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# The intramontane Orava Basin – evidence of large-scale Miocene to Quaternary sinistral wrenching in the Alpine-Carpathian-Pannonian area

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ABSTRACT:

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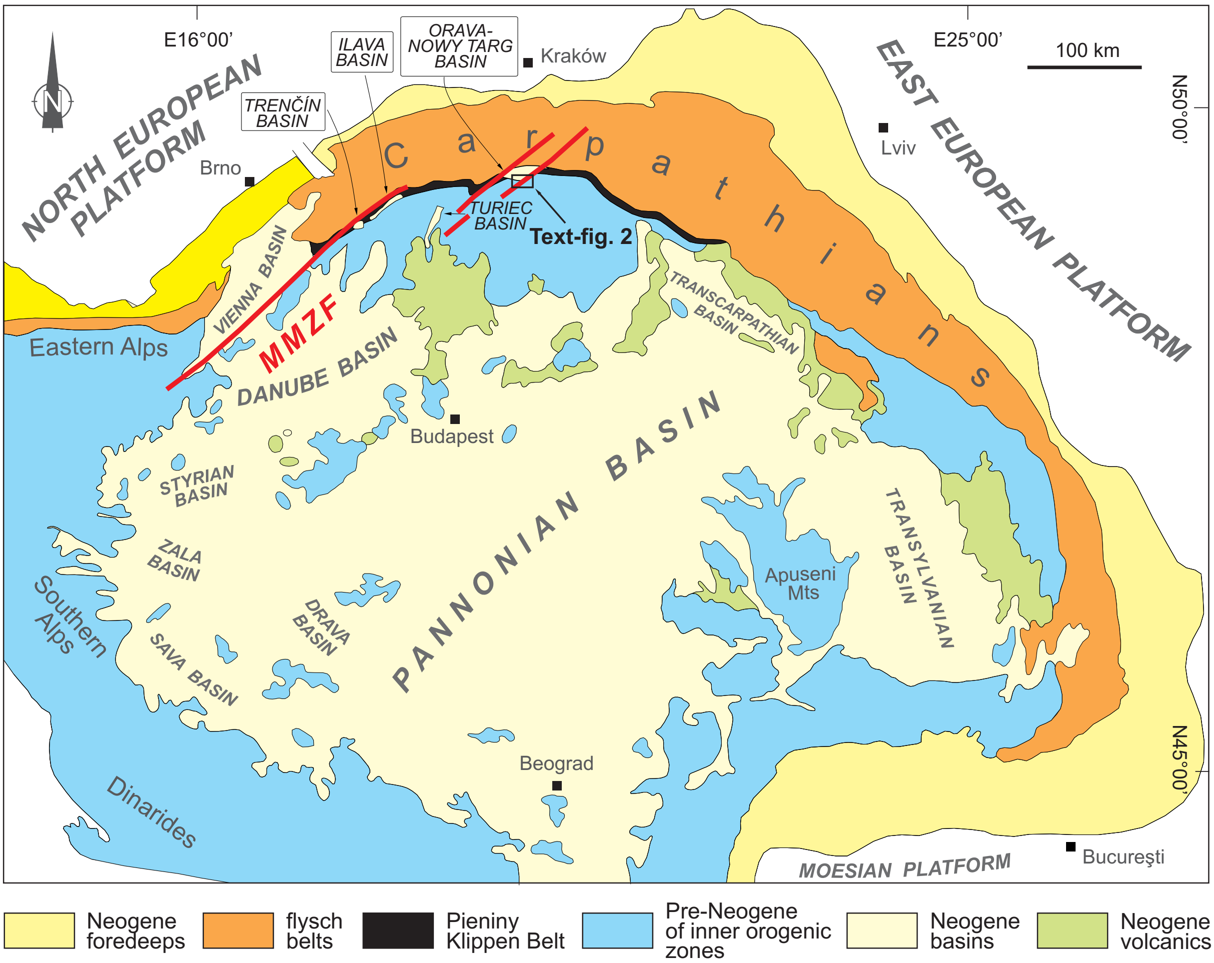
The Carpathian Orava Basin is a tectonic structure filled with Neogene and Quaternary deposits superimposed on the collision zone between the ALCAPA and European plates. Tectonic features of the south-eastern margin of the Orava Basin and the adjoining part of the fore-arc Central Carpathian Palaeogene Basin were studied. Field observations of mesoscopic structures, analyses of digital elevation models and geological maps, supplemented with electrical resistivity tomography surveys were performed. Particular attention was paid to joint network analysis. The NE-SW-trending Krowiarki and Hruštinka-Biela Orava sinistral fault zones were recognized as key tectonic features that influenced the Orava Basin development. They constitute the north-eastern part of a larger Mur-Mürz-Žilina fault system that separates the Western Carpathians from the Eastern Alps. The interaction of these sinistral fault zones with the older tectonic structures of the collision zone caused the initiation and further development of the Orava Basin as a strike-slip-related basin. The Krowiarki Fault Zone subdivides areas with a different deformation pattern within the sediments of the Central Carpathian Palaeogene Basin and was active at least from the time of cessation of its sedimentation in the early Miocene. Comparison of structural data with the recent tectonic stress field, earthquake focal mechanisms and GPS measurements allows us to conclude that the Krowiarki Fault Zone shows a stable general pattern of tectonic activity for more than the last 20 myr and is presently still active.

**Keywords:** Orava Basin; Central Carpathian Palaeogene Basin; Structural analysis; Strike-slip related basin; Transrotational basin; Joint pattern analysis; Western Carpathians.

## INTRODUCTION

The Orava Basin (OB) is located at the border zone between Poland and Slovakia. This young structure is infilled with Neogene and Quaternary deposits. In the tectonic sense, the basin overlies the boundary between the European Plate and the overriding ALCAPA Plate (e.g., Royden 1988; Csontos *et al*. 1992; Kováč *et al*. 1993, 1998; Plašienka *et al*. 1997; Fodor *et al*. 1999; Zoetemeijer *et al*. 1999). It thus belongs to a series of similar tectonic structures, extending from the south-west to the north-east, from the eastern margin of the Alps towards the Western Carpathians (Vienna Basin, Trenčin Basin, Ilava Basin; e.g., Buday and Seneš 1967; Scheibner 1967; Royden *et al*. 1983; Text-fig. 1). At the same time, this

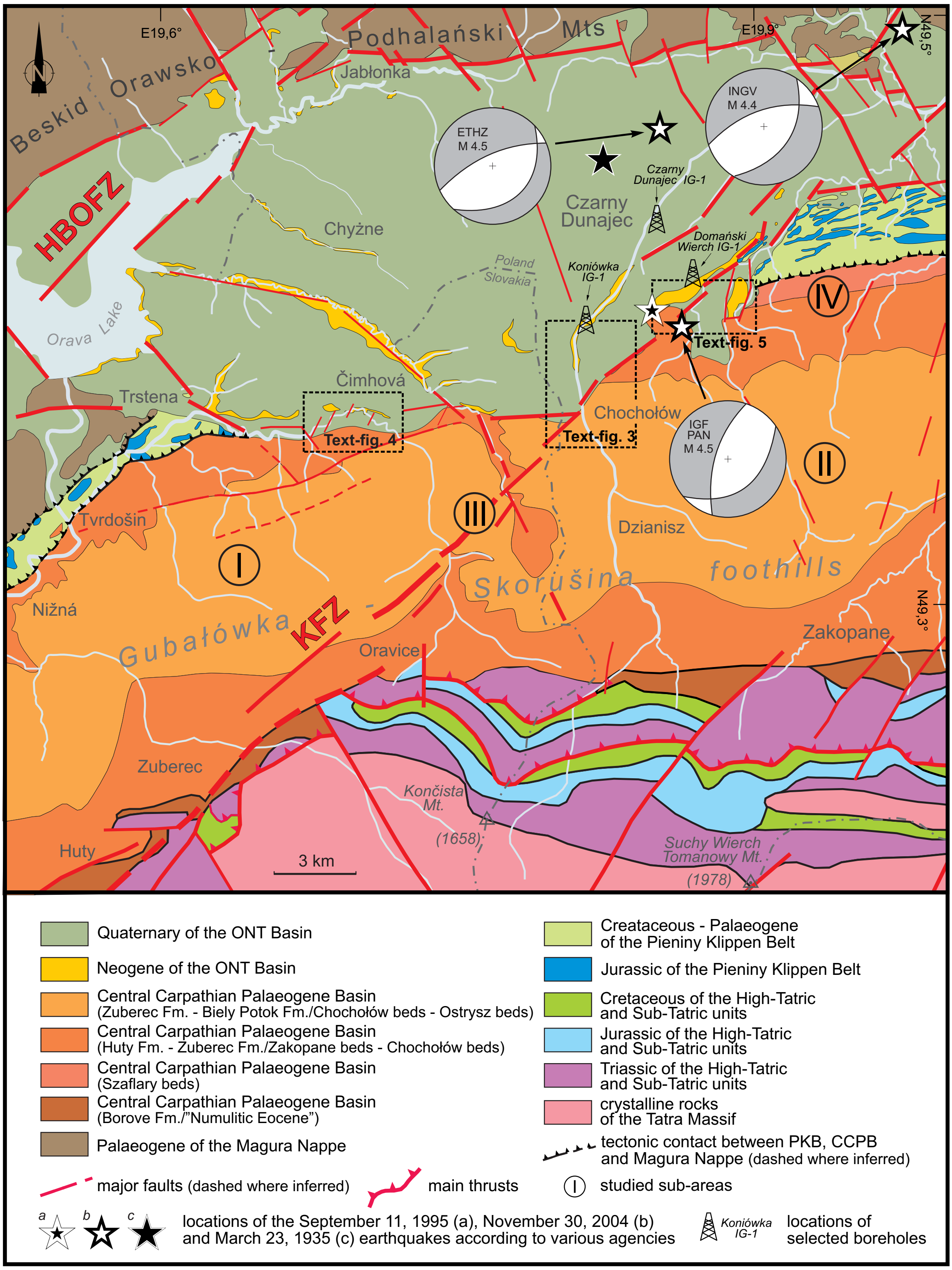



Text-fig. 1. Tectonic sketch map of the Carpathians and the surrounding regions with location of the study area and Neogene basins (after Kováč *et al.* 1998; Lexa *et al.* 2000; modified); MMZF – Mur-Mürz-Žilina fault system

is the only structure in the Western Carpathians that covers a former subduction zone at the place where it changes its trend from W-E to SW-NE, and it contains sediments accumulated through most of the Neogene. Thus, the OB may potentially record processes of postorogenic exhumation of the Carpathians and related tectonic events. This is a natural laboratory for a detailed study of complex phenomena that are rarely preserved in the geological record; accordingly, there is growing interest in the geology of this area (e.g., Baumgart-Kotarba *et al.* 2001, 2004; Pomianowski 2003; Struska 2008, 2009; Tokarski *et al.* 2012, 2016; Łoziński *et al.* 2015, 2016, 2017; Bojanowski *et al.* 2016; Wysocka *et al.* 2018).

Due to the poor degree of exposure, so far only a few structural analyses have been performed in the OB (e.g., Tokarski and Zuchiewicz 1998; Kukulak 1999; Struska 2008, 2009). Fortunately, after local floods in 2009–2011, Neogene deposits became exposed mainly in the south-eastern part of the basin, which enabled us to carry out new investigations in this area (Text-fig. 2).

This report attempts to recognize the character of the tectonic events that led to the shaping of the basin and to situate them in the wider context of the development of the Western Carpathians. The investigations were focused on the south-eastern part of the OB between Trstena (Slovakia) and Stare Bystre (Poland). They included OB deposits and those from its southern margin comprising the much better exposed deposits of the Central Carpathian Palaeogene Basin (CCPB). Analyses in the CCPB were aimed at verifying how the development of the OB became recorded in the deposits of its basement by the for-




Text-fig. 2. Geological map of the study areas and their neighbourhood (based on Watycha 1976a, Gross *et al.* 1993a and Łoziński 2011; modified). The focal mechanism of the November 30, 2004 earthquake is depicted by beach ball type diagrams (according to the IGF PAN, ETHZ and INGV seismic moment tensor solutions; locations are marked by stars) (after Wiejacz and Dębski 2009; location of March 23, 1935 earthquake epicenter after Wołosiewicz 2018). Abbreviations: IGF PAN – Institute of Geophysics, Polish Academy of Sciences; ETHZ – Swiss Seismological Service; INGV – MEDNET, Rome, Italy; KFZ – Krowiarki fault zone mation of new tectonic structures or the reactivation of older structures. The results of structural analyses and cartographic observations were supplemented with electrical resistivity tomography surveys (ERT).

## GEOLOGICAL SETTING

### Orava Basin

The OB represents a distinct geomorphological depression between the Gubałówka-Skorušina foothills to the south, composed of CCPB deposits, and the Orava-Podhale Beskidy Mts to the north, built of flysch deposits of the Magura Nappe (Text-fig. 2). To the east, the OB passes into a smaller, latitudinal Nowy Targ Basin. In many reports, both basins are referred to as a single structure, i.e the Orava-Nowy Targ Basin (e.g., Pomianowski 1995, 2003; Tokarski *et al.* 2012).

The OB is filled mainly with Neogene fine-grained terrestrial and freshwater deposits: claystones, clayey siltstones, coaly claystones and sandstones (Watycha 1976b, 1977; Gross *et al.* 1993b). Interbeds of gravels and conglomerates, and subordinate thin lignite layers are also present (Kołcon and Wagner 1991; Łoziński *et al.* 2015; Jaroszewicz *et al.* 2018). The Neogene deposits infilling the basin were attributed to the Miocene or Miocene–Pliocene (see Birkenmajer 2009 and references therein). Palaeobotanical data point to the middle Miocene (Badenian-Oszast and Stuchlik 1977; Lesiak 1994; Sarmatian-Nagy *et al.* 1996) or late Miocene (Tran Dinh Nghia 1974).

In the south-easternmost OB, between Miętustwo and Stare Bystre, a rhyolite tuff-tuffite layer was identified in the coal-bearing Miocene clays (Sikora and Wieser 1974); its age was determined at 8.7±0.6 Ma (Wieser 1985) and 11.87+0.12/-0.24Ma (Wysocka *et al.* 2018). In this area, Miocene OB deposits are unconformably covered by coarse gravels and conglomerates of the Domański Wierch fan (Watycha 1976a, 1977; late Pliocene or Pliocene/Pleistocene transition – Oszast 1970, 1973; Zastawniak 1972). Quaternary sediments are dominated by gravels and conglomerates (Watycha 1977). Neogene and Quaternary deposits are separated by an erosional disconformity. The maximal thickness of deposits infilling the OB is estimated at c. 1300 m based on borehole data (Watycha 1977).

### Basement of the Orava Basin

Deposits infilling the OB unconformably overlie three tectonic units of the Western Carpathians: the Magura Nappe (MN), the Pieniny Klippen Belt (PKB), and the Podhale-Skorušina Synclinorium (PSS; Text-fig. 2). The PKB is a strongly tectonized unit composed of several successions of Lower Jurassic to Palaeogene rocks, including limestones, marls, claystones and conglomerates (Andrusov 1959; Birkenmajer 1977). It is interpreted as an expression of a suture zone which separates the Outer Carpathians from the Central Carpathians or, in a wider context, as a structure genetically related to the suture between the North European plate and the Alcapa terrane (e.g., Royden 1988; Csontos *et al*. 1992; Kováč *et al*. 1993, 1998; Plašienka *et al*. 1997; Fodor *et al*. 1999; Zoetemeijer *et al*. 1999; Csontos and Vörös 2004; Froitzheim *et al.* 2008). The PKB and Outer Carpathian nappes were both integrated into a Cenozoic accretionary prism at the front of the Alcapa terrane, overriding the North European plate during the Early to Middle Miocene times (Oszczypko and Ślączka 1989; see also Ślączka 1996a, 1996b; Golonka *et al*. 2000). The MN being the southernmost tectonic structure of the Outer Western Carpathians comprises Albian/Cenomanian to Miocene strata, including sandstones, greywackes, claystones, siltstones and marls (Birkenmajer and Oszczypko 1989; Cieszkowski 1995). In its southern part, the OB covers the PSS being a part of the CCPB. The PSS is asymmetric and comprises several parallel tectonic zones (e.g., Mastella 1975; Ludwiniak 2010). The structure is composed mainly of sandstones, claystones, shales, and subordinately conglomerates, of Lutetian–Bartonian to Early Miocene age (Sotak 1998a, b; Garecka 2005). The CCPB is considered to be a remnant of a fore-arc basin developed on the margin of the overriding Alcapa plate (Kázmér *et al.* 2003).

The shaping of the geological structure of the OB basement was related to orogenic processes. After the Alpine folding of the Mesozoic successions during the Late Cretaceous (Late Cretaceous–Palaeocene; Andrusov 1965; Lefeld 2009; Jurewicz 2018), presently exposed in the PKB and the Tatra Massif, sedimentation took place within the CCPB fore-arc basin (Kázmér *et al.* 2003). At the same time, sedimentation also occurred in the Magura Basin (Oszczypko and Oszczypko-Clowes 2010). Successive subduction and closing of the Outer Carpathian basins was related to the northward movement of the Adria and ALCAPA terranes (Eocene to early Miocene) that terminated with their oblique collision with the North European Plate (e.g., Nemčok *et al.*1998). As a result, the accretionary wedge of the Outer Carpathians, composed of a series of flysch nappes, and the Carpathian Foredeep were formed (e.g., Kováč *et al.* 1998; Ślączka 1996a and b). The final formation of overthrusts within the Outer Western Carpathians is dated to the end of the middle Miocene (e.g., Royden 1988; Krzywiec *et al.* 2014).

In the early Miocene, refolding of the PKB and thrusting of the PKB units onto the MN took place, a process that was linked with the folding and thrusting in the Outer Carpathians (Birkenmajer 1986). Partial folding of the deposits in the southern part of the Magura Basin during the latest Oligocene and early Miocene times was followed by the development of a piggyback basin filled with marine deposits (Cieszkowski 1995). The formation of the "flower" structure of the PKB resulted from transpression at the late Burdigalian and middle Miocene boundary (Ratschbacher *et al.* 1993; Oszczypko *et al.* 2010). In effect, some elements of the PKB were retrothrusted onto the CCPB, which caused the development of strong deformation within Palaeogene deposits in the contact zone (e.g., Mastella 1975; Plašienka *et al.* 1998; Plašienka and Soták 1999; Ludwiniak 2018; such backthrusting of the PKB onto the CCPB in northwestern Slovakia accompanied by some ENE-WSW-striking orogen-parallel sinistral faulting is considered to have occurred during the Late Oligocene and Early Miocene – see Peškova *et al.* 2009; Beidinger and Decker 2016). Strike-slip movements along the CCPB/PKB contact zone could also play a significant role at this stage (e.g., Ratschbacher *et al.* 1993; Ludwiniak *et al.* 2009; Ludwiniak 2018). Deposits infilling the OB lie unconformably on such basement.

### Structural development of the Orava Basin

The origin of the OB has been a matter of long-term debate (see Golonka *et al.* 2005 and references therein). Most authors consider that OB formation was related to the activity of strike-slip and normal faults. There is, however, no common agreement as to the mechanism of their activity, mutual age and kinematic relationships. According to Pospišil (1990, 1993), the OB was formed as a pull-apart basin within a dextral fault zone. Other authors following the concept of OB development as a strike-slip-related basin suggesting that it opened as the effect of sinistral movement, with the significant contribution of faults obliquely cutting the Central Carpathian Block and the North-European Plate collision zone (Bac-Moszaszwili 1993; Baumgart-Kotarba 1996, 2001). Based on geoelectrical and gravimetric surveys, Pomianowski (1995, 2003) suggested that the OB was formed in a transtension zone as a releasing band structure located within a regional sinistral non-aligned fault zone. The displacement responsible for OB development could have been related to movements along the PKB. According to Struska (2008), the initial stage of OB development was also linked to the existence of a sinistral shear zone along the PKB, which underwent bending related to the bending of the entire Carpathian arc. The development of transversal faults, separating the basin basement blocks, was linked with this process. Therefore, the OB may be treated as a strike-slip-related basin formed within a sinistral zone through the merging of smaller basins.

Summing up, the main difference between the proposed models of OB development is the character of the faults surrounding the basin. This induces the need to characterize the stress field and the relationship to the geological structures existing at the moment of basin formation.

## MATERIAL AND METHODS

Fieldwork was performed within the Neogene infill in the south-eastern part of the OB and within the CCPB rocks adjoining the OB to the south and south-east (Text-figs 2–5). Observations were made in 932 natural exposures of Palaeogene (889) and Neogene (43) rocks (Text-figs 6–10). The basic lithological description was made and the bedding position was measured in each exposure (c. 1800 measurements in Palaeogene strata and 105 measurements in Neogene strata). Small-scale faults and indicators of the sense of slip were measured where possible (36 faults in Palaeogene rocks and 30 faults in Neogene rocks). The values of faults displacements were measured where possible. Mesofolds were also observed (97 mesofolds in Palaeogene rocks).

During fieldwork, particular attention was drawn to joint network analysis because of its great potential for palaeostress field reconstruction. This results from the omnipresence of fractures in rocks. Depending on the structural setting, fractures may be c. $10^2$ to $10^5$ times more abundant than small-scale faults (Hancock 1994). This issue is particularly important in areas with a small/medium degree of exposure, i.e., in cases when the inventory of tectonic structures available for observation is rather small. The OB belongs to such an area. The dominant joint pattern in each exposure was recognized based on the orientation of fractures, cross-cutting relationships, fissure filling, morphology of fracture surfaces and small-scale, brittle structures associated with fractures, as well as traces of fractures cutting the bedding planes. Comparison of joint patterns between different exposures was made both with and without bedding restoration to horizontal (Price 1966; Ludwiniak 2010). The orientation of 4125 fractures in Palaeogene rocks and 291 fractures in Neogene rocks was measured. All measurements were made with an accuracy of ± 2º.

According to e.g., Price (1959, 1966), Książkiewicz (1968b), Jaroszewski (1972), Sheperd and Huntington (1981), Aleksandrowski (1989), Zuchiewicz (1998a), Mastella and Konon (2002a), and Ludwiniak (2010), a significant proportion of joints is of prefold or early synfold origin. In an attempt to compare joint orientation from different parts of the study area, measurements were corrected for restoration of the bedding to horizontal (see e.g., Murray 1967; Al Kadhi and Hancock 1980; Belousov *et al.* 1996). This back-tilting procedure enabled determination of the orientation of original stress axes for particular joint sets (see e.g., Ramsay and Huber 1987; Zuchiewicz 1998a; Mastella and Zuchiewicz 2000). The prefolding maximum principal stress ($\sigma_1$) directions responsible for the diagonal joint system formation were reconstructed as the bisectors of the dihedral acute angle between the restored joint sets. The orientations of extensional joint sets enabled us to determine the minimum principal stress ($\sigma_3$) directions and, in some cases, indirectly the $\sigma_1$-axis orientations. Two methods were employed for the determination of the palaeostress field and shortening directions from fault-slip data: the “P-T-axes” and the “Right Dihedra” methods (Turner 1953; Angelier and Mechler 1977). The directions of tectonic shortening responsible for the development of folds were determined as being oriented perpendicular to the fold axial planes. Collected data were processed using Stereonet and TectonicsFP software (Reiter and Acs 2000; Ortner *et al.* 2002) and visualized in the form of diagrams. All data were plotted as lower hemisphere Schmidt projections.

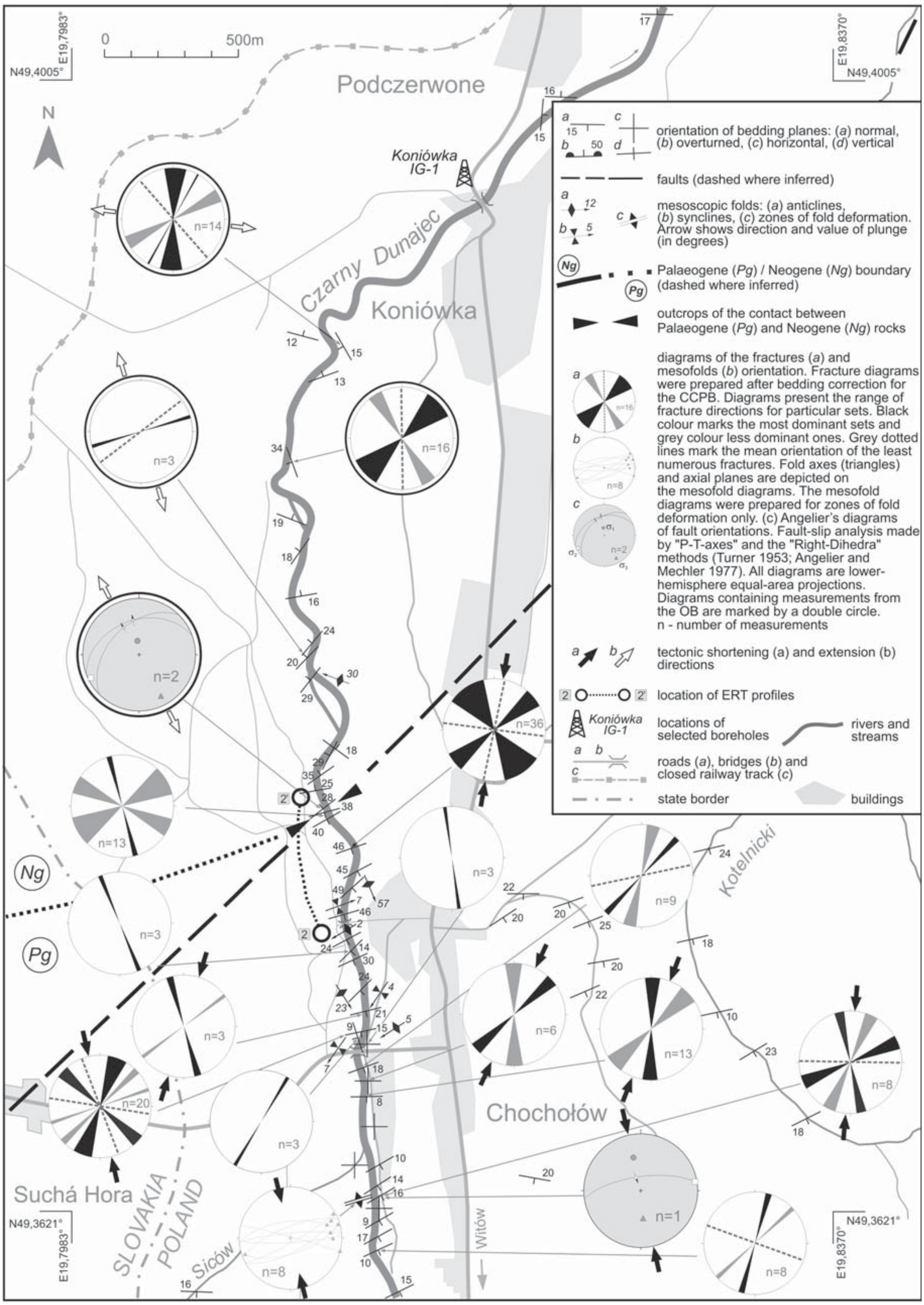
The study area was subdivided into several subareas each having a relatively homogeneous tectonic style (Text-fig. 2). Lastly, the results from particular subareas were compared, allowing for the interpretation of the structural differences between them.

Analysis of surface morphology based on the processing of a Digital Elevation Model (DEM) supported the structural mapping (Text-fig. 11). Two different DEMs were analyzed. The first was a 1” × 1” resolution raster model in the DTED2 standard. The second was a ~10 × 10 m ground resolution raster model based on data from aerial photographs. The first model covers the whole study area and the second – only its part within the area of Poland. Several DEM derivatives were generated with the application of MicroDEM 2014.3.24.40 software. Beside basic elevation models, aspect and slope maps, reflectance maps and openness maps were also generated. DEM analyses were performed following the methods described by Konon and Śmigielski (2006). They were mainly used to trace possible fault zones and block rotations, but also to recognize the continuity of structures along their strike and the position of geological boundaries. Results of DEM analysis were verified by comparison to published maps (Watycha 1976a; Gross *et al.* 1993a) and collected structural data. The usefulness of this method has been proved by numerous studies (e.g., Oguchi *et al.* 2003; Shukla *et al.* 2012; Li *et al.* 2013).

In order to characterize the OB/CCPB boundary, electrical resistivity tomography surveys (ERT) were performed (Text-figs 12–14). The application of such method was justified because the rocks of the OB infill and the OB basement show a strong lithological contrast. Three ERT profiles suborthogonal to the expected lines of the OB/CCPB contact were established (see Text-figs 3–5). The surveys employed ABEM Terrameter LS equipment. For each survey, a dipole-dipole array with 5 m electrode spacing was chosen. The dipole-dipole array is very sensitive to lateral resistivity changes and relatively non-sensitive to vertical changes of resistivity (Loke 2001). Thus, it is appropriate to solve geological problems connected with lateral resistivity changes (e.g., Dahlin 1996). The dipole-dipole array was successfully applied in imaging faults (e.g., Caputo *et al.* 2003; Fazzito *et al.* 2009, 2013; Terrizzano *et al.* 2012). In an attempt to obtain a two-dimensional model of resistivity in the subsurface zone of the rock massif, apparent resistivity data were processed in Res2DInv software (Loke 1996–2002;

| ERT profile name | ERT profile coordinates | | ERT profile length (metres) | measurement points | measurement points taken into account during model construction |
|---|---|---|---|---|---|
| Čimhova | N 49.366233°<br>E 19.700639° | N 49.363858°<br>E 19.702307° | 300 | 955 | 934 |
| Chochołów | N 49.377760°<br>E 19.810448° | N 49.373379°<br>E 19.811160° | 500 | 1705 | 1279 |
| Ciche | N 49.402416°<br>E 19.862056° | N 49.397117°<br>E 19.863410° | 600 | 2493 | 2411 |

Table 1. Characteristics of the ERT profiles




Text-fig. 3. Detailed structural map of part of the study area near Chochołów village

| | Area I (SE Orava – OB/CCPB contact zone) | Area I (SE Orava – central part of the Podhale-Skorušina Synclinorium) | Area II (W Podhale – central part of the Podhale-Skorušina Synclinorium) | Area III (Krowiarki Fault Zone) | Area IV (W Podhale – PKB/CCPB contact zone) |
|---|---|---|---|---|---|
| bedding | Mainly steeply dipping, (50S-90°), rarely overturned beds, striking mainly at 60-70° (locally turning CCW) | Dominant orientation c. 140–160/0–30 in northern limb of Synclinorium; within axial zone of Synclinorium beds lying horizontal or slightly dipping in different directions | Dominant orientation c. 160–170/30–60 in northern limb of Synclinorium; within axial zone of Synclinorium beds horizontal or slightly dipping in different directions | Dominant NE-SW bedding strike orientation. Beds dipping to NW in the southern and to SE in the northern part of Synclinorium | Beds steeply dipping, sometimes vertical or overturned. Strikes of beds commonly parallel to line of PKB/CCPB contact |
| folds | Rare NNE-SSW-trending folds (oblique to the CCPB/OB contact line) | Rare folds with WSW-ENE-trending axes and fault-related folds with NNE-SSW-trending axes | Dominant folds with ENE-WSW to W-E-trending axes (significantly more numerous in comparison to the Area I) | Dominant folds with NNE-SSW to NE-SW-trending axes. Steeply inclined folds, related to strike-slip faults | Commonly parallel or slightly oblique to line of PKB/CCPB contact. Steeply inclined folds related to strike-slip faults |
| joints | Dominant orthogonal joint pattern | Dominant orthogonal joint pattern | Dominant diagonal joint pattern (dominant NNE-SSW $\sigma_1$ orientation). Outcrops where orthogonal pattern is dominant or orthogonal and diagonal patterns co-occur are less numerous. | Dominant disturbed joint pattern | Dominant diagonal joint pattern (dominant NNW-SSE $\sigma_1$ orientation) |
| faults | Dominant WNW-ESE-trending normal faults near the CCPB/OB contact. Frequent NW-SE and NE-SW-trending faults, set oblique to the CCPB/OB contact line occur, too. Rare W-E to WNW-ESE-trending dextral faults (parallel or slightly oblique to CCPB/OB contact line). | Dominant NNW-SSE-oriented, mainly normal faults; dextral faults with the same orientation less numerous. Rare W-E-oriented normal faults | NNW-SSE, NW-SE and W-E-oriented mainly normal faults. NNW-SSE and NE-SW-trending strike-slip faults are less common | Numerous NNE-SSW to NE-SW-trending sinistral, oblique-slip and normal faults c. parallel to the KFZ. Frequent NNW-SSE-oriented normal faults. Rare NNW-SSE-oriented reverse faults | Dominant strike-slip faults parallel or slightly oblique to line of PKB/CCPB contact. Frequent reverse faults with similar orientation |

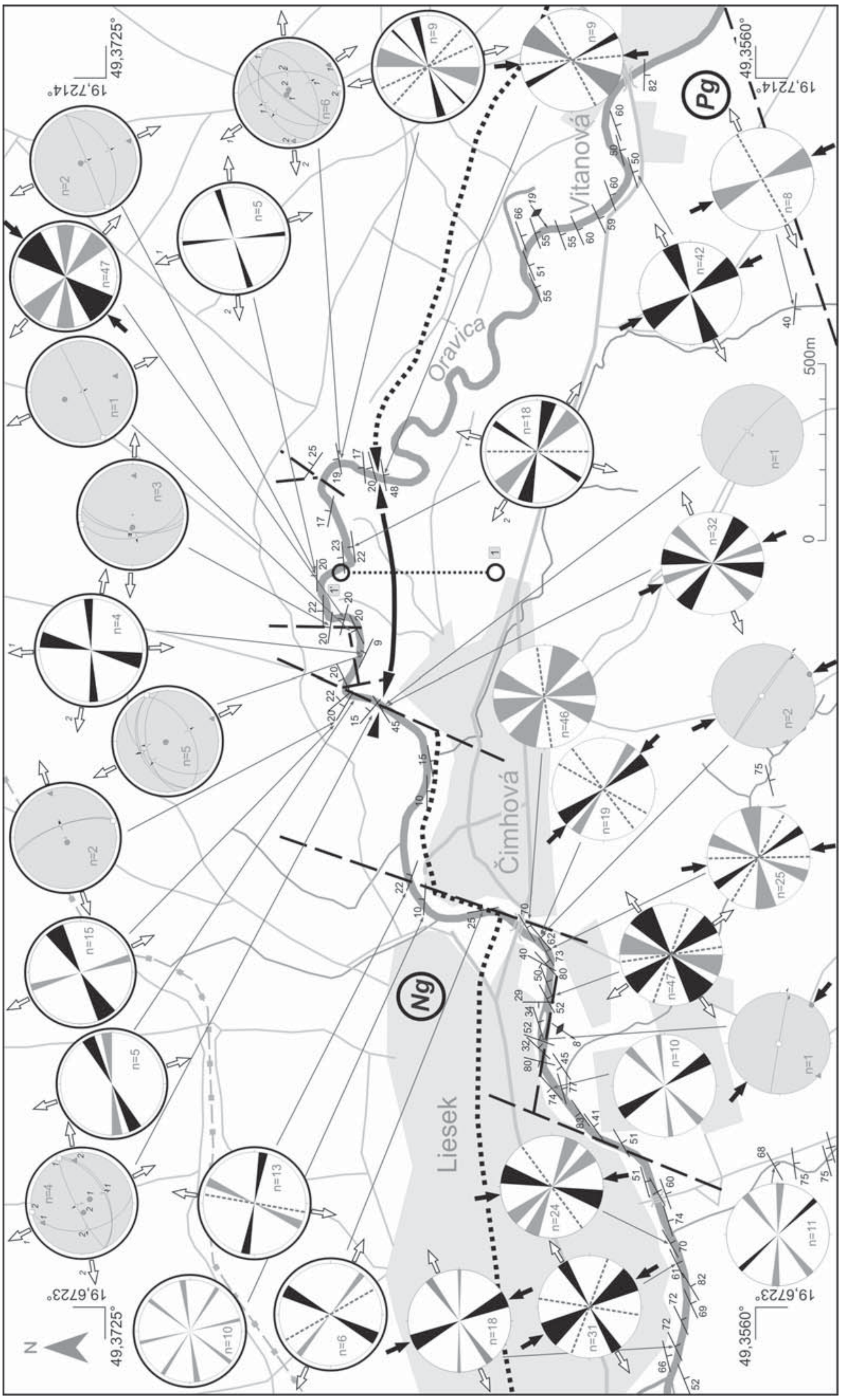
Table 2. Structural features of the CCPB flysch

Loke and Barker 1996; Loke *et al.* 2003). As a first step, bad data points were removed (data used for further analyses are specified in Table 1). Next, topographic corrections based on DEMs were applied to all profiles. Later, inversion was made with the application of settings available in Res2Dinv software (i.e., smooth or robust inversion methods). Results obtained with the application of the smoothness-constrained least-squares method were more realistic.

Structural analysis was also performed in four areas of the CCPB not related to OB development (for location see Text-fig. 2). Their goal was to distinguish the tectonic structures of the CCPB unique for the OB/CCPB contact zone from those inherited from older stages of CCPB development. These four areas represent:

- region I, located to the south of the OB, between Zábiedovo village and Hlboky stream; covering the northern limb and the axial part of the PSS;
- region II, within the western Podhale area to the south-east of the OB, and also covering the northern limb and the axial part of the PSS;
- region III, extending between Chochołów and Oravica, and corresponding to the NE-SW-oriented KFZ within the CCPB; this zone separates regions I and II;
- region IV, within the northernmost part of the CCPB, in the zone of tectonic contact with the PKB, between Stare Bystre and Leśnica.

Thus, a database consisting an array of structures typical of CCPB development that was used to track structures unique for OB vicinity was constructed (see Table 2). The analysis was based on earlier collected and partly published data (Mastella *et al.* 1988; Ludwiniak 2006, 2010; Klimkiewicz *et al.* 2009; Ludwiniak *et al.* 2009; Ludwiniak 2018), supplemented with new measurements and existing maps (Watycha 1976a; Gross *et al.* 1993a).




Text-fig. 4. Detailed structural map of part of the study area near Čimhova village (for explanations see Text-fig. 3)

RESULTS AND INTERPRETATION

## Structures in the southern and south-eastern parts of the Orava Basin

The bedding position of Neogene strata in the OB near Liesek and Čimhova is consistent and usually within 350-10/17-23 (Text-fig. 4). Steeper beds characteristic of fault-related deformation were not observed. The difference in strike between Neogene and Palaeogene strata is consequent and reaches about 20º.

Normal faults can be grouped in two populations: (I) faults subparallel to the OB margin, with orientations at 340-350/45-80 and 160-170/45-60; and (II) transversal faults with orientations at 260-300/45-60 and 70-85/55-70 (Text-fig. 4; Łoziński *et al.* 2015). Additionally, less numerous faults with orientations at 305-315/45-75 were also noted; some of them were diagnosed as normal faults. In turn, strike-slip faults and structures related to them were not noted. Folds were not observed.

The direct contact between the OB infill and its Palaeogene basement was exposed in the Czarny Dunajec river channel (Text-figs 3 and 8)[1]. This contact is tectonic in nature – the deposits are separated by an N-dipping normal fault (Text-fig. 8). Some fluctuations of the strikes of Neogene strata can be observed within the contact zone; their dip is consistently to the north-west or north (average bed position: 322/28; Text-fig. 3). About 0.5 km to the north of the OB/CCPB contact zone, the bedding position of Neogene strata stabilizes at mean values of 305/24 – they are thus subparallel to the eastern OB margin and dip towards its interior (Text-fig. 3). The presence of a single gentle fold with axis orientation at 290/30 was observed close to the contact zone; it may be interpreted as a drag fold related to the displacement along a fault subparallel to the eastern OB boundary (Text-fig. 3). About 7 km to the north-east, near Stare Bystre, the position of Neogene strata is similar (307/21). Small-scale faults with an orientation of 125-148/85-90, of which some are sinistral faults, were observed there.

The area located to the east of Miętustwo village between Bystry and Czerwony streams is tectonically different from the main part of the OB (Text-fig. 5) and could have developed to some extent in an unrelated style. The area is bounded by stream channels and represents high ground with exposures of coarse clastic lower and middle Pliocene deposits. In the Bystre stream channel near Miętustwo, the beds lie horizontally or sometimes attain an orientation of 270-275/10 (Text-fig. 5). Small-scale faults with an orientation of 270-305/55-90 were also observed. Sinistral faults and normal faults with a downfaulted western block were recognized (Text-fig. 5).

### *Joint network in the southern and south-eastern parts of the Orava Basin*

The joint network in the Neogene strata of the OB is developed slightly differently than in the CCPB rocks (see Ludwiniak 2006, 2010). It is less regular and has relatively fewer fractures in relation to Palaeogene rocks. Moreover, it displays an internal diversity – differences in the network architecture are observed between particular exposures.

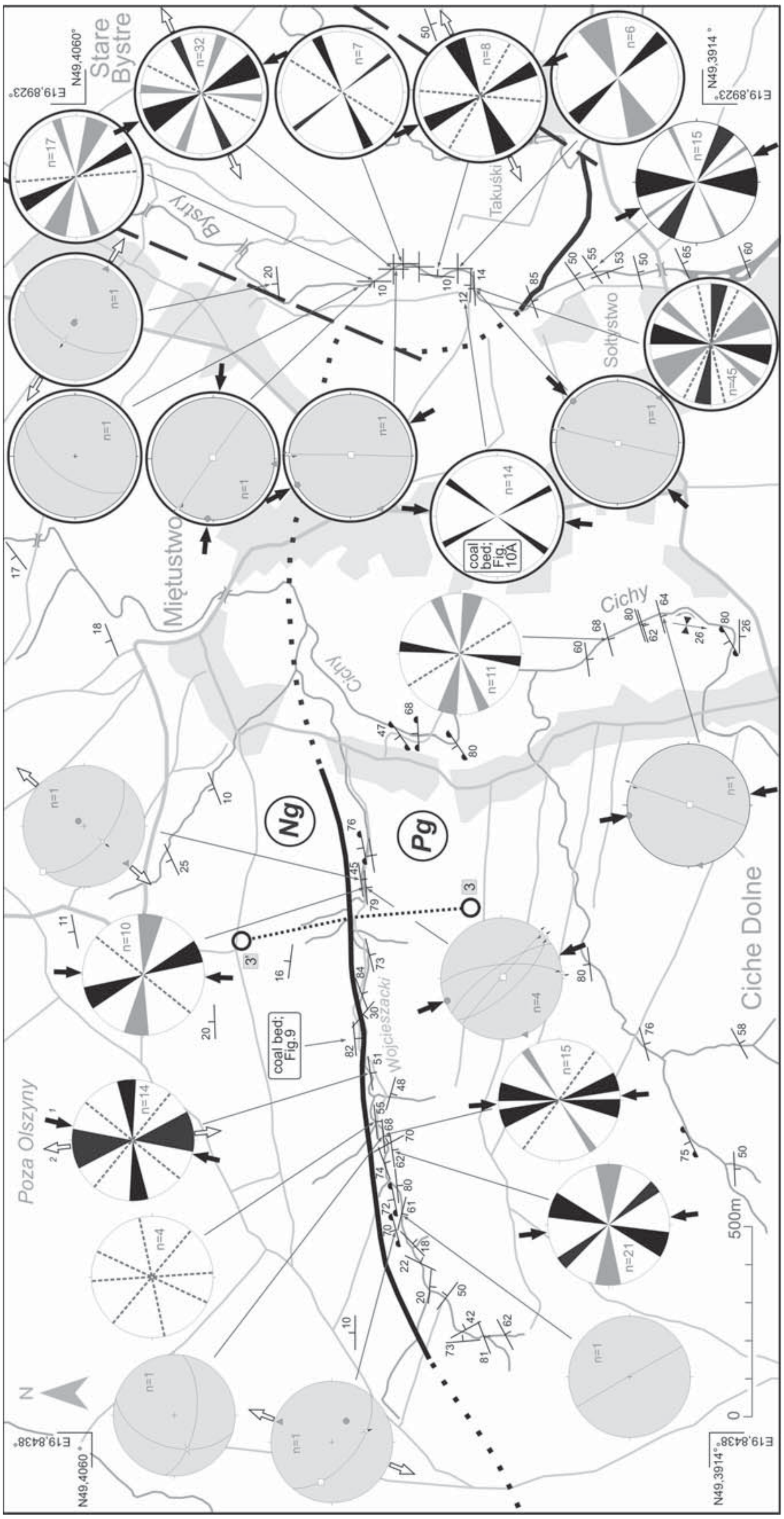
Joint network analyses in the Neogene of the OB are challenging. There is a lack of a clearly defined geometry of the basin infilling in the study area, which results from the lack of an unambiguous definition of the orientation of map-scale structures. Definition of their orientation together with the characteristics of the mesoscopic structures would allow for the interpretation of the joint network based on independent data, especially the regional stress field and the structural evolution of the study area.

Taking into consideration the lack of sufficient recognition of the OB structure, its joint network should be analyzed without any initial assumptions as to its origin, based on statistically significant observations and measurements performed in a large number of exposures. Such an approach is, of course, not possible due to the low degree of exposure of Neogene rocks, confined only to the marginal part of the OB and roughly corresponding to the fault zones surrounding the basin. A possible alternative is the analysis of the entire joint pattern, performed independently in each exposure. Due to its specific character, such an analysis may be executed only in exposures with a visible bedding top, preferably over a large area (of at least several to over ten square metres). Such analysis was performed in two areas: in the Oravica River channel near Čimhova (Slovakia), and in the Bystry stream near Miętustwo (Poland) (for precise location see Text-figs 4 and 5).

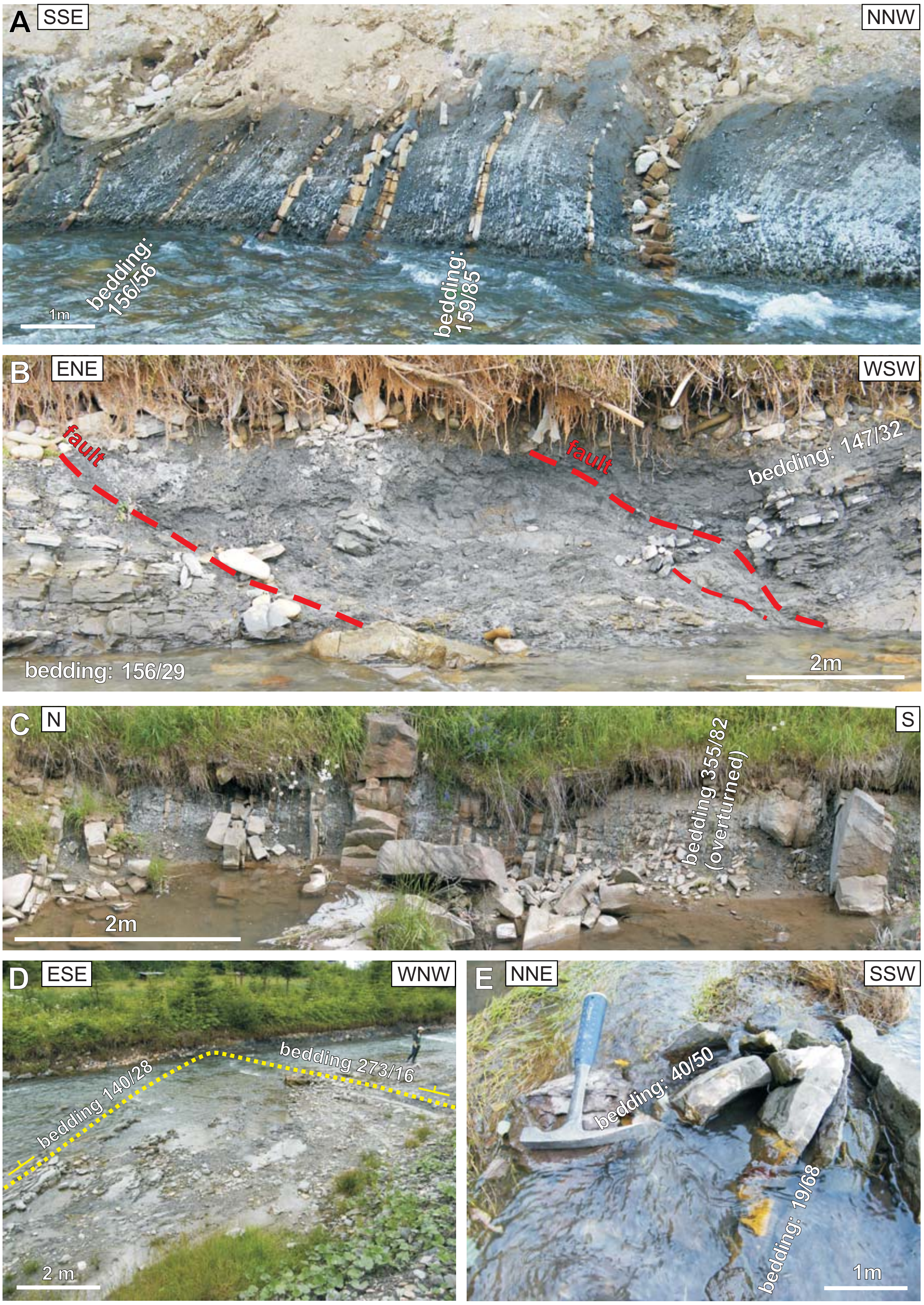
#### *Joint network in the Oravica River channel near Čimhova*

The joint network near Čimhova is characterized by medium orderliness (Text-fig. 4). Five sets char-

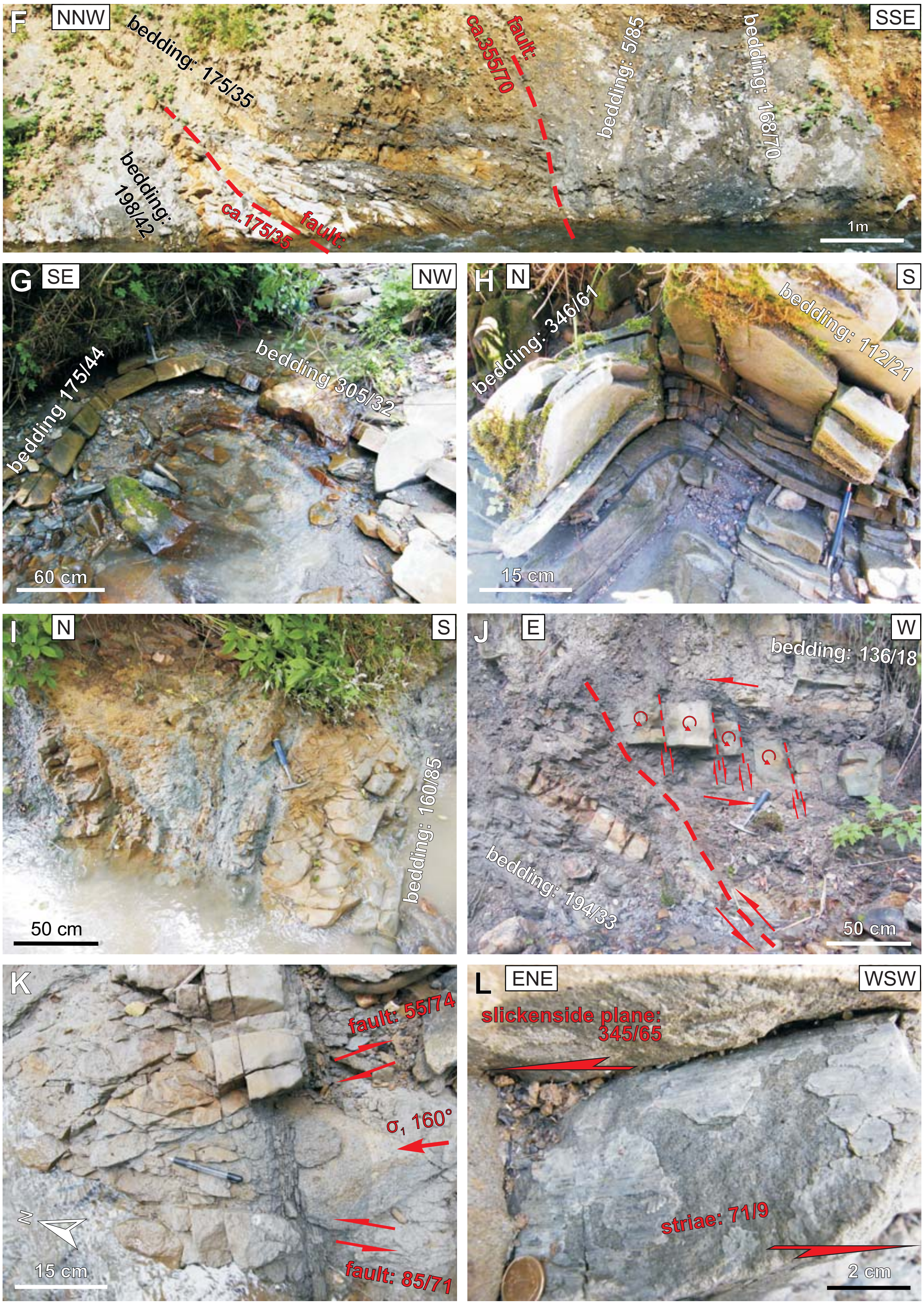
[1] This contact was exposed in 2009 during high water of Czarny Dunajec. In 2013 it was covered by a river bank reinforcement construction and is presently unavailable for observations.




Text-fig. 5. Detailed structural map of part of the study area near Ciche village (for explanations see Text-fig. 3)




Text-fig. 6. Tectonic features of the Central Carpathian Palaeogene Basin in the study area and its surroundings. (A) Steeply-dipping strata within the Huty Beds (Oravica river near Čimhova village). Note strongly fractured medium-bedded sandstones; (B) Fault-related disturbances within the Zuberec Beds (Oravica river near Liesek village); (C) Vertically oriented strata within Zuberec Beds (Jelešňa stream near Hladovka village); (D) Drag-fold (over 10 meters in radius) in the Zuberec Beds (Oravica river near Liesek village); (E) Fault related, steeply plunging drag folds within Szaflary Beds (Biały Dunajec river near Szaflary village); (F) Tectonic disturbances of the Szaflary Beds within the CCPB/PKB con-




tact zone (Leśnica stream near Leśnica village – Eastern Podhale); (G) Mesoscopic anticline within the Lower Chochołów Beds (Domagalski stream – western tributary of the Czarny Dunajec river, near Chochołów); (H) Small-scale anticline within a zone of fold disturbances in the Lower Chochołów Beds (Czarny Dunajec river, near Chochołów); (I) Strongly fractured sandstones and mudstones (Szaflary Beds, Wojcieszacki stream near Ciche village); (J) Domino-structure in the top wall of the fault (Szaflary Beds, Wojcieszacki stream near Ciche village); red arrows depict sense of fault movement; (K) Small-scale conjugate faults within the Szaflary Beds (Wojcieszacki stream near Ciche village); $\sigma_1$ – maximum normal stress axis; (L) Slickenside on the sinistral mesoscopic fault surface (Szaflary Beds, Wojcieszacki stream near Ciche village) acterized by different directions and orientation in relation to the parallel orientation of the OB were distinguished:

– longitudinal set, with average orientation at W-E (80–110º);
– sublongitudinal set (WSW-ENE; 60–75º, respectively);
– first oblique set (NNE-SSW to NE-SW; 20–45º);
– second oblique set (NW-SE; 120–140º);
– transversal set (NNW-SSE; 150–170º).

In exposures in which the joint network was observed in siltstones and sandy siltstones, these sets are characterized by variable contribution and regularity. The most common are longitudinal, sublongitudinal and first oblique sets. In exposures in which one set dominates, usually longitudinal or sublongitudinal sets predominate. Orientations of both sets in some cases deflect counter-clockwise at over ten degrees. In most exposures, fractures of sublongitudinal and longitudinal sets have the longest traces. Only in a few exposures do the longest traces belong to transversal set fractures. Moreover, the joint network architecture is different in exposures in which the first oblique set co-occurs with the longitudinal set. In these cases they form a ladder-type orthogonal system (Text-fig. 10B; Hancock *et al.* 1987). Long, regular fractures of the first oblique set cut across the entire exposure, whereas shorter cross-joints belonging to the longitudinal set fade on them. An orthogonal ladder-pattern system also occurs in exposures with co-occurring fractures of first and second oblique sets, but in this case cross-joints are formed by fractures of the second oblique set. Cases were observed in which sublongitudinal and transversal sets form a grid-lock orthogonal system, with sublongitudinal set fractures being better developed. Such local grid-lock pattern systems may form in cases when rapid, 90º-alternate switching of $\sigma_3$ and $\sigma_2$ axes of nearly equal magnitude takes place in the palaeostress field (Caputo 1995).

The joint network developed in brittle coal layers is much more regular compared to the joint network in fine-clastic deposits. Orthogonal systems close to ladder-patterns dominate here (Text-fig. 10B). They may be subdivided into two characteristic groups. The first includes systems formed by long and regular fractures of the first oblique set, with perpendicular short fractures of the longitudinal set fading on them. The second group includes short fractures of the first oblique set fading on long, straight and regular traces of the sublongitudinal set.

The joint network dominated by orthogonal patterns occasionally shows a trend to gradually pass into a low-angle system of hybrid fractures. The observed cross-cutting relationships indicate that generally the oldest are fractures of longitudinal and sublongitudinal sets, as well as part of the transversal set fractures conjugate with them. These data may indicate that the oldest longitudinal and sublongitudinal sets could be formed as the effect of local extension related to normal faulting. The diagonal system developed at a later stage of network development and overprinted the orthogonal system.

The geometry of both joint systems (orthogonal and diagonal) in siltstones and sandy siltstones would indicate a similar direction of the maximal normal horizontal stress axis $\sigma_1$ (azimuth 160–20º). The direction of the $\sigma_1$ axis for the low-angle system of hybrid fractures is approxmately 10–20º. The results of AMS analyses performed in this area suggest the activity of weak, N-S-oriented compression (Łoziński *et al.* 2016).

### *Joint network in the Bystry Stream channel near Miętustwo*

In the eastern part of the study area, near Miętustwo village, observations of the joint network were performed in two groups of exposures separated by a distance of c. 250 m in a N-S direction, close to the contact of Neogene strata with the CCPB (Text-fig. 5). Here, the joint network is characterized by medium orderliness, slightly greater than in the vicinity of Čimhova (Text-fig. 5). Five sets were distinguished, whose directions, with the exception of the transversal set, are similar to those from the Čimhova area:

– longitudinal set (W-E to WNW-ESE; 90–124º);
– sublongitudinal set (WSW-ENE; 60–80º);
– first oblique set (NE-SW; 30–55º);
– second oblique set (NW-SE to NNW-SSE; 130–165º);
– transversal set (N-S to NNE-SSW; 176–20º).

The joint network in siltstones and sandy siltstones is characterized by the different abundance and regularity of particular sets. Contrary to the joint network near Čimhova, the most common are fractures of longitudinal and transversal sets, whereas the first oblique set fractures are the rarest. In most exposures, the longest traces can be attributed to fractures of the second oblique and transversal sets. Fractures of longitudinal and sublongitudinal sets co-occurring with them in most exposures usually fade on them. In these exposures, in which longitudinal and sublongitudinal sets co-occur, their fractures are usually curvilinear and sometimes pass into each other. Two oblique sets may form a diagonal system. Fractures of both sets are rather straight and regular, and their traces often cross-cut each other. However, these exposures also have a lower number of first oblique set fractures.

In the southern part of the study area, the joint network was also observed in coal layers. It is much more regular as opposed to the joint network in siltstones and sandy siltstones. In contrast to the network observed in coal layers in the Čimhova area, oblique sets dominate, forming a very distinct diagonal system (Text-fig. 10A). Subordinately, an orthogonal system also occurs. The direction of the $\sigma_1$ axis for the diagonal system developed in coal layers is about 5º. A very similar orientation of the $\sigma_1$ axis was observed for diagonal and subordinate orthogonal systems within siltstones and sandy siltstones.

In the northern part of the study area, distinct domination of the second oblique set fractures with an orientation of c. 160º was observed in sandy siltstones. These fractures could be formed as discontinuities corresponding to high-angle Riedel shears (R'), genetically linked with sinistral faults bounding the OB. However, assuming that these fractures are inherently independent of faulting, the entire network should be interpreted here as being dominated by the orthogonal system formed in a stress field where the $\sigma_1$ axis with an orientation at c. 160º would be parallel to the fractures of the set with a similar orientation (in this case the second set would be formed by fractures with an orientation of c. 60–70º). Fractures forming a diagonal system, characterized by the same orientation of the $\sigma_1$ axis have also been noted locally.

The possibility of making observations of the joint network in the vicinity of the eastern OB margin between Chochołów and Koniówka (Poland) (Text-fig. 3) was rather limited due to few exposures, their small dimensions, and the lithology of the exposed strata (predominantly massive siltstones and clayey siltstones). The joint network in this area is characterized by lower orderliness compared to the Čimhova and Miętustwo areas. Four sets were distinguished here:

– transversal set (N-S; 175–15º);
– sublongitudinal set (WSW-ENE; 60–75º);
– first oblique set (NE-SW; 30–55º);
– second oblique set (NW-SE; 120–155º).

The most common are fractures of the transversal and first oblique sets. Contrary to the Čimhova and Miętustwo areas, the longitudinal set was not observed, whereas fractures of the sublongitudinal set are much rarer. Least common are fractures of the second oblique set. Fractures of transversal and first oblique sets have the longest traces. Traces of the second oblique set fractures are short and often fade on fractures of the first oblique set. In comparison to the areas described above, there is no clear trend to form distinct and characteristic joint systems.

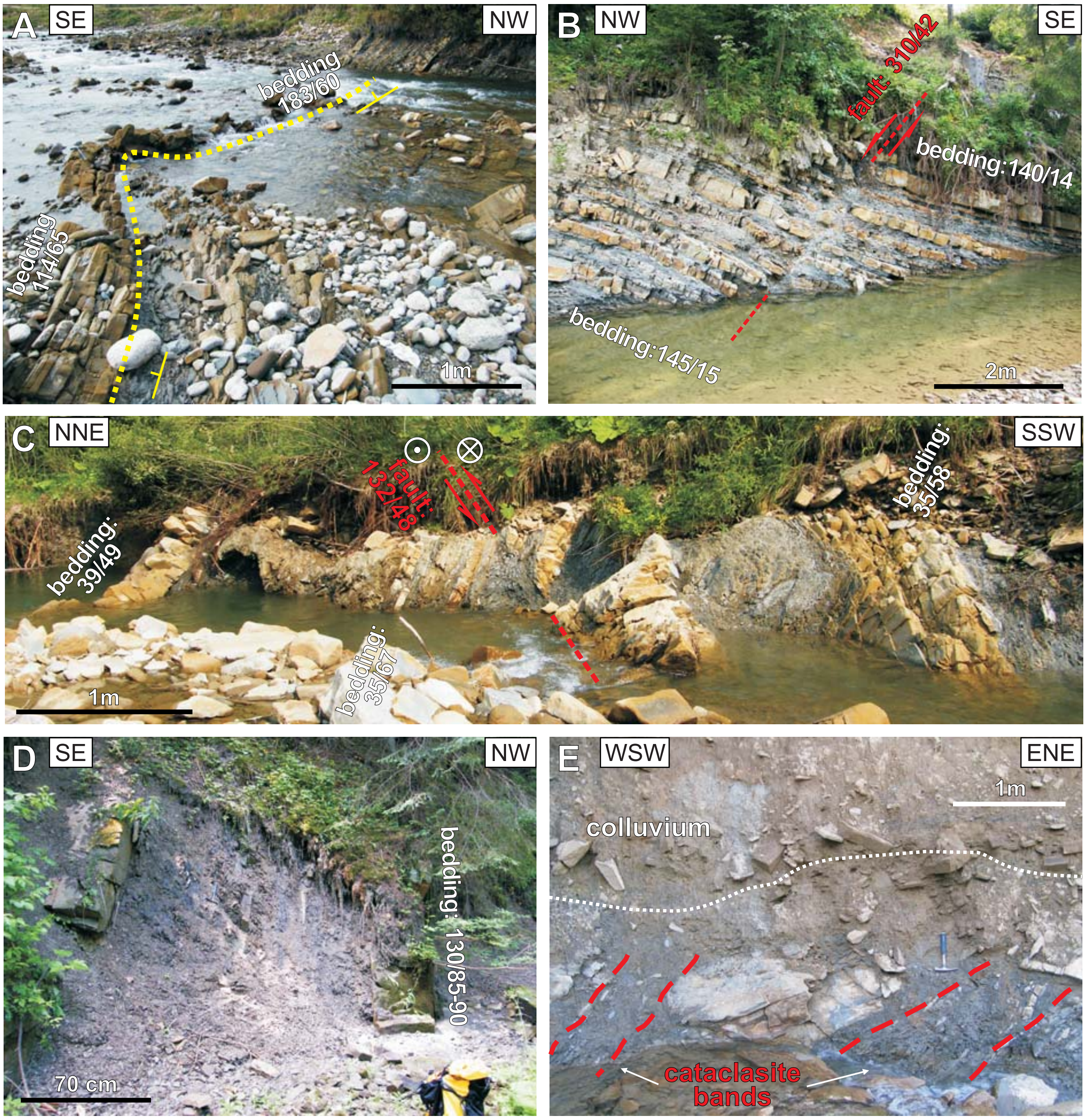
**Structures in the CCPB along the Orava Basin margin**

Along the southern OB margin, between Zabiedovo village and Hlboky stream (region I – Text-fig. 2), beds within the CCPB have a generally stable strike at 65–80º and dip at 40–70º/S, locally attaining a vertical position. Normal faults with an average orientation of 30/75 were observed directly at the OB/CCPB contact (Text-fig. 4). Strike-slip faults occur c. 250 metres to the south of the OB/CCPB contact. They are vertical dextral faults forming two groups, c. 100º- and c. 125º-oriented, locally accompanied by drag folds, in some cases with a radius of over ten metres (Text-fig. 6D).

At c. 1–3 km to the south of the OB margin occurs a c. 15 km long, WSW-ENE-oriented fault (see Gross *et al.* 1993a; Text-fig. 2). The presence of younger deposits of the Biely Potok Fm. to the south and older deposits of the Zuberec Fm. to the north along some of its stretches (Text-fig. 2) indicates the dip-slip nature of this fault. The occurrence of vertical and N-dipping beds in a reversed position (Text-fig. 6C), with strikes in accordance with the fault direction, suggests that it is a reverse fault (see also cross-section 11–12 in Gross *et al.* 1993a). The fault may have deeper foundations, as indicated by calcareous tufas in the Brezovica stream (N49.33694º E19.66186º).

Horizontal to gently plunging mesofolds were noted in part of region I corresponding to the axial part of the synclinorium; they can be subdivided into two groups with different directions: (a) more abundant, with an average axis azimuth of c. 70º and (b) less abundant, with an average axis azimuth of c. 30º. The first group represents folds that are probably the effect of tectonic shortening during PSS formation, whereas the second group contains folds that may be genetically linked with faults perpendicular or oblique to PSS orientation. Mesofolds in this area are less common than in the axial zone of the Podhale segment of PSS (see e.g., Text-fig. 6G).

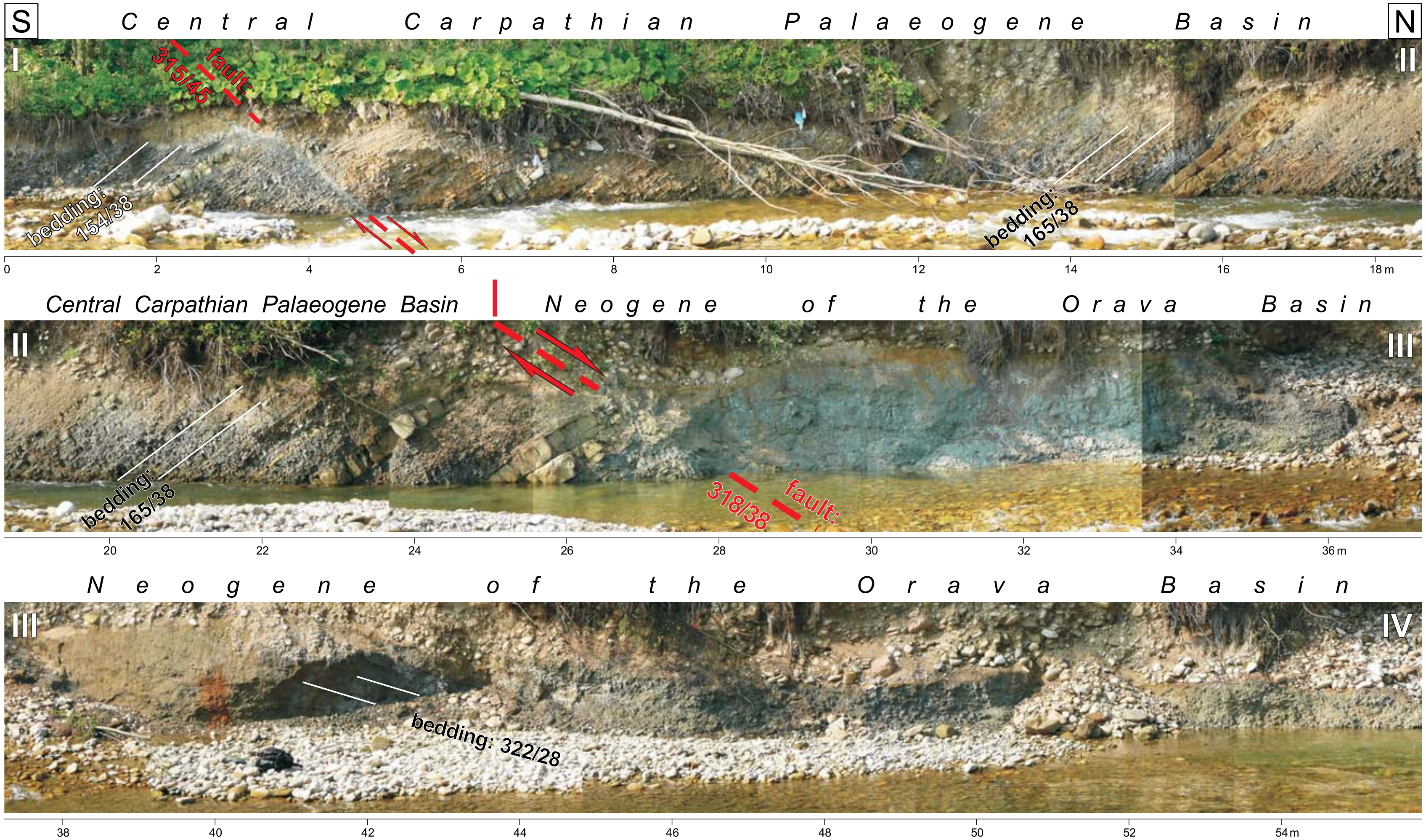
In the Chochołów-Miętustwo area (region II; Text-figs 2, 5), the CCPB structure slightly differs from the regional pattern. Bedding strikes usually attain 70–80º, whereas dips are within c. 30–40º/S in the southern part, and gradually increase to 50–60º/S in the northern part. Most mesofolds have an orientation similar to the regional trend (axis azimuth 60–105º). They are gentle and open (*sensu* Williams and Chapman 1979; Text-fig. 6G, H), horizontal to gently




Text-fig. 7. Tectonic features of the Central Carpathian Palaeogene related to the Krowiarki Fault Zone. (A) Mesoscopic drag-fold with steeply plunging axis in the Czarny Dunajec River bed near Chochołów village; (B) Mesoscopic normal fault in Zuberec Beds (Jelešňa stream); (C) Mesoscopic fault with readable sinistral-movement component within Zuberec Beds (Jelešňa stream); (D) Vertically oriented strata within Biely Potok Beds (Jelešňa stream tributary) – example of fault-related disturbances; (E) Mesoscopic cataclasite bands in Zuberec Beds (Jelešňa stream)

plunging and upright to steeply inclined folds (*sensu* Fleuty 1964). Some of the folds are linked with faults, usually dip-slip ones, and may be considered as drag folds. Among mesofaults observed in this zone dominate those with an orientation of c. 130–150º and 80–90º. They include mainly normal faults, rarely reverse faults. The population of 130–150º faults includes also dextral faults. In turn, the rather sparse population of 175–20º faults contains sinistral faults (Text-fig. 5).

A slightly different structure is observed in the zone separating the two subregions (region III; Text-fig. 2). This zone runs along the eastern OB margin in the vicinity of Chochołów-Stare Bystre (Text-fig. 3) and continues further to the south-west. Bedding




Text-fig. 8. Contact between Central Carpathian Palaeogene and Neogene of the Orava Basin in the Czarny Dunajec River bank near Chochołów village strikes are deflected from the regional trend, at 60–70º, and locally oscillating at 35–50º. Bedding dips are from over ten to 30º/S-SE and reach up to 50º/S-SE in the northern part of this region. Mesofolds were observed with the dominating axis directions at 15–50º. They are usually drag folds, being related to faults characterized by a similar orientation. Those linked with strike-slip or oblique-slip faults are moderately plunging to subvertical, steeply inclined, open to tight folds (e.g., Text-fig. 7A). Those related with normal faults are gentle and open, horizontal, moderately to gently inclined folds. Some of the folds have orientations similar to the regional trend (axis azimuth 70–100º); they are usually gentle and open, horizontal to gently plunging and upright to steeply inclined folds. Most of the observed mesofaults have orientations at 25–45º, although faults with orientations at c. 150º and 70–90º were also noted. They are mainly normal faults, rarely strike-slip faults. Directly at the OB/CCPB contact, in the Czarny Dunajec river channel, occur 45–70º-striking normal faults with their northern blocks downfaulted to the NW, i.e., to the OB centre (Text-fig. 8). A few reverse faults with orientation at c. 350/65 occur about 1.5 km to the south of the OB/CCPB contact (Text-fig. 3).

Deflections between the orientation of structures and the regional trend are related to the presence of the Krowiarki Fault Zone (KFZ), cutting the Mesozoic (Mesozoic–Palaeozoic?) basement of the CCPB (compare also Nemčok *et al.* 1994; Polák *et al.* 2008). The KFZ deformation zone continues to the south-west and is visible in the middle part of the PSS as bending of beds exposed in streams located c. 1.5 km to the south of Sucha Hora village and along Cierny Potok in the vicinity of Oravica (local steepening of beds, even to a vertical position – Text-fig. 7D), strong fracturing and even cataclasis within the rocks (Text-fig. 7E). Mesofaults were observed, mostly normal faults with orientations at c. 35–45º (Text-fig. 7B), rarely strike-slip or oblique-slip faults (Text-fig. 7C). Mesofolds with subhorizontal axes, subparallel to the zone also occur. They are usually drag folds, related to the dip-slip faults mentioned above with a similar orientation. The remaining part are folds with subhorizontal axes oriented in accordance with the regional trend (75–105º), probably being the effect of tectonic shortening of the PSS.

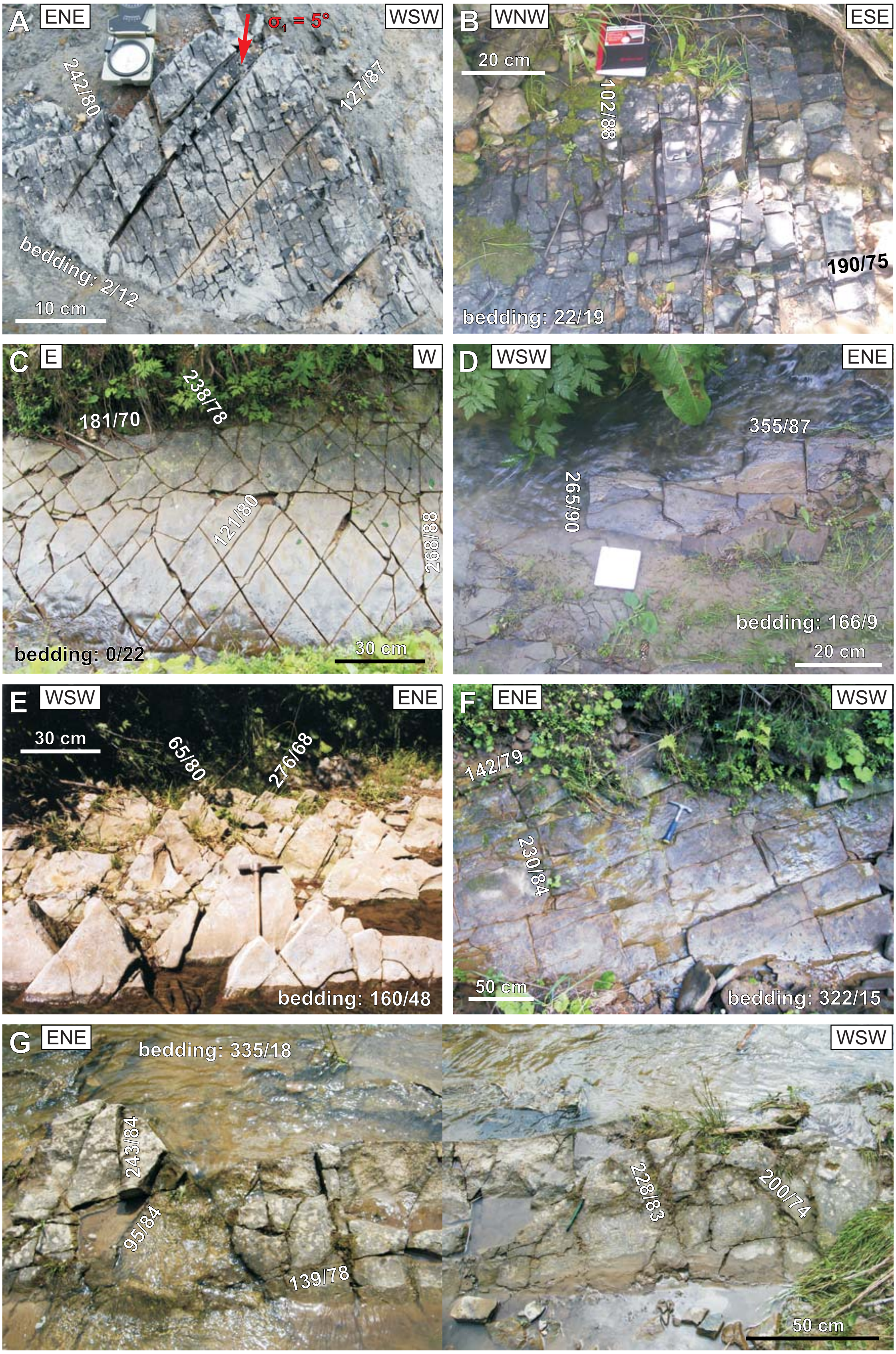
Text-fig. 9. Coal layer cropping out in the Wojcieszacki stream bed

The Wojcieszacki stream area, which is part of region IV (see 'Discussion') is characterized by intense deformation in comparison to the areas described above. Dominating bedding strikes are 70–80º and dips reach 80–90º; in some cases reversed beds occur (Text-fig. 5). Generally their occur NW-SE-oriented, strike-slip and normal small-scale faults. In one case the stream channel runs along the contact of the Palaeogene and Neogene strata on a distance of over 10 m. Despite the very strong weathering of Neogene deposits, fragments of a coal layer in a vertical position could be observed (Text-fig. 9). In the same subregion, within the Bystry stream channel, the position of Palaeogene strata slightly deflects from that observed in the northern limb of the PSS in western Podhale and usually reaches 55–75/50–55S. Only directly at the contact with Neogene strata, the dips become steeper reaching about 80–90º (Text-fig. 5).

### *Joint network in the CCPB*

Fractures were investigated in CCPB rocks in c. 300 exposures from regions I, II and III. Due to the usually gentle dips and locally variable strikes within the analyzed fragments of the CCPB, the general ori-

Text-fig. 10. Joints in the south-eastern margin of the OB and its surroundings. (A) Conjugate joint sets in a coal bed (Neogene of the OB; Bystry stream near Miętustwo village; $\sigma_1$ – maximum normal stress axis); (B) Orthogonal joint pattern in a coal bed (Neogene of the OB; Oravica River near Čimhova village); (C) Joint pattern on the top of a sandstone bed with visible domination of the diagonal conjugate system (Palaeogene, Biely Potok Beds, Oravica river tributary near Vitanová village); (D) Orthogonal joint pattern in a sandstone bed (Palaeogene, Zuberec Beds; Oravica River tributary near Čimhova village); (E) Two joint sets forming a diagonal conjugate system (Palaeogene, Szaflary Beds; PKB/CCPB contact zone; Skrzypny stream near Skrzypne village); (F) Orthogonal joint pattern on the top of a sandstone bed (Palaeogene, Zuberec Beds; Oravica river tributary near Vitanová village); (G) Joint pattern on the top of a sandstone bed (Palaeogene, Zuberec Beds; Oravica River near Oravice village) →


A
ENE
WSW
σ1 = 5°
242/80
127/87
bedding: 2/12
10 cm
B
WNW
ESE
20 cm
102/88
190/75
bedding: 22/19
C
E
W
181/70
238/78
121/80
268/88
bedding: 0/22
30 cm
D
WSW
ENE
355/87
265/90
bedding: 166/9
20 cm
E
WSW
ENE
30 cm
65/80
276/68
bedding: 160/48
F
ENE
WSW
142/79
230/84
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G
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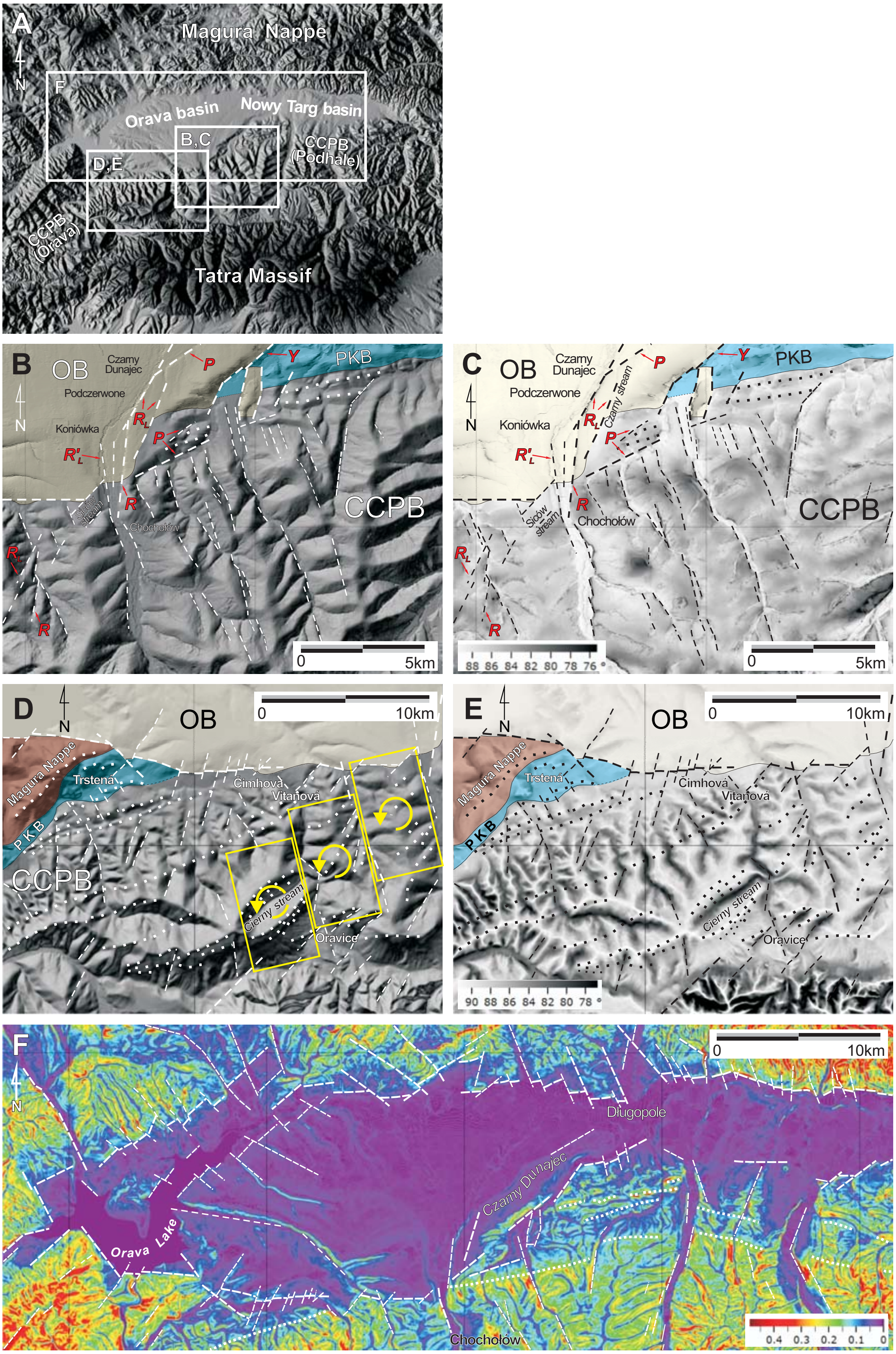
228/83
200/74
50 cm


A
Magura Nappe
F
Orava basin
Nowy Targ basin
B,C
D,E
CCPB (Podhale)
CCPB (Orava)
Tatra Massif
B
OB
Czarny Dunajec
Podczerwone
Koniówka
PKB
CCPB
Chochołów
0
5km
C
OB
Czarny Dunajec
Podczerwone
Koniówka
Czarny stream
Siców stream
Chochołów
PKB
CCPB
88 86 84 82 80 78 76 °
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D
OB
0
10km
Magura Nappe
Trstená
PKB
Cimhová
Vitanová
CCPB
Čierny stream
Oravice
E
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Trstená
PKB
Cimhová
Vitanová
Čierny stream
Oravice
90 88 86 84 82 80 78 °
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0
10km
Długopole
Czarny Dunajec
Orava Lake
Chochołów
0.4 0.3 0.2 0.1 0

entation of the PSS was used as reference for fracture orientation. Defining the joint network geometry in the study area and other segments of the CCPB only by determining the orientation of sets designated stratigraphically and genetically may sometimes be misleading. This is caused by directional fluctuations of particular sets, but also local rotations of the whole blocks along with the entire joint network developed within them.

Therefore, beside measuring the joint orientation, their patterns and cross-cutting relationships were studied in particular exposures, regardless of the superordinate reference patterns (N-orientation, elongation of the synclinorium).

Four joint sets were noted in region I, with two of them distinctly dominating: the first with NNW-SSE to N-S orientations and the second with ENE-WSW to W-E orientations. Less numerous are two sets with NW-SE to NNW-SSE and NE-SW orientations (Text-fig. 4). In the scale of the entire region I, the orientations of some sets mutually coincide, which is the effect of fluctuations within them. In exposures where two dominating sets co-occur, they form a clear orthogonal system. In turn, in cases where two less numerous sets co-occur, they often form a diagonal system. In region I, the orthogonal system dominates in 65% exposures (its presence was noted in 95% exposures; Text-figs 10D, 15), whereas the diagonal system dominates in 6% exposures (it was noted in 25% exposures; Text-figs 10C, 15). Moreover, there occurs locally a joint network with a significant role of the diagonal system related to local compression parallel to the PSS axis.

In region II, the joint network comprises 5 sets, with 2 to 4 sets occurring in particular exposures. It is dominated by three sets: two oblique sets (NNW-SSE and NE-SW-striking sets) and an ENE-WSW-striking sublongitudinal set. In exposures in which two oblique sets co-occur, they are coeval and form a diagonal conjugate system. The $\sigma_1$ orientation of this system is at 10–15º. The third set with regard to abundance is the sublongitudinal set. In exposures in which it co-occurs with fractures of the diagonal system, its fractures usually fade on them. This means that the sublongitudinal set fractures are generally younger than the diagonal system. Longitudinal (W-E to WNW-ESE-striking) and transversal (N-S to NNE-SSW-striking) sets are less common compared to the oblique and sublongitudinal sets. Their cross-cutting relationships, and thus their temporal relations are difficult to estimate, although they are generally younger than the diagonal system. In region II, the diagonal system dominates in over 50% exposures (its presence was noted in over 80% exposures) (Text-figs 10E, 15). The orthogonal system dominates in just 20% exposures (Text-fig. 15). The remaining systems occur subordinately.

The joint network in region III, located along the KFZ, is geometrically deformed in comparison to regions I and II, as well as the remaining regions of the CCPB. It reveals, however, some regularity and repeatability. It is characterized by the domination of the NNW-SSE to NW-SE-striking second oblique set, often accompanied by a perpendicular or subperpendicular first oblique set (NE-SW to ENE-WSW), with which it forms an orthogonal or suborthogonal system (Text-fig. 10F). The first oblique set sometimes shows a strong tendency to deflect to NNE-SSW (the angle between the oblique sets decreases from c. 90º to c. 75º). Often, the first oblique set has an orientation subparallel to the general KFZ direction. Additional sets with an orientation similar to the direction of this zone occur in some exposures. They sometimes form a local diagonal system with small dihedral angle sets and the dihedral subparallel to the zone orientation. In some cases one set distinctly dominates over the other sets.

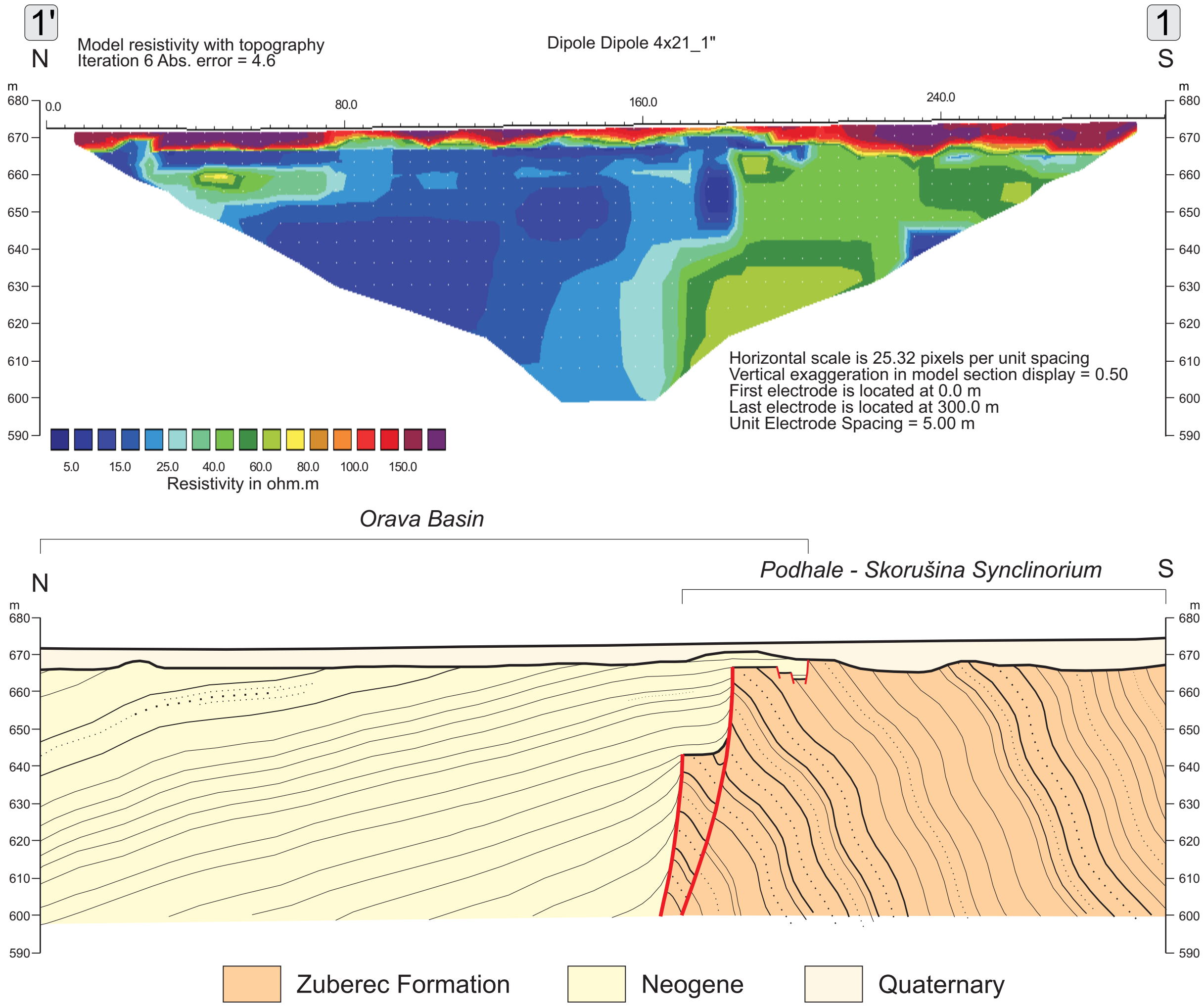
## Analysis of electrical resistivity tomography profiles

ERT surveys supplemented with field observations allowed for the specifying/confirming of the position of the contact of Neogene strata infilling the OB with deposits belonging to the CCPB. In some cases they enabled us to obtain additional information on the lithology and structure of the Neogene and Palaeogene rocks in the OB/CCPB contact zone.

### *Profile 1-1' (Čimhova)*

Profile 1-1' (Text-fig. 12; for location see Text-fig. 4) shows the difference in resistivity resulting from the lithological variability of the deposits. They can

← Text-fig. 11. DEM derivatives of the Orava Basin and adjacent areas. (A) Location of particular DEM images displayed on a shaded-relief image; (B) Shaded-relief image of the south-eastern margin of the OB and western part of the Podhale; (C) Downward-openness map (L = 500 m) of the south-eastern margin of the OB and western part of the Podhale; (D) Shaded-relief image of the south margin of the OB in Orava; (E) Upward-openness map (L = 500 m) of the south margin of the OB in Orava; (F) Slope map of the ONTB area (values of slopes presented as sine of their angles). Lineaments considered as faults are marked by chain-dashed lines, lineaments representing ridges and other lithologically controled linear forms are marked by dotted lines (selected lineaments are depicted only)



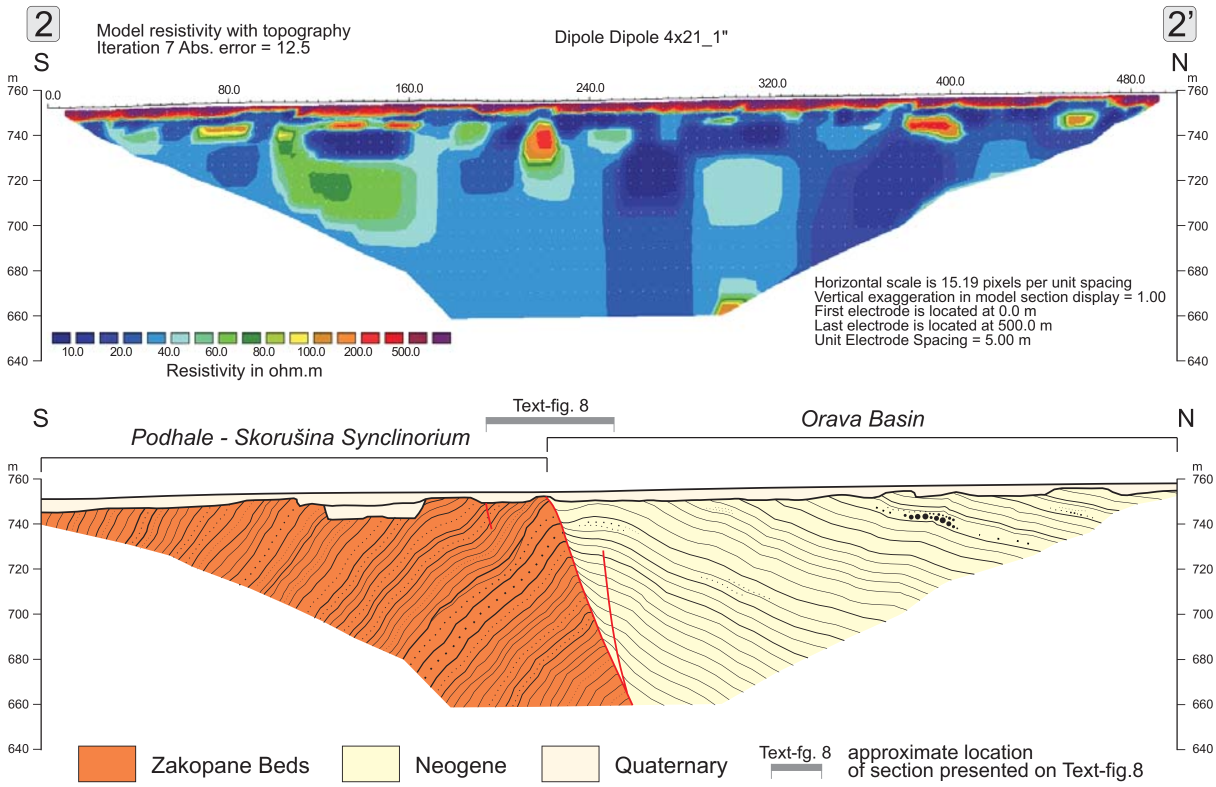

Text-fig. 12. Results of an electrical resistivity tomography survey of the CCPB/OB contact zone near Čimhova village. ERT profile. Geological interpretation of ERT profiling. For ERT profile location see Text-fig. 4

be subdivided into three main groups: (1) Quaternary fluvial sandy gravels to sands and sandy loams (c. 40–200 Ωm) lying in the upper part along the entire profile; (2) Neogene claystones, silty claystones, siltstones and clayey siltstones located in the northern part of the profile (between 0 and 185 m; c. 5–25 Ωm); however, it should be noted that locally in the northern part occurs a complex of deposits with resistivities up to c. 80 Ωm, which would correspond to fine-, rarely medium- to coarse-grained sandstones from the exposures in the Oravica channel); (3) deposits of the Zuberec Fm. (CCPB) – sandstones and claystones, occurring in variable contribution: from 2:1 to 1:2 (c. 35–70 Ωm, only locally resistivities decrease to c. 25 Ωm with increased claystone contribution), located in the southern part of the profile (between 185 and 300 m).

The position of the OB/CCPB contact, covered by several-metre thick Quaternary sediments, could be precisely determined in profile 1-1'. The OB margin is composed of steep, N-dipping normal faults, forming a step-like arrangement. Over 10 m to the south of the principal OB marginal zone, Neogene strata are preserved only scantily within a small, shallow ditch (Text-fig. 12).

***Profile 2-2' (Chochołów)***

A several-metre thick complex with high resistivities (from c. 200–700 Ωm) is observed along the entire profile 2-2' (Text-fig. 13; for location see Text-fig. 3) in its uppermost part. This complex corresponds to the floodplain of Czarny Dunajec, composed of




Text-fig. 13. Results of an electrical resistivity tomography survey of the CCPB/OB contact zone near Chochołów village. ERT profile. Geological interpretation of ERT profiling. For ERT profile location see Text-fig. 3

coarse gravels, sands and muds. Between 122 and 168 m of the ERT profile, below this complex occur deposits that may represent an older floodplain.

Below the Quaternary cover occur older deposits characterized by a relatively complex resistivity distribution. Interpretation of ERT results is facilitated by detailed mapping of the Czarny Dunajec channel stretch with orientation subparallel to profile 2-2' (Text-figs 3 and 8). There is a general trend for the presence of slightly higher resistivities in the southern part of the profile (Text-fig. 13).

Fine- and medium-grained, thin-bedded sandstones, siltstones and clay shales, subordinately medium- and coarse-grained sandstones of the Upper Zakopane Beds (CCPB; Watycha 1977; c. 30–350 Ωm) occur in the southern part of the profile (between 0 and 220 m). Isolated high-resistivity anomalies (c. 200–350 Ωm) indicate the presence of thick sandstone complexes. The rather small dimensions of these anomalies may be the effect of constrained lateral distribution of sandstone beds/complexes, which thin out, laterally passing into complexes of fine-clastic sediments.

Neogene claystones, silty claystones, siltstones and clayey siltstones (c. 10–40 Ωm; Text-fig. 13) occur in the northern part of the profile (between 220 and 500 m). Local high-resistivity anomalies up to 200–300 Ωm (Text-fig. 13) correspond to gravel interbeds and intercalations. The contact of OB/CCPB deposits was located at about 220 m of the profile. Its course in the elevation of 730–745 m is emphasized by the northern margin of a high-resistivity anomaly (Text-fig. 13). The contact is a normal fault, with the fault plane dipping to the north at approximately 60º in its upper part. The fault surface, directly observed in the Czarny Dunajec channel, with Neogene deposits contacting with flysch, dips at a slightly smaller angle (45º; Text-fig. 8; see also Tokarski *et al.* 2012).

### *Profile 3-3' (Ciche)*

The resistivity distribution in profile 3-3' is very complicated (Text-fig. 14; for location see Text-fig. 5). The Szaflary Beds (CCPB) occur in the southern part of the profile (between 305 and 600 m). They comprise complexes of clay shales, siltstones, and thin-bedded sandstones, rarely intercalated with medium-bedded sandstones (c. 10–60 Ωm), and complexes with a larger contribution of sandstones, including coarse-grained sandstones (c. 50–350 Ωm). Large differences in resistivity in the second case may result from the structural features of sandstones – strongly fractured rocks with fractures filled with water have lower resistivities.

Neogene deposits occurring in the northern part are characterized by a large spread of resistivity values (c. 10–650 Ωm; Text-fig. 14). They form two segments differing in lithology. The first (between 130 and 305 m) includes claystones, silty claystones, siltstones and clayey siltstones (c. 10–40 Ωm) with local sand complexes and interbeds (up to c. 80 Ωm). These deposits, assigned to the lower–middle Pliocene (Watycha 1976b, 1977) are locally cut by N-dipping normal faults with small amplitudes (220–240 m of the profile; Text-fig. 14).

The northern segment (between 0 and 130 m) is separated from the southern segment by a steep normal fault (Text-fig. 14). It comprises thick complexes of pebbles and gravels, often strongly cemented and forming conglomerates (c. 100–650 Ωm), separated by complexes of sandy or clay-silty muds (c. 20–90 Ωm). They are probably late Pliocene in age, although it may not be excluded that they pass smoothly into similar Pleistocene sediments (Watycha 1977).

OB and CCPB deposits are separated by a steep fault-bounded block (between 275 and 305 m – Text-fig. 14). It is bipartite: the upper part is characterized by higher resistivities (c. 40–150 Ωm) and the lower – by lower resistivities (c. 20–40 Ωm). Analysis of maps (Watycha 1976a) and logs of the Koniówka IG-1 and Domański Wierch IG-1 boreholes (see Text-figs 2 and 3 for location) allows a confident statement that the block represents a southern, relatively uplifted fragment of the PKB, directly contacting from the south with the CCPB (Text-fig. 14). Its lower part would correspond to series of variegated and green Globotruncana marls and thin-bedded, shaly marls (Cenomanian–Santonian; Alexandrowicz 1966), overlain by sandstones, shales, conglomeratic siltstones and conglomerates of the Sromowce Beds. These deposits are not exposed here, being unconformably covered by Pliocene strata.

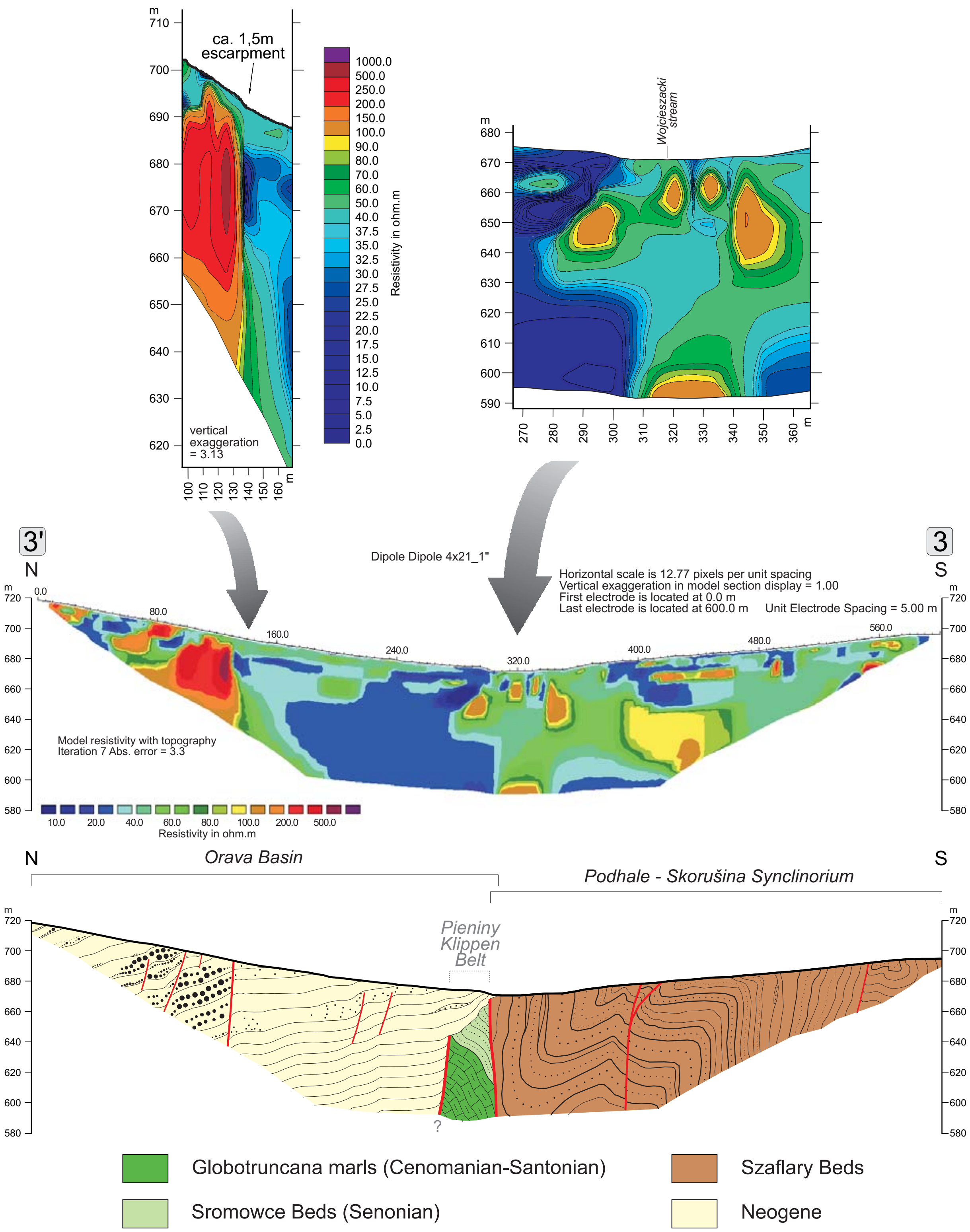
Tectonic deformation of CCPB rocks observed in the vicinity of profile 3-3’ are typical for the CCPB/PKB contact zone, analogously to that observed in other parts of this zone, e.g., western Podhale, Spiš, Spišska Magura and Šariš (e.g., Mastella *et al.* 1988; Plašienka and Soták 1999; Ludwiniak *et al.* 2009; Plašienka *et al.* 2013; Ludwiniak 2018; see Text-fig. 6E, F). Structural observations in the Wojcieszacki and Cichy streams (Text-fig. 5) indicate very strongly deformed CCPB deposits, with steep, in some cases even vertical or reversed beds. Locally there occur very strongly fractured sandstone beds (Text-fig. 6I) and numerous mesofaults (Text-fig. 6J, K, L).

**Analysis of DEM images**

Analysis of DEM images indicates that the OB terrain surface is completely different from the neighbouring areas (Text-fig. 11A, F). The OB is characterized by a monotonous, low-diversity surface and small elevation differences, which is reflected for instance in the very low values of the slope gradient ratio (0–0.05), only sporadically reaching c. 0.25 in stream escarpments (low values of erosional dissection obtained for the OB by Wołosiewicz (2018) are, in his opinion, characteristic for areas of molasse basins). By comparison, values of the slope gradient ratio in the neighbouring areas with a very pronounced terrain surface (CCPB, MN and PKB) reach c. 0.4–0.45 (Text-fig. 11F). In the western part of the OB, poorly delimited valley forms may be seen, in most cases with a straight and constant NW-SE orientation, with the exception of the relatively deeply incised Ješňa stream channel composed of two straight stretches with NW-SE and WNW-ESE orientations (Text-fig. 11A, F).

The morphology of OB margins (rapid change of slope gradient ratio and reflectance value – Text-fig. 11A, B, D, F) suggests their relationship with faults. The southern and northern OB margins have a generally straight orientation (Text-fig. 11A, F), which may indicate that the parallel faults bounding the basin are steep. They are subdivided into segments by transversal and oblique faults (Text-fig. 11D–F).

Between Chochołów and Długopole, the Czarny Dunajec valley is straight and its orientation is similar to the eastern OB margin (Text-fig. 11C, F; compare also Watycha 1976a). Floodplain boundaries, particularly their eastern margins, are sharp, something which is visible e.g., close to Podczerwone (Text-fig. 11B, C). The eastern floodplain margin is characterized by low values of downward openness, which indicates a sharper escarpment profile in comparison to the western margin of this floodplain (Text-fig. 11C). The area to the west of the floodplain is distinctly lower than the area to the east, by an average of over ten metres. Here, the pattern of alluvial terraces is asymmetrical. The terrace system is more




Text-fig. 14. Results of the electrical resistivity tomography survey of the CCPB/OB contact zone near Ciche village. ERT profile. Geological interpretation of ERT profiling. For ERT profile location see Text-fig. 5

extended to the west of the river channel (Watycha 1976a). The NNE-SSW-oriented straight stretch of the Czarny stream, running along the boundary of the higher terraces of Czarny Dunajec, is parallel to this stretch of the river channel (Text-fig. 11C; Watycha 1976a). Structural observations indicate that the strikes of Neogene strata in this region are transversal or oblique to the orientation of both streams. Deflection of beds to the NE-SW was observed only locally (Text-fig. 3). The orientations of both streams are not in accordance with the general strike in the PKB and CCPB being the OB basement (Text-fig. 3; compare also Watycha 1976a). Thus, the orientation of stream channels and their terraces does not depend on the lithology (by the use of less resistant lithological complexes for channel development).

Forms oblique to the general orientation of the eastern OB marginal zone are distinct among linear morphological forms. They are visible for example between Chochołów and Koniówka, where sharply marked eastern terrace boundaries run along a straight line with an azimuth of c. 5º (Text-fig. 11B, C). A straight stretch of the Czarny Dunajec channel with an azimuth of c. 175º is also visible between the mouth of Siców stream and Koniówka (Text-fig. 11B, C).

Distinct valley forms, oblique/transversal to the PSS orientation, occur in the CCPB (Text-fig. 11B, D). Long and straight, NNW-SSE-oriented valleys are clearly visible to the east of Czarny Dunajec (Text-fig. 11B). Forms with NNE-SSW (NE-SW) orientations are much rarer and shorter. Common are straight, ENE-WSW-orientated valley stretches; these stretches are much shorter from those with NNW-SSE orientations (Text-fig. 11B).

Between Trstena and Čimhova (Slovakia) straight, NNW-SSE-oriented valleys and slightly shorter, NNE-SSW-oriented valleys are dominant (Text-fig. 11D). Linear morphostructural elements composed of a series of ridges or of morphologically and hypsometrically similar elevations forming sequences several to over 10 km long may also be observed. In the segment between Trstena and Čimhova these forms are ENE-WSW-trending (Text-fig. 11D). Between Vitanova and Oravice, ridge lines change their orientation to NE-SW (Text-fig. 11D). Such a case is visible in the Cierny Potok area, where the NE-SW-orientation of the valley and the surrounding ridges is almost parallel to a consequently stable bedding orientation (c. 318/20). Such deviation of bedding orientation from the regional trend coupled with the lack of fault-related deformation along the Cierny Potok channel indicates the possibility of counter-clockwise rotation of the entire block surrounding the Cierny Potok valley, caused by sinistral displacement along faults bounding this block and belonging to the KFZ (Text-fig. 11D).

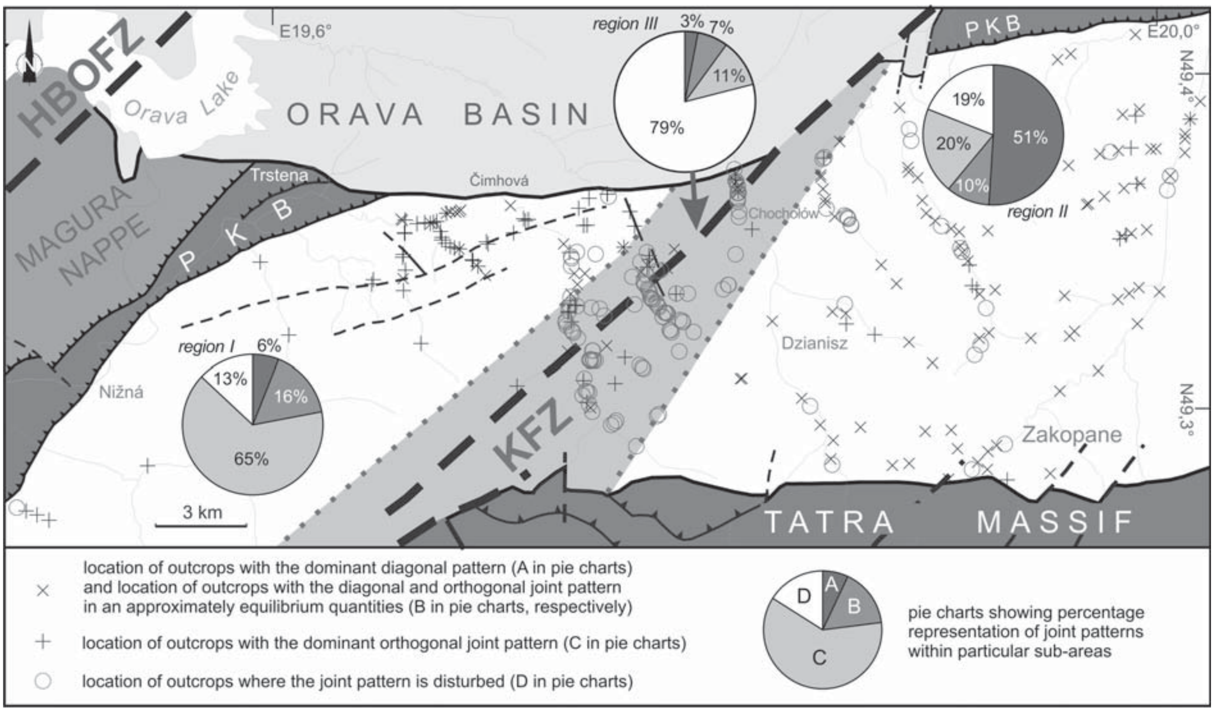
These observations indicate that the location, orientation and straight course of linear morphological objects (excluding series of ridges, which are not always straight) may be the consequence of the presence of faults in pre-Quaternary strata. Linear forms in the eastern OB margin may be linked with faults belonging to the KFZ. Taking into account that the KFZ is characterized by a clear component of sinistral displacement, according to e.g., Naylor *et al.* (1986) and Schreurs (1994, 2003), some of these faults may be interpreted as being parallel to the main strike-slip zone (Y faults), and some as series of oblique faults (synthetic Riedel shears – R; low-angle synthetic faults – $R_L$, low-angle antithetic faults – $R_L$' and low-angle synthetic faults – P) (Text-fig. 11B, C). In turn, the pattern and geometry of the alluvial terraces of Czarny Dunajec (sharply delimited eastern margins, a more extended terrace system in the western part of the channel, the western channel area much lower in relation to the eastern area) are premises that point to the activity of a normal dip-slip component of fault displacement with downfaulted blocks on the western side along the analyzed stretch of the KFZ (see also Pomianowski 1995 and Baumgart-Kotarba *et al.* 2001).

## DISCUSSION

### Structural features of the CCPB vs. structural features of the Orava Basin

The beginning of OB formation took place when essential structural elements of the tectonic units forming its basement were already established (see e.g., Golonka *et al.* 2005). In the discussion on the deformation of CCPB deposits in the context of OB opening and development, it is crucial to determine which deposits may be linked with this process and which are older and genetically linked with earlier stages of PSS development. To achieve this goal, it was important to compare structures occurring in the CCPB in the part adjoining the OB with typical structures from other parts of the synclinorium and structures developed in the Neogene OB infill.

The CCPB in Podhale and south-eastern Orava is a wide-radius, asymmetrical syncline with parallel structural zones (Mastella and Mizerski 1977; Ozimkowski 1991; Ludwiniak 2010). The character of structures slightly differs among particular zones (Text-fig. 16). In the synclinorium limbs, beds have stable strikes, subparallel to its orientation in a given




Text-fig. 15. Sketch-map of spatial distribution of the joint pattern types in the study area and adjacent areas

segment. In the southern limb they generally dip at 10–25º/N (c. 40º/N close to the contact with the Tatra Massif), whereas in the northern limb they dip at several tens of degrees to the south (to steepen to vertical positions at the contact with the PKB). In the axial part of the synclinorium, bedding dips are usually small (from 0º to several degrees), whereas the strikes are extremely variable. Numerous gentle and open, horizontal to gently plunging and upright to steeply inclined mesofolds with almost parallel axes occur in this zone (Ludwiniak 2006, 2010; Głowacka 2010). Some of the folds are linked with faults, usually dip-slip faults, and can be treated as drag folds.

To the west of the KFZ, in south-eastern Orava, the PSS orientation changes from latitudinal to ENE-WSW, or even NE-SW between Tvrdošin and Huty (Text-fig. 2). The PSS zonal structure is not very clear here. Strata in the southern limb dip monotonously to the north-west at angles from over 10º to 45º, and their strikes are usually within 50–70º. Bedding strikes in the northern limb are usually subparallel to the extrapolated PKB/CCPB contact (covered here by Neogene sediments) and are at c. 60–80º (c. 45–55º near Tvrdošin), whereas dips are at 30–60º/S, reaching 80º/S near the OB contact. Contrary to the situation at Podhale and Spiš, this part of the PSS is characterized by a wider axial zone. This segment of the axial zone differs also from the Podhale-Spiš segment in having fewer mesofolds, which are mostly gentle, horizontal, rarely gently plunging upright folds with NE-SW to ENE-WSW-oriented axes. They are characterized by slightly larger values of the interlimb angle compared to those from Podhale and Spiš (Głowacka 2010; Ludwiniak 2010), and their abundance gradually increases to the south. Slightly less numerous folds with NNW-SSE to NNE-SSW-oriented axes are related with faults having a similar orientation and being mainly dip-slip faults, and are drag folds.

The PKB/CCPB contact zone is characterized by much stronger tectonic deformation compared to the remaining part of the CCPB. This is visible directly in the contact zone and in an adjacent, parallel belt, which occurs to the south and is several hundred metres wide (in some cases even up to 1.5 km; see also Mastella 1975; Plašienka *et al.* 2013; Ludwiniak 2018). The contact itself is tectonic in nature and is a narrow (several to over 10 m wide), strongly deformed zone of strongly cataclased rocks, developed through transpression (see Ludwiniak 2018). The contact line has a variable orientation: from c. 90–110º in eastern Podhale and Polish Spiš, c. 90º between Szaflary and Trybsz, c. 75º near Stare Bystre, to c. 45º between Tvrdošin and Dlhá nad Oravou. The Palaeogene strata in this zone are very steep, often vertical, and sometimes attain a reversed position, whereas their strikes are rather stable and usually parallel to the contact line. Some of the folds are subparallel to the contact line. Large forms can be distinguished in this group, e.g., the fold near Ciche ("Pasieka fold" – Gołąb 1954) and fold deformations in the peri-Pieniny monocline in eastern Podhale and Spiš (Mastella 1975; Ludwiniak 2018). S-verging overturned and recumbent folds and N-dipping reverse faults point to rather large tectonic shortening of Palaeogene rocks caused by transpression along the contact zone with the PKB (Ludwiniak 2018).

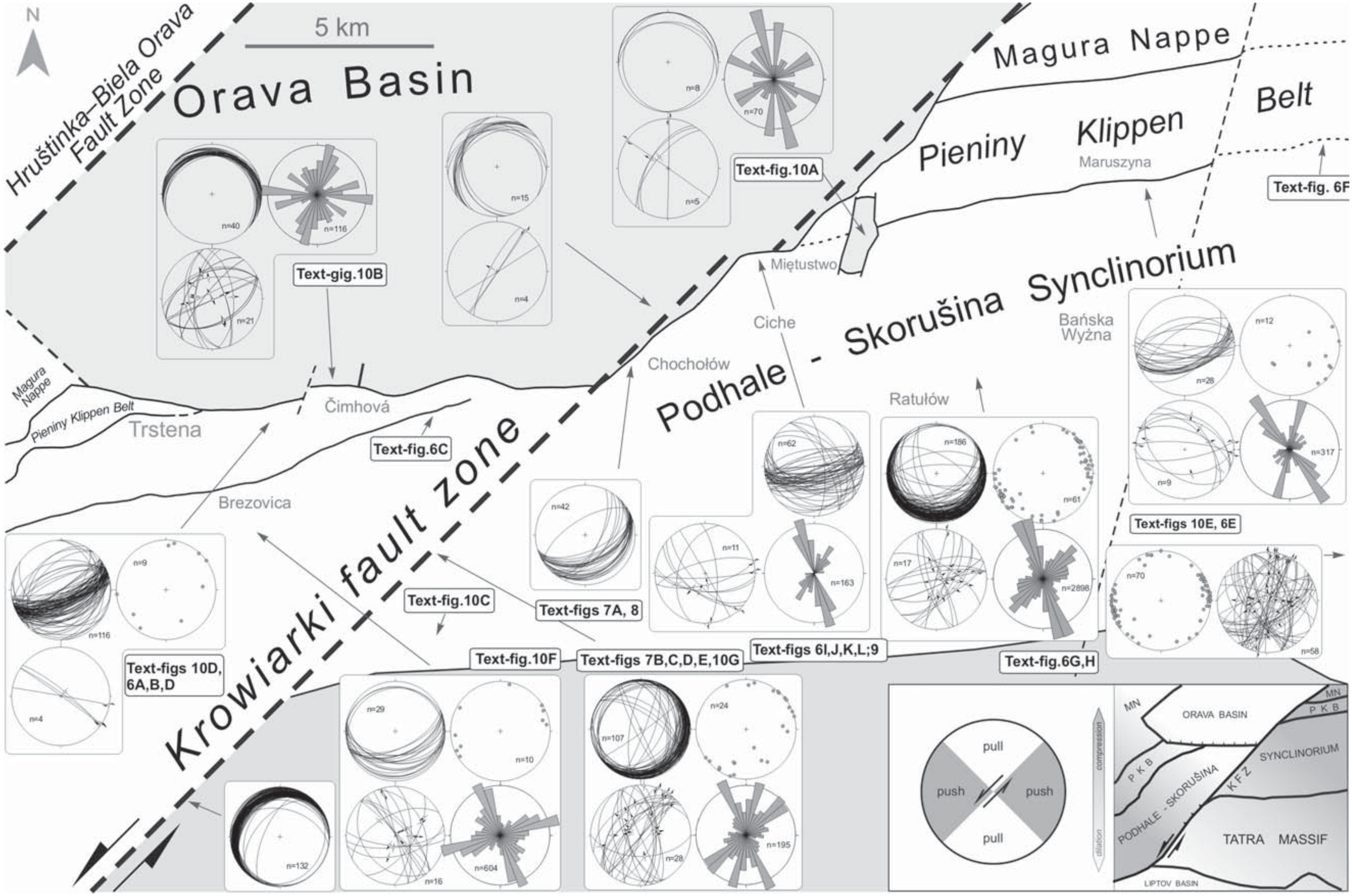
Among the numerous faults that are subparallel to the contact, dextral faults dominate, although prevailing sinistral faults occur between Maruszyna and Leśnica (Text-fig. 16). Numerous drag-folds are related to them; they are steeply plunging to vertical or reclined, close to isoclinal mesofolds with axial surfaces oriented parallel or oblique to these faults and to the general orientation of the zone. Parallel dip-slip reverse and normal faults with downfaulted southern blocks occur also in the contact zone. Although having a similar orientation, these faults represent two different generations. The reverse faults are older and linked with the transpression stage of contact development, whereas the normal faults are related to a later stage of CCPB uplift. Beside reverse faults, strike-slip reverse faults were also noted. They are mostly oblique strike-slip dominated, rarely oblique dip-slip dominated faults (*sensu* Angelier 1994). This points to a significant role of transpression in the formation of the PKB/CCPB contact zone (see e.g., Krantz 1995; Dewey *et al.* 1998). Numerous faults oblique to the contact have NNE-SSW to NE-SW and NW-SE to NNW-SSE orientations. Some of them are genetically related with the main dislocation (PKB/CCPB contact) and are secondary feather-faults. Indicators of dextral movement were observed in both fault populations (Mastella *et al.* 1988). Thus, the NNE-SSW (NE-SW)-oriented faults may be interpreted as R'-shears, whereas the NW-SE (NNW-SSE)-oriented faults may be considered as X-shears (*sensu* Logan and Rauenzahn 1987). Evidence of normal dip-slip displacement was also seen in many faults belonging to both populations.

The zonal structure is deformed close to large fault zones (e.g., Biały Dunajec, Białka and Krowiarki; for more details about the latter zone see Results and Interpretation) and slightly smaller transversal fault zones (e.g., Jelešňa and Skrzypne fault zones) (e.g., Mastella *et al.* 1988, 1996, 2012; Bac-Moszaszwili 1993; Ludwiniak and Rybak-Ostrowska 2010). Some of the faults within these zones, especially map-scale faults, are parallel to the orientation of these zones, whereas some are deflected from the general trend – these faults feather the main dislocations (predominantly R and R' faults; Mastella *et al.* 2012). A characteristic feature of these zones is the deflection of bedding position from the regional trend – the strikes become subparallel to the general orientation of the zone and the dips are locally steeper. The Biały Dunajec and Białka zones are scissor faults (Mastella *et al.* 1996, 2012) with a prevalent dip-slip component and a minor strike-slip component. Contrary to these two zones, a major sinistral strike-slip component was observed beside the major dip-slip component along the KFZ.

Deformations in CCPB rocks along the eastern OB margin differ from those along the southern OB margin, and those from the northern limb of PSS in Podhale (see chapter *Results and Interpretation*; Table 2; Text-fig. 16). Bedding strikes in the Palaeogene along the eastern OB margin are counter-clockwise deflected by over 10º to over 20º, in some cases being NE-SW-oriented. Such bedding deflection is the effect of fault-related dragging along the sinistral strike-slip KFZ bounding the OB. Mesofolds occurring in this part of the CCPB are mostly horizontal folds with axis directions at 60–90º and less numerous moderately to steeply plunging folds with axis directions at 150–200º. The first may be interpreted as the effect of tectonic shortening in NNW-SSE (to N-S) direction and related with one of the earlier stages of PSS development. The second group of folds is younger and genetically linked with strike-slip displacement along the KFZ.

Comparison of structural features of the Palaeogene and Neogene strata in the southern and eastern OB margins advocates a hypothesis that most deformations in the CCPB had developed before OB formation. This concept is supported by the following evidence:

- consequent divergence of strikes within Palaeogene and Neogene strata along the southern OB margin;
- folds indicating tectonic shortening towards the N-S (NNW-SSE) within Palaeogene strata, particularly to the east of the KFZ; Neogene OB strata lacking analogous fold structures;
- reverse faults with c. WSW-ENE orientation in Palaeogene strata along the OB contact, pointing to a trend for NNW-SSE tectonic shortening, and lack of such faults in Neogene deposits;
- deformations linked with strike-slip displacement in Palaeogene rocks and lack of analogous structures in Neogene rocks along the southern OB margin. It seems that the hypothetical strike-slip




Text-fig. 16. Distribution of tectonic structures in the south-eastern margin of the OB and adjacent areas, with the orientation of bedding (great circle diagrams), mesoscopic fold axes (lineation diagrams), mesoscopic faults (Angelier diagrams), and fractures (rose diagrams) character of the latitudinal dislocation being the southern OB margin would result in the presence of similar deformations on both its sides. Large difference in rock ductility between Palaeogene and Neogene strata (more consolidated sandstones, claystones and shales in the CCPB *vs.* weakly consolidated fine clastic deposits in the OB) would have resulted in stronger ductile deformations related to fault dragging in OB rocks, recorded as bed bending and drag folds. On the contrary, evidence of ductile deformations pointing to strike-slip displacement along the southern OB margin were noted only in CCPB deposits. Thus, the latter deformations must be linked with strike-slip displacement along the PKB/CCPB contact, covered by Neogene sediments and probably located in the immediate vicinity of the southern OB margin. Therefore, they were older deformations, not related with OB formation.

***Joint network in the CCPB vs. joint network in the Orava Basin***

A characteristic feature in the PSS is the very well-developed systematic joint network (Boretti-Onyszkiewicz 1968; Ludwiniak 2008, 2010). It comprises five sets (2 to 4 sets in individual outcrops). Two coeval joint sets forming a conjugate diagonal system are the oldest joints within the whole network. They developed in the form of mechanical anisotropy in the early stage of the tectonic evolution of the synclinorium when the strata were horizontal. Younger with respect to the diagonal system is the part of the longitudinal and sublongitudinal joints that are genetically fold-related. The youngest joints are the transversal set and part of the longitudinal/sublongitudinal joints that are related to diminishing horizontal compression and PSS uplift.

The joint network pattern differs slightly in individual segments of the synclinorium (Text-figs 15, 16; see also Ludwiniak 2010). Significant differences are particularly visible between areas lying on both sides of the KFZ. A distinct prevalence of the diagonal system is observed in Podhale, on the eastern side of the KFZ (Text-fig. 15). In turn, on the western side of the KFZ in south-eastern Orava, orthogonal systems prevail in the joint network (Text-fig. 15).

The joint network in the KFZ is disturbed in comparison to the network in the areas it separates (Text-fig. 15). The disturbances are both primary and secondary. Primary disturbances are revealed already during fracture initiation and are the effect of the activity of a diverse stress field, usually in fault zones. They are recorded as for instance different cross-cutting relationships of joint sets observed in individual exposures compared to the regional network architecture. Secondary deformations are usually the effect of changes in bedding orientation due to their tilting, folding and fault dragging, along with the fractures developed in them. As a result, rotation of the entire joint system took place, however without changes of the cross-cutting relationships within the rotated block. Another manifestation of secondary deformation is the increase of fracture density in fault zones, being the result of the intensified opening of fractures preexisting in the form of strength anisotropy (compare Mastella 1972; Ludwiniak 2008). Deformations of the joint network in the KFZ are of primary origin. This is demonstrated for example by different cross-cutting relationships in comparison to the surrounding areas and the very low contribution of longitudinal joint set fractures. Other evidence includes local diagonal systems with values of the double shear angle lower in comparison to the neighbouring areas. The orientation of the dihedral of the double shear angle (i.e., the $\sigma_1$ axis) is almost parallel to KFZ orientation (NE-SW), which is most probably caused by a different stress field acting within this zone.

The $\sigma_1$ axis direction shows a clockwise deflection from the regional trend, which means that this is not the effect of secondary bedding reorientation. In the case of hypothetical, later bedding rotation resulting from sinistral movement along the KFZ, the direction of the $\sigma_1$ axis would rather be counter-clockwise deflected. In turn, secondary deformations of the joint network within the KFZ are reflected in the increased density of fractures subparallel to this zone (Text-fig. 16).

The geometry of the joint network in Palaeogene PSS strata indicates that the area to the west of the KFZ was initially subjected to weak compression and later – to extension/transtension during OB opening. The area to the east of the zone, continuing to the east into the Spiš area, was subject to much stronger, latitudinal compression (Głowacka 2010; Ludwiniak 2010).

The joint network in Neogene OB strata is less regular and characterized by variable consistency than the joint network in the CCPB. Most fractures are joints with low/medium consistency, indicating a relatively stable stress field of joint network formation. Disturbances of their consistency could be caused by the following factors: (1) low total values of normal stress resulting from the small overburden of Neogene and Quaternary rocks[2]. At low total values of normal stress, small changes of the stress field may strongly influence the orientation of these fractures; (2) variability of the stress field caused by the neighbourhood of faults in the OB margin; and (3) lithological differences. Despite a small number of data in the analyzed exposures, it was possible to observe the relation between the lithology of individual beds and the degree of geometric orderliness in the joint network. The most orderly joint network occurs within coal layers (Text-fig. 10A, B), a medium order was observed within sandy siltstones, whereas the least orderly network occurs within massive siltstones, clayey siltstones and claystones. This means that the joint network is more regular in beds that are more brittle.

The joint network in Neogene strata of the main part of the OB located to the west of the KFZ is strongly dominated by the orthogonal system. This indicates its formation in a stress field with low values of normal stress and small differences between $\sigma_1$ and $\sigma_3$. The activity of extension/transtension in the OB position was a factor essential for its opening. Taking into consideration the sinistral character of the KFZ, the main part of the OB would be located in its extensional sector during opening. In turn, "weak N- to NE-oriented compression" in Neogene strata of this part of the OB was deduced from AMS study by Łoziński *et al.* (2016, 2017). According to these authors, it was most probably linked with the basin inversion stage (Łoziński *et al.* 2017) and is evidenced by "tectonic AMS fabric" pointing to the activity of such compression mainly in the southern, most uplifted part of the OB. The present-day lithofacies distribution of Neogene strata in the basin indicates that the primary southern OB margin was located more to the south in relation to the present-day margin, whereas deposits of the southernmost part of the OB, subject to the greatest uplift, are not preserved (Łoziński *et al.* 2017). More intense uplift of the southernmost part of the basin combined with a relatively weaker uplift or its lack in the central part would probably result in the development of almost N-S-oriented, low or moderate horizontal compression in the zone transitional between these areas. This would explain the presence of the "tectonic AMS fabric" close to the present-day, southern OB margin. It cannot be excluded that the locally occurring diagonal system of hybrid joints, younger that longitudinal and sublongitudinal joints, is the effect of such late compression (orientation of the $\sigma_1$ axis in this system is close to the orientation of the "weak compression" obtained from the AMS study). Equally possible is the development of local, c. N-S-directed compression during OB opening. Such local, weak, N-S-oriented compression could be linked with extremely ductile deposits due to their squeezing into the downwards narrowing zone between active longitudinal listric normal faults, which form the present-day southern OB margin. The resulting local compression would naturally be quite weak, although directional anisotropy in such poorly consolidated and ductile material may be recorded at very subtle compression (Łoziński *et al.* 2016).

Relating these observations to the Miętustwo village area, it can be concluded that the more common occurrence of the diagonal system in the Neogene strata of this region may indicate development of the joint network in higher normal stress conditions with higher values of the stress deviator. Increased values of normal stress were caused by sublatitudinal compression. Taking into consideration the sinistral character of the KFZ, Neogene strata occurring in a separate, peripheral eastern part of the OB, on the eastern side of the KFZ, would be located in its compressional sector during the joint network formation (Text-fig. 16).

## Model of Orava Basin development

### *Previous models of Orava Basin development*

The model of OB evolution as a pull-part basin (Pospišil 1990, 1993) developed in a step-over between two dextral strike-slip faults does not find confirmation in field observations, DEM analyses and on published geological maps. The eastern basin boundary is a fault zone with a significant sinistral component (KFZ), passing to the south-west into CCPB deposits. This fact is evidenced by sinistral mesofaults along the OB margin and the direction of strike deflection of CCPB strata on both sides of the KFZ. Moreover, bending of outcrops of PKB deposits at the contact with the OB clearly indicates dragging along a sinistral strike-slip fault (Text-fig. 2; Watycha 1976a). As evidenced above, the western OB margin is also a fault zone with a distinct sinistral component (Hruštinka-Biela Orava Fault Zone; HBOFZ). If the

[2] The analyzed exposures are located more or less in the lower part of the Neogene succession. The presently preserved overburden, based on the Czarny Dunajec IG-1 borehole (Watycha 1977), is about 900–950 m, which would have generated vertical stress in the range of about 22–24 MPa. The thickness of the overburden before uplift and exhumation could have been larger.

OB would have been a pull-apart basin developed between NE-SW-trending sinistral fault zones, then the shorter faults, bounding the overlapping overstep (i.e., the place where the basin is located), would have a different orientation (c. NNW-SSE) and the basin itself would be elongated along the NNE-SSW axis, and not latitudinally as in the case of the OB (Text-fig. 2; compare e.g., Mann *et al.* 1983; Sylvester 1988 and references therein; Fyhn *et al.* 2010; Oliva-Urcia *et al.* 2011). The untypical OB geometry probably depends on its basement structure. The present-day orientation of parallel normal faults bounding the OB is similar to the elongation of the PKB, and the course of the CCPB/PKB and MN/PKB contacts in the segment where the basin is situated. The generally latitudinal orientation of thrusts within the MN in the vicinity of the northern OB margin (see Watycha 1975, 1976a; Polák *et al.* 2008) suggests a similar orientation of analogous structures in the OB basement. The thrust zones could be, at least partially, utilized by younger faults bounding the OB. This applies also to faults forming the PKB/CCPB contact zone[3].

The model of OB development proposed by Pomianowski (1995, 2003) assumes that it was initiated in the Badenian along an ENE-WSW (E-W)-trending curvilinear sinistral fault in the sector of transtentional activity as a releasing bend structure. According to this concept, the OB was bounded from the south and east by an arched sinistral strike-slip fault. This, however, is not confirmed by field observations, which indicate rather that the sinistral fault zone bounding the OB from the east consequently continues to the south-west and has a stable orientation (NE-SW) (Text-figs 16, 17E). There is also no evidence for sinistral faulting along the southern OB margin, both in Neogene and Palaeogene CCPB strata. Other deformations characteristic of strike-slip displacement, which would have likely developed because of its activity in the very ductile Neogene strata are also not observed[4]. The compression direction suggested by Pomianowski (1995, 2003) during initiation and early stages of OB development (NNW-SSE during the Badenian, N-S after the Badenian) does not significantly deviate from the direction of contemporary compression in the area (e.g., Fodor 1995; Nemčok *et al.* 1998; Peškova *et al.* 2009). However, according to the existing models (see e.g., Sylvester 1988; Perrit and Watkeys 2003; Tibaldi *et al.* 2010), such orientation of the sinistral fault zone along with the developed releasing and restraining bends would have most probably been initiated in compression (therefore $\sigma_1$ axis) conditions with a different direction, i.e., c. NE-SW (considered for the present-day position of the basin). These assumptions, combined with the structural observations presented above, impose the conclusion that the concept of OB development as a releasing bend likewise does not find confirmation.

According to Bac-Moszaszwili (1993), OB formation was related to the sinistral movement along the Krowiarki Fault. She concluded that in the late Pliocene, the sense of displacement along this fault underwent a change to dextral. Evidence for sense change would be "post-Palaeogene backward thrusting" on the western periphery of the already uplifted Tatra Massif, caused by transpression related to dextral movement along the KFZ. We do not negate the occurrence of such "post-Palaeogene backward thrusting". We only allow the possibility that general sinistral displacement along the KFZ, which is non-planar in character, could cause local tectonic shortening, especially in places where the fault direction was deflected (e.g., near the Osobitá Mt. and Hunova Valley – see Bac-Moszaszwili 1993), and a restraining bend could be formed (see e.g., Woodcock

[3] The possibility of the formation of an intramontane basin in this area due to crust weakening (close vicinity of the Pericarpathian and Peripieniny lineaments and their parallel orientation in the area) was already indicated by Sikora (1976).

[4] The only exception is the intra-basinal, c. 60º-trending, probably strike-slip "Červeny zone", recognized by Łoziński *et al.* (2017) in the south-eastern part of the OB. According to these authors, the zone evolved due to reactivation of faults related to the PKB in the OB basement after Neogene sedimentation. It is also probable that the Červeny Fault Zone is linked with KFZ activity and is a secondary, feather R-fault, which uses only a PKB-related discontinuity. In this case, the sinistral character of the "Červeny zone" suggested by Łoziński *et al.* (2017) would be consistent with the sinistral character of the whole KFZ. In turn, the argument that the activity of N-S compression (or even NNW-SSE compression as indicated by their fig. 10, p. 493) initiated sinistral strike-slip movement along the 60º-trending discontinuity (Łoziński *et al.* 2017, p. 493) is less convincing. Moreover, strike-slip mesofaults determined in Palaeogene strata are, in general, dextral in character and show analogies with faults from the PKB/CCPB contact zone in Podhale and Spiš. They are most probably linked with strike-slip displacements along the PKB/CCPB contact zone, covered here by Neogene sediments. These considerations would point to local reactivation of existing PKB structures due to the late Miocene/post Miocene KFZ activity, rather than widespread tectonic activity of the PKB at that time.

and Schubert 1994; Mastella and Konon 2002b). Our field studies recognized indicators of sinistral displacement along the eastern OB margin and the KFZ, whereas indicators of dextral displacement were not observed. Our results point either directly or indirectly to a persisting sense of displacement along the KFZ from the early Miocene to the present-day. OB opening as a result of sinistral movement along the KFZ is evidenced by the concept of the Tatra Massif uplift and exhumation presented by Śmigielski *et al.* (2016), in which before 21 Ma the Tatra Massif underwent rotation along a W-E-oriented horizontal axis during transportation over a back-thrust ramp developed in the overlap between two major sinistral faults (in this case the western fault corresponds to the KFZ and the eastern – to the Ružbachy Fault; see also Sperner *et al*. 2002 and Beidinger and Decker 2016). Sinistral movement along the Mur-Mürz-Žilina fault system (with KFZ located in its northern segment) from the middle Pleistocene to the present is evidenced by subsidence analysis in the southern part of the Vienna Basin (Decker *et al.* 2005). Precise GPS measurements performed in the OB and its vicinity indicate that the sinistral character of the KFZ is maintained also presently (Łój *et al.* 2009, their fig. 17, p. 237).

***Fault zones bounding the Orava Basin***

Analyses of structural data, DEM and geological maps (Roth 1962; Książkiewicz 1968a; Burtan 1974; Watycha 1975, 1976a; Burtan *et al.* 1976; Paul 1978; Gross *et al.* 1979; Paul and Ryłko 1986; Żytko *et al.* 1989; Bujnovský *et al.* 1997; Lexa *et al.* 2000) indicate that the fault zones forming the western and eastern OB boundaries are parts of large, similarly oriented tectonic zones (NE-SW; Text-fig. 17E). The orientation of the western zone (HBOFZ) can be traced on the DEM image between Zazriva and Mszana Dolna for a distance of about 75 km (Text-fig. 17E)[5]. In turn, the eastern zone, which comprises the Krowiarki Fault bounding the OB, may be traced for a distance of about 120 km, between Ružomberok and Limanowa[6].

The deformations forming these fault zones observed on the surface occur in a relatively wide belt from several to over 10 km. This may result from the fact that large strike-slip faults usually form a flower structure in the subsurface zone. In the case of both zones, subdivision of the main surface of the strike-slip fault into a series of smaller dislocations,

[5] It may not be excluded that the HBOFZ may continue further to the north-east towards Tymbark, as evidenced by deflection of the MN frontal thrust towards the north-east on a distance of about 17 km (Text-fig. 17E; see also Żytko *et al.* 1989). Elongation of the western OB margin shows strong bending of the PKB to the south as a sigmoid with a shape pointing to the activity of sinistral displacement. The central limb of the sigmoid, between Tvrdošin and Dlhá nad Oravou, is NE-SW-oriented and c. 12 km long (Text-fig. 17E). Identical orientations were noted in the case of dislocations bounding the PKB along this fragment, of which the western, separating the PKB from the MN, is the elongation of the western OB margin (Text-fig. 17E). Indicators of sinistral movement were noted along both zones (Pešková *et al*. 2009). The existence of a strike-slip component along the northern extension of the western OB margin is evidenced e.g., by changes in the course of exposures of thin-bedded flysch rocks of the Kowaniec, Piwniczna and Beloveža beds, bending of strikes from ENE-WSW to NE-SW between Machałowa and Raba Wyżna (Jabłonka, Rabka and Zawoja sheets – Detailed Geological Map of Poland; Książkiewicz 1968a; Watycha 1975; Paul and Ryłko 1986), bending of strikes and outcrops of the Beloveža and Łącko beds between Lipnica Wielka-Lipnica Mała-Sidzina (Zawoja sheet – Detailed Geological Map of Poland; Książkiewicz 1968a; see also Aleksandrowski 1989 – his plate XVIII) to Jordanów (Rabka sheet – Detailed Geological Map of Poland; Paul and Ryłko 1986; NNE-SSW to NE-SW strikes), and further to the north-east towards Kasinka Mała (Mszana Dolna sheet – Detailed Geological Map of Poland; Burtan 1974; bending of outcrops of variegated shales and bending of strikes from W-E to NE-SW).

[6] This zone would roughly correspond to the Ružomberok-Mszana Dolna zone determined by Żytko (1999). Its southern part is formed by a series of faults with a significant normal component separating the Liptov Basin (CCPB) from Mesozoic series of the Choč Mts (Gross *et al.* 1979). Sinistral displacement evidenced in the vicinity of the OB is confirmed on maps in other parts of the zone. A sharp, sigmoidal bend of outcrops of the Lgota shales and variegated shales occurs near Półrzeczki village (Mszana Górna sheet – Detailed Geological Map of Poland; Burtan *et al.* 1976), pointing to sinistral displacement, whereas the observed strike separation is about 600–700 m. To the north-east of this site occurs a similar bending of outcrops of the Kanina Beds (Łącko sheet – Detailed Geological Map of Poland; Paul 1978). To the south of this bend, bending of strikes towards the NE-SW was observed, whereas further to the south-west, between Kudłoń Mt. and Turbaczyk Mt., rapid change of thrust orientation of the Inoceramian Beds onto the Magura Beds from W-E to NE-SW, on a distance of about 3.3 km, and analogous bending of outcrops of the Poręba Wielka Beds (Burtan *et al.* 1976) were observed.

dispersion of deformations and upward widening of the zone may also be caused by the fact that they cut a strongly consolidated basement (crystalline basement of the CWC and its Mesozoic sedimentary cover, and the crystalline basement and sedimentary cover of the European Platform) and the overlying cover of rheologically weaker deposits (flysch rocks of the MN and CCPB; see e.g., Bartlett *et al.* 1981; Le Guerroné and Cobbold 2006; Fossen 2010). The zones may undergo alterations in their individual segments. As mentioned above, faults belonging to the KFZ in the part bounding the OB, beside a sinistral component also have a normal dip-slip component with downfaulted western blocks. In the segment where the zone separates CCPB rocks of the Liptov Basin from Mesozoic rocks of the Choč Mts, the faults have both components (normal dip-slip and sinistral strike-slip), with downfaulted eastern blocks (see cross-sections in Gross *et al.* 1979).

Both zones are deeply rooted, reaching to the CCPB and MN basement. In the basement of the western zone (HBOFZ), between Lipnica Wielka and Dobczyce, a NE-SW-trending fault was recognized within Devonian–Carboniferous rocks (Buła and Habryn 2011a and b). Between Rabka and Wilkowisko, a c. 35–50º-oriented discontinuity zone was marked within the pre-Tertiary basement of the MN ("geofracture zone" – Oszczypko *et al.* 1989). In turn, to the west of the KFZ, between Pieniążkowice and Kasina Wielka, Miocene deposits occur in the MN basement, whereas strata of this age were not observed to the east of this zone (Papiernik 2011). Between the two zones, increased values of terrestrial heat flow density (>70 mW) were noted between Chochołów and Rabka (Hajto 2008). The elongated axis of this anomaly is NE-SW-trending and subparallel to HBOFZ and KFZ.

W-E-trending fault zones (northern and southern OB boundaries) form normal faults with a similar trend. They are subordinate with regard to the large sinistral strike-slip zones described above. They play the role of structures compensating strike-slip displacement. Structural observations and ERT surveys performed in the vicinity of the southern OB margin indicate that it has a character of steeply N-dipping, normal step-like faults (Text-fig. 12; see also Pomianowski 2003). Rather monotonous dips of Neogene strata to the north may point to the active character of faults during sedimentation, including gradual downward movement of basement blocks forming a step-like pattern. Monotonous dips of Neogene strata to the north suggest also a steep, nearly planar or listric (but with slight curvature) character of the fault surfaces (in an opposite case of the hypothetically strongly curved, listric N-dipping normal faults, a rollover above them could result in the southward tilting of strata in the southern OB margin – see e.g., Dresen *et al.* 1991; McClay *et al.* 1991). These faults were probably active also later, during a process that was related to CCPB uplift along with the Neogene cover of the presently non-existing part of the basin, located to the south of its present-day margin (Łoziński *et al.* 2017). The uplift of the contemporary southern OB margin resulted also in the northern tilting of Neogene strata occurring in the present-day southern part of the basin.

### *Rotations of the Orava Basin basement blocks*

Horizontal basement block rotations played a significant role in OB development. According to Tokarski *et al.* (2016), Neogene deposits of the basin infill underwent c. 30º counter-clockwise horizontal rotation. This rotation was possible thanks to displacement along minor-order dextral faults in the OB basement, feather the large Mur-Mürz-Žilina dislocation[7], whose north-eastern segment corresponds to the KFZ. Dextral movement along these minor-order faults was thus a compensation of sinistral displacement at the termination of the Mur-Mürz-Žilina dislocation. Our observations are in accordance with the concept presented by Tokarski *et al.* (2016). If the entire OB is bounded by two large NE-SW-trending sinistral fault zones (HBOFZ and KFZ), then its basement blocks, bounded by minor-order dextral faults should undergo the horizontal counter-clockwise rotation which is the effect of a bookshelf mechanism (Mandl 1987). The basement block rotation was accompanied by simultaneous change of primary orientation of these minor-order dextral faults. The faults probably had a primary NNW-SSE (NW-SE) orientation, quite similar to the present-day orientation of oblique faults in the MN and CCPB in the neighbourhood of the basin (Text-fig. 17A; it is also probable that these faults belonged to the same generation). As an effect of the bookshelf mechanism, counter-clockwise rotation of OB basement blocks caused a change of the primary orientation of these faults (Text-fig. 17B, C). Lineaments visible in the present-day OB morphology and most probably corresponding to faults in the Neogene and its

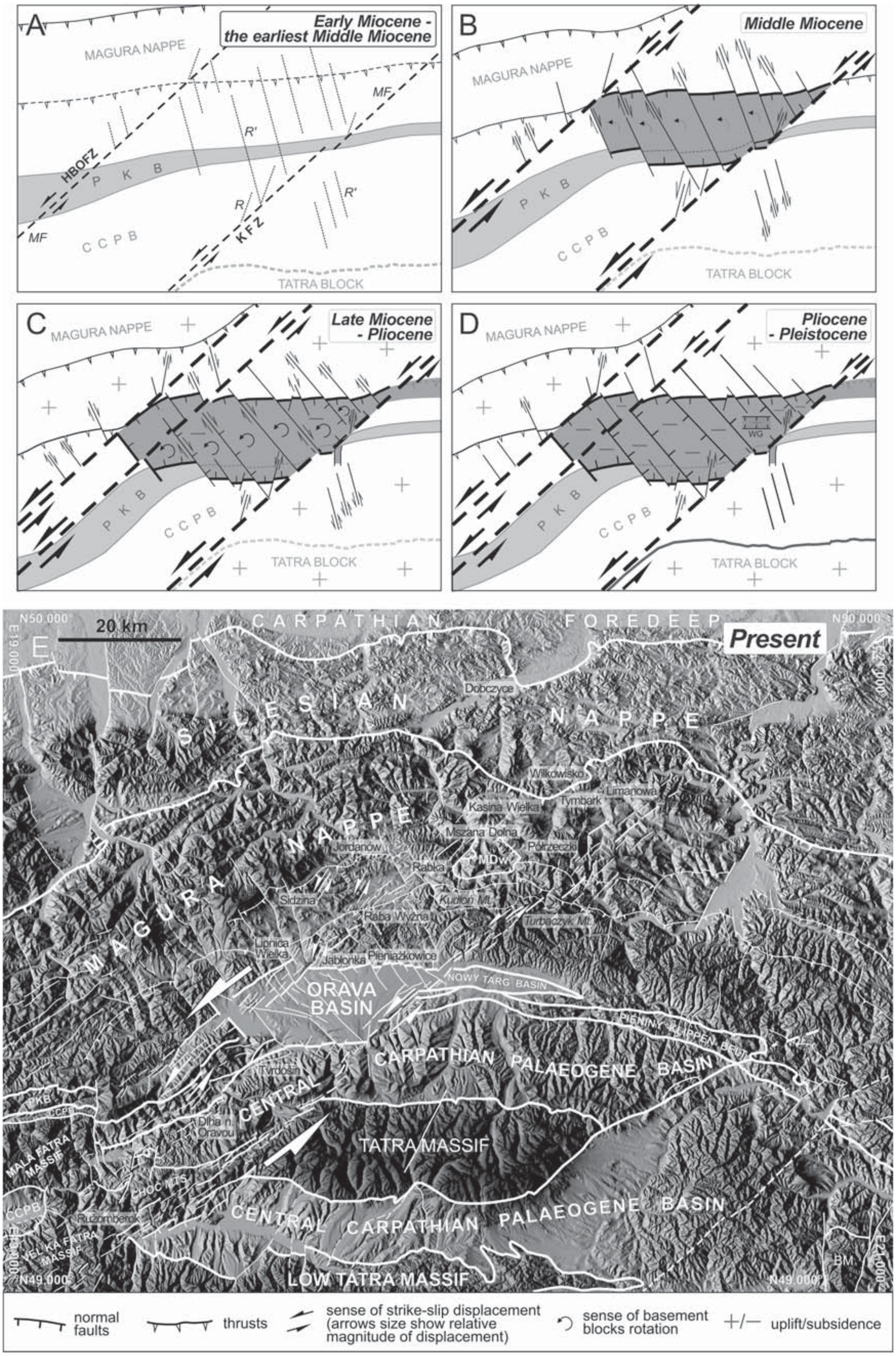
[7] The Myjava fault or Myjava Lineament functioning in the literature (e.g., Jånkú *et al.* 1984; Pospíšil *et al.* 1986) is in accordance with the Mur-Mürz-Žilina fault system, at least in its northern part.

basement, have a general NW-SE (WNW-ESE) orientation, deflected by c. 20–30º counter-clockwise from the NNW-SSE (NW-SE)-trending faults in the older deposits surrounding the basin (Text-fig. 17D, E; the AMS study of Łoziński *et al.* 2017 showed the presence of a strongly deformed Bobrov-Jelešňa zone along one of the lineaments cutting the OB).

Assuming that the surface of the area where OB initiation took place did not undergo significant changes in the further stages of its development and that the distance between the two main sinistral zones bounding the OB (HBOFZ and KFZ) was relatively stable or only slightly increased with time, displacements along the second-order faults bounding the blocks must have been balanced by gapping between the rotating blocks (see model proposed by Luyendyk 1991). This would mean that NW-SE (WNW-ESE)-trending faults bounding the rotating blocks are most probably dextral transtensional faults. A series of NW-SE (WNW-ESE)-elongated gaps between the blocks would become additional accommodation space for sediments and could act as small basins constituting the OB. Such concept of OB development would to some extent harmonize with the composed basin model proposed by Struska (2008) and the concept of the step-like character of the basin bottom (see results of geoelectrical and gravimetric profiling obtained by Pomianowski 2003). Simultaneously with block rotation, the distance between the southern and northern OB margins increased due to displacement along the main strike-slip zones, thus contributing to the increase of OB accommodation space[8].

After the early Miocene, the general shape of the tectonic units composing the OB basement was already established (formation of the final structure of the PKB during the early Miocene transpressional event – Plašienka 2011; early Miocene destruction and inversion of the CCPB – the youngest preserved CCPB deposits are Egerian–Eggenburgian in age – Soták *et al.* 2001; the youngest deposits underlying the OB are the youngest MN strata dated to the Burdigalian (c. 18 Ma) – Kaczmarek and Oszczypko-Clowes 2014; Kaczmarek *et al.* 2016). The OB was initiated after the early Sarmatian (Nagy *et al.* 1996; Wysocka *et al.* 2018; the oldest deposits in the OB infill are dated to the Karpatian–Badenian – Gross *et al.* 1993b). Of key significance for its opening and development was the activity of these large NE-SW-trending fault zones (HBOFZ and KFZ), being part of the strike-slip fault system running from the eastern termination of the Calcareous Alps (Vienna Basin Transform fault system; Mur-Mürz-Žilina fault zone). The sinistral movement along the Mur-Mürz-Žilina fault system started in the late early Miocene (c. 17 Ma; Lankreijer *et al.* 1995; Sachsenhofer *et al.* 2000). It cannot be excluded that the KFZ belonging to the Mur-Mürz-Žilina fault system was active as a sinistral fault zone since the earliest Miocene. Most probably, KFZ activity influenced the development of the joint network in CCPB deposits in western Podhale and south-eastern Orava, as evidenced by differences in joint network patterns on both sides of the KFZ (Text-fig. 15). The joint network in CCPB deposits was largely initiated in the early stage of PSS structural evolution, in horizontal, non-folded, and in some cases also poorly lithified strata (Ludwiniak 2010). As a sinistral fault zone, the KFZ was initiated during regional N-S (NNE-SSW) compression (see Fodor 1995; Nemčok *et al.* 1998). The same $\sigma_1$ orientation was determined for an early joint system in CCPB deposits of western Podhale, within the Zakopane Beds (Ludwiniak 2010) dated to the late Rupelian–middle Chattian (Gedl 2000; Garecka 2005). Such a direction of compression in this area persisted even till the middle/late Miocene, as evidenced by stable, similar $\sigma_1$ orientation for fractures

[8] It should be emphasized that if OB opening and development would be realized solely by strike-slip displacement along the main zones (HBOFZ and KFZ) at a stable distance between them, this would result in a larger offset of older structures in the basin basement in the intersection with these zones. In contrast, strike separation of the KFZ at the intersection with the PKB is c. 1500–2000 m, at a c. 17-km length of the basin measured along the KFZ (which is c. 9–12% of the OB margin). Taking into account the strongly oblique setting of the PKB with regard to the KFZ (c. 25–30º) and the assumed minimal value of the dip-slip component in this part of the KFZ reaching 370–460 m, and assuming a vertical position of the PKB and the KFZ dipping c. 60º to the north-west, it may be concluded that the actual strike-slip component of the KFZ is slightly larger than the observed strike separation (see methodology of fault displacement assessment described by Śmigielski *et al.* 2011; the minimal dip-slip value in the part of the KFZ was assessed based on the depth of the top of Cretaceous strata in the Koniówka IG-1 borehole compared to the position of analogous strata on the surface near Stare Bystre). Taking into account these assumptions, with the only difference that here the PKB would have a southward vergence (compare cross-sections from south-eastern Orava – Gross *et al.* 1993a), it may be concluded that the actual value of strike-slip displacement is smaller compared to the determined strike separation.


A
Early Miocene - the earliest Middle Miocene
MAGURA NAPPE
HBOFZ
P K B
C C P B
KFZ
MF
R'
R
TATRA BLOCK
B
Middle Miocene
MAGURA NAPPE
P K B
C C P B
TATRA BLOCK
C
Late Miocene - Pliocene
MAGURA NAPPE
P K B
C C P B
TATRA BLOCK
D
Pliocene - Pleistocene
MAGURA NAPPE
WG
P K B
C C P B
TATRA BLOCK
E
Present
20 km
N50.000
E19.000
CARPATHIAN FOREDEEP
SILESIAN NAPPE
MAGURA NAPPE
Dobczyce
Wilkowisko
Limanowa
Kasina Wielka
Tymbark
Mszana Dolna
Jordanów
Porzeczki
Rabka
MDw
Sidzina
Kudłoń Mt.
Turbacz Mt.
Raba Wyżna
Lipnica Wielka
Jabłonka
Pieniążkowice
NOWY TARG BASIN
ORAVA BASIN
PIENINY KLIPPEN BELT
CENTRAL CARPATHIAN PALAEOGENE BASIN
Tvrdošín
PKB
CCPB
Dlha n. Oravou
MALA FATRA MASSIF
TATRA MASSIF
CHOČ MTS.
Ružomberok
VEĽKA FATRA MASSIF
LOW TATRA MASSIF
N49.000
BM
normal faults
thrusts
sense of strike-slip displacement (arrows size show relative magnitude of displacement)
sense of basement blocks rotation
+/– uplift/subsidence

of the diagonal system in younger CCPB deposits in western Podhale (Ludwiniak 2010) and in the coal layers near Miętustwo, on the eastern side of the KFZ (Text-fig. 10A; age of the tuffite layer situated several tens of metres above in the succession in relation to the coal layers – 11.87+0.12/-0.24 Ma (Sarmatian/Pannonian) – Wysocka *et al.* 2018).

The palaeostress field in this part of the Western Carpathians underwent a clockwise rotation between the Oligocene and the Quaternary (Csontos *et al.* 1992; Peškova *et al.* 2009; Vojtko *et al.* 2010; Králiková *et al.* 2014), which in turn was related to the counter-clockwise rotation of the ALCAPA microplate (e.g., Márton *et al.* 1999, 2016). The regional compression was NNE-SSW already in the middle Miocene (Fodor 1995), to become NE-SW in the late Miocene (Peškova *et al.* 2009). Proof for this assumption is for example the c. 8º CW deviation of $\sigma_1$ for the younger joint set (T joints) in relation to the $\sigma_1$ orientation for the oldest diagonal system in CCPB rocks (Ludwiniak 2010). T joints formed under diminishing NNE-SSW-horizontal compression during gradual CCPB uplift (which started c. 16–18 myr ago – Środoń *et al.* 2006; c. 14–18 myr ago – Śmigielski *et al.* 2016). Initiation of part of the transversal T joints in OB rocks with contemporary c. NNE-SSW orientation may be linked with this stage; later they attained the presently observed NNW-SSE orientation (Text-fig. 4).

Following the clockwise rotation of the palaeostress field, the study area, primarily being in transpression conditions, gradually passed under the activity of transtention (Nemčok *et al.* 1998; see also Fodor 1995). Gradually weakening and diminishing NNE-SSW compression attained a NE-SW orientation during the late Miocene. Transtension with a NW-SE-directed extension component could favour the counter-clockwise rotation of the OB basement blocks by enabling even slight basin widening in this direction at simultaneous sinistral movement along the KFZ and HBOFZ, according to model of Luyendyk (1991). This event was accompanied by increase of accommodation space in the basin and increase of its dimensions towards the NE-SW, parallel to the main fault zones bounding the basin. According to the observations of Tokarski *et al.* (2016), the last counter-clockwise rotation affected strata that are less than 8 Ma old.

← Text-fig. 17. Stages of Orava Basin development (A-D). (E) Orava Basin in relation to adjacent units of the Western Carpathians. Traces of selected map-scale faults and main thrusts are depicted only. PKB – Pieniny Klippen Belt, CCPB – Central Carpathian Palaeogene Basin, BM – Branisko Massif, MDw – Mszana Dolna tectonic window

During the late Pliocene and Quaternary, the OB underwent partial inversion (Nagy *et al.* 1996; Tokarski *et al.* 2012). The stress field in this part of the Carpathians was reconstructed – it was characterized by E-W extension with the $\sigma_1$ axis in a vertical position (Peškova *et al.* 2009). N-S-trending normal faults, best visible in Neogene strata in the Oravica river channel near Čimhova village (Text-fig. 4; see also Łoziński *et al.* 2015), could be formed in such tectonic regime. It is also possible that NNE-SSW-trending oblique faults occurring there could be reactivated as normal faults. It should be mentioned that Quaternary faults, operating under such E-W (ESE-WNW) extension have been found also in the Tatra Mts (Szczygieł 2015). Further development of the transversal joint set could take place at this stage; joints pre-existing in the form of the strength anisotropy were opened and new fractures with a similar orientation were formed.

In the Pleistocene, the E-W-trending Wróblówka graben (Text-fig. 17D; Baumgart-Kotarba 2001), bounded by normal faults and filled with at least 120 m of glacifluvial and alluvial deposits (Watycha 1973; the oldest sediments of the graben infill are dated to the Günz glacial stage), was formed in the north-eastern part of the OB in extensional conditions. Such a large thickness of Quaternary sediments points to subsidence in this place.

The OB and its surroundings are areas of present-day tectonic activity. Geodetic and gravimetric surveys performed in the area point to the present-day subsidence of the central part of the basin and uplift of the basin margins (Łój *et al.* 2007a, b, 2009). Subsidence of the basin is particularly intense in the vicinity of Wróblówka and Pieniążkowice grabens (Baumgart-Kotarba 2001; Perski 2008; Łój *et al.* 2009), which may indicate activity of latitudinal normal faults bounding them. The activity of fault zones surrounding the OB is confirmed by numerous earthquakes in the area (e.g., Baumgart-Kotarba and Hojny-Kołoś 1998; Tokarski and Zuchiewicz 1998; Guterch 2006). Some of them are interpreted as earthquakes related with KFZ activity (e.g., 1995 earthquake – Baumgart-Kotarba 2001; 2004 earthquake – Wiejacz and Dębski 2009). In the case of the latter event, the hypocentre was estimated at the depth of c. 7 km (see references in Jarosiński 2006). Thus, it was located on the PSS or MN basement. According to Jarosiński (1998), recent activity of strike-slip fault zones bounding the OB may be linked with the accommodation of sinistral movement along the Mur-Mürz-Žilina fault system within the Outer Carpathians[9].

Registered by precise GPS measurements, directions of horizontal displacements in the OB and PSS on both sides of the KFZ point to its present-day activity as a sinistral fault (Łój *et al.* 2009). In turn, focal mechanism data obtained for the 2004 earthquake indicate KFZ activity as a fault with a dominating normal component (see Text-fig. 2). Present-day activity of faults bounding the OB is also evidenced by the presence of calcareous tufas along the eastern (Kukulak 1999) and southern basin margins (see Text-fig. 2). The present-day subsidence of the central part of the OB and the active, oblique-slip character of the KFZ indicate the activity of present-day transtension in the area between the KFZ and the HBOFZ.

## CONCLUSIONS

Based on structural observations, DEM analysis and geological maps supplemented with ERT surveys and archival reports, the existing models of OB development were verified. The investigations allowed us to present a new model of basin development:

- OB is a complex strike-slip-related basin formed in transtensional conditions, with some features of a transrotational basin (see e.g., Luyendyk and Hornafius 1987; Schreiber and Rotsch 1998). The beginning of its formation was after the early Sarmatian and is related to the middle Miocene and post-Miocene, large-scale sinistral faulting in the Alpine-Carpathian-Pannonian area (e.g., Neubauer 1988; Csontos *et al.* 1992; Horváth 1993; Kováč *et al.* 1993; Nemčok *et al.* 2006; Ratschbacher *et al.* 1991; Marko 2015; the existence of large scale faults is proved by geophysical data – see e.g., Šutora *et al.* 1988; Pospíšil *et al.* 1989).
- Regional NE-SW-trending, sinistral-normal oblique fault zones (KFZ and HBOFZ) played a key role in OB opening and later development. These zones cut the basement of the CCPB and MN and are part of a major Mur-Mürz-Žilina fault system running from the central Eastern Alps and continuing to the north-east within the MN. W-E-trending normal faults constituting the southern and northern OB margins are structures of lower range with regard to the regional fault zones and play the role of compensation structures.
- DEM analysis combined with palaeomagnetic data (Tokarski *et al.* 2016) indicate that sinistral displacements along the NE-SW-trending KFZ and HBOFZ bounding the OB were compensated (at least partly) by counter-clockwise rotations of basement blocks according to the bookshelf mechanism (Mandl 1987). Faults separating individual blocks were primarily formed as R' and T secondary faults, feathering the main sinistral fault zones. Such a manner of compensation of strike-slip movement probably influenced the complex character of the basin (Struska 2008).
- Sinistral movement along the KFZ had a relatively stable and long-term character (as late as the late early Miocene till the present-day). No deformations indicating dextral movement, which would be linked with the late Miocene (late Pannonian to Pliocene), transient E-W-trending compressive episode in the Alpine-Carpathian-Pannonian area (Peresson and Decker 1996, 1997), were observed along the analyzed fragment of the KFZ.
- Contrary to the hypothesis of Bac-Moszaszwili (1993), our observations did not confirm the presence of structures pointing to change of the kinematic character of the KFZ into a dextral fault in

[9] Sinistral movement along the Mur-Mürz-Žilina fault system (Vienna Basin fault system) started not later than in the late Early Miocene (Karpatian; c. 17 Ma; Lankreijer *et al*. 1995; Decker *et al*. 2005). The MMZF system developed during the north-eastward movement of a major Alpine-Carpathian crustal block (so called "Styrian-West Carpathian Wedge"; e.g., Ratschbacher *et al*. 1991; Linzer *et al*. 1997). Quaternary-active faults are reactivated Miocene structures. The Middle Pleistocene to recent kinematics of the MMZF system strongly resembles the Miocene one (see e.g. Pospíšil *et al.* 2013). The average Miocene strike-slip rate along the MMZF system and the Vienna Basin area is estimated at 3.3–5 mm/y (Decker *et al.* 2005), whereas the slip rate during the last 400 ky was calculated at 1.6–2.5 mm/y. This is in accordance with the c. 2 mm/y northeast-directed displacement of the "Styrian-West Carpathian Wedge" with respect to the Bohemian Massif and the European foreland, derived from GPS measurements (Grenerczy *et al.* 2000; Grenerczy 2002). Moreover, earthquake focal mechanisms from the Vienna Basin area point to the recent activity of northeast to north-striking faults and E-W-directed extension (Decker *et al.* 2005 and references therein). It should be mentioned that the earthquake epicentres in the MMZF system and the Vienna Basin area are NE-aligned (e.g., Aric 1981; Reinecker and Lenhardt 1999; Cloetingh et al. 2003) and stretch north-eastward into the Orava region (see Decker *et al.* 2005, their fig. 1). Furthermore, geomorphological data point to large-scale folding being an effect of NE-SW-oriented tectonic shortening along the frontal edge of the "Styrian-West Carpathian Wedge" during Quaternary times (Zuchiewicz 1998b).

the late Pliocene. Due to the same reasons, we also consider the pull-apart concept for the OB basin developed between dextral fault zones (Pospíšil 1990, 1993) as unjustified. The geometry of the OB marginal zones, kinematics of their faults, and orientation of palaeostress axes indicate that the concept of OB development as a releasing band structure developed along the curved WSW-ENE (W-E)-trending large sinistral fault (Pomianowski 2003) is also unwarranted.

- Strong tectonic deformation in rocks along the southern and south-eastern OB margins was observed almost solely in CCPB deposits. These deformations are related to the early Miocene transpression along the PKB/CCPB contact zone and are older with regard to OB opening.
- The different architecture of joint networks in CCPB rocks in western Podhale and south-eastern Orava points to differences of palaeostress fields acting on both sides of the KFZ. Podhale was the area of stronger longitudinal compression in comparison to the south-eastern Orava area. Taking into account that the CCPB joint network was generally initiated at a very early stage of structural development in horizontal, non-deformed rocks (Ludwiniak 2010 and references therein), it may be assumed that the KFZ within the CCPB was active earlier than hitherto accepted, already from the earliest Miocene.
- The abundant and dominating occurrence of orthogonal joint systems, observed on the western side of the KFZ within the Neogene strata of the OB, indicates that they developed in extensional/ transtensional conditions. The horizontal $\sigma_1$ axis determined for the ladder-pattern orthogonal systems had a c. N-S (NNE-SSW) orientation, whereas the horizontal $\sigma_3$ axis – a c. W-E (WNW-ESE) orientation. A large part of transversal normal faults developed also in a stress field with a similar orientation of the $\sigma_3$ axis. Numerous longitudinal (W-E) and sublongitudinal (WSW-ENE) joints are most probably syngenetic with regard to the W-E-trending normal faults forming the southern OB margin. Sublongitudinal joints could be primarily initiated as W-E-oriented; later they were subject to counter-clockwise rotation in the range of over 10º to over 20º along with Neogene rocks during later stages of OB development.
- Abundant diagonal joint systems occur in Neogene rocks on the eastern side of the KFZ. In this case the horizontal $\sigma_1$ axis is almost N-S-oriented or is clockwise deflected by several degrees from this direction. This may indicate the trend for N-S-oriented tectonic shortening on the eastern side of the KFZ at the middle/late Miocene boundary and during the late Miocene. The same orientation of $\sigma_1$ ($S_{Hmax}$) of the present-day stress field in the area was indicated by Jarosiński (1998; see also Cloetingh *et al.* 2003). Close to the KFZ, the $\sigma_1$ axis direction deflects to the NNW-SSE. This may indicate either counter-clockwise rotation of Neogene rocks in the range of over 10º along with the primary joint network, or a deformed stress field within the KFZ.

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