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New palaeomagnetic results from the Polish part of the Pieniny Klippen Belt, Carpathians — evidence for the palaeogeographic position of the Czorsztyn Ridge in the Mesozoic

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Middle and Upper Jurassic limestones from the Polish part of the Pieniny Klippen Belt (PKB) were palaeomagnetically studied at six localities. The Middle Jurassic red crinoidal limestones of the Krupianka Limestone Formation and Oxfordian radiolarites of the Czajakowa Radiolarite Formation, sampled in the eastern part of the Polish section of the PKB, were either unsuitable for palaeomagnetic studies (Krupianka Klippe) or remagnetized in the Neogene (Baba and Zaskalskie-Bodnarówka klippen). The Czorsztyn Limestone Formation was investigated at the localities of Krempachy (upper Middle Jurassic: uppermost Bajocian?–Callovian?), Obłazowa (middle Oxfordian) and Rogoźnik (Rogoża Coquina Member — Kimmeridgian). A pre-folding, mixed polarity component of magnetization was revealed, which was interpreted as primary. Palaeoinclinations differ slightly, but not significantly, between localities. The palaeolatitude of the Polish sector of the PKB, averaged for the Middle/Upper Jurassic, amounts to 22°N (5°). It corresponds to the estimated palaeolatitudes of the northern margins of the Adriatic microplate and indicates a significantly large distance from the European plate. There is a growing evidence for a northward drift of the PKB in the Late Jurassic up to the earliest Cretaceous: from the palaeolatitude of 22°N in the Late Jurassic up to 28°N in the western part, in Poland/W Slovakia, and from 28° up to 36°N in the eastern part of the PKB in Ukraine. Systematically lower palaeolatitudes in the west combined with existing palaeogeographic and geotectonic scenarios would account for a NE–SW orientation of the Czorsztyn Ridge in the Late Jurassic/earliest Cretaceous.

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Key words: Poland, Pieniny Klippen Belt, Carpathians, Jurassic, palaeomagnetism.

INTRODUCTION

The palaeomagnetic method is a sensitive tool for detection of tectonic rotations within fold- and thrust belts (e.g. Peacock *et al.,* 1998; Van der Voo, 2004) and terrane translations along the active margins of a continent (e.g. Umhoefer, 2000). It is also widely used to detect the tectonic affinity of "suspect" terranes by comparison of the palaeomagnetic direction with a reference curve from neighbouring cratons (Van der Voo, 1993; Morris and Tarling, 1996). The Pieniny Klippen Belt (PKB) is a narrow zone, from a few hundreds metres to about 20 km wide, that stretches along the strike of the Western Carpathian Arc from the Vienna Basin to Poiana Botizei (Romania) (Fig. 1). It constitutes a boundary between the Central and Outer Western Carpathians. The detailed history of both orogens in the Mesozoic from the point of view of plate tectonics is still insufficiently known due to a scarcity of palaeomagnetic data. It is relatively well established that, in the Berriasian, both the Pieniny Klippen Belt and Central West Carpathians were situated rather close to the European Craton: Berriasian palaeolatitudes for the Fatric Unit in the Tatra Mts. and PKB in the Western Slovakia amount to 27–28°N (Houša *et al*., 1996; Grabowski, 2005) which is not statistically different from the palaeolatitude of the southern edge of the European Plate, calculated from the reference Berriasian palaeopole (Galbrun, 1985). Also the Berriasian latitudinal difference between European Craton and the eastern part of the PKB in Ukraine is palaeomagnetically undetectable (Lewandowski *et al*., 2005). Contrasting results exist for the Late Jurassic for the

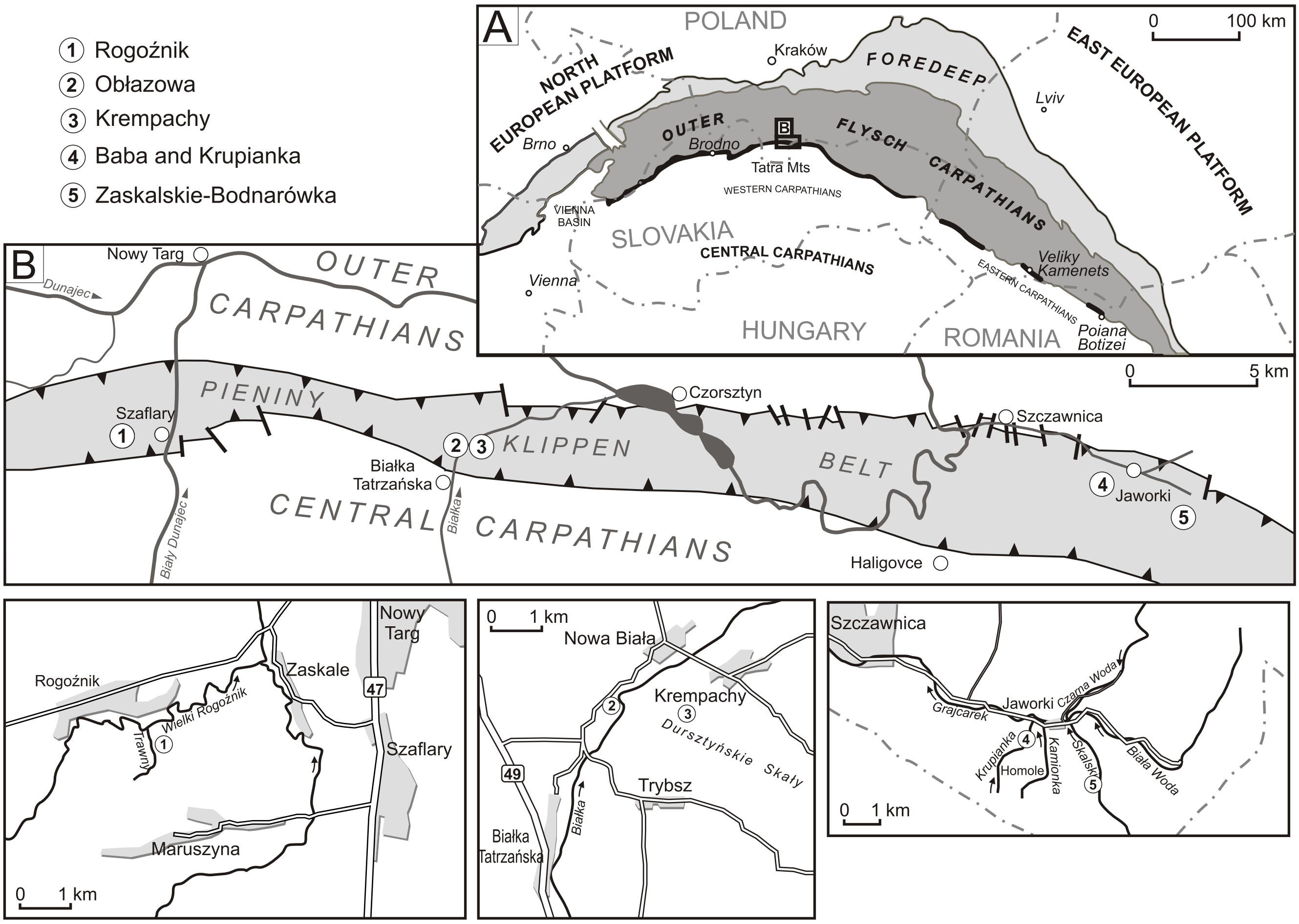

Fig. 1. Location of the study area (A — general view, B — details) with sampling points

eastern and western part of the PKB. The results of Kruczyk and Kądziałko-Hofmokl (2006) indicate a palaeolatitude of 36°N for the broad Mid to Late Jurassic (Bathonian–Oxfordian) time span for the Polish part of the Pieniny Klippen Belt, which is very close to the reference palaeolatitude calculated from the Besse and Courtillot (2002) apparent polar wander paths. Lewandowski *et al.* (2005) report important palaeolatitudinal changes of the Ukrainian sector of the PKB in the Middle–Late Jurassic: from 41°N in the Bajocian–Bathonian, through 28°N in the middle Oxfordian to 36°N in the Berriasian. In this study we present new data from the Polish part of the Pieniny Klippen Belt, from localities which hitherto have not been palaeomagnetically studied. The results are compared with the existing palaeomagnetic database for the PKB and adjacent areas, in order to provide more data for the palaeotectonics and palaeogeography of the Carpathian domain during the Mesozoic.

GEOLOGICAL SETTING

The Mesozoic of the PKB is composed of several successions of predominantly deep and shallower-water limestones, covering a time span from the Early Jurassic up to the Late Cretaceous (Andrusov, 1938, 1959; Birkenmajer, 1958, 1977, 1986, 1988; Andrusov *et al.*, 1973; Mišík, 1994; Golonka and Krobicki, 2001, 2004). During the Jurassic and Cretaceous within the Pieniny Klippen Basin the submarine Czorsztyn Ridge (= "pelagic swell" of Mišík, 1994, mainly Czorsztyn Succession) and surrounding zones formed an elongated structure dominated by pelagic sedimentation (Fig. 2) (Birkenmajer, 1977, 1986; Mišík, 1994; Michalík and Reháková, 1995; Aubrecht *et al*., 1997; Plašienka, 1999; Wierzbowski *et al.,* 1999; Golonka and Krobicki, 2001, 2004). Its deepest part shows the presence of deep water Jurassic–Early Cretaceous deposits (pelagic limestones and radiolarites). Basinal sedimentary zones have been occupied by the Pieniny and Branisko successions, whilst the Niedzica and Czertezik successions have been located between these basinal units and the shallowest Czorsztyn Succession (Birkenmajer, 1977, 1986, 1988; Aubrecht *et al*., 1997; Wierzbowski *et al*., 2004). Strongly condensed Jurassic–Early Cretaceous pelagic cherty limestones (Maiolica-type facies) and radiolarites (of the Grajcarek Unit) were also deposited in the northwestern Magura Basin (Outer Carpathian Basin).

The Pieniny Klippen Basin probably opened during Pliensbachian–Aalenian time, forming a part of the global system related to the opening of the Alpine Tethys. The Alpine Tethys, that is the Ligurian, Penninic and Pieniny/Magura

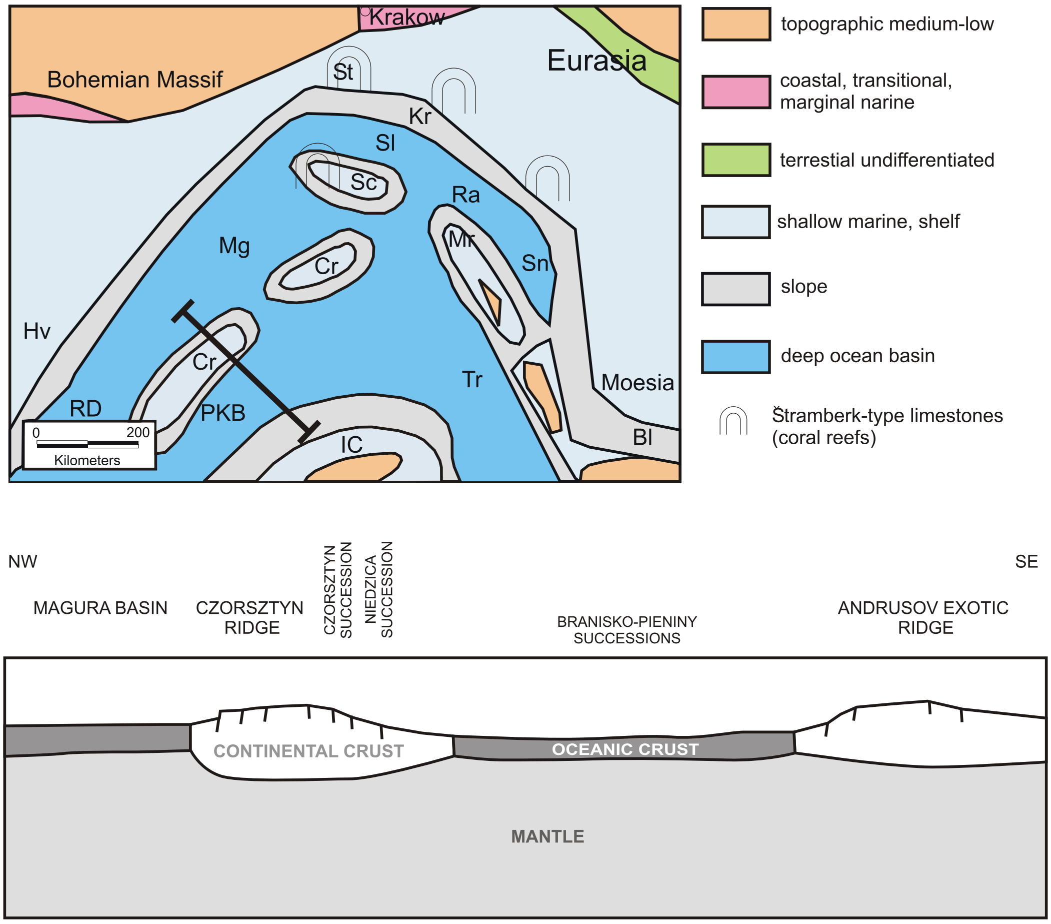

Fig. 2. Palaeogeography of the circum-Carpathian area during the latest Late Jurassic — earliest Early Cretaceous and palinspastic section through the Pieniny Klippen Basin (below)

Bl — Balkan, Cr — Czorsztyn Ridge, Hv — Helvetic shelf, IC — Central Carpathians, Kr — Kruhel, Mg — Magura Basin, Mr — Marmaros Massif, PKB — Pieniny Klippen Basin, Ra — Rahov Basin, RD — Rheno-Danubian Basin, SC — Silesian Ridge (Cordillera), Sl — Silesian Basin, Sn — Sinaia Basin, St — Štramberk, Tr — Transilvanian Ocean; black line indicates position of palinspastic cross-section (below); plate position at 140 Ma (after Golonka and Krobicki, 2001; Krobicki and Golonka, 2006, modified), palinspastic reconstruction (after Birkenmajer, 1986, 1988, modified)

Oceans, constitute an extension of the Central Atlantic system (Stampfli *et al*., 1998). The synrift stage lasted in the Pieniny Klippen Basin from the late Early Jurassic to the Tithonian. Generally, the Pieniny Klippen Basin sedimentary history is connected with three tectonic/sedimentary events reflected firstly by oxygen-reduced dark/black terrigenous deposits of the Early–early Mid Jurassic age (Gresten-type and Fleckenkalk/Fleckenmergel facies), secondly by Middle Jurassic–earliest Cretaceous crinoidal, nodular (of the ammonitico rosso type) or cherty (of the Maiolica = Biancone type) limestones and radiolarites and thirdly by Late Cretaceous pelagic marls (i.e. Scaglia Rossa type) facies and/or flysch/flyschoidal deposits (Fig. 3) (i.a. Birkenmajer, 1986, 1988; Mišík, 1994; Aubrecht *et al*., 1997; Bąk, 2000; Golonka and Krobicki, 2004; Krobicki and Golonka, 2006).

The Pieniny Klippen Basin was closed at the Cretaceous/Tertiary transition as an effect of strong Late Cretaceous (Subhercynian and Laramian) compression (Birkenmajer, 1977, 1986). The Mesozoic successions were detached and thrusted towards the present-day north, with the Czorsztyn Unit in the lower plate, and the Niedzica, Branisko and Pieniny units in the upper plate position. The total crustal shortening was estimated as minimum of 100 km (Birkenmajer, 1986). The next major tectonic events took place in the Early and Middle Miocene. They were related to the tectonic escape of the composite North Pannonian (ALCAPA) terrain from the Alpine collision zone (Balla, 1987; Csontos *et al*., 1992). The location of the PKB just at the active northern margin of the North Pannonian terrain resulted in soft continental collision (e.g. Royden and Burchfiel, 1989; Lille *et al*., 1994) and several compressional and transpressional phases (e.g. Ratschbacher *et al*., 1993); these were manifested by refolding of the Cretaceous nappes and the development of a system of strike-slip faults that constitute the northern and southern boundaries of the PKB (Birkenmajer, 1986).

SAMPLING AND METHODS

36 oriented drill cores, taken with a gasoline powered drilling machine, and 6 oriented hand samples, were collected

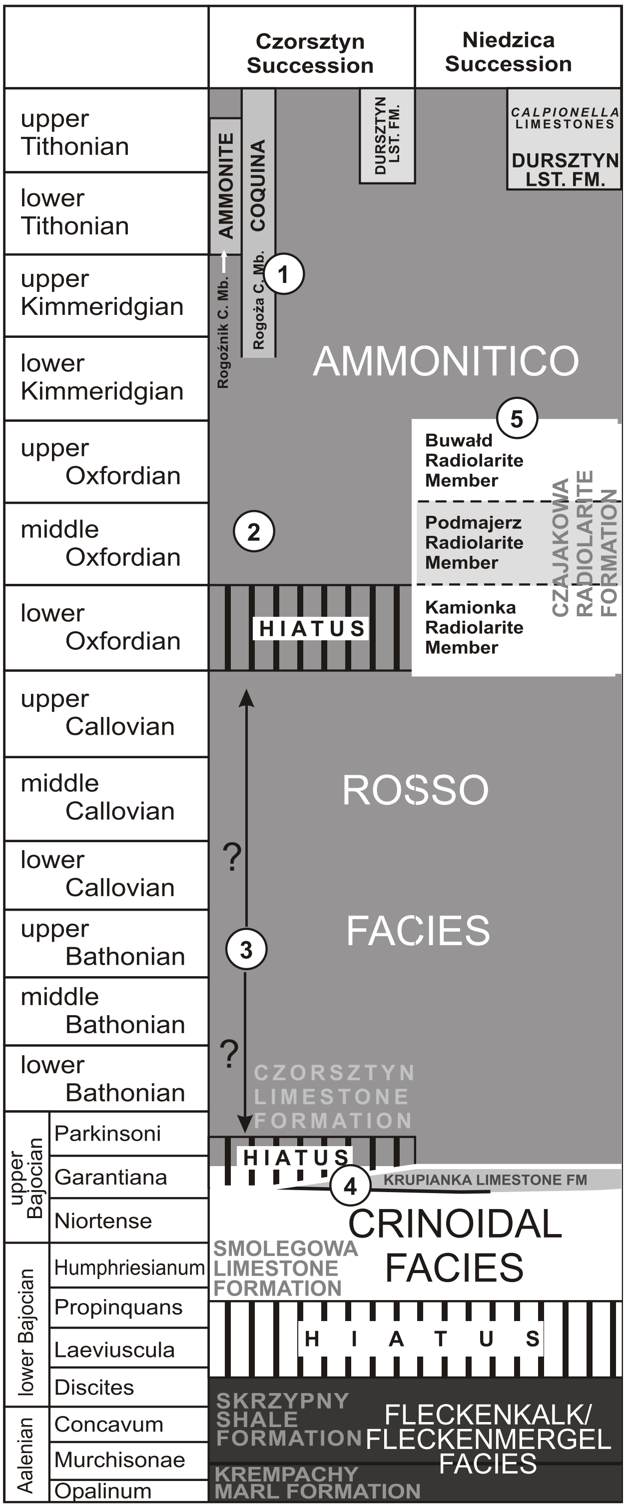

Fig. 3. Stratigraphical correlation between Jurassic lithofacies (lithostratigraphic units after Birkenmajer, 1977) of the Pieniny Klippen Belt successions (after Wierzbowski *et al.*, 2004; Krobicki and Golonka, 2006, modified) with position of sections sampled

from the Upper Jurassic deposits at 6 localities (Fig. 1B). Five localities were situated within the Czorsztyn Unit and one locality within the Niedzica Unit. In Rogoźnik, near Nowy Targ (1 in Figs. 1 and 3), 5 cores were drilled in the lower part of the abandoned quarry (Birkenmajer, 1979; Reháková and Wierzbowski, 2005) from the red micritic limestones of the Rogoża Coquina Member of the Czorsztyn Limestone Formation. The sampled part represents most probably the Kimmeridgian (Parvula–Borzai zones; Reháková and Wierzbowski, 2005). Five cores were collected from blocks of breccia interfingering with the coquinas in order to perform a conglomerate test. In the Obłazowa Klippe (2 in Figs. 1 and 3), 7 cores were taken from the of the Czorsztyn Limestone Formation, 1.3 to 2.5 m above the contact with the Krupianka Limestone Formation. The age of the sampled interval is estimated as middle Oxfordian, basing on ammonites and microfacies (Krobicki *et al.*, 2006*b*). From one of the klippen, south of Krempachy (3 in Figs. 1 and 3), 5 hand samples were collected from the Czorsztyn Limestone Formation. Filament microfacies and a lack of protoglobigerinids indicate the pre-Oxfordian (uppermost Bajocian–Callovian) part of the formation (Pszczółkowski pers. comm.; Wierzbowski *et al.*, 1999), without the possibility of closer age determination. In two klippen in the eastern part of the PKB (Sołtysie Skałki — 4 in Figs. 1 and 3), red crinoidal limestones of the Krupianka Limestone Formation (Middle Jurassic) were sampled: 8 cores were taken from the Baba and 8 cores from the Krupianka Klippe. In the single locality of the Niedzica Unit (Zaskalskie-Bodnarówka — 5 in Figs. 1 and 3), 3 cores and one hand sample were taken from the Oxfordian radiolarites of the Buwałd Radiolarite Member of the Czajakowa Radiolarite Formation.

From each core and hand sample 1–3 specimens were obtained for further palaeomagnetic analysis. Natural remanent magnetisation (NRM) was measured with JR-5 and JR6a spinner magnetometers (*AGICO*, Brno; noise level 10^{-5} A/m) in the palaeomagnetic laboratory of the Polish Geological Institute (PGI) in Warsaw. Samples were demagnetised thermally using the non-magnetic oven MMTD (Magnetic Measurements, UK, rest field <10 nT). NRM measurements and demagnetisation experiments were carried out in magnetically shielded space (a low-field cage, Magnetic Measurements, UK, which reduces the ambient geomagnetic field by about 95%). Magnetic susceptibility was monitored with a KLY-2 bridge (*AGICO*, Brno; sensitivity 10^{-8} SI units) after each thermal demagnetisation step. Characteristic remanence magnetisation (ChRM) directions were calculated by principal component analysis (Kirschvink, 1980) using the *PALMAG* package of Lewandowski *et al.*, (1997) and, occasionally, a remagnetization circle method (McFadden and McElhinny, 1988). Rock magnetic studies included mostly stepwise acquisition of the isothermal remanent magnetisation (IRM) and thermal demagnetisation of a composite IRM acquired along 3 perpendicular axes (Lowrie, 1990); the IRM was imparted using a MMPM1 pulse magnetiser produced by Magnetic Measurements (UK).

RESULTS

IRM experiments enabled distinction of different magnetic minerals in the outcrops studied. In the red crinoidal limestones of the Krupianka Limestone Formation (Baba Klippe), saturation of the IRM was not achieved at 1.4 T, indicating the dominance of a high coercivity magnetic fraction. Its maximum unblocking temperatures of between 600–700°C are characteristic for hematite (Fig. 4A). In the red micritic limestones of the Rogoża Coquina Member (Rogoźnik quarry) rapid increases of the IRM in applied fields of up to 200 mT indicates low coercivity minerals. The character of the IRM/IRM_0 curve revealed also the occurrence of a subordinate high coercivity mineral-hematite. The dominant soft magnetic fraction is probably fine-grained magnetite, with an unblocking temperature about 450°C, as shown by the three-axis thermal demagnetization curves (Fig. 4B).

Rocks were moderately magnetic with NRM intensities mostly between 0.5 and 4 mA/m and magnetic susceptibility values between 10–80 × 10^{-6}. Because of the presence of hematite, only thermal demagnetization was applied. Two components of magnetizations were clearly defined at Rogoźnik, Obłazowa and Krempachy. Between 100 and 250°C a component A was demagnetized (Fig. 5A). Its direction is quite similar to the present-day geomagnetic field direction in the area in Rogoźnik (Fig. 6). However, it reveals an almost vertical downward inclination at Obłazowa and Krempachy (Fig. 6) indicative of a near-pole latitude. As the rocks studied could not reach sub-polar position during last 20 My, it can be interpreted in terms of a resultant vector or, for instance, a recent block rotation around a horizontal axis due to neotectonics. The neotectonic activity of the PKB is well known (Zuchiewicz, 1980) and Quaternary rotations of the Mesozoic klippen around a horizontal axis were reported e.g. from the Szaflary area (Fig. 1) (see Birkenmajer 1979 p. 59). Recent horizontal motions in the area are directed NNE (Hefty, 1998) and rates of vertical movements do not exceed 0.5 mm/yr (Ząbek *et al.*, 1993; Czarnecki, 2004).

Between 300 and 550°C another component B was revealed (Fig. 5B, C). It reveals a N to NNW declination with a moderate positive inclination at Rogoźnik and a similar declination but negative inclination at Obłazowa and Krempachy (Figs. 7A and 8A). After tectonic correction the component B from all three localities is reasonably well clustered. (Figs. 7B and 8B). The polarity of component B is normal, though in two specimens from Obłazowa the reversed polarity was observed. In one specimen from Obłazowa an anomalous magnetization was found which, in geographic coordinates, corresponds to a steep inclination reversed component C from locality Baba (Fig. 9).

Specimens from breccia in the Rogoźnik quarry revealed the same structure of magnetization, with component A and B of comparable unblocking temperatures to those described above (Fig. 5D). However, both components are dispersed (Fig. 10) which indicates that they were acquired before the origin of the breccia.

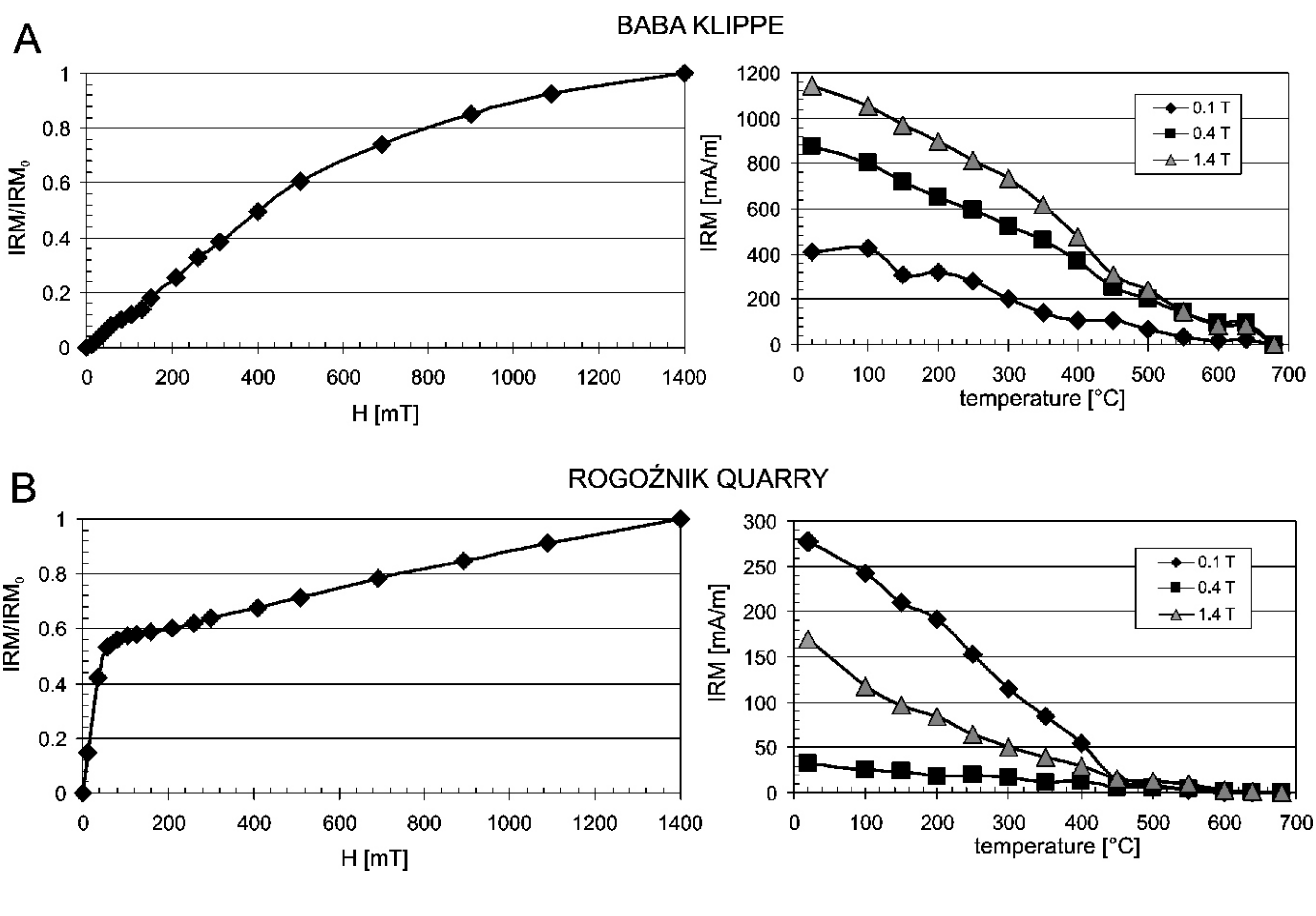

Fig. 4. Stepwise acquisition of IRM and thermal demagnetization of IRM (Lowrie test) for Baba Klippe (A) and Rogoźnik quarry (B)

IRM — isothermal remanent magnetization

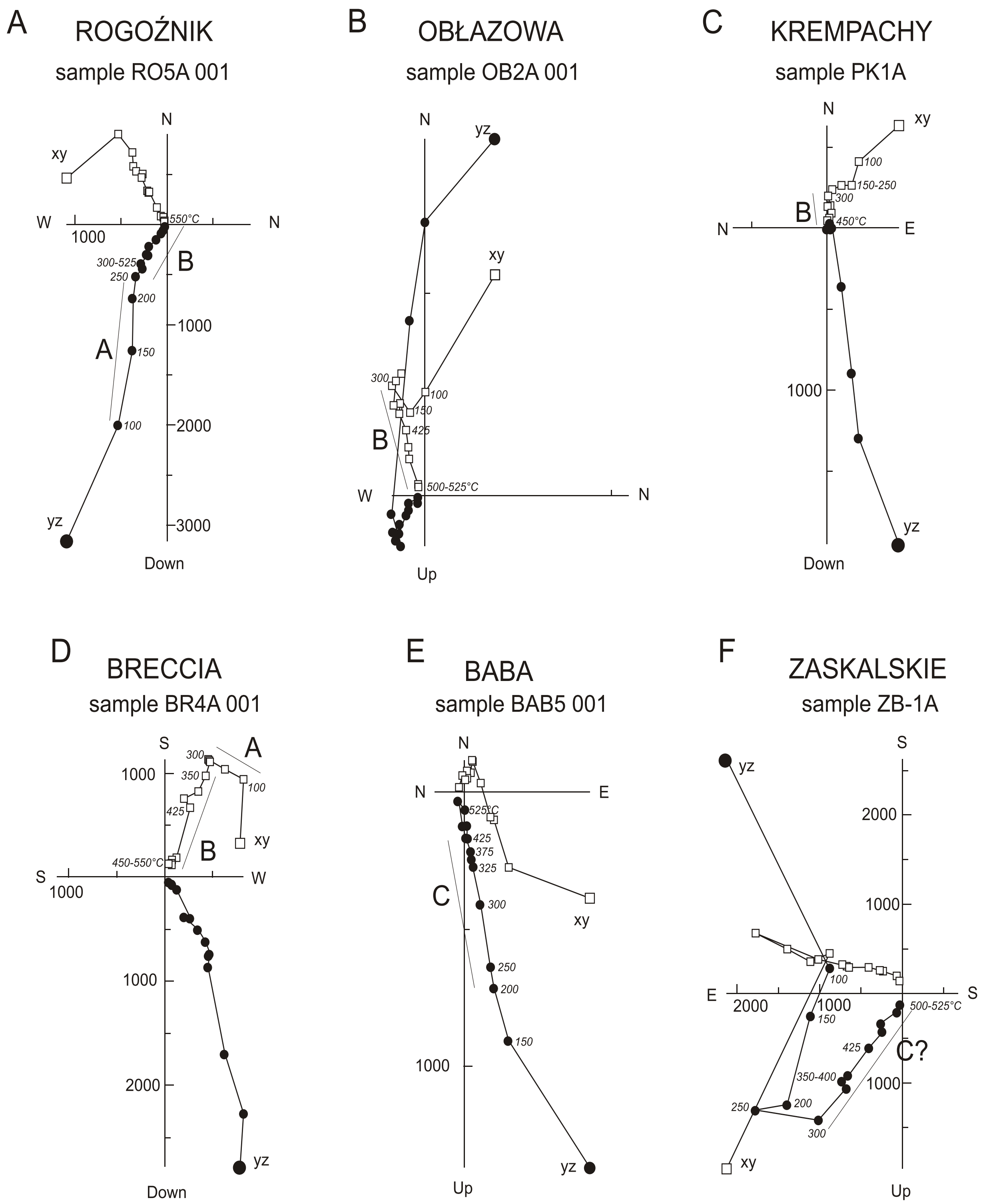

Fig. 5. Examples of orthogonal projections (Zijderveld diagrams) of demagnetization paths during thermal treatment

Intensities of NRM: × 10^{-6} A/m

In the Baba locality, all specimens of red crinoidal limestones revealed the presence of component C, demagnetized between 150 and 400°C (Fig. 5E). At higher temperatures, the demagnetization paths show great circles towards the NNW indicating the presence of another, yet undetermined, component of normal(?) polarity. However, stable end points have not been reached and this component has not been determined. Demagnetization paths for red crinoidal limestones of the Krupianka Limestone Formation in their type locality were highly variable and it was not possible to isolate any characteristic component that might be statistically significant.

At Zaskalskie-Bodnarówka, two low unblocking temperature (100–250°C) components A1 and A2 were calculated (Fig. 11A). They reveal exclusively normal polarity and the di-

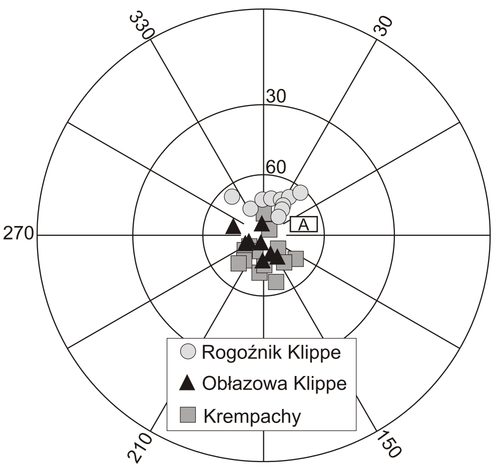

Fig. 6. Stereographic projection of low temperature component A from Rogoźnik quarry, Obłazowa Klippe and Krempachy; lower hemisphere projection

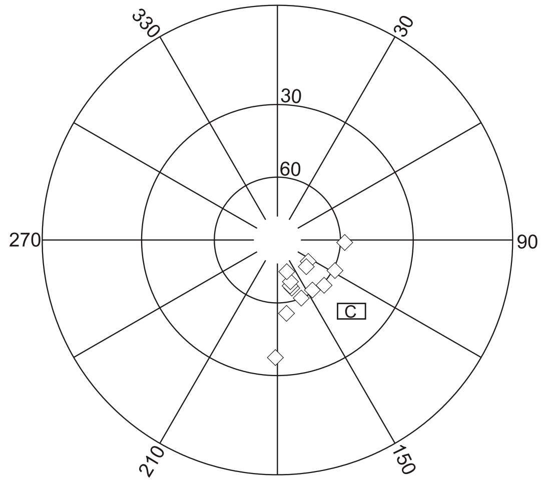

Fig. 9. Stereographic projection of high temperature component C from Baba Klippe; upper hemisphere projection

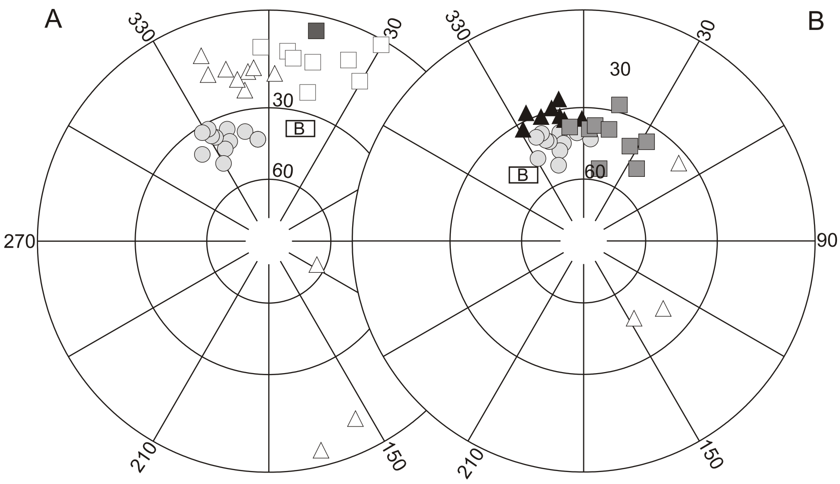

Fig. 7. Stereographic projection of high temperature component B from Rogoźnik quarry, Obłazowa Klippe and Krempachy

A — before tectonic correction, B — after tectonic correction; white symbols — upper hemisphere projection, other — lower hemisphere projection; for other explanations see Figure 6

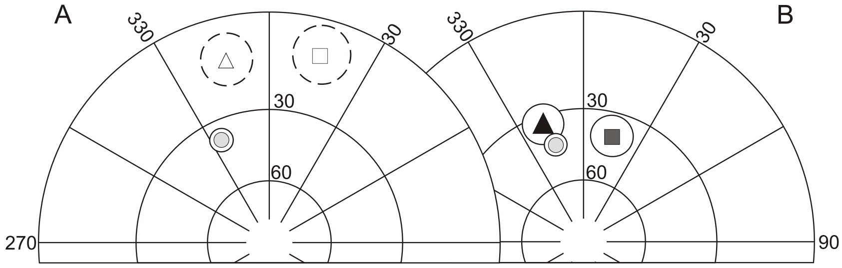

Fig. 8. Mean directions calculated from Rogoźnik quarry, Obłazowa Klippe and Krempachy with δ_{95} ovals plotted

For other explanations see Figures 6 and 7

rection of component A2 after tectonic correction approaches that of component A1 before tectonic correction (Fig. 11B and Table 1). At higher temperatures (300–500°C) a reversed polarity component appeared in all specimens, although, only in two cases was a well-defined linear decay to the origin observed (Fig. 5F). In 5 specimens it was possible to calculate the component using a method of remagnetization circles (McFadden and McElhinny, 1988) (Fig. 12). The component was tentatively compared to component C from the Baba locality, because it reveals the same steep negative inclination in both *in situ* and tectonic coordinates. However, the declination of component C from Zaskalskie-Bodnarówka is closer to that of its counterpart from Baba after application of tectonic correction (Fig. 13). Two possible interpretations of the component C at Zaskalskie-Bodnarówka (in pre- and postfolding coordinates) are given in Table 2.

TIMING OF MAGNETIZATION

The age of the component A in Rogoźnik must be Late Tertiary or younger, as inferred from its inclination (Fig. 6). Component A is surely older than the sampled breccia because its direction is dispersed between the breccia clasts (see Fig. 10). This implies that the breccia itself is also relatively young. More careful inspection of the breccia reveals that it might be related to

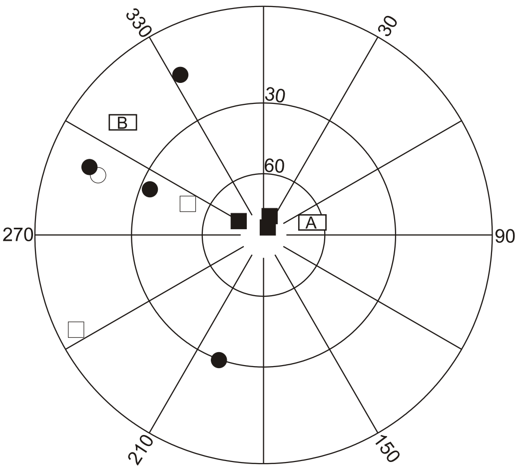

Fig. 10. Stereographic projection of low temperature component A (squares) and high temperature component B (circles) from Rogoźnik Breccia

white symbols — upper hemisphere projection, black symbols — lower hemisphere projection

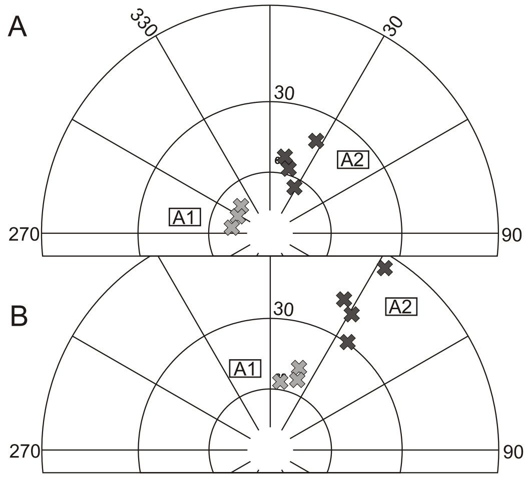

Fig. 11. Stereographic projection of low temperature components A1 and A2 from Zaskalskie-Bodnarówka, lower hemisphere projection

A — before tectonic correction, B — after tectonic correction

T a b l e 1

Low temperature components

Locality	Tect. corr.	Component	Pol.	*D*/*I*	õ$_{95}$	*k*	*Dc*/*Ic*	õ$_{95}$	*k*	N	n_o/n
Rogoźnik	92/12	A	NR	16/73	6.3	59.7	45/67	6.3	59.7	5	10/11
Obłazowa	199/55	A	NR	212/86	6.2	62.3	200/31	6.2	62.3	7	12/10
Krempachy	197/50	A	NR	177/80	5.9	49.6	193/31	5.9	49.6	5	13/13
Zakalskie-Bodnarówka	38–50/ 35–40	A2	NR	20/54	12.2	57.3	31/18	13.1	49.7	4	7/4
		A1	NR	297/72	8.8	195.0	16/53	8.9	192.8		7/3

Tect. corr. — tectonic correction (azimuth of bedding dip/ bedding dip); Pol. — polarity; *D*/*I* — declination/inclination before tectonic correction; *Dc*/*Ic* — declination/inclination after tectonic correction; õ$_{95}$, *k* — Fisher statistics parameters; N — number of independently oriented cores/hand samples; n_o/n — number of specimens demagnetized/number of specimens used for calculation of characteristic direction; NR — normal

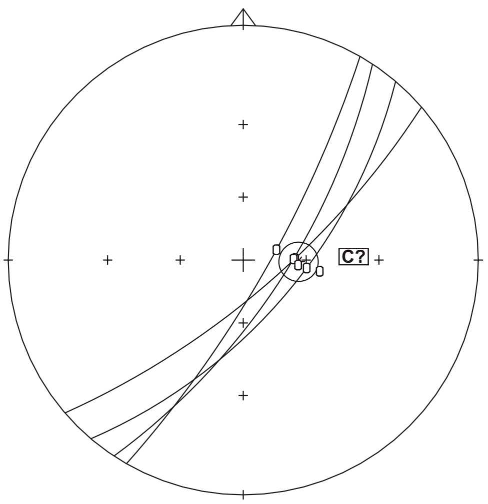

Fig. 12. High temperature component C? from Zaskalskie-Bodnarówka, calculated using a method of remagnetization circles (see McFadden and McElhinny, 1988)

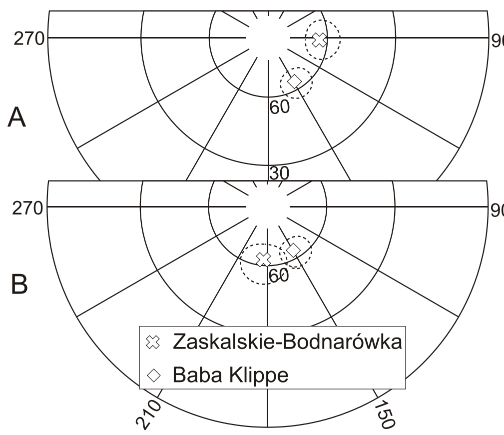

Fig. 13. Stereographic projection of high temperature component C from Zaskalskie-Bodnarówka and Baba Klippe, upper hemisphere projection

A — before tectonic correction, B — after tectonic correction

Table 2

Characteristic directions from the studied localities — high temperature components B and C

Locality	Tect. corr.	Component	Pol.	*D*/*I*	$\tilde{o}_{95}$	*k*	*Dc*/*Ic*	$\tilde{o}_{95}$	k	Paleopole: Lat. N/ Long. E	*Dp*/*Dm*	N	n_o/n
Rogoźnik	92/12	B	NR	335/38	4.7	95.7	**344/43**	4.7	95.7	63/233	3/6	5	11/11
Obłazowa	199/55	B	NR +RV	347/-12	7.9	38.4	**341/34**	7.9	38.4	56/234	5/9	7	12/10
Krempachy	197/50	B	NR	15/-10	8.5	37.7	**15/40**	8.5	37.7	61/171	6/10	5	13/9
Zakalskie-Bodnarówka	38–50/ 35–40	C?	RV	**92/-64**	9.1	69.2	**184/-63**	10.6	51.0	33/323 (btc) 86/169 (atc)	8/10 9/11	4	7/6
Baba	–	C	RV	**148/-64**	7.6	28.6	**148/-64**	7.6	28.6	68/293	10/12	8	14/14
Krupianka	–	no results	8	no results									0/13

Dp/*Dm* — 95% confidence ovals of palaeopole calculation; btc — before tectonic correction; atc — after tectonic correction; RV — reversed; directions accepted for geological intersections are indicated with bold; other explanations as in Table 1

karst phenomena which are well developed in the quarry. We presume that karstification of the limestones might have taken place in the Late Neogene. Therefore component A must have been acquired earlier, most probably during weathering in the warm climate of the Late Tertiary. The direction of component A from Obłazowa and Krempachy might have been subsequently modified due to neotectonic phenomena (see above). Component B is interpreted as pre-folding at all three localities (Rogoźnik, Obłazowa and Krempachy). It might be a primary magnetization and this is additionally supported by its mixed polarity. The inclinations of component B at particular localities, in pre-folding coordinates, are not identical: the inclination is the shallowest at Obłazowa (Oxfordian) and slightly steeper in older (Krempachy — Middle Jurassic) and younger (Rogoźnik — Kimmeridgian) rocks. This might reflect a gradual latitudinal drift of the area (Table 3). However, as each stage is represented by a single locality, and 95% error bars for the inclinations of component B largely overlap, it might be possible that inclination and palaeolatitude differences are not statistically significant and a mean palaeoinclination 39° (±7°) must be calculated for the area, as representative for the late Mid to early Late Jurassic. This will be discussed in the next section. Component C is interpreted as Neogene remagnetization coeval with intrusion of andesite dykes, one of which is situated just 300 m from the Baba Klippe (Birkenmajer, 1970), close enough to elevate the temperature of the host rock. The direction of component C also corresponds well to reversed polarity components of steep inclinations, noted from the Pieniny andesites (Birkenmajer and Nairn, 1968; Kruczyk, 1970; Márton *et al*., 2004).

DISCUSSION

Palaeoinclination 39° (7°) calculated from component B at 3 localities implies a palaeolatitude for the area studied of 22°N (5°) in the late Mid to early Late Jurassic (Oxfordian–Kimmeridgian). This result clearly contradicts the conclusion of Kruczyk and Kądziałko-Hofmokl (2006) who obtained a mean palaeolatitude of 36°N (7°) for the Polish part of the PKB for the Bathonian–Oxfordian. We do not have a good explanation for this contradiction. Contrasting palaeolatitudes from several localities in the Ukrainian and Slovakian sectors of the PKB were recently reported by Lewandowski *et al*., (2006*a*) who postulated that the Czorsztyn Ridge might be composed of several microblocks (terranes). This explanation cannot reconcile our results and those of

Table 3

Comparison of Mesozoic palaeolatitudes from the western (Poland) and eastern part of the PKB (Ukraine)

PKB western part			PKB eastern part		
Locality	Age	Palaeolatitude	Locality	Age	Palaeolatitude
Brodno[1]	Tithonian/ Berriasian	27°N (5°)	Kamenets[2]	Berriasian	36°N (8°)
Rogoźnik[3]	Kimmeridgian	25°N (4°)		Kimmeridgian	30°N (10°)
Obłazowa[3]	Oxfordian	21°N (5°)		Oxfordian	28°N (6°)
Krempachy[3]	Callovian	23°N (5°)		Bajocian/Bathonian	41°N (5°)
	Mean Callovian–Kimmeridgian	22°N (5°)		Mean Bajocian–Berriasian	31°N (3°)

[1] — Houša *et al*. (1996), [2] — Lewandowski *et al*. (2005), [3] — this study

Kruczyk and Kądziako-Hofmokl (*op. cit.*). It is difficult to accept that nearby localities in the Polish part of the PKB (e.g. Rogoźnik and Czorsztyn) were separated in the Late Jurassic by as much as 14° (6°) of latitude which equals almost 1500 km! The difference must result from interpretation of the palaeomagnetic data. In general, concerning the results of Kruczyk and Kądziałko-Hofmokl (*op. cit.*), the magnetic record in their rocks is much more complicated than that in ours, with many components interpreted as "intermediate" directions. Their sampling area embraced mostly a central part of the Pieniny Klippen Belt in Poland (between Czorsztyn and Niedzica) with an isolated locality in the eastern part (Homole). Only two localities belonged to the Czorsztyn Unit, while five other localities were situated in the Niedzica and Branisko units which are more disturbed tectonically. Our results from the western part of PKB in Poland (Rogoźnik, Obłazowa, Krempachy — exclusively Czorsztyn Unit) reveal a relatively simple structure of magnetization without significant Neogene remagnetization. On the other hand, more easterly localities were either remagnetized in the Neogene (Baba and Zaskalskie-Bodnarówka) or did not give any coherent results (Krupianka). It may be postulated that the eastern localities might have been affected thermally in the Neogene due to andesite intrusions, what probably resulted in more than one remagnetization event and significant loss of primary magnetization. The generally convincing results of Kruczyk and Kądziałko-Hofmokl (*op. cit.*) from the Czorsztyn Castle Klippe (although also affected by Tertiary remagnetization) revealed a palaeolatitude of 34° (7°) during deposition of the nodular limestones. However, it is not certain which part of the Czorsztyn Limestone Formation was studied. If the samples were taken from the lowermost part of the formation they might represent even the uppermost Bajocian/lowermost Bathonian Parkinsoni Zone (Wierzbowski *et al*., 1999; Krobicki *et al*., 2006*a*), thus the results are not comparable with ours.

PALAEOGEOGRAPHIC IMPLICATIONS

ORIENTATION OF THE CZORSZTYN RIDGE IN THE LATE JURASSIC

As interpretation of palaeomagnetic data from the PKB, at the present state of knowledge, is equivocal, the geological implications based on them must also be accepted with some caution. Nevertheless, we believe that our results, when compared to those of Lewandowski *et al.* (2005) shed some light on the original orientation of the Czorsztyn Ridge.

The structural orientation of the Czorsztyn Ridge remains a matter of debate. Various trends have been drawn on palaeotectonic maps but mostly with little comment. Rakús *et al.* (1988) suggested an E–W to ENE–WSW orientation of the Czorsztyn Ridge, roughly parallel to the Carpathian prolongation of the Penninic ocean. The reconstructions of Vašíček *et al.* (1994) and Michalík (1994) (in his fig. 5B), although essentially similar to those of Rakús *et al.* (1988), indicate a NW–SE direction of the Czorsztyn Ridge in the Late Jurassic, thus sub-perpendicular to the NE–SW trend of the Penninic ocean. The same orientation of the Czorsztyn Ridge is supported by Channell and Kozur (1997). An alternative position of the Pieniny Klippen Basin (and also of the Czorsztyn Ridge), parallel to the Penninic NE–SW trend is given by Stampfli *et al.* (1998).

Golonka *et al.* (2000) in their figures 4 and 5, suggest an E–W direction of the Czorsztyn Ridge in Mid Jurassic–Early Cretaceous time without any discussion. Some geological arguments for NE–SW orientation of the Czorsztyn Ridge in the Tithonian–Berriasian were given by Golonka and Krobicki (2001). They include indirect evidence basing on general palaeogeographic considerations and accept also an E–W orientation as a possible option. The NE–SW orientation, however, conforms with their modeled wind and upwelling directions in the Alpine–Carpathian sector of the Western Tethys. Aubrecht and Túnyi (2001) postulated NE–SW orientations of neptunian dykes, cutting the Czorsztyn Ridge at some localities in W Slovakia. The original orientation of neptunian dykes was obtained using new palaeomagnetic data from the Vršatec, Babina, Bolesovska Dolina and Mestečská skala localities. The results are, however, confusing and should be reinterpreted. They were partially questioned by the authors (Túnyi *et al.,* 2004), who rejected the results from Vršatec. Moreover, new palaeomagnetic results from the same localities (e.g. Babina klippe — Lewandowski *et al.,* 2006*b*) differ markedly from those reported by Aubrecht and Túnyi (2001). Palaeomagnetic arguments for a NE–SW orientation of the Czorsztyn Ridge in the Mid Jurassic were given by Golonka *et al.* (2003), using the preliminary data of Lewandowski *et al.* (2000, in the final form as Lewandowski *et al*., 2005). The palaeolatitudes of the eastern termination of the Czorsztyn Ridge in the Bajocian–Bathonian correspond to the "expected" palaeolatitudes of the SE European margin (Lewandowski *et al*., 2005). This implies a NE–SW orientation of the structure, parallel to the edge of the European Platform, at least in the Bajocian–Bathonian.

When we accept that the Czorsztyn Ridge was a roughly continuous structure of unvarying length and that the Kamenets locality, studied by Lewandowski *et al.* (2000, 2005), was localized on the ridge, we might compare the coeval palaeolatitudes in the present-day western and eastern part of the Czorsztyn Unit (Table 3). It appears that palaeolatitudes from the western part are systematically lower than from the eastern part. The difference amounts to 6–8° between the Oxfordian and the Berriasian. At the present-day, the studied western part of the PKB is situated 1° more to the north than the eastern part (Kamenets locality, Ukraine). That means that the western part of the PKB must have been pushed considerably northwards, in relation to the eastern part, during Late Mesozoic and/or Tertiary orogenic phases. This also implies an original NE–SW orientation of the Czorsztyn Unit in the Oxfordian–Berriasian, consistent with the palaeogeography postulated by Stampfli *et al.* (1998), Golonka and Krobicki (2001), Golonka *et al.* (2003) and Krobicki and Golonka (2006). Existing palaeomagnetic data account for a northwards drift of the PKB in the Late Jurassic up to the earliest Cretaceous (Fig. 14): from the palaeolatitude of 22°N in the Late Jurassic up to 28°N in the western part, and from 28° up to 36° in the eastern part (Lewandowski *et al*., 2005; this paper). The method implemented does not allow estimations of palaeolongitude, which is why there is only a schematic interpretation on Figure 14.

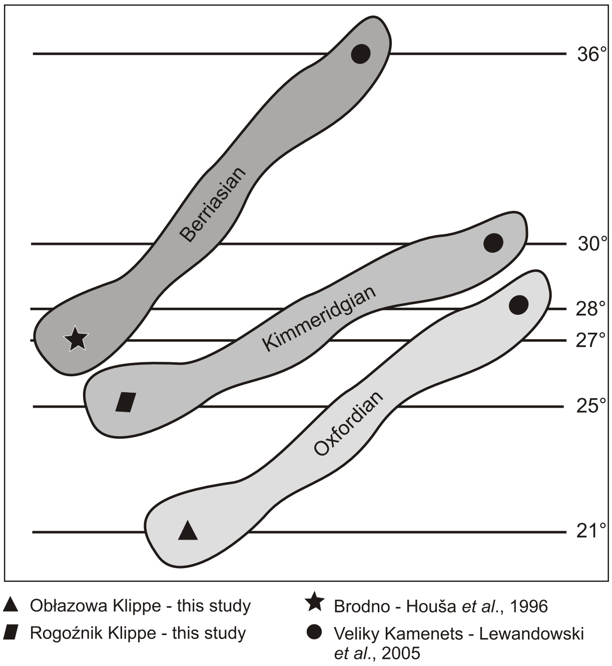

Fig. 14. Schematic orientation and drift of the Czorsztyn Ridge in the Late Jurassic/ Early Cretaceous time interval proposed on the basis of palaeogeographic and palaeomagnetic considerations

POSITION OF THE CZORSZTYN RIDGE WITH RESPECT TO MAJOR PLATES

A possible age of magnetization was estimated by plotting inclinations from Rogoźnik, Obłazowa and Krempachy against reference inclination trends for Europe, South (Fig. 15A) and North Africa (Fig. 15B), calculated for the Pieniny Klippen Belt geographic coordinates (49°N, 20°E) as a function of time.

The Mesozoic Apparent Polar Wander Paths (APWP) of Besse and Courtillot (2002) was used for Europe (Fig. 15).

The main problem in the African APWP construction is the relative lack of reliable African Mesozoic poles. This could be compensated for by using palaeomagnetic data from other continents rotated into African coordinates according to their age as did Besse and Courtillot (2002).

To define a master APWP for Africa, they used original Eurasian, North American and Indian data, transferred to the South African coordinates and combined with African data. Average poles were calculated every 10 Ma with a 20 Ma window (Fig. 15A).

Agreement between data from Africa and Adria indicate their affinity and coherent motion in the Late Jurassic/Early Cretaceous time interval. This is why palaeomagnetic data from Adria are commonly used to improve the poorly documented Mesozoic APW path of Africa. A composite APW path in North African coordinates was created from Adria and West Gondwana data integration by Muttoni *et al.* (2001) (Fig. 15B).

An inclination versus time plot shows inclination which would be expected if the Czorsztyn Ridge remained attached to Europe or Africa and allows measurement of its relative displacements with respect to the major plates. Comparison of the mean PKB inclinations with the expected European and African inclinations and significant large distance from the European trend in the Mesozoic lead to the conclusion that Czorsztyn Ridge might have been very close to the African plate in the Late Jurassic. This conclusion is in line with recent data by Lewandowski *et al.* (2006*b*).

Moreover, computed inclinations are very close to those expected from the stratigraphic age of the rocks sampled. Good quality data enable determination of magnetic remanence age for the Mesozoic: Late Jurassic or Early/Late Cretaceous. We believe that the magnetization in sampled localities is primary of Jurassic age, which is supported by its mixed polarity in

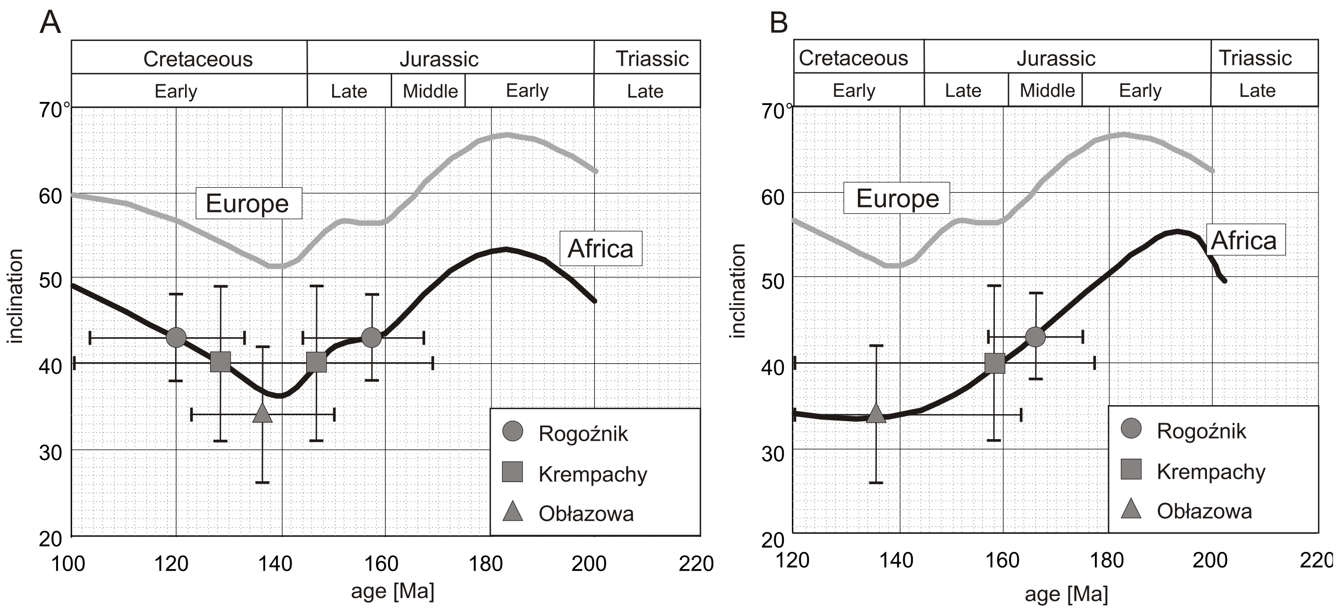

Fig. 15. Expected European (after Besse and Courtillout, 2002) and African palaeoinclinations (A — after Besse and Courtillout, 2002; B — after Muttoni *et al.*, 2001) calculated for the geographic coordinates of a given locality in the Polish sector of the Pieniny Klippen Belt and inclinations of the B component calculated in this study

Obłazowa. A Cretaceous age of magnetization is less probable. There is no evidence for any Cretaceous thermal event in the Czorsztyn Ridge region, which could have led to remagnetization. In the Early Cretaceous, the Jurassic rocks were covered by relatively thin layer (about 50 m) of rock. A Late Cretaceous age of secondary magnetic remanence was reported by Grabowski (2000) and Grabowski and Michalík (2005) in the Fatric Unit of the Central West Carpathians. However, this remagnetization is accompanied by thermal reset of $\delta^{18}O$ ratios in the Central West Carpathians which, so far, have not been observed in the PKB (Michalík *et al.,* 1995).

CONCLUSIONS

1. Palaeomagnetically investigated Middle and Upper Jurassic limestones of the Czorsztyn Limestone Formation (Polish sector of the Pieniny Klippen Belt) revealed a pre-folding, mixed polarity component, interpreted as primary. A mean Middle/Late Jurassic palaeolatitude of 22°N (5°) was calculated for the area studied.

2. There is a growing evidence for a northward drift of the PKB in the Late Jurassic up to the earliest Cretaceous: from a palaeolatitude of 22°N (this study) in the Late Jurassic up to 28°N (Houša *et al*., 1996) in the western, Polish–Slovakian part, and from 28° up to 36° in the eastern, Ukrainian part (Lewandowski *et al*., 2005). Systematically lower palaeolatitudes in the west would imply a NE–SW orientation of the Czorsztyn Ridge in the Mesozoic.

3. The mean pre-Oxfordian–Kimmeridgian palaeolatitudes from the western part of the PKB (this study) are lower by about 10° from those suggested by Stampfli and Borel (2002). They are concordant with Adriatic/African rather than with European palaeolatitudes.

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REFERENCES

ANDRUSOV D. (1938) — Geologický výskum vnitřního bradlového pásma v Západních Karpatech. III. Tektonika: Rozpravy Státneho Geologickeho Ústavu ČSR, **9**.

ANDRUSOV D. (1959) — Geológia československých Karpát II. SAV, Bratislava.

ANDRUSOV D., BYSTRICKÝ J. and FUSÁN O. (1973) — Outline of the structure of the West Carpathians. Guide Book, X Congress CBGA, GÚDŠ, Bratislava.

AUBRECHT R. and TÚNYI I. (2001) — Original orientation of Neptunian dykes in the Pieniny Klippen Belt (Western Carpathians): the first results. Contribut. Geophys. Geod., **31** (3): 557–578.

AUBRECHT R., MIŠÍK M. and SÝKORA M. (1997) — Jurassic synrift sedimentation on the Czorsztyn Swell of the Pieniny Klippen Belt in Western Slovakia. In: Alpine Evolution of the Western Carpathians and Related Areas (eds. D. Plaaienka, J. Hók, J. Vozár and M. Ellecko): 53–64. Dionýz Stur Publisher, Bratislava.

BALLA Z. (1987) — Tertiary palaeomagnetic data for the Carpatho-Pannonian region in the light of Miocene rotation kinematics. Tectonophysics, **139**: 67–98.

BĄK K. (2000) — Biostratigraphy of deep-water agglutinated Foraminifera in Scaglia Rossa-type deposits of the Pieniny Klippen Belt, Carpathians, Poland. In: Proceedings of the Fifth International Workshop on Agglutinated Foraminifera (eds. M. B. Hart, M. A. Kaminski and C. W. Smart). Grzybowski Foundation Special Publication, **7**: 15–41. Kraków.

BESSE J. and COURTILLOT V. (2002) — Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr. J. Geophys. Res., **107**(B11), 2300, doi: 1029/2000JB000050. EPM 6.

BIRKENMAJER K. (1958) — Submarine erosional breaks and Late Jurassic synorogenic movements in the Pieniny Klippen Belt geosyncline. Bull. Acad. Polon. Sc., Sér., Sc. Chim., Géol. Géogr., **8**: 551–558.

BIRKENMAJER K. (1970) — Pre-Eocene fold structures in the Pieniny Klippen Belt (Carpathians of Poland). Stud. Geol. Pol., **31**: 1–77.

BIRKENMAJER K. (1977) — Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. Stud. Geol. Pol., **45**: 1–158.

BIRKENMAJER K. (1979) — Przewodnik geologiczny po pienińskim pasie skałkowym. Wyd. Geol., Warszawa.

BIRKENMAJER K. (1986) — Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. Stud. Geol. Pol., **88**: 7–32.

BIRKENMAJER K. (1988) — Exotic Andrusov Ridge: its role in plate-tectonic evolution of the West Carpathian Foldbelt. Stud. Geol. Pol., **91**: 7–37.

BIRKENMAJER K. and NAIRN A. E. M. (1968) — Palaeomagnetic studies of Polish Rocks. III. Neogene igneous rocks of the Pieniny Mountains, Carpathians. Ann, Soc. Geol. Pol., **38**: 475–489.

CHANNELL J. E. T. and KOZUR H. W. (1997) — How many oceans? Meliata, Vardar and Pindos oceans in Mesozoic Alpine paleogeography. Geology, **25**: 183–186.

CSONTOS L., NAGYMAROSY A., HORVÁTH F. and KOVÁ M. (1992) — Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics, **208**: 221–241.

CZARNECKI K. ed. (2004) — Geodynamical studies of the Pieniny Klippen Belt — Czorsztyn Region (in Polish with English summary). Instytut Geodezji Wyższej i Astronomii Geodezyjnej. Warszawa. Monography.

GALBRUN B. (1985) — Magnetostratigraphy of the Berriassian stratotype section (Berrias, France). Earth Planet. Sc. Lett., **74**: 130–136.

GOLONKA J. and KROBICKI M. (2001) — Upwelling regime in the Carpathian Tethys: a Jurassic–Cretaceous palaeogeographic and palaeoclimatic perspective. Geol Quart., **45** (1): 15–32.

GOLONKA J. and KROBICKI M. (2004) — Jurassic paleogeography of the Pieniny and Outer Carpathian basins. Rivista Italiana di Paleontologia e Stratigrafia, **110** (1): 5–14.

GOLONKA J., KROBICKI M., OSZCZYPKO N., ŚLĄCZKA A. and SŁOMKA T. (2003) — Geodynamic evolution and palaeogeography of the Polish Carpathians and adjacent areas during Neo-Cimmerian and preceding events (latest Triassic–Earliest Cretaceous). In: Tracing tectonic deformation using the sedimentary record (eds. T.Mc Cann and A. Saintot). Geol. Soc. London, Spec. Publs., **208**: 138–158.

GOLONKA J., OSZCZYPKO N. and ŚLĄCZKA A. (2000) — Late Carboniferous–Neogene geodynamic evolution and paleogeography of the circum-Carpathian region and adjacent areas. Ann. Soc. Geol. Pol., **70**: 107–136.

GRABOWSKI J. (2000) — Palaeo- and rock magnetism of Mesozoic carbonate rocks in the sub-Tatric series (Central West Carpathians) — palaeotectonic implications. Pol. Geol. Inst., Spec. Pap., **5**: 1–88.

GRABOWSKI J. (2005) — New Berriasian palaeopole from the Central West Carpathians (Tatra Mountains, southern Poland): does it look Apulian? Geophys. J. Internat., **161** (1): 65–80.

GRABOWSKI J. and MICHALÍK J. (2005) — Remagnetization and thrusting in the Krizna nappe of the Central West Carpathians: a case study from the Tatra and Stražov Mts. TSG Annual Meeting 2005. Univ. Plymouth. Abstract volume.

HEFTY J. (1998) — Estimation of site velocities from CEGRN GPS campaigns referred to CERGOP reference frame. Rep. Geodesy, **9** (36): 67–79.

HOUŠA V., KRS M., KRSOVÁ M. and PRUNER P. (1996) — Magnetostratigraphy of Jurassic-Cretaceous limestones in the Western Carpathians. In: Palaeomagnetism and Tectonics of the Mediterranean region (eds. A. Morris and D. H. Tarling). Geol. Soc. Spec. Publ., **105**: 185–194.

KIRSCHVINK J. L. (1980) — The least square line and plane and the analysis of palaeomagnetic data. J. Roy. Astr. Soc., **62**: 699–718.

KROBICKI M. and GOLONKA J. (2006) — Field trip A — from Tethyan to Platform Facies. Pieniny Klippen Belt. In: Jurassic of Poland and Adjacent Slovakian Carpathians. Field trip guidebook (eds. A. Wierzbowski, R. Aubrecht, J. Golonka, J. Gutowski, M. Krobicki, B. A. Matyja, G. Pieńkowski and A. Uchman): 15–22. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

KROBICKI M., SIDORCZUK M. and WIERZBOWSKI A. (2006*a*) — Field trip B3 — Inside Tethys. Pieniny Klippen Belt (Poland). Stop A1 — Czorsztyn Castle Klippe–Czorsztyn Succession (Bajocia-Berriasian). In: Jurassic of Poland and Adjacent Slovakian Carpathians (eds. A. Wierzbowski, R. Aubrecht, J. Golonka, J. Gutowski, M. Krobicki, B. A. Matyja, G. Pieńkowski and A. Uchman): 23–28. Field trip guidebook. 7th International Congress on the Jurassic System, 6–18 September 2006, Kraków, Poland.

KROBICKI M., SIDORCZUK M. and WIERZBOWSKI A. (2006*b*) — Field trip B3 – Inside Tethys. Pieniny Klippen Belt (Poland). Stop B3.15 – Obłazowa Klippe: stratigraphy and microfacies of the Czorsztyn Limestone Formation (Bathonian-Tithonian, Czorsztyn Succession). In: Jurassic of Poland and adjacent Slovakian Carpathians (eds. A. Wierzbowski, R. Aubrecht, J. Golonka, J. Gutowski, M. Krobicki, B. A. Matyja, G. Pieńkowski and A. Uchman): 116–117. Field trip guidebook. 7th International Congress on the Jurassic System, 6–18 September, 2006, Kraków, Poland.

KRUCZYK J. (1970) — Palaeomagnetic investigations of the Mt. Wżar andesites (in Russian). Publs. Inst. Geophys. Pol. Acad. Sc. **35**.

KRUCZYK J. and KĄDZIAŁKO-HOFMOKL M. (2006) — Palaeomagnetic study of Middle–Upper Jurassic sediments from the Polish segment of the Pieniny Klippen Belt. Acta Geophys., **54**: 205–224.

LEWANDOWSKI M., NOWOŻYŃSKI K. and WERNER T. (1997) — PDA — a package of FORTRAN programs for palaeomagnetic data analysis (manuscript).

LEWANDOWSKI M., KROBICKI M., MATYJA B. A. and WIERZBOWSKI A. (2000) — Rekonesans paleomagnetyczny w jurajskie skały pienińskiego pasa skałkowego Ukrainy Zakarpackiej. Polska Grupa Robocza Systemu Jurajskiego, I Spotkanie, Wiktorowo, 28–29.09.200; Abstracts, Polskie Towarzystwo Geologiczne, Kraków.

LEWANDOWSKI M., KROBICKI M., MATYJA B. A. and WIERZBOWSKI A. (2005) — Palaeogeographic evolution of the Pieniny Klippen Basin using stratigraphic and palaeomagnetic data from the Veliky Kamenets section (Carpathians, Ukraine). Palaeogeog., Palaeoclim., Palaeoecol., **216**: 53–72.

LEWANDOWSKI M., ZIÓŁKOWSKI P. and SIDORCZUK M. (2006*a*) — Palaeogeography of some Jurassic basins of the Central Europe — palaeomagnetic approach. In: Jurassic of Poland and Adjacent Slovakian Carpathians (eds. A. Wierzbowski, R. Aubrecht, J. Golonka, J. Gutowski, M. Krobicki, B. A. Matyja, G. Pieńkowski and A. Uchman). Field trip guidebook of the 7th International Congress on the Jurassic System. Poland, Kraków, September 6–18, 2006.

LEWANDOWSKI M., AUBRECHT R., KROBICKI M., MATYJA B. A., REHÁKOVÁ D., SCHLÖGL J., SIDORCZUK M. and WIERZBOWSKI A. (2006*b*) — Palaeomagnetism of the Pieniny Klippen Belt (Carpathians): evidence for low-latitude origin and palaeogeographic dispersion of the Jurassic carbonates. Vol. Jurassica, IV, 56–58. 7th International congress on the Jurassic System, Abstracts.

LILLE R. J., BIELIK M., BABUŠKA V. and PLOMEROVÁ J. (1994) — Gravity modelling of the lithosphere In the Eakstern Alpine — western Carpathian–Pannonian Basin region. Tectonophysics, **231**: 215–236.

LOWRIE W. (1990) — Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. Geophys. Res. Lett., **17**: 159–162.

MÁRTON E., TOKARSKI K. and HALÁSZ D. (2004) — Late Miocene counter-clockwise rotation of the Pieniny andesites at the contact of the Inner and Outer Western Carpathians. Geol. Carpath., **55**: 411–419.

MCFADDEN P. L. and MCELHINNY M. W. (1988) — The combined analysis of remagnetization circles and direct observations in palaeomagnetism. Earth Planet. Sc. Lett., **87**: 161–172.

MICHALÍK J. (1994) — Notes on paleogeography and paleotectonics of the Western Carpathian area during the Mesozoic. Mitt. Osterr. Geol. Ges., **86**: 101–110.

MICHALÍK J. and REHÁKOVÁ D. (1995) — Sedimentary records of Early Cretaceous tectonic activity in the Alpine-Carpathian region. Slovak Geol. Mag., **2**: 159–164.

MICHALÍK J., REHÁKOVÁ D., HLADÍKOVÁ J. AND LINTNEROVÁ O. (1995) — Lithological and biological indicators of orbital changes in Tithonian and Lower Cretaceous sequences, Western Carpathians, Slovakia. Geol. Carpath., **46** (3): 161–174.

MIŠÍK M. (1994) — The Czorsztyn submarine ridge (Jurassic-Lower Cretaceous, Pieniny Klippen Belt): an example of a pelagic swell. Mitt. Österr. Geol. Gess., **86**: 133–140.

MORRIS A. and TARLING D. H. (1996) — Palaeomagnetism and tectonics of the Mediterranean region: an introduction. In: Palaeomagnetism and Tectonics of the Mediterranean region (eds. A. Morris and D. H. Tarling). Geol. Soc. Spec. Publ., **105**: 185–194.

MUTTONI G., GARZANTI E., ALFONSI L., CIRILLI S., GERMANI D. and LOWRIE W. (2001) — Motion of Africa and Adria since the Permian: palaeomagnetic and paleoclimatic constraints from northern Libya. Earth Planet. Sc. Lett., **192**: 159–174.

PEACOCK D. C. P., ANDERSON M. W., MORRIS A. and RANDALL D. E. (1998) — Evidence for the importance of "small" faults on block rotation. Tectonophysics, **299**: 1–13.

PLAŠIENKA D. (1999) — Tektonochronológia a paleotektonický model jursko-kriedového vývoja centralnych Západných Karpat. Veda, Bratislava.

RAKÚS M., MIŠÍK M., MICHALÍK J., MOCK R., ĎURKOVIČ T., KORÁB T., MARSCHALKO R., MELLO J., POLÁK M. and JABLONSKÝ J. (1988) — Paleogeographic development of the West Carpathians: Anisian to Oligocene. In: Evolution of the Northern Margin of Tethys (eds. M. Rakus, J. Dercourt and A. E. M. Nairn). Mem. Soc. Geol. France, **154** (3): 39–62.

RATSCHBACHER L., FRISCH W., LINZER H-G., SPERNER B., MESCHEDE M., DECKER K., NEMCOK M., NEMCOK J. and GRYGAR R. (1993) — The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression. Tectonophysics, **226**: 471–483.

REHÁKOVÁ D. and WIERZBOWSKI A. (2005) — Microfacies and stratigraphic position of the Upper Jurassic Rogoża Coquinas at Rogoźnik, Pieniny Klippen Belt, Carpathians. Tomy Jurajskie, **3**: 15–27.

ROYDEN L. H. and BURCHFIEL B. C. (1989) — Are systematic variations in thrust belt style related to plate boundary processes? (The Western Alps versus the Carpathians). Tectonics, **8** (1): 51–61

STAMPFLI G. M., MOSAR J., MARQUER D., MARCHANT R., BAUDIN T. and BOREL G. (1998) — Subduction and obduction processes in the Swiss Alps. Tectonophysics, **296**: 159–204.

STAMPFLI G. M. and BOREL G. D. (2002) — A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones. Earth Planet. Sc. Lett., **196**: 17–33.

TÚNYI I., JELEŃSKA M. and AUBRECHT R. (2004) — Middle/Late Jurassic extension in the Pieniny Klippen Belt inferred from the orientation of neptunian dykes. Contribut. Geophys. Geodesy, **34**: 156–157. Special Issue. Paleo, Rock and Environmental Magnetism 9th Castle Meeting, Abstracts.

UMHOEFER P. J. (2000) — Where are the missing faults in translated terranes? Tectonophysics, **326**: 23–35.

VAN DER VOO R. (1993) — Palaeomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge Univ. Press.

VAN DER VOO R. (2004) — Palaeomagnetism, oroclines and growth of the continental crust. GSA Today, **14** (12): 4–9.

VAŠÍČEK Z., MICHALÍK J. and REHÁKOVÁ D. (1994) — Early Cretaceous stratigraphy, paleogeography and life in Western Carpathians. Beringeria, **10**: 3–168.

WIERZBOWSKI A., JAWORSKA M. and KROBICKI M. (1999) — Jurassic (Upper Bajocian-lowest Oxfordian) ammonitico rosso facies in the Pieniny Klippen Belt, Carpathians, Poland: its fauna, age, microfacies and sedimentary environment. Stud. Geol. Pol., **115**: 7–74.

WIERZBOWSKI A., AUBRECHT R., KROBICKI M., MATYJA B. A. and SCHLÖGL J. (2004) — Stratigraphy and palaeogeographic position of the Jurassic Czertezik Succession, Pieniny Klippen Belt (Western Carpathians) of Poland and Eastern Slovakia. Ann. Soc. Geol. Pol., **74**: 237–256.

ZĄBEK Z., BARLIK M., KNAP T., MARGAŃSKI S. and PACHUTA A. (1993) — Continuation of geodynamic investigations in the Pieniny Klippen Belt, Poland, from 1985 to 1990. Acta Geophysica Polonica, **41**: 131–150.

ZUCHIEWICZ W. (1980) — Young tectonic movements and morphology of the Pieniny Mts, Polish Western Carpathians. Ann. Soc. Geol. Pol., **50**: 263–300.