Annales Societatis Geologorum Poloniae (1997), vol. 67: 13–23.

PALEOMAGNETIC RESULTS FROM THE COVER (HIGH-TATRIC) UNIT AND NUMMULITIC EOCENE IN THE TATRA MTS (CENTRAL WEST CARPATHIANS, POLAND) AND THEIR TECTONIC IMPLICATIONS

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Grabowski, J., 1997. Paleomagnetic results from the cover (High-Tatric) unit and nummulitic Eocene in the Tatra Mts (Central West Carpathians, Poland) and their tectonic implications. *Ann. Soc. Geol. Polon.*, 13–23.

Abstract: Paleomagnetic studies of the Mesozoic and Eocene sedimentary rocks from the High-Tatric (para-autochthonous and Czerwone Wierchy units) and Paleogene cover formations of the Polish Tatra Mts were carried out. In the Middle Jurassic–Lower Cretaceous limestones a normal polarity pre-thrusting (pre-Senonian) component was identified (5 sites, 32 samples, 92 specimens). Its occurrence also in several localities of the Lower Jurassic–Upper Jurassic rocks of the Križna unit in Poland and Slovakia indicates the possibility of the regional remagnetization which took place between 119 and 88 my (Middle Cretaceous). Another component of reversed polarity (2 sites, 17 samples, 28 specimens) is compared with the magnetization of the Middle Miocene andesites from the Pieniny Klippen Belt. The inclination of the Middle Cretaceous component accounts for proximity of the Central West Carpathian (CWC) region to the European plate in that time. Declinations in the para-autochthonous unit are rotated about 23° (±6°) clockwise from the coeval reference European paleomagnetic direction.

Abstrakt: Przeprowadzono badania paleomagnetyczne skał osadowych mezozoiku w Tatrach Polskich na obszarze wierchowej jednostki para-autochtonicznej i jednostki Czerwonych Wierchów oraz eocenu numulitowego. W skałach węglanowych od środkowej jury po dolną kredę (5 odsłonięć, 32 próby ręczne, 92 próbki) stwierdzono występowanie namagnesowania o normalnej polarności, utrwalonego przed ruchami płaszczowinowymi w późnej kredzie. Podobny kierunek paleomagnetyczny został już wcześniej stwierdzony w kilku miejscach w Polsce i na Słowacji w skałach dolnej–górnej jury jednostki kriżniańskiej. Ponieważ kierunek ten występuje na znacznym obszarze w skałach różnego wieku i ma niemal wyłącznie normalną polarność, może on być regionalnym przemagnesowaniem które nastąpiło między 119 a 88 mln lat temu (środkowa kreda). Inny kierunek o odwrotnej polarności (2 odsłonięcia, 17 prób ręcznych, 28 próbek) porównano z namagnesowaniem neogeńskich andezytów z Góry Wżar (Pieniński Pas Skałkowy). Inklinacja składowej kredowej świadczy o bliskości obszaru Wewnętrznych Karat Zachodnich i płyty europejskiej, przynajmniej na pograniczu wczesnej i późnej kredy. Deklinacja tego kierunku w para-autochtonie wierchowym wykazuje 23° (±6°) rotacji zgodnej z ruchem wskazówek zegara w stosunku do deklinacji kierunków kredowych z obszaru "stabilnej Europy".

Key words: Central West Carpathians, Tatra Mts, Mesozoic, High-Tatric units, Eocene, paleomagnetism.

Manuscript received 23 April 1996, accepted 3 January 1997

INTRODUCTION

Paleomagnetic data from the Mesozoic rocks of the Central West Carpathians (CWC) are less numerous as compared with other Western Tethyan regions. Sedimentary Jurassic rocks of the Križna nappe in Poland and Slovakia yielded pre-folding directions compatible with Jurassic reference directions from the European Platform, with some local tectonic rotations (Kądziałko-Hofmokl & Kruczyk, 1987; Kruczyk *et al.*, 1992). However these results were not related to paleomagnetic data base for Tethyan realm (i.e. Marton & Mauritsch, 1990) and their paleotectonic significance was not fully understood. Recently it was established (Grabowski, 1995a; 1995b) that the Mesozoic paleomagnetic directions from the CWC reveal similar trend (mostly clockwise rotations) as the directions from the Northern Calcareous Alps (Mauritsch & Becke, 1987; Channel *et al.* 1992a; Mauritsch & Marton, 1995). On the other hand they differ from the coeval directions from the Transdanubian Central Mts (Marton & Marton, 1983) and other Apulian fragments (i.e. Lowrie, 1986; Channel *et al.*, 1992b).

In this paper new paleomagnetic results from the Mesozoic High-Tatric unit and nummulitic Eocene of the Tatra Mts in Poland are presented. Some paleotectonic problems

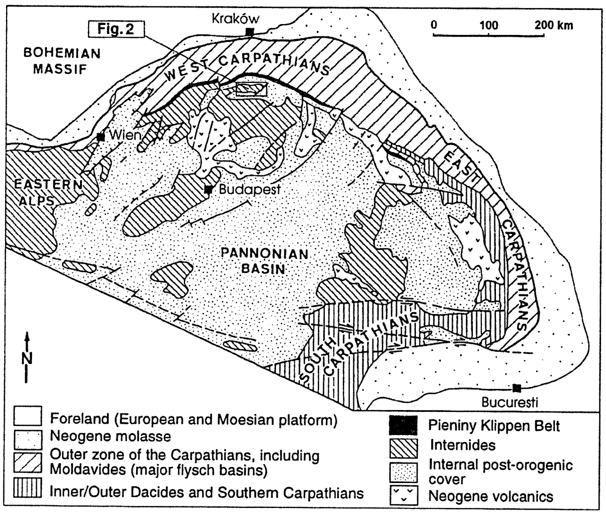

Fig. 1 Structural map of the Carpathians (after Winkler and Ślączka 1994). Box indicates the area presented in Fig. 2

such as distribution of oceanic domains in the northern Carpathian area and paleogeographic affinities of the region are briefly discussed. Preliminary results from sites 7, 9 and 12 (see Tab. 3) were published by Grabowski (1995b).

GEOLOGY

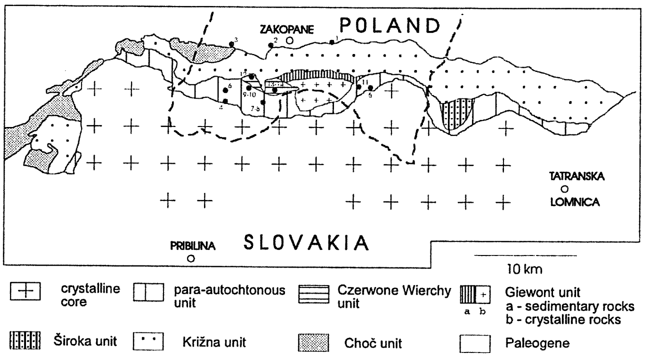

Fig. 2 Structural map of the Tatra Mts with sampling sites (numbering according to the Tab. 3)

The Tatra Mts contain the northernmost occurrence of “core mountains” in the CWC (Fig. 1). It is a horst of crystalline pre-Mesozoic rocks covered by sedimentary sequence of Early Triassic–Late Cretaceous (Turonian) age (see Książkiewicz, 1977 and references herein). The Late Cretaceous (pre-Senonian) orogeny resulted in the formation of a nappe pile thrusted northward. The High-Tatric (Cover) and Sub-Tatric (lower – Križna and upper – Choč) units are distinguished (Fig. 2). Terms such as Tatricum, Fatricum and Hronicum are also widely used for High-Tatric, lower and upper Sub-Tatric units, respectively (Biely, 1990). The High-Tatric units were subjected to only minor horizontal displacements. They are divided into para-autochthonous unit, which is a roughly *in situ* sedimentary cover of the crystalline rocks and several detached units. Among them the most important are (from west to east): Czerwone Wierchy, Giewont and Široka units. The Sub-Tatric units were detached, transported from the south and thrusted over the High-Tatric units. Paleogene rocks overlay discordantly the Mesozoic and the crystalline core. The Tatra Mts and other massifs in the CWC were uplifted during Neogene (Kovac *et al.* 1994) producing “core mountains” surrounded by basins filled with Tertiary sediments. According to Piotrowski (1978) the Neogene uplift of the Tatra Mts was rotational with amplitude greater in the southern than in the nortnern part of the massif. The axis of rotation by about 20° was roughly horizontal and latitudinal. More detailed description of geological structures in the Polish and Slovak Tatra Mts can be found in Rabowski (1959), Kotański (1961), Książkiewicz (1977), and Mahel (1968). Stratigraphical review of the investigated profiles was published by Lefeld *et al.* (1985).

PALEOGEOGRAPHIC SETTING AND EXPECTED PALEOMAGNETIC DIRECTIONS

According to a common view the Central West Carpathians area during Mesozoic and Tertiary was situated between the European and African plates in the Western Tethys domain (Burchfiel, 1980; Ricou *et al.*, 1986; Gealey, 1988). Numerous paleogeographic reconstructions differ in details. Wieczorek (1995) assumes that in the Triassic and Early Jurassic Tatricum belonged to the southern, passive margin of the European plate. The Tatricum was separated from Apulia by Meliata ocean (Kozur, 1991) which was opened during the Middle Triassic and closed in the Late Jurassic. In the Middle Jurassic rifting occurred north of the Tatricum and Vahic (Pieniny) ocean (Mahel, 1981, Birkenmajer, 1986, Winkler & Ślączka, 1994, Plašienka, 1995) had developed which was closed by the Late Cretaceous. On the other hand Tollmann (1990) in series of paleogeographic maps does not introduce oceanic domains in the CWC and Outer Carpathians area. He accepts the existence of Vardar ocean between the Austro–Alpine units and Southern Alps and prolongates it south of the CWC.

The “expected” paleomagnetic directions should indicate the position of the Central West Carpathians as intermediate between Africa and Europe. It should be possible to determine paleomagnetically the paleogeographic (i.e African versus European) affinity of the Tatric area. The movement between Africa and Europe was so distinct that Mesozoic/Early Tertiary paleomagnetic poles and directions obtained from these two plates differ significantly. During last 240 m.y. Africa was situated always south of Europe, so the African inclinations of the characteristic paleomagnetic directions should be lower than the inclinations of coeval directions from Europe (see Tabs 1, 2). Differences in paleodeclination should also be noted. During the Mesozoic Africa rotated 30° counter-clockwise, while the sense of rotation of European plate was opposite (Tabs 1, 2).

Table 1

"Expected" paleodirections for the Tatra Mts, as if they were part of the European Plate, calculated from paleopoles for the geographical coordinates 20°E, 49°N. Data 0–200 Ma after Besse and Courtillot (1991), Triassic data after Van der Voo (1993).

Age (m.y.)	Declination	Inclination
245–233 (Early Triassic)	30.0	35.4
232–216 (Late Triassic)	39.1	44.2
200 Sinemurian	32.2	62.3
180 (Bajocian)	34.5	59.4
160 (Oxfordian)	17.7	51.8
140 (Berriasian)	9.7	51.5
120 (Barremian)	356.5	53.5
100 (Albian)	0.8	55.2
80 (Campanian)	0.3	54.7
60 (Paleocene)	5.3	57.5
40 (Eocene)	10.9	61.6
20 (Miocene)	8.5	62.6
0 (Recent)	0	68

Table 2

"Expected" paleodirections for the Tatra Mts, as if they were part of the African Plate, calculated from paleopoles for the geographical coordinates 20°E, 49°N. Data 0–200 Ma after Besse and Courtillot (1991), Triassic data after Van der Voo (1993).

Age (m.y.)	Declination	Inclination
245–233 (Early Triassic)	328.3	36.9
232–216 (Late Triassic)	330.8	41.5
200 Sinemurian	341.6	48.9
180 (Bajocian)	344.6	45.7
160 (Oxfordian)	334.4	36.4
140 (Berriasian)	329.3	36.4
120 (Barremian)	323	40.5
100 (Albian)	337.7	44.9
80 (Campanian)	346	46.7
60 (Paleocene)	354	52
40 (Eocene)	3.4	58.6
20 (Miocene)	5.8	61.5
0 (Recent)	0	68

SAMPLING AND LABORATORY METHODS

Results from 14 sites in 3 tectonic units are described. The term "site" describes an outcrop of several meters height and width. 108 hand samples of Mesozoic and Tertiary sedimentary rocks, mainly limestones, were collected from the Polish part of the Tatra Mts (Fig. 2). 27 samples were taken from the nummulitic Eocene and 81 from the High-Tatric units (para-autochthonous and Czerwone Wierchy unit) in the western part of the Tatra Mts where the most complete profiles of sedimentary series occur. The Mesozoic collection consisted of Lower Triassic quartzitic sandstones and the Middle Triassic, Middle/Upper Jurassic and Lower Cretaceous limestones. High-Tatric series, except sites 5 and 11, were sampled along the Kościeliska Valley and in some smaller valleys in its vicinity. Sites 5 and 11 were situated in the Gąsienicowa Valley. Unfortunately the studied formations dip uniformly to the north (Tab. 3), so the fold test in the High-Tatric units could not be applied. The conglomerate test was performed at the field of boulders at Wantule (upper part of the Miętusia Valley, site No. 14). The boulders resulted from a large rockfall during the last glacial epoch (Rabowski, 1959). Three localities of the Eocene nummulitic limestones were sampled along the northern edge of the Tatra Mts (Fig. 2).

Cylindrical specimens, 20 mm in diameter and 22 mm height, were drilled from the hand samples. Usually 2–4 specimens were obtained from each hand sample. Natural remanent magnetization (NRM) was measured by means of the JR-5 spinner magnetometer while magnetic susceptibility was monitored with KLY-2 bridge. The rock specimens were thermally demagnetized with the MMTD non-magnetic oven. Alternating field demagnetization was carried out in a 2-axis tumbler produced by the Institute of Geophysics, Polish Academy of Sciences. Demagnetization experiments and the NRM measurements were performed inside a Helmholz coils that reduced the geomagnetic field by 95%. Characteristic directions were calculated using the principal component analysis (Kirschvink, 1980) and in few cases the Hoffman–Day method (Hoffmann & Day, 1978).

Magnetic minerals were identified by means of thermomagnetic analysis. It relied on thermal demagnetization of isothermal remanence (IRM) acquired in the field of about 1 T (the first curve in appropriate figures). Then the sample was cooled, magnetized and demagnetized again (the second curve in the figures). This method gives values of blocking temperatures for magnetic minerals and shows what new minerals originate in the rock due to its heating in the air.

Table 3

List of sampled localities

No	Site	Age	Tectonic unit	Bedding	N
1	Pod Capkami	Eocene	Tertiary cover	356/40	12
2	Mała Łąka			0/30	7
3	Lejowa			384/40	8
4	Ornak	T1	High-Tartic para-autochthonous unit	45/36	9
5	Żółta Turnia	T1		10/32	6
6	Kominy Tylkowe	T2		21/71	5
7	Wąwóz Kraków	J2		16/62	3
8	Wąwóz Kraków	J2/J3		16/62	4
9	Raptawicka Turnia	J3/K1		34/54	12
10	Wąwóz Kraków	K1		45/54	12
121 1	Hala Gąsienicowa	K1		345/46	4
12	Brama Kraszewskiego	J2/J3	High-Tatric Czerwone Wierchy unit	24/10	8
13	Wielka Świstówka	J3		20/30	11
14	Wantule	J3	Quaternary field of boulders	–	7

T – Triassic, J – Jurassic, K – Cretaceous, (1 – lower, 2 – middle, 3 – upper,) N – number of hand samples taken from the site

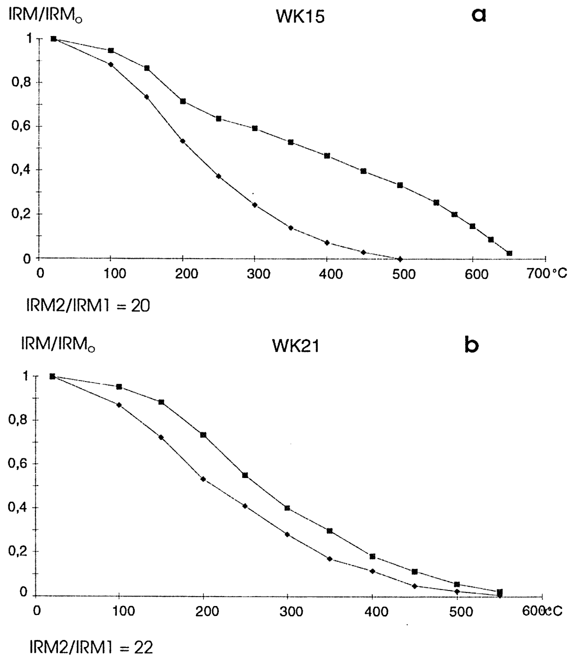

Fig. 3. Thermal demagnetization of the isothermal remanent magnetization (IRM). **a** – red sandy limestone (site 7); **b** – grey limestone (site 10); *squares* – first heating curve, *diamonds* – second heating curve; IRM2/IRM1 ratio indicates the increase of the IRM intensity after the first heating

PROBLEM OF TECTONIC CORRECTION FOR MESOZOIC ROCKS

Question of tectonic correction is of fundamental importance for dating the paleomagnetic components. Common way is to estimate their age in relation to folding processes i.e. to establish whether they are post-folding, synfolding or pre-folding features.

In the Tatra Mts there were two tectonic events that could change the position of the Mesozoic sedimentary rocks. First it was a Late Cretaceous nappe thrusting and second was the Neogene uplift of the Tatra Mts referred further to as a tilting event. Especially the effects of the latter are difficult to estimate in the rocks of High-Tatric and Sub-Tatric series. It is very likely that some deformations and displacements of Mesozoic rocks took place in Tertiary (Bac-Moszaszwili, 1995). A logical consequence of the model of rotational uplift of the Tatra Mts during the Neogene (Piotrowski, 1978; Bac-Moszaszwili *et al.*, 1984; Sperner 1996) is that all sedimentary sequences which now dip at the angle 20–30° to the north were resting subhorizontally from the late Cretaceous to early Miocene (for example some strata in the para-autochthonous High-Tatric or lower Sub-Tatric unit, see Bac-Moszaszwili *et al.*, 1984, fig. 8b). Therefore it is important to distinguish between pre-tilting and pre-thrusting magnetization. The age of the latter is constrained as pre-Coniacian. Pre-tilting magnetization in such case would imply pre-Neogene age of paleomagnetic component.

ROCK MAGNETISM

Magnetic susceptibility of the investigated specimens was rather low and did not exceed 100 × 10^{-6} SI units. The magnetic fabric is not well developed. Thermomagnetic analysis reveal magnetite and hematite as magnetic minerals. Only in the site 7 hematite without magnetite admixture was found (Fig. 3a). The IRM of the grey limestones of High-Tatric unit is based upon magnetite (Fig. 3b) but the presence of maghemite can not be excluded. Second heating curve in both figures (3a,b) and increase of the IRM intensity indicates that secondary magnetite originates during heating which was typical of all the samples investigated.

PALEOMAGNETIC RESULTS

NRM intensities of grey Mesozoic and Tertiary limestones were between 0,2 and 9 × 10^{-4} A/m. Red Lower Triassic sandstones and Upper Jurassic limestones had higher intensities close to 10^{-3} A/m. The results from sites 4, 5, 6 and 11 were rejected because the NRM vectors were dis-

Table 4

Directions of the low stability component R

Site	D	I	Dc	Ic	α_{95}	k	n/N
1	341	65	349	26	5	12	54/12
2	10	72	4	42	8	21	17/7
3	348	55	348	15	9	26	11/3
8	14	69	15	7	5	54	16/4
9	348	71	17	20	5	28	33/11
10	354	63	22	26	7	42	10/5
13	356	68	9	39	6	33	16/8
14	12	63	–	–	10	42	18/6

	D	I	α_{95}	k	Dc	Ic	α_{95}	k
Mean	357	65	5	103	8	24	12	24

Present day field (PDF): D = 0, I = 68

D, I – declination, inclination before tectonic correction; Dc, Ic – declination, inclination after tectonic correction; α_{95}, k – Fisher statistics parameters; n(N) – number of specimens (samples) used for calculation of characteristic direction

Table 5

Directions of the high stability components A, B and C. Explanations as in the Tab. 4

Site	D	I	Dc	Ic	α_{95}	k	n/N	Comp
7	173	66	30	49	5	70	13/3	A
8	183	74	21	44	9	22	13/4	A
9	228	72	21	52	6	23	25/8	A
10	282	72	20	53	6	26	23/10	A

	D	I	α_{95}	k	Dc	Ic	α_{95}	k
Mean A:	211	76	17	29	23	50	6	256

Site	D	I	Dc	Ic	α_{95}	k	n/N	Comp
12	301	50	312	48	5	48	18/7	B
10	70	-57	181	-71	7	25	16/8	C
13	69	-79	179	-66	9	22	12/9	C
Mean C:	70	-68	180	-69	–	–		

persed and demagnetization did not improve the clustering of directions.

Most of the Eocene samples (sites 1,2,3) revealed the presence of a component which was demagnetized at low fields (up to 20mT) and low temperatures (up to 300°C, see Fig. 4a). That component (labelled R) in the present (geographical) coordinates system is similar to the present-day local geomagnetic field (PDF) direction (Tab. 4, Fig. 5). After removing the component R the internal consistency between samples and sites was lost, the intensity of magnetization fell down to about 10% of the initial NRM and no other characteristic magnetization of higher stability could be isolated. The R component should be considered as post-tilting (i.e. post-Neogene) because after tectonic correction (Tab. 4) its inclination is much lower than the predicted Eocene–Miocene inclinations for European and African plates (Tabs 1, 2).

Bathonian red sandy limestones of the para-autochthonous unit (site 7) from the Kraków Gorge revealed a single component which was stable up to 620°C (Fig. 4b). After tectonic correction (understood as restoring beds to the horizontal position) the component is situated in the I quadrant of the stereonet with moderately steep inclination (Tab. 5, Fig. 6a, b).

The overlying Callovian/Oxfordian red nodular limestone (site 8) had more composite magnetization. The low stability R component (Tab. 4) was removed after demagnetization steps of 20mT and 250°C. Intermediate component of normal polarity was observed between 450 and 515°C. In some samples this component could be defined using the Hoffmann–Day method (Fig. 7). Before tectonic correction it is situated in the south-western quadrant of the stereonet with steep inclinations (Tab. 5, Fig. 6a). After tectonic correction the component is placed in the north-eastern quadrant with moderately steep inclination (Tab. 5, Fig. 6b). At higher temperatures a reversed component appeared but the increase of magnetic susceptibility during thermal demagnetization precluded its isolation.

Another component of magnetization was discovered in the red Callovian/Oxfordian limestone of the overthrusted Czerwone Wierchy unit (site 12). It was stable between 380 and 600°C (Fig. 4c) and its declination was rotated over 60° counter-clockwise (Tab. 5, Fig. 6a, b). The rocks at this site lay almost horizontally (Tab. 3) so the position of this component before and after tectonic correction does not change very much.

Very interesting results were obtained from weakly magnetized grey limestones of the Malm–Neocomian and Neocomian age from the sites 9, 10 and 13. In all these sites the low stability R component (Tab. 4) constituted 80–90% of the initial NRM intensity (Fig. 4d). After its removing, usually in the temperature interval 350–450°C the normal polarity component was observed (Tab. 5, Fig. 4d). This direction was encountered in the sites 9 and 10. Alike in the sites 7 and 8 this component before tectonic correction revealed steep downward inclinations with the south-westerly declinations (Tab. 5, Fig. 6a). After tectonic correction the declinations became north-eastern while inclinations are about 50^0 (Fig. 6b). In some samples from the site 10 and in most samples from the site 13 a reversed polarity component was revealed, unblocked between 250–350°C (Fig. 4e, Tab. 5). In some samples from the site 10 the reversed component occurred together with higher stability normal component and their unblocking temperature spectra were sepa-

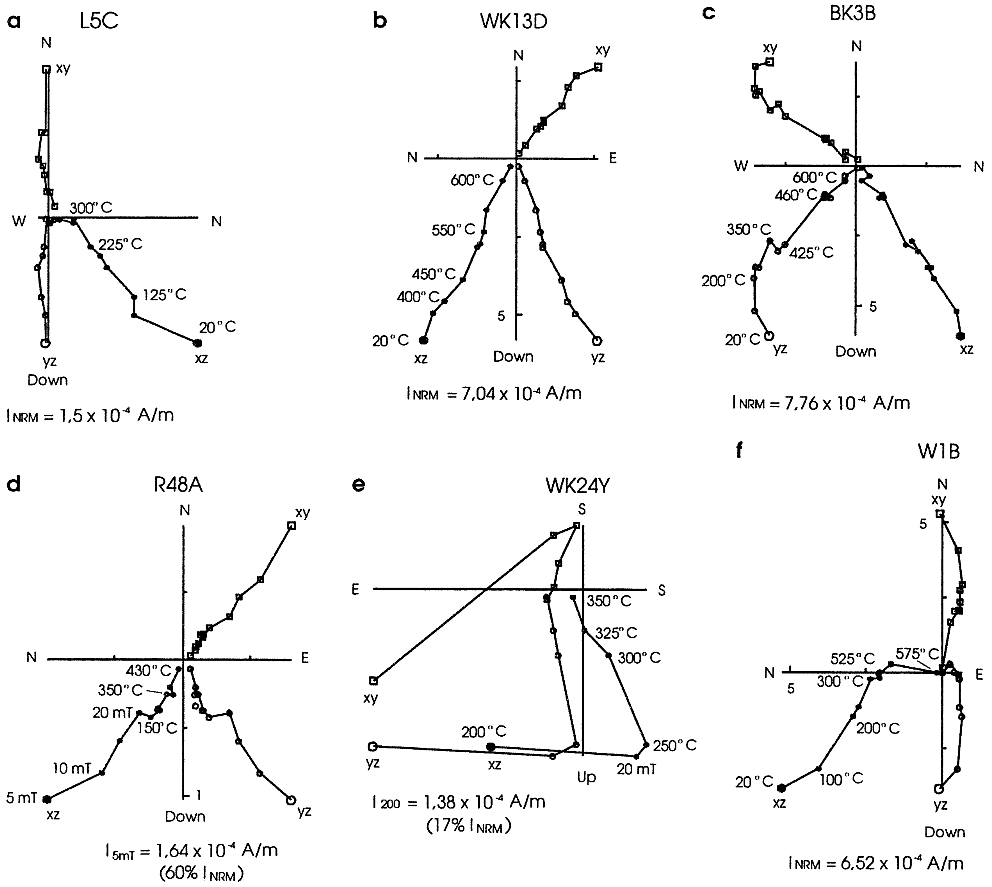

Fig. 4. Demagnetization diagrams of typical specimens. **a** – grey nummulitic limestone (site 3); **b** – red sandy limestone (site 7); **c** – red limestone (site 12); **d** – grey limestone (site 9); **e** – grey limestone (site 10); **f** – grey limestone (site 14); (**a**) and (**f**) before tectonic correction, (**b**)-(**e**) – after tectonic correction; xy, xz, yz – the planes of projection, units are in 10^{-4} A/m

rate. It reveals steep upward inclinations before as well as after tectonic correction (Tab. 5, Fig. 6a, b). "In situ" declination is about 70° while after tectonic correction it is close to 180°.

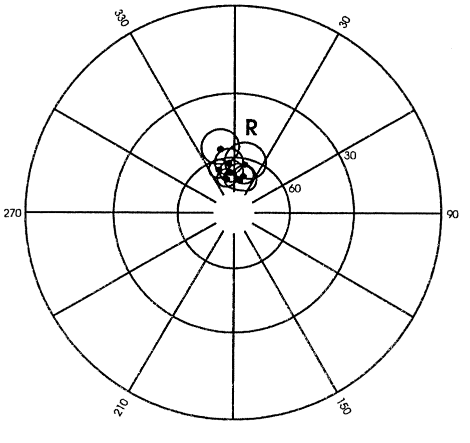

Fig. 5. Stereographic projection of the component R before tectonic correction

Stability test

Similarity of the component R (Tab. 4) to the PDF direction could suggest that it represents the recent viscous remanent magnetization (VRM). Alternative explanation that component R is due to a Neogene remagnetization is also possible. Fission track ages of apatites from the crystalline core of the Tatra Mts yielded ages between 10 and 23 Ma (Burchart, 1972). This was interpreted as the last thermal event related to the post-orogenic uplift of the Tatra massif and erosional removal of the sedimentary cover.

In order to establish the age of the post-folding component R a conglomerate test was performed at the site 14 (Wantule). 7 hand samples were taken from independent blocks of grey Upper Jurassic limestones. Magnetite was the only carrier of magnetization in these rocks. Thermal demagnetization was applied to most of specimens (Fig. 4f). One specimen from each hand sample was treated with the AF demagnetization. The NRM consisted of two components of separate unblocking temperature spectra. Low stability (LS) component was removed up to 300°C. Its direction in all samples is close to the PDF direction (Tab. 6). High stability (HS) component is removed between 525 and 575°C. It clustered well within a single hand sample but varied between samples. (Tab. 6) AF demagnetization was not effective in separation of the two components. Intermediate

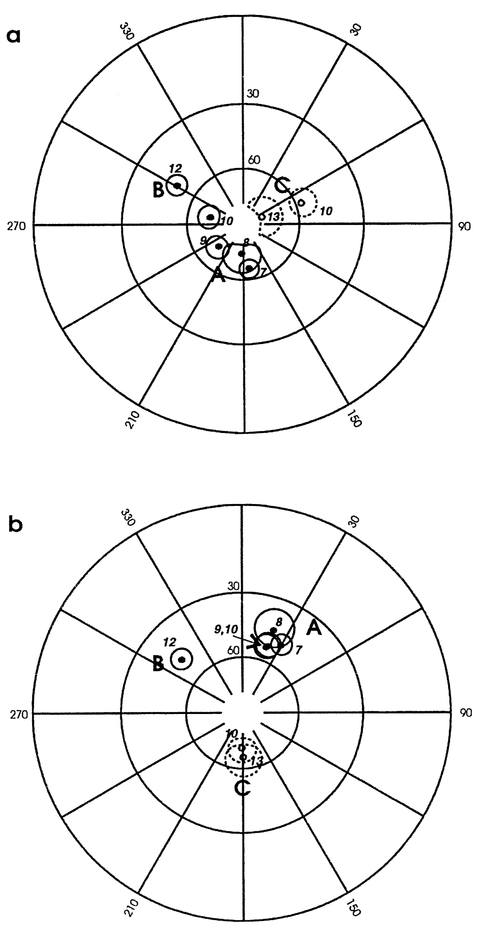

Fig. 6. Stereographic projection of the components A, B and C; **a** – before tectonic correction, **b** – after tectonic correction; numbering of sites corresponds to that in the Table 3

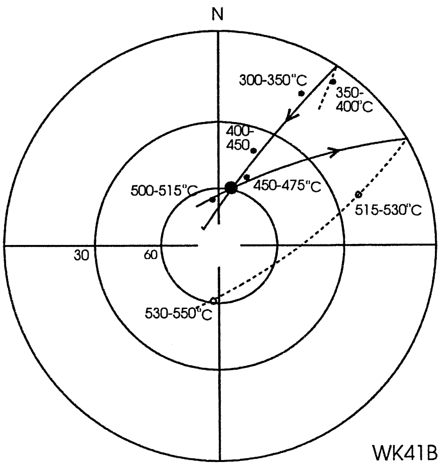

Fig. 7. Determination of characteristic magnetization using Hoffmann–Day method, site 8. Stereographic projection of the differential vectors (*dots*) and demagnetization planes (*great circles*) after tectonic correction. *Black dots* and *continuous line* – lower hemisphere projection, *white dots* and *broken line* – upper hemisphere projection. Intersection point of demagnetization planes (*large dot*) indicates the characteristic direction

Table 6

Results of conglomerate test in the Wantule site

Sample	D_{LS}	I_{LS}	α_{95}	k	n	D_{HS}	I_{HS}	α_{95}	k	n
W1	22	62	14	29	4	11	-9	14	46	4
W2	358	67	–	–	2	236	-38	–	–	1
W3	14	68	10	163	3	170	-11	6	366	3
W4	26	46	17	56	3	7	28	13	85	3
W6	332	64	23	17	4	153	58	15	67	3
W7	23	64	–	–	2	215	-25	–	–	1
Mean:	12	63	10	42	6	–	–	–	–	–

DLS, (ILS) – declination (inclination) of the low stability component; DHS, (IHS) – declination (inclination) of the high stability component; n – number of entries

directions between the low and high stability components were observed.

The results of the conglomerate test are obvious. The LS component is a recent VRM acquired during last 20 000 years. It corresponds to the low stability R component obtained in most sites (Tab. 4). The HS component is an older magnetization of Mesozoic or Tertiary age.

Age of characteristic magnetizations

The low stability component R is a recent viscous magnetization, as confirmed by the conglomerate test.

The higher stability components are divided into three groups: A, B and C (Tab. 5, Fig. 6a,b). Group A is characterized by normal polarity and north-eastern declination after tectonic correction. It can be reasonably assumed that the components A are pre-tilting (i.e. pre-Neogene). Their declination and inclination in the post-tilting coordinates (Tab. 5) would require the location of the studied area in the southern polar region in the Neogene or later which is very unlikely. Moreover the components A from various sites cluster better after than before tectonic correction (Tab. 5, Fig. 6a, b).

Group B (site 12 only) reveals normal polarity and counter-clockwise rotated north-western declination. This component is also considered as pre-tilting. Its inclination fits the expected Jurassic–Early Tertiary inclinations of African and European plates after tectonic correction.

Reversed polarity components in the sites 10 and 13 were included to the group C (Fig. 6a, b). They should be interpreted as pre-tilting too. If they were post-tilting a 80–110° counter-clockwise rotation would be required to match them with Late Tertiary/Quaternary declinations of Africa and Europe. After tectonic correction the amplitude of rotation is no more than 30°.

It is not certain whether the components A are primary. Although the sampled rocks covered the time span between Bathonian and Neocomian, reversed components were not observed. The reversed magnetizations in sites 10 and 13

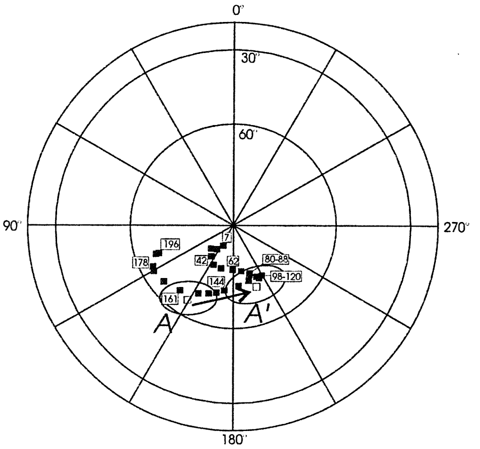

Fig. 8. Paleopole A at the background of the European Apparent Polar Wander Path (after Besse and Courtillot, 1991). A' indicates the position of paleopole A after 23° clockwise rotation of the Tatra Mts around local vertical axis. Age of paleopoles in m.y.

(component C) revealed lower blocking temperatures and steeper inclinations than those of component A. So, the component C can not be considered as the reversed counterpart of the component A. Moreover the components A seem to have a regional significance. Pre-folding components that could be assigned to the A group were obtained from the variegated Bathonian to Kimmeridgian rocks of the Križna nappe in the Western Tatra Mts and Belianske Tatry (Kądziałko-Hofmokl and Kruczyk, 1987, Kruczyk *et al.*, 1992, Grabowski, 1995a). They are all (except one at Dolina Filipka, see Kądziałko-Hofmokl and Kruczyk, 1987) of normal polarity, too. Single polarity nature of the component A could may indicate its secondary character because between Middle Jurassic and Early Cretaceous numerous reversals of the geomagnetic field took place (Hailwood, 1989; Ogg *et al.*, 1991; Juarez *et al.*, 1995). A question arises whether this component could be pre-thrusting. The evidence of pre-thrusting origin of the component A comes from the Gładkie Upłaziańskie tectonic slice (Grabowski, 1995a) belonging to the Križna unit in the Western Tatra Mts. Red radiolarian limestones of Late Jurassic age revealed the presence of pre-folding component A. The strata in this site dip steeply (60–80°) to the north while the Križna thrust plane is dipping only gently to the north (Bac-Moszaszwili *et al.*, 1984, fig. 8a) and obliquely cuts the bedding so that folding obviously pre-dates thrusting. Thus the component A might have been acquired later than early Aptian (upper age limit of the rocks containing this component, site 10) and before the Coniacian (termination of the Late Cretaceous thrusting) in a long period of exclusively normal polarity of geomagnetic field (Hailwood, 1989). The age constraints for acquisition of the component A would be 119–88 m.y., what roughly corresponds to the boundary between Early and Late Cretaceous. The pole of the component A falls close to the Late Jurassic segment of the European Apparent Polar Wander Path (APWP, Fig. 8). After 23° counter-clockwise rotation it could be matched with the Cretaceous paleopoles. This movement corresponds to 23° (±6°) clockwise rotation of the Tatra Mts around the local vertical axis after Early Aptian. Possibility of such rotation was suggested in the earlier paper (Grabowski, 1995b). The amplitude and sense of rotation correspond to that inferred for the Lower Sub-Tatric nappe in the western Tatra Mts (17–30° clockwise, see Grabowski, 1995a).

North-westerly directed component B was encountered in the overthrust Czerwone Wierchy unit only (site 12). The component is also interpreted as pre-thrusting. The counter-clockwise rotation, induced from the NW deviation of the characteristic remanent magnetization must have taken place during the thrusting of the Czerwone Wierchy unit over the para-autochthonous High-Tatric cover.

The interpretation of reversed polarity component C is difficult. Its inclination is steeper than any expected Mesozoic inclination. The component C after tectonic correction becomes very similar to the characteristic magnetization obtained in the Miocene andesites from the Polish sector of the Pieniny Klippen Belt at Mt. Wżar (Birkenmajer & Nairn, 1968) – about 25 km to the north-east from the Western Tatra (Tab. 5). The radiometric age of younger phase of the intrusions was established by Birkenmajer *et al.* (1987) as 12.6 m.y. (Sarmatian) while the older phase is regarded as Early Badenian (16–13 m.y.). The age of component C could correspond to the fission track ages from the crystalline core (10–23 m.y. – Burchart, 1972) which indicate the age of post orogenic uplift of the Tatra massif. The component C would be an example of pre-tilting magnetization which postdates the thrusting.

GEOLOGICAL IMPLICATIONS

It was already pointed out by Kądziałko-Hofmokl and Kruczyk (1987) that the characteristic paleomagnetic directions from the Tatra Mts are closer to the European rather than Apulian or African reference directions. This conclusion was confirmed by further studies in Slovakia (Kruczyk *et al.*, 1992) and Poland (Kruczyk & Kądziałko-Hofmokl, 1988; Grabowski, 1995a; 1995b;). These results are listed in the Table 7. Most declinations reveal clockwise rotations. Counter-clockwise rotations in the overthrust Czerwone Wierchy unit in the Tatra Mts and in the Križna unit of Mala Fatra might be of local character. Also the values of inclinations fit the expected European Mesozoic inclinations and they are significantly higher than the inclinations from Transdanubian Central Mts or Southern Alps (Fig. 9). Thus, if component A is tentatively regarded as the post-early Aptian/pre-Coniacian (119–88 m.y.) remagnetization the following conclusions can be drawn:

– during acquisition of the component A the Tatricum and Fatricum (sensu Biely, 1990) of the Central West Carpathians are related to the southern margin of the European Plate. The total width of three hypothetical oceanic domains (e.g. Vahicum, Magura and Silesian basins, see Mahel, 1981; Birkenmajer, 1986; 1988; Winkler & Ślączka, 1994; Plašienka, 1995) between the CWC and the European plate around the Early/Late Cretaceous boundary is below the resolution of the current paleomagnetic data. It should be stressed that existence of wider oceans in the Early Creta-

Table 7

Characteristic directions from the Mesozoic rocks of the Central Wesy Carpathians. N – number of sites

Locality and age of rocks	D	I	N	α_{95}	k	References
Pieniny Klippen Belt, Niedzica unit, Bathonian–Callovian	16	52	1	7	57	Kruczyk & Kądziałko-Hofmokl (1988)
Tatra Mts, High-Tatric para-autochton (Bathonian–Neocomian)	23	50	4	6	256	tis paper
Tatra Mts, High-Tatric Czerwone Wierchy unit (Callovian–Oxfordian)	312	48	1	5	48	this paper
Tatra Mts, Križna unit (Bajocian–Kimmeridgian)	22	59	7	4	198	Kądziałko-Hofmokl & Kruczyk (1987)
Tatra Mts, Križna unit, (Oxfordian)	37	53	4	9	108	Grabowski (1995a)
Belianske Tatry, Križna unit, (Middle–Upper Jurassic)	40	59	4	8	118	Kruczyk *et al.* (1992)
Choč Hills, Križna unit, (Lower Jurassic)	39	63	3	12	104	Kruczyk *et al.* (1992)
Nizke Tatry, Križna unit, (Middle Jurassic)	2	56	4	14	73	Kruczyk *et al.* (1992)
Magura Spišska, Križna unit, (Middle Jurassic)	75	46	3	12	114	Kruczyk *et al.* (1992)
Mala Fatra, Križna unit, (Middle–Upper Jurassic)	321	44	21	3	96	Kruczyk *et al.* (1992)

Mean inclination: 53°, (± 8°)

ceous and Middle/Late Jurassic can not be excluded. Maximum amount of tectonic shortening during the Late Cretaceous compression in the region from Fatricum in the south to the southern edge of the European platform in the north (including the subduction of oceanic crust and intra-continental overthrusts) did not exceed 1200 km (sum of α_{95} parameters of mean inclination of the component A from the Table 7 and mean Eurasian Early /Late Cretaceous paleopoles of Besse and Courtillot, 1991);

– clockwise rotation of the component A (23°, ± 6°) suggests that the Tatra Mts participated in the Late Cretacous or later tectonic movements which have changed their position in relation to the European Platform. The nature of these movements is unknown and can not be inferred at the present stage of investigation. This could be either a clockwise tectonic rotation around the local vertical axis, strike-slip movement or combination of both. Sinistral strike-slip movement along the faults bordering the Pieniny Klippen Belt on the south were suggested by Birkenmajer (1985) and clockwise rotation of the component A does not contradict the proposed model;

Very interesting are geological consequences of pre-folding age of component C. If its Miocene age was proved (more data is required) it would be an evidence that dips of bedding and thrust planes in the High-Tatric series were indeed changed during the Neogene uplift of the Tatra Mts.

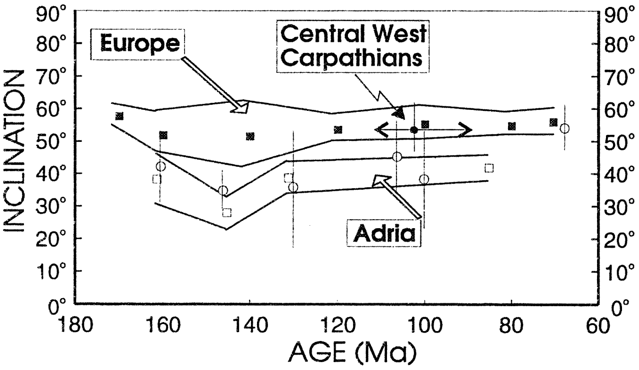

Fig. 9. Comparison of the inclination of the characteristic components from the Central West Carpathians (*full dot*, inclination value plotted after Tab. 7) and Transdanubian Central Mts (*open dots*, after Marton and Marton, 1983) with expected paleoinclinations for the European (*full squares*, after Besse and Courtillot, 1991) and Adriatic plates (*open squares*, after Channel 1992b). Inclinations are recalculated from the pole positions for the geographical coordinates 20°E, 49°N. 95% confidence error bars for all data and age error for the component from the CWC are indicated

CONCLUSIONS

1. The Middle Jurassic–Lower Cretaceous sedimentary rocks in the Tatra Mts reveal post-and pre-folding magnetizations. The post-folding component R is a recent viscous remanent magnetization as confirmed by conglomerate test. The pre-folding normal polarity components A and B were acquired before the Late Cretaceous thrusting. Because they occur in the rocks of Bajocian–Early Aptian age it is suggested that they may represent the post-early Aptian/pre-

Coniacian remagnetization (119–88 m.y.). The reversed component C could be contemporaneous with Miocene andesite intrusions in the Polish part of the Pieniny Klippen Belt.

2. Mean inclination of the pre-thrusting components in the Tatra Mts, other CWC massifs (Mala Fatra, Choč Hills, Nizke Tatry, Magura Spišska) and Pieniny Klippen Belt indicates their proximity to the European plate at least in the post Early Aptian/pre-Coniacian time span. The width of hypothetical oceanic domains between the CWC and European Platform in this time is below the resolution of current paleomagnetic data.

3. In the Late Cretaceous or later Tatra Mts were either rotated 23° (±6°) clockwise or translated along a strike-slip fault.

Acknowledgements

Author gratefully acknowledges the financial support of State Committee for Scientific Research (grant no. 6 6208 92 03). Critical remarks of Doc. Marek Lewandowski, Doc. Andrzej Żelaźniewicz and an anonymous reviewer are appreciated. Thanks are also due to the authorities of the Tatra National Park for permission to carry out the field work.

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Streszczenie

REZULTATY BADAŃ PALEOMAGNETYCZNYCH Z SERII WIERCHOWYCH I EOCENU NUMULITOWEGO TATR (CENTRALNE KARPATY ZACHODNIE, POLSKA) I ICH TEKTONICZNE IMPLIKACJE

Jacek Grabowski

Artykuł prezentuje wyniki prac paleomagnetycznych przeprowadzonych w Tatrach Polskich (Fig. 1). Przedmiotem badań były wierchowe serie osadowe należące do jednostek para-autochtonicznej i Czerwonych Wierchów oraz autochtoniczne osady eoceny numulitowego (Fig. 2). Osady te powstawały na obszarze basenu Tetydy między płytami afrykańską i europejską. Oczekiwane kierunki paleomagnetyczne z obszaru tatrzańskiego (Tab. 1, 2) powinny wpasowywać się w te ramy geotektoniczne. Opróbowano pełny profil jednostki para-autochtonicznej, od triasu dolnego po dolną kredę, w rejonie doliny Kościeliskiej i Wąwozu Kraków. Skały dolnego triasu i dolnej kredy pobrano też z rejonu Hali Gąsienicowej. W jednostce Czerwonych Wierchów opróbowano wapienie górnej jury w Bramie Kraszewskiego (dolina Kościeliska) i w kotle Wielkiej Świstówki (dolina Miętusia). Wapienie eocenu wzięto do badań z odsłonięć w dolinach Lejowej i Małej Łąki oraz w kamieniołomie pod Capkami (Tab. 3).

Pozostałość magnetyczna badanych skał jest oparta na magnetycie i hematycie (Fig. 3). W skałach eoceńskich oraz w większości szarych wapieni górnej jury i dolnej kredy przeważa współczesne lepkie przemagnesowanie (składowa R – Tab. 4, Fig. 4a, f, Fig. 5). Jego wiek został potwierdzony testem na blokach wapiennych w osuwisku Wantule (Tab. 6). W odsłonięciach skał dolnego i środkowego triasu z profilu Kominów Tylkowych i Żółtej Turni nie udało się wydzielić żadnych kierunków charakterystycznych. W rejonie Doliny Kościeliskiej w skałach węglanowych od środkowej jury po dolną kredę (5 odsłonięć, 32 próby ręczne, 92 próbki) stwierdzono występowanie przedfałdowego namagnesowania (składowa A – Tab. 5, Fig. 4b–d, Fig. 6). W czerwonych wapieniach jury górnej w Wąwozie Kraków kierunek ten wydzielono stosując metodę Hoffmanna–Day'a (Fig. 7). Podobny kierunek paleomagnetyczny utrwalony przed szariażem późnokredowym został już wcześniej stwierdzony w kilku miejscach w Polsce (jednostka kriżniańska, jednostka niedzicka) i na Słowacji (Mała Fatra, Góry Choczańskie, Niżnie Tatry, Tatry Bielskie, Magura Spiska) w skałach dolnej–górnej jury (Tab. 7). Ponieważ kierunek ten występuje na znacznym obszarze w skałach różnego wieku i ma niemal wyłącznie normalną polarność, może on nie być kierunkiem pierwotnym, a raczej przedsenońskim przemagnesowaniem, utrwalonym między 119 i 88 mln lat. Paleobiegun składowej A lokuje się w pobliżu późnojurajskich biegunów płyty europejskiej (Fig. 8). Po rotacji bieguna A o kąt 23° (±6°) wokół lokalnej osi pionowej można go zgrać z biegunami środkowokredowymi. W rejonie Bramy Kraszewskiego (jednostka Czerwonych Wierchów) kierunek paleomagnetyczny jest skręcony 70° przeciwnie do ruchu wskazówek zegara (Tab. 5, Fig. 4c, Fig. 6 – składowa B) co sugeruje lokalną rotację tektoniczną. Inny, niewątpliwie wtórny, przedfałdowy kierunek o odwrotnej polarności (Tab. 5, Fig. 4e, Fig. 6, składowa C – 2 odsłonięcia, 17 prób ręcznych, 28 próbek) porównano z namagnesowaniem neogeńskich andezytów z Góry Wżar (Pieniński Pas Skałkowy). Inklinacja składowej A świadczy o bliskości obszaru Wewnętrznych Karpat Zachodnich i płyty europejskiej, przynajmniej na pograniczu wczesnej i późnej kredy (Fig. 9). Szerokość hipotetycznych oceanów Vahicum, Magurskiego i Śląskiego w tym czasie jest poniżej rozdzielczości metody paleomagnetycznej. Deklinacja kierunku A na obszarze para-autochtonicznej serii wierchowej Tatr wykazuje 23° (±6°) rotacji zgodnej z ruchem wskazówek zegara w stosunku do deklinacji kierunków kredowych z obszaru „stabilnej Europy". Może to być wynik rotacji tektonicznej wokół lokalnej osi pionowej lub ruchu wzdłuż uskoku przesuwczego. Obecność przedfałdowego namagnesowania, którego wiek zinterpretowano jako mioceński (składowa C) świadczy, że upady warstw oraz powierzchni nasunięć skał mezozoicznych w Tatrach mogły ulec zmianie w wyniku neogeńskiego wypiętrzenia.