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Basement structure below the West-Carpathian–East Carpathian orogen junction (eastern Poland, north-eastern Slovakia and western Ukraine)

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Abstract: The morphology and tectonics of the consolidated basement of the Carpathians has been analysed using magnetotelluric and deep seismic sounding. The results of these two methods allow for reconstruction of the depth of the consolidated basement in a similar manner. The magnetotelluric sounding has mainly been applied for the area of Poland and deep seismic sounding for the area of Slovakia and Ukraine. The products of the research are: the map of the depths of the consolidated basement, sketch of the main tectonic elements layout and numerous deep cross-sections. It has been stated that the morphology of the consolidated basement of the Carpathians is very variable. The depth of the top of the consolidated basement ranges from a few kilometers to ca. 24 km. The top surface of the basement dips from the north-west towards the east. It has the shape of a trough with the Tarnów–Putila axis. North and south of the trough axis the surface of the consolidated basement rises from a few to several kilometers at the Carpathian overthrust and the Pieniny Klippen Belt, respectively. The greatest drops are observed in eastern part of the studied region, in Ukraine, where the surface of the consolidated basement is at depths below 22 km. The axis of the largest depths of the consolidated basement from Rahiv to Krosno is regular and has a SE–NW orientation. Near Krosno, it bends southward to the Krynica region where it again reverts to the SE–NW orientation. The consolidated basement between the Dunajec and Tisa rivers has a blocky pattern and is dissected by numerous longitudinal and transverse dislocations. Along the transverse dislocation, this surface is systematically thrown in a south-eastern direction. The basement surface between the "regional basement slope" and the peri-Pieninian dislocation has a form of the trough with the axis Rahiv–Krynica. This graben is likely filled up with Paleozoic and Mesozoic deposits. It is believed that flysch units are rooted in this graben.

Key words: Carpathian Foreland, consolidated basement, tectonics, dislocations, seismic and magnetotelluric sounding.

Introduction

The purpose of this paper is to determine the depth and the tectonics of the consolidated basement of the Carpathians in south-eastern Poland, north-eastern Slovakia and western Ukraine between the Dunajec and Tisa rivers. The study area (Fig. 1) extends between south-eastern Poland, from the Dunajec river line to the state border, and north-eastern Slovakia, from Vyšné Ružbachy to the Ukrainian border, as well as south-western Ukraine, from its border with Poland and Slovakia to the Tisa Valley. In geological terms the study area extends between the Carpathian overthrust in the north to the Pieniny Klippen Belt in the south. Magnetotelluric sounding was mainly applied for the area of Poland and deep seismic sounding for the areas of Slovakia and Ukraine. Interpretation of the magnetotelluric sounding of the Polish part of the Western Carpathians was based on the examination performed by Przedsiębiorstwo Badań Geofizycznych (*Geophysical Exploration Company*) of Warsaw in 1986–1990 (Molek & Oraczewski 1988; Molek & Klimkowski 1991) and papers by Ryłko & Tomaś (1989, 1990, 1991, 1995a,b, 1998, 1999a,b, 2001). In Slovakia the seismic profiles obtained in the region of Košice have been used. These are profiles 80/87 and 84/85 in the region of the Topľa river and profiles 107/88 and 107/89 along the Stropkov–Medzilaborce line and profile 53/83 in the region of Sabinov (Vozár & Šantavý 1999). Their interpretation by Slovak geologists (Varga & Lada 1988; Tomek et al. 1987, 1989, 1993; Dvořáková et al. 1992; Tomek 1993; Červ et al. 1994) has been used as well. In the case of western Ukraine, UkrNIGRI materials of the MGPD international project and materials of the West-Ukrainian Geophysical Expedition have been used. These are deep seismic soundings along the geotraverses: Horohiv–Sambir–Užgorod, Višnieviec–Dolyna–Berehove, Gorodok–Kolomyja–Rahiv and Putila–Viseu de Sus. Papers by Ukrainian geologists (Borisov & Kruglakova 1962; Jarish et al. 1969; Rokutianskiy 1975; Subottin et al. 1976; Burianov et al. 1977, 1978; Dolenko et al. 1978; Kruglov et al. 1985; Sheremeta Ed. 1999) have been used as well.

High-frequency magnetotelluric survey along 17 regional transects was performed in the Carpathians during 1997–2003. Unfortunately, they are of limited access. Therefore, the authors used only the data available in the published materials in this domain (Stefaniuk et al. 1998, 1999; Czerwiński & Miecznik 1999; Stefaniuk & Klityński 1999, 2000; Stefaniuk & Pepel 2000; Stefaniuk & Wójcicki 2000; Królikowski et al. 2000; Czerwiński & Stefaniuk 2001; Klityński & Wójcicki 2001; Królikowski & Petecki 2001; Stefaniuk 1999, 2000, 2001).

The map of the depths of the consolidated basement, sketch of the layout of the main tectonic elements and numerous deep

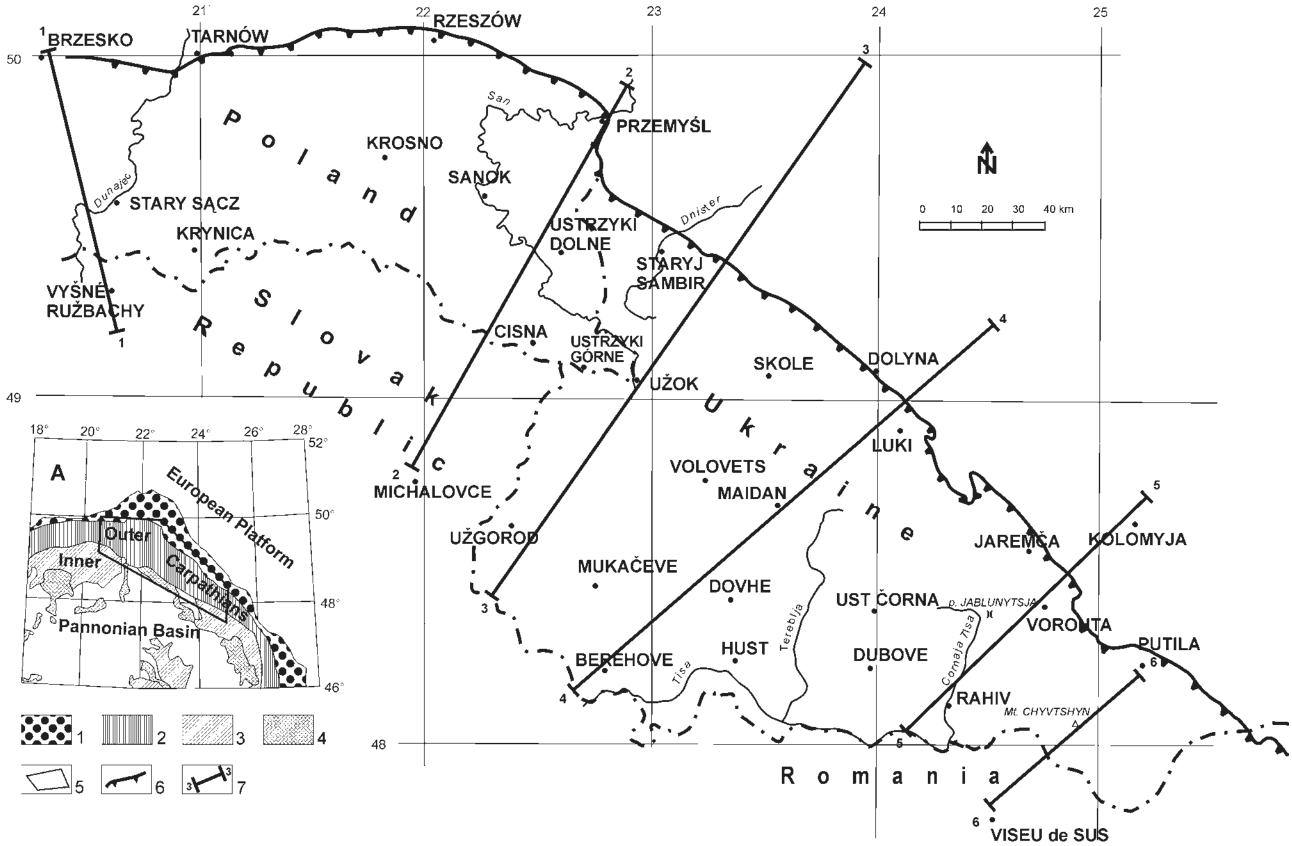

Fig. 1. Schematic tectonic map of the Carpathian region with location of the deep geological profiles. **1** — Foredeep, **2** — Outer Carpathians, **3** — Inner Carpathians, **4** — Neogene volcanics, **5** — Outline of studied area, **6** — Outer Carpathians — northern boundary, **7** — Lines of the deep geological profiles.

cross-sections has been derived. The analysis of the morphology of the consolidated basement has been performed using mathematical statistics. The point results of the depths of the basement have been approximated by krigging method using SURFER software. Based on the point depths of the consolidated basement, regional seismic profiles and their former interpretations (op.cit.) the major tectonic elements and cross-sections have been sketched.

Geology of the consolidated basement of the Carpathians

Main structural-geological units of Paleozoic basement of the Carpathians and their Foredeep as distinguished in the studied area

The study area is located in the range of two geological units formed by tectonic processes of the Alpine orogenesis, i.e. the Outer Carpathians and the Carpathian Foredeep. The basement of these structural-geological units includes Mesozoic platform deposits and lithologically, facially and thickness differentiated Paleozoic deposits. They form vari-aged structural zones resting on tectonic units known as: the Upper Silesia and Malopolska block, massifs and terrans (Bukowy 1964, 1984; Brochwicz-Lewiński et al. 1968; Pożaryski & Kotański 1979; Bogacz 1980; Kotas 1982, 1985; Pożaryski 1990; Pożaryski et al. 1992; Pożaryski & Tomczyk 1993; Buła 1994, 2000; Buła & Jachowicz 1996; Buła et al. 1997; Żaba 1999).

The Upper Silesia and Malopolska block, formed of Precambrian rocks of various genesis and metamorphism are often jointly called "the consolidated basement of the Carpathians" (Ryłko & Tomaś 1999a,b, 2001).

In recent years lithostratigraphic and tectonic studies on the Lower Paleozoic deposits in the Lubliniec-Kraków Upper Silesia and western Malopolska regions have been performed. The outcomes of these studies became the background to identification of the 0.5 km wide Kraków-Lubliniec tectonic zone separating the Upper Silesia block from the Malopolska one (Buła 1994, 2000; Buła et al. 1997; Żaba 1999). The zone is reliably documented in the section between Myszków and Kraków. A precise location of this zone south-east of Bochnia is difficult as the Paleozoic basement plunges under the Carpathian Flysch very rapidly.

Multi-phase tectonic development of the zone Kraków–Lubliniec, which continues in the Paleozoic basement of the Carpathians south-east of Kraków, had an influence on differentiated sedimentation of Paleozoic deposits, especially the Lower Paleozoic ones, on the Upper Silesia and Malopolska block. Detailed treatment of the stages of structural evolution of the Paleozoic sequences of the border zone of the Upper Silesia and Malopolska blocks is given in the work of Żaba (1999).

The Upper Silesia block together with the Brno block (Moravia) in the west belong to a larger tectonic unit, which is called Brunovistulicum by Dudek (1980) or Brno (Brunii) — Upper Silesia massif according to Kotas (1982, 1985). The Upper Silesia block is the tectonic unit of Cadomian consolidation and is built of Precambrian crystalline and anchimetamorphic rocks (Dudek 1980; Moryc & Heflik 1998). The Precambrian rocks of the Upper Silesia block have been identified in the boreholes only in the southern part in the basement and in the direct foreland of the Outer Carpathians.

The crystalline Bruno-Vistulicum basement is exposed in the south-western part, in region of Brno (so-called Brunia — Zapletal 1933). Maybe, the consolidated basement is represented by the Proterozoic series as well, exposed in the north-eastern margin of the Upper Silesia block in the Eastern Sudetes. The existence of the older crystalline basement here was assumed for a long time (Petrascheck 1928; Stille 1948, 1951), however, at first a considerably greater extent to the north-eastern so-called Vistulicum (Stille 1948, 1951) was supposed. Bukowy (1964), on the basis of the results from the boreholes in the southern border of the Upper Silesia Coal Basin, distinguished the so-called Cieszyn block which horizontal range coincides in general with the Bruno-Vistulicum area, distinguished later by Dudek (1980). The Bruno-Vistulicum block is delimited on all sides by large, crustal, structural discontinuities which, most often, were active many times. The Moravian-Silesian zone is the western boundary of the discussed block. The south-eastern and southern margins of the Bruno-Vistulicum dip under the Carpathian overthrust (Karnkowski 1977; Dvořák 1978, 1995; Tomek 1993). It is assumed the peri-Pieninian Fault Zone is perhaps the southern boundary of this block (Sikora 1976; Dudek 1980; Kotas 1982). It is possible, however, that the crystalline Bruno-Vistulicum basement extends further southward, and plunge under the Inner Carpathian structures. In the north-east the Bruno-Vistulicum borders with the Malopolska block, where the Kraków–Lubliniec Fault Zone separates the two (Buła 2000). Near Kraków this fault dips under the Carpathian overthrust front (Buła 1994) and continues further towards east as far as Ukraine (Ryłko & Tomaś 2003a,b). In the west, the Kraków–Lubliniec Fault Zone is jointed probably with the Odra Fault Zone and becomes an element of the transcontinental dislocation zone Hamburg–Kraków Fault Zone (Żaba 1995).

The Malopolska block is a tectonic unit for which a consolidation age as well as the northern and north-eastern boundaries have not been determined yet. The anchimetamorphic clastic rocks are the oldest rocks forming the Malopolska block (Samsonowicz 1955; Głowacki et al. 1963; Głowacki & Karnkowski 1963; Jawor 1970; Jurkiewicz 1975; Karnkowski 1977; Kowalczewski 1981; Kowalski 1983; Buła 2000; Moryc & Jachowicz 2000; Moryc & Łydka 2000). These rocks have been identified in various regions of the block apart from the Kielce part of the Holy Cross Mountains and are represented by claystones, mudstone and sandstone locally accompanied by conglomerates and sporadically by inserts of tufaceous rocks. The discussed rocks differ in colours and are: green, dark grey with greenish or pale greenish shade, maroon, slate grey or greyish-violet. These rocks are strongly lithified, massive, with dips in a range of 40°–90° (smaller dips rarely), vertically cleaved in places, with variable anchimetamorphism in the greenstone facies, phyllitified in certain segments (that mainly refers to the profile sections formed by clayey-mudstone rocks).

East of the tectonic zone Kraków–Lubliniec (apart from Kielce part of the Holy Cross Mountains), the rocks with aforementioned features are topped with inconsequently arranged, vari-aged rocks of the Paleozoic, Mesozoic and Tertiary, beginning with the Ordovician and ending with the Miocene. The stratigraphic position of anchimetamorphic crystalline rocks is a subject of years lasting discussions. Primarily, the anchimetamorphic crystalline rocks were assumed to be Vendian and were compared with the Vendian phyllites of Dobrogea (Głowacki & Karnkowski 1963). On the basis of the acritarch studies carried out by G. Vidal (*in:* Pożaryski et al. 1981) they were believed to be Lower Cambrian. On the basis of more recent palynological studies of anchimetamorphic rock samples from Zalasowa 1 and Stawiska 1 boreholes located near Tarnów, Jachowicz (*in:* Moryc & Jachowicz 2000) has identified Vendian acritarchs.

At the current state of research it can be accepted that the anchimetamorphic rocks representing the Malopolska block are of the Vendian age. In the southern part of the massif (between Bochnia–Tarnów–Rzeszów) and further in Ukraine they have been identified under the Ordovician or younger rock complexes. They are commonly assumed to be flysch deposits and due to that they differ from the Cambrian of the Upper Silesia block and the Cambrian of the Holy Cross Mountains (Buła 2000).

On the Upper Silesia block, the position of the Cambrian deposits with respect to the Precambrian ones is clearly defined (Buła 2000). On the other hand, in the case of the Malopolska block this problem has not been solved yet and is a subject of numerous ongoing discussions. According to Pożaryski & Tomczyk (1968) and Jurkiewicz (1975) the Malopolska and Sandomerian orogeny played an important role in sedimentation-diastrophic development of the Vendian–Lower Cambrian sediments in the Holy Cross Mountains. Pożaryski & Tomczyk (1968), Jurkiewicz (1975) and Znosko (1996) assume these orogeny movements to be in the Vendian yet in an undefined time interval. The movements resulted in folding and disjunctive deformation of rock complexes. Jurkiewicz (1975) attributes a weak regional greenstone facies metamorphism of the Vendian rocks to the Malopolska orogeny. That author considers the Upper Vendian-Cambrian rocks, which he assigns to the Sandomerian stage, to rest disconformably on the rocks of the Malopolska stage. According to Pożaryski (*in:* Pożaryski 1990; Pożaryski et al. 1992) the Vendian–Lower Cambrian rocks form the base of the Malopolska block, on which the Ordovician deposits rest almost horizontally.

For understanding the geological structure of the Malopolska block it is important to realize that the paleontologically documented Cambrian rocks, known from the Kielce part of the Holy Cross Mountains and from the region of Tarnogród–Lubaczów, have a limited extent and do not spread out over the entire area of the Malopolska block. They are present only in the northern and north-eastern part of the block.

The oldest Lower Paleozoic rocks, which have been found over the entire area of the Malopolska block, represent the Ordovician and Silurian. They rest disconformably on the Precambrian and (Lower and Middle) Cambrian. This inconsistence is emphasized by sedimentation disconformity and angular discordance of various magnitudes. The size of the stratigraphic gap between the Ordovician deposits and the older basement in the Malopolska block increases in the southern and western directions.

Remarks on the consolidated basement exotics and their occurrence in the flysch Carpathians and in the Carpathian Foredeep deposits

In the flysch Carpathian basement, the Mesozoic–Paleozoic are underlain by Precambrian crystalline and metamorphic deposits known from the literature as the crystalline basement or consolidated basement (Nowak 1975; Karnkowski 1977; Oszczypko et al. 1989; Buła et al. 1997; Buła 2000; Ryłko & Tomaś 2001). Until now, the crystalline basement of the Polish Carpathians has been recognized by a few boreholes. It is best documented in the western and northern part of the Polish sector of the flysch Carpathians where it rests relatively shallow (Ryłko & Tomaś 2001). In the western part two regions are distinguished. The first region is located between Bielsko and Andrychów while the second one is located between Rzeszotary–Dobczyce–Wiśniowa. In the region Bielsko–Andrychów the consolidated basement is under the flysch, Miocene and Paleozoic (mainly Devonian) deposits. In the area Rzeszotary–Dobczyce–Wiśniowa the consolidated basement is under the Carpathian Flysch and the Mesozoic rocks. The metamorphic Precambrian deposits, mainly schists, gneisses and granitoides as well as, locally, pyroxene-olivine gabbros (borehole Andrychów 2) have been stated there.

In the northern part of the flysch Carpathians, located east of the Tarnów meridian, the consolidated basement has bean drilled in several boreholes in the region of Brzozowa, Rzeszów, Dubiecko, Przemyśl and Cisowa.

Borehole Cisowa IG-1 has provided interesting evidence with respect to the nature of the deposits forming the consolidated basement as well as its tectonics (Wdowiarz et al. 1974). In the borehole profile, from the depth of 4310 m to 4365.5 m the so called autochthonous basement has being drilled. According to Wieser's description (in: Wdowiarz et al. 1974) the basement is built of muddy or muddy-calcareous metaargillites known in the literature as phyllitized clayey shales (Głowacki & Karnkowski 1963), phyllites (Parachoniak 1963) or mudstones (Łydka & Siedlecki 1963).

The roks representing the consolidated basement, identified in the boreholes located in the northern and eastern parts of the flysch Carpathians show a complete consistence with the analogue rocks that have been recognized earliest and best in the area of the Carpathian Foreland (Karnkowski 1977). That area has been examined due to geological-prospecting of hydrocarbon deposits. The boreholes usually pierced the Miocene series that fill the Carpathian Foredeep and reached to the underlying Mesozoic and Paleozoic rocks at the basement (Karnkowski & Głowacki 1961). Beneath, in some cases directly under the Miocene deposits, phyllitized clayey shales and mudstone, with inserts of fine-crystalline quartzites, have been found. The dips of the laminas are very high, 70–90°. These deposits are of the Riphean age according to Samsonowicz (1955).

In the central and south-eastern part of the eastern sector of the flysch Carpathians, comprising the Ukrainian Carpathians as well, where the flysch is over 8000 m thick, the consolidated basement is exclusively known from the exotics encountered in the flysch and from tectonic detached blocks. The exception is the Marmarosh massif in the Ukrainian part of the Carpathians, where the crystalline rocks and calcareous Mesozoic deposits covered with the flysch occur on the surface. Accepting to Nowak's opinion (1927) it can be assumed that the crystalline rocks of the Marmarosh massif form the basement in the eastern part of the Flysch Carpathian Geosyncline.

The majority of rounded clasts stated in the conglomerates that occur in the Paleogene profile of the flysch of the northern slope of the Ukrainian Carpathians and in the Miocene molasses of the Carpathian Foredeep are metamorphic rocks known from the literature as phyllites, phyllite shales or exotic crystalline rocks. Paul & Tietze (1877) distinguished these rocks, in the conglomerates of the Ropienice Beds of the Skole Unit and elsewhere. According to them the exotic material was supposed to originate from the old cordillera bounding the Carpathian basin from the north-east. In the region of Bukovina green shales and Jurassic limestones accumulated in the flysch rocks were believed to be root elements protruding to the surface. These root elements comprise the conglomerates often built of chunks of phyllites and Jurassic limestones with a small amount of matrix also built of similar material.

In the conglomerates, stated in the profile of the Upper Cretaceous of the northern slope of the Eastern Carpathians, the metamorphic rocks occur in Sambir and Pokutsk–Bukovina Carpathians but they are absent or occur in small quantities in inter-basins of the Opir and Prut rivers. These rocks are commonly stated in the conglomerates of the Paleogene deposits profile. In the conglomerates, which occur in the deposits of the lower molasses of the Carpathian Foredeep, the discussed rocks have been stated in the Polanice and Worotyszcze Beds in the area of the entire fore-Carpathians excluding the north-western region (Sambir, Chiriv, Dobromil).

In the conglomerates metamorphic rocks have been found. The metamorphic rocks can be divided into three groups. The first group comprises the finest fractions of metamorphic rocks, represented by mudstones cherry-red, green and grey and shales. The maximum concentration of red mudstones and shales has been reported in the Paleogene of the Sambir Carpathians and in the Miocene conglomerates of the fore-Carpathians in the region of Truskavets and Nagujevič. In the inter-basin of the Opir and Prut rivers they occur rarely, they do not occur in the deposits south-east of the Rybnica river. The maximum concentration of the green and grey shales of this group has been reported in the Sambir Carpathians. They disappear rapidly from the deposits towards the south-east of the Opir river. In Poland the discussed deposits have been stated in borehole Jarosław-1 (1642.3–1648.7 m), Kańczuga-1 (1587.5–1590.0 m), Wola Ryżkowa (792.2–798.0 m) and Lipnica (924.0–927.0 m).

The second group of exotic rocks comprises the grey schists. The described rocks have been found in Paleogene conglomerates and in the Miocene molasses filling the Carpathian Foredeep in the area located south-east of the Bystrytsja Nadvornjanska river to the Romanian boundary. Their maximum concentration has been reported in the Pokutsk Carpathians. North-west of the Opir river the exotic rocks of the discussed group have not been reported.

The third group of exotic rocks comprises: crystalline dark green schists. The rocks have been stated only in the conglomerates occurring in the Polanytsa Formation of the Pokutsk–Bukovina Carpathians. They are encountered sporadically in other beds of the northern slope of the Ukrainian Carpathians and the Carpathian Foredeep.

The metamorphic schists, exotic to the flysch Carpathians, are compared to the green schists of the Dobrogea massif. Indirectly their origin was related to the Lower Paleozoic and Cambrian (Murgoci 1914), Ordovician (Grigoras 1956), Silurian deposits (Simionescu 1927). Their origin was also related to the Algonkian age (Paleckelmann 1935). In the case of metamorphic schists occurring in the rounded conglomerates compared with the green shales of Dobrogea, Vialov (1955) assumed the Silurian age yet he did not exclude the Cambrian. Glushko (1957) assigned the green metamorphic schists and phyllites to the Lower Paleozoic age and the red phyllites to the Upper Paleozoic.

In the light of the presented descriptions it can be assumed that a thick series of the Riphean deposits rests in the area of the basement of the Carpathian Foredeep. In this series the lowermost part, being the strongest metamorphosed and represented by the rocks of the third group can be distinguished (crystalline dark green schists). The middle, less metamorphosed part is represented by the rocks of the second group (crystalline grey schists). The upper, least metamorphosed part is represented by the rocks of the first group (mudstones and schists).

The Riphean deposits, forming the basement of the Ukrainian part of the Carpathian Foredeep and continuing in the area of the basement of the Paleozoic Lviv Foredeep comprise various series. The oldest deposits, represented by metamorphosed crystallines schists, have been reported in the central and south-eastern parts of the Carpathian Foredeep and Paleozoic Lviv Foredeep. Thus, they form a wide fragment of the south-western slope of the Ukrainian massif. Crystalline schists represent the Riphean and Older Paleozoic. The eastern border of the occurrence of the crystalline schists can overlap with the eastern border of the Paleozoic Lviv Foredeep, and thereby can end at the line of the Pelča–Kremenets–Trebovlja–Ustečko dislocation.

The oldest Riphean part is the area of the occurrence of the metamorphosed crystalline schists. Subsequently mudstones and schists were deposited on accreted areas located west of the Ukrainian crystalline massif. By the end of the Riphean, after sedimentation of mudstones and pelites, all the deposits of the Riphean of the Lviv Foredeep and the Carpathian Foredeep were subjected to the Baikalian orogeny. Formation of volcanic rocks of the Volyn Complex is associated with the final stage of the orogeny.

The thick series of the Cambrian deposits, identified in the boreholes of Poland (region of Lubaczów, Rudki, Kochanowka, Medyka) as well as of Ukraine, were deposited after the Baikalian orogeny — in the Lower Paleozoic. The described earlier metamorphosed Riphean mudstones and schists were identified as exotics in the Cambrian deposits. The area of those metamorphosed Riphean mudstones and schists spreads from the Holy Cross Mountains to the western part of the fore-Carpathians (Krukenychy Zone). This area was affected by the Caledonian orogeny by the end of the Cambrian.

The diversity of the metamorphic rocks confirms the opinion about a diversified structure of the foredeep basement. This also supports the older opinion (Paul & Titze 1877) about the old buried ridge extending from the Holy Cross Mountains via Ukraine to Dobrogea in Romania.

Morphology of consolidated basement

The morphology of the consolidated basement of the Carpathians between the Dunajec river in Poland and the Tisa river in the Ukraine is very diversified (Fig. 2). The depth to the top of the consolidated basement changes from a few to 24 km.

The surface of the basement dips from north-west to south-east, from the Dunajec to the Tisa rivers. It has the shape of a graben with the Tarnów–Putila axis along which several drops in depth occur. North and south of the trough axis the surface of the consolidated basement rises to the depth of a few to several kilometers at the Carpathian overthrust and at the Pieniny Klippen Belt in the south.

In the eastern part of the studied area, at the edge of the overthrust, from Jaremča to the Skole meridian the surface of the consolidated basement is at the depths of ca. 10 km and the depth isolines are almost parallel to the Carpathian overthrust line. Further westward, the surface rises from Staryj Sambir in Ukraine to Tarnów in Poland and reaches the depth of 6 kilometers. The isolines are oblique to the edge of the overthrust, which is especially clearly visible in the region of Staryj Sambir.

The largest depths are observed in the eastern part of the study area, in Ukraine, in the region of Maidan, Ust–Čorna and the Jablunytsja Pass. The surface of the consolidated basement is here at the depth below 22 km, and reaches 24 km south of the Jablunytsja Pass. The zone of the maximum depth runs from the region of Ust–Čorna, Dubove via Maidan and Užok in Ukraine, and then through the territory of Poland it continues south of Sanok and Krosno and keeps a westward direction to Krynica.

Starting from the south-east, the maximum depths are as follows: east of Dubove (–24 km), in the region of Maidan (–22 km) and Užok (–20 km), south of Sanok in the region of Baligród (–16 km), south of Krosno (–16 km) and in the region of Krynica (–12 km). The descent of the consolidated basement in the region of Krynica seems to be a continuation of the depression located south of Krosno. The axis of the maximum depths of the consolidated basement from Rahiv to Krosno is regular and SE–NW oriented. Near Krosno, the axis curves southward to the region of Krynica where it gets the SE–NW direction again (Ryłko & Tomaś 1995a). The zone of maximum depths is bipartite. At the Ukraine-Poland border, the zone is separated by a transverse elevation. The orientation of that elevation is from Staryj Sambir to Cisna. The dislocation

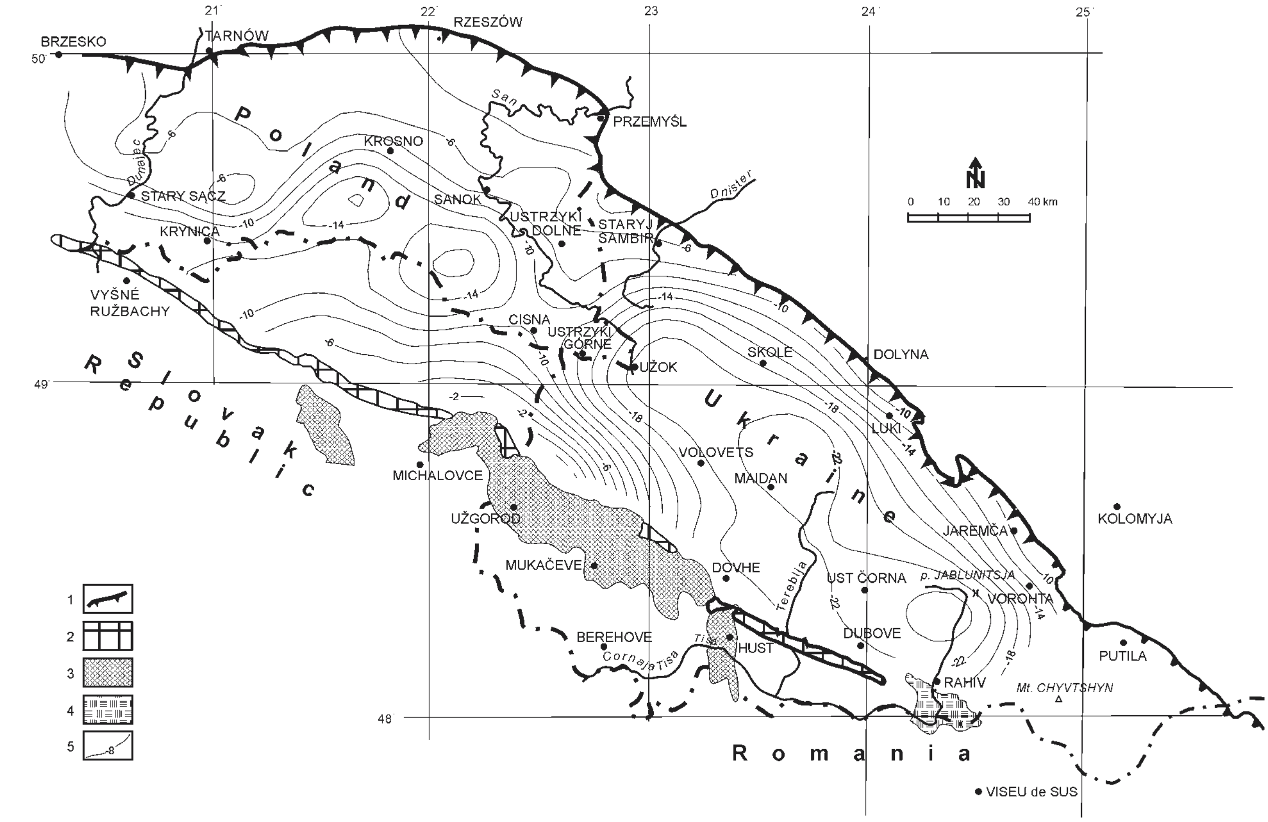

Fig. 2. Map of depths consolidated basement of the Carpathians. **1** — Outer Carpathians — northern boundary, **2** — Pieniny Klippen Belt, **3** — Neogene volcanics, **4** — Marmarosh massif, **5** — isolines of depths of consolidated basement in kilometers.

Staryj Sambir–Ustrzyki Górne–Michalovce (Fig. 3) is the eastern boundary of that elevation. In the region of the discussed elevation the surface of the consolidated basement rises to the depth of 8 km. This rise separates the consolidated basement into two different areas.

The eastern area is regular and the depth of the consolidated basement is significant while the western part is more irregular and the basement is shallower. Using the disjunctive tectonics approach, the dislocation Staryj-Sambir-Ustrzyki Górne-Michalovce (Fig. 3) can be assumed to be a boundary between these two areas.

In the eastern region, between Rahiv and Ustrzyki Górne, the surface of the consolidated basement takes the form of a niche of the axis Rahiv–Ustrzyki Górne. East of the line Vorohta–Rahiv the surface of the consolidated basement rises again to the depth of several tens of kilometers. This rise has been evidenced by seismic profile Viseu de Sus–Putila (RP-55393) made by West-Ukrainian Seismic Expedition in 1993–1994. the regular pattern of the niche is disturbed in the SE part of the Ukrainian area, namely in the region of Dovhe–Dubove–Rahiv, where the surface of the consolidated basement reaches the Pieniny Klippen Belt at a large depth, deeper than 20 km. It is the region between the eastern boundary of the Vihorlat eruption area and the Marmarosh massif.

The western area, west of Staryj Sambir–Ustrzyki Górne line is the most irregular one. To the Krosno meridian, the axis of the maximum depths still preserves its SE–NW direction, and then curves southward to Krynica. Here, a wide plateau appears between the edge of the Carpathian overthrust and the zone of the depths.

Main tectonic features of the consolidated basement

The consolidated basement of the Carpathians between the Dunajec and Tisa rivers has a blocky pattern and is dissected by numerous longitudinal and transverse dislocations.

In the western part of the study area, west of Krosno, the dislocation is NE–SW oriented (Fig. 3, dislocation (1)). That is a transverse dislocation zone B–B (Ryłko & Tomaś 2001). It extends along the line Wysowa–Sędziszów Małopolski and its southern part, at the surface, runs into the fault system of Cigla–Kyjov (Leško in: Maheľ 1974), and then in the south — into the Muráň tectonic system (Leško in*:* Maheľ 1974), and finally in the south-west — into Šahy. In its northern part, in the section between Gorlice and Jasło, this zone runs into the deep dislocation Prešov–Gorlice, as distinguished by Sikora (1976). Further northward this zone can join the dislocation Jasło–Połaniec, distinguished by Żytko (1985). Reaching to the Moho surface, this zone could have a counterpart in the deep dislocation D–D, distinguished by Bojdys & Lemberger (1986). Thereby, the discussed dislocation zone is a part of a great tectonic system extending from Połaniec, through Jasło, Bardejov to Šahy. Along this tectonic system, the blocks of the consolidated basement are shifted about 40 km with respect to each other.

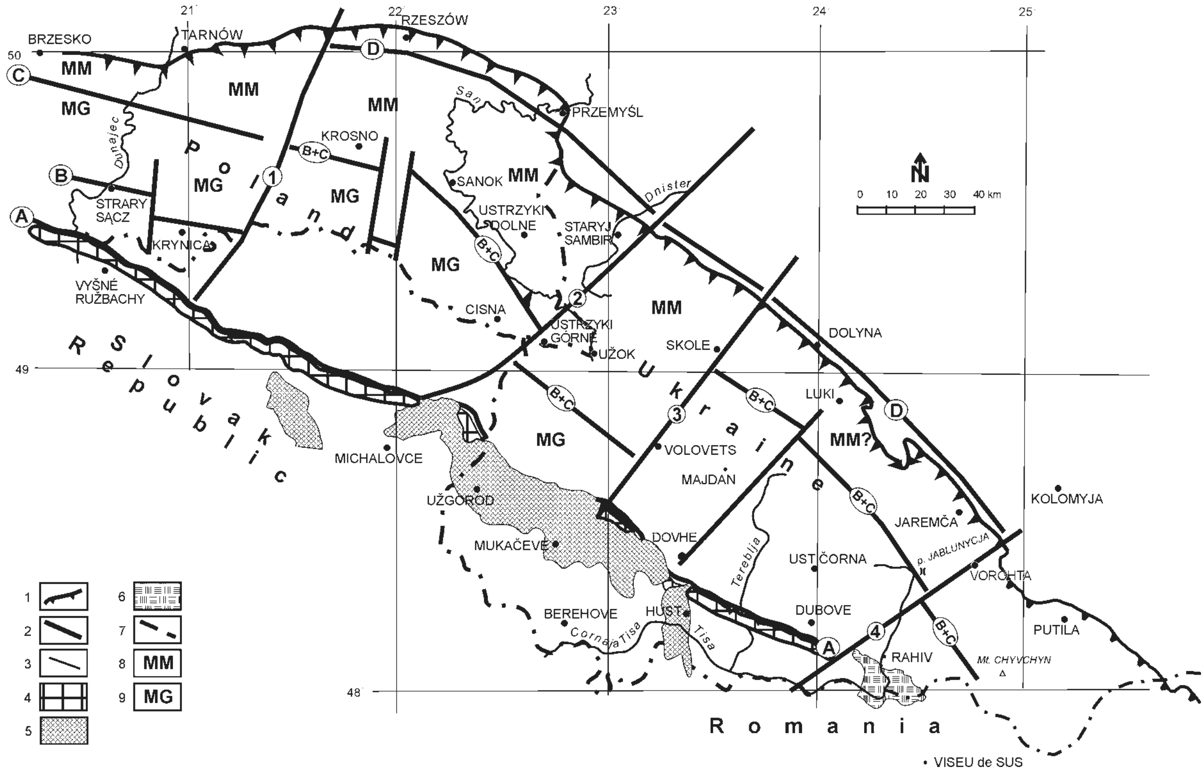

Fig. 3. Main elements of consolidated basement of the Carpathians. **1** — Outer Carpathians — northern boundary, **2** — Main dislocation zones, **3** — Secondary dislocation zones, **4** — Pieniny Klippen Belt, **5** — Neogene volcanics, **6** — Marmarosh massif, **7** — Boundary of the Malopolska and Upper Silesia massifs, **8** — Malopolska massif, **9** — Upper Silesia massif.

The next dislocation in the eastern direction is that running along the line Staryj Sambir–Ustrzyki Górne, and NE–SW oriented (Fig. 3, dislocation (2)). In a wider planar view, this dislocation runs form Lutsk on the East European platform, through Staryj Sambir and Ustrzyki Górne to Michalovce in Slovakia. In its central part, the discussed dislocation bounds from the west the zone of the maximum depressions of the Ukrainian Carpathians basement and from the east cuts off the earlier distinguished elevation of the basement in the region of Staryj Sambir and Cisna (Fig. 2). This dislocation throws the basement towards the SE by 8–10 km. In its southern part, in Slovakia, in the region of Michalovce the discussed dislocation causes disruptions in the zone of the Vihorlat eruptions. That might suggest a young age of this dislocation.

The following transverse deep dislocation in the area of the Ukrainian Carpathians is that running along the line Stryj–Skole (Fig. 3, dislocation (3)) and NE–SW oriented. That is the dislocation of Nemyriv–Javoriv–Stryj–Skole–Mukačeve. It is the western boundary of the zone of the maximum depths (Fig. 2) in the area of the Ukrainian Carpathians. The discussed dislocation plays a significant role in the history of the rocks of the Precambrian and Lower Paleozoic basement. On this dislocation, a change in petrographic-mineralogical features of the rocks of the basement of both the Carpathian and Paleozoic Lviv Foredeeps takes place. West of the dislocation, the basement deposits associated with the post-Baikalian orogeny history in the Early Paleozoic occur. These are mainly Cambrian deposits resting on the Riphean (Liniecka & Utrobin 1961). Exotic rocks of the so called first group, according to Liniecka & Utrobin (1961), representing the weakest metamorphism are present in the basement deposits aforementioned. The above authors suggest that the exotic rocks of the second and third groups of strong metamorphism occur east of the considered dislocation. Thereby, east of the dislocation the oldest part of the Riphean geosyncline would be present. The dislocation has to be of a very old foundation. If the age of the very young Lutsk–Staryj Sambir–Ustrzyki Górne–Michalovce dislocation is compared to the history of the Nemyriv–Javoriv–Stryj–Skole–Mukačeve dislocation, which has a very old foundation, then a very differentiated history of this part of the Carpathian basement can be concluded.

The easternmost transverse dislocation is also NE–SW oriented and runs along the line Vorohta–Rahiv. This is the Kolomyja–Vorohta–Rahiv dislocation (Fig. 3). East of this dislocation, the surface of the consolidated basement rises significantly. The discussed dislocation is the eastern boundary of the zone of the maximum depths in this part of the Carpathians. In the zone of the discussed dislocation the Pieniny Klippen Belt disappears, covered by the Neogene volcanogenic rocks of the Vihorlat mountain group (Mahel' 1974). Moreover, the dislocation is also the western boundary of the Marmarosh Mountains. Further to the south, the dislocation takes the direction close to meridional and becomes the eastern boundary of the Pannonian Basin (Mahel' 1973).

In the study area, in the consolidated basement of the Carpathians between the Dunajec and Tisa rivers, three main lon-

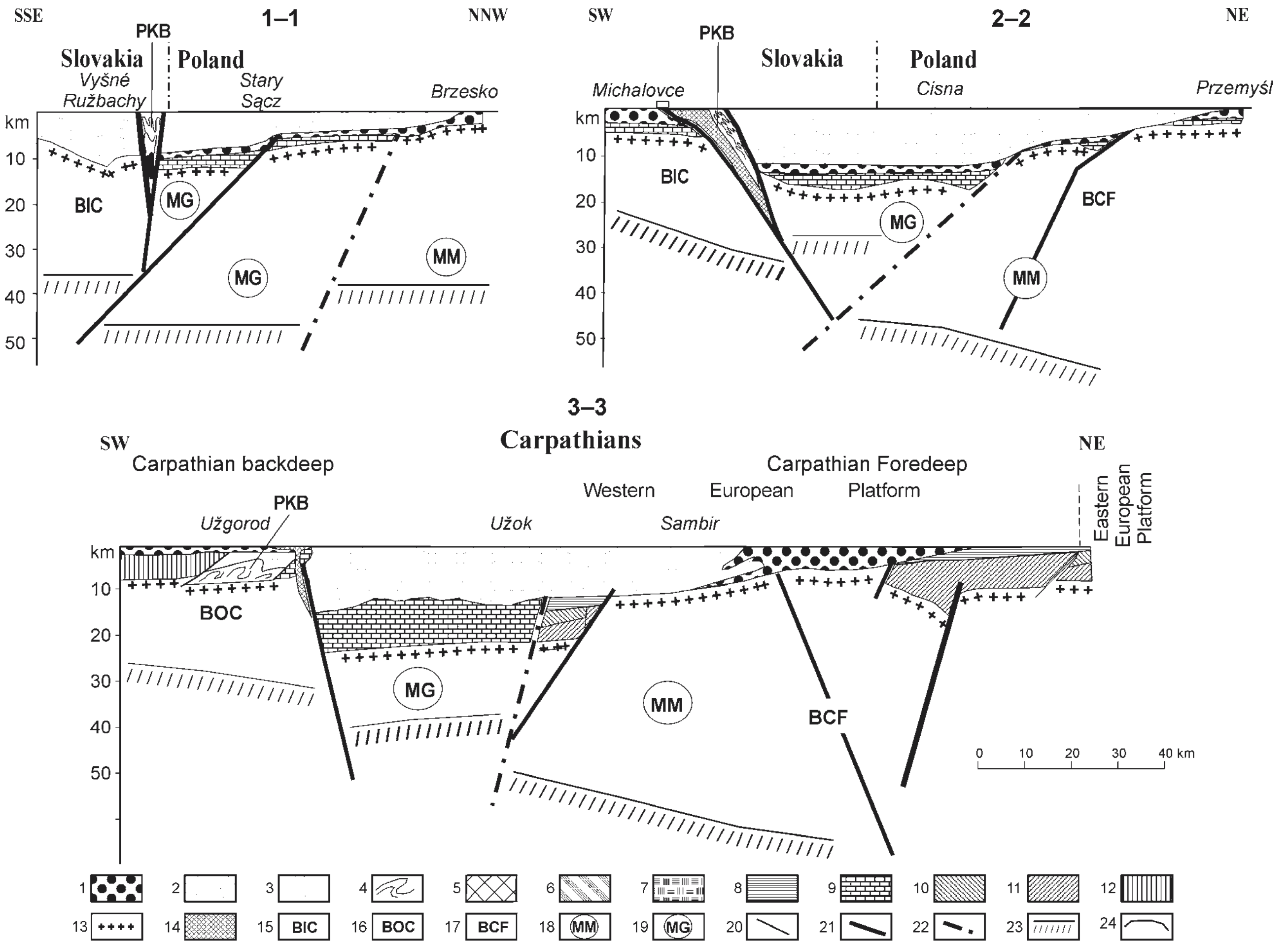

Fig. 4a. Deep geological profiles. **1** — Neogene deposits, **2** — Central Carpathian Paleogene, **3** — Flysch Carpathian deposits, **4** — Pieniny Klippen Belt (PKB), **5** — Penninicum, **6** —Paleogene cover of the Marmarosh massif, **7** — Marmarosh massif, **8** — Mesozoic deposits, **9** — Mesozoic-Paleozoic deposits, **10** — Upper Paleozoic deposits, **11** — Lower Paleozoic deposits, **12** — Paleozoic deposits, **13** — Consolidated basement, **14** — Neogene volcanics, **15** — Inner Carpathian block, **16** — Outer Carpathian block, **17** — Carpathian Foredeep block, **18** — Malopolska massif, **19** — Upper Silesia massif, **20** — Secondary dislocation zones, **21** — Main dislocation zones, **22** — Boundary of the Malopolska and Upper Silesia massifs, **23** — Moho discontinuity, **24** — Geological boundaries.

gitudinal dislocations have been distinguished (Fig. 3). In the northern part it is the peri-Carpathian dislocation (Fig. 2, dislocation (D)), in the southern part — the peri-Pieninian dislocation (Fig. 3, dislocation (A)). In the central part of the study area, the "regional basement slope" has been distinguished (Fig. 3, dislocation (B) and dislocation (C)).

The northernmost dislocation "D" runs along the line Jaremča-Staryj Sambir-Przemyśl-Rzeszów. In Poland, it is the eastern fragment of the peri-Carpathian dislocation (Sikora 1976), while in western Ukraine it is called the fore-Carpathian dislocation (Krugłow et al. 1985). In the planar view of the Baikalian complex, in its western part this dislocation in the area of Poland overlaps with the great dislocation zone of Kniażyce (Karnkowski, Pożaryski & Tomczyk in: Pożaryski 1974). Following these authors approach, the discussed dislocation delineates the southern frame of the Laramian unit — the Neogene Carpathian Foredeep (Pożaryski 1964). Ukrainian geologists are of similar opinions and treat this dislocation as the boundary of the Carpathian Foredeep (Kruglov et al. 1985). South of the discussed dislocation, the Precambrian elevation, dissected by secondary dislocations, dips gradually under the flysch Carpathians.

The dislocation running in the centre of the study area has a more southerly position. In the west, in the territory of Poland between the Dunajec river and Wysowa, this dislocation is almost W-E oriented. East of the transverse dislocation Wysowa-Jasło (Fig. 3) the dislocation is shifted ca. 45 km northward (Ryłko & Tomaś 1999a) and runs along the line Jasło-Sanok-Ustrzyki Dolne to the transverse dislocation Lutsk-Staryj Sambir-Ustrzyki Górne-Michalovce. Further eastward, in the territory of the Ukrainian Carpathians already, between the transverse dislocations Lutsk-Staryj Sambir-Ustrzyki Górne-Michalovce and Nemyriv-Javoriv-Stryj-Skole-Mukačeve it extends along the line Ustrzyki Górne-Volovets. Here, it is shifted several tens of kilometers with respect to the western branch. East of the transverse dislocation Nemyriv-Javoriv-Stryj-Skole-Mukačeve to the transverse dislocation Kolomyja-Vorohta-Rahiv, the discussed dislocation is again shifted ca. 35 km and runs along the line Skole-the Jablunytsja Pass. Further to the east, past the dislo-

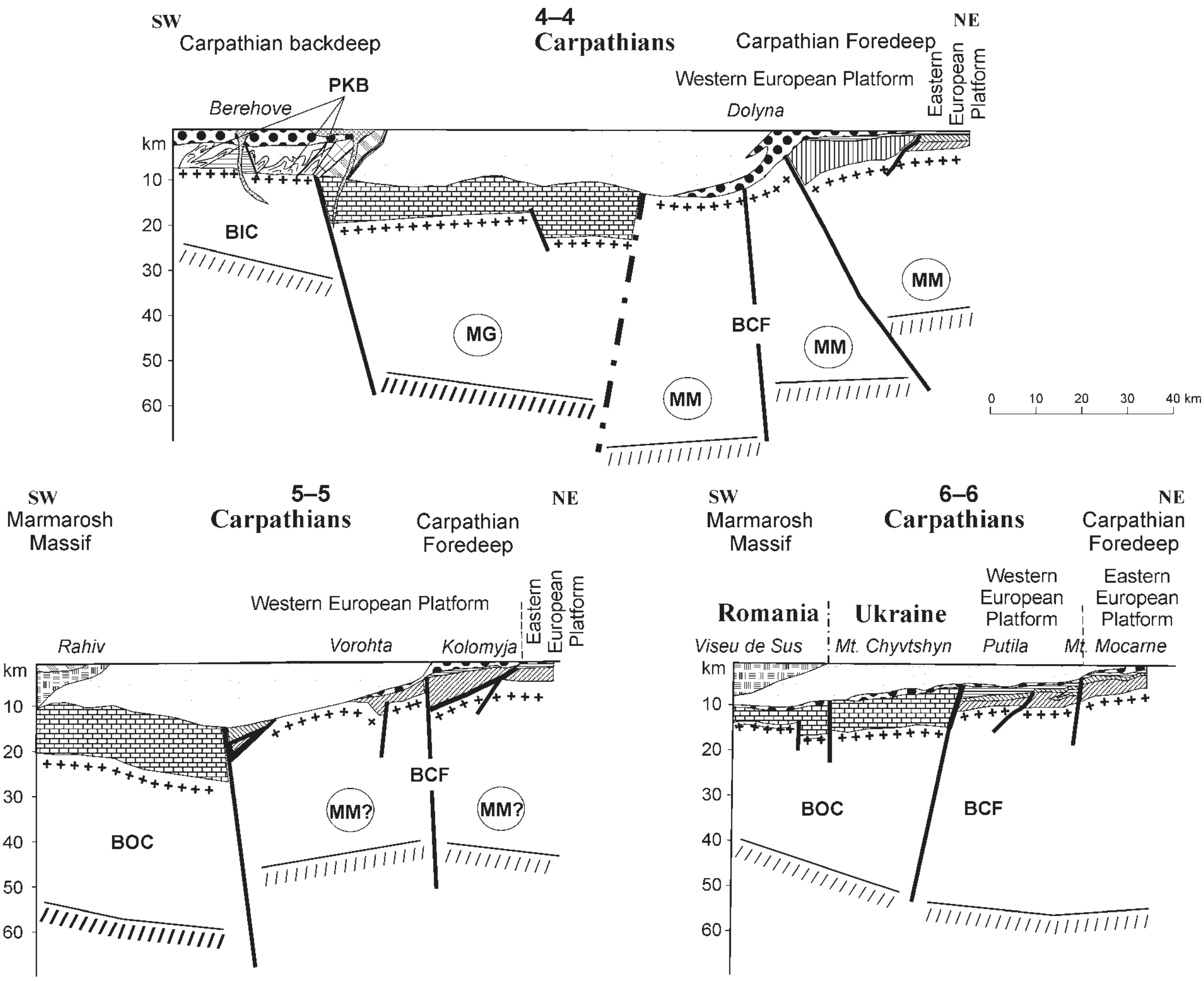

Fig. 4b. Deep geological profiles. Explanation see Fig. 4a.

cation Kolomyja-Vorohta-Rahiv it continues to the Chyvtshyn Mountain. The discussed dislocation along its entire course throws the consolidated basement southward. In the area between the Dunajec river and Wysowa the discussed dislocation throws the basement ca. 5-7 km southward (Ryłko & Tomaś 2001). Further to the east, between Jasło and Ustrzyki Górne the basement shift (Fig. 4a) to the south is ca. 12 km (Ryłko & Tomaś 2001). East of Ustrzyki Górne to Volovets, the "regional basement slope" also throws the basement to the south ca. 10 km (Fig. 4a). In the section between Skole and the Jablunytsja Pass, the basement is thrown to the south also ca. 10 km (Fig. 4b). Further east of the dislocation Kolomyja-Vorohta-Rahiv the throw is initially ca. 12 km (Fig. 4b) and then ca. 3 km (Fig. 4b).

According to the authors of this paper, west of the Dunajec river, the tectonic zone Lubliniec-Kraków, identified from boreholes, passed the dislocation Wysowa-Jasło, continues to the east along the "regional basement slope" — dislocation B+C (Fig. 3). Thereby, the "regional basement slope" turns out to be a high priority feature and east of the dislocation Wysowa-Jasło becomes a boundary between the Malopolska and Upper Silesia massifs, blocks and terrans. As results from the cross-sections (Fig. 4a,b), in the Ukrainian part, the remnants of the Lower and Upper Paleozoic are preserved on this slope.

The peri-Pieninian dislocation is the southernmost distinguished one (Fig. 3). The dislocation in question runs from the Marmarosh massif in the east towards the NW direction across the entire study area. It is in the boundary zone between the Outer and Inner Carpathians. South of the discussed dislocation, the consolidated basement rises significantly in the whole study area (Fig. 4a,b). The magnitude of this rise is comparable with the shifts along the "regional basement slope". Thus, a deep graben is present between the "regional basement slope" and the peri-Pieninian dislocation. Everywhere, the graben is filled with Mesozoic-Paleozoic deposits, thus it had to form in the Early Paleozoic, while during the Neogene transformation of this part of the Carpathian basement it was only slightly changed (Ryłko & Tomaś 2001).

Final conclusions

1. The morphology of the consolidated basement of the Carpathians is very diversified. The depth of the top surface of the basement varies from a few kilometers in the western part of the study area to ca. 24 km in the south-eastern part. Generally, the surface of the consolidated basement dips in a NW to SE direction.

2. North of the Pieniny Klippen Belt the zone of maximum depressions occurs. The axis of this zone is irregular in the major part of the study area and is NW–SE oriented. In the direct vicinity of the Pieniny Klippen Belt the surface of the consolidated basement shows a rising tendency towards the south.

3. The consolidated basement has a blocky pattern. It is dissected by numerous transverse and longitudinal dislocations. Along the transverse dislocation a systematic shift of the basement towards the SE takes place.

4. It can be suggested that the dislocation Lubliniec–Kraków, being the boundary between the Malopolska and Upper Silesia massifs, continues to the south-east along the "regional basement slope".

5. The surface of the consolidated basement between the "regional basement slope" and the peri-Pieninian dislocation has the form of a graben with the axis Rahiv–Krynica. The graben is likely filled with the Paleozoic and Mesozoic deposits.

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