Annales Societatis Geologorum Poloniae (2003), vol. 73: 91–101.

STRESS DIRECTIONS IN THE EASTERN PART OF THE SILESIAN NAPPE (POLISH OUTER CARPATHIANS) RECONSTRUCTED FROM THE SECOND-ORDER FOLDS

Ryszard SZCZĘSNY

Institute of Geology, University of Warsaw, Żwirki i Wigury 93, 02-089 Warszawa, Poland; e-mail: szczesny@geo.uw.edu.pl

Szczęsny, R., 2003. Stress directions in the eastern part of the Silesian Nappe (Polish Outer Carpathians) reconstructed from the second-order folds. *Annales Societatis Geologorum Poloniae*, 73: 91–101.

Abstract: A study of the second-order folds in the eastern part of the Silesian Nappe allows one to distinguish two groups of structures: longitudinal ones and those orientated obliquely to the strike of the first-order fold axes. Analysis of orientation of the second-order fold axes has made it possible to reconstruct the orientation of σ_1 stress axes and compression trajectories for each group of folds individually. The results of such a reconstruction imply that the two groups of folds must have been developing independently one from another. Longitudinal folds were formed together with the first-order folds, under the influence of clockwise rotating compression caused by the Early Miocene plate collision, whereas development of the oblique folds was influenced by counterclockwise rotating compression, what seems to be connected with the final push of the Carpathians in Sarmatian times.

Key words: stress analysis, folds, Silesian Nappe, Polish Outer Carpathians.

Manuscript received 26 June 2003, accepted 21 October 2003

INTRODUCTION

The paper presents the results of a study of folds in the main structural units of the Polish Outer Carpathians. The aim of these investigations is to reconstruct tentatively the orientation of the stress field, which was responsible for folding in that area. Former attempts at regional stress reconstruction, available in the Polish literature were, first of all, focusing on brittle tectonic structures (Zuchiewicz & Henkiel, 1993; Zuchiewicz, 1997; Mastella & Szynkaruk, 1998; Mastella & Zuchiewicz, 2000; Rubinkiewicz, 2000). Some interpretations were supplemented by fold analyses (Tokarski, 1975; Mastella, 1988; Aleksandrowski, 1985; 1989; Mastella *et al.*, 1997; Konon, 2001), but there were no interpretations based on folds only. Previous author's studies concerned the first-order folds (see Szczęsny, 2001, 2003). Their results confirmed opinions by Konior (1981), Buła & Jura (1983), Aleksandrowski (1989), and many others that folds in the Carpathians were formed in several stages.

This paper starts a cycle of studies of the second-order folds which were more sensitive to changes of the stress field. Their analysis could provide information about spatial changes of the orientation of horizontal compression following formation of the first-order folds. It is very important because in the western part of the Magura Nappe several sets of second-order folds of different orientations have been distinguished (Sikora & Żytko 1960; Aleksandrowski, 1985; 1989). These second-order folds strike both parallel and obliquely to the first-order folds. It was proved that the above-mentioned folds have been developing independently, under the influence of differently orientated stress field (*op.cit*).

In this paper, data from the eastern part of the Polish Outer Carpathians are presented. The study area covers a part of the Silesian Nappe between Gorlice and Sanok (Fig. 1).

Lithostratigraphy

In the investigated part of the Silesian Nappe, strata representing only the upper part of lithostratigraphic log are exposed (Żytko *et al.*, 1989; Ślączka & Kamiński, 1998; *cf.* Fig. 2). The oldest, Upper Cretaceous strata are composed of sandstones (Lower Istebna Sandstones), whereas the youngest ones are of Oligocene age. They are composed of dark bituminous shales, cherts, and marls (Menilite beds), passing into sandstones of the Krosno beds. These sandstones mark the final episode of sedimentation in the Silesian basin (Żytko *et al.*, 1989; Ślączka & Kamiński, 1989). In the studied area, mostly the Krosno beds are exposed. They build limbs of the regional folds and cores of synclines (Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989). Older Tertiary strata (Paleocene, Eocene) are exposed in

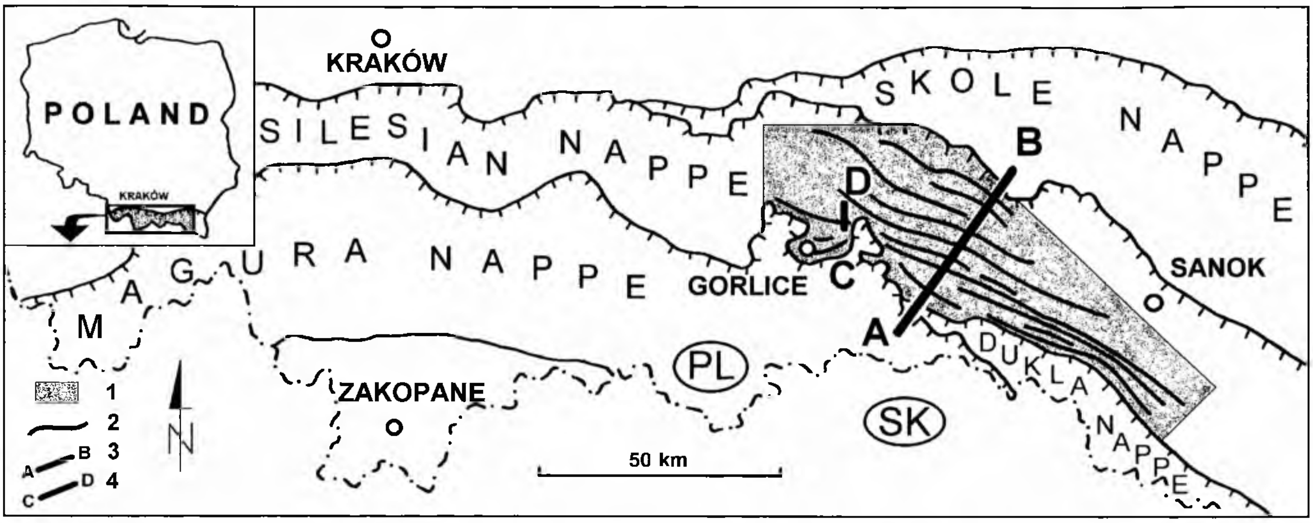

Fig. 1. Location sketch: *1* – study area, *2* – first-order folds, *3* – cross section shown on Fig. 3, *4* – cross section shown on Fig. 4

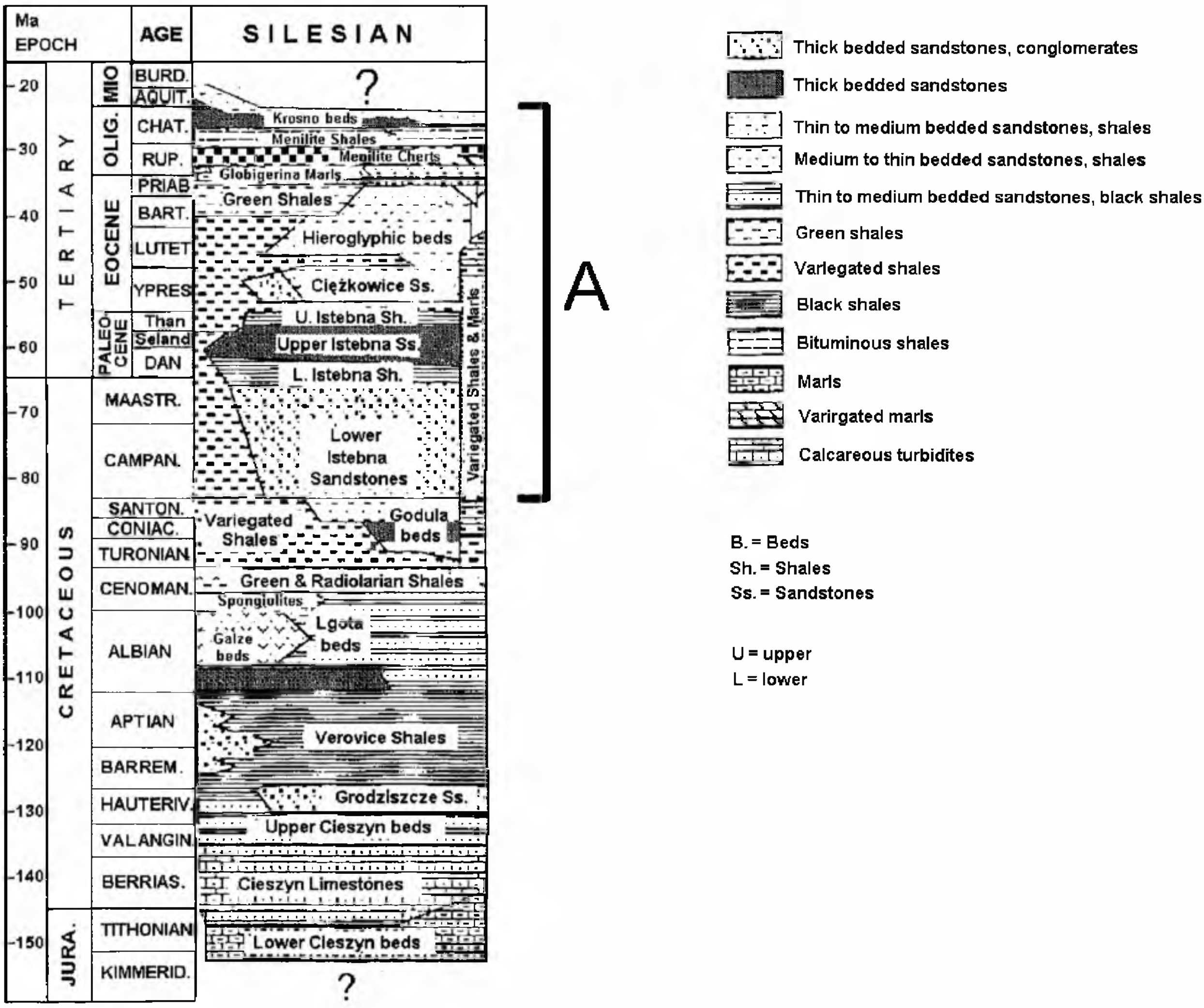

Fig. 2. Lithostratigraphic log of the Silesian Series (after Ślączka & Kamiński, 1998; modified): A – lithostratigraphic units exposed in the study area

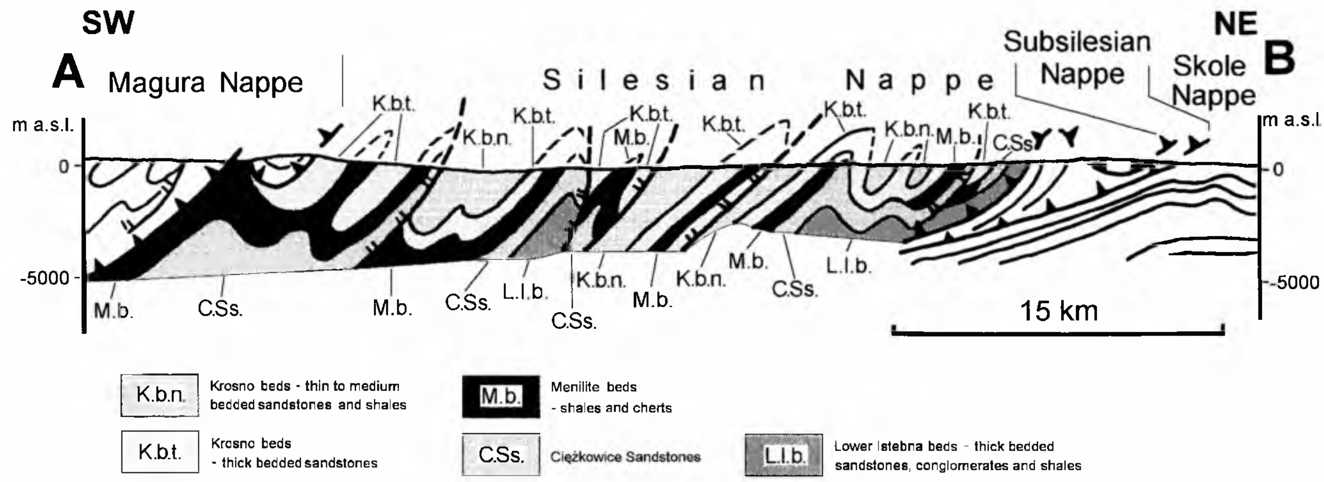

Fig. 3. Schematic cross section through the Silesian Nappe (after Żytko *et al.*, 1989; modified). For location – see Fig. 1

hinges of narrow-spaced anticlines, only (Fig. 3 and 4). However, exposures of the oldest, Cretaceous rocks are known only from cores of anticlines situated in the northern part of the nappe (*op.cit.*)

Tectonics

The studied portion of the Silesian Nappe contains a large number of folds and thrust slices (Fig. 3). Axes of the first-order folds in the western part of the nappe usually strike W–E. Towards the East, the strikes of fold axes gradually turn to the WNW–ESE (Tołwiński, 1921; Guzik & Pożaryski, 1950; Burtan & Sokołowski, 1952; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989; Kuśmierek, 1990; Szczęsny, 2003). The folds are predominantly narrow-spaced, northwards overturned, and often imbricated (Fig. 3). The abundance of faults within the folds is dependent on lithology of host strata (Książkiewicz, 1972; Aleksandrowski, 1989). The main role is played especially by rigid, thick-bedded sandstones of the Lower Krosno beds (Fig. 2). Sandstones are underlain by shally Menilite beds and interbedded by numerous layers of shales (Guzik & Pożaryski, 1950; Burtan & Sokołowski, 1952; Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989). Due to the drastic difference of geomechanical properties between sandstones and shales, along their contacts surfaces of décollements and overthrusts developed. That is the reason why the northern limbs of anticlines and southern limbs of synclines are often reduced (Książkiewicz, 1972; Aleksandrowski, 1989; see also Fig. 3).

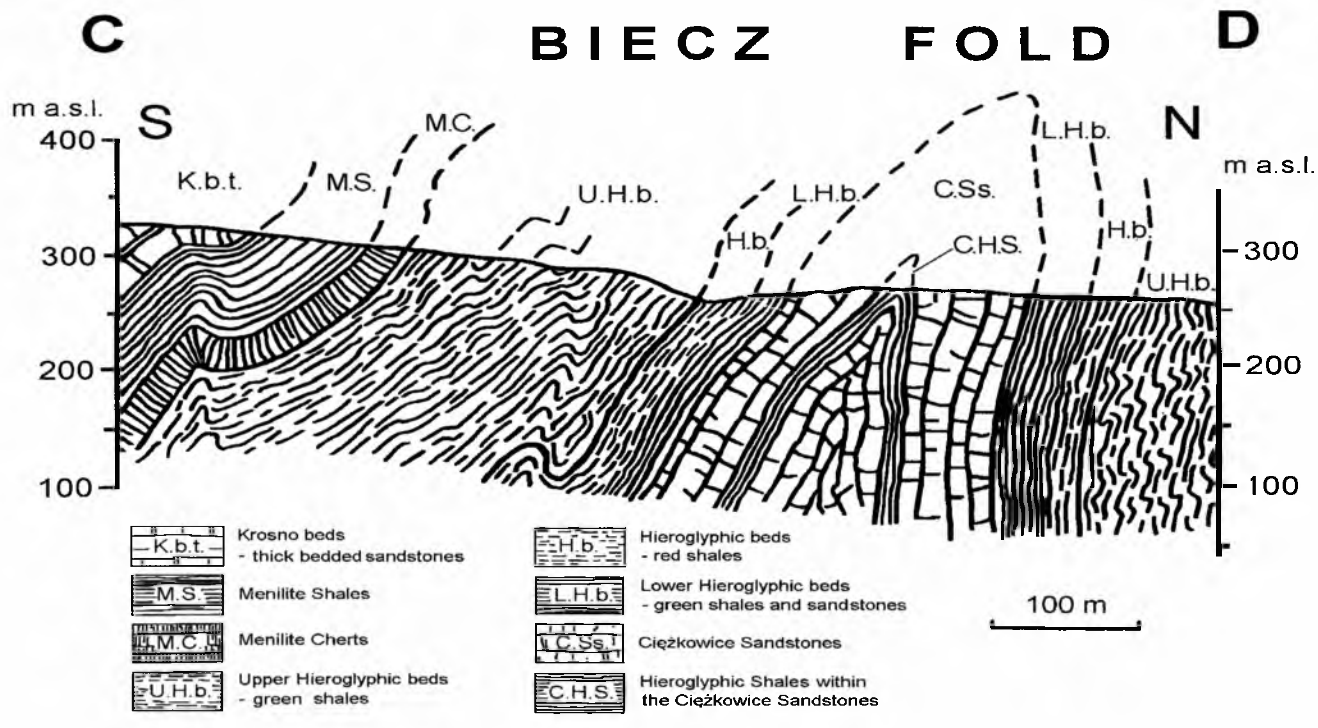

Fig. 4. Cross section through the eastern part of the Biecz fold (after Guzik, 1949; modified). For location – see Fig. 1

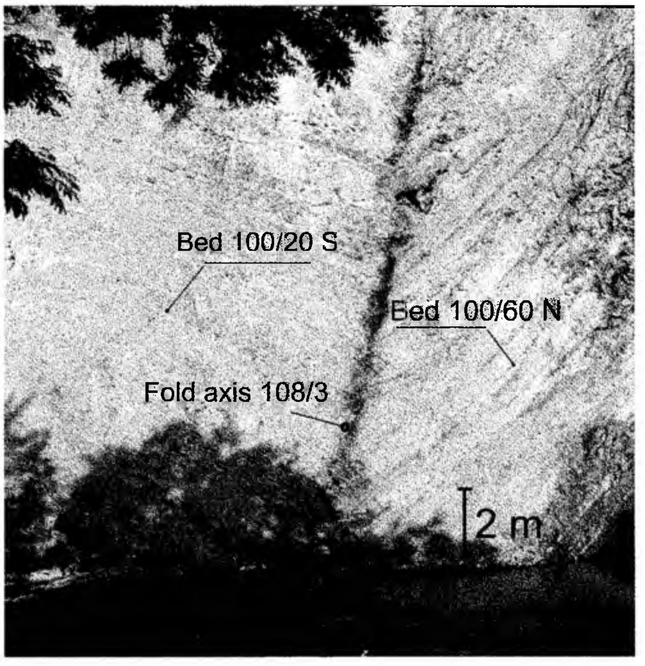

Fig. 5. Syncline built up of the Oligocene Menilite beds on the Wisłok River at Rudawka Rymanowska

Numerous smaller-order folds accompany the first-order folds in the study area. The lithology of flysch strata influenced geometry of the second-order folds, as well. Two main types of flysch complexes can be distinguished: sandstone-dominated, and shale-dominated ones. Quantitative relation of rigid sandstones to ductile shales datermine the geometry of second-order folds. In folds composed mainly of sandstone strata, bed thickness remains constant, *i.e.* the geometry of folds is close to concentric (Fig. 5). However, folding of shale beds induces increase in their thickness in fold hinges, what is typical for similar folds (Fig. 4, see also Aleksandrowski, 1989). Since shale complexes were folded more easily than the others, the majority of second-order folds were formed there (see, e.g., the southern limb of the Biecz Fold – Fig. 4). The analysed folds usually show regular plunge angles; they verge towards the hinge of the first-order antycline as typical drag folds (Fig. 4).

METHODS

The applied methodology is based on the statistic analysis and makes it possible to distinguish general regularity in spatial arrangement of the fold axes, local deviations being eliminated. Recent bed attitudes in limbs of the second-order folds have been measured on the existing geological maps. Measurements were collected from eight sheets of the Geological Map of Poland at the scale of 1: 50,000 (Sikora, 1964; Ślączka, 1964; 1968; Koszarski, 1967; Szymakowska & Wójcik, 1984; Cieszkowski *et al.*, 1988a; Wdowiarz *et al.*, 1991; Wójcik *et al.*, 1992). The database was verified by measurements conducted on detailed maps (Guzik & Pożaryski, 1950; Świdziński, 1973), and author's measurements taken at the selected test sites (Fig. 5). The spacing of the analysed folds varied from tens of metres to several hundreds of metres (see Figs. 4 and 5). Completely exposed folds (Fig. 5) are rare because their extent usually exceeds the dimensions of individual exposures. Therefore, in most cases, only small parts of fold limbs are exposed.

Measurements of bed attitude in fold limbs allow to calculate, with the aid of GEOCALC software, the orientation of fold axes. A total of 703 fold axes have been measured. Taking into consideration the location of individual folds, they were connected with homogenous tectonic domains (fragments of the first-order folds) distinguished in the studied area (Fig. 6; see also Szczęsny, 2003). The boundaries to these domains are: overthrusts, large transversal faults, fault-controlled river valleys, and hinge lines of the first-order folds. The analysed area is covered by 35 domains that comprise from 6 to 62 second-order folds (Fig. 6). The point diagram (Fig. 6), as well as rose-diagram of fold axes (Fig. 7) were prepared for each domain with the aid of the STEREONET software. In this way, predominant direction of fold axes, alongside with one or more secondary directions were distinguished (Fig. 7). The average azimuth of σ_1 stress axis was determined for the main and subsidiary orientation of fold axes in every domain (Fig. 8).

Directions of σ_1 azimuths in the centres of the domains were recalculated, using the second-order polynomial, by the RESICAL software developed by Krzysztof Nowicki (see Szczęsny, 2003), into the trend surfaces of azimuths of the σ_1 axis. It was made for each group of fold axes separately. These surfaces were transformed into contour maps with the help of the SURFER software (Figs. 9 and 10). Contour lines connect points at which values of σ_1 are the same. It means that the folds, being succesively formed towards the foreland of the nappe (Price & Cosgrove, 1990; Fig. 11.41), were influenced by similarly orientated stress. To show how the maximal horizontal stress (compression) changed its direction during formation of the folds, basing on isoline maps, trajectories of compression were drawn (Fig. 11). Finally, the distinguished trajectories of compression inferred from the predominant and secondary directions of fold axes were compared with those distinguished from the analysis of regional, first-order folds (Fig. 12; see also Szczęsny, 2003).

ORIENTATION OF FOLD AXES

In the studied part of the Silesian Nappe, three groups of second-order folds were distinguished (Fig. 7). The most numerous are folds whose axes trend about N95° E (to the north of Gorlice), and constantly turn to N140° E (to the south of Sanok; Fig. 7). Such strikes of fold axes are compatible with those of the first-order folds, from N93° E to N138° E, respectively (see Szczęsny, 2003). The second group, less numerous, contains the folds whose axes change from about N75° E (to the north of Gorlice) to N125° E (to the south of Sanok). They are oblique to the strike of first-order folds, and orientation of their axes is closer to W–E than that of the axes of regional folds (Fig. 7; see also Świdziński, 1958; Książkiewicz, 1972; Żytko *et al.*, 1989).

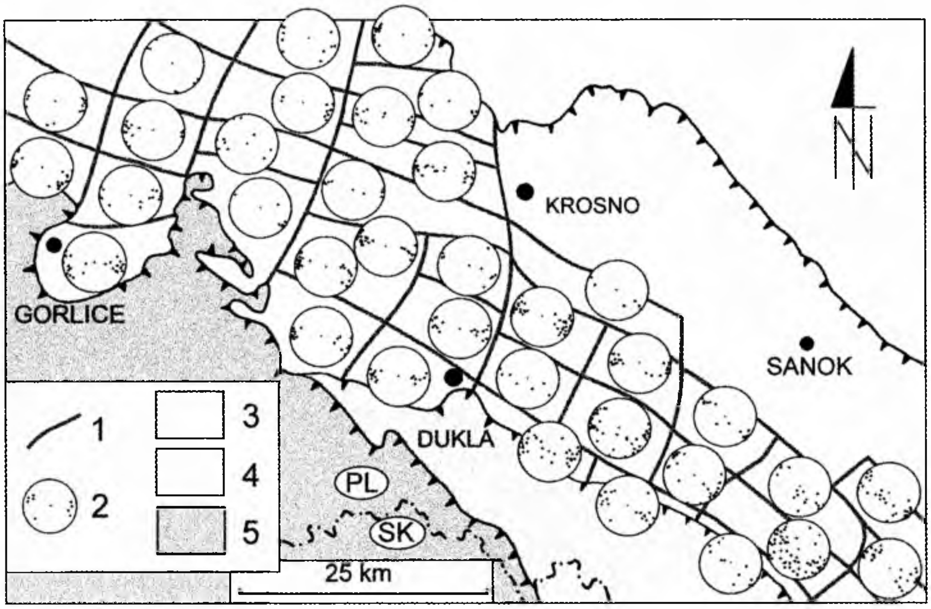

Fig. 6. Characteristics of tectonic domains: *1* – boundaries of tectonic domains, *2* – point diagrams of orientation of the second-order fold axes; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

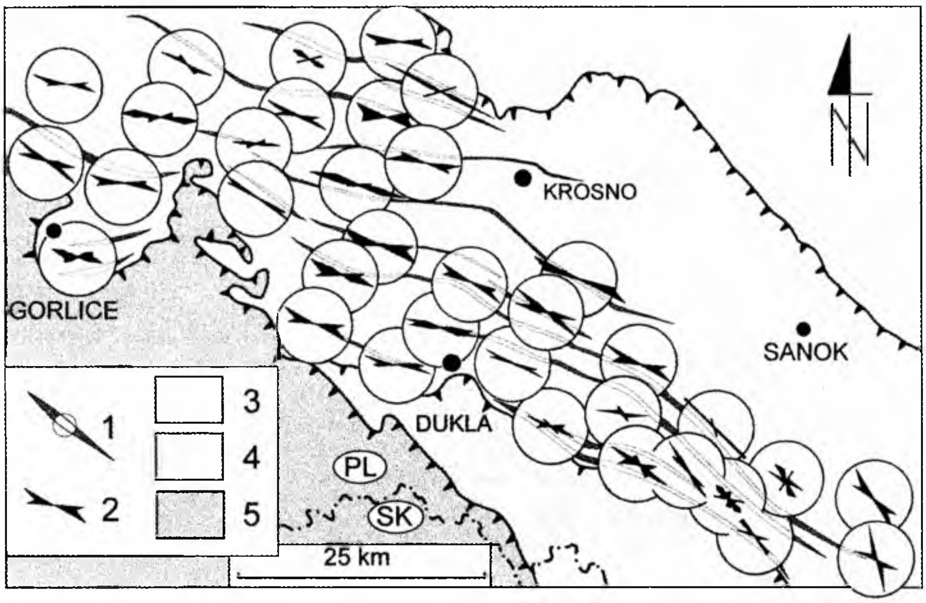

Fig. 7. Distribution of the second-order fold axes within individual domains: *1* – regional folds, *2* – angular histograms of directions of the second-order fold axes; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

Single folds of orientation different than that described as longitudinal and oblique were also distinguished, *e.g.*, to the south-east of the Dukla Unit (Figs. 6 and 7). Azimuths of their axes varies from N–S to S–N without any spatial regularity.

STRESS FIELD RECONSTRUCTION

According to Mastella (1988) and Fodor *et al.* (1999), folding in the Outer Carpathians started under simple horizontal compression conditions. Thus, the axis of maximum stress σ_1 was horizontal and perpendicular to the fold axes. The axis of intermediate stress σ_2 was also horizontal (perpendicular to σ_1 axis) and parallel to the fold axes, whereas the axis of the minimum stress σ_3 was vertical (*op. cit.*). Within each domain, the average direction of the σ_1 stress axis was determined. However, only two groups of the second-order folds were analysed. Folds whose axes were inorderly orientated were not taken into consideration. They were considered as transformed by movements along the transversal faults of regional extent (Tołwiński, 1921; Bur-

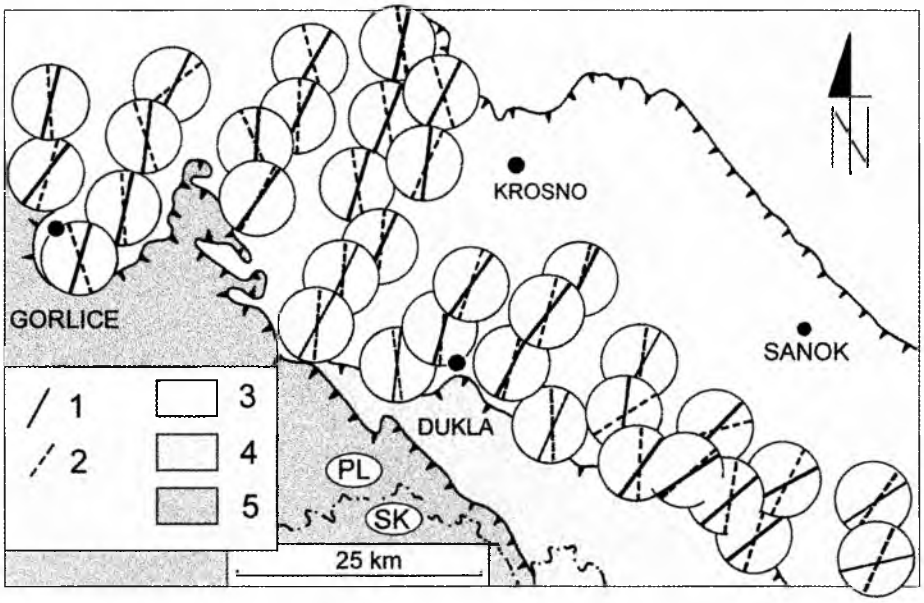

Fig. 8. Distribution of σ_1 stress azimuths within individual domains, based on the analysis of: *1* – longitudinal second-order folds, *2* – oblique second-order folds; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

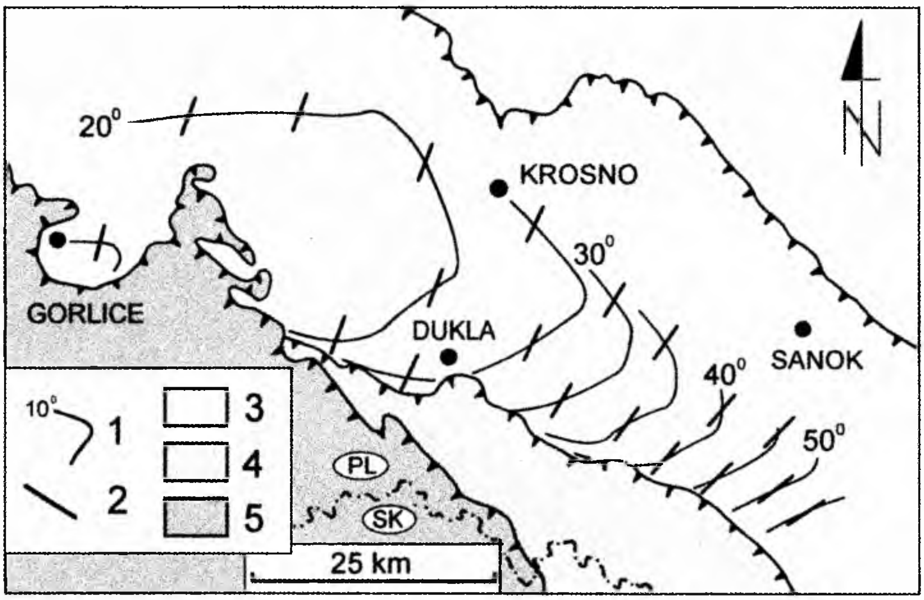

Fig. 9. Trend plane of the σ_1 stress azimuths, based on an analysis of the second-order longitudinal folds: *1* – isolines of σ_1 azimuths, *2* – σ_1 azimuths; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

tan & Sokołowski, 1952; Świdziński, 1958; Książkiewicz, 1972; Jaroszewski, 1984; Mastella, 1988; Żytko *et al.*, 1989; Mastella & Szynkaruk, 1998). Therefore, spatial variation of orientation of the axis of principal horizontal stress σ_1 was calculated only for the second-order folds which are longitudinal and oblique to the first-order ones, and separately for each group of folds.

On the maps of trend surfaces, strikes of the isolines of σ_1 stress azimuths are different for longitudinal and oblique folds (Fig. 9 and 10). In the longitudinal folds, orientation of σ_1 stress axes consistently change eastwards from N20°E to N55°E (Fig. 9). Close to the Magura overthrust isolines run first eastwards, then they turn to the NE and, finally, close to the thrust front, they turn westwards (Fig. 9). However, in the oblique folds, azimuths of σ_1 stress axes change from N10°W in the West to N30°E in the East, and isolines run along the strike of the Silesian Nappe (Fig. 10).

The trajectories of compression reconstructed from the distribution of σ_1 stress in the longitudinal folds, towards the Silesian frontal thrust run from SW to NE, gently bending eastwards (Fig. 11), whereas compression trajectories reconstructed from the oblique folds have SSW–NNE direction and slightly bend westwards (Fig. 11). It means that longitudinal folds, forming successively in the eastern part of the Silesian Nappe, were developed under the influence of NE-orientated compression and gently rotated clockwise.

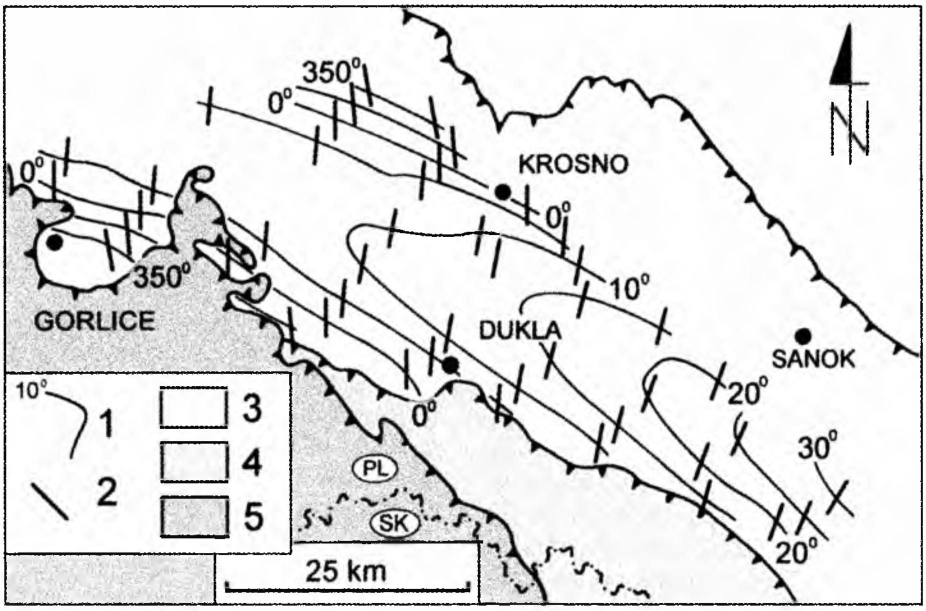

Fig. 10. Trend plane of the σ_1 stress azimuths, based on an analysis of the second-order oblique folds: *1* – isolines of σ_1 azimuths, *2* – σ_1 azimuths; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

This is compatible with the results of an analysis of the first-order folds (Fig. 12; see also Szczęsny 2003). However, formation of the oblique folds was influenced by compression directed to the NNW, with a tendency to counterclockwise rotation. Finally, regional compression interpreted from the oblique folds was directed to the North.

EVOLUTION OF THE STRESS FIELD: DISCUSSION

The analysed area is a part of the Polish Outer Carpathians. Therefore, recently observed distribution of fold axes reflects the stress pattern existing during the fold development, induced by the ALCAPA block (northern part of the Adriatic microplate) advancing towards the East-European Platform (Birkenmajer, 1976; Ney, 1976; Książkiewicz, 1977; Tapponnier, 1977; Burchfiel & Royden, 1982; Pescatore & Ślączka, 1984; Plašienka *et al.*, 1997; Fodor *et al.*, 1999). Development of the Silesian Nappe, as well as of the folds started in Early Miocene time (Oszczypko & Tomaś, 1985; Roca *et al.*, 1995), after formation of most of the folds in the Magura Nappe was completed (Burchfiel, 1980; Burchfiel & Royden, 1982; Pescatore & Ślączka, 1984; Mastella, 1988; Roca *et al.*, 1995). However, there are also opinions that the folds represent synsedimentary deformations, probably of gravitational origin (Żytko, 1985; Kuśmierek, 1990). Thus, they could be older – of Oligocene or even Eocene age.

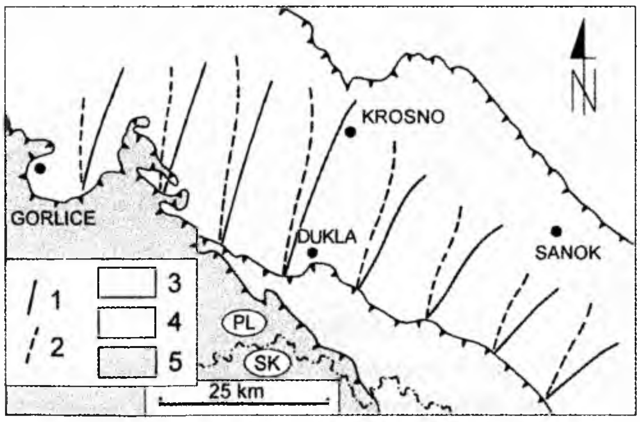

Fig. 11. Trajectories of compression directions based on the analysis of: *1* – longitudinal second-order folds, *2* – oblique second-order folds; *3* – Skole Nappe, *4* – Dukla Nappe, *5* – Magura Nappe

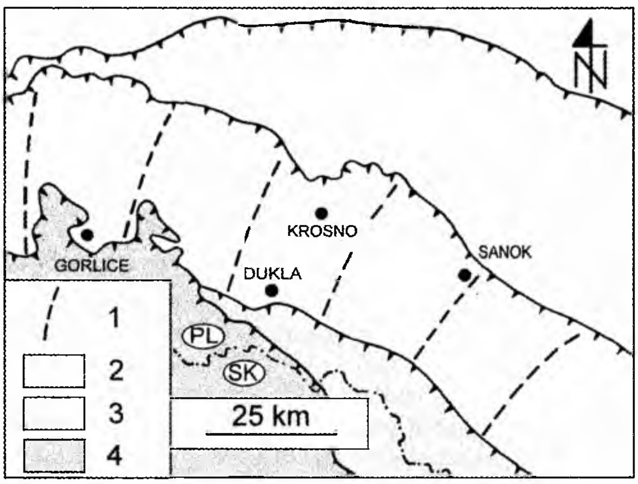

Fig. 12. Trajectories of compression directions based on the analysis of the first-order folds (after Szczęsny, 2003): *1* – trajectories of the maximum compression; *2* – Skole Nappe, *3* – Dukla Nappe, *4* – Magura Nappe

It seems, nevertheless, that the Early Badenian oblique collision of the Carpathian orogen with the East-European Platform was the most important factor in the formation of folds in the Silesian Nappe (Marko *et al.*, 1991; Kováč *et al.*, 1996; Plašienka *et al.*, 1997). The WSW–ENE-orientated strike-slip faults were activated in the Inner Carpathians (Marko *et al.*, 1991; Plašienka *et al.*, 1997) after this collision. Sinistral displacements along these faults caused counter-clockwise rotations of the basement blocks (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). Such changes of the regional stress field influenced the trend of axes of the first-order folds, developing together with the second-order longitudinal folds (Figs. 11 and 12; see also Szczęsny, 2003). Oblique second-order folds in the Magura Nappe were formed then (Aleksandrowski, 1985, 1989).

Interpretation of the oblique second-order folds in the Silesian Nappe shows that their development was influenced by compression orientated meridionally (Fig. 11). It corresponds with the results of investigations by Zuchiewicz (1998), Csontos *et al.* (1991), and Jarosiński (1998, 1999) who pointed out that recent principal horizontal stress, in this part of the Carpathians, is orientated to the North.

In the interpretation of oblique folds, several reasons of their formation could be taken into consideration (see Aleksandrowski, 1989). They could be a result of:

– Miocene transpressive movement between the Inner and Outer Carpathians, and sinistral displacement along the Pieniny Klippen Belt (Morawski, 1972; Unrug, 1979, 1984; Birkenmajer, 1985, 1986; Jaroszewski, 1984; Royden *et al.*, 1983);

– additionally activated movements along the parallel strike-slip faults in the substratum of the Outer Carpathians could have facilitated development of oblique folds within the flysch cover under the influence of a force couple in a horizontal plane (Jaroszewski, 1984; p. 495);

– subsidiary, thin-skinned overthrusting and folding conformable with the model of the Vienna Basin extension (Ottangian to Badenian), proposed by Royden *et al.* (1983);

– very late tectonic event. Proofs for the existence of tectonic deformations in the Sarmatian were provided by Ney (1968), Książkiewicz (1972), Karnkowski (1974), Buła & Jura 1983, Oszczypko & Tomaś (1985), Cieszkowski *et al.* (1988b), Aleksandrowski (1989), Mastella *et al.* (1997), and Mastella & Szynkaruk (1998). These deformations were connected with the final push of the Magura Nappe (Cieszkowski *et al.*, 1988b).

Taking into consideration the distinguished pattern of compression trajectories (Figs. 11 and 12), in author's opinion, the last interpretation seems to be the most plausible one.

CONCLUSIONS

In the eastern part of the Silesian Nappe, two groups of second-order folds were distinguished (Fig. 7). The first group includes folds whose axes are parallel to the axes of the first-order folds. The second group includes folds oblique to the extent of the first-order folds. Directions of the reconstructed axis of principal stress σ_1 (Figs. 9 and 10), as well as the trajectories of compression (Fig. 11) are different for each group of folds.

The pattern of trajectories of compression inferred from longitudinal second-order folds corresponds with that of the first-order folds (Figs. 11 and 12), i.e. the formation of longitudinal folds must have been connected with the development of the first-order folds. Changes of the compression direction show that formation of these folds was influenced by the NE directed compression which slightly rotated clockwise (Fig. 12; see also Szczęsny, 2003) after the Early Miocene plate collision (Birkenmajer, 1976; Ney, 1976; Książkiewicz, 1977; Tapponnier, 1977; Burchfiel & Royden, 1982; Pescatore & Ślączka, 1984; Plašienka *et al.*, 1997; Fodor *et al.*, 1999). However, the oblique second-order folds were formed under the influence of compression which changed its orientation from the NE to North (Fig. 11). Investigations by Zuchiewicz (1998), Csontos *et al.* (1991), and Jarosiński (1998, 1999) have shown that recent regional compression in the Carpathians is directed to the North. That is why, in author's opinion, the oblique second-order folds are the result of very late tectonic event. It could be the last tectonic push of the Magura Nappe in Sarmatian time, as suggested by Ney (1968), Książkiewicz (1972), Karnkowski (1974), Buła & Jura (1983), Oszczypko & Tomaś (1985), Cieszkowski *et al.* (1988b), Mastella *et al.* (1997), and Mastella & Szynkaruk (1998). The maximum horizontal stress was not strong enough then to destroy a general pattern of the first-order and second-order longitudinal folds. The second-order oblique folds are superimposed on the above mentioned folds.

Validity of the presented interpretation for the whole Polish segment of the Outer Carpathians needs, however, to be confirmed by further studies of the second-order folds.

Acknowledgements

I am indebted very much to Dr. hab. Leonard Mastella for helpful discussions, and to Dr. Jacek Rubinkiewicz for his help in preparing the photographic documentation. Two anonymous reviewers are also thanked for detailed and constructive remarks. This paper was financially supported by the Project BW 1567/02, realised at the Department of Geology of the University of Warsaw.

REFERENCES

Aleksandrowski, P., 1985. Structure of the Mt. Babia Góra region, Magura Nappe, Western Outer Carpathians: an interference of West and East Carpathian fold trends. (In Polish, English summary). *Annales Societatis Geologorum Poloniae*, 53: 373–422.

Aleksandrowski, P., 1989. Structural geology of the Magura Nappe in the Mt. Babia Góra region, Western Outer Carpathians. (In Polish, English summary). *Studia Geologica Polonica*, 96: 1–140.

Birkenmajer, K., 1976. The Carpathian orogen and plate tectonics. *Publications of the Institute of Geophysics, Polish Academy of Sciences*, A-2 (101): 43–53.

Birkenmajer, K., 1985. Major strike-slip faults of the Pieniny Klippen Belt and the Tertiary rotation of the Carpathians. *Publications of the Institute of Geophysics, Polish Academy of Sciences*, A-16 (175): 101–115.

Birkenmajer, K., 1986. Outline of geological evolution of the Pieniny Klippen Belt, Carpathians. (In Polish, English summary). *Przegląd Geologiczny*, 6 (389): 293–304.

Buła, Z. & Jura, D., 1983. Litostratygrafia osadów rowu przedgórskiego Karpat w rejonie Śląska Cieszyńskiego. (In Polish). *Zeszyty Naukowe Akademii Górniczo–Hutniczej, Geologia*, 9 (1): 5–27.

Burchfiel, B. C., 1980. Eastern European alpine system and the Carpathian orocline as an example of collision tectonics. *Tectonophysics*, 63: 31–61.

Burchfiel, B. C. & Royden, L., 1982. Carpathian foreland fold and thrust belt and its relation to Pannonian and other basins. *American Association of Petroleum Geologists Bulletin*, 66: 1179–1195.

Burtan, J. & Sokołowski, S., 1952. Mapa tektoniczna Karpat Północnych 1:500 000. *Prace Państwowego Instytutu Geologicznego*, 8.

Cieszkowski, M., Ślączka, A. & Zuchiewicz, W., 1988. Szczegółowa Mapa Geologiczna Polski 1:50 000, arkusz Jaśliska. *Wydawnictwa Geologiczne*, Warszawa.

Cieszkowski, M., Gonera, M., Oszczypko, N., Ślęzak, J. & Zuchiewicz, W., 1988. Lithostratigraphy and age of Upper Miocene deposits at Iwkowa, Polish West Carpathians. *Bulletin of the Polish Academy of Sciences, Earth Sciences*, 36: 309–329.

Csontos, L., Tari, G., Bergerat, F. & Fodor, L., 1991. Evolution of the stress field in the Carpatho-Pannonian area during the Neogene. *Tectonophysics*, 199: 73–91.

Fodor, L., Csontos, L., Bada, G., Györfi I. & Benkovics, L., 1999. Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data. In: Durand, B., Jolivet, L., Horváth, F. & Séranne, M. (eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. *Geological Society of London, Special Publications*, 156: 295–334.

Guzik, K. & Pożaryski, W., 1950. Biecz anticline (Middle Carpathians). (In Polish, English summary). *Biuletyn Państwowego Instytutu Geologicznego*, 53: plates II, IIa, III, IIIa, IV, V.

Jarosiński, M., 1998. Contemporary stress field distorsion in the Polish part of the Western Outer Carpathians and their basement. *Tectonophysics*, 297: 91–119.

Jarosiński, M., 1999. Badanie współczesnych naprężeń skorupy ziemskiej w głębokich otworach wiertniczych w Polsce metodą analizy struktur breakouts. (In Polish). *Instrukcje i metody badań geologicznych,* 56: 1–144, Państwowy Instytut Geologiczny, Warszawa.

Jaroszewski, W., 1984. Fault and fold tectonics. *Ellis Harwood*, Chichester, 565 pp.

Karnkowski, P., 1974. Zapadlisko przedkarpackie. Część wschodnia (na wschód od Krakowa). (In Polish). In: Budowa Geologiczna Polski, Tom IV. Tektonika, cz. 1. Niż Polski. *Wydawnictwa. Geologiczne*, Warszawa: 402–416.

Konon, A., 2001. Tectonics of the Beskid Wyspowy Mountains (Outer Carpathians, Poland). *Geological Quarterly*, 45 (2): 179–204.

Konior, K., 1981. The role of the Miocene in structure and tectogenesis of the marginal zone of the Carpathians in the Cieszyn-Wadowice area. (In Polish, English summary). *Przegląd Geologiczny*, 1: 5–13.

Koszarski, L., 1967. Szczegółowa Mapa Geologiczna Polski 1:50000, arkusz Rzepiennik – wydanie tymczasowe. *Wydawnictwa Geologiczne*, Warszawa.

Kováč, M., Hudáčková, N., Rudinec, R. & Lankreijer A., 1996. Basin evolution in the foreland and hinterland of the Carpathian accretionary prism during the Neogene: evidence from the Western to Eastern Carpathians Junction. *Annales Tectonicae*, 10 (1-2): 3–19.

Kuśmierek, J., 1990. Outline of geodynamics of Central Carpathian Oil Basin (In Polish, English summary). *Prace Geologiczne Komisji Nauk Geologicznych Polskiej Akademii Nauk, Oddział w Krakowie*, 135: 7–76.

Książkiewicz, M., 1972. Budowa geologiczna Polski, Tom IV, Tektonika cz. 3, Karpaty. (In Polish). *Wydawnictwa Geologiczne*, Warszawa, 228 pp.

Książkiewicz, M., 1977. Hypotesis of plate tectonics and the origin of the Carpathians. *Annales Societatis Geologorum Poloniae*, 47: 329–353.

Marko, F., Fodor, L. & Kováč, M., 1991. Miocene strike-slip faulting and block rotation in Berezovske Karpaty Mts. (Western Carpathians). *Mineralia Slovaca*, 23: 189–200.

Mastella, L., 1988. Structure and evolution of Mszana Dolna tectonic window, Outer Carpathians, Poland. (In Polish, English summary). *Annales Societatis Geologorum Poloniae*, 58: 53–173.

Mastella, L. & Szynkaruk, E., 1998. Analysis of the fault pattern in selected areas of the Polish Outer Carpathians. *Geological Quarterly*, 42: 263–276.

Mastella, L., Zuchiewicz, W., Tokarski, A. K., Rubinkiewicz, J., Leonowicz, P. & Szczęsny, R., 1997. Application of joint analysis for paleostress reconstructions in structurally complicated settings: Case study from Silesian nappe, Outer Carpathians (Poland). *Przegląd Geologiczny*, 45 (10): 1064–1066.

Mastella, L. & Zuchiewicz, W., 2000. Jointing in the Dukla Nappe (Outer Carpathians, Poland): an attempt of palaeostress reconstruction. *Geological Quarterly*, 44: 377–390.

Morawski, W., 1972. Tectonics of the northern limb of the Podhale synclinorium. *Acta Geologica Polonica*, 22: 573–591.

Ney, R., 1968. The role of the "Cracow bolt" in the geological history of the Carpathian foredeep and in the distribution of oil and gas deposits. (In Polish, English summary). *Prace Geologiczne Komisji Nauk Geologicznych Polskiej Akademii Nauk, Oddział w Krakowie*, 45: 7–61.

Ney, R., 1976. The Carpathians and plate tectonics. *Przegląd Geologiczny*, 6: 309–314.

Oszczypko, N. & Tomaś, A., 1985. Tectonic evolution of marginal part of the Polish Flysch Carpathians in the Middle Miocene. *Kwartalnik Geologiczny*, 29: 109–128.

Pescatore, T. & Ślączka, A., 1984. Evolution models of two flysch basins: the Northern Carpathians and the Southern Apeninnes. *Tectonophysics*, 106: 49–70.

Plašienka, D., Grecula, P., Putis, M., Kovač, M. & Hovorka, D., 1997. Evolution and structure of the Western Carpathians: an overwiew. In: Geological evolution of the Western Carpathians. *Mineralia Slovaca – Monograph*, Bratislava: 1–24.

Price N. J. & Cosgrove J. W., 1990. Analysis of Geological Structures. *Cambridge University Press*, Cambridge, 502 pp.

Roca, E., Bessereau, G., Jawor, E., Kotarba, M. & Roure, F., 1995. Pre-Neogene evolution of the Western Carpathians: Constrains from the Bochnia-Tatra Mountains section (Polish Western Carpathians). *Tectonics*, 14: 855–873.

Royden, L., Horváth, F. & Rumpler, J., 1983. Evolution of the

Pannonian basin system 1. Tectonics. *Tectonics*, 2: 63–90.

Rubinkiewicz, J., 2000. Development of fault pattern in the Silesian Nappe: Eastern Outer Carpathians, Poland. *Geological Quarterly*, 44: 391–403.

Sikora, W., 1964. Szczegółowa Mapa Geologiczna Polski, 1:50 000, arkusz Gorlice – wydanie tymczasowe. *Wydawnictwa Geologiczne*, Warszawa.

Sikora, W. & Żytko, K., 1960. Budowa Beskidu Wysokiego na południe od Żywca. (In Polish, English summary). *Biuletyn Instytutu Geologicznego*, 141: 61–204.

Szczęsny, R., 2001. Uwagi o fałdach regionalnych w polskich Karpatach zewnętrznych. (In Polish). *Przegląd Geologiczny*, 49 (9): 833–834.

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

Szymakowska, F. & Wójcik, A., 1984. Szczegółowa Mapa Geologiczna Polski, 1:50 000, arkusz Jedlicze. *Wydawnictwa Geologiczne*, Warszawa.

Ślączka, A., 1964. Szczegółowa Mapa Geologiczna Polski, 1:50000, arkusz Bukowsko. *Wydawnictwa Geologiczne*, Warszawa.

Ślączka, A., 1968. Szczegółowa Mapa Geologiczna Polski, 1:50000, arkusz Żmigród Nowy – wydanie tymczasowe. *Wydawnictwa Geologiczne*, Warszawa.

Ślączka, A. & Kamiński, M. A., 1998. A guidebook to excursions in the Polish Flysch Carpathians. *Grzybowski Foundation Special Publication*, 6, 171 pp.

Świdziński, H., 1958. Mapa Geologiczna Karpat Polskich (część wschodnia), 1:200 000. *Wydawnictwa Geologiczne*, Warszawa.

Świdziński, H., 1973. Z badań geologicznych w Karpatach. (In Polish). *Prace Geologiczne*, 80, 109 pp.

Tapponnier, P., 1977. Evolution tectonique du sistème alpin en Méditerranée: poinçonnement et écrasement rigide plastique. *Bulletin de la Société Geologique de la France*, 19: 437–460.

Tokarski, A. K., 1975. Structural analysis of the Magura Unit between Krościenko and Zabrzeż (Polish Flysch Carpathians). *Annales Societatis Geologorum Poloniae*, 45: 327–359.

Tołwiński, K., 1921. Dyslokacje poprzeczne oraz kierunki tektoniczne w Karpatach Polskich. (In Polish, French summary). *Prace Geograficzne E. Romera*, 6: 27–47.

Unrug, R., 1979. Palinspastic evolution of the Carpathian arc before the Neogene tectogenesis. *Annales Societatis Geologorum Poloniae*, 49: 3–21.

Unrug, R., 1984. Geodynamic evolution of the Carpathians. *Annales Societatis Geologorum Poloniae*, 52: 39–66.

Wdowiarz, S., Zubrzycki, A. & Frysztak-Wołkowska, A., 1991. Szczegółowa Mapa Geologiczna Polski, 1:50 000, arkusz Rymanów. *Wydawnictwa Geologiczne*, Warszawa.

Wójcik, A., Jasionowicz, J. & Szymakowska, F., 1992. Szczegółowa Mapa Geologiczna Polski, 1:50 000, arkusz Jasło. *Wydawnictwa Geologiczne*, Warszawa.

Zuchiewicz, W., 1997. Reorientation of the stress field in the Polish Outer Carpathians in the light of joint pattern analysis. (In Polish, English summary). *Przegląd Geologiczny*, 45 (1): 105–109.

Zuchiewicz, W., 1998. Cenozoic stress field and jointing in the Outer West Carpathians, Poland. *Journal of Geodynamics*, 26: 57–68.

Zuchiewicz, W. & 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, English summary). *Annales Universitatis Mariae Curie-Skłodowska*, 48 (23): 311–348, Lublin.

Żytko, K., 1985. Some problems of a geodynamic model of the Northern Carparhians. *Kwartalnik Geologiczny*, 29: 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., & Matejovska, O., 1989. Geological Map of the Western Outer Carpathians and their foreland without Quaternary formations, 1:500,000. In: Poprawa, D. & Nemčok, J. (Eds.), *Geological Atlas of the Western Outer Carpathians and their Foreland*. Państwowy Instytut Geologiczny, Warszawa.

Streszczenie

REKONSTRUKCJA KIERUNKÓW GŁÓWNEGO NAPRĘŻENIA POZIOMEGO WE WSCHODNIEJ CZĘŚCI PŁASZCZOWINY ŚLĄSKIEJ (POLSKIE KARPATY ZEWNĘTRZNE) NA PODSTAWIE ANALIZY FAŁDÓW DRUGIEGO RZĘDU

Ryszard Szczęsny

Niniejsza praca jest kontynuacją studiów nad rekonstrukcją zmian pola naprężeń odpowiedzialnego za powstanie fałdów w głównych jednostkach strukturalnych polskich Karpat Zewnętrznych (Szczęsny, 2001, 2003). Analiza fałdów drugiego rzędu ma uszczegółowić interpretację uzyskaną z analizy fałdów regionalnych.

Stwierdzone w zachodniej części płaszczowiny magurskiej nałożenie się na siebie zespołów fałdów drugiego rzędu – zgodnych i ukośnych do przebiegu fałdów nadrzędnych (Sikora & Żytko, 1960; Aleksandrowski, 1985, 1989) – wskazuje, iż po głównej fazie deformacji fałdowych miało miejsce wtórne fałdowanie w inaczej już zorientowanym polu naprężeń. Celem niniejszej pracy jest potwierdzenie powyższej sugestii w oparciu o dane pochodzące z innego fragmentu Karpat Zewnętrznych. Wybrany do badań obszar stanowi fragment płaszczowiny śląskiej pomiędzy Gorlicami a Sanokiem (Fig. 1–4).

Interpretacji poddano pomiary współczesnego położenia warstw w skrzydłach fałdów drugiego rzędu. Dane pochodziły głównie z arkuszy Szczegółowej Mapy Geologicznej Polski w skali 1: 50 000 (Sikora, 1964; Ślączka, 1964; Koszarski, 1967; Ślaczka, 1968; Szymakowska & Wójcik, 1984; Cieszkowski *et al.*, 1988a; Wdowiarz *et al.*, 1991; Wójcik *et al.*, 1992). Zostały one uwiarygodnione i uzupełnione w trakcie własnych badań terenowych (Fig. 5), a także przez porównanie z mapami szczegółowymi (np. Guzik & Pożaryski, 1950; Świdziński, 1973). Pomiary położeń warstw ze skrzydeł fałdów posłużyły do obliczenia orientacji osi tych struktur. Łącznie opracowano 703 fałdy, które ze względu na lokalizację zostały połączone w grupy. Granice grup odpowiadały wyznaczonym przez autora granicom jednorodnych tektonicznie domen, będących fragmentami struktur fałdowych wyższego rzędu (Fig. 6; Szczęsny, 2003). Dla każdej z domen opracowano diagram punktowy (Fig. 6) oraz rozetowy położenia osi fałdów, na którym uwidocznił się dominujący kierunek osi oraz jeden lub więcej kierunków podrzędnych (Fig. 7).

Za Mastellą (1988) oraz Fodorem *et al.* (1999) przyjęto, że formowanie fałdów w Karpatach Zewnętrznych było zapoczątkowywane w warunkach prostej kompresji horyzontalnej. W tych warunkach oś największego naprężenia głównego σ_1 była pozioma. Oś pośredniego naprężenia głównego σ_2 była również pozioma i jednocześnie prostopadła do osi σ_1, a jej położenie pokrywało się z kierunkami osi powstających fałdów. Oś naj-

mniejszego naprężenia głównego σ_3 była wówczas pionowa. Kierując się powyższym założeniem w każdej z domen, dla każdego stwierdzonego kierunku osi fałdów, wyznaczono azymuty osi naprężenia głównego σ_1 (Fig. 8).

Wartości azymutów osi σ_1 z fałdów niższego rzędu przypisane środkom domen o określonych współrzędnych zostały w dalszej kolejności przetworzone wielomianem drugiego stopnia na obraz izoliniowy – mapę trendu azymutów σ_1. Sporządzono dwie mapy, jedną dla dominującego kierunku osi głównego naprężenia (Fig. 9), drugą zaś dla najwyraźniejszego kierunku drugorzędnego (Fig. 10). Na podstawie tych map wyznaczono przebiegi trajektorii kierunków kompresji zarówno dla dominującego, jak i drugorzędnego kierunku fałdów (Fig. 11). Ostatnim zabiegiem było porównanie uzyskanych trajektorii z analogicznymi wynikami analizy fałdów pierwszego rzędu (Fig. 12).

W badanej części płaszczowiny śląskiej stwierdzono obecność niezależnych grup fałdów drugiego rzędu (patrz Fig. 7). Osie liczniejszej z nich przebiegają od N95° E na zachodzie do N140° E na wschodzie i wykazują dużą zgodność z rozciągłością fałdów regionalnych (Fig. 7).

Drugą, mniej liczną grupę, stanowią fałdki o przebiegu ukośnym do rozciągłości struktur nadrzędnych. Ich osie, w stosunku do regionalnego przebiegu struktur WNW–ESE, mają w większości przebieg bardziej równoleżnikowy, a ich azymuty mieszczą się w przedziale od N75° E do N125° E (Fig. 7–10).

Trajektorie kompresji odtworzone z fałdów podłużnych mają, przy nasunięciu magurskim, przebieg SW–NE i ku brzegowi płaszczowiny zakręcają lekko na wschód (Fig. 11). Tymczasem trajektorie wyinterpretowane z fałdków ukośnych mają przebieg SSW–NNE i wykazują tendencję do skręcania na zachód (Fig. 11). Oznacza to, zgodnie z modelem Price'a i Cosgrove'a (1990), że kolejne, coraz młodsze generacje fałdów podłużnych były formowane pod wpływem kompresji rotującej zgodnie z ruchem wskazówek zegara. Tymczasem fałdki ukośne poddane były wpływowi kompresji rotującej w przeciwną stronę tak, że ostatecznie była ona skierowana ku północy.

Obszar poddany analizie jest niewielkim fragmentem polskiego odcinka łuku karpackiego. Łuk ten został uformowany na skutek oddziaływania bloku ALCAPY – północnego fragmentu mikropłyty adriatyckiej na płytę euroazjatycką (Birkenmajer, 1976; Ney, 1976; Książkiewicz, 1977; Tapponnier, 1977; Burchfiel & Royden, 1982; Pescatore & Ślączka, 1984; Plašienka *et al.*, 1997; Fodor *et al.*, 1999). Uruchomienie płaszczowiny śląskiej i formowanie fałdów w jej obrębie rozpoczęło się we wczesnym miocenie (Oszczypko & Tomaś, 1985; Roca *et al.*, 1995), po uformowaniu większości analogicznych struktur w płaszczowinie magurskiej (Burchfiel, 1980; Burchfiel & Royden, 1982; Pescatore & Ślączka, 1984, Mastella, 1988; Roca *et al.*, 1995). Po wczesnomioceńskiej skośnej kolizji wymienionych płyt, kierunek regionalnej kompresji na ich przedpolu zaczyna skręcać z S–N na SW–NE pod koniec badenu (Aleksandrowski, 1985; Mastella, 1988; Marko *et al.*, 1991; Jarosiński, 1998; Fodor *et al.*, 1999, Konon, 2001). Rozciągłość formowanych wówczas w płaszczowinie śląskiej fałdów pierwszego rzędu oraz fałdów podłużnych podporządkowała się tak rotującej kompresji (por. Fig. 11 i 12). Wtedy też formowana była część fałdów ukośnych w płaszczowinie magurskiej (Aleksandrowski, 1985, 1989). Z kolei przebieg osi fałdów ukośnych stwierdzonych w płaszczowinie śląskiej wskazuje na powolną rotację kierunku kompresji ponownie ku N–S (Fig. 11), zgodnie z obserwacjami Csontosa *et al.* (1991), Zuchiewicza (1998) i Jarosińskiego (1998, 1999), dotyczącymi innych struktur tektonicznych.

Powstanie fałdów ukośnych może być tłumaczone na kilka sposobów (por. Aleksandrowski, 1989). Stwierdzone przez autora geometryczne zależności pomiędzy fałdami pierwszego i drugiego rzędu sprawiają, że skłania się on do opinii, iż fałdy te są rezultatem bardzo późnych – sarmackich nasunięć i fałdowań (Ney, 1968; Książkiewicz, 1972; Karnkowski, 1974; Buła & Jura, 1983; Oszczypko & Tomaś, 1985; Cieszkowski *et al.*, 1988; Aleksandrowski, 1989; Mastella *et al.*, 1997; Mastella & Szynkaruk, 1998), być może związanych z resztkowymi ruchami dosuwczymi płaszczowiny magurskiej (Cieszkowski *et al.*, 1988b).