as well as the pyroxene andesites of the locality 2Ad.

Paleomagnetic results and conclusions

Paleomagnetic results from the volcanics of individual localities as well as investigated stratigraphic horizons are presented in Tab. 1, (localities 2N, 3N, 5N were studied by Nairn et al. 1967, stable RMP of rocks of stratigraphic horizons are in Fig. 7). We see from Tab. 1 that rhyodacite bodies near Malý and Veľký Kamenec (Fig. 1, loc. 87, 88, 3N, MK, VK) as well as lava flows of pyroxene andesites of locality 2Ad show exclusively normal polarity of RMP. Rhyolite extrusions and lava flows (loc. 81, 82, 85), rhyodacite pumiceous tuffs (loc. 75), pyroxene andesites (loc. 72, 74, 76, 77, 5N, 78, 79, 83, 84, SM), as well as lava flows of basaltic andesites (loc. 86, 2N, 1Ad) show reversed polarity of stable RMP. The inclinations of stable RMP are variable, but declinations of stable RMP are quite uniform. We see that besides the Middle-Late Badenian (MLB) pyroxene andesites, rocks of both, normal and reversed polarities show the symmetrical declinations of RMP. The directions of rocks were summarized into investigated stratigraphic horizons (Tab. 1, Fig. 7). We see that MLB pyroxene andesites show inclination of RMP I = -28°, declination D = 164°. The declinations of RMP of all other volcanics of the Late Badenian (LB) to Late Sarmatian (LS) period are D = 323 to 328° (locality of normal polarity of RMP) and D = 139-145° (localities of reversed polarity RMP). We know that the investigated neovolcanics originated at different times. We also summarized the paleomagnetic directions for individual tectonic (or neotectonic) structures (Tab. 2, Fig. 8). We see that volcanic bodies of investigated tectonic structures show declinations of RMP ranging from 323° to 328° (normal polarity of RMP) and from 139° to 145° (reversed polarity of RMP) regardless of the petrographical type or time the origin of the rocks.

All tectonic structures are bounded by faults of the NW-SE directions (declinations of RMP of volcanics of tectonic structures have also been drawn on the sketch map — Fig. 1). The presented declinations of stable RMP of volcanics of stratigraphic horizons as well as tectonic structures probably do not correspond to the declination of the geomagnetic field from the time the rocks originated. I prefere the idea that these declinations reflect the tectonic movements which were active in the post-magmatic period. The most probable explanation is thought to be that a counter-clockwise rotation of geological units occurred. The directions of RMP of individual volcanic bodies show that they rotated and moved non-uniformly. For example the volcanics of the Chlmec Horst rotated in the counter-clockwise direction about 16°, but their southern part

Table 2: Paleomagnetic characteristics of neovolcanics of individual tectonic structures.

Tectonic structure	Type of rock	Localities	Number of localities	I°	D°	k	α_{95}
Tarbucka Horst (TH)	Basaltic andesite, Pyroxene andesite, Rhyodacite	1AD, 2N, 86	3	-48	144	47	18
		2Ad	1	75	323		
		87, 88, 3N, MK, VK	5	67	328	175	6
		All	9	61	326	41	8
Podpiliská depression (PD)	Rhyolite	81, 82, 85	3	-44	139	20	29
Horst of Zemplínske vrchy (HZV)	Rhyodacite	75	1	-46	145		
Horst of Veľký vrch (HVV)	Pyroxene andesite	72, 74	2	-57	141	8	111
Horst of K. Vršok (HKV)	Pyroxene andesite	83, 84, SM	3	-57	144	50	18
Chlmec Horst (ChH)	Pyroxene andesite	76, 77, 5N, 78, 79	5	-28	164	93	8

I°, D° - inclination, declination of RMP of rocks, respectively
k - precision parameter, α_{95} - semiangle of cone confidence for P=0.05

sank and northern part was elevated about 37° against their original horizontal position. The rhyodacites of the Tarbucka Horst rotated about 32° in the counter-clockwise direction, but their position with respect to the horizontal plane appears to have been preserved. I need to note that no correction for post-volcanic tilting has been applied, so part of the variations may be attributed to this phenomenon. What was the source of the movements and when did the counter-clockwise rotation (CCR) take place?

The southern part of the East-Slovak Lowlands is disturbed by the faults of three strike systems according to Baňacký et al. 1989. The main NW-SE striking fault system divided the area into blocks. In the Neogene-Quaternary neotectonic phase the gradual restructuring of the East-Slovak Lowlands

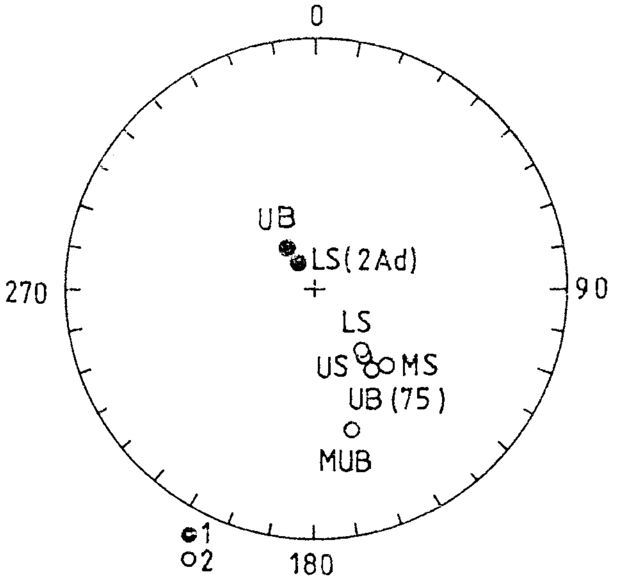

Fig. 7. Directions of the remanent magnetic polarization (RMP) of volcanics of the stratigraphic horizons. 1, 2 — normal, reversed polarity of the RMP, respectively. **MLB** — Middle-Late Badenian; **LB** — Late Badenian; **ES** — Early Sarmatian; **MS** — Middle Sarmatian; **LS** — Late Sarmatian.

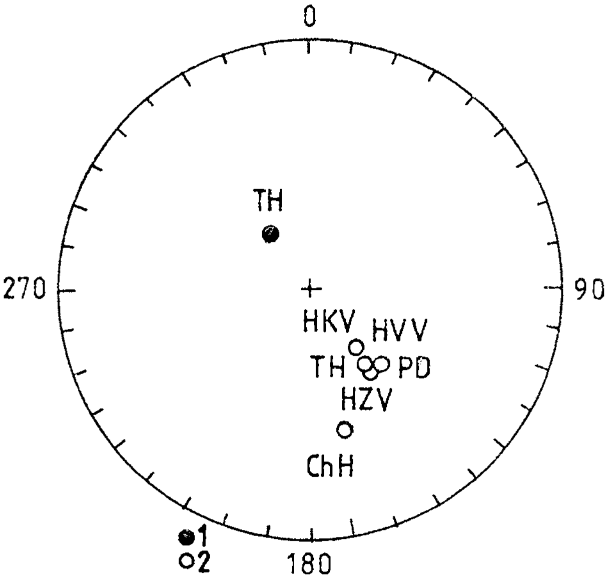

Fig. 8. Directions of the remanent magnetic polarization (RMP) of volcanics of individual tectonic structures. 1, 2 — normal, reversed polarity of the RMP, respectively. **ChH** — Chlmec Horst; **TH** — Tarbucka Horst; **PD** — Podpiliská Depression; **HZV** — Horst of the Zemplínske vrchy Mts.; **HVV** — Horst of Veľký vrch; **HKV** — Horst of K. Vršok.

relief commenced. In the course of general subsidence some more intense movements dissected the lowlands into particular neotectonic units, which gave the lowlands a subsidence character. As has been pointed out above, the younger faults of the NW-SE direction are more conspicuous, they bound most of the neotectonic structures. The directions of the NW-SE faults correspond very closely to the general directions of stable declinations of RMP of the volcanic bodies.

Paleomagnetic data have detected the counter-clockwise rotation of the volcanic bodies of all stratigraphic horizons (32° on average), including the youngest Late Sarmatian basaltic andesites (15-12 Ma). It appears that the movements of volcanic bodies took place in a post-volcanic, younger period. Baňacký et al. 1989 presented an idea that the neotectonic structures were formed in the course of the Pliocene-Quaternary period. The main source of the movements of the geological units was general subsidence in the area under consideration. Experimental evidence obtained by other authors call for consideration of a more comprehensive interpretation of the counter-clockwise rotations of geological units. Márton & Márton (in press) have presented a "large rotations in Northern Hungary during the Neogene" (one group 70-90°, second one CCR about 30°) based on the paleomagnetic results of igneous intrusions, limestones burnt by the intrusions and lava rocks from Recsk in the north central Mátra Mountains, and limestones in the Bükk Mountains. On the other hand the products of the Miocene andesite volcanism along the North Hungarian Central Range — namely the Börzöny, Czerhát, Mátra and Tokaji Mountains possess paleomagnetic directions nearly parallel or antiparallel to the present direction of the geomagnetic field, which implies that the area of the North Central Range has not moved since the Middle Miocene (according to Márton & Márton, in press). Nairn et al. 1971 studied the Tertiary and Quaternary rocks of the Tokaji Mountains. They did not indicate a counter-clockwise rotation of the rocks under study. Nairn et al. 1967, Orlický et al. 1974 and Orlický 1993 studied the Tertiary and Quaternary rocks of Eastern Slovakia. CCR of volcanics from the East-Slovak Lowlands and Zemplínske vrchy Mts., and from four localities of the Veľký Milič Mountains was detected. But the northern part of the Slanské vrchy Mts. do not show a CCR. The same age volcanic rocks in the Central Slovak volcanic field (Orlický 1992) do not show a counter-clockwise rotation.

The counter-clockwise rotations of the volcanics of the East-Slovak Lowlands, Zemplínske vrchy Mts., as well as Veľký Milič Mts. may be explained by the fact, that during the Badenian-Sarmatian time, the western part of the Carpathian Arc was no longer active, while in the eastern part the final stage of arc-continental collision and related subduction continued (Lexa, personal information).

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