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STRUCTURAL INTERPRETATION OF SEISMIC DATA IN POLISH OUTER CARPATHIANS SOUTHWEST AND SOUTHEAST OF KRAKOW

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Abstract: The deep structure of the Polish Outer Carpathians and its basement, that is southern prolongation of the North European Platform, has been recognized by deep boreholes as well as by deep seismic sounding profiles. The Polish Outer Carpathians are built up from the flysch deposited during Late Jurassic-Neogene times. Their form nappes thrust over the southern part of the North European platform covered by the autochthonous Miocene deposits. Relationship between basement and flysch nappes in the Outer Carpathians is based on interpretation of seismic and magnetotelluric survey. The Precambrian basement beneath the Outer West Carpathians is divided into two basement blocks: the Upper Silesia Block on the west and the Małopolska Block on the east. The Krakow-Smilno Fault system marks the boundary between two different tectonic realms within the North European Plate. In the area southwest of Krakow, the Precambrian basement is covered discordantly by Devonian and Upper Paleozoic formations. The Mesozoic sequences are known only from the eastern part of the investigated area, their thickness significantly increase eastwards. The Miocene deposits lay discordantly on the various Paleozoic, Mesozoic and Paleogene rocks. The series of mainly normal faults reach top of Paleozoic, sometimes Miocene rocks. The biggest strike-slip faults cuts also allochthonous flysch sequences. In the area southeast of Kraków, the oldest rocks are represented by Precambrian phyllites covered by Paleozoic, Triassic Jurassic, Upper Cretaceous and Miocene deposits. The investigated top of Jurassic horizon is cut by series of faults, dividing the Mesozoic basement into separate blocks. The large thrust Łąkta faults are cutting through Paleozoic, Mesozoic, Miocene and allochthonous flysch sequences. The southwestern fault systems developed under mainly extensional regime with strong strike-slip component, while southeastern systems developed under mainly compressional regime.

Keywords: Carpathians, flysch, basement, overthrust, fault, seismic survey.

1. Introduction

The structural style of the Polish Outer Carpathians and its basement was recently refined by seismic survey data from the areas southwest and southeast of Krakow (Figs. 1, 2). This survey was performed by Geofizyka Kraków Ltd. and tied to geophysical and geological borehole and surface data .The Carpathians define an extensive mountain arc, which stretches at a distance of more than 1 300 km, from Vienna area in Austria, to the Iron Gate on the Danube in Romania (Fig. 1). To the west, the Carpathians are linked with the Eastern Alps whereas to the east, they continue into the Balkan mountain chain. Traditionally, the Carpathians are subdivided into their western and eastern parts. The West Carpathians consist of an older, internal orogenic zone known as the Inner or Central Car pathians and the external, younger one, known as the Outer or Flysch Carpathians (Golonka et al., 2005; Ślączka et al., 2006). The interpreted seismic survey was located in generally northernmost part of the Outer Flysch Carpathians).

2. Previous work

The deep structure of the Polish Outer Carpathians and its basement, that is southern prolongation of the North European Platform, has been recognized previously mainly by extrapolation of outcrops and by deep boreholes supplemented by magnetotelluric, gravimetric, magnetic, geomagnetic, and deep seismic sounding profiles. This work on the stratigraphy of Outer Flysch Carpathians was summarized by Ślączka et al. (2006, see also Oszczypko, 2004). The Carpathian Foredeep as well as rela-

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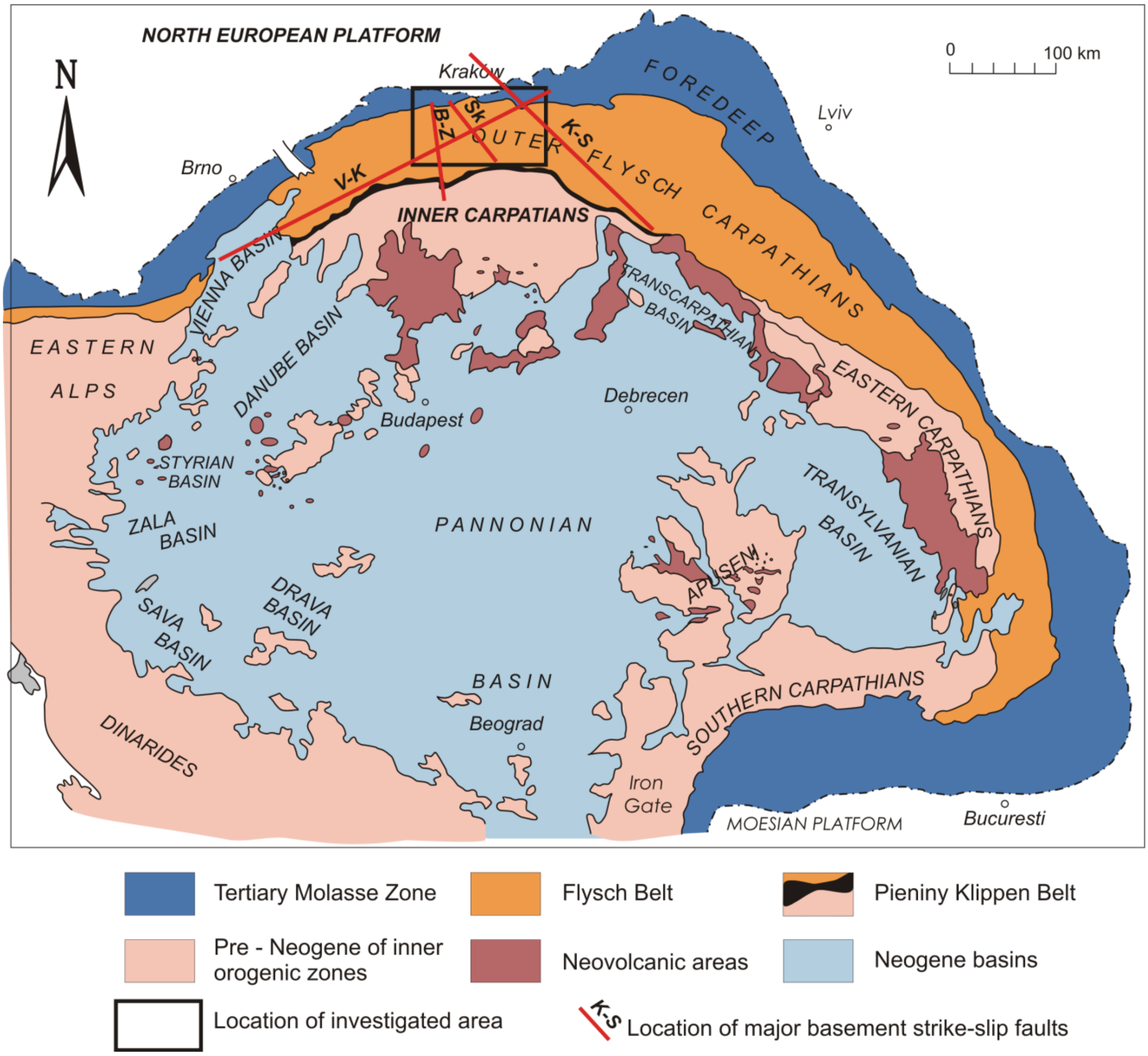

Fig. 1. Tectonic sketch map of the Alpine-Carpathian-Pannonian-Dinaride basin system (after Kováč *et al*., 1998) with location of the investigated area and major strike-slip faults. V-K–Vienna-Krakow fault, B-Z–Bielsko-Biała–Zazriva fault, Sk–Skawa river fault, K-S–Krakow-Smilno fault (extension of Kraków-Lubliniec fault)

tionship between basement, its sedimentary cover and allochthonous flysch nappes was summarized by Oszczypko et al. (2006).

The results of these works depict the North European Platform as a great continental plate amalgamated in the Precambrian and Paleozoic. Its basement consists of Proterozoic, Vendian (Cadomian) and Lower Paleozoic (Caledonian) fragments, deformed and metamorphosed. The platform sedimentary cover includes Paleozoic, Mesozoic and Neogene sequences (Oszczypko and Tomaś, 1985; Moryc et al., 2005; 2006; Oszczypko et al., 2006; Pietsch et al., 2007; Golonka et al., 2009).

The Precambrian basement beneath the Outer West Carpathians is divided into two basement blocks: the Upper Silesia Block on the west and the Małopolska Block on the east, (Żaba, 1999; Żelaźniewicz in Golonka et al., 2005) The Upper Silesia Block belongs to the larger plate known as Brunovistulicm (Dudek, 1980.). The palaeogeographic provenance of the Małopolska block to the Dobrudgea-Crimea sector of Baltica was suggested by Lewandowski (1993) on the basis of paleomagnetic data. The refraction seismic data (Janik et al., 2009) prove the different crustal structures of the both blocks. Differences in the distribution of metamorphic zone boundaries between Upper Silesia and Małopolska testify to subsequent mutual strike-slip displacements of the two blocks

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along the Kraków-Lubliniec Fault Zone (Żelaźniewicz in Golonka et al., 2005). This fault was active through the Phanerozoic times until Quaternary (Zuchiewicz et al., 2002; Tokarski et al., 2006). It extends southeast of from Krakow under the Outer Carpathian thrust to Rajbrot south of Bochnia (Kraków-Rajbrot fault, see Moryc, 2006) and according to Zuchiewicz et al. (2002) further through Gorlice area to Polish-Slovak border. The diapiric-type migration of the less competent older formations along the strike-slip fault forms the so-called tectonic windows or out-of-sequence (see Jankowski, 2007) thrust zones (Ropa window west of Gorlice for example). Following this "windows" rule we can expect extension of this fault to Smilno in Slovakia and perhaps further to Presov and Vihorlat area (Żaba, 1999).

The Polish Outer Carpathians are built up from the Upper Jurassic-Neogene flysch deposits strongly imbricated due to thrusting. All the Outer Carpathian nappes are thrust over the southern part of the North European platform covered by the autochthonous Miocene deposits of the Carpathian Foredeep on the distance of 70 km, at least. During overthrusting movement the northern Carpathians nappes became uprooted from the basement and only their basinal parts were preserved. The fol-

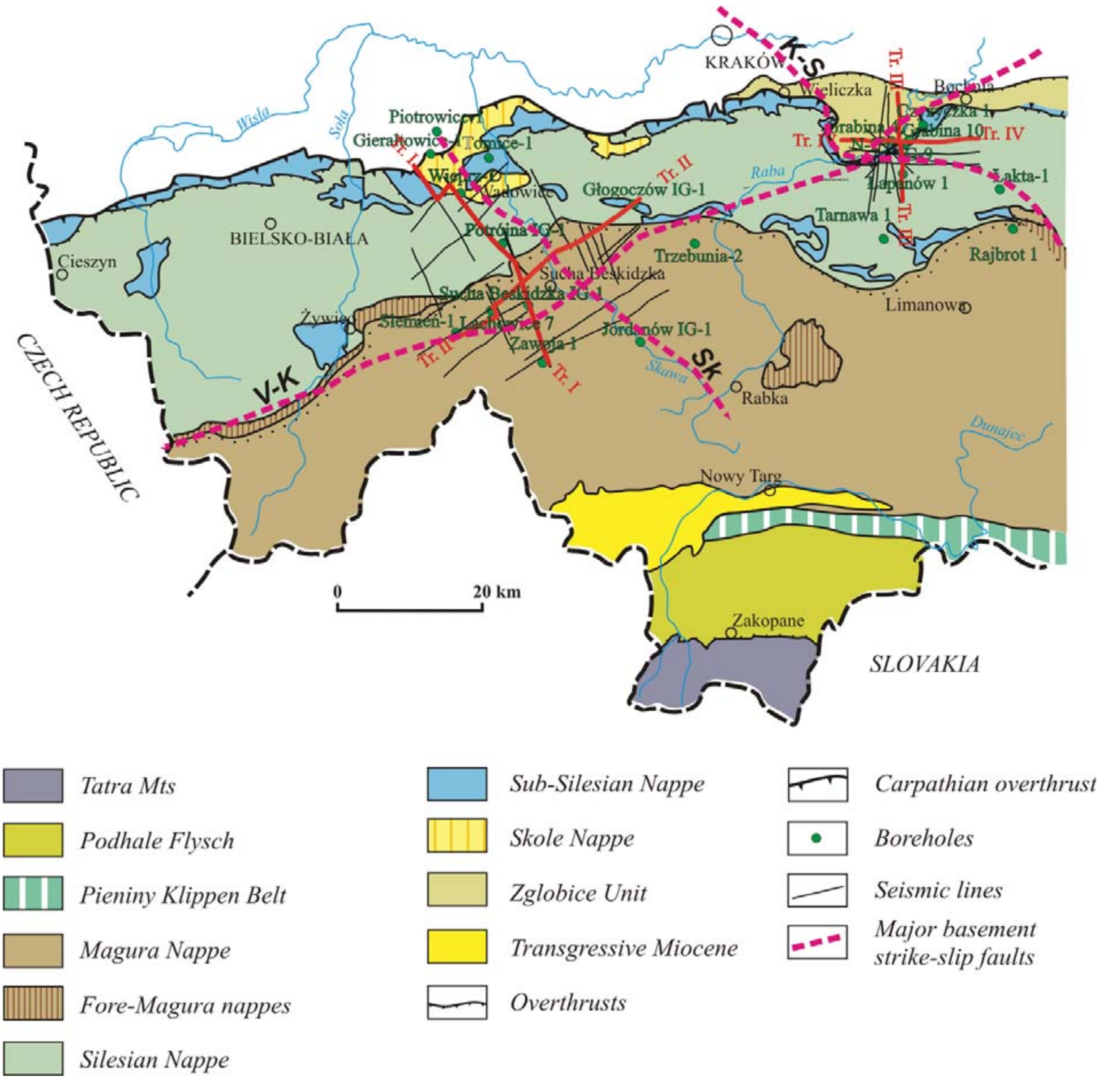

Fig. 2. Map of the Polish Carpathians south of Krakow with location of seismic profiles and major strike-slip faults. V-K – Vienna-Krakow fault, Sk – Skawa river fault, K-S – Krakow-Smilno fault (Łąkta fault).

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lowing Outer Carpathian nappes have been distinguished: Magura Nappe, Fore-Magura group of nappes, Silesian, Subsilesian and Skole nappes (Fig. 2). A narrow zone of folded Miocene deposits was developed along the frontal Carpathian thrust (Oszczypko, 1998; 2004; Oszczypko and Oszczypko-Clowes M., 2003; Golonka et al., 2005; 2009; Oszczypko et al., 2006, Ślączka et al., 2006).

3. Methods

Several seismic boundaries within the North European Platform and allochthonous cover were identified explicitly in the area southwest of Kraków, margin between Wadowice and Kraków. The seismic profiles in this area were tied to borehole data from wells (see Pietsch et al., 2007; Golonka et al., 2009): Głogoczów IG1, Potrójna IG1, Sucha Beskidzka IG1, Zawoja 1 among the others (Fig. 2). The seismic boundaries were defined on the basis of interpretation of time reflection seismic sections in version of final sums after migration (Geofizyka Kraków Ltd.) tied to geophysical and geological borehole and surface data. Geological identification of seismic boundaries was made on the basis of synthetic seismograms (seismic modeling 1D), computed with the LogM program in the GeoGraphix (*Landmark Graphics Corp.*) system for all boreholes where PAP measurements were made.

Correlation of seismic horizons was performed in the SeisVision program of the GeoGraphix system. The following boundaries were identified: **JMsp** – the Magura unit base, **JSsp** –the Silesian unit base, the flysch base – **Flsp, PALstr** - the top of various Paleozoic formations pinching out to the Sub-Miocene surface, **C1str** – the top of the Lower Carboniferous, **D2str** – the top of carbonate formations of the Middle Devonian, **Cm+D1str** – the top of shaly-sandstone formations of the Lower Devonian and the Lower Paleozoic (Cambrian) and **Pr** – the top of consolidated basement, mainly Precambrian.

4. Results

The characteristic features of the top of Precambrian boundary are horsts and troughs of general direction NW-SE turning W-E in the area southwest of Kraków. The Precambrian basement is covered discordantly by Devonian and Upper Paleozoic formations. The Devonian rocks were encountered north of Babia Góra in borehole Zawoja 1, their southern extent remains unknown. In some Precambrian horsts, Devonian rocks are missing. The Devonian is covered by Lower and Upper Carboniferous deposits similar to those known in the Carpathian Foreland and Upper Silesian Coal Basin. The Mesozoic sequences are known only from the eastern part of the investigated area, their thickness significantly increase eastwards. The clastic Eocene-Oligocene rocks, mainly conglomerates of the Zawoja Formation, representing autochthonous Paleogene were drilled in Zawoja 1 well. The Miocene deposits lay discordantly on the various Paleozoic, Mesozoic and Paleogene rocks

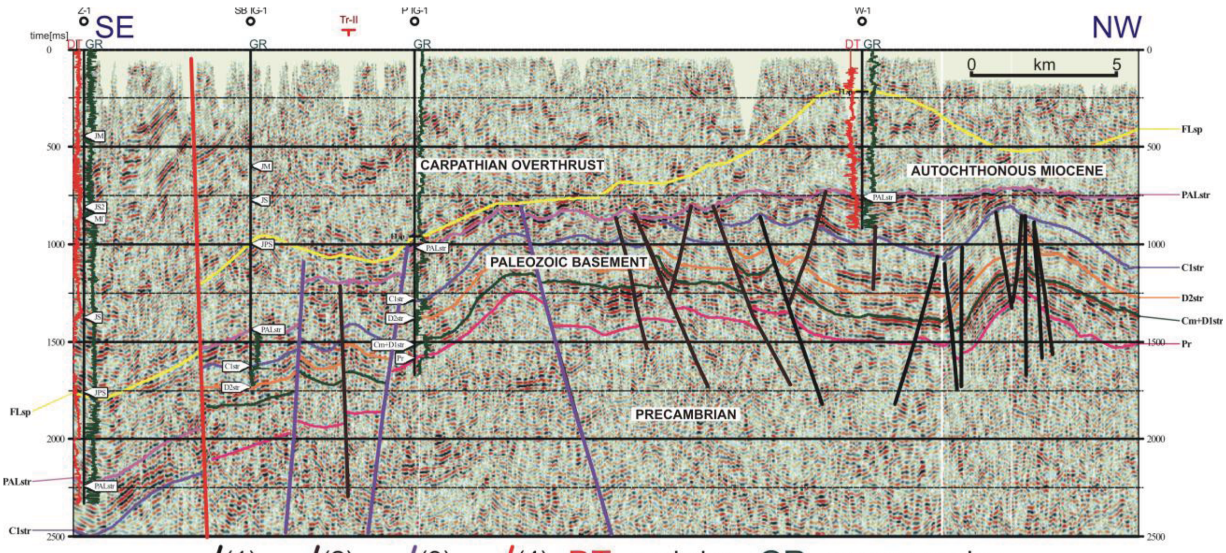

Fig. 3. Interpreted SE-NW seismic transect I-I, through Wieprz 1 (W-1), Potrójna IG 1 (P IG 1), Sucha Beskidzka IG 1 (SB-IG 1) and Zawoja 1 (Z-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text.

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(Ślączka et al., 1976; 2006; Golonka et al., 2005; 2009; Pietsch et al., 2007).

The NW-SE seismic transect I-I (Fig. 3) is going through the Wieprz 1, Potrójna IG 1, Sucha Beskidzka IG 1 and Zawoja 1 boreholes. The Flsp boundary is dipping from 60m un northern part to above 3300 m b.s.l. in southern part, over the 35 km distance. The flysch sequences form nappes and thrustsheets. The top of Paleozoic surface, cut by several faults is also gradually dipping under Carpathians. The consolidated basement seismic boundary is tied to Potrójna IG among the others (Figs. 2, 3). Outside boreholes, it was interpreted according to reflex character. The Precambrian-Paleozoic structure is characterized by horsts and grabens NW-SE, and W-E oriented, dipping south. The series of mainly normal faults reach Top of Paleozoic, sometimes Miocene. The biggest fault between Zawoja 1 and Sucha Beskidzka IG1 boreholes cuts also allochthonous flysch sequences. The displacement of nappes of the Carpathian overthrust and diapiric extrusion of plastic formations of the lower flysch units occurred along this fault (Pietsch et al., 2007; Golonka et al., 2009).

The SW-NE seismic transect II-II (Figs. 2, 4) is going through the Ślemień 1, Lachowice 7 and Głogoczów IG 1 boreholes. The fault system forming the flower structure is cutting the platform basement as well as allochthonous flysch sequences reaching the surface. This system known as Skawa Fault Zone (Cieszkowski et al., 2006; Zuchiewicz et al., 2009) is related to huge strike-slip crustal fault.

In the area southeast of Kraków, the oldest rocks are represented by Precambrian phyllites covered by Lower Cambrian sandstones and mudstones, Lower Devonian clastics, Middle and Upper Devonian carbonates, Lower Carboniferous carbonates, Upper Carboniferous coal-bearing series, and Permo-Triassic red beds. Jurassic is represented by Liassic and Dogger claystones, mudstones and sandstones, coaly layers and by Malm carbonates. Upper Cretaceous sandstones, marls and limestones cover Jurassic deposits with unconformity. The Miocene molasse complex, covering Mesozoic, contains clastics and evaporites (Moryc, 2006; Florek et al., 2006).

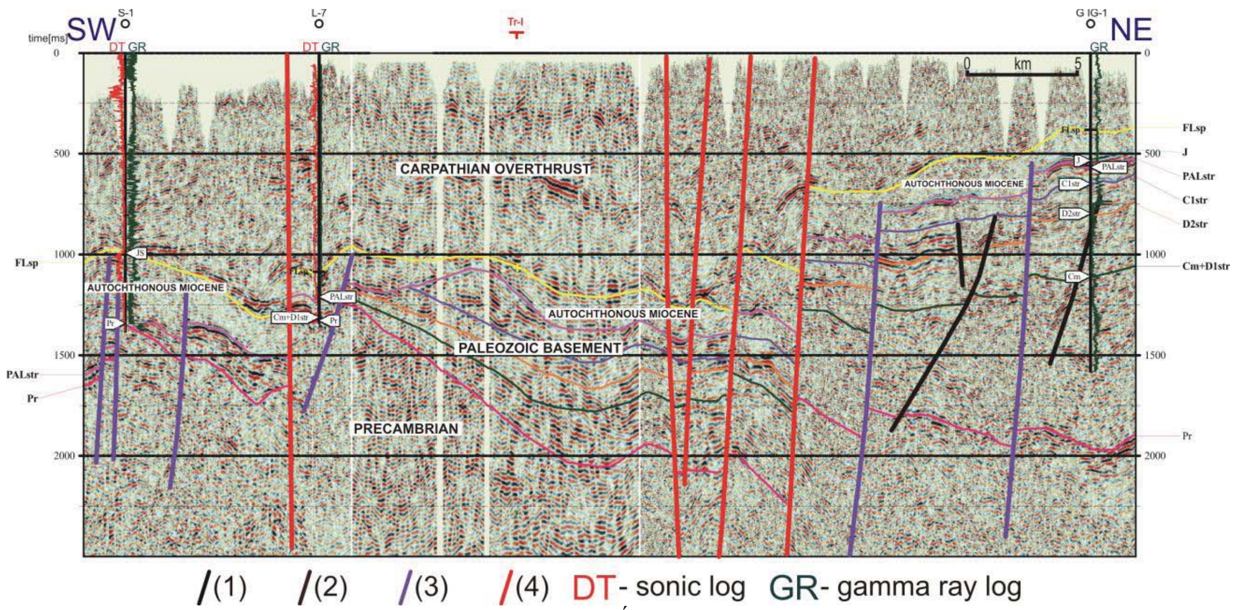

Fig. 4. Interpreted W-E seismic transect II-II through the Ślemień 1 (S-1), Lachowice 7 (L-7) and Głogoczów IG 1 (G IG-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text.

The wavely seismic image on the Figs. 5 and 6 shows the upper complex built by folded flysch sequences characterized by changing seismic boundary, and lower complex built by Miocene, Mesozoic and Precambrian rocks characterized by more regular, quietly dipping reflexes. The quality of seismic survey performed in 1978 – 2007 and limited number of deep boreholes with full package of well logging caused difficulties in distinguishing fault zones originated under different stress regimes, with varied depth and directions.

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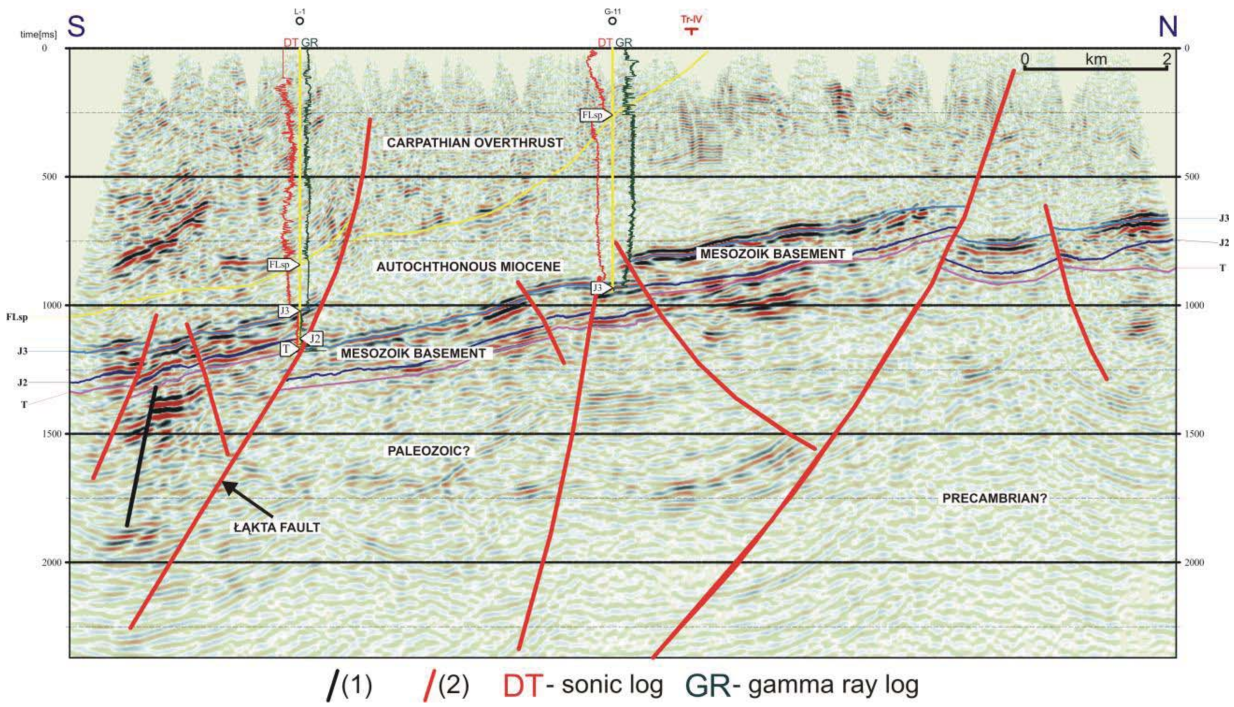

Fig. 5. Interpreted S-N seismic transect III-III through the Łapanów-1 (L-1) and Grabina-11 (G-11) boreholes. Faults: (1) normal fault (2) thrust fault. Horizons abbreviations explained in text.

The diffraction waves were helpful; they broke correlation of phased seismic horizons allowing identifications of faults. The following boundaries were identified: the flysch base-**Flsp,** the Sub-Miocene surface-**M1,** the top of Upper Jurassic carbonates-**J3,** the top of Middle Jurassic clastics-**J2**, and the top of Triassic and older formations-**T1**.

The N-S seismic transect III-III (Figs. 2, 5) is going through the Łapanów-1 and Grabina-11 boreholes. The Mesozoic basement is covered by thin Miocene and thick flysch complexes in this transect. The bottom of flysch sequences is tied to boreholes and quite well visible. The image of Miocene strata is poor and hard to interpret. The top of Upper Jurassic carbonates (**J3)** horizon is well visible. It is cut by series of faults, dividing the Mesozoic basement into separate blocks. The large (250 ms vertical displacement) thrust Łąkta fault is cutting through Paleozoic, Mesozoic, Miocene and allochthonous flysch sequences. It is closing Łapanów oil field, accumulating hydrocarbons in Malm and Miocene reservoir rocks. The Łąkta fault is related to the Krakow- Smilno Fault system (Figs. 1,2). Another large thrust fault, showing similar displacement is located in the northern part of the profile. The. Grabina – Nieznanowice graben is located in the Grabina-11 borehole vicinity. It is limited by the thrust faults reaching only Miocene sequences below Carpathian flysch. The inverted Podgrodzie horst is located south of this fault zone.

The W-E seismic transect IV-IV (Figs. 2, 6) is going through the Nieznanowice-2, Grabina-5 and Grabina-4 boreholes. The poorly visible Miocene sequences are covered by Carpathian flysch in the eastern part of the profile. The top of Jurassic (**J3**) and intra-Miocene horizons are well distinguished in the western part following the same structural monoclinal pattern. The very strong positive reflex, tied to the top of Upper Jurassic, is cut by the system of thrust faults dipping in opposite directions and closing Grabina – Nieznanowice graben. The erosional, deeply cut valley in the top of Jurassic is visible at the eastern end of the profile (Fig. 6)

5. Discussion: the origin of major faults and differences in structural styles

Interpretation of seismic survey, allows identification of dislocations cutting only basement rocks and less frequent dislocations cutting both flysch nappes and their basement. Analysis of magnetotelluric data (Golonka et al., 2009) basically confirms the interpretation of seismic survey.

In the area southwest of Kraków faults cutting only the consolidated basement and the Paleozoic cover were formed during the Variscan Orogeny during the Carboniferous and Early Permian times (Figs.

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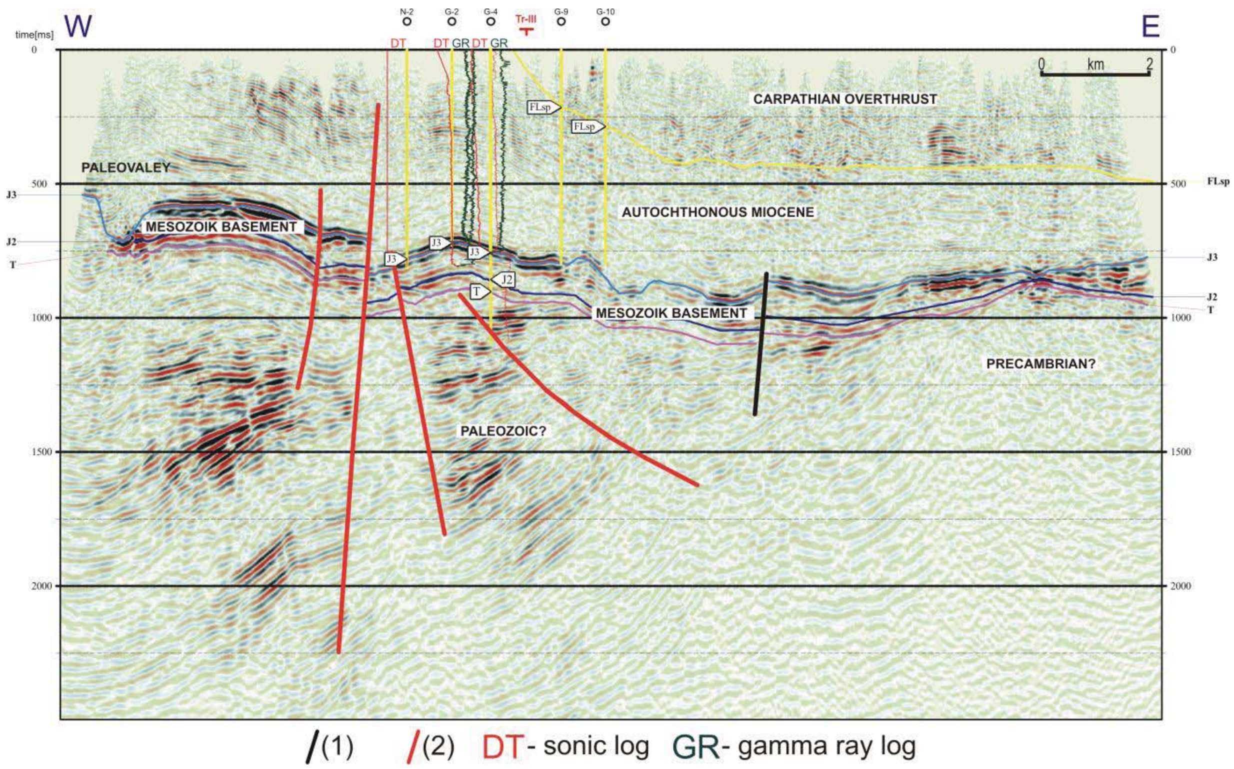

Fig. 6. – - Interpreted W-E seismic transect IV-IV through the Nieznanowice-2 (N-2), Grabina-2, 4, 9 and 10 (G-2, G4, G-9, G-10) boreholes. Faults: (1) normal fault (2) thrust fault. Horizons abbreviations explained in text.

3, 4). Normal faults reaching the Sub-Miocene surface prevail there. Some of them display trace of later Neogene reactivation. They have NE-SW to W directions. Also during Jurassic and Cretaceous times intensive extension took place. This extension is linked with the Pangea break-up and the origin of Alpine Tethys (Golonka et al., 2006).

Due to the Miocene tectonic movements, most of the older normal faults were covered by allochthonous flysch nappes forming the blind faults. During the last stage of the geodynamic development the Carpathians thrustsheets moved towards their present position and dextral strike-slip faults of N—S direction developed. Typical strike-slip fault forms an asymmetrical flower structure. Its orientation coincides with the surface position of the major faults of. Skawa river fault zone perpendicular to the strike of the Outer Carpathian thrust sheets (Pietsch et al., 2007; Golonka et al., 2009).

Some normal faults of E-W orientations were renewed during the stress period and they controlled formation of morphostructures – horsts and depressions of E-W orientation. Huge fault, oriented NEE – SWW, cuts formations from the Paleozoic basement through the flysch allochton between the boreholes Zawoja 1, from the south, and Sucha Beskidzka1 and Lachowice 7, from the north. It constitutes a fragment of the major Vienna-Krakow fault zone (Fig. 1). The displacement of nappes of the Carpathian overthrust and diapiric extrusion of plastic formations of the lower flysch units occurred along this fault.

The thrust faults in the area southeast of Krakow clearly indicate the compressional regime (Figs. 5, 6). Stress data point to present-day compressive reactivation of the Carpathians (Jarosiński in Golonka et al., 2005) The Alcapa block, advancing towards NNE exerts thin-skinned compression in the flysch nappes of the Outer Carpathians. Alcapa push seems to involve also the autochthonous basement of the Małopolska Massif domain, as analogue SHmax orientation was documented under the front of the accretionary wedge and in the foreland (Jarosiński in Golonka et al., 2005). Therefore, resistive contact between the Alcapa and Małopolska Massif can be anticipated. In contrary, contact between overriding and subducting plates in the Upper Silesian Massif segment of the Outer Carpathians seems to be weak, as the Alcapa push does not affect the basement. In this domain, SHmax rotations can be interpreted in terms of stress partitioning due to interference of two stress generating factors, SE-oriented Mid-Atlantic ridge push that might propagate from Bohemian massif

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to the basement of the Upper Silesian Massif and Alcapa push component that governs stresses in the nappes. The Krakow- Smilno Fault system (Figs. 1, 2) marks boundary between western, mainly extensional, with strong strike-slip component and eastern compressional regime affecting the basement rocks, their Miocene cover and often also the Carpathian flysch nappes. The thrust system is also related to the triangle zone located in the Miocene sequences north of investigated area (Porębski and Oszczypko, 1999; Krzywiec et al., 2004).

6. Conclusions

1. Tectonics of the Polish Outer Carpathians and its basement reflects the long, Late Precambrian to present plate tectonic process.
2. The newest mapping, lithostratigraphic, seismic and magnetotelluric surveys confirmed the nappe structures of the Outer flysch Carpathians.
3. Interpretation of seismic and magnetotelluric survey allows observation that defines relationship between basement and flysch nappes in the Outer Carpathians.
4. The basement structure in the southwest and southeast of Krakow displays different structural styles.
5. Southwestern fault systems developed under mainly extensional regime with strong strike-slip component.
6. Southeastern fault systems developed under mainly compressional regime.
7. The Krakow-Smilno Fault system marks the boundary between two different tectonic realms with the North European Plate.

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