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Analysis of the fault pattern in selected areas of the Polish Outer Carpathians

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Fault pattern was studied in selected areas of the Polish Outer Carpathians. The study was based on the author's own mapping data, radar images and the *Geological Map of Poland* 1:200 000. A dense and regular fault pattern is present in all the studied areas. It consists of two sets of faults diagonal to the strike of the main tectonic structures, D_R and D_L, and a set of less common transverse faults T. The azimuths of the set T faults correspond approximately to the azimuths of the σ_1 axis of the D_R and D_L system. The azimuths change accordingly to the bending of the Carpathian arc, from ca. 40° in the east to ca. 175° in the west. All the fault sets dissect the regional structures and their overthrust planes, which indicates that the faults formed after folding and overthrusting of the nappes.

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Key words: Carpathians, conjugate fault sets, faults, fault pattern, photointerpretation, radar images, tectonics.

INTRODUCTION

This study presents an analysis of the fault pattern in selected areas of the Polish Outer Carpathians (Fig. 1A). The fault pattern was studied in the following areas: the eastern part of the Fore-Dukla unit, tectonic windows of Mszana Dolna and Świątkowa, Silesian nappe near Solina, between the rivers Skawa and Dunajec and near Żywiec (Fig. 1B). The analysis was based on:

— author's own field studies documented at the scale of 1:10 000 and supplemented with geological interpretation of air photos at approximate scales of 1:17 000 and 1:50 000;

— geological interpretation of radar images at approximate scale of 1:100 000;

— analysis of *Geological Map of Poland* 1:200 000 (sheets Jasło, Nowy Sącz, Bielsko-Biała; Fig. 1B)

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METHODS

Diverse methods were applied. Classical methods of geological mapping were used in the field work, together with structural analysis made according to the general suggestions presented by W. Jaroszewski (1972) and L. Mastella (1988). The methods of interpretation of air photos, including the radar ones, was based on the works by A. Pszczółkowski (1968), S. Doktór, M. Graniczny (1982), M. Graniczny *et al.* (1989), S. Ostaficzuk (1978), P. Vergely, H. Zadeh-Kabir (1988), D. J. Sanderson *et al.* (1991). Especially useful were the radar images at a scale 1:100 000 and resolution of ca. 30 m (S. Doktór, M. Graniczny, 1982). The masking effect of vegetation is partly removed on these images (S. Doktór, M. Graniczny, 1982; P. Vergely, H. Zadeh-Kabir, 1988; M. Graniczny *et al.,* 1989) and the low angle of incidence of the radar beam (S. Doktór, M. Graniczny, 1982; M. Graniczny *et al.*, 1989) increases the legibility of linear geological elements,

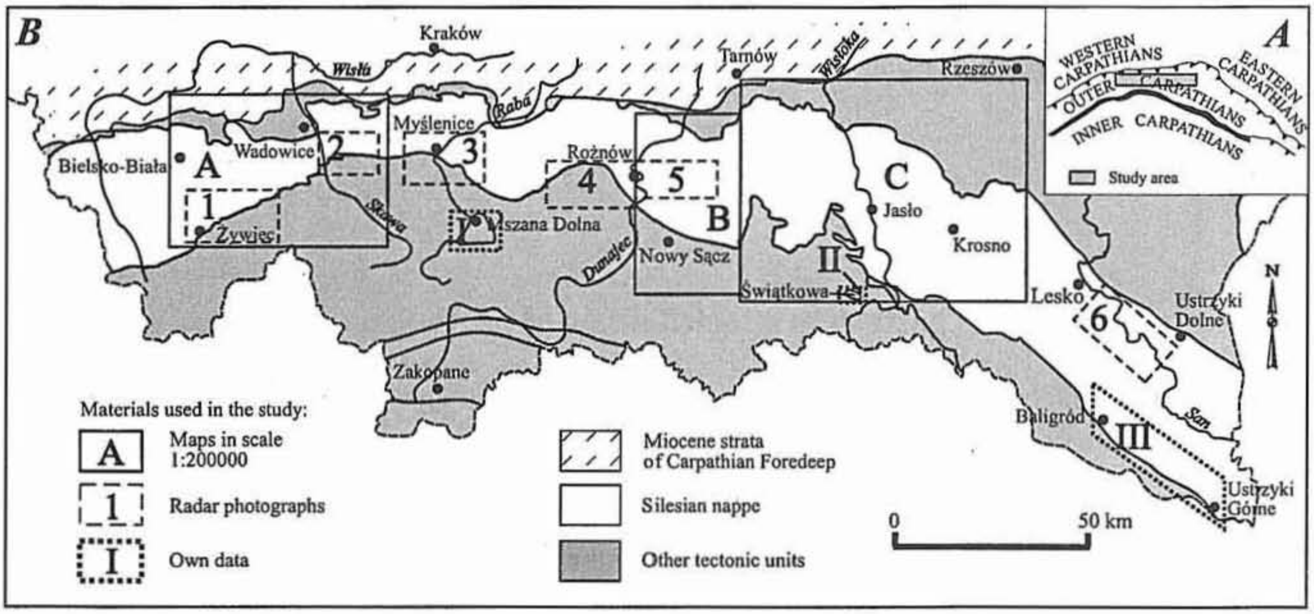


Fig. 1A. General location of the study area
B. Location of the areas of detailed investigations
Lokalizacja obszaru badań
B. Schemat rozmieszczenia odcinków badawczych

including faults (M. Graniczny *et al.*, 1989). The direction of flight was parallel to the regional structural strike, so the legibility of the faults oblique and normal to this direction increased markedly.

The faults oblique and normal to the structural strike were analyzed, as longitudinal faults are indistinguishable from thrusts on air photographs. The analysis included the faults which were directly mapped in the field, distinguished by interpretation of air photos and marked on existing geological maps. The faults manifest themselves in exposures by the presence of zones of breccia and cataclasites, folded shales and broken sandstone beds. The nature of these faults was established using folds (Pl. I, Fig. 10), fault drag (Pl. II, Fig. 11), slickensides, *en echelon* arrangement of faults and shears within the zones of breccia (Pl. II, Fig. 12).

Fault positions were established by photointerpretation where zones of breccia and cataclasites extended on valley slopes as narrow and often dry gullies, and where they were marked on hill crests as steps, gaps or small shifts in ridge axes (see L. Mastella, 1975; L. Mastella *et al.*, 1996; L. Mastella, J. Rubinkiewicz, 1998). The interpretation of faults on the radar photos and geological maps involved analysis of their surface traces, their *en echelon* patterns and the displacement of rock series along them — all using the methods tested earlier in the Polish part of the Carpathians (L. Mastella, 1975, 1988; A. Konon, 1996, 1997; J. Rubinkiewicz, 1996).

The fault pattern was represented as (depending on its complexity — see S. Doktór, M. Graniczny, 1982; P. Vergely, H. Zadeh-Kabir, 1988; D. J. Sanderson *et al.*, 1991): schematic maps based mainly on field studies, directly on the radar images or on maps drawn from them. In a few cases the patterns are illustrated by rose diagrams only.

Fault azimuths were measured to the nearest 1°. Rose diagrams were drawn by grouping measurements into 5° classes, each representing the sum of the lengths of faults within the azimuth class and shown as percent of the total length of all faults in the area. Azimuth of the centre of each class was then used for calculation.

The faults of the diagonal sets in the whole studied area are mostly right-lateral — D_R (Pl. I, Fig. 11) and left-lateral — D_L (Pl. I, Fig. 10; Pl. II, Fig.12) strike-slip faults, in many cases reactivated as dip-slip faults. Mutual geometrical relationships of the two sets, namely the offsets of some faults along the others and mutual terminations of some faults on the others, as seen in exposures (L. Mastella, 1988) and air photos (S. Doktór, M. Graniczny, 1982; L. Mastella, 1988; P. Vergely, H. Zadeh-Kabir, 1988; D. J. Sanderson *et al.*, 1991) indicate that a large part of the faults were synchronous (during the strike-slip phase of their development). In such a situation (W. Jaroszewski, 1980) the acute angle between the two sets is twice the shearing angle 2Θ and it is usually close to 60° (*op. cit*; J. Handin *et al.*, 1963). It can be said of such faults (G. Mandl, 1988; T. Engelder, 1989; R. Dadlez, W. Jaroszewski, 1994) that they were formed in a triaxial field of stresses. In that case, according to the general rules (R. Dadlez, W. Jaroszewski, 1994), the bisector of the acute angle between the surfaces of faults from both sets was used to determine the axis of main stress σ_1. The σ_2 direction is determined by the

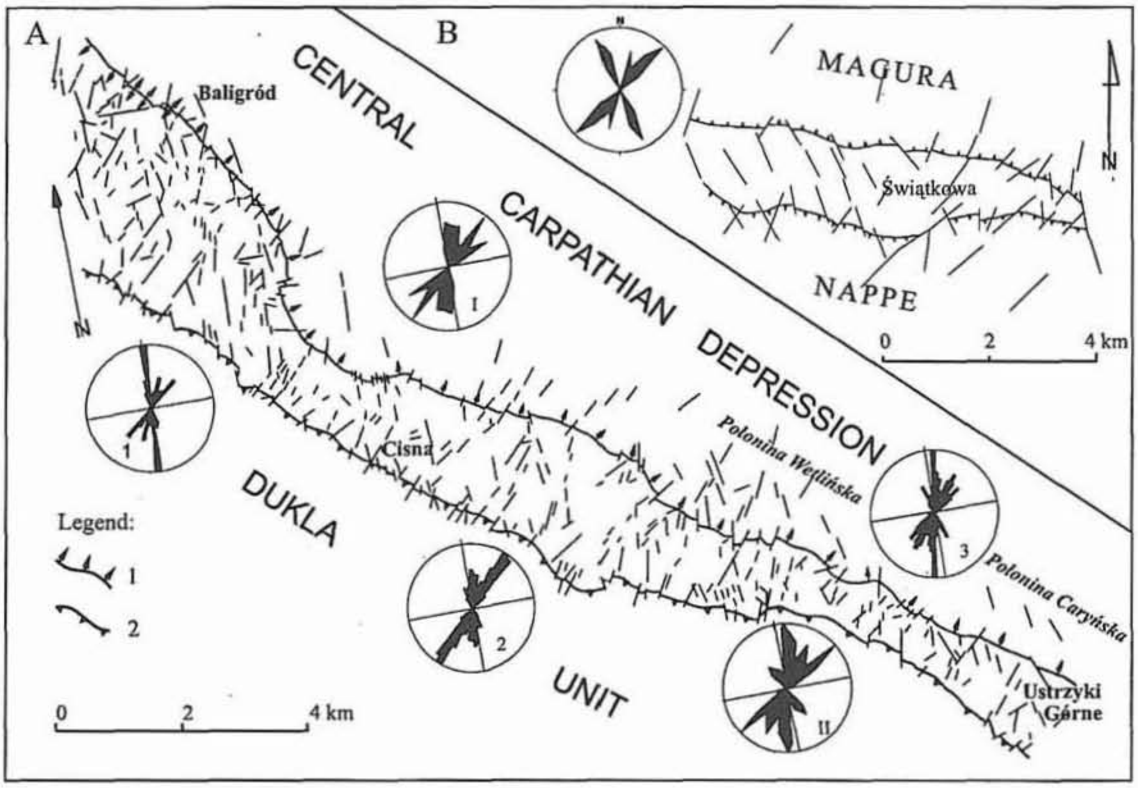


Fig. 2A. Fault pattern in the Fore-Dukla unit and its margin between Baligród and Ustrzyki Górne with rose diagrams of faults in its western (1), central (2) and eastern (3) parts and in the Central Carpathian Depression (I) and in the Dukla nappe (II) (after L. Mastella, 1995)
1 — fault separating the Central Carpathian Depression (upthrown side) from the Fore-Dukla unit (downthrown side), arrows show the direction of dip; 2 — overthrust of the Dukla unit; the radius of the rose diagrams corresponds to 15% of the total length of faults in the area represented by the diagram
B. Fault pattern in the Świątkowa tectonic window with a rose diagram of fault directions (after L. Mastella and J. Rubinkiewicz, 1998)
The radius of the rose diagrams corresponds to 20%

Sieć uskokowa w jednostce przeddukielskiej i jej obramowaniu między Baligrodem a Ustrzykami Górnymi z rozetami kierunków uskoków w jej części zachodniej (1), środkowej (2) i wschodniej (3) oraz w centralnej depresji karpackiej (I) i płaszczowinie dukielskiej (II) (według L. Mastelli, 1995)
1 — dyslokacja oddzielająca centralną depresję karpacką (skrzydło wiszące) od jednostki przeddukielskiej (skrzydło zrzucone), strzałki wskazują kierunek upadu; 2 — nasunięcie jednostki dukielskiej; promień koła rozet równa się 15% ogólnej długości uskoków na obszarze, z którego wykonano rozetę
B. Sieć uskokowa w oknie tektonicznym Świątkowej z rozetą kierunków uskoków (według L. Mastelli i J. Rubinkiewicza, 1998)
Promień koła rozet równa się 20%

direction of the intersection line of the planes of the two fault sets, and the σ_3 is perpendicular to both (*op.cit.*).

ANALYSIS OF THE FAULT PATTERN

THE FORE-DUKLA UNIT AND ITS MARGIN

The studied fragment of the Fore-Dukla unit and its immediate surrounding extends for ca. 40 km, from Ustrzyki Górne in the east to Roztoki Dolne near Baligród in the west. It is 1 to 6 km wide (Fig. 2A). On SW the unit is bound by the overthrust of the Dukla unit built here of the Upper Cretaceous Łupków and Cisna Beds (A. Ślączka, 1961; G. Haczewski, 1971; J. Rubinkiewicz, 1996), and on the NE by a large inverse fault whose hanging wall consists of the Upper Oligocene Krosno Beds of the Central Carpathian Depression (A. Ślączka, K. Żytko, 1978; J. Kuśmierek, 1979; L. Mastella, 1995). The Fore-Dukla unit consists of numerous steeply inclined tectonic slices of various size, aligned NW–SE, in accordance with the regional strike of the unit (L. Mastella, 1995). They include almost complete sequence of the Silesian unit (A. Ślączka, 1959), from the Lower Cretaceous (*op. cit.*) to the Upper Oligocene Passage Beds (J. Kuśmierek, 1979).

The obtained cartographic representation shows a regular pattern of faults (Fig. 2A) whose position is independent of lithology of the affected rock series (L. Mastella, 1995). Individual faults cross through both the slices and the large faults that border the Fore-Dukla unit (L. Mastella, 1995; J. Rubinkiewicz, 1996), and through folds in the Central Carpa-

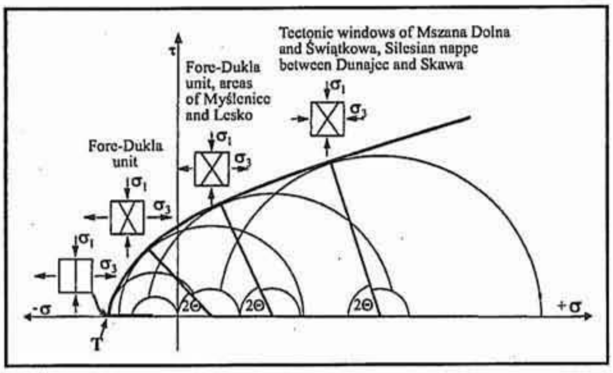


Fig. 3. Mohr diagram with shown 2Θ angles from various fragments of the studied area and T set faults (after R. Dadlez and W. Jaroszewski, 1994), slightly modified

Diagram Mohra z zaznaczonymi kątami 2Θ z różnych fragmentów badanego obszaru oraz uskoków zespołu T (według R. Dadleza i W. Jaroszewskiego, 1994), nieco zmieniony

thian Depression. They were thus formed after establishment of the general structural features of the area.

Three sets of faults with steep surfaces dominate in the pattern. The directions of two of them (D_R and D_L) are diagonal to the strike of regional units and the third (T) is perpendicular to it.

Faults of the D_R and D_L sets. The directions of the faults of the D_R set (right-lateral) in the western and eastern parts of the studied fragment of the Fore-Dukla unit are N–S, while those of the D_L set (left-lateral) are NE–SW (Fig. 2A, diagrams 1 and 3). These sets are undoubtedly conjugate synchronous shears (L. Mastella, 1995). This is indicated, among others, by the fact that in the middle part, where the azimuths of the directions of faults D_R vary between 7 and 15°, and of faults D_L — 42–50° they intersect at an angle 2Θ of ca. 35°. In the southern part of the Central Carpathian Depression and in the northern part of the Dukla nappe the directions of the D_R set are 10° and those of the set D_L are 60° (Fig. 2A, diagrams I and II) (J. Rubinkiewicz, 1996, fig. 8).

The 2Θ angle varies from 33° in the northern part of the Dukla unit and in the middle part of the Fore-Dukla unit to ca. 46° on its ends. Such shears, whose 2Θ angle is distinctly smaller than 60° are called hybrid shears (P. L. Hancock, 1985) and they originate in a triaxial stress-field when the σ_3 value is negative (Fig. 3; R. Dadlez, W. Jaroszewski, 1994, fig. 58), i.e. extension occurs along this axis. In the Fore-Dukla unit extension occurred by lateral expansion of its mostly ductile layers, compressed between the sandstone complexes of the Dukla unit and the Central Carpathian Depression (L. Mastella, 1995). Additional extension occurred also in the Central Carpathian Depression and the Dukla unit near sigmoidal bends of their contacts with the Fore-Dukla unit (Fig. 2A) (L. Mastella, 1995). The shearing angle in the southern part of the Central Carpathian Depression is about 50°. This is due to the fact that the faults cut there through thick-bedded sandstones. In this lithology the 2Θ angle is usually slightly smaller than 60° (G. Mandl, 1988).

The mean direction of σ_1 over the whole studied section of the Fore-Dukla unit, equivalent to the direction of maximum compression, is close to 25°, and in its margins, both in the Central Carpathian Depression and in the Dukla unit it reaches 35° (Fig. 2A). The σ_3 directions are ca. 115° and ca. 125°, respectively. Both these axes are horizontal and the σ_2 axis is vertical.

Faults of the T set. The faults of the transverse set (T) are usually readily mappable, wide zones of tectonic failure (Pl. II, Fig.13). Their nature is in many cases impossible to determine. The vertical and horizontal component, if they can be determined at all, often have variable orientations, even in a single zone. However, normal faults generally predominate. Faults with azimuths 24–28° predominate in the Fore-Dukla unit, while those within its margins have azimuths about 35°. The directions of those faults are nearly identical with the direction of σ_1, i.e. they are nearly perpendicular to σ_3, thus they seem to be normal faults (*cf.* G. Mandl, 1988; R. Dadlez, W. Jaroszewski, 1994) (Fig. 3).

TECTONIC WINDOW OF ŚWIĄTKOWA

A small tectonic window occurs near the village of Świątkowa (Fig. 2B), in which the Grybów unit crops out from beneath the overlying Inoceramian Beds of the Magura unit (M. Książkiewicz, 1972; L. Koszarski, 1985). The Grybów unit comprises a sequence from the Hieroglyphic Beds to the Krosno Beds (L. Koszarski, A. Tokarski, 1968). Large faults of mappable sizes clearly cut through the window unit as well as through the Magura nappe (Fig. 2B), hence they are younger than the overthrust of the Magura nappe.

The described fault pattern is overprinted by steep faults with distinct strike-slip component and azimuths ca. 165° (D_R — right-lateral) and 45° (D_L — left-lateral) (L. Mastella, J. Rubinkiewicz, 1998). The faults form a diagonal system of conjugated simultaneous shears with the 2Θ angle ca. 60° and with the σ_1 axis azimuth of ca. 15° (*op. cit.*). Subordinately occur faults with azimuths ca. 16° (Fig. 2B). The conformity of their directions to the σ_1 direction of the diagonal system make it possible that the faults have the same origin as the T set faults in the Fore-Dukla unit, though some smaller ones are feather faults around the D_L faults. Most of the described faults were reactivated as dip-slip faults after the strike-slip phase (*op.cit.*).

THE MSZANA DOLNA TECTONIC WINDOW

The tectonic window of Mszana Dolna extends at the most curved fragment of the arcuate Magura unit (Fig. 1B). Many authors have shown (H. Kozikowski, 1972; J. Burtan, 1974, 1978; J. Burtan *et al.*, 1976, 1978; L. Mastella, 1988) that two tectonic units crop out within it. The lower, folded and locally broken into tectonic slices Mszana Dolna tectonic unit (L. Mastella, 1988) is built of sandstones and shales of the Krosno Beds (J. Burtan, 1974, 1978; J. Burtan *et al.*, 1976, 1978). It is overlain by small tectonic caps of the sliced Grybów unit (H. Kozikowski, 1972; L. Mastella, 1988).

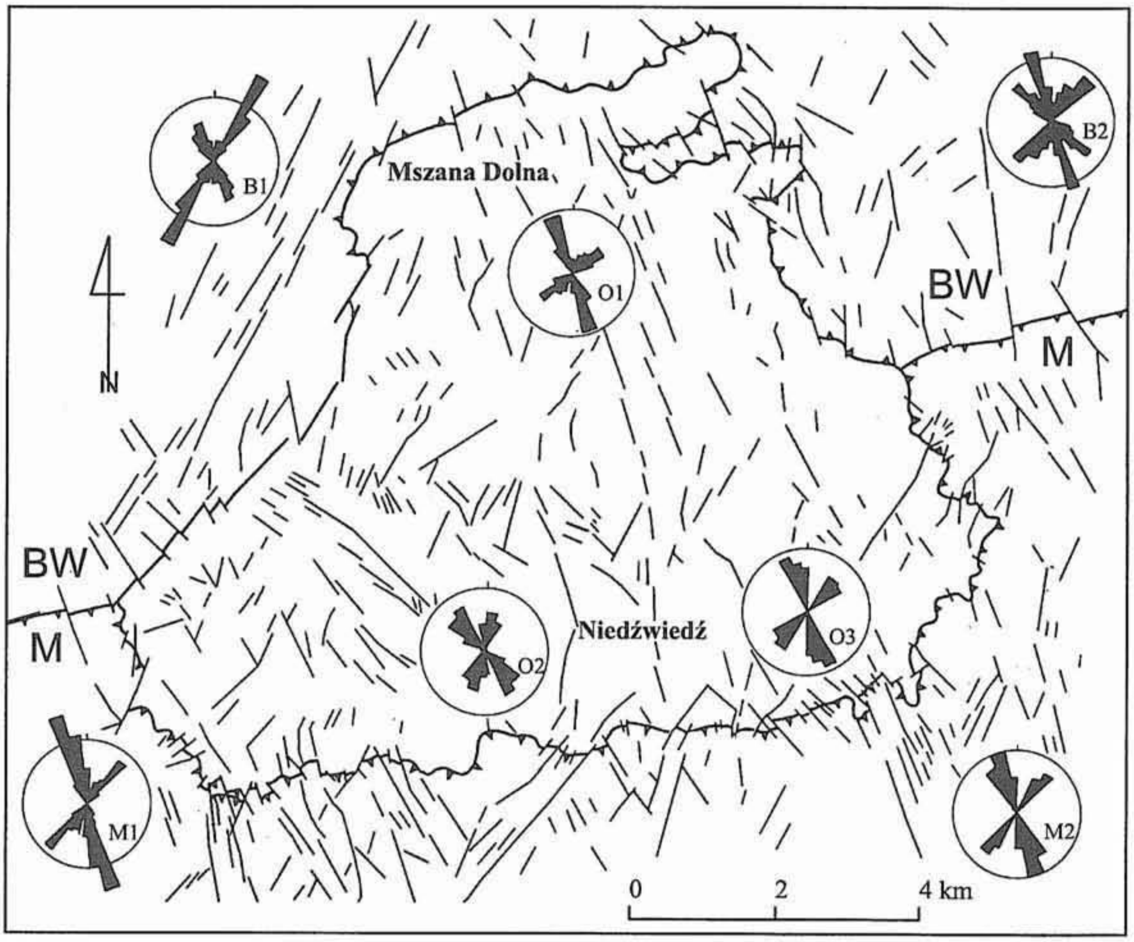


Fig. 4. Fault pattern in the Mszana Dolna tectonic window (rose diagrams 01, 02, 03) and its margin (after L. Mastella, 1988), slightly modified
BW — the Beskid Wyspowy overthrust (diagrams B1, B2); M — Mogielica overthrust (diagrams M1, M2); the radius of the rose represents 15%

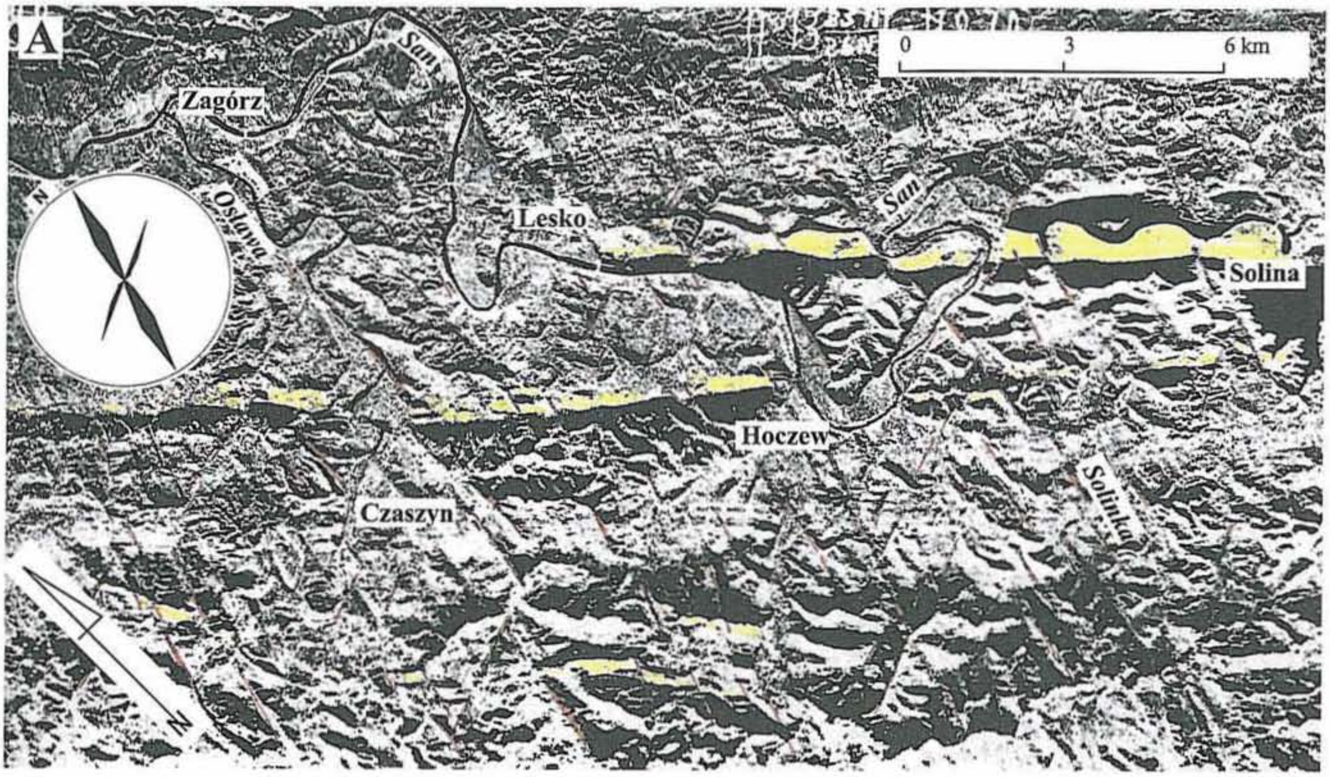
Sieć uskokowa w oknie tektonicznym Mszany Dolnej (rozety O1, O2, O3) i jego obramowaniu (według L. Mastelli, 1988), nieco zmieniona
BW — skiba Beskidu Wyspowego (rozety B1, B2); M — skiba Mogielicy (rozety M1, M2); promień koła rozet równa się 15%

The fault pattern in the window and its margins was studied in detail in the field (L. Mastella, 1988) and supplemented with interpretation of air photographs, and radar images (Fig. 4) over an area of ca. 180 km^2. Here also the faults postdate the overthrusts, as they cut through all the three tectonic units. The fault pattern consists mostly of steep faults oblique to the regional tectonic structures (L. Mastella, 1988). Two sets of initially strike-slip faults dominate (*op.cit.*): D_R — right-lateral and D_L — left-lateral ones, both forming a conjugate system of synchronous shears. The faults with azimuths 160–164° (D_R) and 44–50° (D_L) dominate within the window and in the adjacent part of its margin. The 2Θ angle is ca. 66° and the azimuth of the σ_1 is 14° (Fig. 4, diagrams O1, O2, O3, B1 and B2). Faults with the azimuth 160° dominate in the D_R set in the highest parts of the Magura unit and 40° in D_L set (Fig. 4, diagrams M1 and M2) at the 2Θ angle about 60° and the azimuth of the σ_1 about 10° (Fig. 9). This small difference in the σ_1 azimuths between the window and the basal parts of the Magura nappe (σ_1 — 14°) when compared to its higher parts (σ_1 — 10°) may be due to the clockwise rotation of the lower parts relative to the higher ones. This is corroborated by transformation of the right-lateral faults (D_R) into left-lateral ones (L. Mastella, 1988) suggesting in turn (*op. cit.*) the earlier reported (R. Unrug, 1984; K. Birkenmajer, 1985; C. Tomek, 1988; P. Aleksandrowski, 1989) clockwise regional rotation.

Most of the discussed faults were reactivated as dip-slip faults, some of them active until now (M. Gruszczyński, L. Mastella, 1986; L. Mastella, 1988).

CENTRAL CARPATHIAN DEPRESSION (AREA OF LESKO)

The analysis of the fault pattern was made on radar images which cover about 200 km^2 in the Central Carpathian Depression south-west of Lesko (Fig. 1B). The area is built mainly of thick-bedded sandstones of the Lower Krosno Beds folded into several steep folds oriented NW–SE, locally dissected by thrusts (S. Gucik *et al.*, 1979; S. Gucik, A. Wójcik, 1982; A. Ślączka, K. Żytko, 1978; S. Wdowiarz, 1980, 1985).



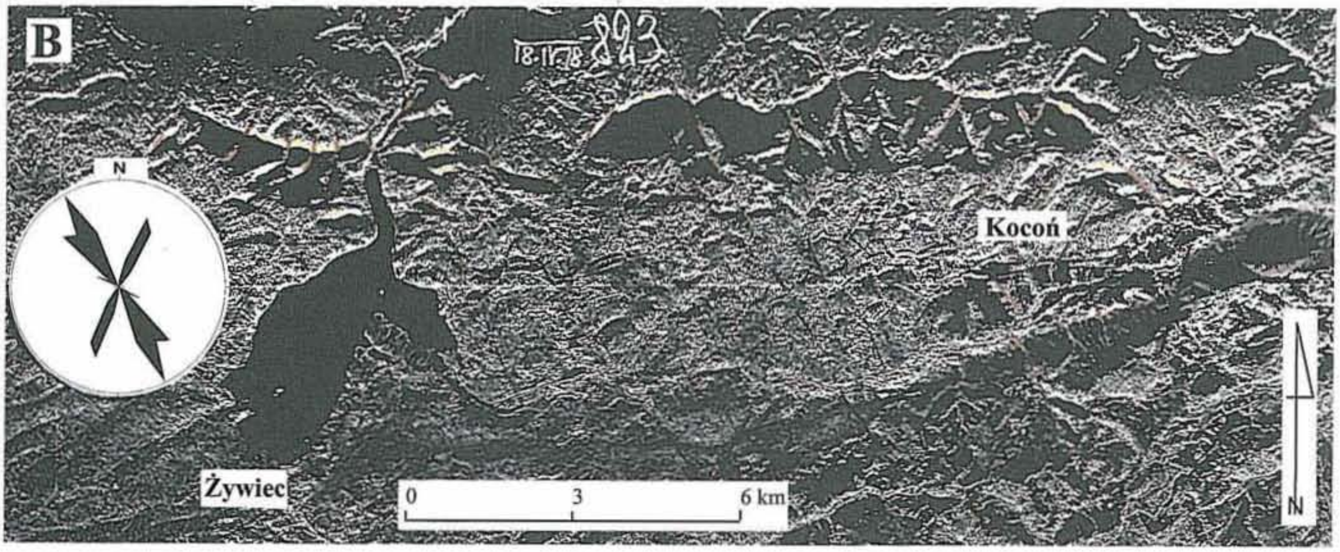


Fig. 5A. Fault pattern (red lines) in area of Lesko (Central Carpathian Depression) interpreted from air-born radar images and rose diagrams of their orientations
Some sandstone series in the Krosno Beds are shown in yellow; the radius of the rose represents 25%
B. Fault pattern (red lines) in area of Żywiec interpreted from air-born radar images and the rose diagram of their orientations
Some sandstone series in the Godula Beds are shown in yellow; the zone of the overthrust of the Magura nappe is marked in violet; the radius of the rose represents 15%

A. Sieć uskokowa (kreski czerwone) w rejonie Leska (centralna depresja karpacka), wyinterpretowana ze zdjęcia lotniczego radarowego i rozeta ich kierunków
Kolorem żółtym zaznaczono niektóre kompleksy piaskowcowe w obrębie warstw krośnieńskich; promień koła rozety równa się 25%
B. Sieć uskokowa (kreski czerwone) w rejonie Żywca wyinterpretowana ze zdjęcia lotniczego radarowego i rozeta ich kierunków
Kolorem żółtym zaznaczono niektóre kompleksy piaskowcowe w obrębie warstw godulskich, kolorem fioletowym — strefę nasunięcia płaszczowiny magurskiej; promień koła rozety równa się 15%

The fault pattern as seen on the radar images is very dense and regular (Fig. 5A), in contrast to how it is represented on geological maps. It consists of two sets of steep faults cutting diagonally through the overthrusts and folds, regardless of their lithology. The faults of the set D_R with azimuths ca. 15° dominate (Fig. 5A — rose diagram). They are arranged into

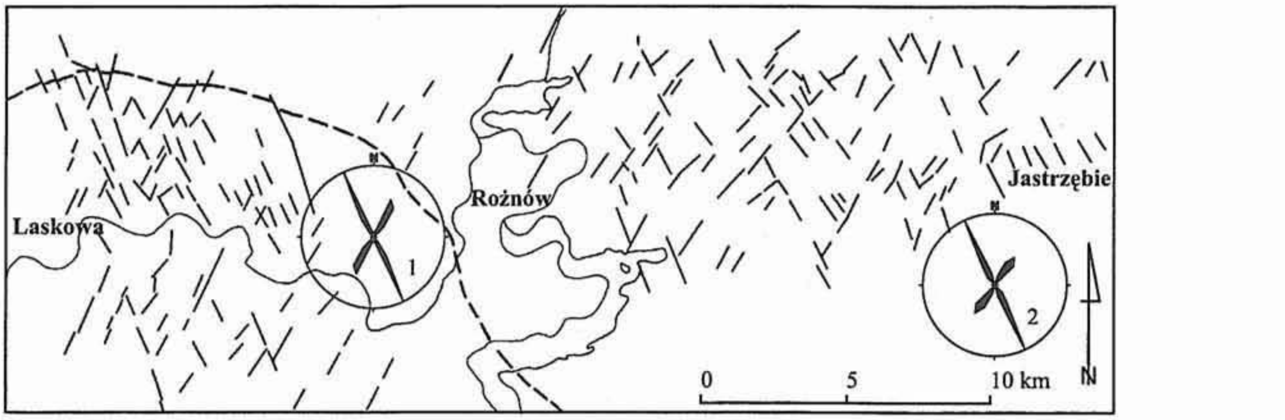


Fig. 6. Sketch of the fault pattern drawn from interpretation of radar image with rose diagrams in the Magura nappe (diagram 1) and the Silesian nappe (diagram 2)

The radius of the rose diagrams represents 25%; dashed line marks the zone of the overthrust of the Magura nappe

Odrys sieci uskokowej, wyinterpretowanej ze zdjęcia radarowego, z rozetami ich kierunków w obrębie płaszczowiny magurskiej (rozeta 1) i śląskiej (rozeta 2)

Promień koła rozet równa się 25%; linią przerywaną zaznaczono strefę nasunięcia płaszczowiny magurskiej

three distinct fault zones extending approximately along the valleys of the Osława river, Hoczewka stream, and the lower course of the Solinka river (Fig. 5A). The fault zone of the Hoczewka and lower Solinka (Fig. 5A) extends clearly to the south to the fault cutting across the Bystre tectonic slices along the Jabłonki stream (A. Ślączka, 1959; L. Mastella, 1995). Similar directions of faults were observed by A. Pszczółkowski (1968). The described fault zones as well as individual accompanying faults with the same direction have a component of right-lateral movement. The faults of the D_L set are less numerous and are usually dispersed (Fig. 5A). Both sets intersect at an angle close to 50°. The described features and regional analogies suggest that both sets are conjugate and synchronous and the σ_1 azimuth of ca. 40° is similar to that measured near the southern boundary of the Silesian unit in this part of the Carpathians (Fig. 9).

THE SILESIAN NAPPE BETWEEN THE DUNAJEC AND SKAWA RIVERS

This area is considered after M. Książkiewicz (1972) as a structurally uniform domain within the Silesian nappe. The Silesian nappe in this area consists of flat, indistinct folds and it is divided into the northern and southern parts by the strongly tectonically sliced Lanckorona–Żegocina zone, extending east-west. The northern part is built mainly of Cretaceous strata ranging from the Lgota Beds through Istebna Beds, while the southern part is built mainly of Palaeogene strata, mainly the Krosno Beds (M. Książkiewicz, 1972). The western boundary is marked by the fault extending along the Skawa river valley. The tectonic style of the Silesian nappe changes eastward of the Dunajec river to one of distinct folds (M. Książkiewicz, 1972). From the south the studied area includes also a fragment of the Magura nappe.

The fault pattern, as interpreted from the air photos, mainly radar images, is regular all over this area, both in the Silesian nappe and in the adjacent fragment of the Magura nappe. It consists mainly of two sets — the NNW–SSE and the NE–SW ones, diagonal to the strike of the main regional structures, similarly as over the whole area described earlier. The directions of faults are independent of the lithology of the dissected rock series.

The analysis of images, supplemented with the author's and A. Konon's (1996, 1997) field studies indicates that also here the described faults had a strike-slip phase in their evolution, as conjugate synchronous shears: NNW — right-lateral (D_R), NE — left-lateral (D_L) and were formed after the formation of the folds and overthrusts in this part of the Outer Carpathians. The post-thrust age of the faults of this type was accepted for the western part of the discussed fragment of the Silesian nappe by M. Książkiewicz (1974) and also partly by P. Aleksandrowski (1989).

The area near the Rożnów reservoir. The fault pattern was studied here over an area of 140 km^2 in the Silesian nappe east of the Rożnów reservoir and in the Magura nappe to the west of the reservoir (Figs. 1B, 6). The directions of the two fault sets are nearly identical in both areas — 150–155° (D_R) and 30–35° (D_L) (Fig. 6, diagrams 1 and 2). The 2Θ angle is about 60°, and the azimuth of σ_1 — about 5°.

The fault pattern consists of uniformly dispersed faults of both sets (Fig. 6). The faults with NNW strikes though clearly predominating (Fig. 6) are not grouped into distinct fault zones. The faults marked on the map (J. Burtan *et al.*, 1976) do not appear on the radar image. Only the meridional fault east of the Rożnów reservoir (*op. cit.*) is manifested on the radar image as a concentration of faults of both sets. It can be thus suggested that no significant horizontal displacements occurred in this area after the formation of the described fault pattern.

The area of Myślenice. The studied fragment, about 140 km^2 in area, extends in the southern, strongly folded and thrusted part of the Silesian nappe near its contact with the overthrust of the Magura nappe (M. Książkiewicz, 1972, fig. 8). The fault pattern consists of uniformly dispersed faults of

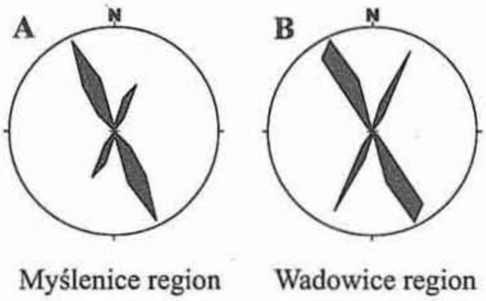


Fig. 7. Rose diagrams of fault directions in the area of Myślenice (A) and Wadowice (B)
The radius of the diagrams A and B represents 20%

Rozety kierunków sieci uskokowej w okolicy Myślenic (A) i Wadowic (B)
Promień koła rozet równa się 20%

both sets. Some of them cut the overthrust of the Magura nappe.

The D_R set with the azimuth ca. 156° clearly dominates, less numerous is the set D_L oriented at ca. 24° (Fig. 7A). The 2Θ angle is ca. 48° and the σ_1 azimuth is ca. 0° (Fig. 9). The low value of 2Θ seems to indicate the presence of east-west extension during the formation of the discussed fault pattern.

The area of Wadowice covers about 160 km^2 and extends from the river Skawa in the west as far as 16 km to the east (Fig. 1B). It includes the Pogórze Lanckorońskie element — a flat syncline (M. Książkiewicz, 1972) and a fragment of the northern margin of the Magura nappe. The fault pattern consists, similarly as in the area of Myślenice, of the dominant D_R set and less frequent D_L faults (Fig. 7B). Faults with azimuth ca. 145° predominate in the D_R set, and about 25° in the D_L set. The 2Θ angle is ca. 60° and the σ_1 azimuth is ca. 175° (Fig. 9). Also here the discussed faults cut through both the Silesian and Magura nappes without any change in direction.

The fault network is uniformly distributed over the area. A small concentration of the NNW–SSE oriented faults, visible along the Skawa river coincides with the large fault known here (M. Książkiewicz, 1972). A much more distinct NNW–SSE oriented fault zone is formed by the faults of D_R set concentrated along the Cedron stream.

THE AREA OF ŻYWIEC

The area extends over ca. 200 km^2 (Fig. 1B) in the Silesian and Magura nappes. The fault pattern consists of the D_R faults with azimuths 140–155° and D_L faults with azimuths 25–30° (Fig. 5B). The 2Θ angle is between 55 and 65°. The σ_1 azimuth is ca. 175° (Fig. 9). While both sets are uniformly distributed, the less numerous D_L faults form two fault zones with azimuths ca. 30°. The more distinct of them lies on the eastern side of the Żywiec reservoir and the second, more dispersed one is near Kocoń (Fig. 5B). The faults clearly cut through the Magura nappe overthrust, maintaining the same direction in the Silesian and Magura nappes (Fig. 5B).

ANALYSIS OF THE FAULT PATTERN ON GEOLOGICAL MAPS 1:200 000

The analysis of the fault pattern revealed by field studies and interpretation of air photographs and radar images were supplemented with the analysis of faults shown on geological maps 1:200 000, sheets Jasło (P. Nescieruk *et al.*, 1992), Nowy Sącz (J. Burtan *et al.*, 1981) and Bielsko-Biała (J. Golonka *et al.*, 1978). The striking feature of the fault pattern in this area is the clear domination of steep faults of one set with widely changing (within 30°) orientations (*op.cit.*) The faults of this set that are identified in the field form usually wide zones of tectonic disruption, cataclasites and breccias, similarly as the T set faults in the Central Carpathian Depression (Pl. II, Fig. 13). These are usually oblique slip-faults in which the direction of movement along the fault plane changes even along one fault. Similarly as earlier described faults in the Central Carpathian Depression, these faults were found by W. Zuchiewicz and A. Henkiel (1993) to be approximately perpendicular to the strike of the regional tectonic structures (J. Golonka *et al.*, 1978; J. Burtan *et al.*, 1981; P. Nescieruk *et al.*, 1992). Their azimuths, as was noted by S.

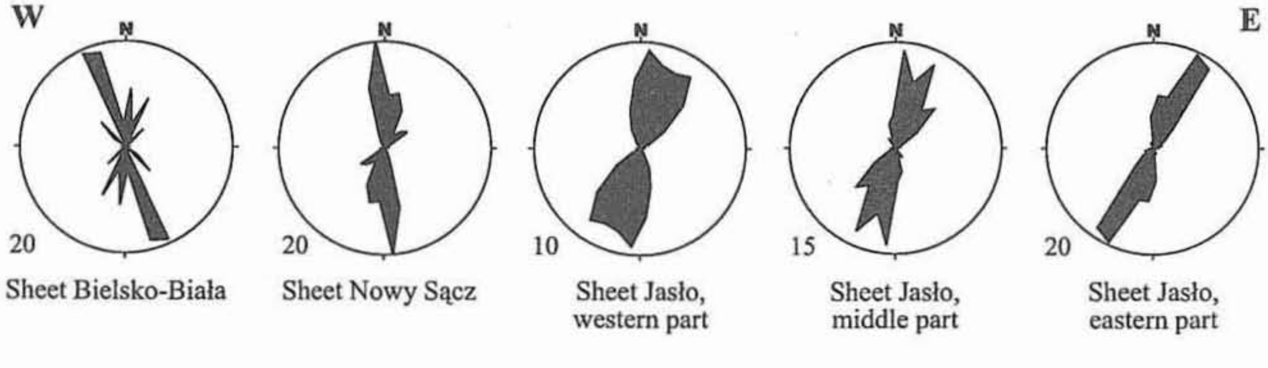


Fig. 8. Rose diagrams of transverse faults T drawn after geological maps 1:200 000, sheets Bielsko-Biała, Nowy Sącz and Jasło
Numbers on the lower left sides of the diagrams indicate percentage values of the diagram radius

Rozety uskoków poprzecznych zespołu T wykonane na podstawie map geologicznych w skali 1:200 000, ark. Bielsko-Biała, Nowy Sącz i Jasło
Liczby z lewej dolnej strony rozet oznaczają wartość procentową promienia

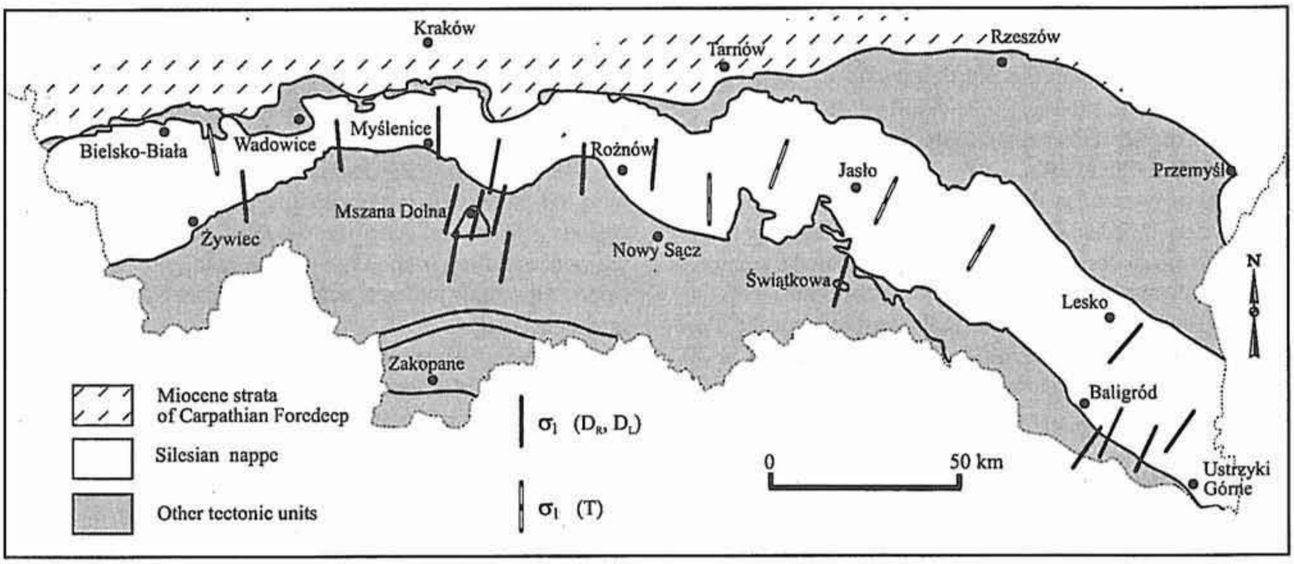


Fig. 9. Schematic map of the study area with σ_1 axes determined for the D_R and D_L fault system (solid lines) and for the T faults (dashed lines)
Schematyczna mapa obszaru badań z wyznaczonymi osiami σ_1 z systemu uskoków D_R i D_L (kreski ciągłe) i z zespołu uskoków T (kreski przerywane)

Doktór and M. Graniczny (1982) approximately correspond to the described σ_1 of D_R and D_L sets. This additionally confirms that these are T set faults. Their origin should be thus the same as of the faults of this set in the Fore-Dukla unit and its margin. Taking into account the evolution of the stress field in various parts of the Polish Carpathians (P. Aleksandrowski, 1989; L. Mastella, 1975, 1988) one may suppose that these faults are the youngest and have been formed during the post-orogenic uplift of the Carpathians under conditions of vanishing submeridional compression.

The faults of the D_R and D_L sets on the studied maps are not numerous, but they almost always correspond to the faults detected in the field and on the radar images.

THE FAULT PATTERN AND JOINTS

The directions of the fault pattern described above largely correspond to the directions of the two conjugate sets of joints (D_1 and D_2) and the T set (L. Mastella *et al.*, 1997; W. Zuchiewicz, 1997*a, b*) observed by us and reported by other authors (M. Książkiewicz, 1968; P. Aleksandrowski, 1989; W. Zuchiewicz, A. Henkiel, 1993; L. Mastella *et al.*, 1997; W. Zuchiewicz, 1997*a, b*). These sets change their orientation from the east to the west, maintaining stable position with respect to the regional fold structures. The D_1 and D_2 joint sets display a tendency to left- and right-lateral displacement along them, respectively (L. Mastella *et al.*, 1997). As in the case of D_L and D_R faults, the 2Θ angle of D_1 and D_2 joint sets is about 60° (W. Zuchiewicz, A. Henkiel, 1993; L. Mastella *et al.*, 1997). The analogy is so close that in the areas of Myślenice, Fore-Dukla zone and in its southern margin the 2Θ angle is lower than the dominant one and is 30–48° for the D_L and D_R faults as well as the joint sets D_1 and D_2, as it is shown by the author's observations. The joints there are hybrid shears formed at negative values of σ_3. This constatation has far-reaching consequences. It indicates that the faults (D_L and D_R) and joints D_1 and D_2, regardless of the age of the host rocks, appeared in nearly the same time, after the overthrusting of nappes and formation of the fault that separates the Fore-Dukla unit from the Central Carpathian Depression. As is suggested by the use of the method of D. J. Sanderson *et al.* (1991) the formation of the D_L and D_R faults was facilitated by mechanical weakening of the terrane by the slightly earlier formed joints D_1 and D_2.

Also the directions and origin of the faults of T set and transverse joints (L. Mastella *et al.*, 1997; W. Zuchiewicz, 1997*b*; W. Zuchiewicz, A. Henkiel, 1993) seem to be the same.

SUMMARY

The results of the field studies and air photo interpretation, especially radar images, indicate that a dense pattern of steep faults is present in the studied fragment of the Polish Outer Carpathians. It consists mainly of two sets, D_R and D_L of faults diagonal to the strike of major regional structures and of a less dense set T of faults transverse to these structures.

The D_R and D_L faults are mostly strike-slip faults reactivated as dip-slip faults. In the strike-slip faults the D_R faults were right-lateral and the D_L ones — left-lateral. Their azimuths display a regional variation: D_R — from about 10° in the east to about 150° in the west, and D_L — from 60 to 25°, respectively. The results of the structural analysis indicate that they form a system of conjugate simultaneous shears with

dominant 2Θ angle of about 60°. Locally the value of this angle is smaller. In the Fore-Dukla unit and its direct vicinity it is about 35° and in the Myślenice area near the overthrust of the Magura nappe on the Silesian nappe — about 48°. In both cases this is probably the result of extension in the direction of strike of the regional structures during the formation of the described faults.

It may be concluded that the system of D_R and D_L faults originated in a triaxial field of stresses in which only locally σ_3 attained small negative values. The calculated direction of compression, corresponding to the axis of the main stress (σ_1), varies regionally from about 40° in the east (except the Fore-Dukla unit strongly dissected by thrusts, where $\sigma_1 = 25°$) through about 0° in the central part to about 175° in the western end of the studied section of the Western Outer Carpathians (Fig. 9).

The pattern of T set faults consists mainly of faults transversal to the regional structures, so that faults with azimuths 35° dominate in the east and 165°— in the west (Fig. 8). Their directions correspond approximately to the σ_1 directions of the D_R and D_L fault system (Figs. 8, 9). This seems to indicate the T faults formed under a significant extension over the whole area in the direction perpendicular to then vanishing compression of the stage of the D_R and D_L fault formation. Therefore the system of D_R and D_L is older than the T faults.

Both, the D_R and D_L faults and the T faults cut through the regional structures in the Silesian, Dukla and Magura nappes and the zones of their overthrusts. This indicates that the discussed pattern of faults formed already after folding and thrusting of the nappes. The regular pattern of faults and the stability of its directions in all tectonic units in the area indicate that they are primary faults, formed in the regionally homogeneous stress field (R. Freund, 1974). It also indicates the lack of major horizontal movements in this part of the Carpathians after their formation.

The directions of the described fault pattern coincides well with the pattern of joints oblique and perpendicular to the regional structures. Also the value of the 2Θ angle and its regional variation in the fault pattern and joint pattern are the same. This may indicate nearly simultaneous origin of the joints and faults.

The review of papers by other authors (N. Oszczypko, A. Tomaś, 1985; M. Cieszkowski *et al.*, 1992) may suggest that the D_R and D_L fault system originated in the early Sarmatian when the Magura nappe was finally pushed (M. Cieszkowski *et al.*, 1988). It was probably only from that time when the joints of shearing system (D_L and D_R — L. Mastella *et al.*, 1997) began to appear. The T faults (and probably also the T joints) should be attributed to post-orogenic uplift of the studied area which, according to M. Cieszkowski *et al.* (1992), should be referred to the end of Neogene Period.

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ANALIZA SIECI USKOKOWEJ WYBRANYCH OBSZARÓW Z POLSKIEJ CZĘŚCI KARPAT ZEWNĘTRZNYCH

Streszczenie

Opracowanie dotyczy sieci uskokowej na wybranych obszarach polskiej części Karpat zewnętrznych (fig. 1A). Analizę oparto na własnych badaniach terenowych, interpretacji zdjęć lotniczych, w tym radarowych, oraz mapach geologicznych (fig. 1B). Posługiwano się metodami klasycznymi, uzupełnionymi analizą strukturalną (tabl. I, fig. 10, 11; tabl. II, fig. 12). Stwierdzono, że na badanym obszarze występuje gęsta i regularna sieć stromych uskoków. Składa się ona głównie z dwóch zespołów: D_R i D_L — uskoków skośnych do rozciągłości struktur regionalnych — i zespołu T — poprzecznego do tych struktur (fig. 2, 4–7). Wszystkie one wykazują regionalną zmienność azymutów: D_R — od około 10° na wschodzie do około 150° na zachodzie, D_L —

odpowiednio od około 60°do około 25°. Ich kierunki są niezależne od litologii przecinanych przez nie kompleksów skalnych. Uskoki D_R i D_L są uskokami przesuwczymi: D_R — prawoskrętnymi, a D_L — lewoskrętnymi. Tworzą one system ścięć sprzężonych równoczesnych o dominującym kącie 2Θ około 60°. Lokalnie, w jednostce przeddukielskiej i jej północnym obramowaniu oraz w rejonie Myślenic kąt ten jest znacznie mniejszy — 35–48° i uskoki nabierają charakteru ścięć hybrydowych. Powstały one w trójosiowym polu naprężeń, w którym, w wyniku rozciągania zgodnego z przebiegiem struktur regionalnych, σ_3 przyjmowała lokalnie wartość ujemną (fig. 3). Obliczony kierunek kompresji (odpowiadający σ_1) zmienia się regionalnie od około 40° na wschodzie do około 175° na zachodzie (fig. 9). Sieć uskoków T składa się głównie z dużych uskoków poprzecznych do rozciągłości struktur regionalnych tak, że w części wschodniej dominują uskoki o azymucie około 35°, a w zachodniej około 165° (fig. 8). Ich azymuty pokrywają się z kierunkami σ_1 (fig. 9). Wynikałoby z tego, że uskoki T powstawały przy występującym już na całym obszarze rozciąganiu prostopadłym do kierunku zanikającej już kompresji z etapu powstawania uskoków D_R i D_L. W tej sytuacji uskoki te są starsze od uskoków T. Zarówno uskoki D_R i D_L, jak i T przecinają regionalne struktury w płaszczowinie śląskiej, dukielskiej i magurskiej oraz nasunięcia tych jednostek. Wskazuje to, że omawiana sieć uskoków powstała już po sfałdowaniu i nasunięciu tych płaszczowin.

Analizując prace innych autorów (N. Oszczypko, A. Tomaś, 1985; M. Cieszkowski i in., 1992), można wnioskować, że system uskoków D_R i D_L powstał we wczesnym sarmacie, kiedy to nastąpiło dopchnięcie płaszczowiny magurskiej (M. Cieszkowski i in., 1988). Prawdopodobnie dopiero od tego czasu zaczęły ujawniać się spękania ciosowe systemu ścięciowego (D_L i D_R — L. Mastella i in., 1997). Natomiast uskoki T (a zapewne i cios T) wiązać należy z postorogenicznym wypiętrzaniem badanego obszaru, co zgodnie ze zdaniem M. Cieszkowskiego i in. (1992) wiązać należy ze schyłkiem neogenu.

EXPLANATIONS OF PLATES

PLATE I

Fig. 10. Strike-slip left-lateral fault with a fault drag. Azimuth of the plane is shown next to the fault line; strike and dip of strata are also shown. The arrows show the direction of strike-slip movement. Tectonic window of Mszana Dolna. Exposure of the Krosno Beds in the Konina river between Niedźwiedź and Konina

Uskok przesuwczy lewoskrętny z przyuskokowym zafałdowaniem. Przy linii uskoku zaznaczono jego azymut, a przy warstwach ich bieg i upad. Strzałki wskazują zwrot ruchu przesuwczego. Okno tektoniczne Mszany Dolnej. Odsłonięcie warstw krośnieńskich w korycie rzeki Konina między wsiami Niedźwiedź i Konina

Fig. 11. Small *en echelon* low-angle faults and fault-drag near a right-lateral strike-slip fault. Fore-Dukla unit — Bystre slice. Exposure of the Cieszyn Beds in the Jabłonka stream at Jabłonka village

Drobne uskoki kulisowe niskokątowe i podgięcia warstw przy uskoku przesuwczym prawoskrętnym. Jednostka przeddukielska — łuska Bystrego. Odsłonięcie warstw cieszyńskich w potoku Jabłonka we wsi Jabłonka

PLATE II

Fig. 12. Breccia with *en echelon* joints in the zone of a left-lateral strike-slip fault. Central Carpathian Depression. Exposure of the Otryt sandstones in the Stężnica river

Brekcja z kulisowymi spękaniami w strefie uskoku przesuwczego lewoskrętnego. Centralna depresja karpacka. Odsłonięcie piaskowców z Otrytu w korycie rzeki Stężnicy

Fig. 13. Fault zone. Central Carpathian Depression. Exposure of the middle part of the Krosno Beds in the Solinka river at Buk

Strefa uskokowa. Centralna depresja karpacka. Odsłonięcie środkowej części warstw krośnieńskich dolnych w korycie rzeki Solinka we wsi Buk

Fig. 10

Fig. 11

Leonard MASTELLA, Ewa SZYNKARUK — Analysis of the fault pattern in selected areas of the Polish Outer Carpathians

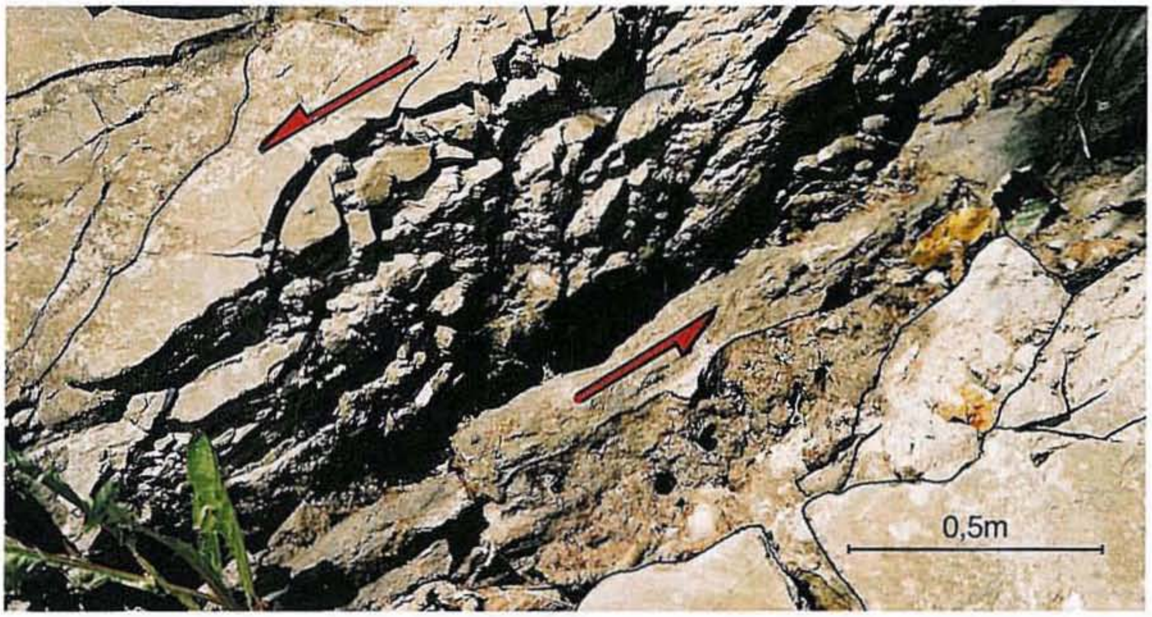

Fig. 12

Fig. 13