Geological Quarterly, 2003, **47** (3): 289–298

Reconstruction of stress directions in the Magura and Silesian Nappes (Polish Outer Carpathians) based on analysis of regional folds

Ryszard SZCZĘSNY

Szczęsny R. (2003) — Reconstruction of stress directions in the Magura and Silesian Nappes (Polish Outer Carpathians) based on analysis of regional folds. Geol. Quart., **47** (3): 289–298. Warszawa.

Statistic analysis of the bed orientation in the Magura and Silesian Nappes was performed in order to establish the directions of regional fold axes. On this ground, variations of the main horizontal stress directions were inferred for both nappes. In the Late Oligocene, in the foreland of the northwards moving Adriatic Microplate, a fan-like pattern of the σ_1 stress trajectories was formed. Initiation of the Magura Nappe and the related regional folds began in such conditions. Evolution of the regional compression involved clockwise rotation from S–N to SW–NE direction. The rotation was caused by the Early Miocene oblique collision of the Carpathian Orogen with the East European Platform. The pattern of fold axes in the Silesian Nappe reflects this rotation.

Ryszard Szczęsny, Institute of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland; e-mail: szczesny@geo.uw.edu.pl *(received: January 3, 2003; accepted: June 16, 2003).*

Key words: Polish Outer Carpathians, stress reconstruction, regional folds, axes directions.

INTRODUCTION

This paper presents a tentative reconstruction of the principal horizontal stress directions, leading to the formation of the first order regional fold structures in the Magura and Silesian Nappes, in the Polish part of the Outer Carpathians (Fig. 1). A few previous attempts of the regional palaeostress reconstruction, available in the Polish literature, are based either on extrapolation of local results — for example from Babia Góra region (Aleksandrowski, 1989, fig. 21 F_L) — or on using the recognised regional schemes (Konon, 2001, fig. 25). In the above publications, the Outer Carpathians were presented as a homogenous tectonic unit. The past palaeostress interpretations were largely based on observations of brittle tectonic mesostructures, such as joints (Zuchiewicz and Henkiel, 1993; Mastella *et al*., 1997; Zuchiewicz, 1997; Mastella and Zuchiewicz, 2000), or faults (Mastella and Szynkaruk, 1998; Rubinkiewicz, 2000), sometimes supplemented by fold analyses (Tokarski, 1975; Mastella, 1988; Aleksandrowski, 1989; Konon, 2001). Data for these studies were collected from limited areas, and as a result the palaeostress reconstructions were of local character (*op. cit.*). There are also interpretations based on data from small number of localities (Tokarski, 1978; Zuchiewicz, 1998; Mastella and Konon, 2002). In such cases, regional stress interpretations could be regarded as hypothetical only.

This paper reports the first research results based on fold analysis. It is based on statistically significant data, from nearly all Polish Outer Carpathians region and provides independent reconstruction of the main stress directions for the both studied nappes.

This study is focused on one group of the first order regional folds, and analysed recent orientation of bedding and fold axes. The inferred directions of the main horizontal stress are influenced by several stages of deformations, with prevailing effects from the period of the most intensive folding. It was designed to determine a general pattern of the main stress distribution and minor stages of folding are not discussed. Their interpretation will be possible after performing analysis of the second order fold axes related to the regional structures.

TECTONIC SETTING

Polish part of the Outer Carpathians comprises three groups of overlapping nappes: marginal, middle and Magura group (Nowak, 1927). This paper concentrates on a study of the Silesian and Magura Nappes, which are parts of the middle group and the

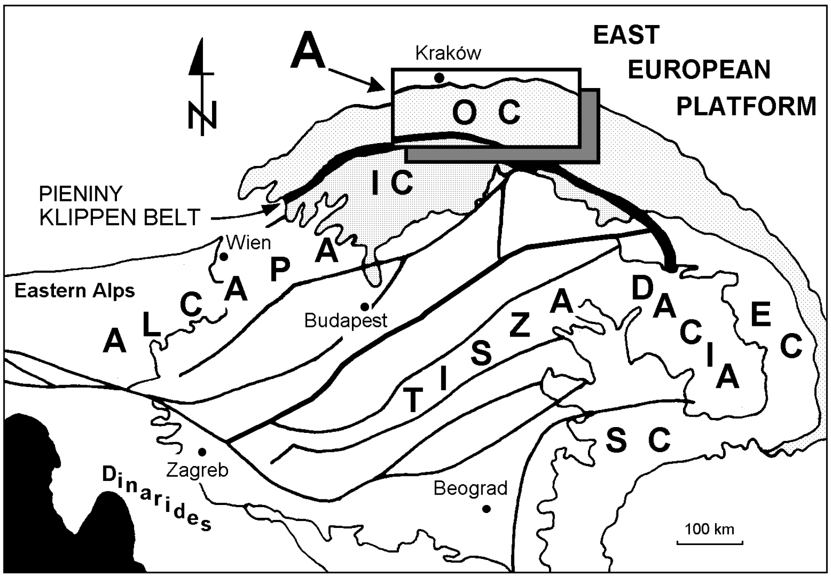

Fig. 1. Carpathians — tectonic sketch with location of the investigated area (after Plašienka *et al*., 1997)

A — investigated area, OC — Outer Carpathians, IC — Inner Carpathians, EC — Eastern Carpathians, SC — Southern Carpathians

Magura group respectively (Fig. 2). Such a scope of their research was chosen because of the wide lateral distribution of these nappes, which allows a detailed analysis of the variability of folds in the Polish part of the Outer Carpathians (Fig. 3).

In cross-sections, both nappes contain a large number of folds (Fig. 2), (Burtan and Sokołowski, 1952; Sokołowski, 1954; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al*., 1989). The folds are of a regional scale, and are parallel to the general strike of both nappes. They usually exceed several tens of kilometres in length (*op. cit*.). The exceptions are fragments of the western part of the Silesian Nappe, and the central part of the Magura Nappe, which are dissected into isolated blocks, rotated against each other (Świderski, 1952; Książkiewicz, 1972; Konon, 2001).

Geometry of the regional folds generally depends on their lithology (Książkiewicz, 1958, 1972; Aleksandrowski, 1989), which is dominated by the presence of rigid, thick-bedded sandstones (e.g. Magura or Istebna Beds, Fig. 4). Such rocks usually form widely-spaced, concentric synclines. Their geometry is influenced by the under- and over-lying ductile shale members, which are typically also folded into lower order structures (Aleksandrowski, 1989). The absence of thick-bedded sandstones and increased content of shales changes folds geometry (Aleksandrowski, 1985, 1989; Ramsay and Huber, 1987).

The difference of geomechanical properties between the sandstones and shales, caused, along their contacts, formation of décollement structures and numerous lower order overthrusts. The northern regional vergency of associated folds resulted in reduction of the northern limbs of anticlines and the southern limbs of synclines (Książkiewicz, 1972; Aleksandrowski, 1989.

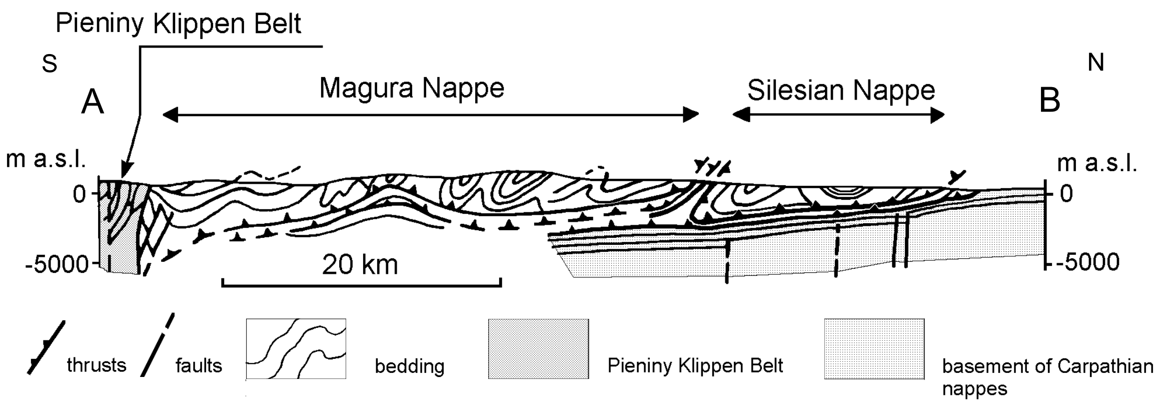

Fig. 2. Schematic cross-section through the Polish Outer Carpathians (after Żytko *et al*., 1989)

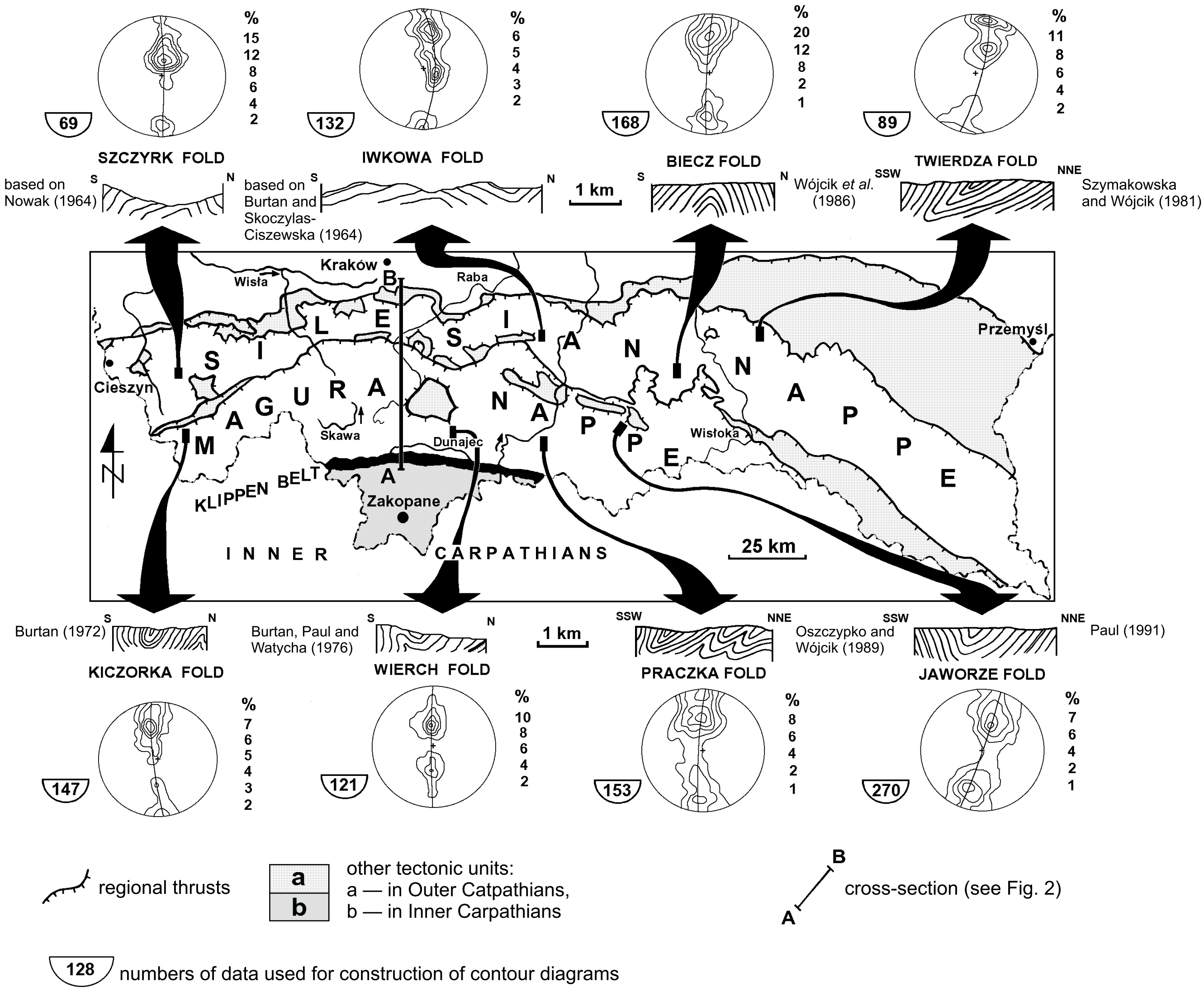

Fig. 3. Silesian and Magura Nappes in the Polish part of Outer Carpathians — map of the investigated area with illustration of selected folds

FOLDS

FOLDS IN THE SILESIAN NAPPE

The relationship between lithology, bed competence and fold geometry is clearly visible in the Silesian Nappe. In the westernmost part of this nappe, up to 2000 m thick complex of thick-bedded, rigid, Cretaceous Godula Sandstones (Fig. 4; Sokołowski, 1954; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989) induced the formation of widely-spaced folds gently inclined to the north (see Szczyrk and Iwkowa Folds — Fig. 3).

To the east, the Godula Sandstones are gradually replaced by more ductile Variegated Shales (*op. cit.*, see also Fig. 4). As a result, to the east of the Dunajec River, the beds were more deformed. Narrow folds (e.g. Biecz Fold; Fig. 3), often imbricated and overturned to the north (e.g. the Twierdza Fold; Fig. 3), occur there. In comparison with the western part of the nappe, these folds are dominated mostly by the shaly beds (*op. cit.*). The number of folds and the width of the nappe increase eastwards.

FOLDS IN THE MAGURA NAPPE

The rigid sandstone of the Inoceramian Beds (known also as the Ropianka Beds), along with the Hieroglyphic and Magura Beds, had the largest influence on the fold geometry of the Magura Nappe (Fig. 2) (Sokołowski, 1954; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989; Ślączka and Kamiński, 1998). But the change of fold shapes is not as clear as in the Silesian Nappe. The lateral lithological changes in members responsible for the fold geometry reflect facies differences of tectonic sub-units such as the units of Krynica, Bystrzyca, Rača and Siary (Fig. 4). The thick-bedded sandstone members play different role within the individual sub-units.

In general, in the western part of the nappe, west of the Skawa River, the synclines are closer spaced than in the Silesian Nappe and fold limbs become steeper. In some cases the beds are overturned. The anticlines are tight (e.g. Kiczorka — Fig. 3) and often imbricated. In the latter case the inverted limbs are absent.

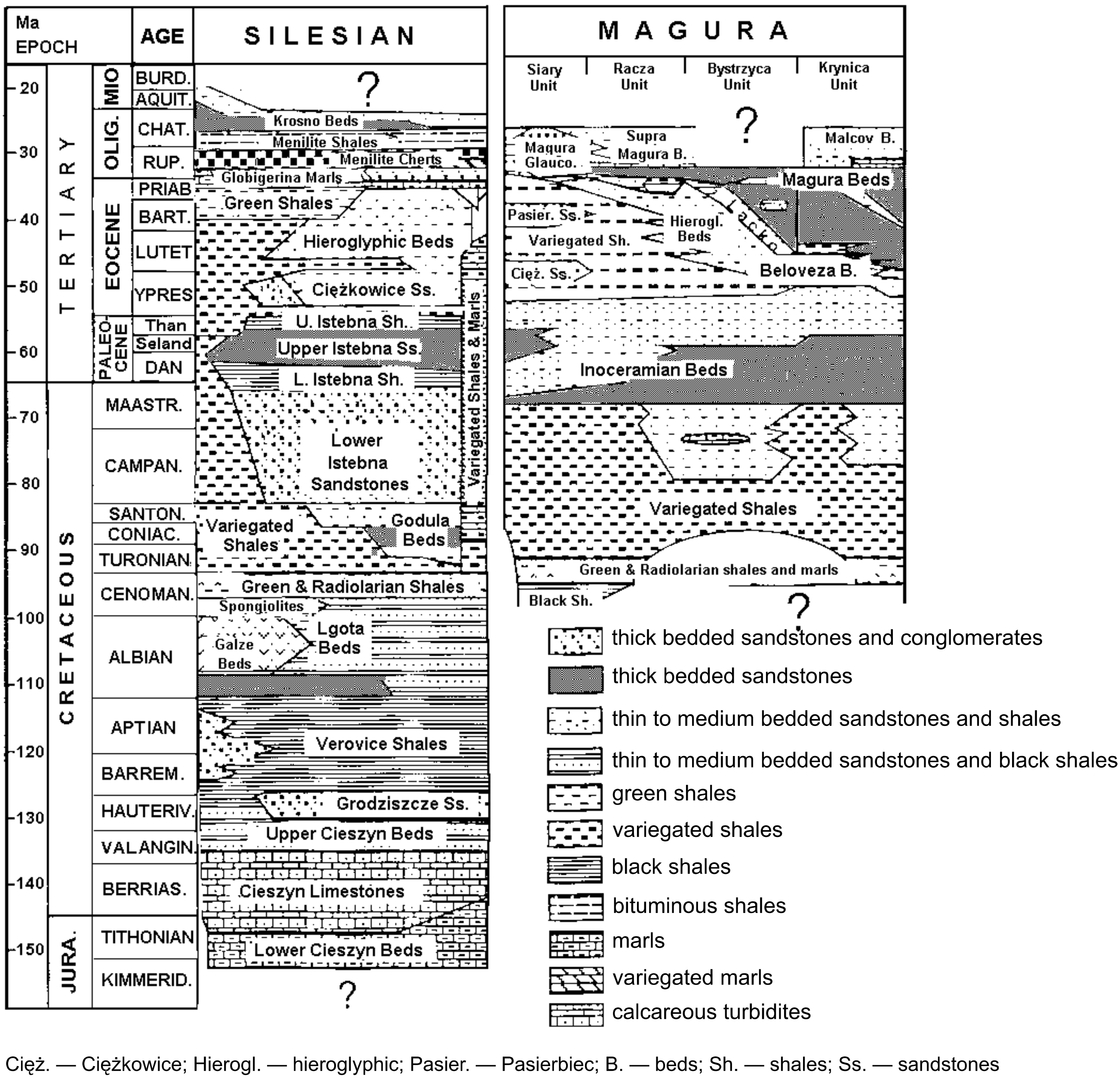

Fig. 4. Lithostratigraphic columns of the Silesian and Magura series (after Ślączka and Kamiński, 1998, modified)

The northernmost part of the Magura Nappe is characterised by wide, asymmetric or overturned to the north synclines, dissected into separate units by transverse dislocations. Anticlines in this area are significantly less common (Konon, 2001). East of the Dunajec River folds are closely-spaced and inclined or overturned to the north (e.g. the Praczka and Jaworze Folds, Fig. 3).

METHODOLOGY

This study is based on the analysis of measurements of bed orientations taken from the relevant 1:50 000 scale map sheets of the Detailed Geological Map of Poland (Bugała *et all.*, 1977). The reliability of the source data was confirmed by author's field observations on selected test sites, and by comparison with more detailed maps (e.g. Guzik and Pożaryski, 1950; Książkiewicz, 1958; Węcławik, 1969; Ryłko, 1992). The database for the eastern part of the Silesian Nappe was supplemented by measurements made by the staff and students of the Tectonics and Geological Cartography Division of the University of Warsaw. A total of 35 000 measurements of bedding orientation were collected.

The above data together comprised the suitable basis for a statistical analysis (Fig. 5). The study area was divided into homogenous tectonic domains according to the requirements by

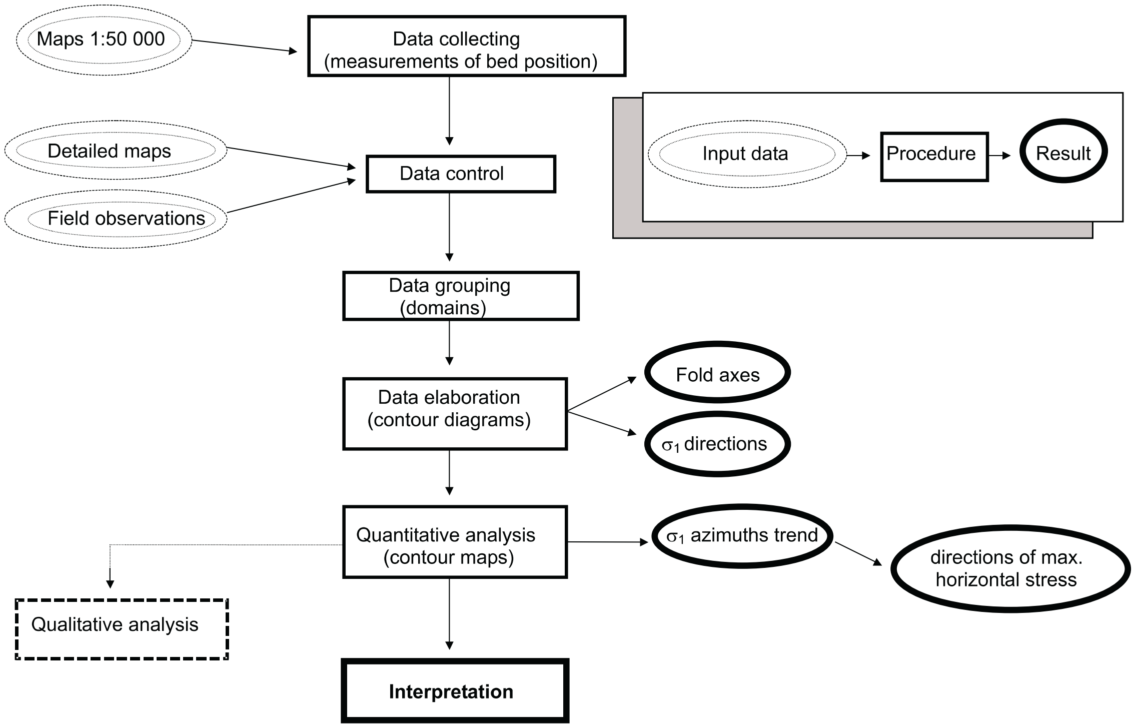

Fig. 5. Methods of study

Jaroszewski (1972) and Mastella (1988). The boundaries of the domains were, in order of importance, overthrusts, large transverse faults, and fault-controlled river valleys. Additionally, the hinge lines of the regional folds were also interpreted as domain boundaries. In consequence, 258 domains were distinguished, including 139 in the Magura Nappe and 119 in the Silesian Nappe (Fig. 6). The number of measurements varied from 26 in regions with a poor exposure, eg. in the Jawornik region (Fig. 6), to 384 in well-exposed areas, eg. the region of Nasiczne (Fig. 6), and was statistically sufficient for each domain (Wilson, 1968). In most cases, the number of measurements in each domain varied from 100–200. Contour diagrams with bedding orientation were prepared for each domain. Normals to the bedding planes were plotted on the lower hemisphere of the Schmidt net (Fig. 7). The diagrams were prepared with the aid of a *STEREONET* software (licence no. 81/1-2, Institute of

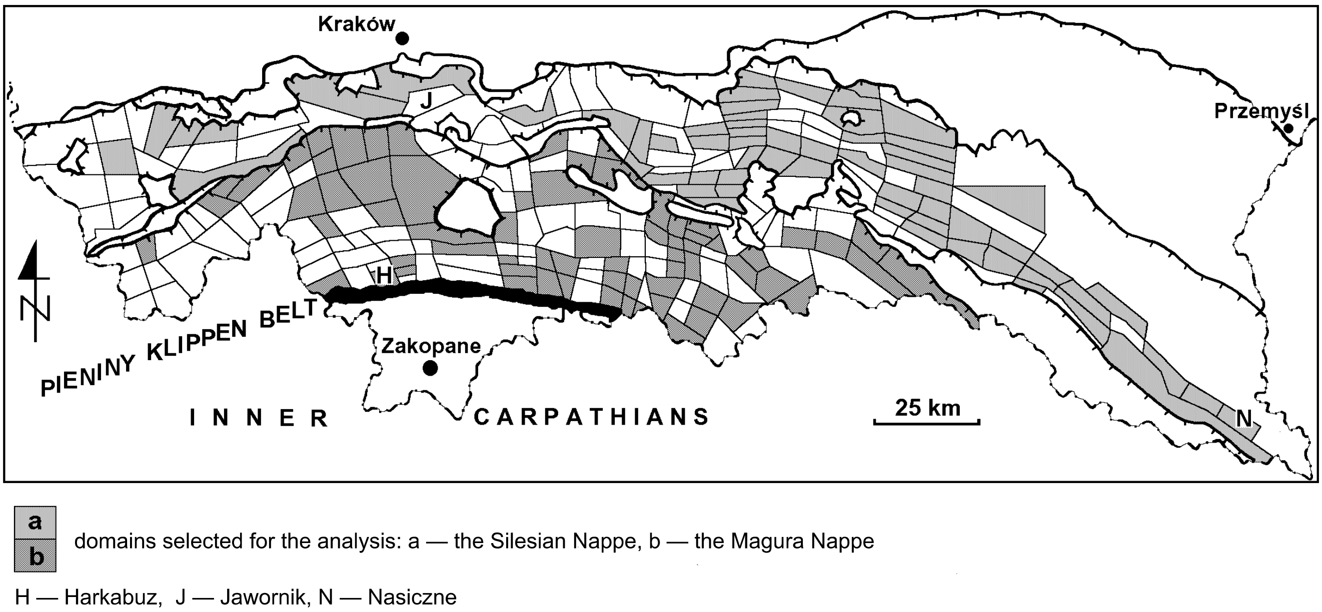

Fig. 6. Boundaries of the tectonic domains

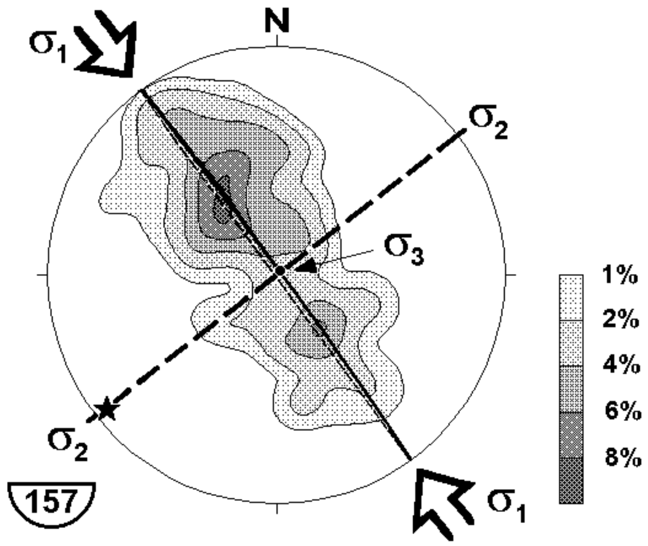

Fig. 7. An exemple of a contour diagram with bed orientation (Harkabuz domain, Magura Nappe — location see Fig. 6)

Geology). Conventional record of bed orientation — strike/dip/dip direction was recalculated by an algorithm (Korput, 1999) to the form strike/dip azimuth, accepted by this software.

According to Ramsay and Huber (1987), the described method of data analysis can be applied only for cylindrical or sub-cylindrical folds. Although the folds analysed are not wholly cylindrical or sub-cylindrical, in some domains short parts of these structures comply with these requirements. 69 domains in the Magura Nappe and 63 domains in the Silesian Nappe were recognised as reliable for this model and were used in this analysis (Fig. 6).

Because fold structures were analysed, two maxima of bedding planes orientation, representing the most frequent positions of beds in limbs, are shown on each diagram. In most cases, higher values of maxima were attained by fold limbs dipping to the south. Asymmetric forms are dominant in the analysed folds and most of them are inclined or overturned northwards (Figs. 2 and 3), therefore outcrops of their southern limbs are wider (Jaroszewski, 1984). The positions of fold axes were determined from the orientation of the fold limbs (Fig. 7), (Jaroszewski, 1984; Ramsay and Huber, 1987).

The final step in the diagram analysis was the determination of the main stress axes. According to Mastella (1988) and Fodor *et al*. (1999), the formation of folds in the Outer Carpathians commenced under horizontal compression, and continued under the influence of force couple in the vertical plane. In this case, the axis of the largest stress σ_1 was horizontal and perpendicular to the fold axes. The medium stress axis σ_2 was also horizontal and perpendicular to σ_1. Its position was parallel to the fold axes. The smallest stress axis σ_3 retained a vertical position (Fig. 7).

The directions of σ_1 stress, determined in the neighbouring domains, were often markedly different (Fig. 8). As a result, the regional direction of σ_1 was difficult to determine. Therefore, the values of σ_1 in the centres of the domains were recalculated using the second-order polynomial by the *RESICAL* software, developed by Krzysztof Nowicki, into the trend surfaces, separately for the Silesian and the Magura Nappes. The trend surfaces are presented, as a contour maps drawn using *SURFER* software (Fig. 9). Contour lines of σ_1 indicate that, in places where the fold axes successively formed towards the foreland of the nappe (Pescatore and Ślączka, 1984; Price and Cosgrove 1990, fig. 10.41), they have the same strike. To show how the maximum horizontal stress changed its direction during formation of the above mentioned folds, the image was supplemented by the trajectories of compression (Fig. 9).

FOLD AXES ORIENTATION TRENDS

Strike of the regional fold axes generally corresponds to the curvature of the Carpathian Arc (Fig. 8). But the trend lines of the Magura and the Silesian Nappes folds are not concentric

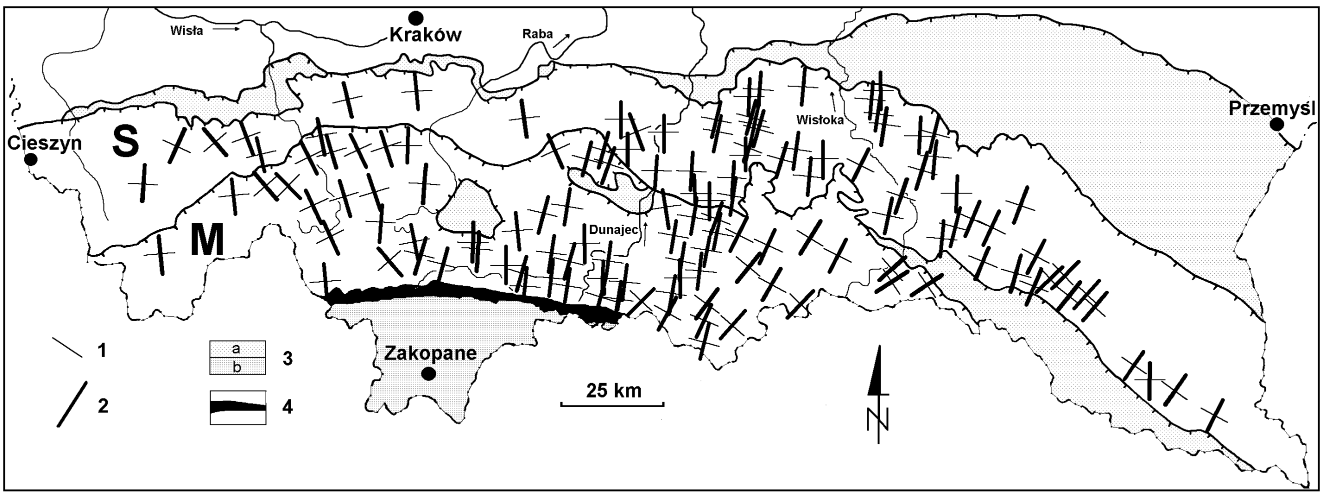

Fig. 8. Distribution of the fold axes and axes of the σ_1 stress estimated for the selected domains in the Silesian and Magura Nappes

S — Silesian Nappe, M — Magura Nappe; 1 — fold axes; 2 — σ_1 stress axes; 3 — other tectonic units: a — in Outer Carpathians, b — in Inner Carpathians; 4 — Pieniny Klippen Belt

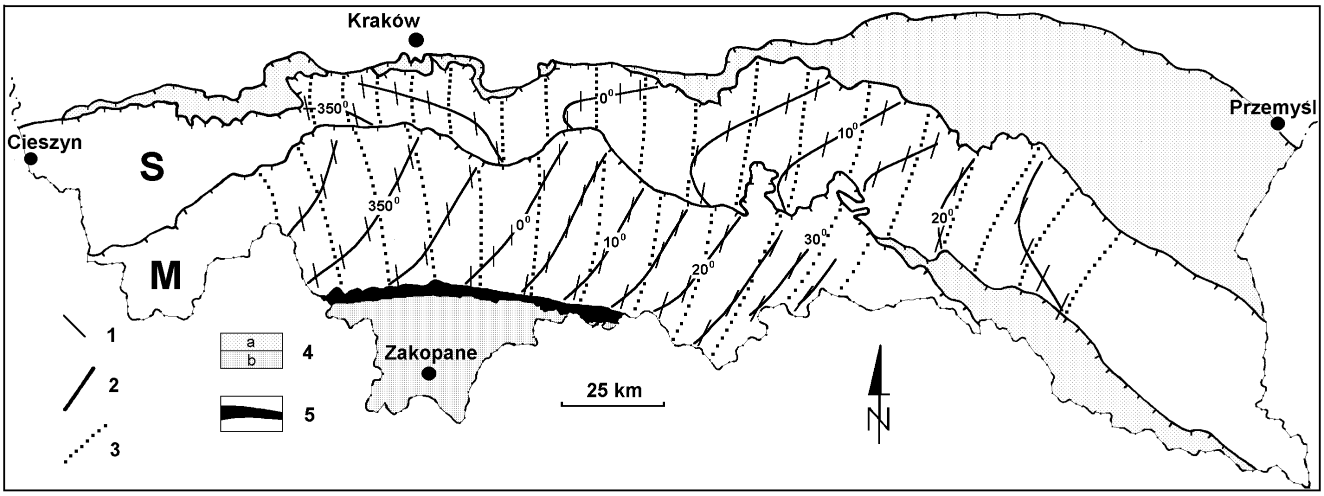

Fig. 9. Trend plane of the σ_1 stress azimuths in the Silesian and Magura Nappes

S — Silesian Nappe, M — Magura Nappe; 1 — isolines of the σ_1 stress azimuths; 2 — σ_1 stress axes; 3 — trajectories of compression; 4 — other tectonic units: a — in Outer Carpathians, b — in Inner Carpathians; 5 — Pieniny Klippen Belt

(Nowak, 1927; Świderski, 1952). The direction of the fold axes is independent of the mapped extent of the thrusts. The thrust boundaries, due to their erosional character, are characterised by variable frontal geometries (Fig. 8, see also Sokołowski, 1954; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989).

SILESIAN NAPPE

In the Silesian Nappe, axes of the regional folds in the analysed part of the Outer Carpathians, form an northward pointing arc (Fig. 8). In the middle part of the Polish section of the Carpathian Arc, between Raba and Wisłoka Rivers, folds with nearly parallel axes prevail. Towards the east they gently turn to the WNW–ESE. In the easternmost part of the arc, east of the Wisłoka River, 100–120° azimuths of fold axes dominate. Towards the west of the Raba River fold axes striking 55–85° are most common (Fig. 8).

MAGURA NAPPE

Similar pattern of fold axes is also observed in the Magura Nappe. In the middle part of the nappe, between the Skawa and Dunajec Rivers, most of the fold axes strike 90–100° (Fig. 8). West of the Skawa River folds with axes striking 70–80° prevail, while towards the east of the Dunajec River, strikes of fold axes gradually turn to the NW–SE.

STRESS FIELD RECONSTRUCTION

SILESIAN NAPPE

In the Polish part of this nappe the directions of the σ_1 stress, which are perpendicular to the fold axes, form a fan-like pattern, open towards the north (Fig. 8). In the middle part of the arc, between the Raba and Wisłoka Rivers, the dominating directions of σ_1 are almost meridional (Fig. 8). In the eastern part of the nappe, east of the Dunajec River, σ_1 directions turn eastwards while in the west, west of the Skawa River, they turn westwards. This pattern is visible on the contour map. On the map of σ_1 trend (Fig. 9), the σ_1 azimuths in the Silesian Nappe west of the Raba River trend WNW–ESE, whereas east of the Raba they change from NW–SE near the Magura thrust front, to NNE–SSW or to NE–SW near the Silesian frontal thrust. The σ_1 azimuths along the nappe strike change consequently from 350° in the west to 25° in the east (Fig. 9).

In the Silesian Nappe, the compression directions determined from the σ_1 azimuths have a fan-like pattern. North of the Magura thrust front they slightly bend to the east, especially in the western and eastern parts of the nappe (Fig. 9).

MAGURA NAPPE

Like in the Silesian Nappe, the σ_1 stress directions in the Magura Nappe have also a fan-like pattern (Fig. 8). Between the Dunajec and Raba Rivers, the σ_1 directions are almost meridional. East of the Dunajec River they turn eastwards, whereas in the west of the Raba River they change to westwards (Fig. 8).

On the map of σ_1 trends (Fig. 9), the contour lines of σ_1 azimuths, in almost the entire Magura Nappe have SW to NE directions. Directions of the σ_1 azimuths gradually change westwards, from 35° east of the Dunajec River to 345° west of the Skawa River.

The final trajectories of compression directions determined in the Magura Nappe have a similar pattern to these in the Silesian Nappe. But in this case, the trajectories change weakly to the west from the hinterland to the foreland of the nappe (Fig. 9).

INTERPRETATION OF THE RESULTS

STRESS FIELD EVOLUTION

The analysed part of the Carpathian Arc (see Fig. 1) was formed as a result of the influence of the ALCAPA block (northern fragment of the Adriatic Plate) on the Eurasiatic Plate (Birkenmajer, 1976; Ney, 1976; Książkiewicz, 1977; Tapponier, 1977; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984; Plašienka *et al.*, 1997; Fodor *et al.*, 1999).

If the development of the Magura Nappe began in the Late Oligocene (Burchfiel, 1980; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984; Mastella, 1988; Roca *et al.*, 1995), and forming of the Silesian Nappe commenced in the Early Miocene (Oszczypko and Tomaś, 1985; Roca *et al.*, 1995), then the folds forming in the Magura Nappe should reflect the influence of the earlier regional stress field compared with the folds of the Silesian Nappe.

Such interpretation is confirmed by the diverse changes in trajectories of compression direction determined in both nappes (Fig. 9). This indicates, that the formation of folds in the Magura and the Silesian Nappes was not a continuous and the internal deformations of both these megastructures reflect different stages of the regional stress field evolution.

The Late Oligocene regional stress compression in the hinterland of the Flysch Carpathians was from SSE to NNW (Marko *et al*., 1991; Fodor *et al*., 1999). The fan-like distribution of the compression trajectories within the Magura Nappe (Fig. 9) reflects the press of the Adriatic Microplate (Laubscher, 1972), similar to stress patterns observed in other collision zones, such as Taiwan (Angelier *et al*., 1986; Huchon *et al*., 1986) or on the Alpine foreland (Laubsher, 1972). This study was limited to the Polish part of the Carpathian Arc and the recognised fan is not complete. Nevertheless, the observed distribution of trajectories in the Magura Nappe is consistent with interpretations of the compression directions from the Oligocene/Miocene boundary obtained by Aleksandrowski (1989) and based on observations of tectonic structures in the western part of this nappe. It is also in agreement with interpretation of Fodor *et al*. (1999) based on multidisciplinary investigations.

According to Mastella (1988), beds within the developing Magura Nappe were already folded. Therefore, the recently observed distribution of fold axes direction reflects stress pattern during the fold development implied by the ALCAPA advancing towards the East European Plate.

An opposite compression trajectories change pattern exists in the Silesian Nappe (see Fig. 9). This indicates that that there was a change in the direction of regional compression prior to the development of folds in the Silesian Nappe. This change was probably caused by the Early Miocene oblique collision of the Carpathian Orogen with the East European Platform (Marko *et al*., 1991; Kováč *et al*., 1994; Plašienka *et al*., 1997). As a result, large WSW–ENE strike-slip faults were activated in the Inner Carpathians (Marko *et al*., 1991; Plašienka *et al*., 1997). Sinistral displacements along these faults caused counter-clockwise rotations of the basement blocks (domino effect — Marko *et al*., 1991). The dynamic processes in the Inner Carpathians influenced the stress field in their foreland.

In the Outer Carpathians, the direction of regional compression changed gradually from N–S to SW–NE by the end of the Badenian (Aleksandrowski, 1985; Mastella, 1988; Marko *et al*., 1991; Jarosiński, 1998; Fodor *et al*., 1999). Concurrent migration of the front of fold deformations towards the foreland and eastwards (Tokarski, 1978; Pescatore and Ślączka, 1984; Żytko, 1985; Aleksandrowski, 1989), responding to the pattern of trajectories of the compression directions within the Silesian Nappe (Fig. 9), reflects such changes of the regional stress field. This interpretation is consistent with the pattern of the stress field changes proposed by Aleksandrowski (1989).

RELATION OF FOLDS TO OTHER TECTONIC STRUCTURES

Folds in the Outer Carpathians were formed after formation of shear joints and before the development of strike-slip faults and extensional joints (Mastella, 1988; Zuchiewicz and Henkiel, 1993; Mastella and Szynkaruk, 1998; Mastella and Zuchiewicz, 2000).

The results of this study are similar as in other publications on brittle deformations. Directions of the principal horizontal stress $\sigma_{1,}$ separated from the pre-folding (Eocene–Oligocene) shear joints, show that until Miocene, the regional compression in the Outer Carpathians had stabile northward direction (Mastella *et al*., 1997; Zuchiewicz, 1998; Fodor *et al*., 1999; Mastella and Konon, 2002). Under such conditions, regional folds of the Magura Nappe were developed at the turn of Oligocene and Miocene (Burchfiel, 1980; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984; Mastella, 1988; Roca *et al*., 1995; Fodor *et al*., 1999). Folds in the Silesian Nappe developed in response to the Early Miocene collision of the Carpathians. This collision caused also fold bending in the Magura Nappe and the development of post-folding deformations (Nemčok *et al*., 1993) similar to those recognised on the Alpine foreland (Laubsher, 1972) or in Taiwan (Angelier *et al*., 1986; Huchon *et al*., 1986). Bending of the Carpathians generated strong extension, parallel to the strike of regional structures, which lead to formation of fan-like network of dextral strike-slip faults, cutting through the existing folds (Mastella and Szynkaruk, 1998; Rubinkiewicz, 2000; Konon, 2001).

This extension, together with the Late Miocene uplift of the Carpathians, produced extension joints (Mastella *et al*., 1997). Their analysis indicates that the directions of decreasing regional compression had a fan-like pattern, weakly divergent to the north (Mastella *et al*., 1997; Zuchiewicz, 1998; Mastella and Konon, 2002).

SUMMARY

The statistical analysis of bedding orientation in limbs of the regional folds was based on data from the existing 1:50 000 geological maps, supplemented by author's field observations. On this ground, strikes of fold axes in homogenous tectonic domains of the Polish part of the Silesian and Magura Nappes were reconstructed (Fig. 8).

Directions of compression responsible for fold development were inferred from the recent fold pattern (Fig. 9). This work improved understanding of compression directions in this part of Carpathians.

In this study, the Outer Carpathians were shown as a homogenous tectonic unit and the presented compression directions disregarding the real, more complicated tectonics of the region (Aleksandrowski, 1989; Fodor *et al*., 1999). Moreover, strikes of trajectories were extrapolated onto the entire Polish Outer Carpathians from the results of local observations (*op. cit*.).

Compression directions in the Magura and Silesian Nappe are different. The trajectories in the Magura Nappe generally propagate radially northwards, but towards the thrust front they turn westwards (Fig. 9). In the Silesian Nappe, the compression directions form similar fan-like pattern opened to the north, except near the foreland where the directions turn eastwards. The fan of the trajectories is more open to the north in the Magura than in the Silesian Nappe.

In previous interpretations that the regional folds developed independently in both nappes, under different stress fields. Considering the order of folding (Burchfiel, 1980; Mandl and Shippam, 1981; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984; Oszczypko and Tomaś, 1985; Roca *et al*., 1995), the older compression directions were preserved in the Magura Nappe and the younger ones in the Silesian Nappe. Folding in both nappes was caused by the northwards movement of the ALCAPA Block (Birkenmajer, 1976; Ney, 1976; Książkiewicz, 1977; Tapponier, 1977; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984; Plašienka *et al*., 1997; Fodor *et al*., 1999).

A fan-like pattern of compressional directions, typical for orogenic development was formed in the foreland of this block (Laubsher, 1972; Angelier *et al*., 1986; Huchon *et al*., 1986). Local directions of the main horizontal stress σ_1 were subordinated to the regional stress field. The regional fold axes in the Magura Nappe, formed at the Oligocene and Miocene transition (Burchfiel, 1980; Burchfiel and Royden, 1982; Pescatore and Ślączka, 1984) and are northwards convex along their strikes. The main cause of folding of the Silesian Nappe was Early Miocene oblique collision of the ALCAPA with the East European Platform (Marko *et al*., 1991; Kováč *et al*., 1994; Plašienka *et al*., 1997). This collision changed the direction of regional compression and initiated its clockwise rotation (*op. cit*.). Stress caused by progression of the Magura Nappe resulted in successive development of folds from the hinterland to the foreland. The direction of folding was changing gradually, following rotation of the direction of the regional compression. This interpretation of the main horizontal stress directions is in agreement with the existing publications on the pre-folding (shear joints — Pescatore and Ślączka, 1984; Mastella, 1988; Zuchiewicz and Henkiel, 1993) and post-folding tectonic structures (strike-slip faults, extension joints — Mastella *et al*., 1997; Zuchiewicz, 1998; Mastella and Szynkaruk, 1998; Rubinkiewicz, 2000; Mastella and Konon, 2002).

Post-folding tectonic processes, did not significantly change strikes of the regional folds, but their geometry was complicated by thrusting of nappes. As a result, a new generation of second order folds was formed (Aleksandrowski, 1989). These are, however, invisible in statistical analysis of regional folding.

Acknowledgements. This study was sponsored, in its initial phase, by research project KBN 9T12B02009 (Dr hab. Antoni K. Tokarski) and continued with financial support of project BW 1454/9 conducted in Department of Geology Warsaw University.

The database of bedding orientation was supplemented by measurements from unpublished maps by Leonard Mastella and masters thesis by Monika Cieciura, Piotr Jakubowski, Grzegorz Jaźwiński, Marcin Mazur, Adam Misiuwianiec, Paulina Leonowicz, Piotr Panufnik, Jacek Rubinkiewicz, Jerzy Świątek and Marcin Tarnicki.

I would like to extend my gratitude to Dr hab. Leonard Mastella for useful discussions and critical remarks. I am also indebted to anonymous reviewers for constructive comments on the manuscript.

REFERENCES

ALEKSANDROWSKI P. (1985) — Structure of Mt. Babia Góra region, Magura Nappe, Western Outer Carpathians: an interference of West and East Carpathian fold trends (in Polish with English summary). Ann. Soc. Geol. Polon., **55** (3–4): 373–422.

ALEKSANDROWSKI P. (1989) — Structural geology of the Magura Nappe in the Mt. Babia Góra region, Western Outer Carpathians (in Polish with English summary). Stud. Geol. Pol., **96**.

ANGELIER J., BARRIER E. and HAO TSU CHU (1986) — Plate collision and paleostress trajectories in a fold-thrust belt: the foothills of Taiwan. Tectonophysics, **125** (1–3): 161–178.

BIRKENMAJER K. (1976) — The Carpathian orogen and plate tectonics. Publ. Inst. Geoph. PAN, **A-2** (101): 43–53.

BURCHFIEL B. C. (1980) — Eastern European Alpine system and the Carpathian oroclines — an example of collision tectonics. Tectonophysics, **63**: 31–61.

BURCHFIEL B. C. and ROYDEN L. (1982) — Carpathian Foreland Fold and Thrust Belt and its relation to Pannonian and other Basins. Bull. Am. Ass. Petrol. Geol., **66** (9): 1179–1195.

BURTAN J. (1972) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Wisła. Wyd. Geol. Warszawa.

BURTAN J., PAUL Z. and WATYCHA L. (1976) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Mszana Górna. Wyd. Geol. Warszawa.

BURTAN J. and SKOCZYLAS-CISZEWSKA K. (1964) — Szczegółowa Mapa Geologiczna Polski 1:50 000 (wydanie tymczasowe), Arkusz Męcina. Wyd. Geol. Warszawa.

BURTAN J. and SOKOŁOWSKI S. (1952) — Mapa tektoniczna Karpat Północnych 1:500 000. Pr. Państ. Inst. Geol., **8**.

FODOR L., CSONTOS L., BADA G., GYRFI I. and BENKOVICS L. (1999) — Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data. In: The Mediterranean Basins: Tertiary Extension with the Alpine Orogen. (eds. B. Durand, L. Jolivet, F. Horváth and M. Séranne). Geol. Soc. London Spec. Publ., **156**: 295–334.

GUZIK K. and POŻARYSKI W. (1950) — Biecz anticline (Middle Carpathians) (in Polish with English summary). Biul. Państ. Instyt. Geol., **53**.

HUCHON P., BARRIER E., DE BREMACKER J-C. and ANGELIER J. (1986) — Collision and stress trajectories in Taiwan: a finite element model. Tectonophysics, **125** (1–3): 179–191.

BUGAŁA j., GUZIK O., SŁOWAŃSKA B. AND ROSTKOWSKA W. (1977) — Instrukcja opracowania i wydania Szczegółowej Mapy Geologicznej Polski w skali 1:50 000. Państ. Inst. Geol.

JAROSIŃSKI M. (1998) — Contemporary stress field distortion in the Polish part of the Western Outer Carpathians and their basement. Tectonophysics, **297** (1–4): 91–119.

JAROSZEWSKI W. (1972) — Mesoscopic structural criteria of tectonics of non-orogenic areas: an example from the north-eastern Mesozoic margin of the Świętokrzyskie Mountains (in Polish with English summary). Stud. Geol. Pol., **38**.

JAROSZEWSKI W. (1984) — Fault and fold tectonics. PWN.

KONON A. (2001) — Tectonics of the Beskid Wyspowy Mountains (Outer Carpathians, Poland). Geol. Quart., **45** (2): 179–204.

KORPUT A. (1999) — Algorytm konwersji klasycznego zapisu położenia płaszczyzn geologicznych na wymagany przez oprogramowanie komputerowe. Prz. Geol., **47** (7): 623–624.

KOVÁČ M., KRÁ J., MÁRTON E., PLAŠIENKA D. and UHER P. (1994) — Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. Geol. Carpath., **45**: 83–96.

KSIĄŻKIEWICZ M. (1958) — Stratigraphy of the Magura series in the Średni Beskid (Carpathians) (in Polish with English summary). Biul. Inst. Geol., **153**: 43–96.

KSIĄŻKIEWICZ M. (1972) — Budowa geologiczna Polski. IV. Tektonika. Karpaty. Wyd. Geol.

KSIĄŻKIEWICZ M. (1977) — Hypothesis of plate tectonics and the origin of the Carpathians (in Polish with English summary). Rocz. Pol. Tow. Geol., **47**: 329–353.

LAUBSCHER H. P. (1972) — Some overall aspects of Jura dynamics. Am. J. Sc., **272** (4): 293–304.

MANDL G. and SHIPPAM G. K. (1981) — Mechanical model of thrust sheet gliding and imbrication. In: Thrust and Nappe Tectonics (eds. K. R. McClay and N. J. Price): 79–98. Geol. Soc. London.

MARKO F., FODOR L. and KOVÁČ M. (1991) — Miocene strike-slip faulting and block rotation in Brezovské Karpaty Mts. (Western Carpathians). Miner. Slov., **23**: 189–200.

MASTELLA L. (1988) — Structure and evolution of Mszana Dolna tectonic window, Outer Carpathians, Poland (in Polish with English summary). Ann. Soc. Geol. Polon., **58**: 53–173.

MASTELLA L. and KONON A. (2002) — Tectonic beding of the Outer Carpathians in the light of joints analysis in the Silesian Nappe (in Polish with English summary). Prz. Geol., **50** (6): 541–550.

MASTELLA L. and SZYNKARUK E. (1998) — Analysis of the fault pattern in selected areas of the Polish Outer Carpathians. Geol. Quart., **42** (3): 263–276.

MASTELLA L., ZUCHIEWICZ W., TOKARSKI A. K., RUBINKIEWICZ J., LEONOWICZ P. and SZCZĘSNY R. (1997) — Application of joint analysis for paleostress reconstructions in structurally complicated settings: case study from the Silesian nappe, Outer Carpathians (Poland). Prz. Geol., **45** (10): 1064–1066.

MASTELLA L. and ZUCHIEWICZ W. (2000) — Jointing in the Dukla Nappe (Outer Carpathians, Poland): an attempt of palaeostress reconstruction. Geol. Quart., **44** (4): 377–390.

NEMČOK M. (1993) — Transistion from convergence to escape: field evidence from the Western Carpathians. Tectonophysics, **217**: 117–142.

NEY R. (1976) — The Carpathians and plate tectonics. Prz. Geol., **24** (6): 309–314.

NOWAK J. (1927) — Zarys tektoniki Polski. II Zjazd Słowiańskich Geografów i Etnografów w Polsce. Kraków.

NOWAK W. (1964) — Szczegółowa Mapa Geologiczna Polski 1:50 000 (wydanie tymczasowe), Arkusz Skoczów, Wyd. Geol. Warszawa.

OSZCZYPKO N. and TOMAŚ A. (1985) — Tectonic evolution of marginal part of the Polish Flysch Carpathians in the Middle Miocene. Geol. Quart., **29** (1): 109–128.

OSZCZYPKO N. and WÓJCIK A. (1989) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Nowy Sącz. Wyd. Geol. Warszawa.

PAUL Z. (1991) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Grybów. Wyd. Geol. Warszawa.

PESCATORE T. and ŚLĄCZKA A. (1984) — Evolution models of the flysch basins Northern Carpathians and the Southern Apeninnes. Tectonophysics, **106** (1–2): 49–70.

PLAŠIENKA D., GRECULA P., PUTIŠ M., KOVÁČ M. and HOVORKA D. (1997) — Evolution and structure of the Western Carpathians: an overwiew. In: Geological Evolution of the Western Carpathians. Miner. Slovaca-Monograph, Bratislava.

PRICE N. J. and COSGROVE J. W. (1990) — Analysis of geological structures. Cambridge Univ. Press.

RAMSAY J. G. and HUBER M. I. (1987) — The techniques of modern structural geology. 2, Folds and Fractures. Acad. Press Ltd. London.

ROCA E., BESSEREAU G., JAWOR E., KOTARBA M. and ROURE F. (1995) — Pre-neogene evolution of the Western Carpathians: constrains from the Bochnia-Tatra Mountains section (Polish Western Carpathians). Tectonics, **14** (4): 855–873.

RUBINKIEWICZ J. (2000) — Development of fault pattern in the Silesian Nappe: Eastern Outer Carpathians, Poland Western Bieszczady Mts. Geol. Quat., **44** (4): 391–403.

RYŁKO W. (1992) — Lithostrtatigraphy of the magura-nappe sediments in the south-east part of the Beskid Żywiecki Mts. (External Carpathians) (in Polish with English summary). Biul. Państw. Inst. Geol., **368**: 37–64.

SOKOŁOWSKI S. (1954) — Mapa Geologiczna Karpat Polskich (część zachodnia) skala 1:200 000. Wyd. Geol. Warszawa.

SZYMAKOWSKA F. and WÓJCIK A. (1981) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Jedlicze. Wyd. Geol. Warszawa.

ŚLĄCZKA A. and KAMIŃSKI M. A. (1998) — A guidebook to excursions in the Polish Flysch Carpathians. Grzybowski Foundation Spec. Pub., **6**.

ŚWIDERSKI B. (1952) — Z zagadnień tektoniki Karpat północnych. Pr. Państ. Inst. Geol., **8**.

ŚWIDZIŃSKI H. (1958) — Mapa Geologiczna Karpat Polskich (część wschodnia). Skala 1:200 000. Wyd. Geol. Warszawa.

TAPPONIER P. (1977) — Evolution tectonique du systeme alpin en Méditerranée: poinçonnement et écrasement ridige plastique. Bull. Soc. Géol. France, **19**: 437–460.

TOKARSKI A. K. (1975) — Structural analysis of the Magura Unit between Krościenko and Zabrzeż (Polish Flysch Carpathians). Ann. Soc. Geol. Polon., **45** (3–4): 327–359.

TOKARSKI A. K. (1978) — Orogenesis and morphogenesis of Outer Carpathians and plate tectonics. Stud. Geomorph. Carpatho-Balcanica, **12**: 29–43.

WĘCŁAWIK S. (1969) — The geological structure of the Magura Nappe between Uście Gorlickie and Tylicz, Carpathians, Lower Beskid (in Polish with English summary). Prace Geol. PAN, **59**.

WILSON E. B. (1968) — An introduction to scientific research (Polish edition). Wyd. Naukowe PWN, Warszawa.

WÓJCIK A., JASIONOWICZ J. and SZYMAKOWSKA F. (1986) — Szczegółowa Mapa Geologiczna Polski 1:50 000, Arkusz Jasło. Wyd. Geol. Warszawa.

ZUCHIEWICZ W. (1997) — Reorientation of the stress field in the Polish Outer Carpathians in the light of joint pattern analysis (in Polish with English summary). Prz. Geol., **45** (1): 105–109.

ZUCHIEWICZ W. (1998) — Cenozoic stress field and jointing in the Outer West Carpathians, Poland. J. Geodynamics, **26** (1): 57–68.

ZUCHIEWICZ W. and HENKIEL A. (1993) — Orientation of Late Cainozoic stress field axes in the light of joint pattern analysis in SE part of the Polish Carpathians (in Polish with English summary). Ann. Univ. M. Curie-Skłodowska, **48** (23): 311–348.

ŻYTKO K. (1985) — Some problems of a geodynamic model of the Northern Carpathians. Geol. Quart., **29** (1): 85–108.

ŻYTKO K., GUCIK S., RYŁKO W., OSZCZYPKO N., ZAJĄC R., GARLICKA I., NEMČOK J., ELIÁŠ M., MENČIK E., DVOŘÁK J., STRÁNIK Z., RAKUS M. and MATEJOVSKA O. (1989) — Geological map of the Western Outer Carpathians and their foreland without Quaternary formations 1:500 000. In: Geological Atlas of the Western Outer Carpathians and their Foreland (eds: D. Poprawa and J Nemčok). Wyd. Geol. Warszawa.