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# Structure and Plate Tectonic Evolution of the Northern Outer Carpathians

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## 1. Introduction

The paper published in previous year (Golonka et al., 2009) was dealing with tectonics of the western part of the Outer Carpathians in Poland. Now, present authors expanded the area of investigation into the central and eastern part of the northern Outer Carpathians (Figs. 1, 2). The structural style of this area was recently refined by seismic survey data, especially from the areas southwest and southeast of Krakow (Fig. 2). This survey was performed by Geofizyka Kraków Ltd. and tied to geophysical and geological borehole and surface data. The authors also utilized the recently published tectonic work, integrating geological and geophysical data (Dziadzio, 2006; Kuśmierek, 2010). The structural style is explained by complex plate tectonic evolution of the Carpathian Mountains and adjacent areas.

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 Carpathians and the external, younger one, known as the Outer or Flysch Carpathians (Golonka et al., 2005a; Ślaczka 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 Ślaczka et al. (2006; see also Oszczypko, 2004). The Carpathian Foredeep as well as relationship 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 & Tomáš 1985; Moryc et al., 2005, 2006; Oszczypko et al., 2006; Pietsch et al., 2007; Golonka et al., 2009).

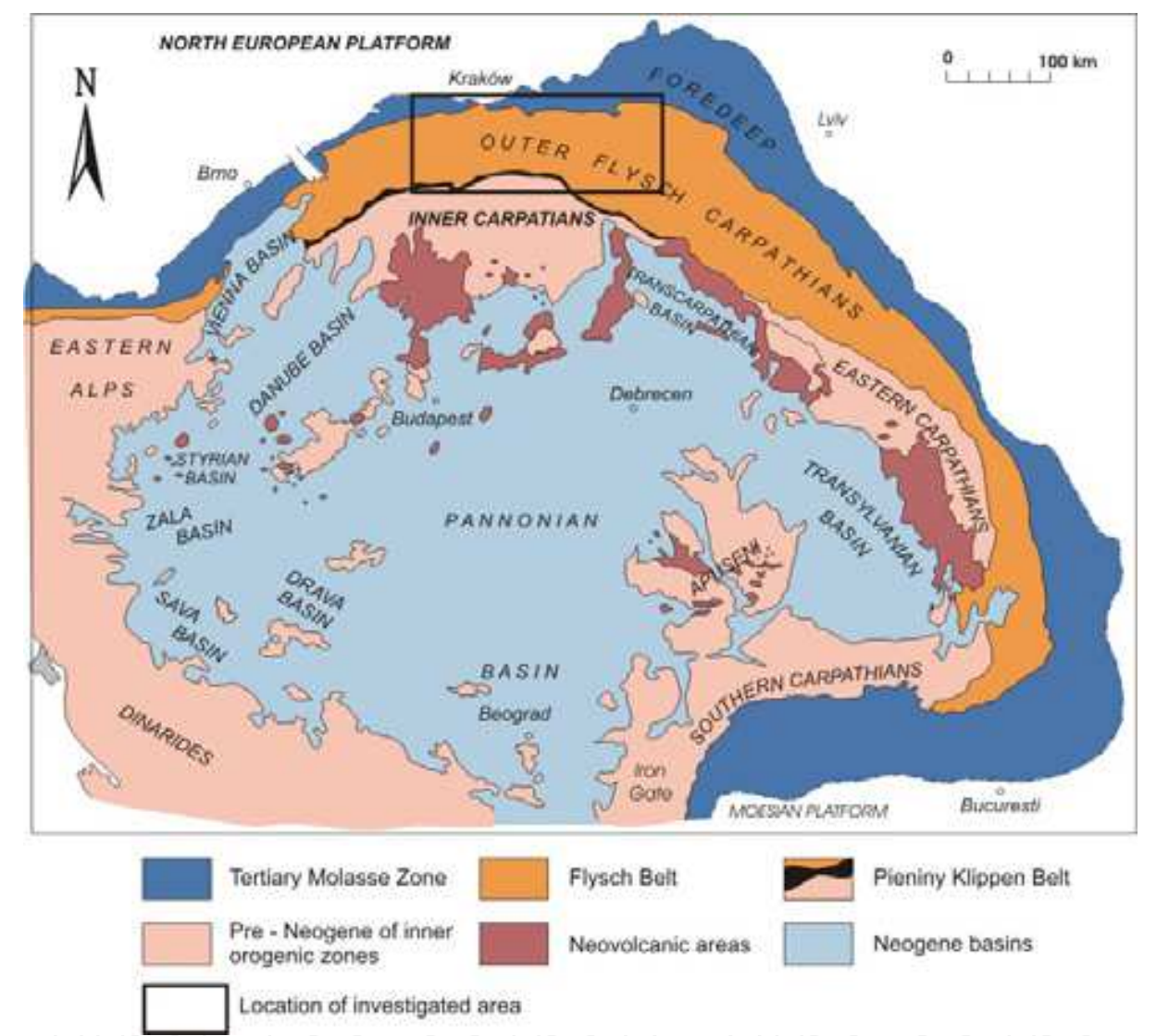


Fig. 1. Geological map of West Carpathians and adjacent areas with location of investigated area. Modified from Kováč et al. (1998); Golonka et al. (2006).

The Polish Outer Carpathians were depicted as a complex structure built up from the Upper Jurassic-Neogene flysch deposits strongly imbricated due to thrusting (Kováč et al., 1998; Oszczypko, 1998, 2004; Oszczypko & Oszczypko-Clowes M., 2003; Golonka et al., 2005a; 2009; Oszczypko et al., 2006, Ślaczka et al., 2006). 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. The northern Carpathians nappes became uprooted from the basement during their overthrusting movement and only their basal parts were preserved. The following Outer Carpathian nappes have been distinguished: Magura Nappe, Fore-Magura group of nappes, Silesian, Subsilesian and Skole nappes. A narrow Zgłobice-Stebnik zone of folded Miocene deposits was developed along the frontal Carpathian thrust (Fig. 2).

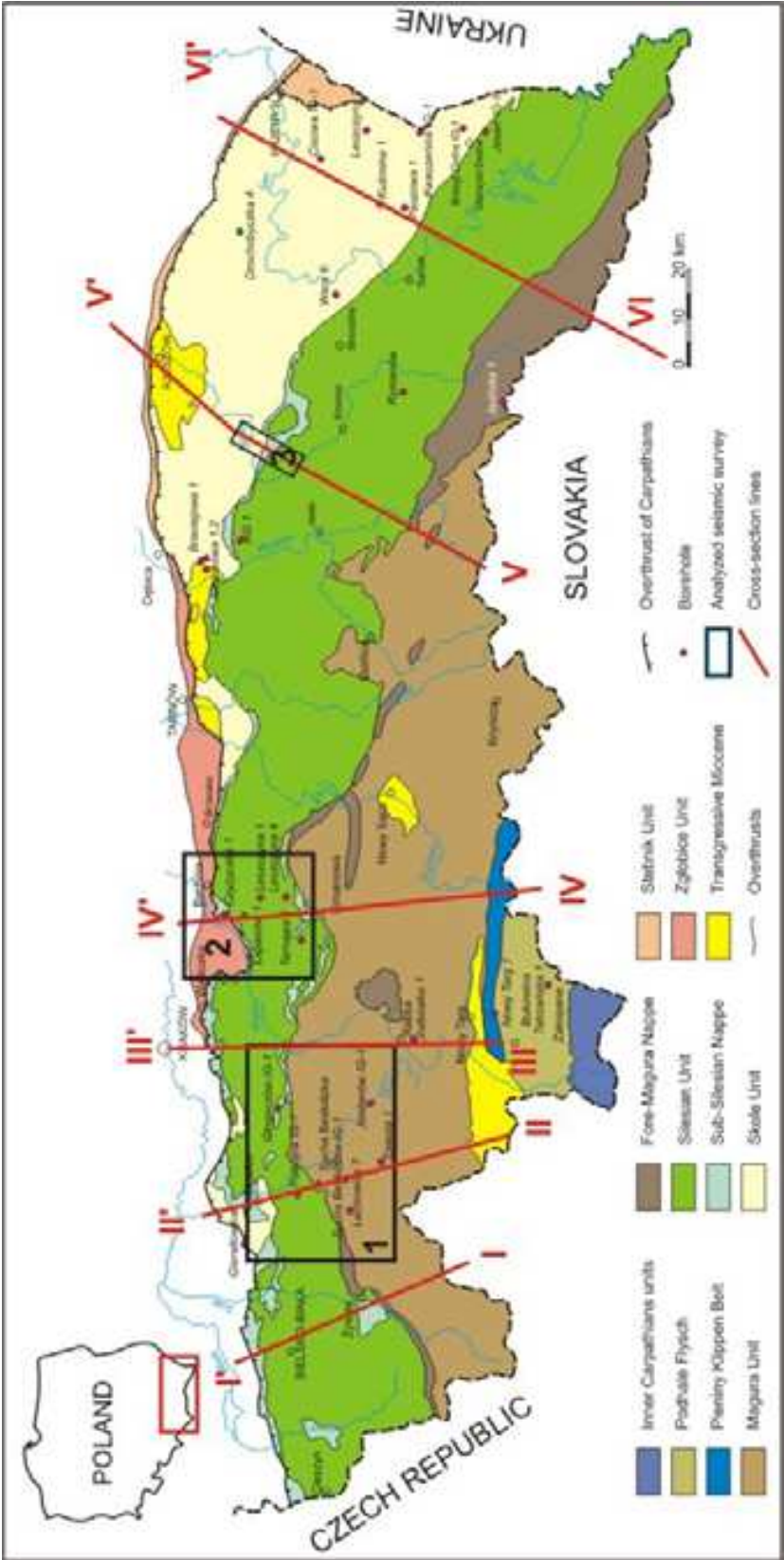


Fig. 2. Map of the northern Outer Carpathians in Poland with locality of cross-sections and seismic survey. Compiled and modified from various sources (Żytko et al., 1989; Pietsch et al., 2007; Golonka et al., 2009).



The seismic survey was conducted in the area southwest of Kraków, between Wadowice and Kraków (see Pietsch et al., 2007; Golonka et al., 2009). The seismic profiles in this area were tied to borehole data from wells: Głogoczów IG1, Potrójna IG1, Sucha Beskidzka IG1, and Zawoja 1 among the others. Similar work was performed and published in the eastern part of the Polish Outer Carpathians (Dziadzio, 2006; Kuśmierek, 2010). The interpretation of seismic survey was integrated with other geophysical research (Grabowska et al., 2007; Stefaniuk et al., 2007 and references therein) as well as with surface mapping and borehole data. The Polish Outer Carpathians were covered by maps in scale at least 1:50 000, performed and published by Polish Geological Institute; the results of this mapping were presented in the compiled maps in scale 1:500 000 (Żytko et al., 1989; Lexa et al., 2000; see also reference therein). The integration of geological and geophysical data enabled reinterpretation of the complex structure of the other Carpathians structure and geodynamic processes leading to the complex tectonics of this area (Golonka et al., 2005a, 2006, 2009; Golonka, 2007; Oszczytko, 2004, 2006; Pietsch et al., 2007; Kuśmierek, 2010).

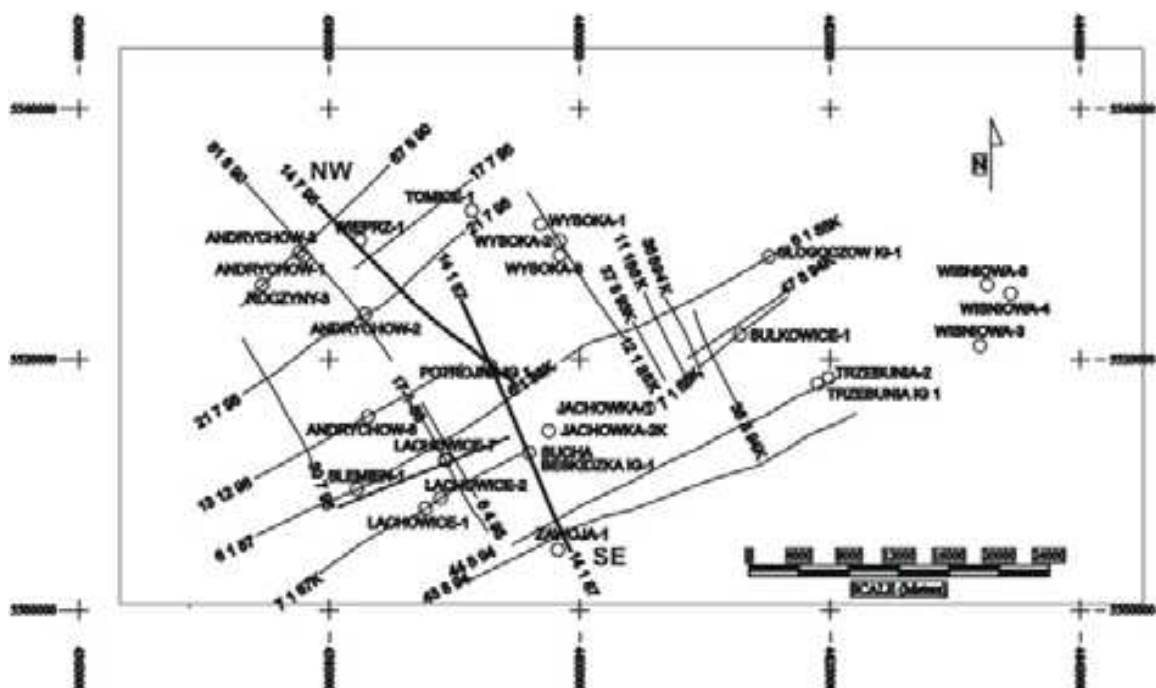


Fig. 3. Seismic survey and well location map of the area southwest from Kraków (location 1 on Fig. 2). Modified from Golonka et al. (2009).

### 3. Methods

The Carpathian nappes as well as North European platform were investigated by the seismic surveys ordered by Polish Oil and Gas Co. (PGNiG) and Geofizyka Kraków, Ltd. The present authors analyzed these surveys in areas southwest (location 1 on Fig. 2, Figs. 3, 5) and southeast of Kraków (location 2 on Fig. 2, Figs. 4, 6, 7). 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.)

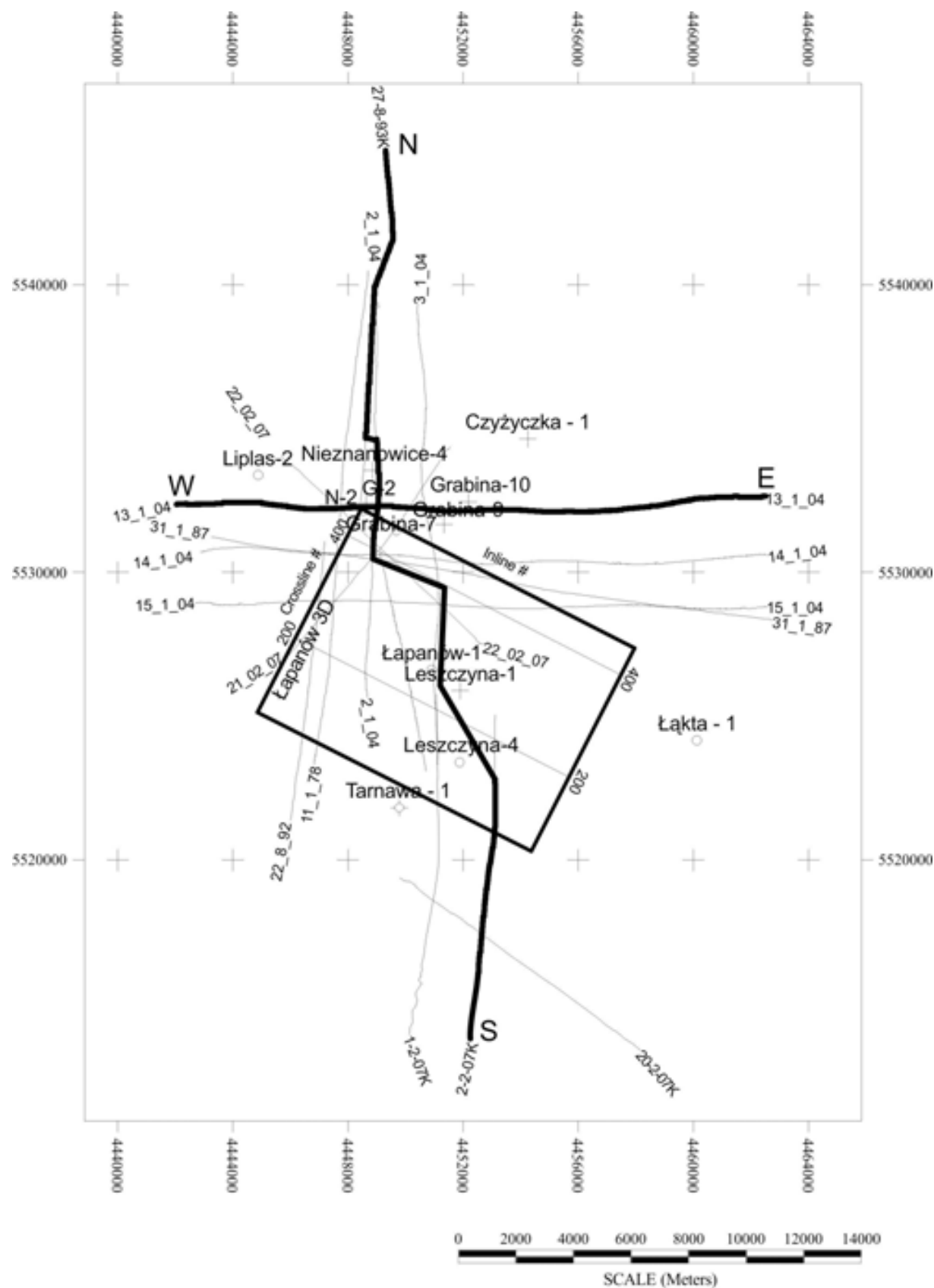


Fig. 4. Seismic survey and well location map of the area southeast from Kraków (location 2 on Fig. 2).

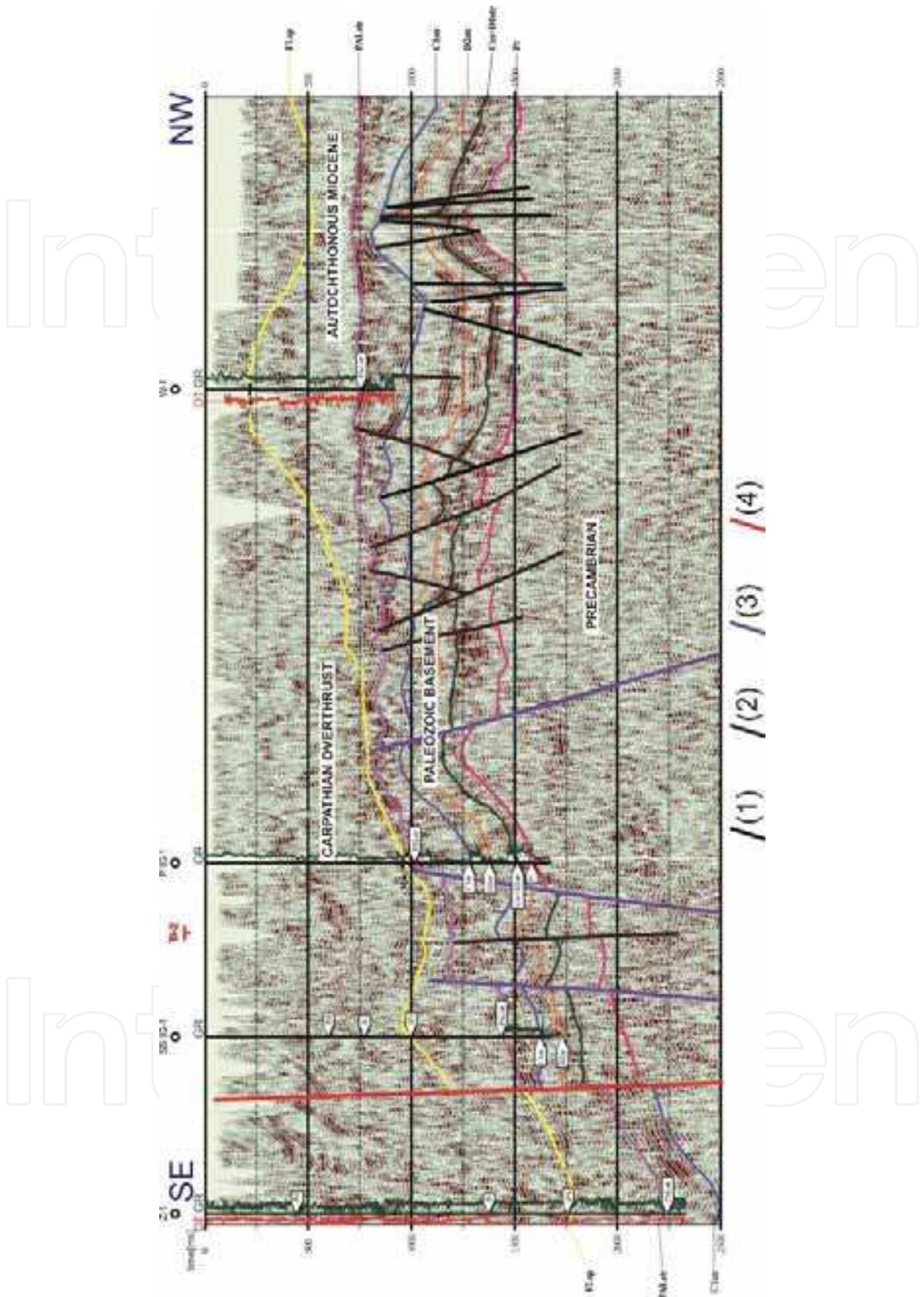


Fig. 5. Interpreted SE-NW seismic transect through Wieprz 1 (W-1), Potrójna IG 1 (P IG 1), Sucha Beskidzka IG 1 (SB-IG 1) and Zawoja 1 (Z-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text. Location on Fig. 3.



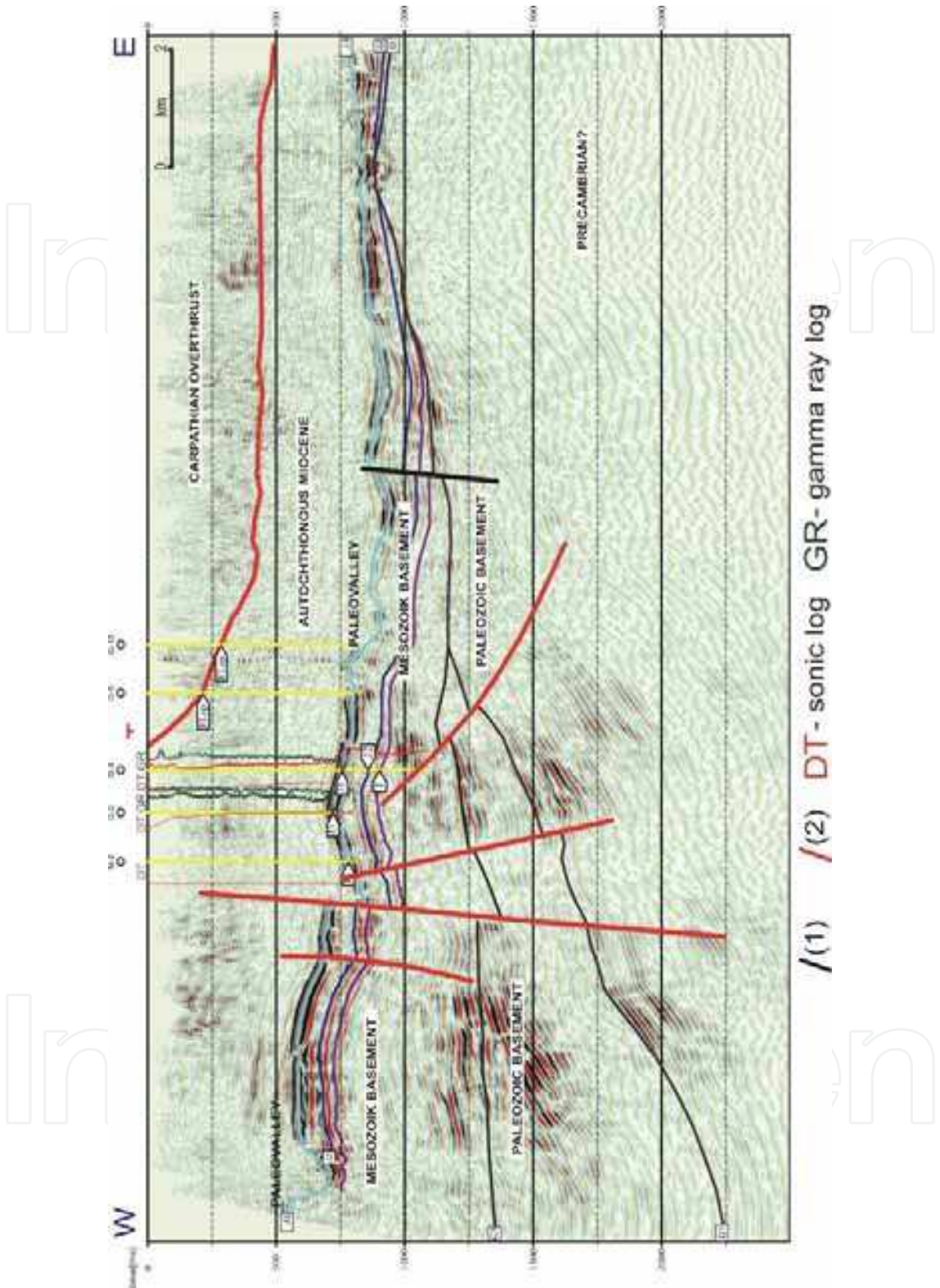


Fig. 6. Interpreted W-E seismic transect through the Nieznanowice-4 (N-2), Grabina-2, 4, 9 and 10 (G-2, G4, G-9, G-10) boreholes. Faults: (1) normal fault (2) thrust fault. Horizons abbreviations explained in text. Location on Fig. 4 (SB-IG 1) and Zawoja 1 (Z-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text. Location on Fig. 3.



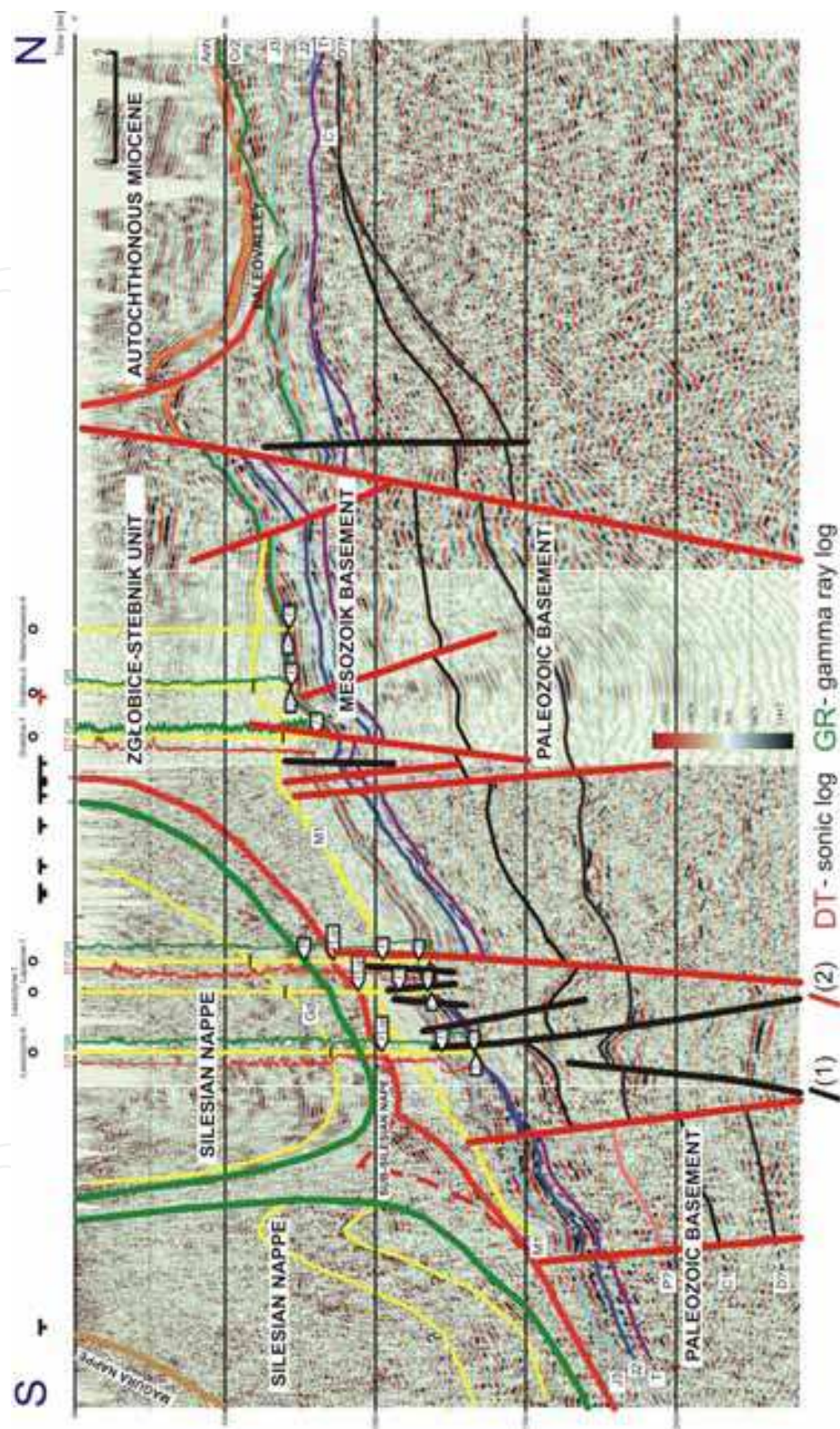


Fig. 7. Interpreted S-N seismic transect through the Nieznanowice-4, Grabina-2, 7, Łapanów-1 and Leszczyna-1, 4 boreholes. Faults: (1) normal fault (2) thrust fault. Horizons abbreviations explained in text. Location on Fig. 4. F1 (SB-IG 1) and Zawoja 1 (Z-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text. Location on Fig. 3.

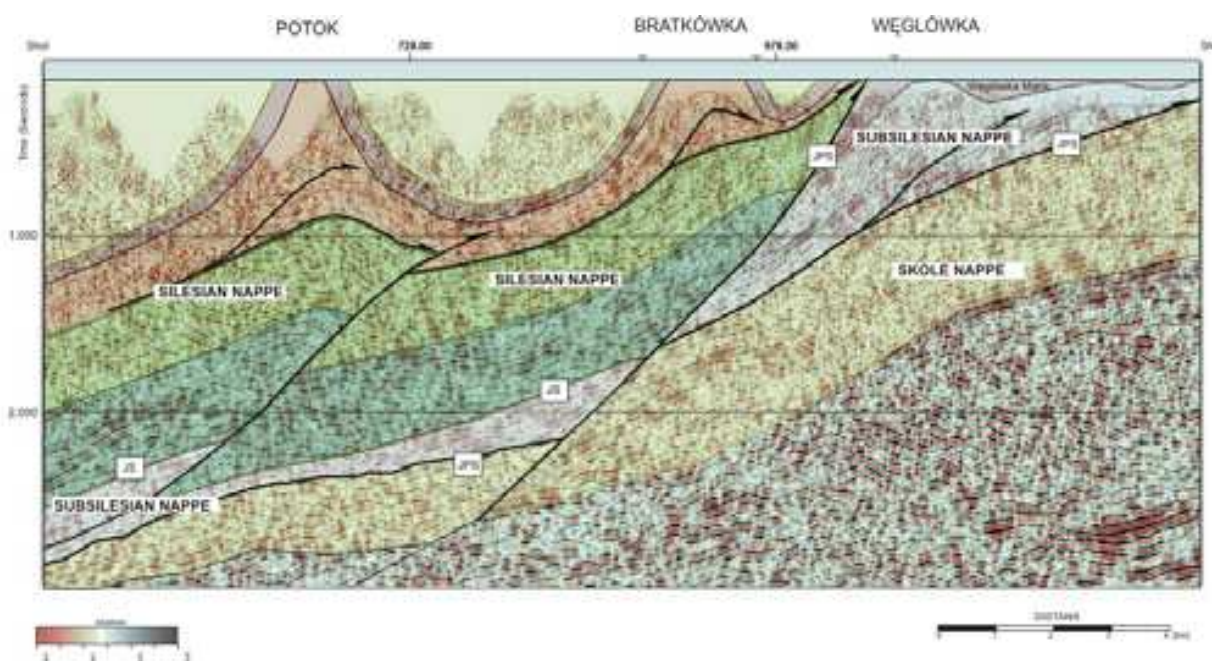


Fig. 8. Seismic transect through the Węglówka area (location on Fig. 2). From Dziadzio (2006), modified.

system for all boreholes where PAP measurements were made (Golonka et al., 2009). 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, Leszczyna 1, 4, and Łapanów 1 among the others (Figs. 5-7). The seismic profile from Węglówka area (Dziadzio, 2006) was also utilized (location 3 on Fig. 2, Fig. 8).

Several seismic boundaries were identified within the North European Platform and allochthonous cover: JMsp – the Magura Nappe base, Gd – top of the Upper Cretaceous Godula Formation (Silesian Nappe), JS – the Silesian Nappe base, JPS – the Subsilesian Nappe, Flsp – the Outer Carpathian flysch base, Anh – top of the Miocene evaporites, M1 – top of the Lower Miocene, Cr2 – top of the autochthonous Upper Cretaceous, J3 – top of Upper Jurassic, J2 – top of the Middle Jurassic, T – top of Triassic, P – top of the Permian, PALstr – the top of various Paleozoic formations pinching out to the Sub-Miocene surface, C1str or C1 – the top of the Lower Carboniferous, D2 – top of the undivided Devonian, 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. Several normal and thrust faults were also distinguished.

The results of seismic surveys were interpolated, extrapolated as well as integrated with other geophysical data, geological, especially mapping data and other published information (Ślaczka, 1976; Książkiewicz, 1977; Oszczypko & Tomáš, 1985; Ryłko & Tomáš, 1995; Żytka et al., 1989; Oszczypko, 1998, 2000, 2004; Paul et al., 1996; Żaba, 1999; Lexa et al., 2000; Poprawa et al., 2001; Zuchiewicz et al., 2002; Czerwiński et al., 2003; Golonka et al., 2005a, 2006, 2009; Moryc, 2005, 2006; Cieszkowski et al., 2006, 2009; Dziadzio, 2006; Guterch & Grad, 2006; Tokarski et al., 2006; Ślaczka et al., 2006; Pietsch et al., 2007, 2010; Golonka, 2007; Zuchiewicz & Oszczypko, 2008; Kuśmerek, 2010). The several cross-sections (Figs. 9-14) were constructed on the basis of this integration.



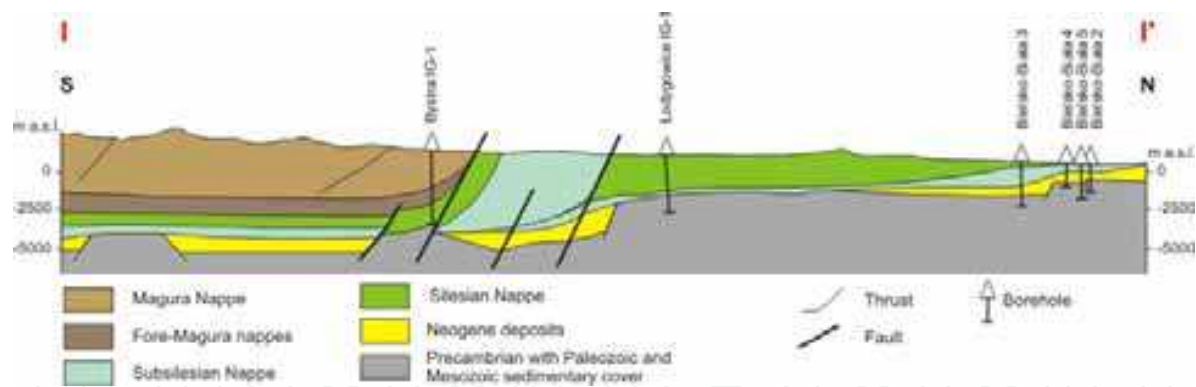


Fig. 9. Cross-section I -I' through the Outer Carpathians and their foreland. Compiled from various sources (Żytko et al. 1989; Paul et al., 1996; Golonka et al., 2009). Cross-section location on Fig 2.

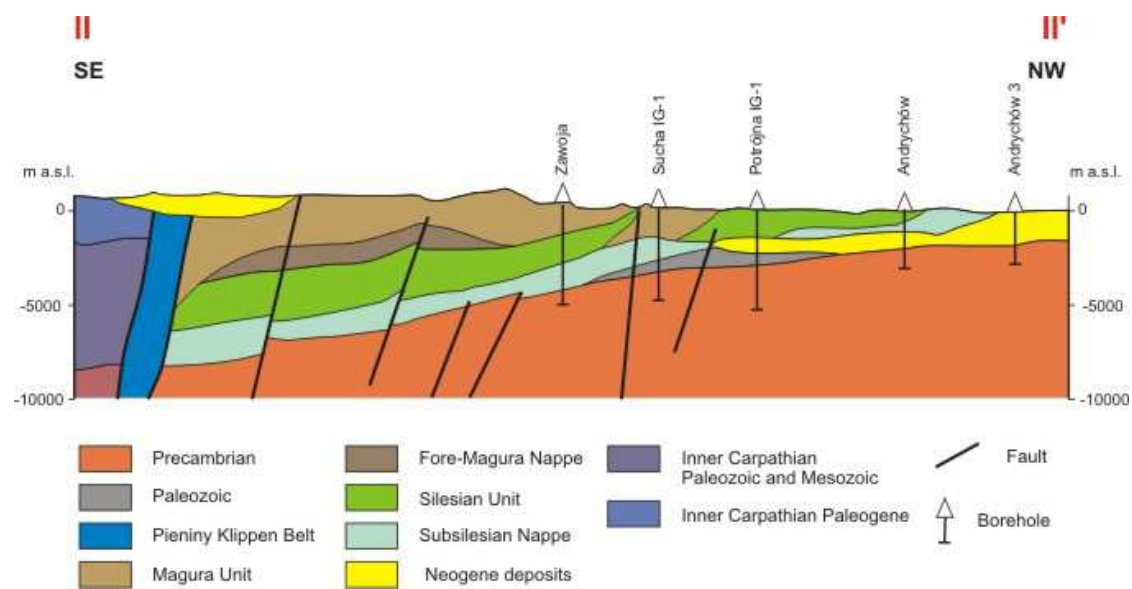


Fig. 10. Cross-section II-II' through the Outer Carpathians and their foreland. Compiled from various sources (Oszczypko et al., 2006; Pietsch et al., 2007; Golonka et al., 2009). Cross-section location on Fig 2.

4. Structure of the Northern Carpathians

4.1 The North European Platform

The great continental plate, known as North European Platform, forms the basement of the Northern Carpathians. This plate consists of Proterozoic, Vendian (Cadomian) and Lower Paleozoic (Caledonian) fragments, deformed and metamorphosed. The Paleozoic, Mesozoic, Paleogene and Neogene strata cover the crystalline, metamorphosed basement. The crystalline, mainly Precambrian basement is depicted on all cross-sections (Figs. 9-14). It is well constrained in the northern marginal part of the Carpathian and quite speculative in the southern part. The Precambrian metamorphic rocks are well visible in seismic profiles in the western seismic survey area (Figs. 3, 5, 9) and, according to Kuśmierek (2010), in the eastern area (Fig. 14). In the central part, SE from Kraków (Figs. 6, 7) Precambrian is hard to distinguish below thick Paleozoic and Mesozoic sedimentary cover.

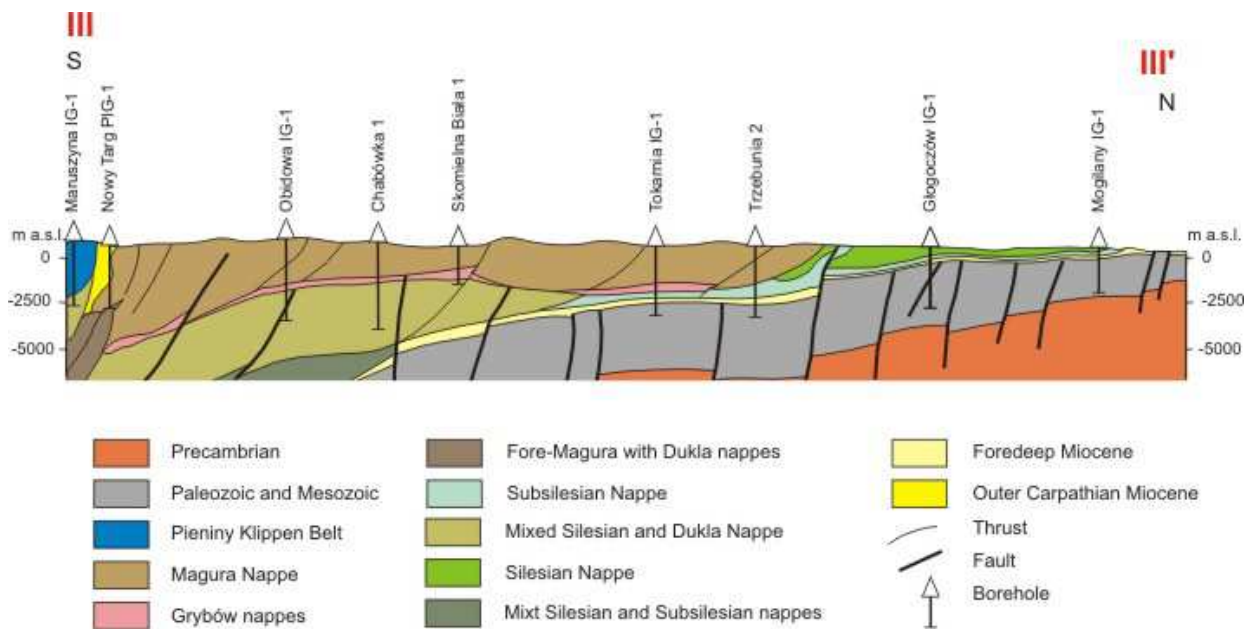


Fig. 11. Cross-section III-III' through the Outer Carpathians and their foreland. Compiled from various sources (Golonka et al., 2006, 2009). Cross-section location on Fig 2.

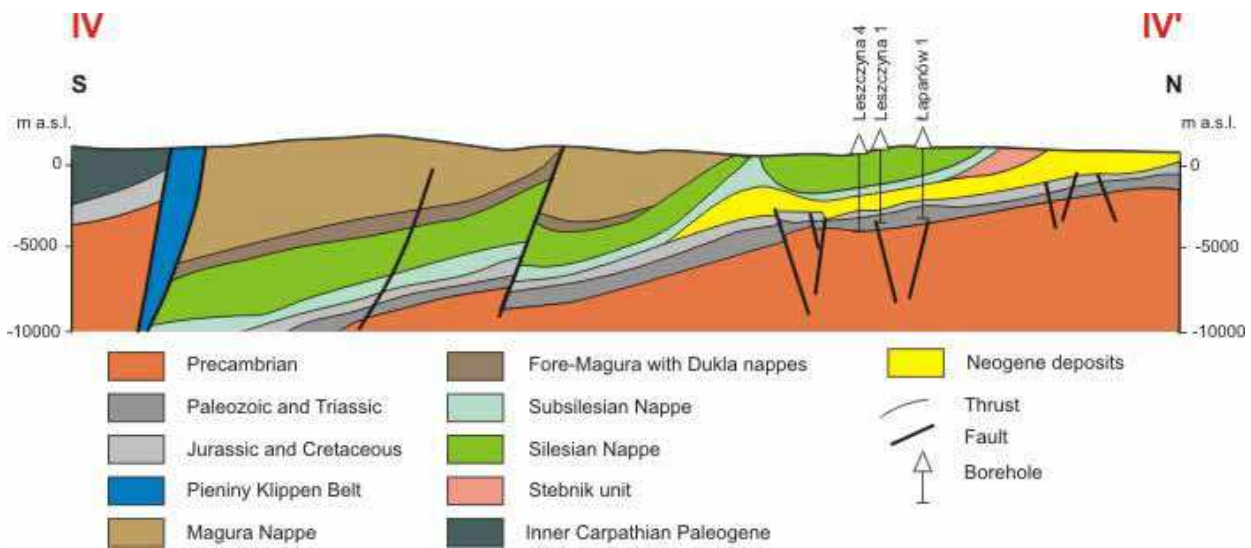


Fig. 12. Cross-section IV-IV' through the Outer Carpathians and their foreland. Cross-section location on Fig 2.

The allochthonous, mainly flysch rocks were uprooted and thrust over the southern part the North European Platform at least 60-100 km (Ślaczka et al., 2006; Golonka et al., 2009). The bottom of the Outer Carpathian flysch nappes is well visible on all seismic profiles from areas southwest and southeast from Kraków (Figs. 5-7). Like the basement, it is well constrained in the northern part and speculative in the southern part of the Polish Outer Carpathians.

The Precambrian basement beneath the Outer West Carpathians is divided into two basement blocks: the Bruno-Vistulicum Block on the west and the Małopolska Block on the east (Dudek, 1980; Buła, 2000). The Krakow-Presov Fault system marks the boundary between these two different tectonic realms within the North European Plate.



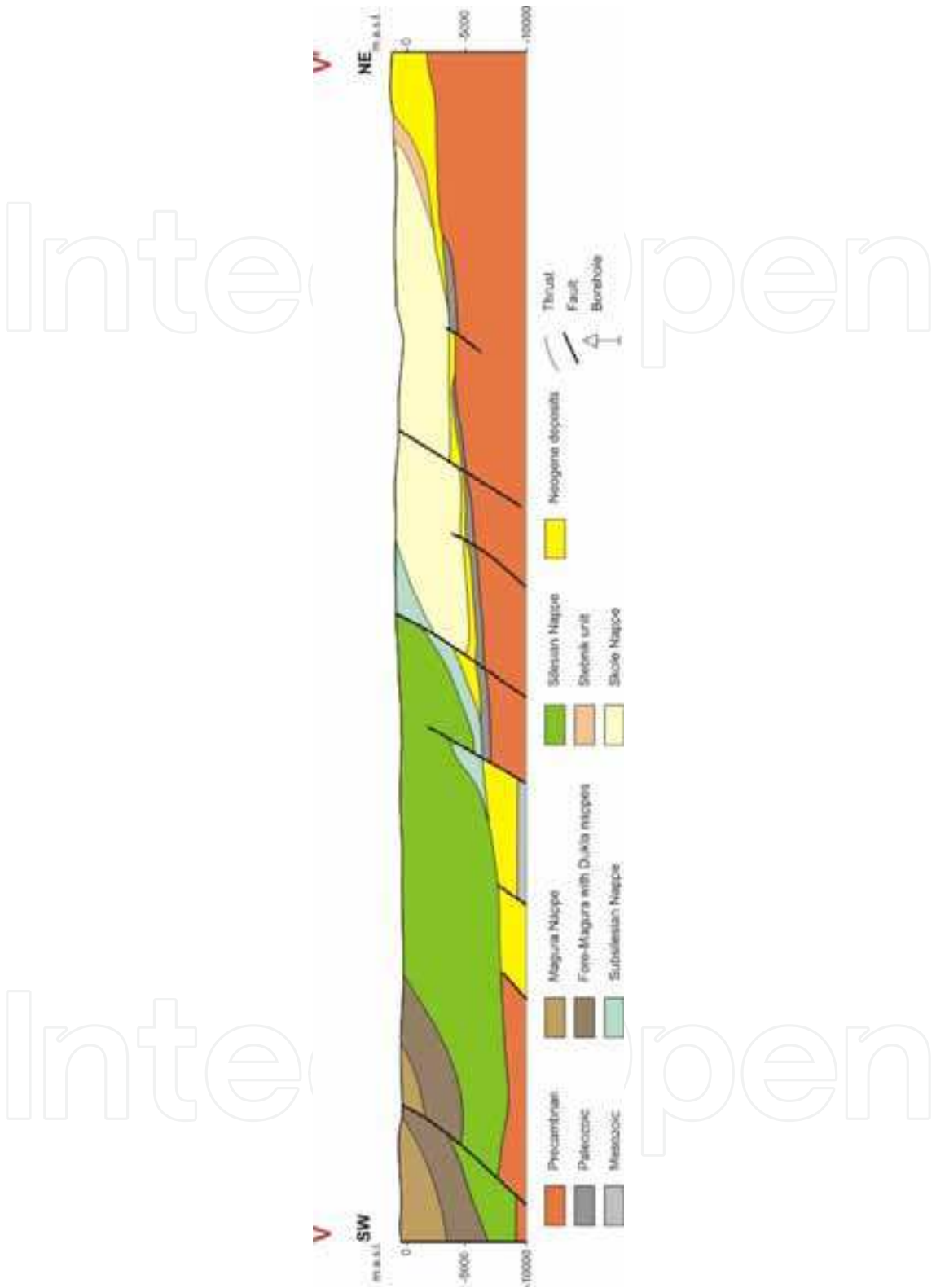


Fig. 13. Cross-section V-V' through the Outer Carpathians and their foreland. Compiled from various sources (Żytko et al. 1989; Oszczypko, 2004; Ślaczka et al., 2006; Dziadzio, 2006). Cross-section location on Fig 2. 1 (SB-IG 1) and Zawoja 1 (Z-1) boreholes. Faults: (1) reaching top of Lower Carboniferous, (2) reaching top of Paleozoic, (3) reaching Miocene, (4) reaching surface. Horizons abbreviations explained in text. Location on Fig. 3.

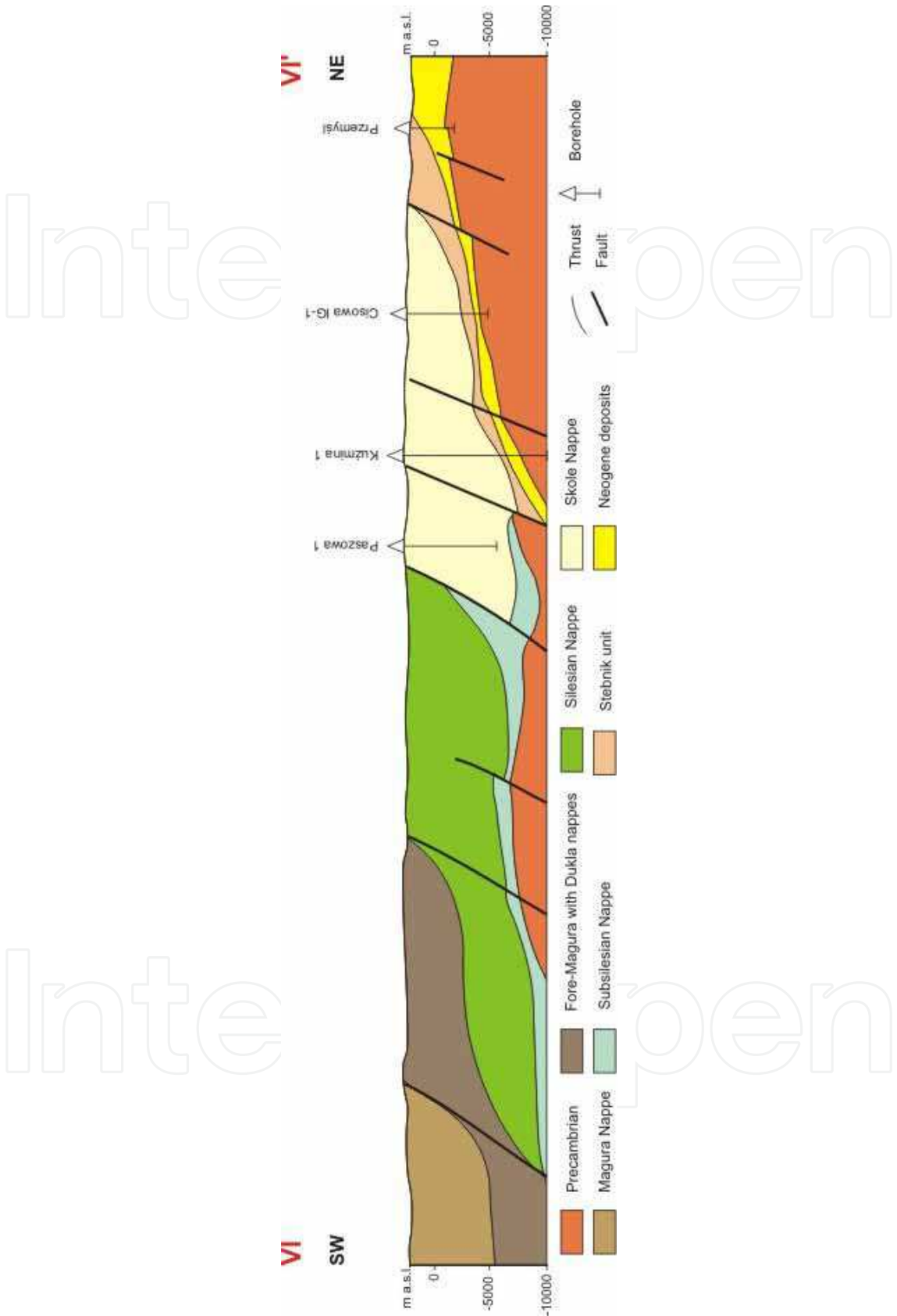


Fig. 14. Cross-section V-V' through the Outer Carpathians and their foreland. Compiled from various sources (Żytko et al. 1989; Kuśmierk, 2010). Cross-section location on Fig 2.

The Bruno-Vistulicum terrane, consolidated in Vendian, during Cadomian orogeny times and composed of the Precambrian metamorphic rocks, is a main component of the consolidated basement in the western area (Pietsch et al., 2007; Golonka et al., 2006, 2009). The top of Precambrian boundary is cut by several faults into horsts and graben system. The Precambrian basement is covered discordantly by Devonian and Upper Paleozoic formations. The Devonian rocks were encountered in numerous wells, their southern extent remains unknown. In some Precambrian horsts, Devonian is missing (Pietsch et al., 2007; Golonka et al., 2009). The Lower and Upper Carboniferous deposits cover the Devonian. The thick Permian-Triassic deposits were encountered in wells SE from Krakow (Poprawa et al., 2001). The Mesozoic sequences are known only from the central part of the northern Outer Carpathians (Figs. 10-11) their presence in the southern part of the Outer Carpathians farther eastward (Fig. 13), postulated by Ślaczka et al., (2006) is quite speculative. The clastic Paleogene rocks were encountered locally. The Miocene deposits lay discordantly on the various Paleozoic, Mesozoic and Paleogene rocks.

## **4.2 The Outer Carpathian Nappes**

### **4.2.1 The Magura Nappe**

The Magura Nappe forms the largest tectonic unit of the northern Outer Carpathians (Ślaczka et al., 2006; Golonka et al., 2009). The boundary between this nappe and Pieniny Klippen Belt display a flower structure characteristics (Figs. 10, 11, 12), running along the major strike-slip fault. The northern boundary of the Magura Nappe is erosional and runs along the arc from Czech Republic border through Żywiec to Myślenice, turning southeastward south of Kraków. The Magura Nappe has been completely uprooted from its substratum and thrust over the Fore-Magura and Silesian nappes, at least 20, perhaps up to 50 km during the orogenic movements (Figs. 10, 11, 12). The following tectonic units have been distinguished within the Magura Nappe: the Krynica, Bystrzyca, Racza and Siary units. These units display distinctive thrust boundaries in the western part of the northern Outer Carpathians (Paul et al., 2006; Golonka et al., 2009). Especially Bystrzyca Unit is thrust several kilometers over the Racza unit south of Żywiec.

Twenty north-vergent anticlines and associated synclines of W-E orientation were distinguished in the area south of Sucha Beskidzka. The Skawa line system of faults displaces the nappe margin 2 km northward in this area (Cieszkowski et al., 2006; Golonka et al., 2009). The so-called tectonic windows, showing out-of-sequence Fore-Magura nappes basement, are located between Rabka and eastern limit of the Magura Nappe. They are known by names Mszana Dolna, Szczawa, Klęczany, Ropa, Ujście Gorlickie, Świątkowa and Smilno tectonic windows). Fig. 13 is showing out-of-sequence thrust of Fore-Magura and Dukla nappes in the so-called Świątkowa window, related to the major fault zone, cutting the basement as well as allochthonous flysch nappes.

### **4.2.2 The Fore-Magura Group of Nappes**

Several units, known as the Fore-Magura Group of nappes (Fig. 2) occur in the northern Outer Carpathians, north from the Magura Nappe. (Ślaczka et al., 2006). The Dukla Nappe is the largest tectonic unit belonging to this group. In the East It is stretching from Poland through Slovakia to Ukrainian Carpathians. It consists of several imbricated, thrust-faulted folds with a north-west - south-east strike. The Dukla plunge gradually towards the north-

west and disappears below the Magura Nappe. Two subunits were distinguished within the Dukla Nappe. The folds within the internal subunit are generally gently dipping towards the south-west and the unit's overthrust is low dipping, whereas within the external subunit folds are steep and often with a reversed (south-western) vergence (Ślaczka et al., 2006).

The narrow zone, known as Fore-Magura *sensu stricto* nappes runs from Milówka to the area east from Żywiec, where it disappears from the surface (Golonka et al., 2009). It is possible that some elements of these nappes represent olistoliths within Menilite and Krosno formations (Cieszkowski et al., 2009). Scales and scaled north-vergence folds, originated as a result of strong compression between Magura Nappe and sandstone-dominated blocks of Silesian Nappe, dominate Fore-Magura zone structure (Golonka et al., 2009).

In the central part of the northern Outer Carpathians, the Fore-Magura group of nappes occur in the mentioned above so-called tectonic windows from Mszana Dolna tectonic window to Smilno tectonic window in Slovakia and was also encountered in the numerous wells below the Magura Nappe e.g. in the Rabka - Nowy Targ area (Obidowa IG-1, Chabówka 1) and Limanowa - Słopnice area (Słopnice 1, Słopnice 20, Leśniówka 1 and others). Many different names were applied to these units, like Grybów, Słopnice-Obidowa, Jasło, and Zboj. Their relationships are unclear and speculative; considering limited data it is perhaps better to leave the traditional local names and to use the broad term "Fore-Magura Group of Nappes" (Golonka et al., 2009). Some of these units probably belonged to a bigger nappe, which was divided into separate units during the Neogene folding, other represent olistoliths within the youngest deposits of the Silesian Nappe (Ślaczka et al., 2006; Jankowski, 2007; Cieszkowski et al., 2009).

#### 4.2.3 The Silesian Nappe

The Silesian Nappe borders with Fore-Magura Nappes south of Silesian Beskid and with Magura Nappes south of Mały Beskid. The northern border with Sub-Silesian Nappe is erosional. In the western part of the Silesian Nappe, the structures are generally shallow and gently folded, whereas towards the East they pass into long, narrow, steeply dipping, imbricated folds. The southern part of the Silesian Nappe is hidden beneath the Magura Nappe and Fore-Magura nappes (Ślaczka et al., 2006). The West of the Soła River, near the western border of Poland, the Silesian Nappe is composed of two subunits. The Cieszyn Subunit is built of a strongly folded Upper Jurassic and Lower Cretaceous Vendryně, Cieszyn Limestone, Hradište and Veřovice formations (Golonka et al., 2009). This unit includes several small anticlines visible between Cieszyn and Soła River. The Godula Unit is built mainly of sandstone-dominated formations. It is divided into two blocks: - Silesian Block and Mały (Lesser) Beskid Block, separated by fault. These blocks dip monoclinaly southward, display uplifted northern margin and slightly marked longitudinal folds with Cretaceous rocks. The eastern part of the Silesian Nappe is cut by several transverse faults (Ślaczka et al., 2006). The large tectonic window with Subsilesian Nappe is located in the Żywiec area (Fig. 9). Smaller windows are located in Lanckorona-Myślenice area. The border of the Silesian Nappe displays the significant offset along the Skawa dislocation zone. The eastern part of the nappe is located 10 km north of the western part. This fault zone divides the nappe into two segments the western one is characterized by the development of Cretaceous Godula Sandstones, eastern by the occurrence of Krosno Beds. Two separate zones are visible within the Silesian Nappe east of Skawa line. The lower,



northern zone, known as Pogórze Lanckorońskie sheet form large syncline with Eocene-Oligocene Menilite and Krosno formations. The upper zone pinches out on the Myślenice area (Golonka et al., 2009).

Farther to the east the Cieszyn Subunit and the Godula Subunit join and the Silesian Nappe is built of several gently folded structures. East of the Dunajec River, these structures pass into imbricated folds. The eastern part of the Silesian Nappe, east of the Wisłok River, is plunging towards the south-east and is represented by a synclinorium (Central Carpathian Synclinorium), which is built mainly of the Oligocene deposits. The Central Carpathian Synclinorium is built of several long, narrow, imbricated, thrust-faulted folds which are often disharmonic. These folds are cut by several transverse faults that divide them into separate blocks. The folds display, along the strike, several axial culminations, where along the northern and southern margins of the Synclinorium the Cretaceous and Eocene strata are exposed.

#### 4.2.4 The Subsilesian Nappe

The Subsilesian Nappe underlies tectonically the Silesian Nappe. In the western sector of the West Carpathians both nappes are thrust over the Miocene molasse of Carpathian Foredeep and in the eastern sector they are thrust over the Skole Nappe (Golonka et al., 2005a; Ślaczka et al., 2006). The presence of the Subsilesian Nappe was also established in numerous boreholes beneath the Silesian and the Magura nappes (Figs. 9-12). The Subsilesian Nappe occurs as broken pieces along the northern margin of the Silesian Nappe, as well as in the tectonic windows in the Żywiec and Lanckorona-Myślenice-Żegocina areas within the Silesian Nappe (Golonka et al., 2009). The diapiric-type migration of the less competent formations of Subsilesian nappe along the strike-slip fault forms this so-called tectonic windows or out-of-sequence (see Jankowski 2007) thrust zones (figs. 9, 11, 12). Locally the Silesian Nappe is missing and the Subsilesian Nappe contact directly the Magura Nappe. Several imbricated scale-folds build up the Subsilesian Nappe. In the Andrychów area several blocks known as Andrychów Klippes contain crystalline rocks as well as Jurassic, Cretaceous and Paleogene Limestones. Traditionally they were considered as tectonic slices in linked to the Silesian Nappe front, recently the opinion about their olistostrome origin prevails (Cieszkowski et al., 2009, Golonka et al., 2009). In the frontal part of the Silesian Nappe, north of the town Krosno (Ślaczka et al., 2006) the Subsilesian Nappe is exposed in the Węglówka area (Figs. 8, 13), The seismic survey and wells connected with the Węglówka oil field show that it is steeply thrust over the Skole Nappe.

#### 4.2.5 The Skole Nappe

The Skole Nappe forms a large, 40 kilometers wide, portion of the eastern part of the Northern Carpathians and is thrust over the Miocene sediments that cover the North European Platform (Figs. 13, 14). The most distinctive structural feature of this nappe is occurrence of large thrust-folds "skybas" (duplexes) thrust over each other in the north-east direction and traced for several hundreds of kilometers along the stretch of the Carpathian Arc. The width of such "skybas" is from the single kilometers up to 12 km (Ślaczka et al., 2006).

Towards the west, the well defined Skole Nappe plunges under the Subsilesian and Silesian nappes near Brzesko (Fig. 2), and its prolongation further towards the West is not clear. According to Żytka et al. (1989) and Paul et al. (1996) the Skole Nappe is thrust over the

Miocene deposits of Carpathian Foredeep in the area north of Wadowice and Andrychów (Golonka et al., 2009). This tectonic element contains the deposits of the basin and slope part of the Skole Basin as wells of Subsilesian Sedimentary Area and is very hard to distinguish from the Subsilesian Nappe. Additionally some of these formations could form huge olistoliths within the Neogene deposits in the frontal part of the Outer Carpathians (Cieszkowski et al., 2009; Golonka et al., 2009).

South-west from the town of Przemyśl the folds create a sigmoidal arc which reflects a similar sigmoidal bend of the Carpathian margin. Near the town of Rzeszów the marginal part of the Skole Nappe is covered by Miocene molasses, which form a piggy-back basin. Farther towards the west, near the town of Pilzno the northern part of the Skole Nappe is probably folded together with the Miocene cover. The inner part of the Skole Nappe is represented by a synclinal area built of several folds with broad synclines composed of the Oligocene/Lower Miocene Krosno Beds (Ślaczka et al., 2006). The thrust-plane of the Skole Nappe changes from a very gentle to a very steep.

#### 4.2 The major faults and their origin

The Carpathian nappes are cut by several major faults of different origin. Some of these faults are local, some form the huge systems sometimes over one hundred kilometers long. These systems affected all outer Carpathian nappes, the Pieniny Klippen Belt and the Inner Carpathians. An oblique collision between the North European Plate and the West Carpathians terranes invading it, lead to development of outer accretion prism, formation of a range of flysch nappes and formation of a foredeep (Ślaczka et al., 2006). Through the Miocene tectonic movements caused final folding of the basins fill and created several imbricate thrust sheets (nappes) which generally reflect the basin margin configurations after the Cretaceous reorganization and Paleogene development of the Carpathian accretionary prism. The thrust faults dip southward. 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. Displacement of the Carpathians northwards is related to development of dextral strike-slip faults of N–S direction. Typical strike-slip fault is limited on the west and on the east by normal faults, configuration of which is similar to an asymmetrical flower structure. The orientation of this strike-slip fault zones zone more or less coincides with the surface position of the major faults (e.g. Skawa river fault zone) perpendicular to the strike of the Outer Carpathian thrust sheets. Some normal faults of E-W orientations were renewed during the final stress period and they controlled formation of morphostructures – horsts and depressions of E-W orientation. A fault of this type is perfectly visible in the seismic profiles (Pietsch et al., 2007). It has the NEE – SWW orientation. This huge fault cuts formations from the Paleozoic basement through the flysch allochthon between the boreholes Zawoja 1, from the south, and Sucha Beskidzka1 and Lachowice 7, from the north (Figs. 5, 10). The displacement of nappes of the Carpathian overthrust and diapiric extrusion of plastic formations of the lower flysch units occurred along this fault, which constitutes fragment of the major Vienna-Krakow fault zone. Another major fault zone is known as Krakow- Presov fault (Žaba 1999). It is an extension of subsequent mutual strike-slip displacements of the two blocks along the Kraków-Lubliniec Fault Zone (Żelaźniewicz in Golonka et al. 2005a). This fault was active through the Phanerozoic times until Quaternary (Zuchiewicz et al. 2002; Tokarski et al. 2006). It extends southeast from Krakow under the Outer Carpathian thrust to Rajbrot south of Bochnia (Kraków-Rajbrot fault, see Moryc 2006).

and according to further through Gorlice area to Polish-Slovak border and to Presov area in Slovakia (Žaba 1999; Zuchiewicz et al. 2002).

The thrust faults in the area southeast of Krakow clearly indicate the compressional regime (Figs. 6, 7, 12). Stress data point to present-day compressive reactivation of the Carpathians (Jarosiński in Golonka et al., 2005a). 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. 2005a). The Krakow- Smilno Fault system (Figs. 1, 2) marks the 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 (Pietsch et al., 2010). The thrust system is also related to the triangle zone located in the Miocene sequences north of investigated area (Fig. 7).

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. The normal thrustsheet (nappe) sequence of the Polish Outer Carpathians is from south to north: Magura, Fore-Magura, Silesian, Subsilesian and Skole. The strike-slip associated migration causing thrusting of Fore-Magura unit over Magura unit and Subsilesian Unit over Silesian Nappe.

The series of deep-rooted transversal faults dislocates the flysch nappes as well and their basement in the eastern part of Poland, close to the Polish-Ukrainian border. These dislocations are known as the so-called Przemyśl Sigmoid, marking the transitional zone between the northern and eastern part of the Carpathian arc.

## 5. Plate tectonic evolution

The western part of North European platform, known as The Bruno-Vistulicum plate, was consolidated in Late Proterozoic (Vendian) during Cadomian orogeny. It was amalgamated with the eastern part (Małopolska Block) during Paleozoic times.

The southern part of the North European Platform, started to be rifted and new basins were created during the Jurassic times. The Alpine Tethys, which constitutes important paleogeographic elements of the future Outer Carpathians, developed as an oceanic basin during Jurassic as a result of the Pangea break-up (Golonka et al, 2006, 2007). The NE part of the Alpine Tethys between Carpathian- Eastern Alpine terrane and North European Platform is known as Pieniny Magabasin. The NW part of this megabasin is Magura Basin (Fig. 15). This basin is separated by the Czorsztyn Ridge from the Pieniny Klippen Belt Basin. The Silesian Ridge is an uplifted area, originally part of the North European platform separating during Jurassic-Early Cretaceous times the Magura and the Severin-Moldavide basins. It is known only from exotics and olistoliths occurring within the various allochthonous units of the Outer Carpathians.

The following geodynamic evolution stages could be distinguish in the Outer Carpathians: I –synrift and postrift, formation of passive margin and basin with the attenuated crust, II – collisional, development of subduction zones partial closing of oceanic basin, development of flysch basin, III – orogenic, perhaps terrane – continent collision with the accompanying convergence of two large continents, IV – postcollisional. These stages correspond with the global sequence stratigraphy, the three supersequences encompassing one stage.

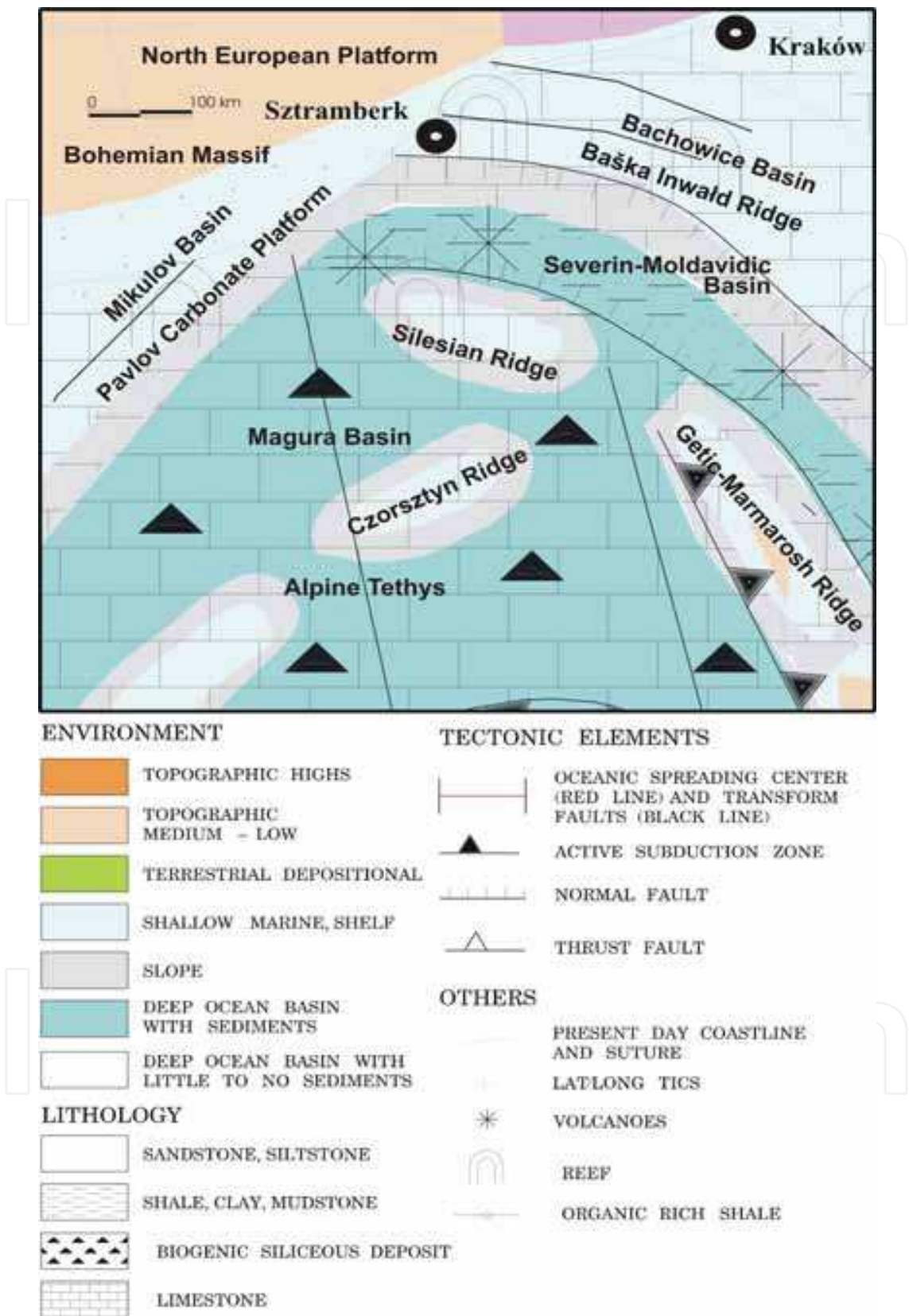


Fig. 15. Paleoenvironment and paleolithofacies with main paleogeographical element of the West Carpathians and adjacent areas during the latest Jurassic – Early Cretaceous (from Golonka et al., 2008, modified). Plate position 140 Ma.



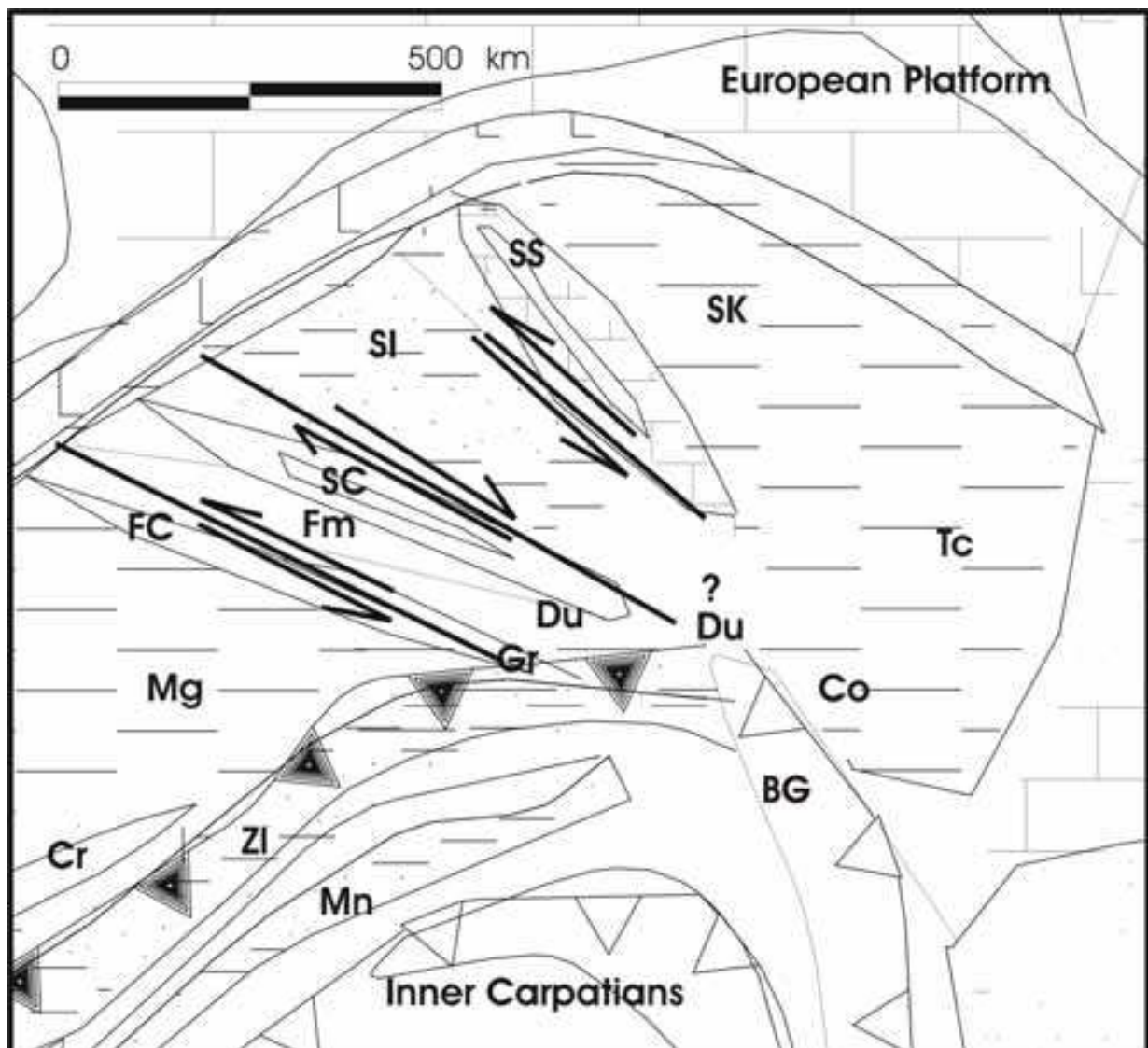


Fig. 16. Paleogeography of the Outer Carpathian basins during Late Cretaceous. Explanations as on Fig. 15. Abbreviations: BG = Bucovinian-Getic, Co = Cornohora, Porkulec, Audia, Teleajen, Cr = Czorsztyn ridge, Du = Dukla, FC = Fore-Magura ridge (cordillera), Fm - Fore-Magura basin, Gr = Grybów, Mg = Magura, Mn = Manin, Si = Silesian basin, SK = Skole, SC = Silesian ridge (cordillera), SS = Sub-Silesian ridge, Tc - Tarcau, Zl = Zlatna. From Golonka et al. (2005b).

The shallow-water marine sedimentation prevailed on the Silesian Ridge during Late Jurassic and earliest Cretaceous times. The carbonate material was transported from the ridge toward the Severin-Moldavidic Basin. Severin-Moldavidic Basin developed within the North European Platform as rift and/or back-arc basin. Its basement is represented by the attenuated crust of the North European plate with perhaps incipient oceanic fragments. The sedimentary cover is represented by several sequences of Late Jurassic - Early Miocene age belonging recently to various tectonic units in Poland and Czech Republic (Golonka et al., 2007).

The rifting process was accompanied by a volcanic activity, which persisted up to the end of Hauterivian. The Late Jurassic - Hauterivian deposition of the Severin-Moldavidic was

controlled by syn-rift subsidence and later (Barremian-Cenomanian) by post-rift thermal subsidence, which culminated with the Albian-Cenomanian expansion of deep-water facies. The Cenomanian – late Eocene collisional stage is characterized by formation of subduction zones along the active margin, partial closing of oceanic basin and development of main flysch basins associated with these rifting on the platform (passive margin) with the attenuated crust. Several basins became distinctly separated within the Outer Carpathian realm (Figs. 16-17). Severin-Moldavidic basin was divided by the Subsilesian Ridge into Silesian and Skole basins. Also Fore-Magura basins emerged during these times. From uplifted areas, situated within the Outer Carpathian realm as well as along its northern margin, enormous amount of clastic material was transported by various. Each basin had the specific type of clastic deposits, and sedimentation commenced in different time (Golonka et al., 2005b).

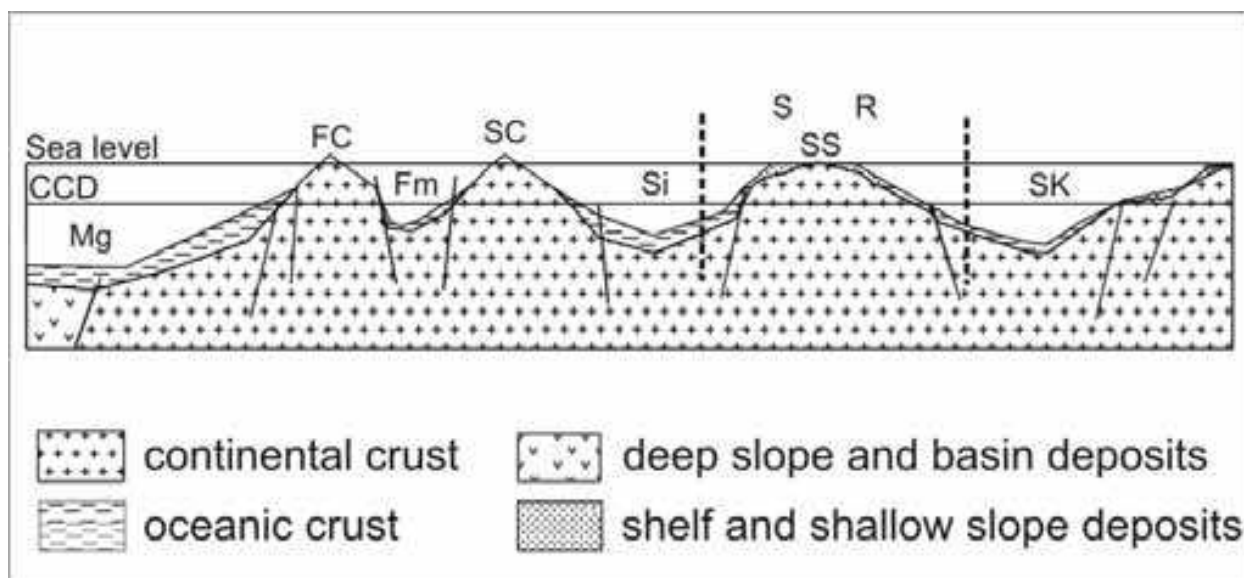


Fig. 17. Palinspastic cross-section showing the Outer Carpathian basins during Paleocene. Abbreviations: FC = Fore-Magura Ridge, Fm = Fore-Magura Basin, Mg = Magura Basin, Si = Silesian Basin, SK = Skole Basin, SC = Silesian Ridge, SS = Sub-Silesian Ridge, SR = Subsilesian sedimentary area. (From Waśkowska et al., 2009).

The Latest Eocene – Burdigalian – orogenic stage is characterized by collision, perhaps terrane – continent, with the accompanying convergence of two large continents. In the circum-Carpathian region, Adria-Alcappa (Inner Carpathians) terranes continued their northward movement during Eocene-Early Miocene times (Golonka et al., 2006). Their oblique collision with the North European plate led to the development of the accretionary wedge of Outer Carpathians. During the Priabonian and Rupelian, a prominent uplift in the Outer Carpathian basin was recorded. The Outer Carpathian remnant oceanic basins turned into foreland basins. Through the Miocene Africa converged with Eurasia. The direct collision of the supercontinents never happened, but their convergence did not leave much space, leading to the permanent setting of the Alpine-Carpathian system. Tectonic movements caused final folding of the basins infillings and created several imbricated nappes, which generally reflect the original basin configurations. During the overthrusting movements, the marginal part of the advanced nappes has been uplifted, whereas in inner part

sedimentation lasted in the remnant basin. Big olistoliths often glided down from uplifted part of the nappes into the adjacent, more outer basins (Cieszkowski et al., 2009). The nappes became uprooted from the basement and the Outer Carpathians allochthonous rocks overthrust northward in the west and eastward in the East onto the North European platform for the distance of 50 km to more than 100 km.

Overthrusting movements migrated along the Carpathians from the West towards the East. In front of the advancing Carpathians nappes the inner part of the platform, in the eastern part also with the marginal part of the flysch basin started to downwarp and tectonic depression formed during the Early Miocene. Thick molasse deposits filled up this depression. At the end of Burdigalian that basin became overthrust by the Carpathians and a new, more external one, developed. Clastic and fine-grained sedimentation of the

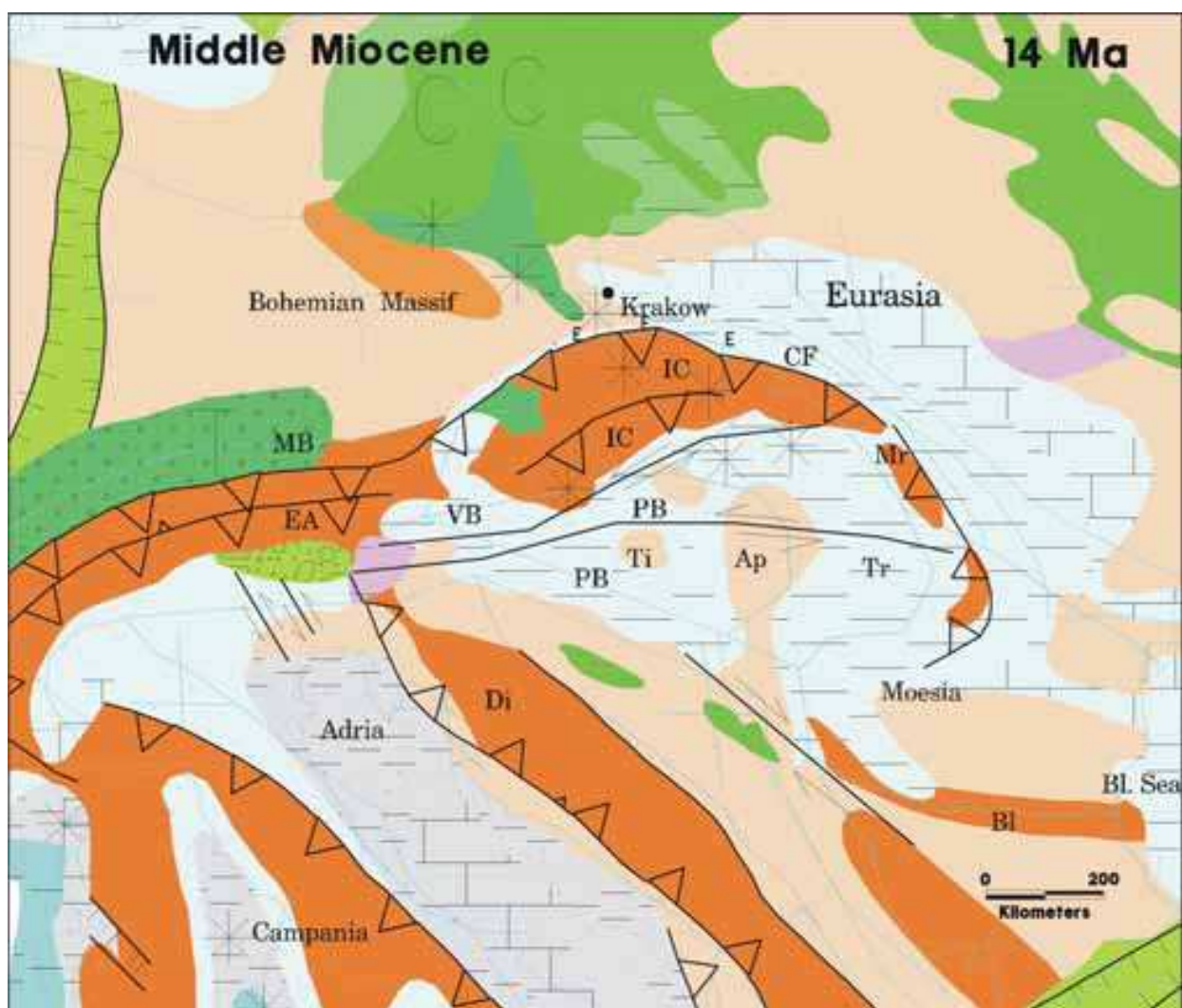


Fig. 18. Paleoenvironment and lithofacies of the circum-Carpathian area during Middle Miocene (Burdigalian- Serravallian); plates position at 14 Ma (Modified from Golonka et al., 2000, 2006). Explanations as on Fig. 15. Abbreviations: Ap – Apusen Mountains, Bl – Balkan foldbelt, CF – Carpathian Foredeep, Di – Dinaric Mountains, EA – Eastern Alps, IC – Inner Carpathians, MB – Molasse Basin, Mr – Marmarosh Massif, PB – Pannonian Basin, Ti – Tisa plate, Tl -Teleajen Basin, Tr – Transilvanian Basin, VB – Vienna Basin.



Carpathian and foreland provenance prevailed with a break during the Late Langhian to Early Serravallian, when younger evaporate basin developed. Locally olistostromes were deposited with material derived from the Carpathians and the inner margin of the molasse basin. During Langhian and Serravallian part of the northern Carpathians collapsed and sea invaded the already eroded Carpathians (Fig.18). The Carpathian foreland basin continued its development partly on the top of the thrust front with mainly terrestrial deposits forming the clastic wedge. This clastic wedge along the Carpathians could be comparable with the Lower-freshwater Molasse of the Alpine Foreland Basin. During the Serravallian the marine transgression flooded the foreland basin and adjacent platform (Golonka et al, 2000, 2003, 2005a, 2006).

The foreland basin and its depocenter migrated outwardly and eastward during Langhian and Tortonian times, contemporary with the advancing Carpathians nappes. As a result the Neogene deposits show diachrony in the foreland area. In the west sedimentation terminated already in Langhian and in the east lasted till Pliocene. These events mark the postcollisional stage in the Outer Carpathian evolution.

The SW-NE direction of the compression and the movement of the Carpatho/Pannonian lithospheric blocks is typical for the Tortonian times. An active front of orogen has been removed far from Western Carpathians area. The NE-SW compression was gradually inverted to extension. The E-W extension was induced in the Carpathian realm due to the westward direction of subducting plate (Royden et al., 1982; Doglioni et al., 1991) and related roll back effect. Numerous new N-S oriented faults developed and many old strike-slip faults were reactivated as normal extensional faults within this youngest tensional event. Normal faults played a dominant role as sedimentation controlling structures. These faults are the most numerous and conspicuous brittle features within the recent architecture of the Western Carpathians (Golonka et al. 2006, 2009.)

## 6. Conclusions and future work

1. The Late Precambrian to present plate tectonic process contributed to the complex structure of the northern Outer Carpathians and their basement.
2. The newest geological and geophysical research confirmed the nappe structures of the Outer flysch Carpathians and defined relationship between basement and flysch nappes.
3. The out-of-sequence-thrusts within the nappe system reflect the influence of deep rooted faults.
4. The basement structure in the western and eastern part of the investigated area, divided by the Krakow-Presov displays different structural styles.
5. The western fault systems developed under mainly extensional regime with strong strike-slip component while the eastern fault systems developed under mainly compressional regime.
6. The deep structure of northern Outer Carpathians is well constrained in the marginal part of the nappe system and speculative in the inner, southern part.
7. The development of Carpathian Foredeep basin is related to the advancing Outer Carpathian nappes.
8. The answer to the remaining scientific questions requires several reflexion seismic transects through the whole Outer Carpathians.
9. The deep drilling in the Orava area has been postulated (Golonka et al., 2005a).



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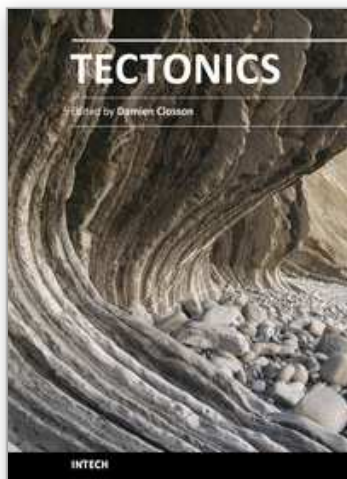


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The term tectonics refers to the study dealing with the forces and displacements that have operated to create structures within the lithosphere. The deformations affecting the Earth's crust are result of the release and the redistribution of energy from Earth's core. The concept of plate tectonics is the chief working principle. Tectonics has application to lunar and planetary studies, whether or not those bodies have active tectonic plate systems. Petroleum and mineral prospecting uses this branch of knowledge as guide. The present book is restricted to the structure and evolution of the terrestrial lithosphere with dominant emphasis on the continents. Thirteen original scientific contributions highlight most recent developments in seven relevant domains: Gondwana history, the tectonics of Europe and the Near East; the tectonics of Siberia; the tectonics of China and its neighbourhood; advanced concepts on plate tectonics are discussed in two articles; in the frame of neotectonics, two investigation techniques are examined; finally, the relation between tectonics and petroleum researches is illustrated in one chapter.

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