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Fold-thrust-belt geometry and detailed structural evolution of the Silesian nappe – eastern part of the Polish Outer Carpathians (Bieszczady Mts.)

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ABSTRACT:

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On the basis of field studies of mesoscopic structures, and analysis of radar and aerial photos together with seismic data, the structure and structural evolution of a part of the Silesian nappe was established. In the study area the Silesian nappe comprises two tectonic units: the Central Carpathian Depression and the Fore-Dukla thrust sheet, separated by a fault. The Central Carpathian Depression is built of several map-scale slices. The slices comprise map-scale NE-verging anticlines, with additional synclines to the south-east. The slices are separated by steeply dipping forelimb-thrusts, which connect together at a depth of *ca*. 6-7 km into a single sole thrust and form a leading imbricate fan. To the west of the Rabe-Baligród fault zone the fault between the Central Carpathian Depression and the Fore-Dukla thrust sheet is a typical thrust. Eastwards from this fault zone it becomes a steeply NE-dipping normal fault. The Silesian nappe is cut by map-scale oblique and transverse, mainly strike-slip faults – some of them are tear faults. Longitudinal strike-slip faults indicate dextral movement along the pre-existing thrusts. The structural evolution of the Silesian nappe comprises here eight pre-, syn- and post-orogenic stages beginning with the formation of clastic veins, followed by folding, thrusting, strike-slip faulting and terminating with normal faulting.

Key words: Fold-thrust belt, Imbricate slices, Mesoscopic structures, Structural analysis, Outer Carpathians, Silesian nappe, Central Carpathian Depression, Fore-Dukla thrust sheet.

INTRODUCTION

The aim of this study is the reconstruction of the structure and structural evolution of a part of the Silesian nappe in the eastern part of the Polish Outer Carpathians in the Bieszczady Mts. It is one of the few comprehensive structural studies in the Polish Outer Carpathians based on detailed field studies (e.g., MASTELLA 1988; ALEKSANDROWSKI 1989; KONON 1999, 2000). Except for the papers by TOKARSKI (1975), KUŚMIEREK (1979) and MASTELLA (1995), no detailed structural analysis, based also on seismic and borehole data has been made in the eastern part of the area.

The studies were carried out in several stages. The first stage included the analysis and interpretation of geological maps (ŚLĄCZKA 1957; MALATA 1997), aerial and radar photos, borehole (Polish Geological Institute archives) and seismic data (MŁYNARSKI & *al*. 1982; STEFANIUK 2001; RYŁKO & TOMAŚ 2005). The second stage focused on field geological mapping in *ca*. 1500 outcrops within an area of about 200 km^2. Lithology, bedding and mesostructures in particular were studied in each outcrop. A total of 1600 bedding planes, 2300 fractures (joints, master joints, cleavage), 500 faults and tens of folds, boudinage and clastic dykes have been measured. The last stage included statistical analysis of the structural data using structural software (Stereonet ver. 3.0, Tectonic FP ver. 1.6, Geocalculator ver. 9). The analysis of map-scale and mesoscopic tectonic structures has enabled their origin to be interpreted. Palaeostress fields have also been reconstructed together with the stages of structural evolution of the study area. As a result, a map and geological cross-section at the scale 1: 25 000 were compiled.

The study area has a structure typical of this fragment of the Carpathian arc, and it can therefore serve as reference for the structural evolution of the nappe system in the area.

GEOLOGICAL SETTING

The Outer Carpathians arc stretches more than 1300 km from the Vienna Forest to the Iron Gate on the Danube. The Outer Carpathians are composed mainly of flysch sequences and form an accretionary prism which originated during the collision of the Alcapa and Tisza-Dacia microplates (CSONTOS & *al*. 1992; FODOR & *al*. 1999) (Apulia plate – PICHA 1996) with the North European platform. They are built of stacked nappes, which were folded and thrust during late Oligocene to middle

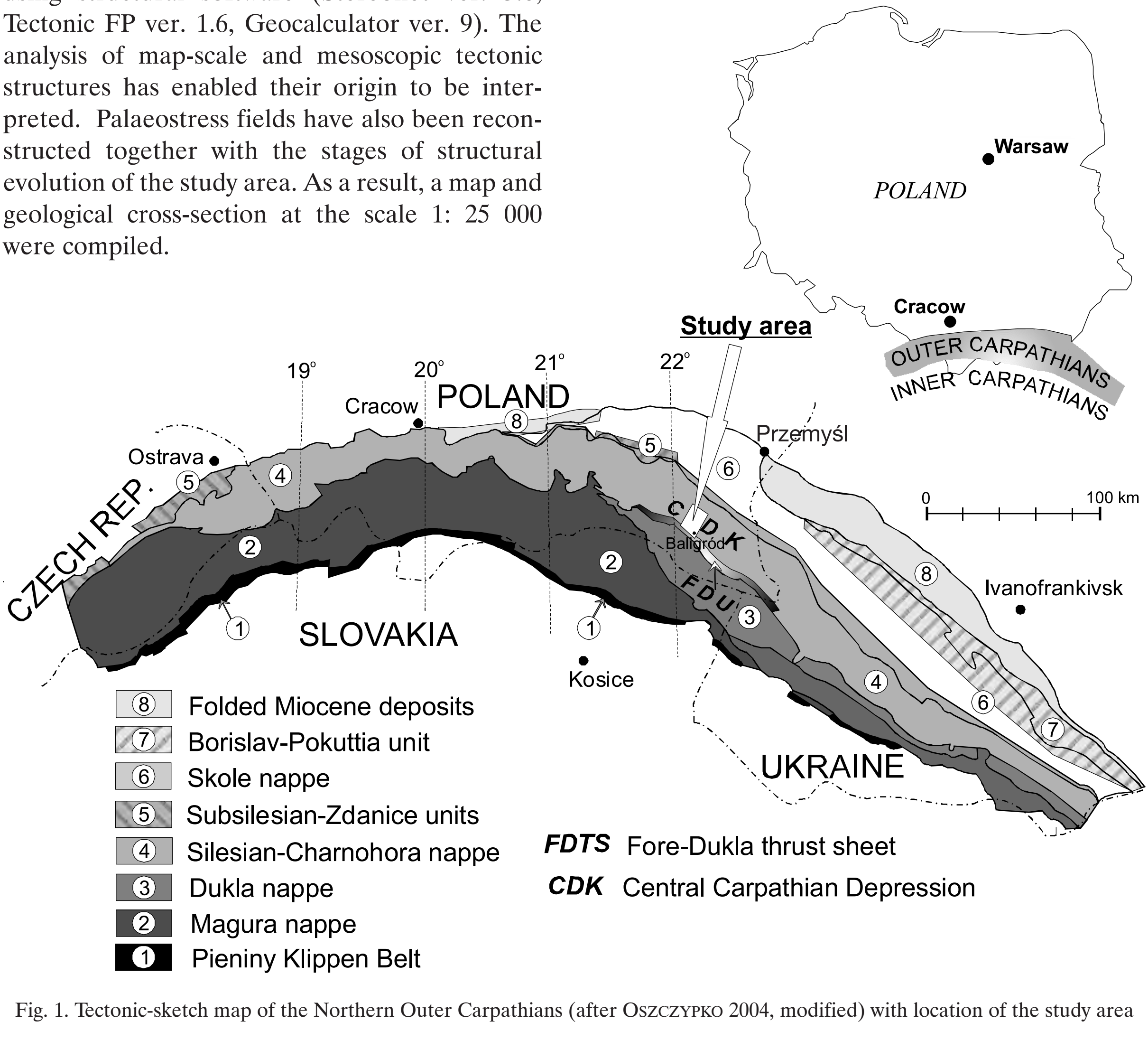

Fig. 1. Tectonic-sketch map of the Northern Outer Carpathians (after OSZCZYPKO 2004, modified) with location of the study area

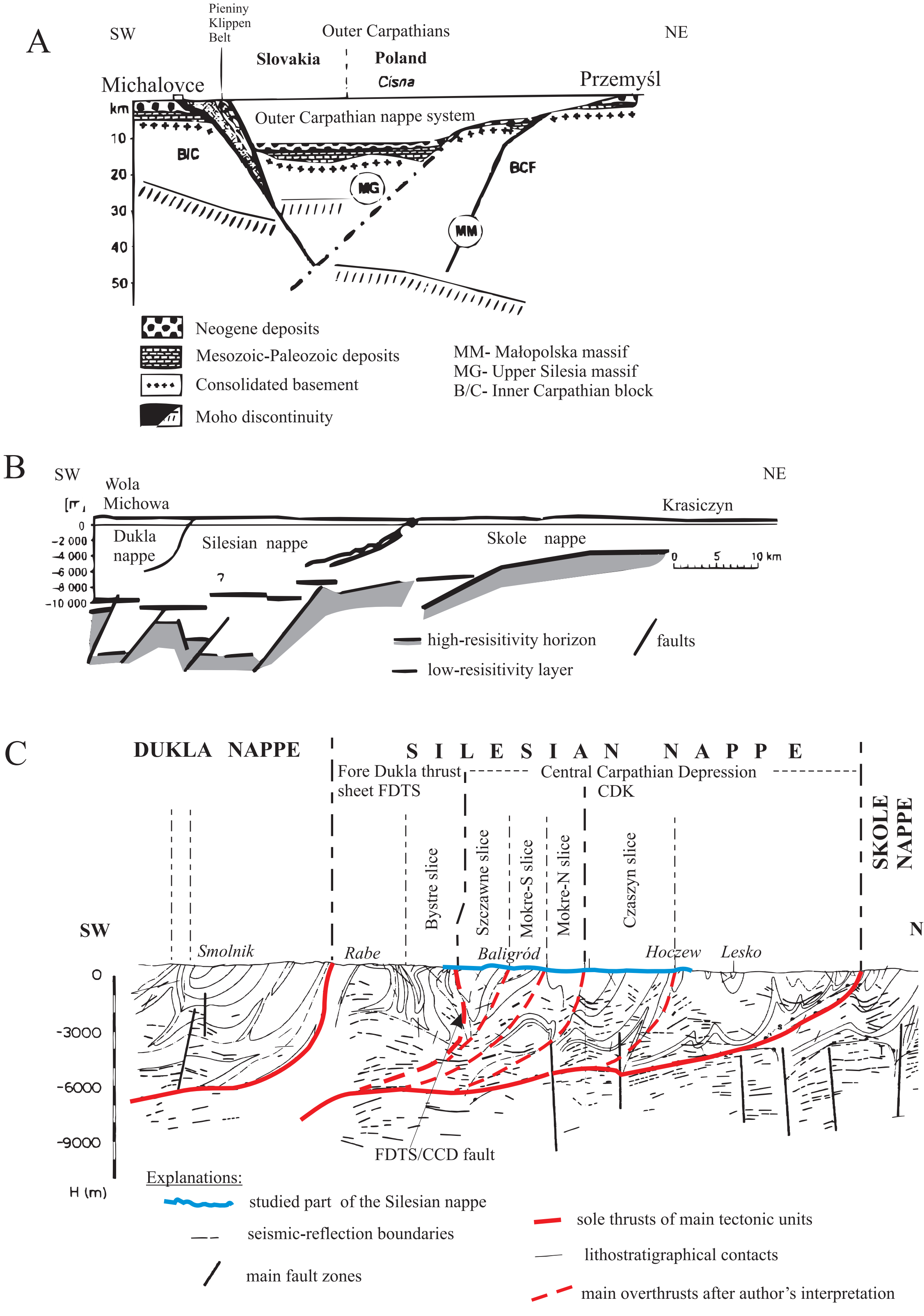

Fig. 2. A – Michalovce–Przemyśl deep geological profile (after Ryłko & Tomaś 2005, modified). B – Wola Michowa–Krasiczyn magnetotelluric profile (after Stefaniuk 2001, slightly modified). C – Part of Baligród–Radymno seismic-reflection profile (Młynarski & *al.* 1982, modified and reinterpreted)

Miocene times (OSZCZYPKO 2004). In Poland they include: the Magura, Dukla, Silesian, Subsilesian and Skole nappes (Text-fig. 1).

A crucial role in the structure of the Polish Outer Carpathians is played by the depth of the basement and its palaeorelief (Text-fig. 2). Seismic (including magnetotelluric) studies indicate that in the eastern part of the Polish Outer Carpathians the basement lies distinctly deeper than in the western part (KSIĄŻKIEWICZ 1972). On the Michalovce–Przemyśl deep geological profile (RYŁKO & TOMAŚ 2005), the consolidated basement under the Silesian nappe lies at a depth of about 18 km (Text-fig. 2A). Moreover, it is cut by several faults, which evidently disturb its relief (Text-fig. 2A, B) and have influence on the tectonics of the flysch nappes.

In the eastern part of the Silesian nappe the basement deepens progressively southwards (Text-fig. 2B). Accordingly, the sole thrust of the Silesian nappe also deepens (Text-fig. 2C) and lies at a depth of about 6-7 km (OSZCZYPKO & *al.* 1998) below the study area. In its marginal part the sole thrust is underlain by folded flysch rocks belonging to the Subsilesian unit and the Skole nappe (*op. cit.*) and, farther to the south, by Neogene autochthonous deposits, Palaeozoic–Mesozoic rocks, as well as Proterozoic rocks of the consolidated basement.

The deep location of the faulted basement and the presence of thick flysch sequences implies a complex fold-thrust structure of the Silesian nappe in the eastern part of the Polish Outer Carpathians, including the study area. In cases when the basement occurs at smaller depths, the style of the nappe structure is less complicated, as can be observed in the western part of the Polish Outer Carpathians (KSIĄŻKIEWICZ 1972).

In Poland, the Silesian nappe stretches from the Cieszyn area in the west to Ustrzyki Dolne in the east. The orientation of the main (regional) structural directions within the Silesian nappe (Text-fig. 1) changes from SWW–NEE in the west, through W–E in the middle part, to NW–SE in the east.

In the eastern part the Silesian nappe is subdivided into two tectonic subunits (Text-fig. 1): the **Central Carpathian Depression** (**CDK**, TOŁWIŃSKI 1933) and the **Fore-Dukla thrust sheet** (**FDTS**, ŚWIDZIŃSKI 1958), which are separated from each other over a distance of about 80 km by a fault (in part a typical thrust) displaying a variable character.

The general structure of the CDK has been described in a number of papers (ŚLĄCZKA 1957, 1961, 1968; WDOWIARZ 1980, 1985). This unit, located between the Gorlice meridian in the west and the Polish-Ukrainian border in the east, is the main tectonic unit of the Silesian nappe in the eastern segment of the Polish Outer Carpathians (Text-fig. 1). In the study area the CDK comprises only the Oligocene to lower Miocene (MALATA 1997) Lower Krosno beds.

The FDTS was described for the first time by OPOLSKI (1930) as a zone of strongly uplifted folds located in the foreland of the Dukla nappe. It is a narrow zone (Text-fig. 1) stretching from the Ukrainian border in the south-east to the Dukla area in the north-west. ŚLĄCZKA (1963, 1968) subdivided the FDTS into two parts along the Suliła dislocation (Text-fig. 3): the western part with a simple structure and the eastern part with a rather complex structure. The complex internal structure of the FDTS (MASTELLA 1995) is the result of the great incompetence of the rocks forming it and its location between two units (Dukla nappe and CDK) composed of competent rocks in their marginal parts. Details of the lithostratigraphic succession of the FDTS were documented by ŚLĄCZKA (1959) and KUŚMIEREK (1979).

The study area is generally located within the CDK, however, in order to determine the geometry and origin of the FDTS/CDK fault, a narrow part of the FDTS was also studied.

STRATIGRAPHY

The flysch rocks which belong to the Silesian series represent Lower Cretaceous to Lower Miocene strata and comprise the Cieszyn, Lgota, Istebna, Hieroglyphic, Menilite, Transition and Krosno beds (ŚLĄCZKA 1959; KUŚMIEREK 1979). In the study area (Text-fig. 4B) the Silesian series comprises only the Cieszyn and Transition beds in the FDTS and the Lower Krosno beds (GUCIK & WÓJCIK 1982; MALATA 1997) in the CDK.

The Lower Cretaceous Cieszyn beds (C) crop out only in the south-western part of the study area (Text-figs 3, 4A – cross-section G–H). They include dark grey and black thin- to medium-bedded,

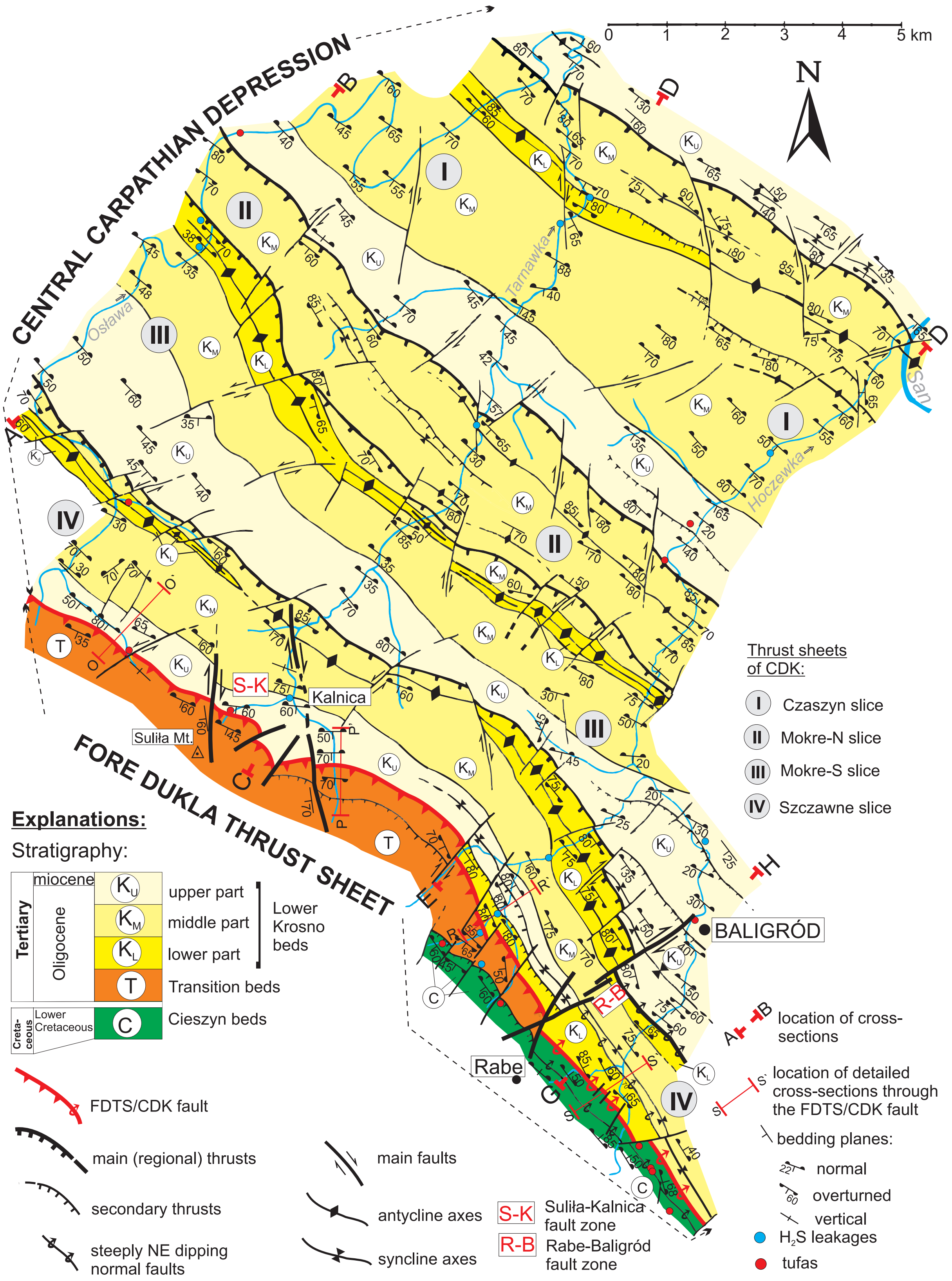

Fig. 3. Geological map of the study area

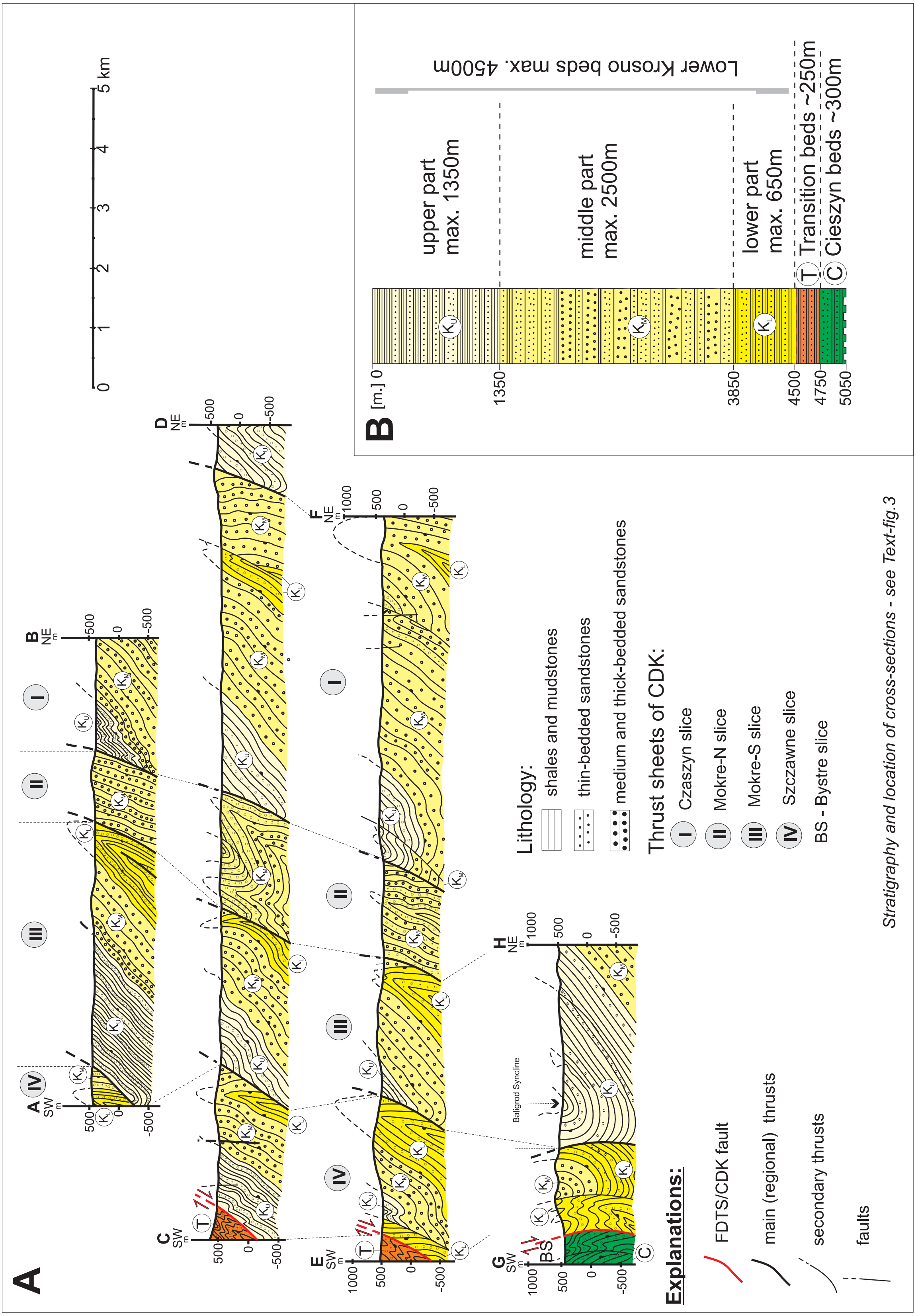

Fig. 4. A. Geological cross-sections through the study area. B. Simplified stratigraphic profile of the Silesian nappe

medium- and fine-grained sandstones with a strongly calcareous matrix, intercalating with black and dark grey mudstones and shales with a siliceous, occasionally calcareous matrix. Medium-bedded sandstones dominate in the upper part of the succession. The thickness of these beds is estimated at 300 m (Text-fig. 4B).

The Oligocene Transition beds (T) crop out in the south-western part of the study area (Text-figs 3, 4A – cross-sections C–D and E–F) and include elements typical of the older Menilite beds as well as the younger Krosno beds. They consist of dark grey thin- and medium-bedded fine-grained sandstones with intercalations of dark and grey shales as well as single beds of ankerites (ferruginous dolomites), mudstones and thick-bedded sandstones. The thickness of the Transition beds is variable and reaches up to 250 m (Text-fig. 4B).

The Oligocene to Miocene Lower Krosno beds occur almost throughout the entire study area (Text-figs 3, 4A) and, based on lithology, can be subdivided into three distinct parts (Text-fig. 4B). The lower part (K_L) consists of grey thin-, occasionally medium-bedded fine- and medium-grained sandstones intercalated with grey marly shales with a calcareous matrix. Sporadically, single beds of ankerites and thick-bedded sandstones also occur. The total thickness is 650 m. The middle part (K_M) is composed of thick- and medium-bedded sandstones with intercalations of dark grey shales and mudstones. Two facies can be distinguished here. In the north-western and north-eastern part of the study area occur sandstones of the ‘Lesko sandstones’ facies (MALATA 1997); in the south-east the ‘Otryt sandstones’ facies is developed (SIKORA 1959). The latter facies is characterized by greater thicknesses of the sandstone beds and also includes conglomerates, which, as resistant rocks building their ridges, are very important in the structure of the highest ranges of the Bieszczady Mts. The thickness of the ‘Lesko sandstones’ reaches 2500 m and that of the ‘Otryt sandstones’1175 m. The upper part (K_U) comprises grey and dark grey marly shales and mudstones intercalated with grey thin- and medium-bedded sandstones, which become sparse upwards in the succession. The thickness of this beds changes from 800 m in the north-western to 1350 m in the south-eastern part of the study area.

THE STRUCTURE OF THE CENTRAL CARPATHIAN DEPRESSION

The CDK comprises a sequence of fold-thrust structures, the geometry of which has not been described in detail until now. These structures form thrust sheets (BOYER & ELLIOTT 1982) referred to as regional-scale slices with NW–SE trend, and which are separated by thrusts and cut by map-scale faults.

Structure of slices – description

In the study area fragments of four slices occur. From north to south they comprise the Czaszyn (I) Mokre-N (II), Mokre-S (III) and Szczawne (IV) slices. In order to describe their structure in detail, each slice was subdivided into several domains (Text-fig. 5).

The main structures which build each slice are anticlines (Text-figs 3, 4A). In the south-east synclines also occur within the Mokre-S and Szczawne slices. Each of the slices (except for the Mokre-N slice) is composed of all three parts of the Lower Krosno beds. The competent middle part of the Lower Krosno beds maintains the geometry of the folds. The other two parts are mostly incompetent – the lower part crops out in the cores of anticlines whereas the upper crops out in front of the thrusts separating the slices. The structure of the slices is described below from north-west to south-east.

The **Czaszyn slice (I)** has a width of about 5.5 km (Text-fig. 3) and comprises an anticline. In the back-limb the beds in a normal position are characterized by orientations of 219/60 and 223/45 (Text-fig. 5-Ia), through 218/40 and 208/65 (Ib), up to 217/70 and 222/55 (Ic). In the fore-limb the beds in a normal position display a progressively increasing dip from the north-west to the south-east, from 40/65 (Ia), through 30/88 (Ib), up to 38/90 (Ic).

The hinge zone is represented by a narrow belt about 250 metres wide. The dips change rapidly from S-directed (fore-limb) to steep N-directed or overturned S-directed (back-limb).

The anticline axis (Text-fig. 5) is orientated at 309/2, through 120/4, to 126/4. Accordingly, in the western part (Text-fig. 3) occurs a culmination with an exposure of the lower part of the Lower Krosno beds. Axial surfaces of the anticline are orientated at 216–227/65–87, with a westwards trend of increasing dip. The interlimb angle measured near the surface decreases successively from north-west to south-east from 55°–70°, through 29°–49°, to 23°–38°.

The **Mokre-N slice (II)** is the narrowest slice (Text-figs 3, 4A) and is characterized by a different structure from that of the other slices. This slice occurs in a 1.2-1.5-km wide zone in the marginal

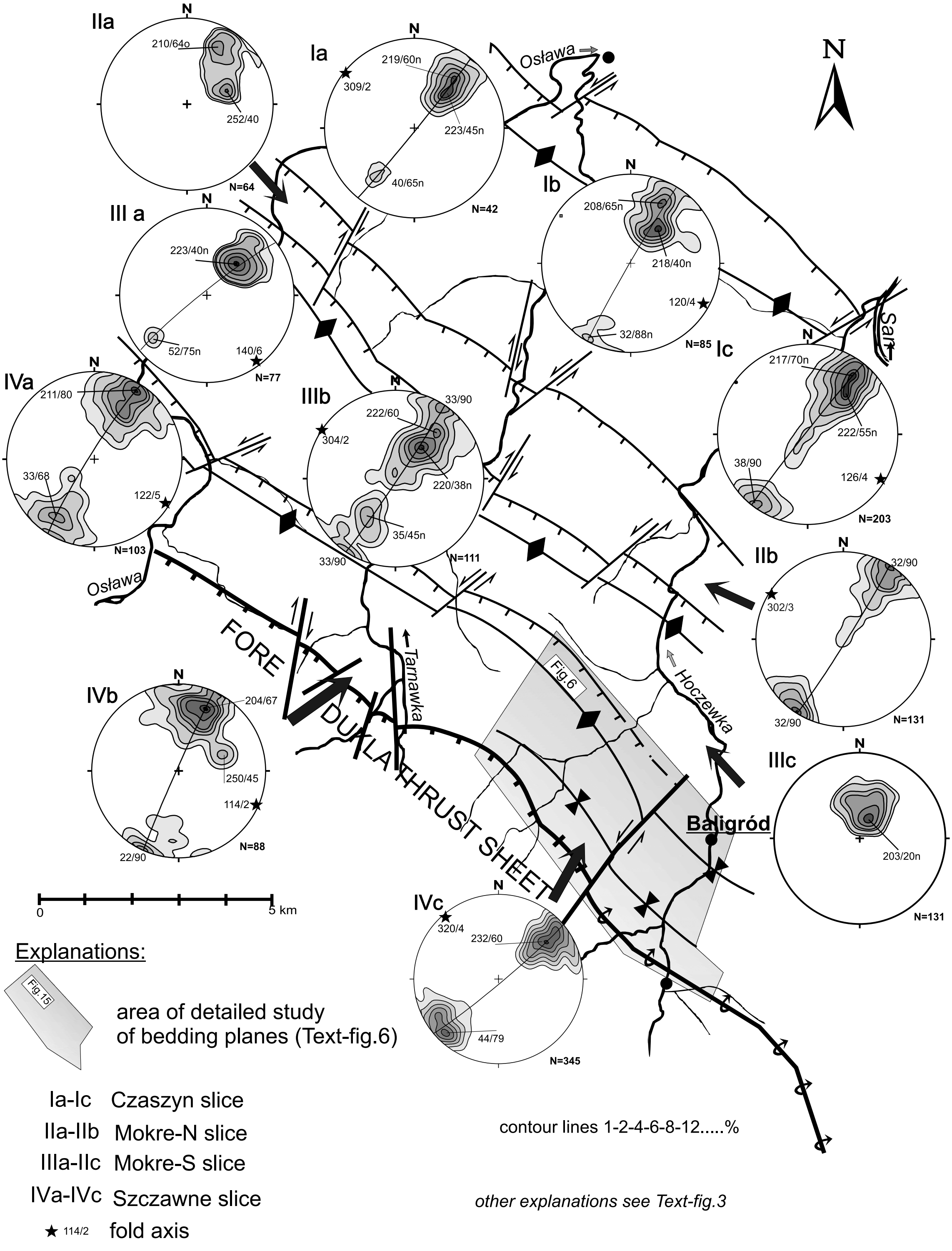

Fig. 5. Tectonic sketch map of the study area with contour diagrams of bedding planes within particular domains, showing the internal structure of the slices in CDK

parts of the study area and a 2.5 km wide zone in its middle part. In the north-west, the bedding planes (Text-fig. 6) are typically overturned with an orientation of 210/65 (IIa), and in the middle part beds with a normal and overturned position orientated at 252/40 are the most common. In the south-east the bedding planes are typically orientated at 32/90 (IIb).

The simplest structure of the Mokre-N slice is observed in the Osława river (Text-fig. 4A – cross-section A–B). In the Tarnawka stream three second-order folds are seen: two anticlines separated by a syncline (Text-fig. 4A – cross-section C–D). They represent overturned NE-verging similar folds, partly cut by second-order thrusts. In the south-east (Hoczewka river) the structure consists of an anticline represented by an almost isoclinal similar fold.

The **Mokre-S slice (III)** crops out in a zone 4 km wide in the west, through 2.5 km in the middle part, to 4.5 km in the east. The main structure within this slice is an anticline (Text-figs 3, 4A); in the south-west, there is also syncline in front of the Szczawne slice.

The back-limb of the anticline is dominated by normal bedding orientation (Text-fig. 5) changing

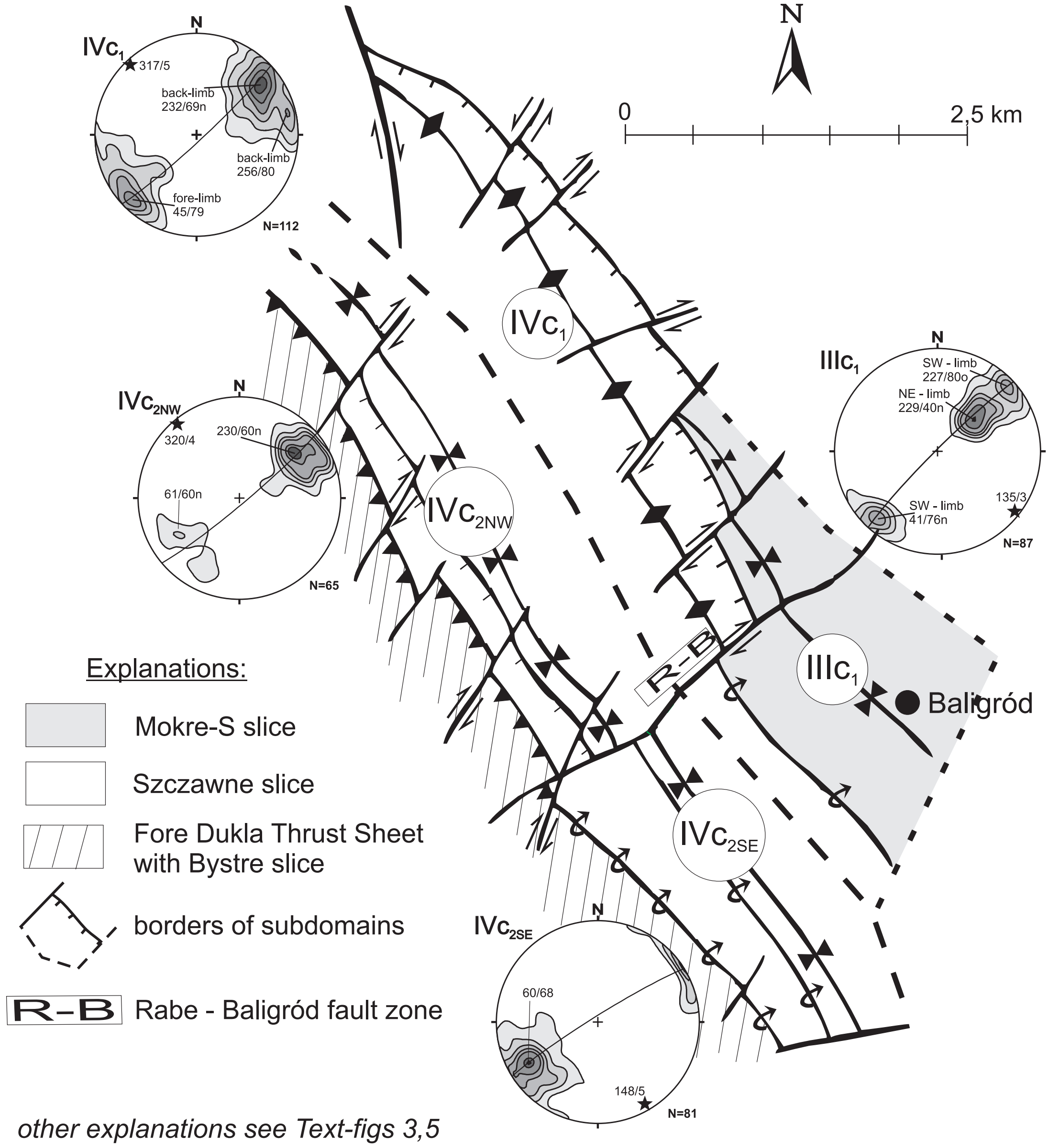

Fig. 6. Tectonic map of the south-eastern part of the study area with contour diagrams of bedding planes within the subdomains

from 223/40 (IIIa), through 220/38 and 222/60 (IIIb), to 203/20 (IIIc). In the fore-limb the bedding is also in a normal position with orientations from 52/75 (IIIa), through 35/45 (IIIb), to 33/90 (IIIc). In the hinge zone occur numerous second-order folds and steep reverse faults. The anticline axis changes its orientation (Text-fig. 5) from 140/6 to 304/2. Axial surfaces are orientated at 220–228/70–80, whereas the interlimb angles range from 45°–65°, through 20°–35°, to 50°.

In the south-western part of the Mokre-S slice there is a syncline in front of the thrust of the Szczawne slice (Text-figs 3, 4a – cross-section G–H). The north-eastern limb of this syncline is dominated by 229/40 bedding in a normal position (Text-fig. 6 – IIIc$_1$) and the south-western limb is orientated at 41/76 in a normal position to 227/80 in an overturned position. The hinge zone is over a dozen metres wide. The syncline axis is orientated at 135/3, the axial surface at 224–228/60–72, and the interlimb angle range from 40° to 64°.

The **Szczawne slice (IV)** crops out in a zone 2.5 km wide in the north-west to 1.5 km wide in the south-east. This slice is cut by the Rabe–Baligród fault zone (see below), along which occur distinct changes in its internal structure. The Szczawne slice is composed of an anticline, and in the south-western part also of a syncline.

The wide back-limb of the anticline is dominated by normal bedding orientation at 211/80 in the north-west (Text-fig. 5 – IVa), 204/67 and 250/45 (IVb) in the middle part and 232/69 and 256/80 in the south-east (Text-fig. 6 – IVc). South-eastwards from the Rabe–Baligród fault zone the back-limb is orientated at 45/79 in an overturned position. In the fore-limb the beds are orientated at 33/68 (Text-fig. 5 – IVa) north-west of the slice, 22/90 in the middle part (IVb), to 44/79 (IVc) in the south-east in an overturned position. Beginning from the Rabe–Baligród fault zone, the back-limb is reduced along the thrust separating it from the Mokre-S slice.

The anticline axis (Text-fig. 5) changes its orientation from 125/5, through 114/2, to 315/5. Such undulations of the fold axis result in the existence of two culminations separated by a depression in the middle part of the slice (Text-fig. 3). Axial surfaces are orientated at 212/78, through 40/86, to 228/88. The interlimb angle ranges from 47° in the west, through 23°–32° in the middle part, to 33° in the east.

In the FDTS foreland, there is a syncline within the zone of bending of the thrust separating it from the CDK (Text-fig. 3). North-westwards from the Rabe–Baligród fault zone (Text-fig. 6 – IVc$_{2NW}$), the north-eastern limb of the syncline is orientated at 61/60 and the south-western limb at 230/60. The orientation of the syncline axis is 320/4, of the axial surface 145/90 and the interlimb angle is 61°. South-westwards from the fault zone (Text-fig. 6 – IVc$_{2SE}$) the bedding planes are typically orientated at 60/68. The south-western limb of the syncline is also cut by a second-order thrust (Text-figs 3, 6).

Thrusts which separate the particular slices are parts of map-scale (regional) NW–SE-trending thrusts (Text-fig. 3) and tens of kilometres long.

The northernmost thrust separates the Czaszyn slice from the Tarnawa-Wielopole fold (ŚLĄCZKA 1968) and has an orientation of 215/50-65 (Text-figs 3, 4A). The next thrust, the Mokre-N thrust, is orientated at 220/60-70. Between the Tarnawka stream and the Hoczewka river the intersection line of the Mokre-N thrust is displaced distinctly to the north-east (Text-fig. 3) along strike-slip faults. The Mokre-S thrust is orientated at 220/70 in the north-west, through 250/65 between the Osława river and the Tarnawka stream, to 215/70–80 in the south-east. The surface of the Szczawne thrust is orientated at 215–225/50–60 in the north-west; south-eastwards it becomes steeper and orientated at 230/70 and 240/90. The orientation of the Szczawne thrust changes to 50/80 in the south-east beyond the Rabe–Baligród fault zone.

In outcrops the thrusts can be observed as zones tens of metres wide. Within them occur breccia, cataclasites and strong deformations, which prevail in the footwall thrust block composed of the incompetent upper part of the Lower Krosno beds. Mesoscopic folds with the axes orientated parallel to the strike of the thrust surface are also observed. The breccia is composed of fragments of rocks ranging from a few centimetres to a few metres in diameter and with different degrees of rounding. Particular fragments are often strongly fractured and slickensided and occur within strongly folded dark grey and black shales. The cataclasites are composed of a blue-grey clayey mass. Hydrogen sulphide leakages and tufas (cold-water travertines) often occur within the thrust zone (Text-fig. 3).

Structure of slices – discussion and interpretation

The geological structure of the study area was not previously interpreted as a slice structure. The names of each slice are generally consistent with the names of folds as applied by ŚLĄCZKA (1957, 1968) and MŁYNARSKI & *al.* (1982). The slices studied are parts of regional-range slices. From north to south these regional slices comprise: the Czaszyn – Polany – Skorodne (I) slice, the Mokre N – Rajskie – Otryt (II) slice, the Mokre S – Zatwarnica (III) slice and the Bóbrka – Rogi – Szczawne – Suche Rzeki slice. The syncline located in the south-eastern part of the Mokre N slice (Text-figs 3, 6) is part of the Baligród syncline (ŚLĄCZKA 1961; MALATA 1997) which, to the east, equates with the Magurka – Stoły syncline. The syncline in the southern part of the Szczawne slice is the equivalent of the Roztoki Dolne syncline (ŚLĄCZKA 1963) which, to the east, equates with the Połoniny syncline (MASTELLA 1995). To the east, the prolongation of the Mokre-N thrust (Text-fig. 3) is the Otryt thrust, which divides the Bieszczady Mts. into two facial sub-regions.

The anticlines which form the slices have similar geometries (Text-fig. 4A). They include asymmetrical folds with wide back-limbs and very narrow and steeply dipping fore-limbs cut by thrusts. They represent similar folds with a narrow hinge zone which – close to the surface – are upright or NE-verging inclined or overturned folds (Text-fig. 4A). According to borehole data (Czaszyn 1 and Czaszyn 2 boreholes – PGI archives), the inclination of the folds increases with depth. Small undulations of the anticline axes confirm the existence of culminations and depressions (Text-fig. 3). The lower part of the Lower Krosno beds is exposed within the culminations. The magnitudes of the interlimb angles described above indicate that the folds are tight to close. Moreover, changes in the magnitudes of the interlimb angles, together with the variable width of the slices and different degrees of complexity in their internal structure (related to lithology) indicate variable tectonic shortening. In general, both the shortening and the complexity increase from west to east and from north to south.

The structure of the Mokre-N slice (Text-figs 3, 4A) should be interpreted separately, because of the differences in comparison to the other slices. The Mokre-N slice is composed only of the middle part of the Lower Krosno beds. The south-eastward increase in the complexity of this slice results from the presence there of more incompetent beds (thinner sandstone beds, prevalence of shales). At an early stage of its evolution the Mokre-N slice was probably an integral part of the Mokre-S slice (II), forming the fore-limb (north-eastern limb) of the anticline. Later, a thrust was initiated in the hinge zone, subdividing the anticline into two independent slices. The thrust can be interpreted as an into-anticline thrust (MITRA 2002).

In the south-eastern part of the study area two synclines originate. They represent regional structures which extend to the Polish-Ukrainian border. The Baligród – Magurka Stołów syncline is an inclined NE-verging concentric fold (Text-fig. 4A – cross-section G–H). The Roztoki Dolne syncline is an upright or inclined NE-verging similar fold (Text-fig. 4A); to the south-east of the Rabe – Baligród fault zone its geometry changes to a SW-verging concentric fold.

Thrusts separating the slices dip steeply near the surface, the dip decreasing progressively with depth as suggested by borehole (PGI archives) and seismic profile data (Text-fig. 2). They represent typical listric faults. Simultaneously, the thrusts (with the exception of the Mokre-S thrust) cut the forelimbs of the anticlines which form the slices. In this respect they are forelimb-thrusts (BUTLER 1982) forming an imbricate system (BOYER & ELLIOTT 1982) and, more precisely, leading imbricate fan. The thrusts join at the same plane at a depth of *ca*. 6-7 km (Text-fig. 2C; OSZCZYPKO & *al*. 1998) to form a single detachment thrust – sole thrust.

The NW-SE thrust orientation is similar to the fold trend. This evidences that the shortening was the same during folding and thrusting and was SW-NE-directed. Local trend changes can be the result of basement palaeorelief and also of later strike-slip faults cutting the slices.

Map-scale faults and fault zones

Based on field investigations and interpretation of aerial photo and radar images, a variety of map-scale faults and fault zones transverse or oblique to the trend of regional structures have been recognized (Text-fig. 3). The faults range from several hundred metres to several kilometres in length.

Oblique faults predominate in the study area and form two vertical or steeply dipping fault sets with strikes between 170°-10° (first set) and 65°-75° (second set). Map analysis (Text-fig. 3) and field investigations indicate that they are predominantly strike-slip faults, with the first set forming a dextral strike-slip fault, and the second a sinistral fault. Both sets form a complementary, conjugate system.

The third set is composed of faults which occur in the south-eastern part of the area westwards of Baligród (Text-fig. 3), where the trend of the structures changes locally. The third set comprises transverse vertical faults with strikes orientated at 45°-50°. They are dextral faults which transfer the tectonic structures of the Szczawne and Mokre-S slices from the south-east to the north-west.

Two fault zones at the boundary of the CDK and the FDTS have a crucial effect on the structure of the study area. These zones are located between Suliła Mt. and the village of Kalnica, in the north-west, and between Rabe and Baligród in the south-east (Text-fig. 3).

Suliła – Kalnica fault zone, which includes the Suliła dislocation (ŚLĄCZKA 1963; TOKARSKI 1964, 1966), is composed of two S–N-striking dextral strike-slip faults, 2-4 km long (Text-fig. 3) and two smaller sinistral and dextral faults. Second-order faults have also been observed at outcrop. Within this zone, the FDTS/CDK fault changes its direction from NW–SE to W-E (Text-fig. 3), with a simultaneous adjustment of tectonic structures adjacent to the fault. Moreover, the internal structure of the FDTS changes from simple folded in the west to strongly sliced in the east across this (ŚLĄCZKA 1963, 1968). According to field studies, the Suliła – Kalnica fault zone has a more complex structure than previously suggested (ŚLĄCZKA 1963; TOKARSKI 1964, 1966).

Rabe – Baligród fault zone (Text-figs 3, 6), not described hitherto, is composed of two dextral and sinistral strike-slip faults about 2 km long, which cut the FDTS/CDK fault. The sinistral fault extends towards Baligród as an array of *en echelon* faults. At the same time, the area north-westwards of the zone is more uplifted (Text-fig. 3), which indicates that some of the faults can be interpreted as dip-slip faults. The Rabe – Baligród fault zone is of regional importance, because south-eastwards of it a considerable structural reconstruction of the marginal parts of the CDK (SW-verging folds) and FDTS takes place and the FDTS/CDK fault steeply dips to the north-east. The Rabe-Baligród fault zone originated during the latest stages of thrusting and later during strike-slip and normal faulting.

Summing up, the map-scale faults described above represent mainly strike-slip faults which cut fold-thrust structures (Text-fig. 3) and thus originated at a later stage, as suggested by MASTELLA (1988) and ALEKSANDROWSKI (1989). The oblique conjugate fault system formed during SW–NE compression (see also MASTELLA & SZYNKARUK 1998). The transverse fault set which occurs near Baligród and some faults within the Rabe-Baligród fault zone can be interpreted as a group of tear faults which originated simultaneously with the folding. Some of the strike-slip faults were reactivated at a later stage as normal (dip-slip) faults.

Mesoscopic structures

During field investigations mesoscopic structures were recognized; these originated during different deformation stages and can often be related to the evolution of regional structures. Mesoscopic folds, faults, master joints and clastic dykes are described in detail below, whereas the joints were investigated earlier (RUBINKIEWICZ 1998, 2002; MASTELLA & KONON 2002).

Folds

In the study area occur mesoscopic folds with wavelengths in the range of 0.2-15 m. Folds have been divided into two distinct groups depending on the plunge of the axis: vertical folds with steeply dipping or vertical axes and folds with subhorizontal or horizontal axes.

Vertical folds occur almost only within the zones of strike-slip faults and have a very diverse geometry. They comprise similar, concentric as well as disharmonic folds with steeply dipping or vertical limbs with diverse orientations.

Folds with subhorizontal axes (Text-fig. 7) occur in a different tectonic position: predominantly in the hinge zones of first-order folds (**F_H folds**), in the limbs of regional folds (**F_L folds**) and within thrust zones (**F_T folds**).

F_H folds occur in the hinge zones of anticlines, where the incompetent lower part of the Lower Krosno beds is exposed (Text-figs 3, 4A). They comprise series of asymmetrical similar folds cut by reverse faults.

F_L folds occasionally occur in the shallow-dipping back-limbs of map-scale anticlines within shale beds (incompetent layers) located between sandstone beds (competent layers). They include series of hinge zone-verging similar folds. Slickensides which occur on the bedding planes of the folds are secondarily folded.

F_T folds occur only in the footwall thrust block. They comprise asymmetrical similar, sometimes concentric folds. In the fold limbs displacements on bedding planes and lamination have been observed. Considerable changes in thickness of the incompetent layer result from the extraction of the rock from limbs into the hinge zones. Small fold-accommodation faults (MITRA 2002) are also present. In the external parts of the hinge zones occur hinge radial (extensional) fractures.

The orientation of fold axes of all three groups of mesoscopic folds is very similar (Text-fig. 7A) and ranges between 100–145/0–15 and 290–320/0–15, with a dominant strike of 130°. The axial planes of the F_H and F_T folds are orientated at 217/79 (Text-fig. 7B). The south-western limbs dip gently and the north-eastern limbs dip steeply in a normal (north-eastern dip) or overturned (south-western dip) position. They represent steeply inclined or overturned NE-verging folds. The interlimb angles of F_H and F_T folds vary between 15°-60° and 70°-90° (Text-fig. 7C). Lower values are typical of similar folds with steeply dipping limbs composed of incompetent rocks, whereas higher values are characteristic of concentric folds with gently dipping limbs consisting of competent rocks.

Vertical folds are significant indicators of specific deformation styles. Because they occur in strike-

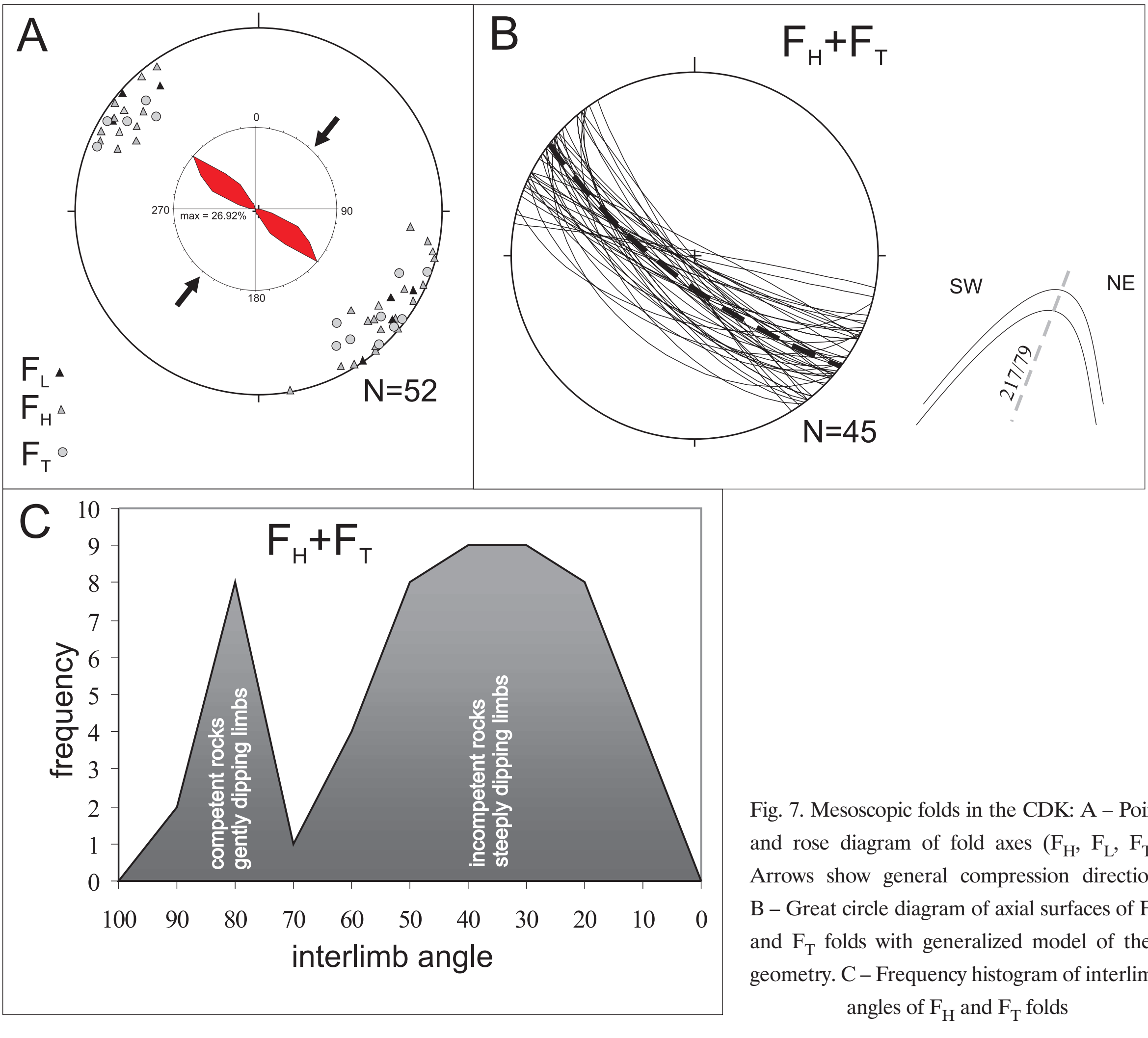

Fig. 7. Mesoscopic folds in the CDK: A – Point and rose diagram of fold axes (F_H, F_L, F_T). Arrows show general compression direction. B – Great circle diagram of axial surfaces of F_H and F_T folds with generalized model of their geometry. C – Frequency histogram of interlimb angles of F_H and F_T folds

slip fault zones in most cases, their origin is connected with horizontal or subhorizontal displacement. They originated as a result of dragging (GRASEMANN & *al*. 2005).

The occurrence of F_H folds in the study area depends on the incompetence-competence of the rocks which compose the hinge zones of regional folds and the amount of shortening. The anticlines which form particular slices reveal considerable shortening (Text-fig. 4A) and their hinge zones are composed of incompetent rocks (lower part of the Lower Krosno beds) in which the F_H folds originated.

The origin of F_L folds has already been described in the Polish (e.g., JAROSZEWSKI 1980; MASTELLA 1985) and non-Polish literature (TWISS & MOORES 2001). They originate as a result of bending and mutual displacement of beds within the first-order fold, which is related to flexural slip folding. The initial stage of flexural slip folding took place before the F_L folds originated and the displacement occurred only on bedding planes (slickensides). The next stage took place during increasing flexural slip and resulted in the development of F_L folds together with folding of slickensides.

F_T folds originated in incompetent rocks (upper part of the Lower Krosno beds) in front of regional thrusts (Text-figs 3, 4A) as a result of push from competent rocks which formed the hanging wall block. Thrusting was compensated by continuous strain within a narrow zone.

Both F_L and F_H folds are genetically related to the evolution of map-scale folds, therefore their analysis gives the possibility of determining the direction of compression responsible for the origin of regional folds. On the other hand, F_T folds are related to the origin and evolution of thrusts. Because all three groups of mesoscopic folds have an almost identical orientation of fold axes, the map-scale folds and thrusts must have originated in an unchanged stress field under SW–NE compression (Text-fig. 7A). The NE-vergence of the F_H and F_T folds indicates that tectonic transport was directed from SW to NE.

Faults

Mesoscopic faults occur mostly within the map-scale fault zones and thrusts and in the hinge zones of folds of different scale (RUBINKIEWICZ 2000). The relatively regular fault network comprises several sets and systems of different orientation and sense of movement. Faults have been divided into oblique (diagonal), longitudinal or transverse to the NW–SE trend of the map-scale structures. They comprise dip-slip reverse (R) and normal (N) faults as well as strike-slip faults (S).

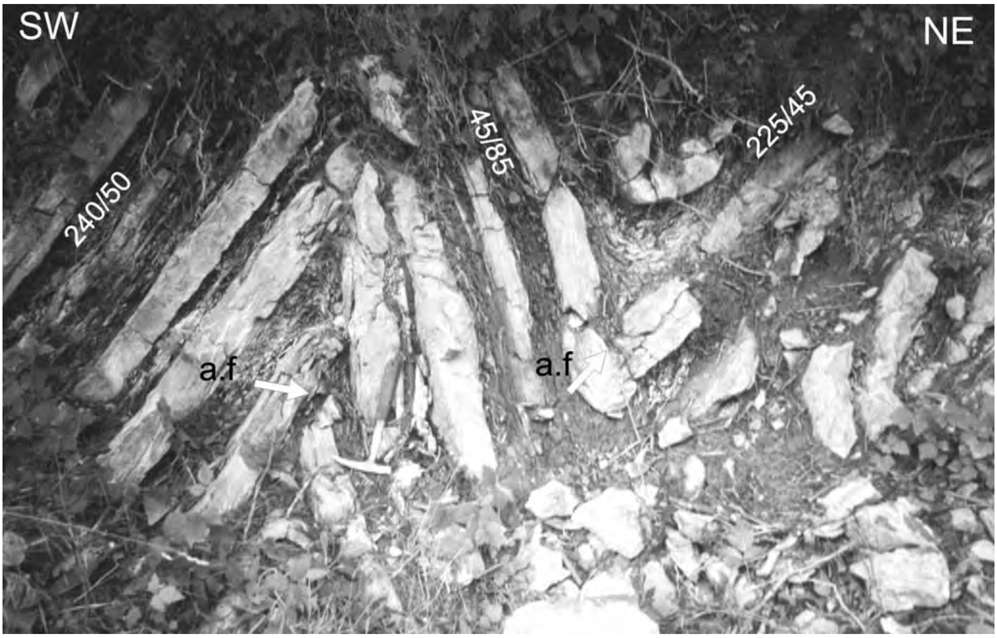

Fig. 8. F_T similar folds with fold-accommodation faults (a.f.) in front of the Mokre-N thrust. Osława river – upper part of the Lower Krosno beds

Reverse faults occur in thrust zones or in the hinge-zones of folds. Two longitudinal sets (Text-fig. 9A) have been distinguished. The strikes of both sets range from 115° to 130°, with 125° dominant, and the dip ranges between 5° and 55°, with 35° dominant, which is typical of reverse faults (Anderson 1951; Jaroszewski 1980). SW-dipping faults prevail, whereas NE dips are less common.

Reverse faults are accompanied by drag folds (Text-fig. 10). Some of the reverse faults die out towards the surface, passing into the overlying fold and creating a fault-propagation fold (Mitra 1990). In some cases, reverse faults form a ramp-flat structure (Butler 1982; Text-fig. 10A) or a set of listric faults (Text-fig. 10B), which sometimes join deeper into a single slip surface. The average amount of displacement ranges between several centimetres to tens of metres.

Strike-slip faults occur in zones of map-scale faults and in thrust zones. Their length ranges from a dozen centimetres to a dozen metres. Strike-slip faults form sets and systems comprising conjugate faults which often occur together within a single outcrop (Rubinkiewicz 2000; Text-fig. 12A). Based on the similar orientation and sense of movement, two systems and one set of strike-slip faults were distinguished.

The **S_1** system, predominating in the study area, comprises two fault sets, oblique to the orientation of map-scale structures: dextral, with the dominant strike at 5°; and sinistral, with the dominant strike at 66° (Text-fig. 11A). The dextral set is strongly mineralized. Because the faults often coexist in a single outcrop (Text-fig. 12A) and crosscut each other at acute angles, they can be referred to as conjugate faults (Angelier 1994; Rubinkiewicz 2000). They occur mostly in zones of map-scale strike-slip faults and are accompanied by drag folds and contractional duplexes.

The **S_2** system, which is also oblique, occurs locally in the Tarnawka stream in the vicinity of the FDTS/CDK fault (Text-fig. 3), predominantly in the

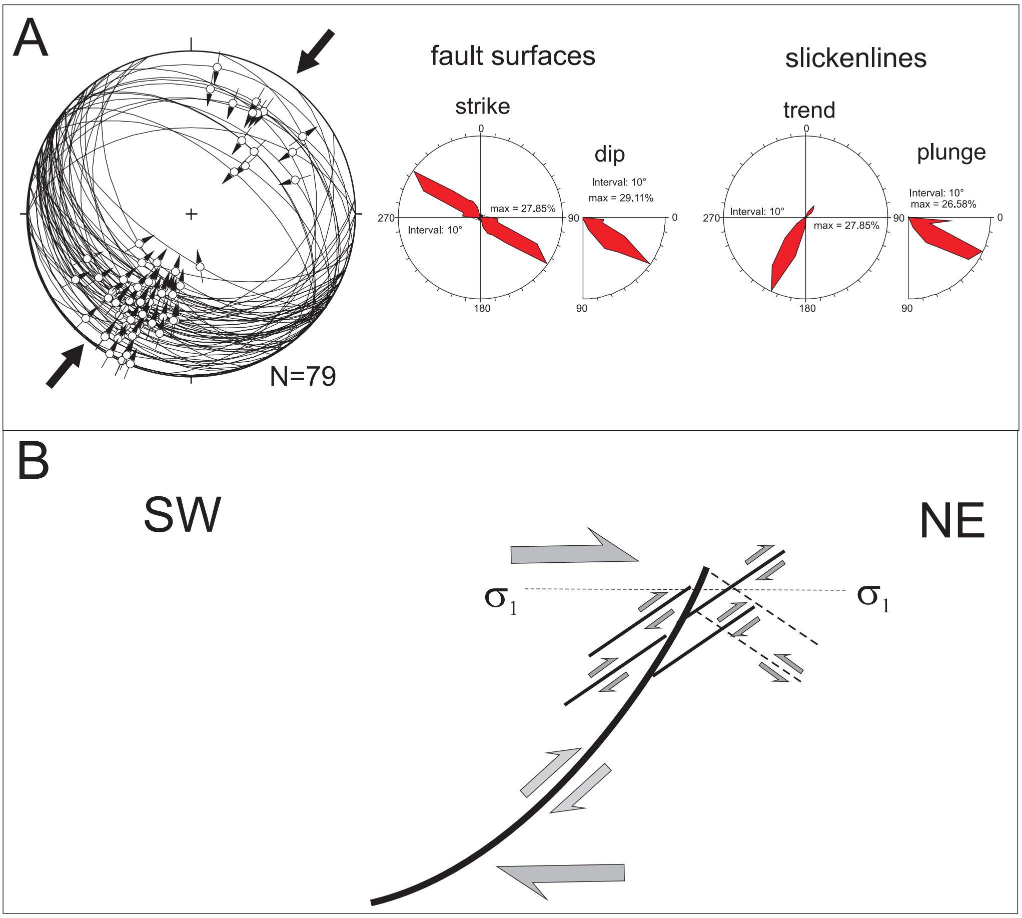

Fig. 9. Geometry of mesoscopic reverse R faults observed within the thrust zones. A – Angelier diagram of orientation of reverse faults and rose diagrams of fault surfaces and slickenlines. B – Relation of reverse R faults to the main thrust

Suliła – Kalnica fault zone. It is composed of two conjugate fault sets (Text-fig. 11B): a sinistral set striking at 33° and a dextral set striking at 145°.

The **S_3** set (Text-fig. 11C) comprises longitudinal, mostly dextral, faults striking at 125°. They occur in thrust zones mainly in the southern part of the study area. Displacements within them reach a dozen metres. Evidence of dextral movement was also found on some reverse fault surfaces.

Normal faults have been found close to the thrust zones and in the hinge zones of map-scale folds. They comprise (RUBINKIEWICZ 2000) two fault systems. The **N_1** system comprises two sets striking sub-perpendicular to the trend of map-scale structures and dipping NW or SE at about 60° (Text-fig. 13A). In some cases a similar dip-slip movement component was observed on the surfaces of the S_1 system strike-slip faults.

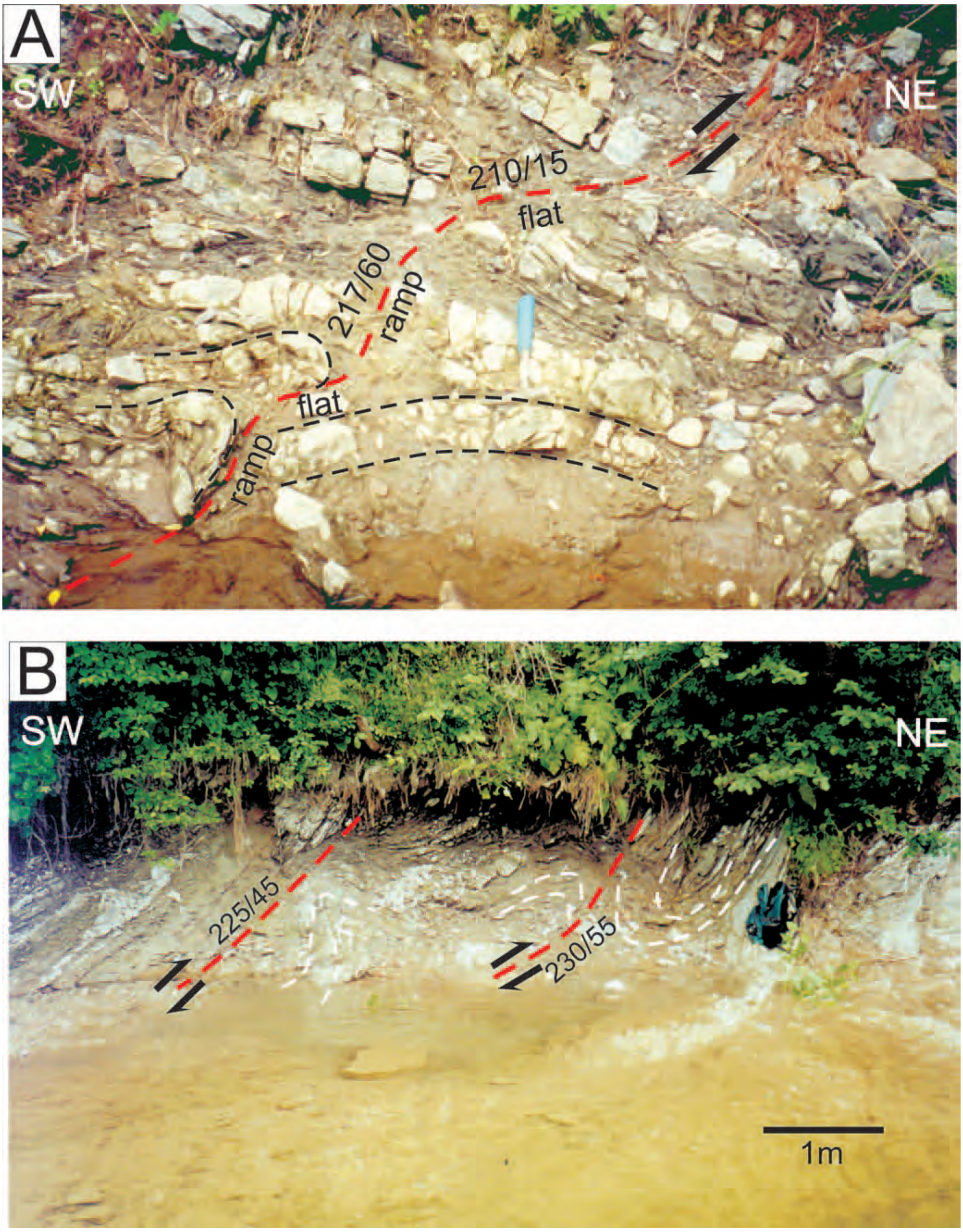

Fig. 10. A – Reverse fault with ramp-flat geometry. Mokre-S slice, upper part of the Lower Krosno beds – Hoczewka river near Baligrod. B – Reverse listric faults with drag folds on the footwall of regional thrust. Czaszyn slice, upper part of the Lower Krosno beds – Osława river near Mokre village

The $\mathbf{N_2}$ system comprises two longitudinal fault sets striking at about 125° and dipping at 60° to NE and 35° to SW. Locally they form typical listric faults (Text-fig. 14B). The similar dip-slip movement component was also found on the surfaces of the reverse faults system.

The different fault sets and systems successively originated at different times as a result of shifted stress field and strain (RUBINKIEWICZ 2000), as also recognized in other parts of the Outer Carpathians (e.g., MASTELLA 1988; ALEKSANDROWSKI 1989; DECKER & *al.* 1997, 1999). Their origin is related to the evolution of map-scale faults and to deformations within second-order folds.

The oldest reverse faults R (RUBINKIEWICZ 2000) are typical low-angle faults. Strikes of the reverse fault surfaces are parallel to the strikes of map-scale thrust surfaces, the dips, however, are smaller (Text-fig. 9B). The angle between the reverse faults and thrusts reaches between 15° and 30°; the reverse faults can therefore be interpreted as second-order faults to map-scale thrust surfaces, which originated simultaneously with the thrusting. Hence it is possible to reconstruct regional compression directions (shortening) from the reverse faults. The shortening was SSW–NNE- to SW–NE-directed (Text-fig. 9A). A slightly different S–N-directed shortening was observed locally near the FDTS/CDK fault in the Tarnawka stream (Text-fig. 3). This is consistent with the bending and trend change of structures in this area into a more W-E orientation.

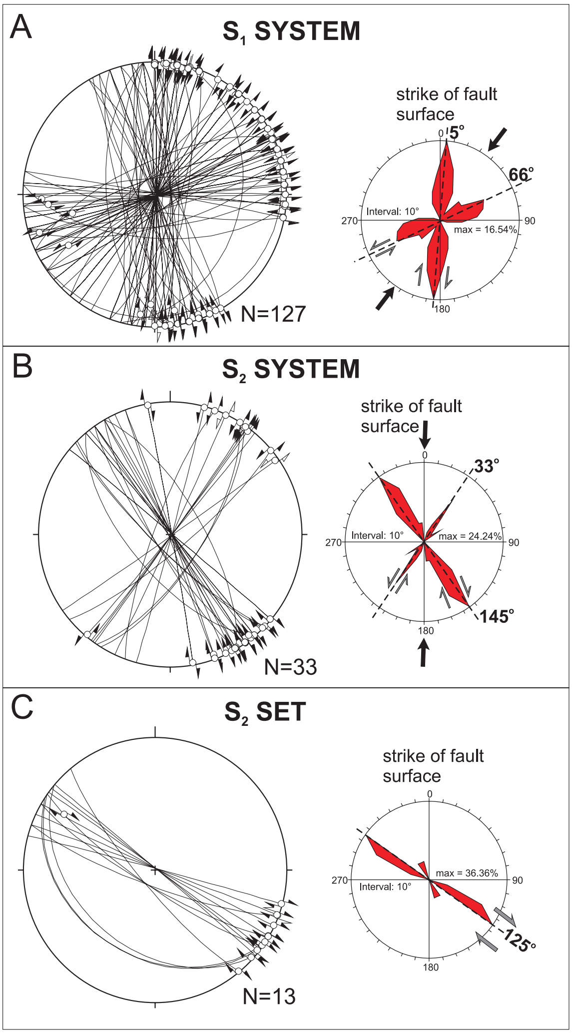

Fig. 11. Mesoscopic strike-slip faults; A – S_1 system prevailing in the study area. B – Local S_2 system (Kalnica area – see Text-fig.3). C – Dextral S_3 set which occurs within the thrust zones

Both sets of reverse faults form a conjugate system; the value of the double shear angle is 68° and the bisector of this angle, the σ_1 axis, is horizontal (Text-fig. 9B).

A distinct genetic relationship of reverse faults with thrusts, and the fact that thrusts cut the limbs of map-scale folds, indicates that they originated after folding when further shortening by folding was not possible.

The orientation of the S_1 system strike-slip faults is similar to the orientation of map-scale strike-slip faults inferred from aerial and radar photos (MASTELLA & SZYNKARUK 1998), and thus it is probable that they originated in the same stress field. They were formed under SW–NE compression (Text-fig. 11A). Because these faults cut map-scale folds, thrusts and reverse faults, they originated after the folding and thrusting.

The local S_2 system originated, as with the S_1 system, after folding and thrusting as a result of local S–N compression (Text-fig. 11B) related to faults of the Suliła – Kalnica fault zone.

The origin of the S_3 set can be related to the regional dextral rotation of slices along the thrust surfaces (see DECKER & *al.* 1999). Additional proof for the dextral rotation is the simultaneous opening and strong mineralization of the dextral set of the S_1 system. Some faults of the S_3 set used the pre-existing reverse fault surfaces which were reactivated. The S_3 set is cut by faults of the other systems, and thus must have formed earlier. The youngest faults comprise two systems of normal faults, with the N_2 system younger than the N_1. Both systems originated during post-orogenic extension. The N_1 system

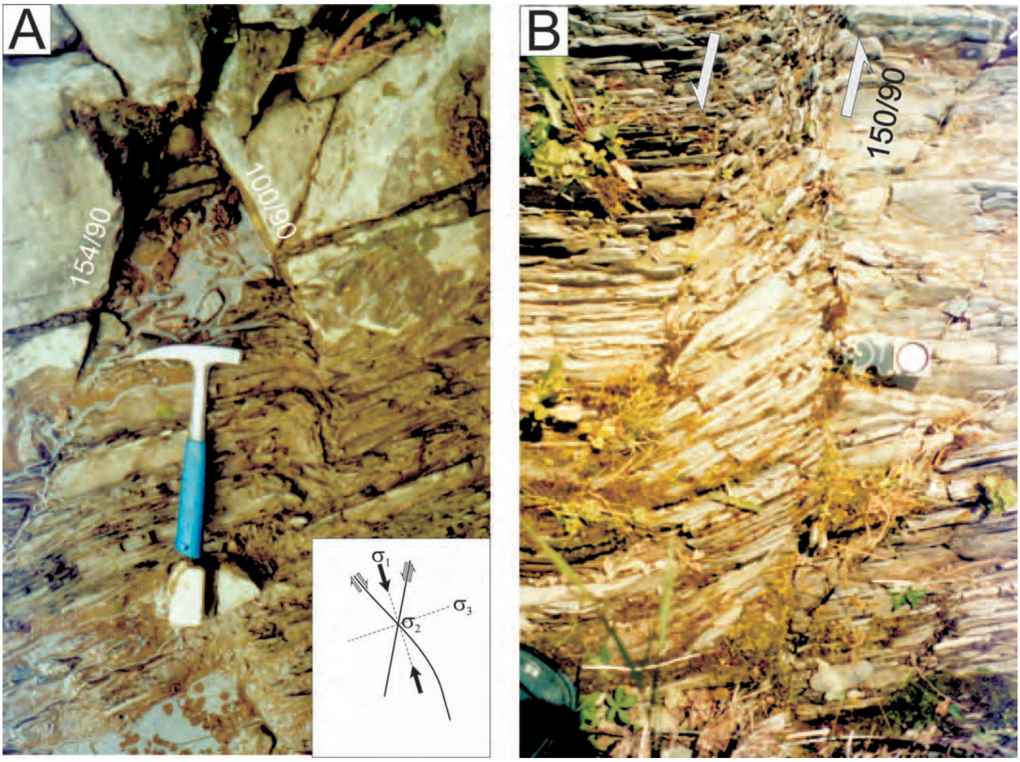

Fig. 12. Examples of strike-slip faults (Osława river, lower part of the Lower Krosno beds). A – conjugate faults of S_1 system. Szczawne slice, lower part of Lower Krosno beds, Osława river. B – contractional duplexes within sinistral fault of S_1 system. Location, as above

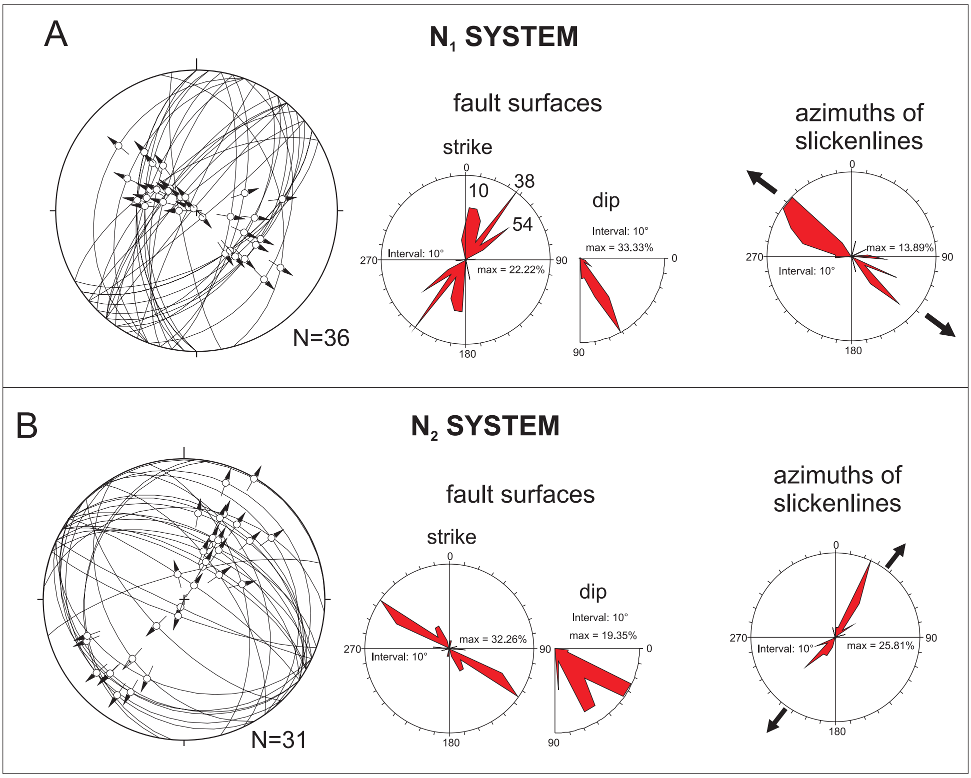

Fig. 13. Systems of mesoscopic normal faults; A – N_1 system formed during NW–SE tension (black arrows); B – N_2 system formed during SW–NE tension

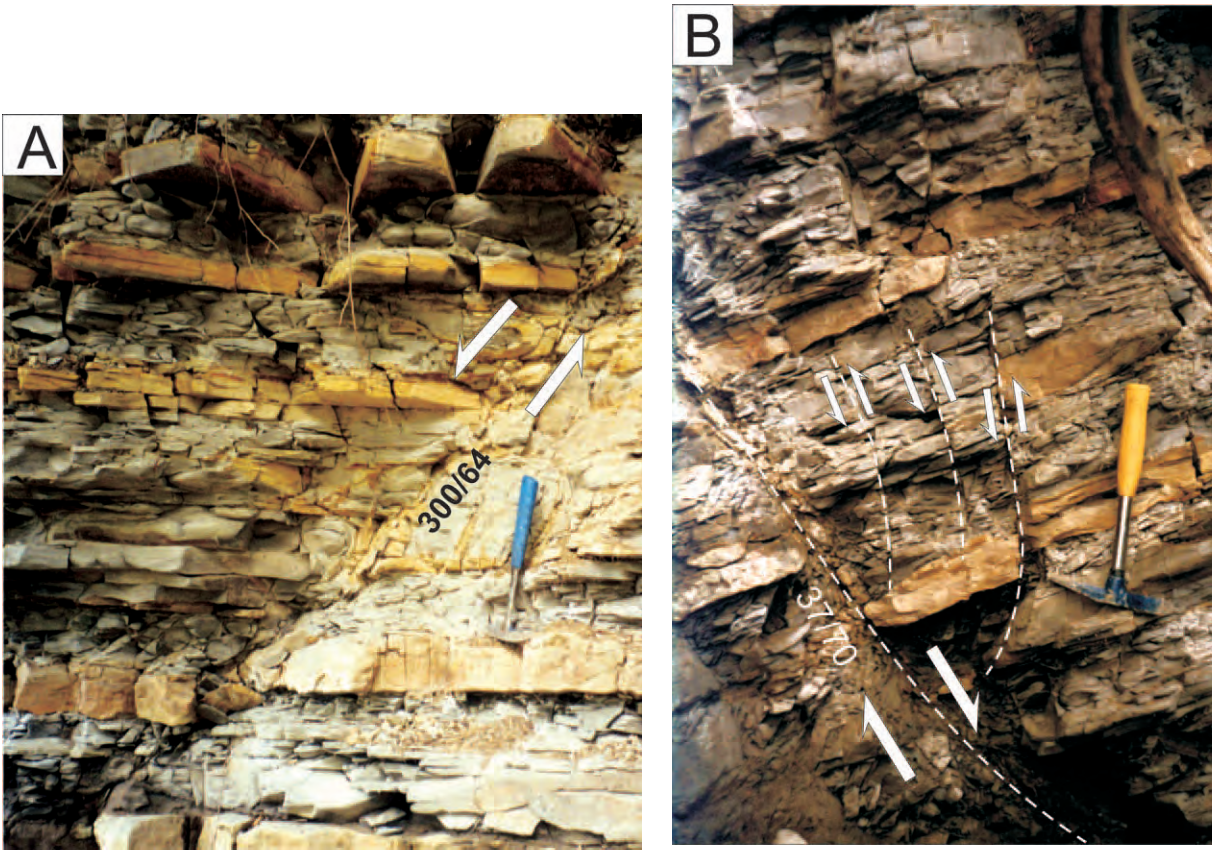

Fig. 14. Examples of normal faults. A – normal fault of the N_1 system with offset of about 10 cm. Mokre-S slice – Hoczewka river, Baligród area, upper part of the Lower Krosno beds. B – normal fault of the N_2 system Szczawne slice - Rabski stream, lower part of the Lower Krosno beds

was formed under NW–SE extension (Text-fig. 13A) parallel to the orientation of map-scale structures, whereas the N_2 system formed under SW–NE to SSW–NNE extension (Text-fig. 13B), perpendicular to the orientation of map-scale structures.

The detailed stages of the evolution of the fault network related to the evolution of other structures are presented below in the concluding chapters of this paper (Text-fig. 21).

Master joints

In the southern part of the study area, within the Szczawne slice in the foreland of the FDTS, occur vertical fractures cutting several to a dozen beds, which can be interpreted and classified as master joints (Jaroszewski 1980; Aleksandrowski 1989; Twiss & Moores 1992).

The joint lengths range from several to a dozen metres (Text-fig. 15A). Master joints form series of fractures with a spacing ranging from a dozen centimetres to several metres. They are strongly mineralized by blocky calcite and form veins 0.5–3 cm (Text-fig. 15A), sometimes even 10–15 cm thick.

The master joints form three sets (Text-fig. 15B, C). The first, orientated at 2°, occurs near the village of Kalnica (Text-fig. 2); the second is orientated at 32° and occurs further to the east in the zone of bending of the FDTS/CDK fault; and the third is orientated at 47° and occurs in the south-east up to the Rabe – Baligród fault zone. Master joints propagate in a fan-like manner and are arranged perpendicular to the trend of folds and thrusts in the area.

The considerable concentration of master joints in the zone of strong tectonic deformations at the foreland of the FDTS (Text-fig. 15C) indicates that their origin depended on strongly folded rocks and steeply dipping beds, as described by Aleksandrowski (1989). Before

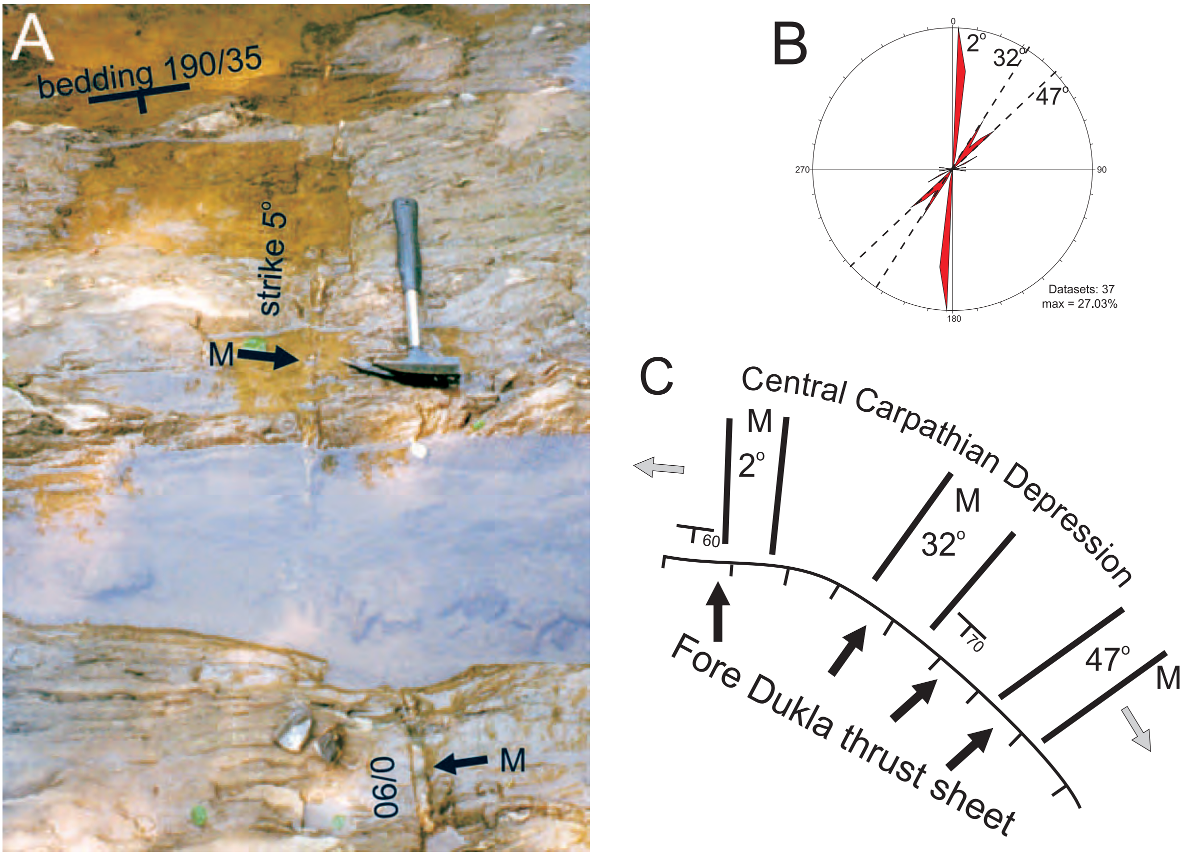

Fig. 15. Master joints architecture. A – mineralized master joints cutting shale and thin sandstone beds. Szczawne slice, upper part of the Lower Krosno beds. Tarnawka stream. B – rose diagram of strikes of master joints in the southern part of CDK. C – Model of development of master joints in the foreland of the FDTS in the zone of its NE bending

the master joints originated, thrusting and stretching of structures at the contact between the CDK and FDTS took place. Next, at the foreland of the FDTS, the structures were subject to extension and the master joints formed simultaneously with the migration of solutions and calcite crystallization. They formed during E–W to NW–SE tension.

Clastic veins

In several outcrops occur fractures with a length of several metres and a width of several centimetres, which commonly cut shale and mudstone beds (Text-fig. 18). The fractures are generally filled with sandy clastic sediment. These structures can be interpreted according to the definition of GRADZIŃSKI & *al.* (1986) as clastic veins. Structures of this type have been documented from the Polish Carpathians by DŻUŁYŃSKI & RADOMSKI (1957).

Boundaries between the fracture wall and the infilling material are commonly sharp. The veins show a rectilinear trend and are orientated at various angles in relation to the bedding (Text-fig. 16). The clastic veins differ from the commonly observed clastic dykes (DŻUŁYŃSKI & RADOMSKI 1957), which have diverse and irregular shapes. The regular structure of the clastic veins indicates that they were formed within fractures of lithified rock. The sediment which fills the fractures intruded from the upper part of the succession, where rocks were poorly lithified and strongly saturated with water. The process was favoured by hydrostatic pressure at great depths.

The occurrence of clastic veins in the study area evidences extensional conditions in the basin. They were probably initiated during synsedimentary tectonic movements connected with the earliest stage of flysch deformation in this part of the CDK.

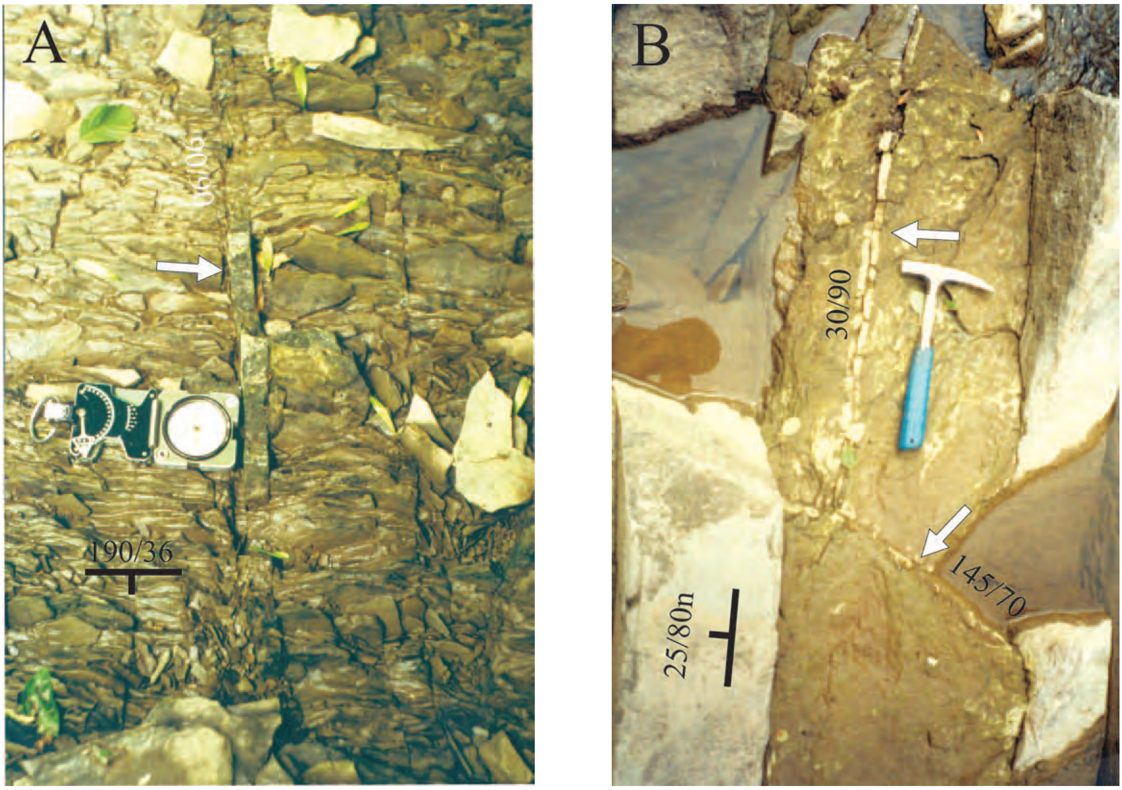

Fig. 16. Clastic veins. A – sandstone clastic vein cutting shales. Szczawne slice, upper part of the Lower Krosno beds, Tarnawka stream. B – sandstone clastic veins cutting mudstone bed. Szczawne slice, middle part of the Lower Krosno beds, Hoczewka river

FDTS/CDK FAULT

The CDK is separated from the FDTS by a distinct fault zone (KUŚMIEREK 1979; MASTELLA 1995). The older rocks that form the FDTS (including the Cretaceous rocks of the Bystre slice) lie to the south-west of the fault, while the Lower Krosno beds of the CDK, which are of younger, Oligocene age, lie to the north-east. The FDTS/CDK fault was interpreted by the majority of authors as a thrust, the course of which was evidenced from the Osława river (ŚLĄCZKA 1957), through the Suliła Mt. area (TOKARSKI 1964, 1966) and Bystre (ŚLĄCZKA 1959), to Ustrzyki Górne, where TOKARSKI (1975) observed that the thrust steeply dips to the north-east. A similar dip direction was found by KUŚMIEREK (1979) in the area between the Hoczewka river and the Polish/Ukrainian border. To the north-west of the Hoczewka river, the thrust surface dips to the south-west (ŚLĄCZKA 1957). In the study area the FDTS/CDK fault changes its dip direction (Text-figs 3 and 4A).

To the west of the Suliła – Kalnica fault zone (Text-fig. 3), the FDTS/CDK fault is a typical thrust (Text-figs 4A and 17 – cross-section O–O') oriented at 210–220/45–60. In front of the thrust occurs a series of folds with broken hinges.

To the east of the Suliła – Kalnica fault zone the thrust surface changes its orientation to almost longitudinal at 180–195/55–70 (Text-fig. 3). In the footwall and hanging wall thrust blocks occur numerous NE-verging inclined or overturned similar folds (Text-fig. 17 – cross-section P–P').

More to the east, the thrust is bent like an arch (Text-fig. 3), beyond which it dips steeply and changes its orientation to 230–245/65–85. The thrust is accompanied by second-order thrusts and reverse faults; between them the beds dip steeply and bend (Text-fig. 17 – cross-section R–R').

To the east of the Rabe – Baligród fault zone (Text-fig. 3) the FDTS/CDK fault changes its dip from south-west to north-east and is oriented at 45–55/65–70. It is accompanied by SW-verging inclined or overturned similar folds (Text-fig. 17 – cross-section S–S') and longitudinal normal faults.

This study partly confirms that the FDTS/CDK fault is a typical thrust, albeit with a gradually increasing dip from the north-west to the south-east (Text-figs 4A and 17), up to the Rabe – Baligród fault zone. Eastwards from this fault zone the FDTS/CDK fault is a steeply NE-dipping normal fault. The trend of the FDTS/CDK fault is similar to that of the adjoining tectonic structures (Text-fig. 3).

The study confirmed that the development of specific tectonic structures within the thrust zone depends on the dip angle of the thrust surface and the lithology and competence-incompetence of rocks occurring deeper or shallower within the succession.

If the thrust surface dips gently, at 15° to 30°, potential shear zones orientated at 20°–30° in relation to the thrust surface can originate under the thrust at high overburden weight (Text-fig. 18A). In the case described, the shear zones are concordant with the axial surfaces of folds with sharp hinges (Anderson 1974) and form kink bands and kink folds. Such folds originate during compression orientated almost parallel to the planes of anisotropy (Reches & Johnson 1976; Rubinkiewicz 2005) – which in this case are bedding planes – and also under considerable ambient pressure, e.g. overburden weight. In the north-west (Text-fig. 17 – cross-section O–O’), the FDTS could play the role of overburden, with kink folds originating under the thrust in densely bedded rocks. Because the kink folds now occur at a considerable distance from the thrust, the thrust range was probably greater, and the present FDTS/CDK fault is of erosional origin.

If the thrust dips at 30°-65° (Text-fig. 17 – cross-section P–P’), then tight similar folds with a NE vergence consistent with the direction of tectonic transport are common in both the hangingwall and footwall thrust block (Text-fig. 18B). The folds originated under smaller overburden pressure, close to the surface.

Where the thrust surface dips at 65-80° (Text-fig. 17 – cross-section R–R’), contractional duplexes occur (Text-fig. 18C) between the floor and roof thrusts. In the study area the contractional duplexes originated during brittle deformation close to the surface.

In the area where the FDTS/CDK fault dips NE, the ‘Otryt sandstones’ facies (middle part of the Lower Krosno beds) is developed, forming a rigid competent rock complex. To the north-west, the ‘Otryt sandstones’ successively disappear and pass into the ‘Lesko sandstones’ facies. The great thickness of the ‘Otryt sandstones’ together with their strong competence could have had an influence on the thrusting of the FDTS on the CDK, composed of incompetent rocks. The CDK acting as a rigid block (‘Otryt sandstones’) could thus impede the thrust process and cause the thrust to become steeper and retro-overturned (formation

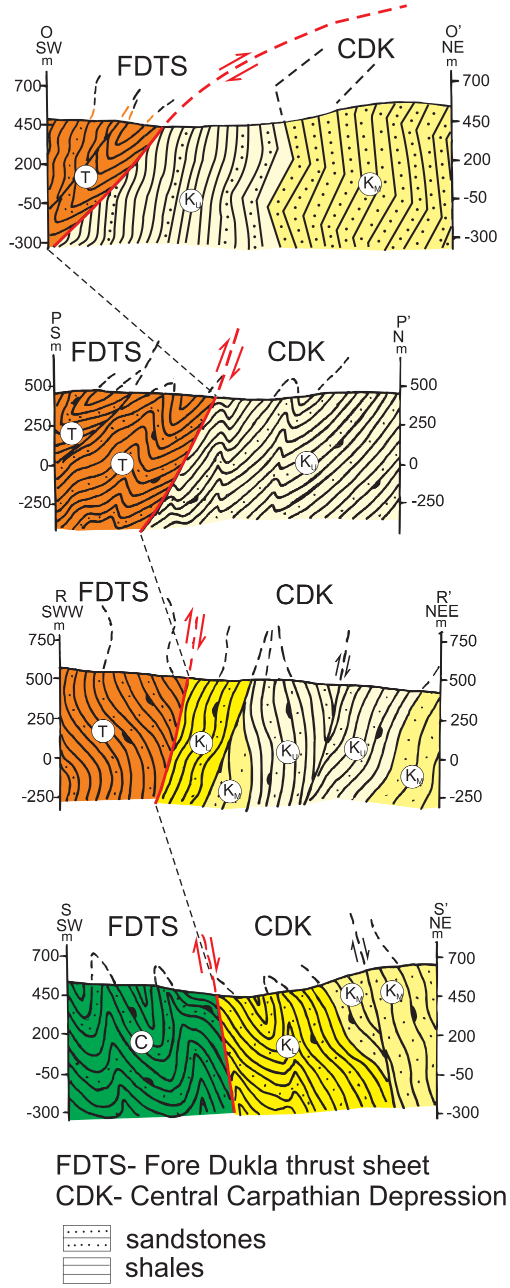

Fig. 17. Detailed geological cross-sections (not to scale) of the FDTS/CDK fault (for location and other explanations see Text-figs 3, 4A)

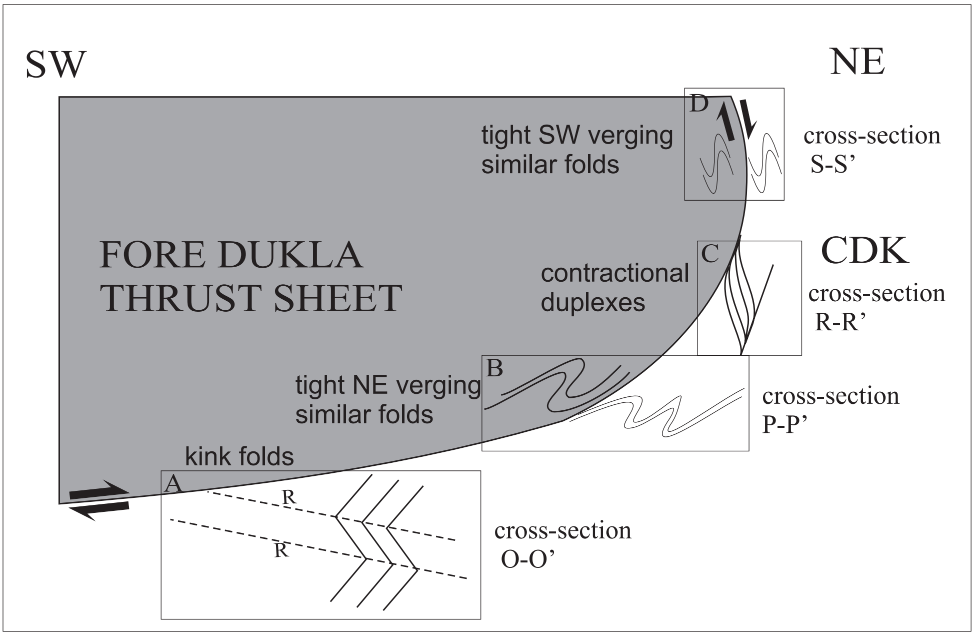

Fig. 18. Schematic diagram of tectonic structures related to the dipping of the FDTS/CDK fault; A – kink folds originated along potential R-shear zones under a large overburden pressure; B – NE-verging similar folds; C – contractional duplexes; D – SW-verging similar folds

of a normal fault directly below the surface), with a simultaneous overturning and SW-vergence of the folds building the marginal part of the CDK. The impeding of the thrust process in this fragment is also indicated by the presence of synclines 'unconsumed' by the thrusts in the FDTS/CDK fault foreland. The presence of tight similar folds in the zone under discussion adjacent to the FDTS/CDK fault confirms the compressional character of this fault. The north-eastern dip of the FDTS/CDK fault is observed as far as the country border (HACZEWSKI & *al*. 2000), and possibly also in Ukraine (see map in JANKOWSKI & *al*. 2004). At deeper levels, the FDTS/CDK fault becomes gradually steeper, to vertical, and finally the dip changes to a south-westward direction (typical thrust), which is also confirmed by seismic data (Text-fig. 2C).

This interpretation indicates that the thrusting, as well as the steepening and retro-overturning of the thrust between the FDTS and CDK, took place at the same time, and the differences in the susceptibility of the foreland rocks influenced their present-day geometry. This does not exclude the reactivation of the FDTS/CDK fault in the north-eastern part as a reverse fault during the uplift of the marginal part of the CDK (MASTELLA 1995).

THE STRUCTURE OF THE MARGINAL PART OF THE FORE-DUKLA THRUST SHEET

In the north-west of the study area, the Fore-Dukla thrust sheet is composed (Text-fig. 3) of the Transition Beds; in the south-east, the Cieszyn Beds form a strongly uplifted element of the FDTS – the Bystre Slice.

Orientation of bedding. In the north-west, the beds are predominantly orientated at 220/53 (Text-fig. 19, zone A), and at 270/46 within the Suliła fault zone. East of the fault zone, in the vicinity of Kalnica, beds with W-E strikes dominate; in normal position at 188/97 and in overturned position at 182/48 (Text-fig. 19, zone B). In the next segment (Text-fig. 19, zone C), up to the Rabe – Baligród fault zone, variations in the bedding orientation can be observed, with beds in normal and overturned position at 235/60, 250/30, 220/48 and 53/58. South-eastwards from the fault zone, within the Bystre slice, overturned beds at 56/52 predominate (Text-fig. 19, zone D).

Field observations indicate that, from the western margin of the study area, the beds become steeper and the dips change from a southern to a northern direction. The variable strike orientation is concordant with the above-described variable orientation of the FDTS/CDK fault (Text-fig. 3), which points to a genetic link between the structure of the analyzed fragment of the FDTS with the FDTS/CDK fault.

Faults. Among small faults occurring at the contact with the FDTS/CDK fault the presence of two sets of faults has been determined (Text-fig. 20A): a dextral longitudinal fault and several dip-slip normal faults. These sets are most probably analogous to the relevant S_3 and N_2 sets from the CDK.

Master joints. The master joints occur mainly in the Bystre slice. As in the CDK, they are represented by fractures with a vertical orientation (Text-fig. 20B), up to several centimetres wide and several metres long, filled with blocky calcite. They were formed as a result of NW–SE tension orientated perpendicular to their surface at a later deformation stage, and point to the uplift of the Bystre slice as part of the FDTS.

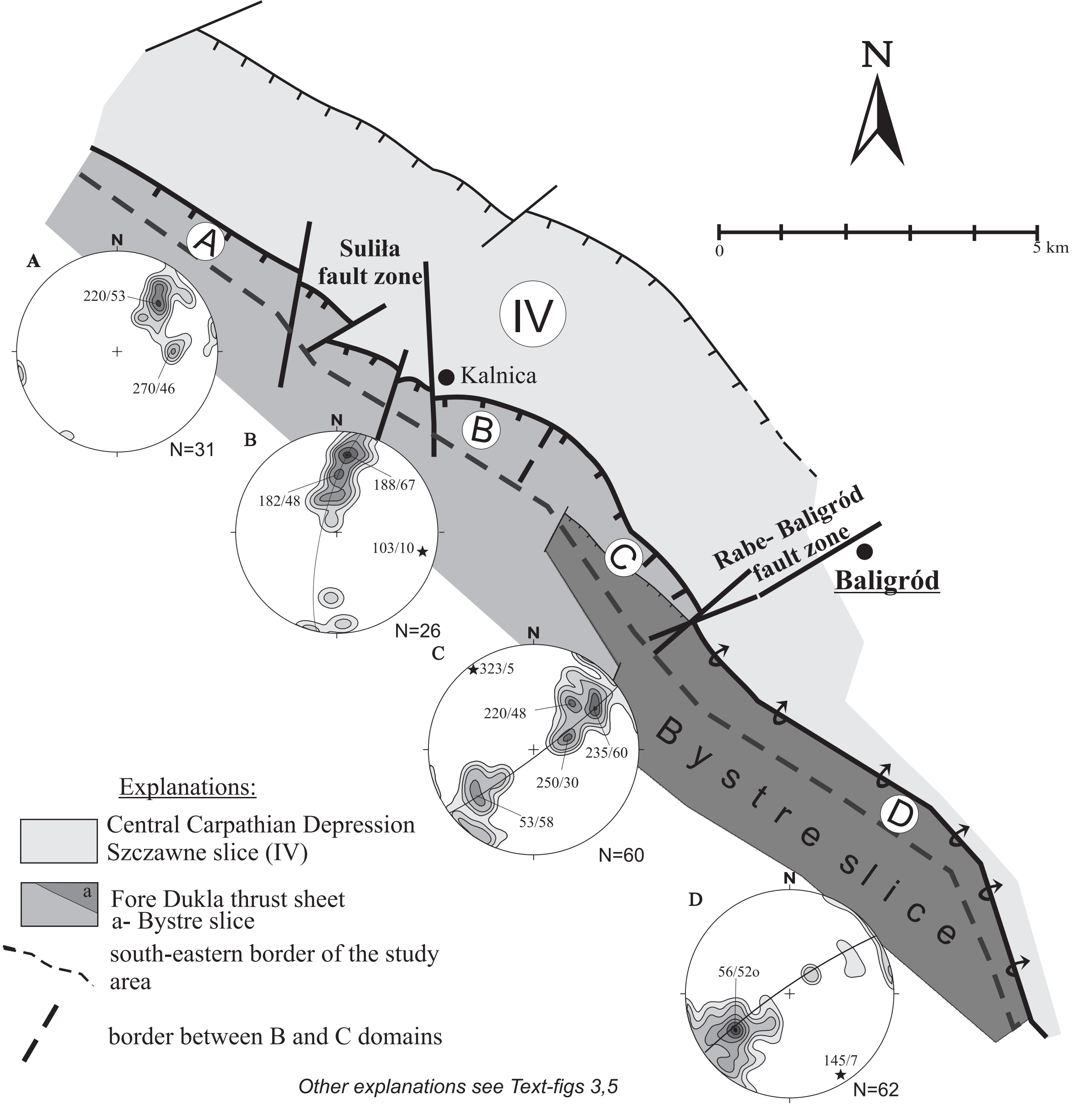

Fig. 19. Tectonic sketch-map of the Fore-Dukla thrust sheet adjoining to the Central Carpathian Depression along FDTS/CDK fault with contour diagrams of bedding within four domains (A–D)

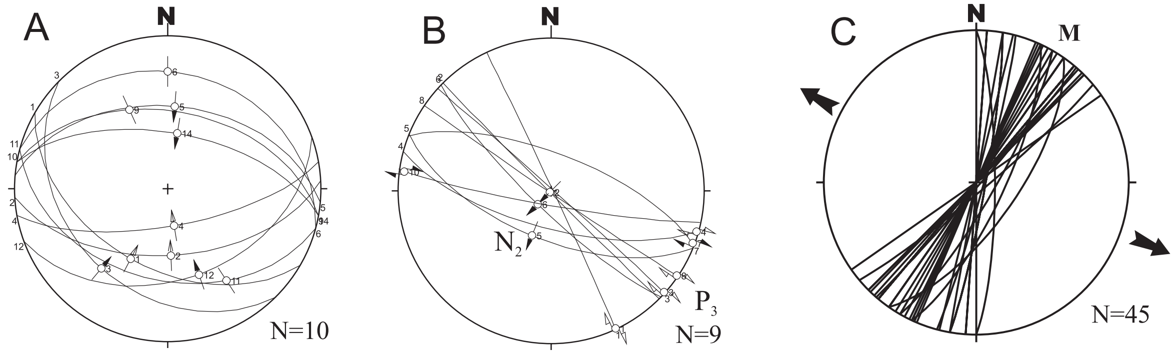

Fig. 20. A – Angelier diagram of second-order reverse faults observed in domain B near the Suliła fault zone. B – Angelier diagram of normal and dextral strike-slip faults. Two sets are visible, similar to S_3 and N_2 faults in CDK. C – Great-circle diagram of master joints from domains C and D. Arrows show the mean extension direction

STRUCTURAL EVOLUTION

Based on investigations and analysis of existing data, the multi-stage evolution of the fragment of the Silesian nappe studied is presented below (Text-fig. 21) in relation to the main stages of Carpathian evolution (Oszczypko 1992, 2006; Oszczypko & *al.* 2005; Kovacs & *al*. 1996; Fodor & *al*. 1999). The evolution took place during the pre-orogenic extension, through syn-orogenic shortening, to post-orogenic extension.

During the initial stage from the Eocene to the early Miocene, the Alcapa microplate (Fodor & *al*. 1999) caused the folding of the Magura nappe (Oszczypko & *al.* 2005). At the same time, sedimentation took place in its foreland in residual flysch basins, including the Silesian basin (Żytko 1985; Kovacs & *al*. 1996, Oszczypko 2006). At this time (**STAGE I** – pre-orogenic extension) clastic veins developed in the unstable basin floor, composed in part of already lithified rocks.

At the early/middle Miocene boundary, due to the continuing movement of the Alcapa microplate (Fodor & *al*. 1999), the folding front moved from the south to the north and from the west to the east (Książkiewicz 1972; Żytko 1985; Oszczypko 1992, 2006), encompassing the subsequent basins. SW–NE compression started to dominate in the eastern part of the Polish Outer Carpathians. Due to further movement of the Alcapa microplate, the folding included the subsequent flysch basins, first the Dukla subbasin, and next the Silesian basin (Oszczypko-Clowes & Oszczypko 2004). This was the result of increased SW–NE compression at the simultaneous switching of the orientation of the $\sigma_2$and σ_3 stress axes. Within the Silesian nappe, symmetrical upright folds and structures linked with fold slip (F_L folds) were formed in thick rock complexes (**STAGE II**). The folds were formed above the horizontal sole thrust detached from the basement at a depth of about 6-7 km (see Text-fig. 2c).

Due to subduction of the Eurasian plate (Tapponier 1977; Tokarski 1978; Royden 1988) in the middle Miocene (Fodor & *al*. 1999), transformation of the increasing horizontal compression into simple shear took place. The folds changed into NE-verging (**STAGE III**) and became asymmetrical, inclined or overturned. F_H folds originated within hinge zones. At this stage secondary thrusts developed from the surface of the sole thrust.

Gradually increasing tectonic shortening and inability to compensate it by folding caused the steepening of the secondary thrusts and their propagation to the surface (**STAGE IV**). These thrusts are typical forelimb thrusts, with the exception of the Mokre-S into Mokre-N thrust, which is an into-anticline thrust. Imbricate slices thus formed. According to the accepted models of folding for the Outer Carpathians (Książkiewicz 1972; Oszczypko 1992; Burchfiel & Royden 1982), progressive piggy-back imbrication (Butler 1982; piggy-back thrusting – Nemčok & *al*. 1998) occurs in the study area, whereby the subsequent younger thrusts are formed at the footwall of the earlier formed thrusts. These thrusts are accompanied near the surface by faults of the R-system and by F_T folds at the footwall. The CDK/FDTS fault, being earlier a typical

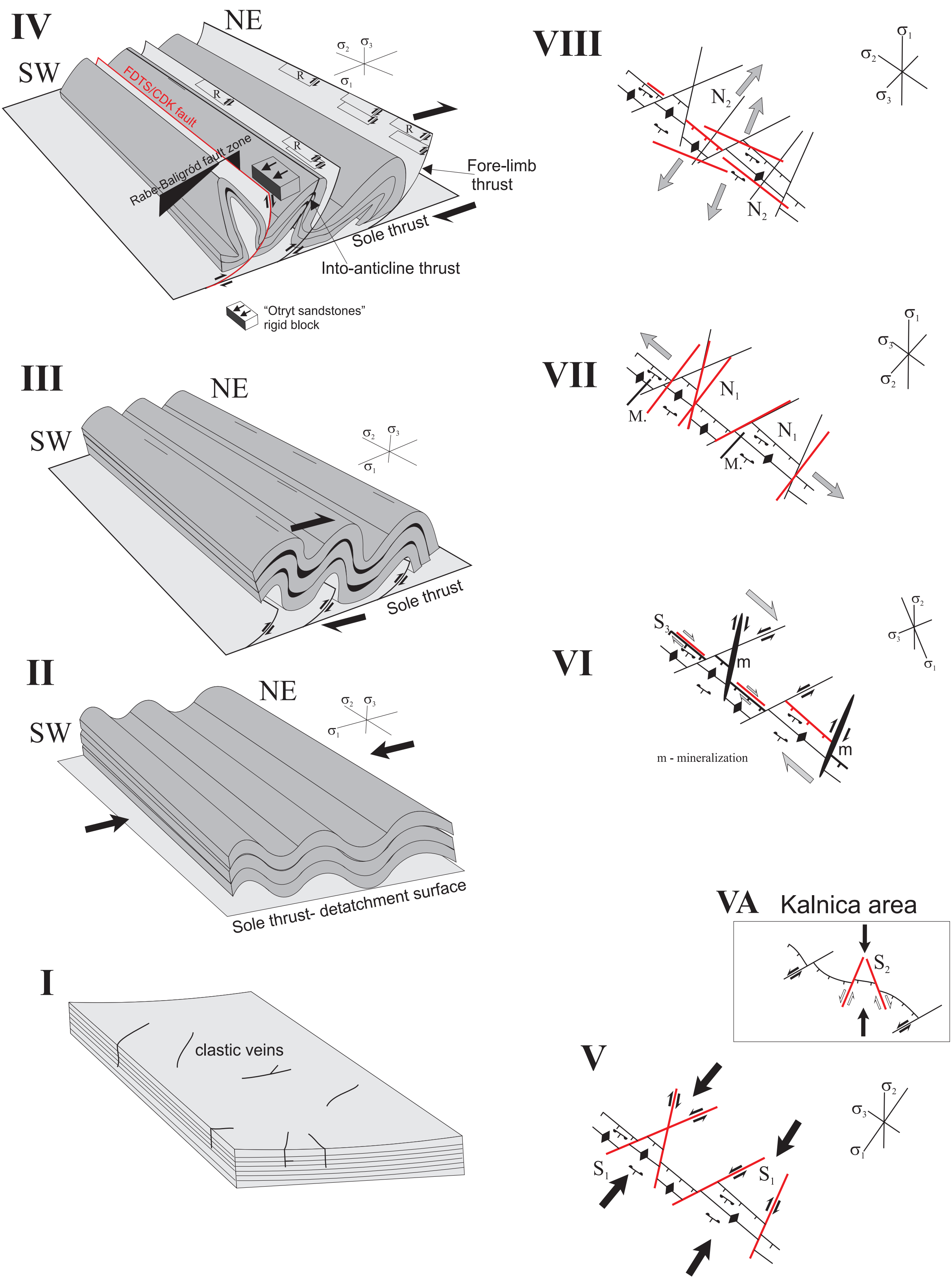

Fig. 21. Main stages of the structural evolution of the Silesian nappe in the study area with stress state regimes (after RUBINKIEWICZ 2000, modified)

thrust, became steeper to the south-east from the Rabe-Baligród fault zone, reacting to the resistance of the folded, incompetent rigid 'Otryt sandstones' (middle part of the Lower Krosno Beds). Also at this time tear faults formed in the southern part of the study area, including the Rabe-Baligród faults.

As a result of the collision between the Alcapa microplate with the Eurasian plate the reorientation of the σ_2 and σ_3 stress axes took place. In the bent Carpathian arc a system of fan-like oblique strike-slip faults developed (ALEKSANDROWSKI 1989; MASTELLA & SZYNKARUK 1998), cutting the folds and thrusts. Faults of the S_1 system (**STAGE V**) and locally of the S_2 system (**STAGE VA**) were formed in the segment studied, including faults in the Suliła and Rabe – Baligród fault zones, which resulted in a block-like sub-division of fragments of the FDTS/CDK fault and its different development in the particular segments. The steep character of the FDTS/CDK fault continues south-westwards from the latter zone, and finally its dip changes to north-eastward.

After the middle Miocene, due to dextral transpression in some fragments of the Carpathian segment studied (see NEMCOK & *al.* 1998; DECKER & *al.* 1999), dextral movement of slices around each other took place along steep thrust zones. Longitudinal faults of the S_3 system were formed (**STAGE VI**), with a simultaneous opening of fractures and mineralisation of the dextral faults of the S_1 system. Such strike-slip movements caused local sigmoidal bending in the trend of structures, including that of the FDTS/CDK fault, emphasizing the local variability in thrusting directions. Such bending is also clearly visible in the course of the Dukla thrust, which points to a crucial role of these movements in the structural evolution of the Eastern part of Polish Outer Carpathians.

The last stages of evolution are linked with post-orogenic extension (ZUCHIEWICZ 2001) of variable magnitude and orientation related to the collapse of the Outer Carpathians (OSZCZYPKO 1998). At first under NW–SE tension, parallel to the regional trend of the structures (**STAGE VII**), faults of the N_1 system formed. Master joints developed in the foreland of the FDTS/CDK fault and in the Bystre slice. Finally, normal faults of N_2 system (**STAGE VIII**) were formed under SW–NE tension.

CONCLUSIONS

The studies have enabled presentation of the detailed geology and structure of the fragment of the Silesian nappe studied in the form of a map and geological cross-sections. Along with the analysis of mesoscopic structures together with seismic data, the stages of evolution from the beginning of sedimentation until the present have been recognised.

1. The fragment of the CDK studied, being part of the Silesian nappe, is composed of imbricated slices separated from each other by thrusts. The structure of the slices is dominated by anticlines and, in the south-eastern part of the study area, additionally by synclines, which appear in the foreland of the thrusts. They are generally represented by similar, overturned or recumbent NE-verging folds with low interlimb angles indicating considerable tectonic shortening. The forelimb thrusts separating the slices are steeply inclined at the surface, with the inclination becoming progressively less with depth; at a depth of about 6-7 km they join into a sole thrust, forming an imbricate thrust system.
2. The fold-thrust structures are cut by a series of generally strike-slip faults, which are found within two main fault zones: the Rabe – Baligród fault zone, described for the first time herein, plays a crucial role in the structural remodelling of the Silesian nappe in this area; and the Suliła fault zone, the description of which is refined here.
3. In the study area appear new fold-thrust structures (including the Baligród – Magurka – Stoły syncline and the Roztoki Dolne – Połoniny syncline) which are characteristic of the Bieszczady area. The occurrence of these structures is linked with smaller tectonic shortening in the foreland of the FDTS/CDK fault in the south-eastern part of the study area and the fact that it had not been 'consumed' by the thrusting synclines as in the north-west part of the area.
4. The FDTS/CDK fault changes its character in the study area: from a typical thrust in the north-west, it gradually becomes steeper and, and beyond the Rabe – Baligród fault zone, dips steeply to the north-east as a normal fault. Similar process takes place with the thrusts from the marginal part of the CDK. To the east of this zone the folds have south-westward vergence.

5. In the structural evolution of the fragment studied a large role is played by sandstones from the middle part of the Lower Krosno Beds (‘Otryt sandstones’ facies), the thickness of which increases towards the south-east in the Bieszczady area. Being incompetent rocks, these sandstones partly influenced the impeding of the thrusting processes east of the Rabe – Baligród fault zone. Additional structural reconstruction took place in the bending zone in the trend of the structures composing the marginal part of the CDK and FDTS. This bending and change in thrust trend could have been caused by variations in the morphology of the basement, which probably lies at a shallower depth in the south-east than in the north-west.
6. The shortening and complexity of CDK fold-thrust structures increases from west to east and from north to south towards the FDTS.
7. Some of the strike-slip faults are tear faults (the Rabe-Baligród fault zone in part) that originated simultaneously with folding.
8. From the folding to the formation of oblique strike-slip faults, the orientation of compression and tectonic shortening did not change and was directed SW–NE.
9. The presence of strike-slip movements along the thrust has been confirmed. These movements evidence the dextral displacement of the slices against each other**.**

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REFERENCES

ALEKSANDROWSKI, P. 1989**.** Structural geology of the Magura Nappe in the Mt. Babia Góra region, western Outer Carpathians. *Studia Geologica Polonica*, **96**, 1-140. [*In Polish with English summary*]

ANDERSON, E.M. 1951. The dynamics of faulting and dyke formation with applications to Britain. *Oliver & Boyd*; Edinburgh.

— 1974. The relationship between kink bands and shear fractures in the experimental deformation of slates. *Journal of Geological Society of London*, **130**, 367-382

ANGELIER, J. 1994. Fault slip analysis and palaeostress reconstruction. *In*: P.L. HANCOCK (*Ed*.), Continental Deformation, pp. 53-100. *Pergamon Press*.

BOYER, S.E. & ELLIOTT, D. 1982. Thrust systems. *The American Association of Petroleum Geologists Bulletin*, **66**, 1196-1230.

BURCHFIEL, B.C. & ROYDEN, L. 1982. Carpathian foreland fold and thrust belt and its relation to Pannonian and other basins. *The American Association of Petroleum Geologists, Bulletin,* **66**, 241-256.

BUTLER, R.W.H. 1982. The terminology of structures in thrust belts. *Journal of Structural Geology*, **4**, 239-246.

CSONTOS, L. NAGYMAROSY, A. HORVATH, F. & KOVAČ, M. 1992. Tertiary evolution of the Intra-Carpathian area: a model. *Tectonophysics,* **208**, 221-241.

DECKER, K. NIEŚCIERUK, P. REITER, F. RUBINKIEWICZ, J. RYŁKO, W. & TOKARSKI, A.K. 1997. Heteroaxial shortening, strike slip faulting and displacement transfer in the Polish Carpathians. *Przegląd Geologiczny*, **45**, 1070-1071.

DECKER, K. TOKARSKI, A.K. JANKOWSKI, L. KOPCIOWSKI, R. NIEŚCIERUK, P. RAUCH, M. REITER, F. & ŚWIERCZEWSKA, A. 1999. Structural development of Polish segment of the Outer Carpathians (eastern part). *In*: 5th Carpathian tectonic workshop Poprad – Szymbark, 26-29.

DŻUŁYŃSKI, S. & RADOMSKI, A. 1957. Clastic dikes in the Carpathian Flysch. *Rocznik Polskiego Towarzystwa Geologicznego*, **26**, 225-254. [*In Polish with English summary*]

FODOR, L. CSONTOS, L. BADA, G. GYORFI, I. & BENKOVICS, L. 1999. Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of paleostress data. *In*: DURAND B., JOLIVET L., HORVATH F., SERANNE M., The Mediterranean Basins: Tartiary extension within the Alpine Orogen. *Geological Society, London, Special Publications*, **156**, 295-334.

GRASEMANN, B. MARTEL, S. & PASSCHIER, C. 2005. Reverse and normal drag along a fault. *Journal of Structural Geology*, **27**, 999-1010

GRADZIŃSKI, R. KOSTECKA, A. RADOMSKI, A. & UNRUG, R. 1986. Zarys Sedymentologii. *Wydawnictwa Geologiczne*; Warszawa.

GUCIK, S. & WÓJCIK, A. 1982. Explanations to the Geological Map of Poland, Przemyśl-Kalników sheet, scale 1:200 000. *Wydawnictwa Geologiczne*; Warszawa.

HACZEWSKI, G. BĄK, K. KUKULAK, J. MASTELLA, L. RUBINKIEWICZ, J. 2000. Explanations to the Geological Map of Poland, Ustrzyki Górne sheet (1068), scale 1:50 000. *Polish Geological Institute Archive*; Warszawa.

JANKOWSKI, L. KOPCIOWSKI, R. & RYŁKO, W. 2004. Geological Map of the Outer Carpathians: Borderlands of Poland, Ukraine and Slovakia. *Polish Geological Institute*.

JAROSZEWSKI, W. 1980**.** Tektonika uskoków i fałdów, 360 pp. *Wydawnictwa Geologiczne*; Warszawa.

KONON, A. 1999. Tektonika płaszczowiny magurskiej w środkowej części Beskidu Wyspowego. *Institute of Geology, University of Warsaw Archive*; Warszawa.

— 2000. Deformation mechanisms of cataclastic rocks from fault zones in the Magura nappe in the Beskid Wyspowy Mountains (Poland). *Acta Geologica Polonica*, **50**, 387-392.

KOVAČ, M. HUDAČKOVA, N. RUDINIEC, 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 Carpathian Junction. *Annales Tectonicae*, **10**, 3-19.

KSIĄŻKIEWICZ, M. 1972. Budowa geologiczna Polski tom IV. Tektonika, część 3, Karpaty. *Wydawnictwa Geologiczne*; Warszawa.

KUŚMIEREK, J. 1979. Deformacje grawitacyjne, nasunięcia wsteczne a budowa wgłębna i perspektywy naftowe przedpola jednostki dukielskiej w Bieszczadach. *Prace Geologiczne PAN*, 1-68.

MALATA, T. 1997. Explanations to the Geological Map of Poland, Lesko sheet, scale 1:50 000. *Polish Geological Institute Archive*; Warszawa.

MASTELLA, L. 1988. Structure and evolution of Mszana Dolna tectonic window, Outer Carpathians, Poland. *Annales Societatis Geologorum Poloniae*, **58**, 53-173. [*In Polish with English summary*]

— 1995. Tektonika jednostki przeddukielskiej (Bieszczady). KBN grant nr 600999101.

MASTELLA, L. & KONON, A. 2002. Jointing in the Silesian Nappe (Outer Carpathians, Poland) – paleostress reconstruction. *Geologica Carpathica,* **53**, 315-325.

MASTELLA, L. & SZYNKARUK, E. 1998. Analysis of the fault pattern in selected areas of the Polish Outer Carpathians. *Geological Quarterly*, **43**, 263-276.

MITRA, S. 1990. Fault-propagation folds: geometry, kinematic evolution and hydrocarbon traps. *American Association of Petroleum Geologists Bulletin*, **74**, 921-945.

— 2002. Fold-accommodation faults. *American Association of Petroleum Geologists Bulletin*, **86**, 671-693.

MŁYNARSKI, S. BACHAN, W. DĄBROWSKA, B. JANKOWSKI, H. KANIEWSKA, E. KARACZUN, K. KOZERA, A. MAREK, S. SKORUPA, J. ŻELICHOWSKI, A.M. & ŻYTKO, K. 1982. Geophysical – geological interpretation of the results of investigations along the profiles of Lublin – Prabuty, Przedbórz – Żebrak, Baligród – Dubienka. *Biuletyn Instytutu Geologicznego,* **333**, 5-57. [*In Polish with English summary*]

NEMČOK, M. HOUGHTON, J.J. & COWARD, M.P. 1998. Strain partitioning along the western margin of the Carpathians. *Tectonophysics*, **292**, 199-144.

OPOLSKI, Z. 1930. Zarys tektoniki Karpat między Osławą – Łupkowem a Użokiem – Siankami. *Sprawozdania Państwowego Instytutu Geologicznego*, **5**.

OSZCZYPKO, N. 1992. Late Cretaceous through Paleogene evolution of Magura Basin. *Geologia Carpathica*, **43**, 333-338.

— 2004. The structural position and tectonosedimentary evolution of the Polish Outer Carpathians. *Przegląd Geologiczny,* **52**, 780-791.

— 2006. Late Jurassic-Miocene evolution of the Outer Carpathians fold-and thrust belt and its foredeep basin (Western Carpathians, Poland). *Geological Quarterly,* **50**, 169-194.

OSZCZYPKO, N., OSZCZYPKO-CLOWES, M. GOLONKA, J. & MARKÓ, F. 2005. Oligocene-Lower Miocene sequences of the Pieniny Klippen belt and adjacent Magura Nappe between Jarabina and Poprad River (East Slovakia and South Poland). *Geological Quarterly,* **49**, 379-402.

OSZCZYPKO-CLOWES, M. & OSZCZYPKO, N. 2004. The position and age of the youngest deposits in the Mszana Dolna and Szczawa tectonic windows (Magura Nappe, Western Carpathians, Poland). *Acta Geologica Polonica*, **54**, 339-367.

OSZCZYPKO, N. KRZYWIEC, P. LEMBERGER, M. STEFANIUK, M. PIETSCH, K. & TRYGAR, H. 1998. Integrated geological-geophysical interpretation of the Rzeszów-Smilno profile (Western Carpathians). Carpatho-Balkan Geological Association 16 Congress, Vienna*.*

PICHA, F.J. 1996. Exploring for hydrocarbons under thrust belts: A challenging new frontier in the Carpathians and elsewhere. *American Association of Petroleum Geologists Bulletin,* **80**, 1547-1564.

RECHES, Z. & JOHNSON, A.M. 1976. Asymmetric folding and monoclinal kinking. *Tectonophysics*, **35**, 295-340.

ROYDEN, L.H. 1988. Late Cenozoic tectonics of the Pannonian Basin System. *In*: L.H. ROYDEN & F. HORWATH (*Ed*.), The Pannonian basin – A study in basin evolution. *American Association of Petroleum Geologists Memoire,* **45**, 27-48.

RUBINKIEWICZ, J. 1998. Rozwój spękań ciosowych w płaszczowinie śląskiej w okolicach Baligrodu (Bieszczady Zachodnie – Karpaty Zewnętrzne). *Przegląd Geologiczny*, **46**, 820-826.

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

— 2002. Ewolucja strukturalna płaszczowiny śląskiej pomiędzy Osławą a Hoczewką – Bieszczady. Archive of the Institute of Geology, University of Warsaw.

— 2005. Kink folds and kink bands – geometry, conditions of nucleation, interpretation (an example from the Outer Carpathian flysch. *Przegląd Geologiczny,* **53**, 1040-1046. [*In Polish with English summary*]

RYŁKO, W. TOMAŚ, A. 2005. Basement structure below the West-Carpathian-East Carpathian orogen junction (eastern Poland, north-eastern Slovakia and western Ukraine). *Geologica Carpathica,* **56**, 29-40

SIKORA W. 1959. Notes on stratigraphy and palaeogeography of Krosno Beds on forefield of Otryt Mt. between Szewczenko and Polana (Carpathians). *Kwartalnik Geologiczny*, **3,** 569-582. [*In Polish with English summary*]

STEFANIUK, M. 2001. Main structural elements of the basement of eastern Polish Carpathians In the Ligot of magnetotelluric investigations. *Zeszyty Naukowe AGH, Geologia,* **27**, 127-155. [*In Polish with English summary*]

ŚLĄCZKA, A. 1957. Geological Map of Poland, Bukowsko sheet, scale 1 : 50 000, *Wydawnictwa Geologiczne*; Warszawa.

— 1959. Stratigraphy of the Silesian serie sof the Bystre slice (to the South of Baligród). *Biuletyn Instytutu Geologicznego*, **131**, 202-260. [*In Polish with English summary*]

— 1961. Problemy południowego obrzeżenia centralnego synklinorium oraz jednostki dukielskiej. Przewodnik 34 Zjazdu Polskiego Towarzystwa Geologicznego; Sanok.

— 1963. Krosno beds from the Roztoki Dolne (Polish Eastern Carpathians). *Rocznik Polskiego Towarzystwa Geologicznego*, **33** (2), 181-188. [*In Polish with English summary*]

— 1968. Explanations to the Geological Map of Poland, Bukowsko sheet, scale 1 : 50 000. *Wydawnictwa Geologiczne*; Warszawa.

ŚWIDZIŃSKI, H. 1958. Mapa geologiczna Karpat polskich 1:200 000. Część wschodnia. *Prace Instytutu Geologicznego*; Warszawa.

TAPPONIER, P. 1977. Evolution tectonique du systeme alpin en Méditeranée: pioncconnement et écrasement ridige – plastique. *Bulletin Societe Geologique du France*, **7**, 437-460.

TOKARSKI, A. 1964. Poprzeczna strefa Kalnicy. *Sprawozdania z posiedzenia Komisji Naukowej Oddziału PAN*; Kraków.

— 1966. O szansach naftowych jednostki Iwonicza na wschód od Osławy. *Zeszyty naukowe Akademii Górniczo Hutniczej*, **139**, 163-172.

TOKARSKI, A.K. 1975. Geology and Geomorphology of the Ustrzyki Górne area (Polish Ekstern Carpathians). *Studia Geologica Polonica*, **48**, 1-90. [*In Polish with English summary*]

— 1978. Orogenesis and morphogenesis of Outer Carpathians and plate tectonics. *Studia Geomorphologica Carpatho – Balcanica*, **12**, 29-43.

TOŁWIŃSKI, K. 1933. Centralna depresja karpacka. *Geologia Statystyki Naftowej*, **11**, Borysław.

TWISS, R.J. & MOORES, E.M. 2001. Structural Geology, pp. 1-532. W.H. *Freeman & Company*; New York.

WDOWIARZ, S. 1980. The geological structure of the Central Carpathian Synklinorium in the Rajskie – Zahoczewie area. *Biuletyn Instytutu Geologicznego*, **326**, 5-24. [*In Polish with English summary*]

— 1985. On some aspects of geological structure and oil and gas accumulation of the Central Carpathian Synclinorium in Poland. *Biuletyn Instytutu Geologicznego*, **350**, 5-52. [*In Polish with English summary*]

ZUCHIEWICZ, W. 2001. Geodynamics and geotectonics of the Polish Outer Carpathians. *Przegląd Geologiczny*, **49**, 710-717. [*In Polish with English summary*]

ŻYTKO, K. 1985 Some problems of geodynamic model of the Northern Carpathians. *Kwartalnik Geologiczny*, **29**, 85-108. [*In Polish with English summary*]

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