Geological Quarterly, Vol. 39, No. 1, 1995, p. 61–74

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New palaeomagnetic data from the Lower Sub-Tatric radiolarites, Upper Jurassic (Western Tatra Mts.)

Red Oxfordian (Upper Jurassic) radiolarites of the Lower Sub-Tatric nappe in the Western Tatra Mts. ($\phi = 49.3^\circ$ N, $\lambda = 19.8^\circ$E) were the subject of palaeomagnetic study. Characteristic remanent magnetization ($D = 31^\circ$, $I = 54^\circ$, $\alpha_{95} = 7^\circ$, for the Bobrowiec unit, $D = 54^\circ$, $I = 49^\circ$, $\alpha_{95} = 6^\circ$, for the Gładkie Upłaziańskie slice) is pre-folding (pre-Turonian) but most probably not primary. Its direction indicates the possibility of 17–30° clockwise rotation of the investigated units relative to stable Europe. AMS study revealed compactional magnetic fabric with minimum susceptibility axes perpendicular to the bedding plane. The set of palaeomagnetic data from the Polish and Slovak Carpathians does not indicate the uniform tectonic rotation of the area in the Tertiary, but rather local rotations of different amplitudes, possibly related to the formation of the Carpathian orocline.

INTRODUCTION

Palaeomagnetic investigations of Lower Sub-Tatric (Križna) rocks were carried out in the 1980s in the laboratory of the Institute of Geophysics, Polish Academy Sciences. (M. Kądziałko-Hofmokl *et al.*, 1985; M. Kądziałko-Hofmokl, J. Kruczyk, 1987). The authors focused on Middle and Upper Jurassic limestones and radiolarites. The rocks revealed characteristic remanent magnetization, which was interpreted as primary and identical with the reference direction for "stable Europe", occurring in the Upper Jurassic limestones of the Cracow Upland (M. Kądziałko-Hofmokl, J. Kruczyk, *op. cit.*). According to these observations the conclusion was drawn that the Križna unit in the Tatra Mts. has not been rotated relative to the stable epi-Variscan platform, at least since the Middle Jurassic.

However, the palaeomagnetic data from other parts of the Western Carpathians and the Pannonian Basin indicated a high degree of tectonic mobility of these areas during the Mesozoic and Cenozoic. Large, 60–70°, counter-clockwise rotation was established for the northern part of the Pannonian area and the southernmost margins of the Inner Western

Carpathians (E. Marton, P. Marton, 1983; E. Marton *et al.*, 1988, 1992). Counter-clockwise rotation relative to the European Platform were also reported from the Outer Western Carpathians (M. Krs *et al.*, 1982, 1991, 1993) and the western part of the Pieniny Klippen Belt (V. S. Burtman, 1988; M. L. Bazhenov, V. S. Burtman, 1990). The latter authors postulated that the entire Slovak (Gemero-Tatric) Massif rotated counter-clockwise in the Tertiary, causing the curvature of the northern Carpathian arc and the bending of the orocline. Preliminary results from the Upper Jurassic High-Tatric rocks also revealed counter-clockwise rotated directions, interpreted as Late Cretaceous remagnetizations (J. Grabowski, 1993). In this light the results from the Sub-Tatric series of the Tatra Mts. could be treated as anomalous, although they were confirmed by investigations of the Križna unit in the Slovak Carpathians (Mala Fatra, Nižne Tatra, Belanske Tatra, Choč Mts., Magura Spišska — J. Kruczyk *et al.*, 1992). The results from the Sub-Tatric Upper Jurassic (M. Kądziałko-Hofmokl *et al.*, 1985; M. Kądziałko-Hofmokl, J. Kruczyk, 1987) were either not included in the palaeomagnetic data bases of the Alpine-Pannonian-Carpathian realm (E. Marton, H. J. Mauritsch, 1990), or cited among the reference directions for stable platforms (R. Van der Voo, 1990).

There were several reasons for which I decided to make a revision of the palaeomagnetism of the Križna radiolarites:

— apparent contradiction between the trend of characteristic directions in the Križna rocks and the general pattern of counter-clockwise rotations in the Western Carpathians;

— lack of the fold test, which would permit interpretation of the magnetization as pre-folding;

— statistical methods used by the previous authors for calculation of characteristic magnetization: stable end point method and mean vector at different demagnetization levels.

Present investigations were performed in the palaeomagnetic laboratory of the Polish Geological Institute in Warsaw. Natural remanent magnetization was measured by means of the *JR-5* spinner magnetometer. The rock specimens were thermally demagnetized with the MMTD oven. Demagnetization experiments and the NRM measurements were carried out in a magnetically shielded room. Characteristic directions were calculated using principal component analysis (J. L. Kirschvink, 1980). Magnetic susceptibility was monitored with *KLY-2* bridge. Anisotropy of magnetic susceptibility was calculated, using the *ANI20* computer program supplied by Geofyzika, Brno.

GEOLOGICAL SETTING AND SAMPLING PLACES

The Tatra Massif is a megaanticlinal horst of crystalline pre-Mesozoic rocks, covered by Mesozoic deposits spanning from Lower Triassic to Upper Cretaceous (M. Książkiewicz, 1972). The Late Cretaceous post-Turonian orogenic movements caused the formation of nappe structures and now the Mesozoic rocks occur in several overthrusted units (Fig. 1). The High-Tatric units, which were subjected to only minor horizontal displacements, are divided into the parautochthonous unit, that is a roughly *in situ* sedimentary cover of the crystalline rocks, and the detached Czerwone Wierchy and Giewont units. The Sub-Tatric nappes were transported and overthrusted from the south. The lower Sub-Tatric (Križna)

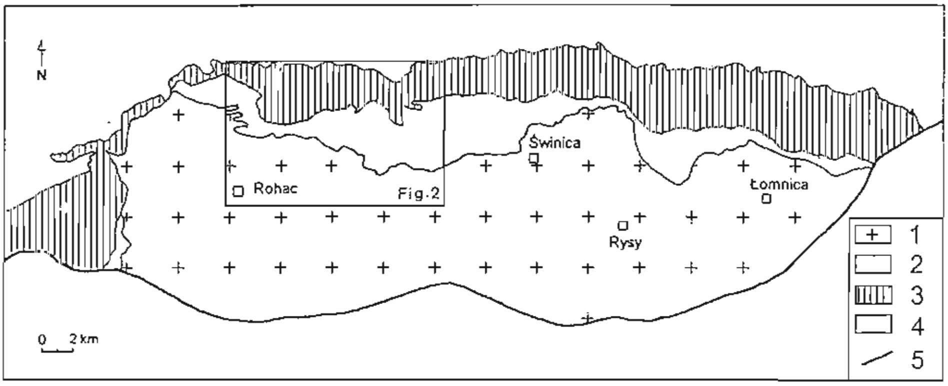

Fig. 1. Geological sketch map of the Tatra Mts. (after J. Lefeld *et al.*, 1985, simplified) with the sampling area (Fig. 2)

1 — crystalline core of the High-Tatric units, 2 — High-Tatric units, 3 — Sub-Tatric units, 4 — Palaeogene, 5 — South-Tatra Dislocation

Schematyczna mapa geologiczna Tatr (według J. Lefelda i in., 1985, uproszczona) z rejonem opróbowania (fig. 2)

1 — trzon krystaliczny, 2 — jednostki wierchowe, 3 — jednostki reglowe, 4 — paleogen, 5 — uskok podtatrzański

and upper Sub-Tatric (Choč) unit are distinguished. The Križna unit occurs in the form of separate tectonic slices and partial nappes (Fig. 2).

Hand samples were taken from the red siliceous limestones (radiolarites) at the following localities:

1. Eastern slope of the Lejowa Valley (7 samples).
2. Western slope of the Lejowa Valley (Rosocha Hill, 5 samples).
3. Banie Hill at the Huciska alp, Chochołowska Valley (7 samples).
4. Western slope of the Chochołowska Valley, ridge between the Długa and Kryta Valleys (7 samples).
5. Gładkie Upłaziańskie slice, between the Kościeliska and Miętusia Valleys (10 samples).

Localities no. 1–4 belong to the Bobrowiec unit (M. Bac, 1971). They follow the localities sampled by M. Kądziałko-Hofmokl *et al.* (1985). The rocks of the Bobrowiec unit dip monoclinally to the north (20/35°), so it is not possible to carry out the fold test. Therefore, the radiolarites of the Gładkie Upłaziańskie slice (Z. Kotański, 1965) were sampled, where the strata dip more steeply (60–80°), also to the north.

RESULTS

Hand samples were cut with a diamond drill into cylindrical specimens, 20 mm diameter and 22 mm height. Usually 4 specimens were obtained from each sample. Pilot specimens were demagnetized thermally at 100, 200, 300, 350, 400, 450, 500, 550 and 600°C. Magnetic

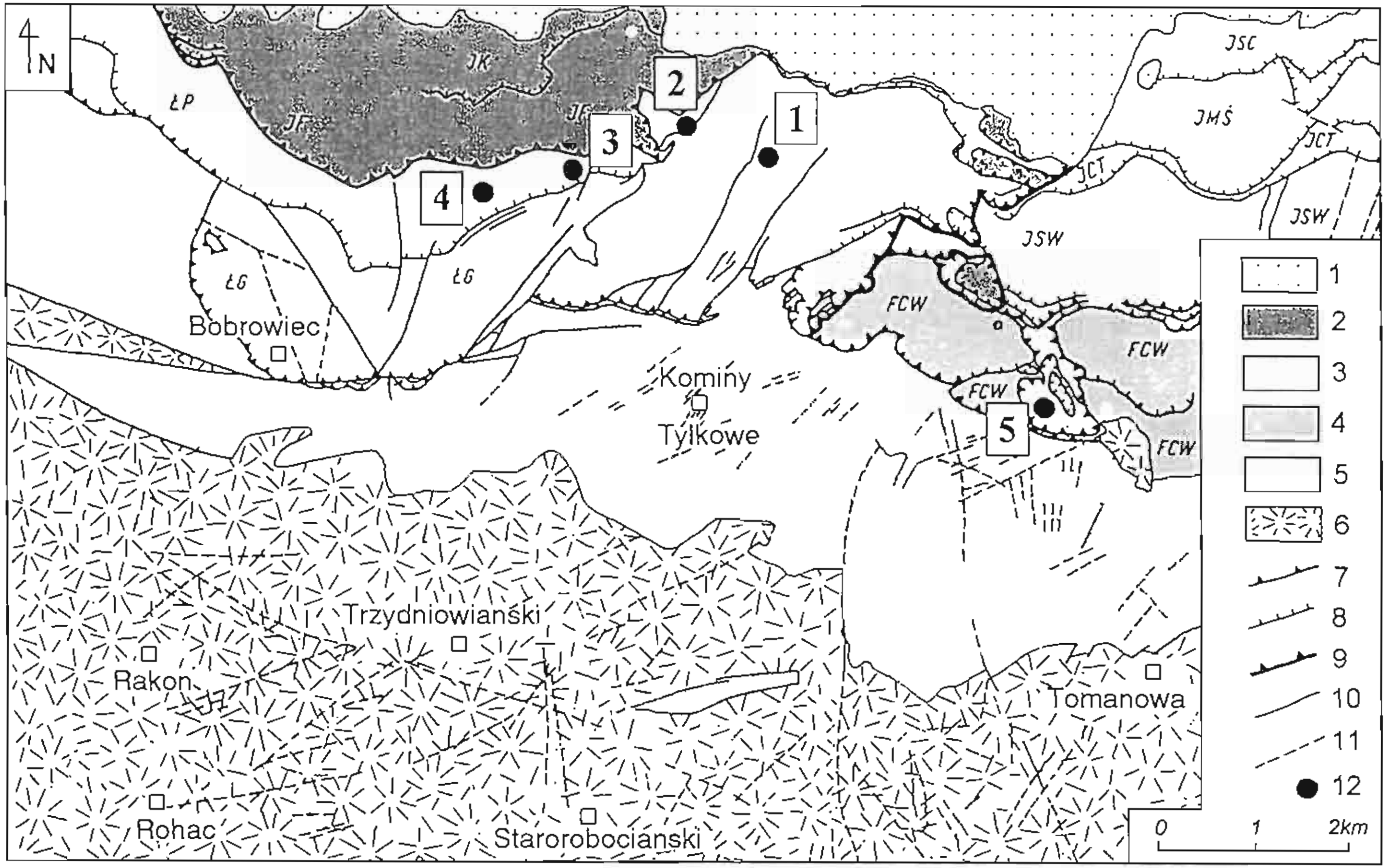
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Table 1

Characteristic components from the Oxfordian radiolarites

Tectonic unit	Locality	N/N_o	D	I	D_c	I_c	α_{95}	k
Bobrowiec	1	7/7	71	83	29	52	9	28
	3	6/7	99	83	31	52	8	80
	4	7/7	207	85	34	59	9	50
Gładkie Upłaziańskie	5	10/10	174	50	54	49	6	17

N — number of samples used for the calculation of the mean direction; N_o — number of samples taken from the outcrop; declination and inclination of the palaeomagnetic direction: D, I — before tectonic correction, D_c, I_c — after tectonic correction; α_{95}, k — Fisher statistics parameters

susceptibility increases sharply between 550 and 600°C because of creation of new magnetic minerals during heating. Therefore the remaining part of the collection was demagnetized up to 525°C. Hematite and magnetite are the magnetic minerals in the Sub-Tatric radiolarites (M. Kądziałko-Hofmokl *et al.*, 1985).

Localities 1, 3, and 4 revealed very good consistency of characteristic directions (Tab. 1), generally confirming the results of previous studies. Only one specimen of each sample was thermally demagnetized and used for the calculation of the mean direction. At locality 2, the characteristic remanence magnetization (ChRM) directions coincided with the main axes of the AMS, therefore they will not be considered here. The new results from the Gładkie Upłaziańskie radiolarites (locality 5) will be presented.

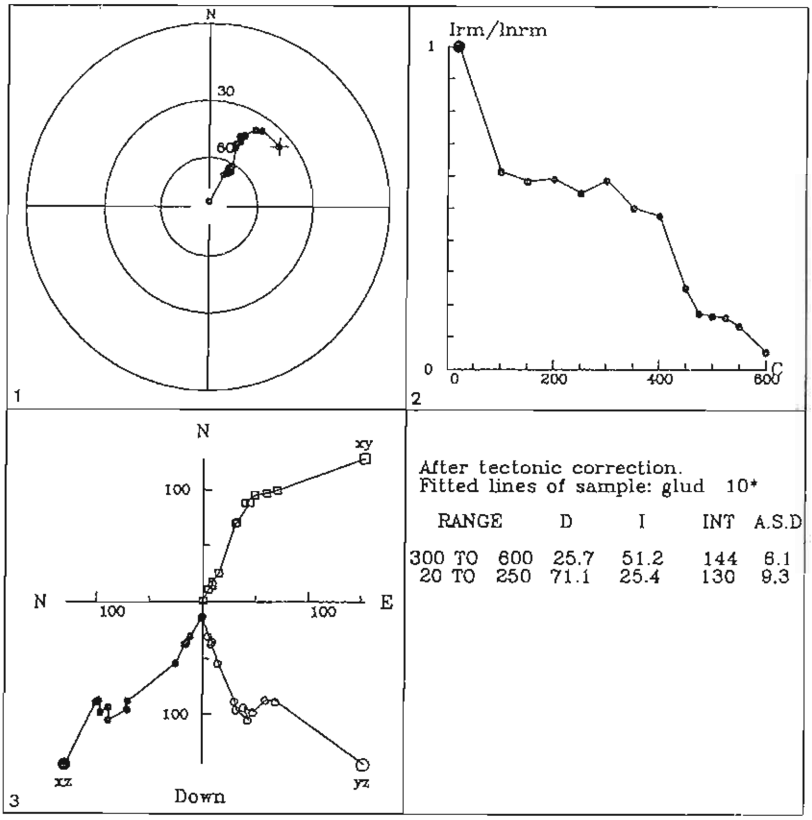
The intensities of the natural remanent magnetization (NRM) of most specimens were within $1\text{–}3 \cdot 10^{-2}$ A/m range. The characteristic component of magnetization is revealed in a temperature range 300–500°C and it occurs in all samples (Fig. 3). Above 500°C, in a part

Fig. 2. Tectonic sketch of neighbouring areas of the Bobrowiec unit (after M. Bac, 1971, modified)

1 — Eocene; 2 — elements of the upper Sub-Tatric nappe: JF — Furkaska unit, JK — Koryciska unit; 3 — elements of the lower Sub-Tatric nappe: Bobrowiec unit: ŁG — Głębowiec slice, ŁP — Parządczak slice; Zakopane part of the Sub-Tatric zone: JSW — Suchy Wierch unit, JCT — Czarna Turnia unit, JMŚ — Mała Świnica unit, JSC — Samkowa Czuba unit; 4 — overthrusted High-Tatric units: FCW — Czerwone Wierchy unit; 5 — sedimentary autochthonous cover; 6 — crystalline rocks; 7 — main overthrusts; 8 — subordinate overthrusts; 9 — boundary of western and Zakopane parts of the Sub-Tatric zone; 10 — faults; 11 — faults recorded by photointerpretation; 12 — sampling locations

Szkic tektoniczny okolic jednostki Bobrowca (według M. Bac, 1971, zmodyfikowany)

1 — eocen; 2 — elementy płaszczowiny reglowej górnej (choczańskiej): JF — jednostka Furkaski, JK — jednostka Korycisk; 3 — elementy płaszczowiny reglowej dolnej (kriżniańskiej): jednostka Bobrowca: ŁG — łuska Głębowca, ŁP — łuska Parządczaka; regle zakopiańskie: JSW — jednostka Suchego Wierchu, JCT — jednostka Czarnej Turni, JMŚ — jednostka Małej Świnicy, JSC — jednostka Samkowej Czuby; 4 — nasunięte jednostki wierchowe: FCW — jednostka Czerwonych Wierchów; 5 — osadowa pokrywa autochtoniczna; 6 — skały krystaliczne; 7 — nasunięcia główne; 8 — nasunięcia podrzędne; 9 — granica regli zachodnich i zakopiańskich; 10 — uskoki; 11 — uskoki wyznaczone fotointerpretacyjnie; 12 — miejsca opróbowania



After tectonic correction.
Fitted lines of sample: glud 10*

RANGE	D	I	INT	A.S.D
300 TO 600	25.7	51.2	144	6.1
20 TO 250	71.1	25.4	130	9.3

Fig. 3. Thermal demagnetization of the red radiolarites from the Gładkie Upłaziańskie (after tectonic correction)
1 — stereographic projection of the demagnetization path (solid symbols — the lower hemisphere directions, crossed symbol — NRM direction); 2 — intensity decay curve (*Inrm* — the intensity of the NRM, *Irm* — the intensity of the remanent magnetization after thermal treatment), 3 — orthogonal projection (Zijderveld diagram) (*x, y, z* — the planes of projection, bigger symbols — the NRM components, 1 unit is 10^{-4} A/m)

Rozmagnesowanie czerwonych radiolarytów z Gładkiego Upłaziańskiego (w układzie po korekcji tektonicznej)
1 — projekcja stereograficzna ścieżki rozmagnesowania (symbole zaczernione — projekcja na dolną półkulę, symbol przekreślony — kierunek NRM); 2 — krzywa spadku natężenia podczas rozmagnesowania (*Inrm* — natężenie NRM, *Irm* — natężenie pozostałości magnetycznej po wygrzaniu); 3 — projekcja ortogonalna (diagram Zijdervelda) (*x, y, z* — płaszczyzny projekcji, większe symbole — składowe NRM, 1 jednostka na osi — 10^{-4} A/m)

of the samples, a component of reversed polarity appears, but because of the mineralogical changes mentioned above, its determination is not possible.

After tectonic correction, the ChRMs clustered in the NE quadrant of the stereoplot, with intermediate positive inclination (Fig. 4A, B). The fold test, performed for the Bobrowiec unit and the Gładkie Upłaziańskie slice, shows that the ChRM clusters better after restoring the beds to the horizontal position — thus, the magnetization is pre-folding (Fig. 5).

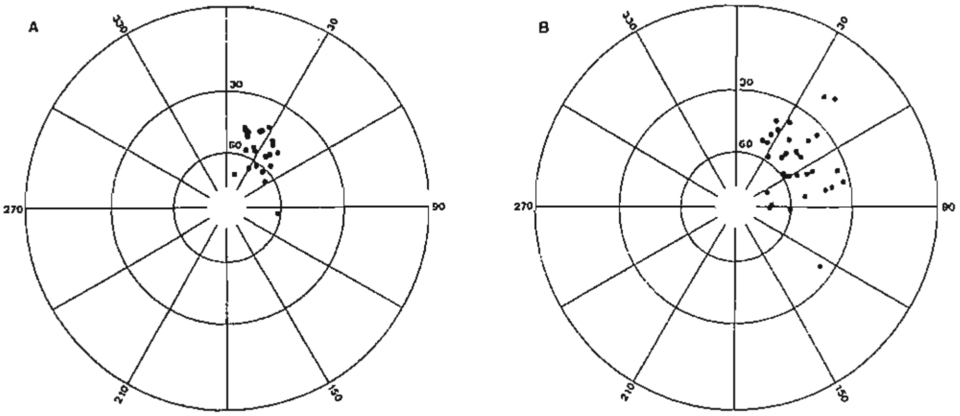


Fig. 4. Directions of the characteristic remanent magnetization from the Bobrowiec unit (A) and the Gładkie Upłaziańskie slice (B), after tectonic correction

Kierunki charakterystycznej pozostałości magnetycznej z jednostki Bobrowca (A) i z łuski Gładkiego Upłaziańskiego (B), w układzie po korekcji tektonicznej

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

Anisotropy of magnetic susceptibility (AMS) is a measure of internal deformation of the rock structure. R. Kligfield *et al.* (1983) investigated the influence of tectonic deformations on the natural remanent magnetization of red sediments containing hematite. Degree of tectonic deformations (shape of the finite strain ellipsoid) was determined using the methods of structural geology and the AMS. The least deformed sedimentary rocks revealed the minimum anisotropy axes perpendicular to the bedding plane. That means that the maximum stress (σ_1) direction was normal to the bedding and its main cause was the pressure of the overlying rocks. The compaction only slightly changes the inclination of the palaeomagnetic vector — it is flatter than in non-deformed rocks.

Shearing processes may cause the reorientation of the palaeomagnetic vector. The minimum susceptibility axes group perpendicular to the shearing plane; it may be the cleavage plane. Rotations of the palaeomagnetic vectors caused by tectonic deformations were postulated for the Permian/Triassic red beds at the Glarus overthrust in the Swiss Alps (A. M. Hirt *et al.*, 1986). Changes of magnetization due to tectonic stresses were also confirmed experimentally (G. J. Borradaile, J. S. Mothersill, 1991). The rocks subjected to the shearing processes may lose any information suitable for palaeotectonic reconstruction.

The minimum susceptibility axes of the Sub-Tatric radiolarites are grouped roughly perpendicular to the bedding planes (Fig. 6). Nappe movements in the Late Cretaceous did not destroy the pre-orogenic magnetic fabric related to the compaction. The bimodal distribution of the minimum AMS axes in the Gładkie Upłaziańskie radiolarites (Fig. 6B) suggests a higher degree of internal deformation than in the rocks of the Bobrowiec unit. This is probably also the reason why the ChRM directions are more dispersed in the Gładkie

Table 2

Mean palaeomagnetic directions for the Oxfordian of the Bobrowiec unit, after tectonic correction

References	D_c	I_c	k	α_{95}	n
This paper	31	54	357	7	3
M. Kądziałko-Hofmokl, J. Kruczyk (1987)	20	59	101	6	7

n — number of localities; other explanations see Tab. 1

Upłaziańskie slice than in the Bobrowiec unit (Fig. 4). However the Sub-Tatric radiolarites seem to carry a very reliable palaeomagnetic record which can be used for unravelling the tectonic history of the area. That remark is also valid for the Upper Jurassic sedimentary rocks of the Križna (Sub-Tatric) unit in the Mala Fatra, where also "compactional" magnetic fabric was also found (M. Kądziałko-Hofmokl *et al.*, 1990).

DISCUSSION

ChRM of the Oxfordian radiolarites of the Bobrowiec and Gładkie Upłaziańskie units was acquired certainly before the Late Cretaceous (post-Turonian) tectonic phase. This component reveals exclusively normal polarity. It is not certain, whether this magnetization is primary, because there are evidences of existence of another, reversed polarity component of higher blocking temperature, above 525°C (Fig. 3). The mineralogical changes of the rock during heating preclude its isolation. Thus the age of the characteristic component is between the Oxfordian and Turonian.

20° difference in declination between the mean directions from the Bobrowiec unit and the Gładkie Upłaziańskie slice is significant at the 95% probability level (Fig. 7), and it may be the result of tectonic rotation. According to Z. Kotański (1965) the Bobrowiec unit is thrusted over the Gładkie Upłaziańskie slice, so rotations between these two elements are very likely.

Mean ChRM directions from the Bobrowiec unit differ, about 10° in declination and 5° in inclination from the directions obtained from the same formation by M. Kądziałko-Hofmokl *et al.* (1985) — Fig. 7, Tab. 2. This may arise from different statistical methods used for calculation of the ChRMs (see introduction) and also from the fact that M. Kądziałko-Hofmokl *et al.* (*op. cit.*) averaged more localities (Tab. 2).

Mean direction from the Bobrowiec unit differs slightly from the Late Jurassic reference direction for "stable Europe" (M. Kądziałko-Hofmokl, J. Kruczyk, 1987) — Fig. 7. The Bobrowiec unit seems to be rotated clockwise, about 17° relative to the European Platform. If the Late Jurassic direction obtained by J. G. Ogg *et al.* (1991) from the Cracow Upland is accepted, the rotation might be even larger, about 30°. However most Late Jurassic palaeopoles from "stable Europe" (R. Van der Voo, 1990) fit rather the results of M. Kądziałko-Hofmokl, J. Kruczyk (*op. cit.*) than those of J. G. Ogg *et al.* (1991).

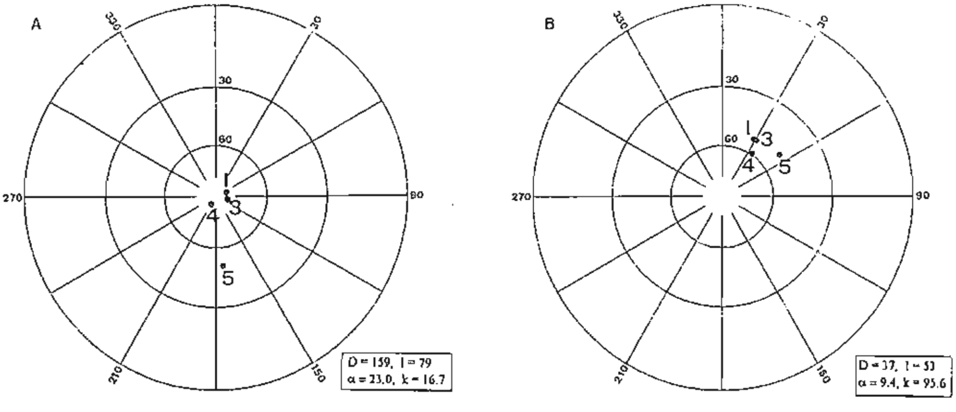


Fig. 5. Fold test for the Bobrowiec unit and the Gładkie Upłaziańskie slice: the characteristic directions from sampled localities (1, 3, 4, 5 — see Fig. 2) before (A) and after (B) tectonic correction

Test fałdowy dla radiolarytów jednostki Bobrowca i łuski Gładkiego Upłaziańskiego: średnie kierunki z opróbowanych odsłonięć (1, 3, 4, 5 — patrz fig. 2) przed korekcją (A) i po korekcji (B) na upad warstw

It should be noted that the palaeodirection from the Sub-Tatric radiolarites is very close to the Late Jurassic directions obtained from the red radiolarites of the Northern Calcareous Alps (Fig. 8). The directions from the Lower Jurassic Adnet Limestones (J. E. T. Channel *et al.*, 1992) and the Upper Cretaceous Gosau deposits (H. J. Mauritsch, M. Becke, 1987) reveal similar trend-clockwise rotation 20–60° relative to "stable Europe".

On the other hand, the post-folding palaeodirections from the Middle-Upper Jurassic limestones of the High-Tatric series are rotated at least 60° counter-clockwise (J. Grabowski, 1993) and resemble the Late Cretaceous directions from the Transdanubian Central Mts. (E. Marton, P. Marton, 1983) and the Gosau Basins south of the Northern Calcareous Alps (H. J. Mauritsch, M. Becke, 1987).

The explanation for opposing sense of rotations in the Sub-Tatric and High-Tatric units is not available yet. Sub-Tatric radiolarites are much better rocks for palaeomagnetic study than the High-Tatric limestones of equivalent age. It is thus probable that the High-Tatric units have a more complicated tectonic history than the Sub-Tatric: for example the High-Tatric units, or a part of them, could have been remagnetized and rotated before the overthrusting of the Sub-Tatric nappes. Counter-clockwise rotated palaeomagnetic directions from the High-Tatric units need better documentation, because they were described from only two localities (Dudziniec Hill in the Chochołowska Valley and Brama Kraszewskiego in the Kościeliska Valley — J. Grabowski, 1993). Moreover, the AMS studies were not performed in these localities, thus the influence of tectonic stresses on the magnetization vector cannot be excluded.

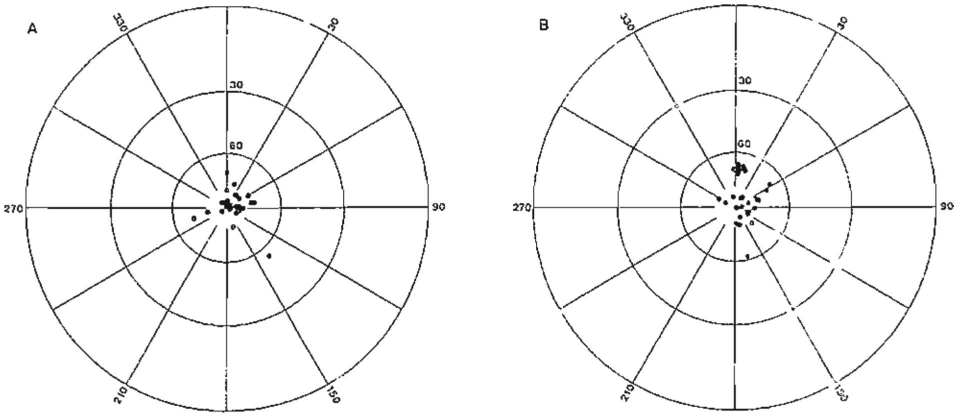


Fig. 6. Minimum axes of the AMS ellipsoid (magnetic foliation poles) from the Bobrowiec unit (A) and Gładkie Upłaziańskie slice (B) after tectonic correction

Kierunki minimalnych osi anizotropii podatności magnetycznej (bieguny płaszczyzn foliacji magnetycznej) z radiolarytów jednostki Bobrowca (A) i łuski Gładkiego Upłaziańskiego (B) w układzie po korekcji tektonicznej

GEOTECTONIC IMPLICATIONS

J. Kruczyk *et al.* (1992) maintained that the characteristic directions from the Lower Sub-Tatric unit in the Tatra Mts. fitted well to the model of the oroclinal bending of the northern Carpathians arc (V. S. Burtman, 1988; M. L. Bazhenov, V. S. Burtman, 1990). However, the geological phenomena responsible for the origin of the orocline are still poorly understood. V. S. Burtman (1988) postulated that the orocline bending was caused by the counter-clockwise rotation of the Gemeric-Tatric Massif, which took place between the Palaeocene and Miocene. Palaeomagnetic data obtained by M. Kądziałko-Hofmokl *et al.* (1985), M. Kądziałko-Hofmokl, J. Kruczyk (1987), J. Kruczyk *et al.* (1992) and in this paper contradict this interpretation. Counter-clockwise rotations occur only at the western and northwestern margins of the Gemeric-Tatric Massif: from the Male Karpaty (Little Carpathians) to the Mala Fatra, Western Slovak sector of the Pieniny Klippen Belt, and the Outer Western Carpathians (M. L. Bazhenov, V. S. Burtman, 1990; M. Kądziałko-Hofmokl *et al.*, 1990; M. Krs *et al.*, 1982, 1991, 1993; E. Marton *et al.*, 1992). In the central part of the massif the declinations of palaeomagnetic directions are between 0 and 70° (Lower Sub-Tatric unit in the Western and Belanske Tatra, Nižne Tatra, Choč Mts. and Magura Spišska, Permian sedimentary and volcanic rocks in the Nižne Tatra) — M. Krs *et al.* (1982), J. Kruczyk *et al.* (1992). Uniform trend of rotations of the whole Inner Western Carpathians in the Tertiary, either counter-clockwise (V. S. Burtman, 1988) or clockwise (K. Birkenmajer, 1985) is not confirmed by the set of palaeomagnetic data. The model of local rotations, related to the strike-slip faults, active in the Late Tertiary seems more promising (S. Doktór *et al.*, 1985; M. Bac-Moszaszwili, 1993). An analogous model was already developed by L. Ratschbacher *et al.* (1991) for the Northern Calcareous Alps.

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Jacek GRABOWSKI

NOWE DANE PALEOMAGNETYCZNE Z RADIOLARYTÓW GÓRNOJURAJSKICH Z TATR ZACHODNICH

Streszczenie

Przedmiotem analizy paleomagnetycznej były czerwone radiolaryty oksfordu z dolnej płaszczowiny reglowej w Tatrach Zachodnich (jednostka Bobrowca, łuska Gładkiego Upłaziańskiego). Charakterystyczna pozostałość magnetyczna utrwaliła się przed ruchami fałdowymi w późnej kredzie; prawdopodobnie nie jest to jednak namagnesowanie pierwotne. Różnica deklinacji, ok. 20°, między kierunkami namagnesowania radiolarytów jednostki Bobrowca i Gładkiego Upłaziańskiego, może być wynikiem rotacji tektonicznej. Kierunki te wykazują 17–30° rotacji, zgodnej z ruchem wskazówek zegara, w stosunku do późnojurajskiego kierunku referencyjnego z platformy europejskiej.

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