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Structure and tectonic evolution of the NE segment of the Polish-Ukrainian Carpathians during the Late Cenozoic: subsurface cross-sections and palinspastic models

JAN KUŚMIEREK[1] and URSZULA BARAN[2]

[1]Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology; Al. Mickiewicza 30, 30-059 Kraków, Poland; kusm@geol.agh.edu.pl
[2]Polish Oil and Gas Company S.A., Department of Petroleum Deposit Exploration; ul. Kasprzaka 25, 01-224 Warszawa, Poland; urszulabaran15@gmail.com

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Abstract: The discrepant arrangement of the Carpathian nappes and syntectonic deposits of the Carpathian Foredeep reveals the oroclinal migration of the subduction direction of the platform margin during the Late Cenozoic. Formation of the nappes was induced by their detachment from disintegrated segments of the European Platform; the segments were shortened as a result of their vertical rotation in zones of compressional sutures. It finds expression in local occurrence of the backward vergence of folding against the generally forward vergence toward the Carpathian Foredeep. The precompressional configuration of sedimentation areas of particular nappes was reconstructed with application of the palinspastic method, on the basis of the hitherto undervalued model which emphasizes the influence of the subduction and differentiated morphology of the platform basement on the tectonic evolution of the fold and thrust belt. Superposition of the palaeogeographic representations and the present geometry of the orogen allows understanding of the impact of the magnitudes of tectonic displacements on the differentiation of the geological structure in the NE segment of the Carpathians. The differentiation has inspired different views of Polish and Ukrainian geologists on structural classification and evolution of the frontal thrusts.

Key words: fold and thrust belt, Outer Carpathians, platform cover, interference of subbasins, kinematics of tectonic movements, Palaeogene, Miocene.

Introduction

The oroclinal arrangement of the Cretaceous–Tertiary nappes, fringed by younger molasse of the foredeep, is a dominant feature of the Outer Carpathians (Fig. 1). Their northeastwards-protruding salient in the vicinity of the Polish-Ukrainian border distinguishes itself by the north–south trend of marginal thrusts of the Skole (Skyba)* and Boryslav-Pokuttya nappes that are highly oblique to the frontal thrust of the Early–Middle Miocene folded molasses of the Stebnik (Sambir) Nappe. The bend, named the Przemyśl Sigmoid (Świderski 1952), connects the eastern part of the Western Carpathians and the western part of the Eastern Carpathians.

To the west of the Przemyśl Sigmoid: (1) the Boryslav-Pokuttya Nappe pinches out; (2) the thick series of folded molasse of the Stebnik Nappe is dismembered into discontinuous tectonic slivers at the base and front of the Skole Nappe, which are correlated with the Stebnik Nappe (Ney 1968), and/or the separated younger (Late Badenian–Early Sarmatian) Zgłobice Unit (Kotlarczyk 1985; Połtowicz 2004); (3) undeformed fragments of the posttectonic transgressive cover of the Badenian–Early Sarmatian deposits are preserved above folded and erosionally truncated outcrops of the Skole, Subsilesian and Silesian nappes (of the so-called Middle Group; Nowak 1927); (4) at the front, the folded molasse — included in the Marginal Group of the Outer Carpathians by Polish geologists (Nowak 1927) — in some zones rests (locally with a sedimentary gap) on flysch deposits, folded with them and termed the "outer flysch" (Książkiewicz 1972).

Tectonostratigraphic identification of the unconformable occurrence of the Miocene sediments on older flysch sequences and heterogeneous structural stages of the sub-Tertiary basement is still an under-recognized problem of Outer Carpathian evolution. It is worth noting that Ukrainian geologists assign the Sambir and Boryslav-Pokuttya nappes to the internal folded zone of the Carpathian Foredeep and consider these nappes to be detached platform covers accreted to the Outer Carpathian orogenic front during the Early Miocene (e.g., Gluško 1968).

In the extensive Carpathian bibliography, and against the background of thorough studies revealing the regularities of the geological structure and evolution of the Outer Carpathians (e.g., Gluško 1968; Świdziński 1971; Książkiewicz 1972; Vjalov et al 1981; Kotlarczyk 1988; Picha 2011), there are remarkably different reconstructions of the pre-orogenic geometry of the sedimentary subbasins (e.g., Unrug 1979; Oszczypko & Tomaś 1985; Kuśmierek 1988; Roure et al. 1993; Golonka et al. 2006; Nemčok et al. 2006; Gągała et al. 2012). They reflect different interpretations of the subsurface structure of the Outer Carpathians and conceptual models for

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* names used by Ukrainian geologists are given in parentheses

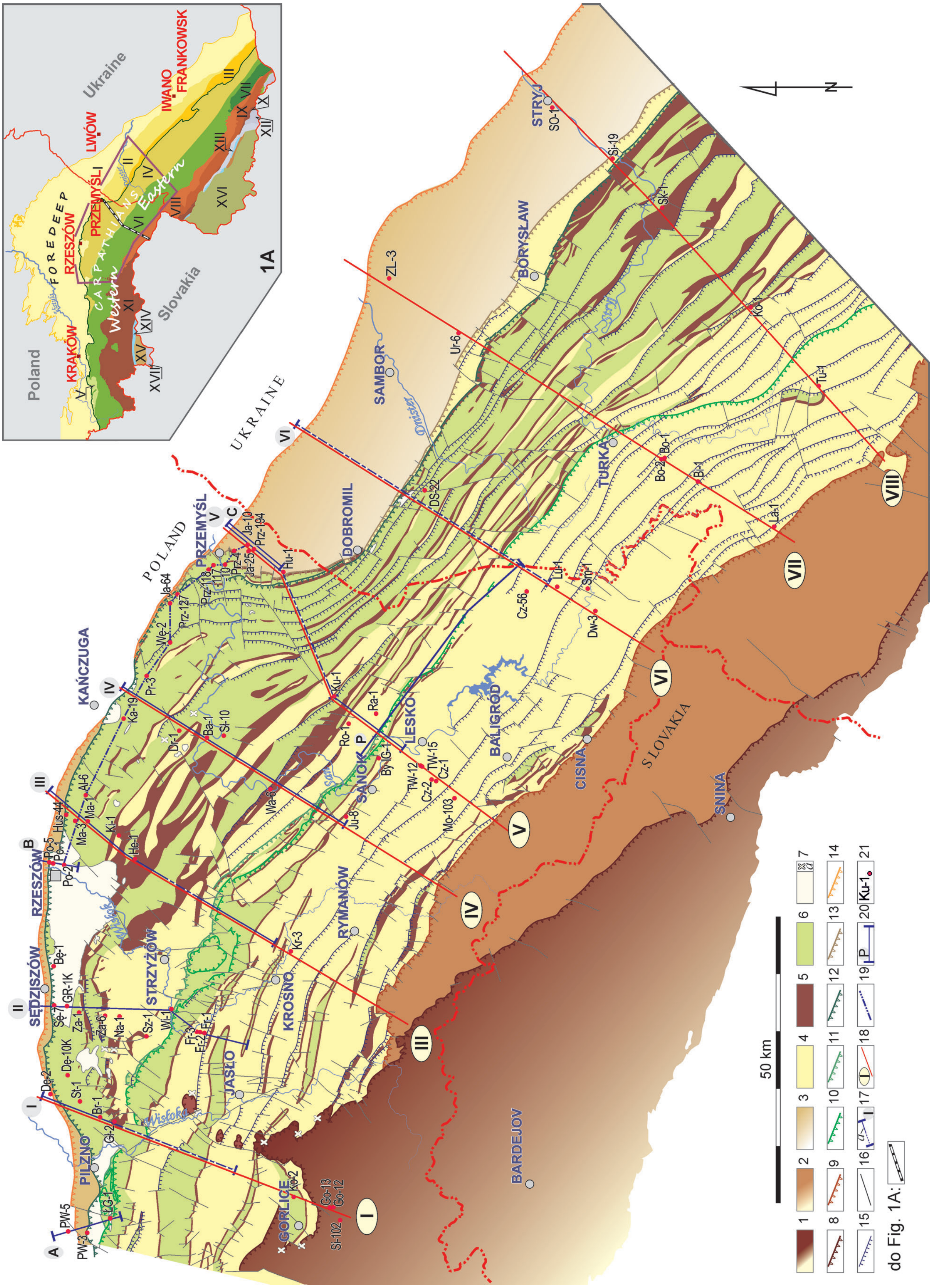
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Fig. 1. Locations of cross-sections and well penetrations on a simplified geological map of the northeastern segment of the Outer Carpathians. **Nappes and allochthonous units (undivided): 1** — Magura; **2** — Dukla (and Porkulets); **3** — Stebnik (Sambir) and Zgłobice. **Sedimentary complexes: 4** — upper Oligocene and lower Miocene (Krosno Beds of the Silesian, Subsilesian and Skole (Skyba) nappes; Polyanytsya and Vorotyshche Beds within the Boryslav-Pokuttya Nappe); **5** — Menilite Beds (lower Oligocene); **6** — Cretaceous and Eocene (older than the Menilite Beds); **7** — transgressive Miocene outliers on flysch (a–with small areal extent).
Overthrusts of nappes and units: 8 — Magura;, **9** — Dukla; **10** — Silesian; **11** — Subsilesian; **12** — Skole (Skyba); **13** — Boryslav-Pokuttya; **14** — Allochthonous Miocene; **15** — minor overthrusts; **16** — faults; **17** — lines of geological cross-sections (a–geological interpretation based on seismic sections); **18** — lines of regional traverses; **19** — line of correlation (Fig. 7); **20** — line of the longitudinal geological cross-section (Fig. 10B); **21** — wells along the cross-sections.
Inset A. Location of the study area within the Polish-Ukrainian Carpathians.
Tectonic units of the Polish and Ukrainian Carpathians: I — Carpathian Foredeep, external part (Bilche-Volytsya); **II** — Stebnik (Sambir); **III** — Boryslav-Pokuttya; **IV** — Skole (Skyba); **V** — Subsilesian; **VI** — Silesian (Krosno); **VII** — Chornohora; **VIII** — Dukla; **IX** — Porkulets; **X** — Rakhiv; **XI** — Magura; **XII** — Maramuresh Crystalline Massif; **XIII** — sedimentary cover of the Maramuresh Massif; **XIV** — Pieniny Klippen Belt; **XV** — Podhale Trough; **XVI** — Transcarpathian Depression; **XVII** — Tatra Mts.; the study area marked by the box;
1A — boundary between the Western and Eastern Carpathians.

the formation of the nappes, in particular their thrusting directions and the reference lines of palinspastic projections, which according to the classic assumptions (Kay 1945) have implied insurmountable difficulties (Khain et al. 1977; Kruglov et al. 1985).

In addition to providing a better understanding of the geological structure of the study area, optimization of those representations is of fundamental importance for the generation of oil and gas reservoirs in the flysch sequences and gas reservoirs in the foredeep molasse (Kuśmierek et al. 1995, 2001; Picha 1996; Kolodij et al. 2004), discoveries of which triggered advances in the study of the subsurface structure of the frontal segment of the Outer Carpathians.

The new cross-sections, models and tectonostratigraphic correlations illustrating the geological structure of the frontal zone of the NE segment of the Outer Carpathians and of their basement — developed by the authors of the presented paper — are based on reinterpretation of extensive data sets. In particular, these include: the most recent seismic sections, well sections and magnetotelluric soundings from the Polish Carpathians, as well as publications and geological maps from the Ukrainian Carpathians (e.g., Shakin et al. 1976; Gluško & Kruglov et al. 1986; Burov et al. 1986; Jankowski et al. 2004).

The geological cross-sections represent modified fragments of regional traverses constructed by the authors in the years 2007–2011, in cooperation with Ukrainian geologists, in the framework of two interdisciplinary research projects. These were oriented towards assessment of the possibility of discovering new hydrocarbon reservoirs and utilization of geothermal waters in the area of the Polish-Ukrainian Outer Carpathians, between the Wisłoka river valley in the Western Carpathians and the Stryi river valley in the Eastern Carpathians (Kuśmierek et al. 2009; Kuśmierek & Baran 2013). Some of those traverses (or their fragments) have already been published (Kuśmierek & Baran 2008; Czopek et al. 2009; Maćkowski et al. 2009; Kuśmierek 2010; Górecki 2013).

New aspects of the interpretation of the structure in the study area are provided by the tectonostratigraphic configuration of the sedimentary successions of the Outer Carpathians and the underlying Małopolska Block, and by the detailed cross-section and correlations (constructed on the basis of compilation of published data and archival well sections) illustrating the "interfingering" of the Miocene cover of the flysch nappes with the foredeep deposits.

Other fundamental theses of the paper, which pertain to the tectonic evolution of the NE segment of the Outer Carpathians (over 300 km in length), are based on: palinspastic reconstructions of the pre-orogenic configuration of the original depositional areas of the nappes; and the tectonic displacements of the nappes during the Oligocene–Middle Miocene along seven traverses (not enclosed here) running from the Dukla Nappe overthrust to the autochthonous deposits of the platform slope.

On the basis of arguments presented in papers of one of the authors (Kuśmierek 1988), it was decided to accept a direction of the palinspastic projection which would be consistent with the vergence of folds and thrusts. According to this assumption, which implies the subduction of the original basement of the sedimentary basins (towards S-SW) as a process that triggered the development of the thrusting and folding, a kinematic model of the Outer Carpathians evolution during the Late Cenozoic was constructed.

The new representation of the evolution of the NE segment of the Outer Carpathians can be supported by interpretations of the tectonics of the slope of the subducted European Platform, which are based on seismic tomography and thermal modelling (Konečný et al. 2002), and magnetotelluric sounding (Kuśmierek 2010).

Outline of the architecture of the NE segment of the Carpathians

The fold and thrust belt

The nappes and tectonostratigraphic units of the Outer Carpathians form a typical fold and thrust belt with a vergence consistently toward the platform margin, except for structural depressions where upright or hinterland-vergent folds appear. The documented amplitudes of nappe overthrusts and the intensity of their folding justify the view that they are detached from their original basement along the basal clay-rich complexes of the Lower Cretaceous and locally Eocene age. Locally, there is also disharmonic folding above minor subhorizontal detachments.

In the Polish Outer Carpathians, three groups of nappes can be distinguished (after Nowak 1927) from S to N: the Magura Group, Middle Group and Marginal Group. In the borderland between Poland and Ukraine, the Middle Group is most extensively developed, reaching its greatest width in the San and Ondava (in Slovakia) river basins.

The frontal zone of the orogen is characterized by a locally very complicated geological structure. In general, the allochthonous covers formed of flysch deposits of Cretaceous–Palaeogene age (up to the Early Miocene in synclinoria) and/or the Miocene molasse (of Early Miocene–Early Sarmatian age) are thrust over younger or coeval terrestrial and marine molasse. The autochthonous molasse transgressively overlies the Meso-Palaeozoic and Precambrian structures of the platform slope or the partly eroded nappes as the top parautochthon, locally folded at the front of the orogen.

Tectonostratigraphic relationships between allochthonous and parautochthonous covers and autochthonous formations of the Carpathian Foredeep were discussed in numerous papers and monographs written by Polish and Ukrainian geologists, such as Tołwiński (1956), Ney (1957, 1968), Gluško (1968), Komorowska-Błaszczyńska (1971), Książkiewicz (1972), Samojluk (1976 b), Wdowiarz (1976), Vjalov et al. (1981), Gluško et al. (1984), Kotlarczyk (1985, 1988), Połtowicz (1991, 2004), Lizoon & Zayats (1997), Oszczypko (2006), Kuśmierek & Baran (2008), and Zayats (2013), on the basis of results of field studies, interpretation of well sections, and geophysical surveys.

The basement and foreland of the frontal zone of thrusts

The fold and thrust arc of the Outer Carpathians is overlapping the slope of the platform basement. According to Konečný et al. (2002), at the contact between the Western and Eastern Carpathians, that slope was offset by an oblique, SW–NE-trending deep-seated fracture which separated the Małopolska Block (Massif) from the basement of the Transcarpathian Depression. Within that depression, no deep well drilled in the Ukrainian Carpathians reached the platform basement under the Skole Nappe (Zayats 2013).

Within the Małopolska Block, beneath the nappes, autochthonous formations of different ages, representing the platform basement, were encountered. In the study area, their most complete section has been preserved between Pilzno and Rzeszów (Fig. 2A), that is in the area of oblique submergence of the Miechów Trough below the frontal zone of thrusts which truncated older and older structural stages of the basement. Its foundation is composed of weakly metamorphosed claystones and mudstones, which in the eastern part of the Małopolska Block are of Neoproterozoic (Ediacaran)–Early Cambrian age (Pożaryski et al. 1981).

In the western part of the Małopolska Block, the eroded top of the basement is overlain by Mesozoic–Palaeozoic formations separated by numerous erosional hiatuses with different spatial and temporal extents. These formations are disrupted by fault systems (Fig. 2A). In the eastern part of the Block, long-lasting post-Laramian erosion (Palaeogene–Early Miocene) over the Leżajsk Massif (Mizerski & Stupka 2005) removed the Mesozoic–Palaeozoic formations. As a consequence, autochthonous Miocene sediments, over which the Stebnik Nappe with erosional outliers of epicontinental facies deposits is thrust, rest directly on the Precambrian–Lower Cambrian rocks (Fig. 2B).

Deposition of the Miocene molasse sediments took place in a depression formed at the Carpathian front during Alpine deformation. The middle Badenian evaporites occurring in the lower part of the Miocene molasse section represent a seismic marker that images the structure of the Carpathian Foredeep, excepting zones of their absence (e.g., the “Rzeszów Island”, Komorowska-Błaszczyńska 1965). Dips of those deposits generally range from a few to more than ten degrees and are disturbed over compactional drape structures of the basement (Krzywiec et al. 2005) or in the foremost part of the frontal thrusts. In the area between Sędziszów and Rzeszów, in erosional palaeochannels, deposits composed of the coarse-grained material from the basement occur; they originated from formations of different ages, from the Precambrian up to the Upper Jurassic, and are covered with silty-sandy terrestrial deposits to which Moryc (1995) ascribed a Palaeogene age.

In comparison with the strongly deformed Proterozoic rocks, with prevailing dips of 60–90°, the unconformably overlying Palaeozoic and Mesozoic sequences are rather low-dipping, with dips from a few to rarely over 20°. The larger dips are generally in the lower clastic series and are related to clastic series that drape the eroded basement. Angular unconformities in the Mesozoic–Palaeozoic cover, the variable extents and numerous sedimentary gaps comprising sometimes whole periods, imply that each series represents a different structural stage.

The tectonics of the Mesozoic–Palaeozoic structural stages is dominated by systems of faults, including extensional faults inverted during the Tertiary, which cut the open folds (Cisek & Czernicki 1965; Jawor 1970, 1983; Jawor & Baran 2004; Krzywiec 1997; Krzywiec et al. 2008; Baran & Jawor 2009).

The morphology of the top of the Małopolska Block foundation has been most easily recognized in wells and seismic surveys in the frontal zone of the fold and thrust belt where it is shallowest. These data have documented the occurrence of faults with throws reaching several kilometres, as well as the reduced thicknesses of the autochthonous formations on the platform slope; for example, they were absent in the Ba-1 well, drilled on an erosional basement high.

Beyond the depth of the drilled wells, important data are supplied by the magnetotelluric sounding (MT) along several regional profiles (Czerwiński & Stefaniuk 2005). In the MT

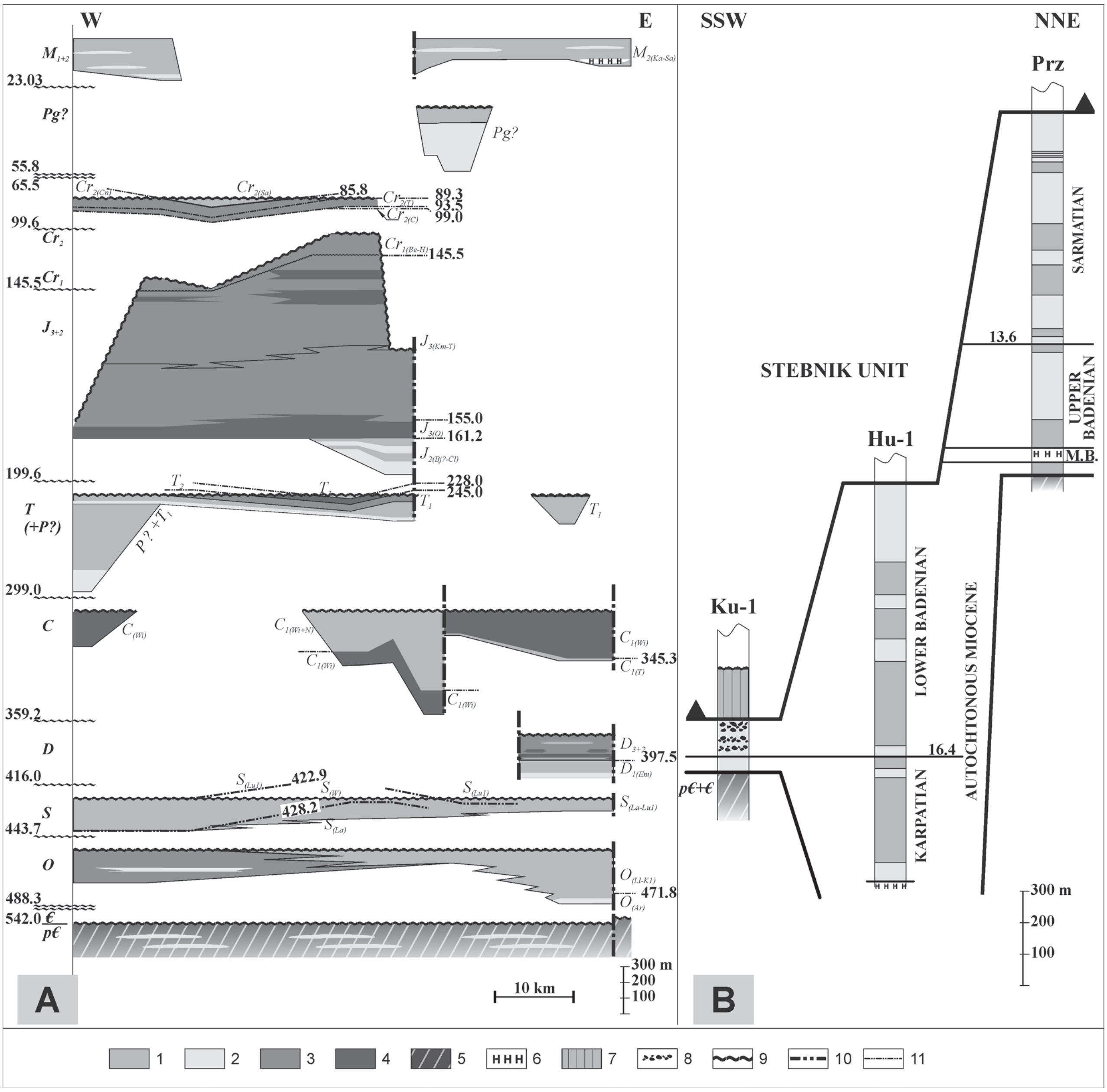

Fig. 2. Lithostratigraphic scheme of the foreland and basement in the frontal zone of the fold and thrust belt: **A** — in the Western Carpathians; **B** — in the Eastern Carpathians (in the transfrontier zone). **1** — claystone and siltstone, **2** — sandstone, **3** — limestone, **4** — dolomite, **5** — metaargillite and metaaleurolite, **6** — evaporites (salt, gypsum, anhydrite), **7** — erosional outliers of the epicontinental facies (olistoliths?), **8** — conglomerate (pebbly mudstone), **9** — stratigraphic discontinuities, **10** — tectonic extents, **11** — stratigraphic boundaries. $\mathbf{M_2}$ — middle Miocene: $M_{2(Ka\text{-}Sa)}$–Karpatian–Sarmatian; **Pg?** — Palaeogene; $\mathbf{Cr_2}$ — Upper Cretaceous: $Cr_{2(Sa)}$–Santonian, $Cr_{2(Cn)}$–Coniacian, $Cr_{2(T)}$–Turonian, $Cr_{2(C)}$–Cenomanian; $\mathbf{Cr_1}$ — Lower Cretaceous: $Cr_{1(Be\text{-}H)}$–Beriasian–Hauterivian; $\mathbf{J_{3+2}}$ — Middle and Upper Jurasic: $J_{3(Km\text{-}T)}$–Kimeridgian–Tithonian, $J_{3(O)}$–Oxfordian, $J_{2(Bj?\text{-}Cl)}$–Bajocian?–Callovian; **T** — Triassic: T_3–Upper Triasic, T_2–Middle Triasic, T_1– Lower Triasic, P?–T_1–Permian?–Lower Triasic; $\mathbf{C_1}$ — Lower Carboniferous: $C_{1(Wi\text{-}N1)}$–Wisean–Lower Namurian, $C_{1(Wi)}$–Wisean, $C_{1(T)}$–Tournisian; **D** — Devonian: D_{3+2}–Upper and Middle Devonian, $D_{1(Em)}$–Emsian; **S** — Silurian: $S_{(Lu1)}$–Lower Ludlow, $S_{(W)}$–Wenlock, $S_{(La)}$–Llandover; **O** — Ordovician: $O_{(Ll\text{-}K1)}$–Llanvirn–Lower Caradoc, $O_{(Ar)}$–Arenig; **€** — Cambrian; **p€** — Precambrian (Ediacaran). **428.2** — ages ascribed to stratigraphic boundaries [m.y.]: for the Western Carpathians, after the Stratigraphic Table of Poland without the Carpathian region (2008); for the Miocene (the Eastern Carpathians), after Steininger (1996).

profiles, the Precambrian basement is identified as a high-resistivity complex traced over a long depth interval. The top basement horizon is shallowest (2.0–8.5 km) in the frontal zone of the orogen and dips beneath the southern (synclinorial) part of the Skole Nappe where it is offset by SW- to vertical-dipping fault systems, with throws exceeding 1 km (Fig. 3). According to the geoelectric characteristics (Stefaniuk & Kuśmierek 1986; Stefaniuk 2003), these fault

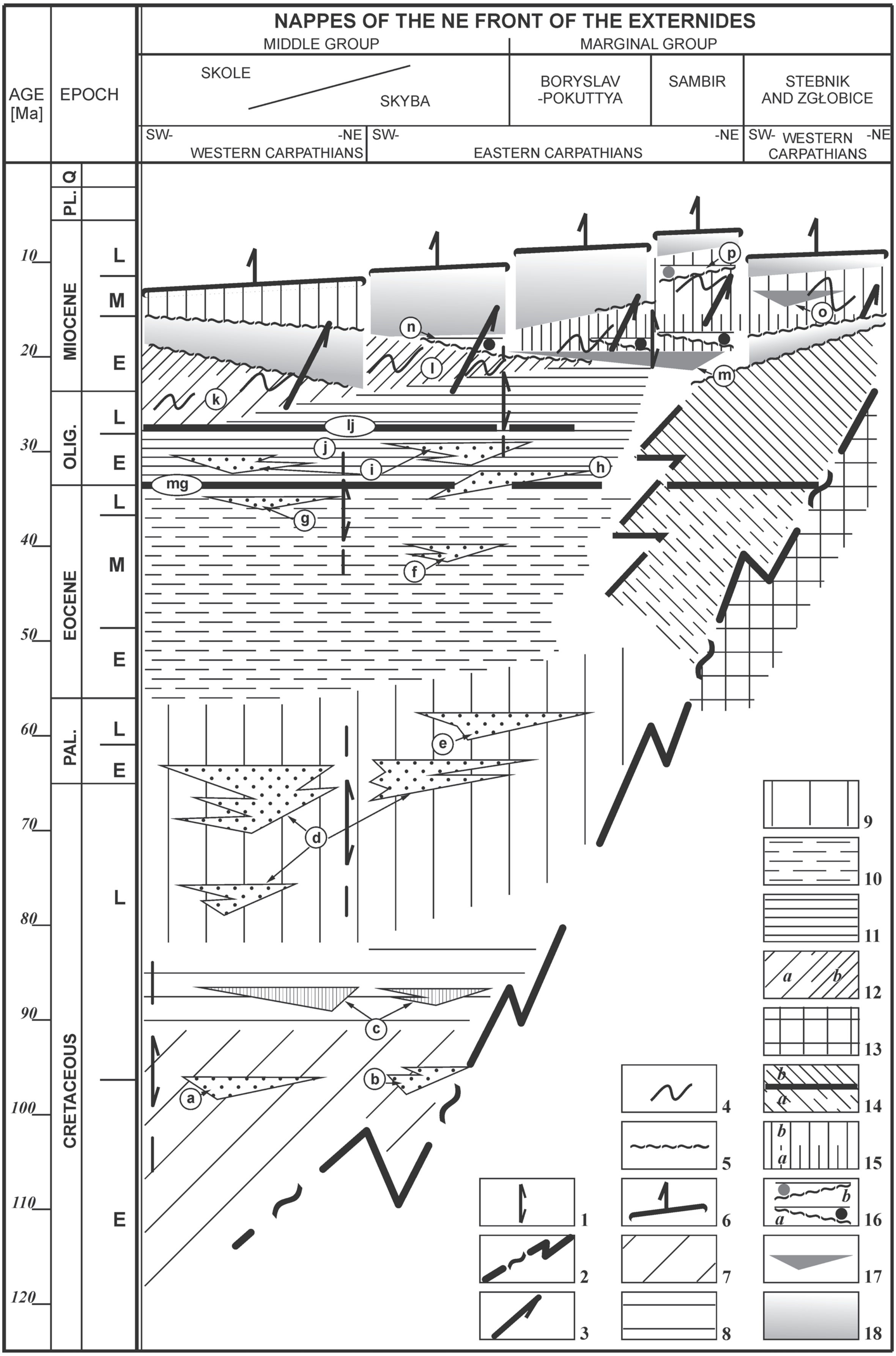
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Fig. 3. Tectonostratigraphic scheme of sedimentary successions in the frontal zone of the fold and thrust belt. **Tectonic regime: 1** — subvertical tectonic movements in the basement of sedimentary subbasins, **2** — trend of expansion of Cretaceous–Tertiary sedimentary subbasins, **3** — main phases of Tertiary tectonic thrusts, **4** — expansion of continuous deformation, **5** — surfaces of sedimentary discontinuity, **6** — stages of final inversion of nappes. **Sedimentary megacomplexes: 7** — early flysch, **8** — clayey-marly Cenomanian–Coniacian deposits (synrift formations?), **9** — turbiditic formations of Senonian–early Palaeocene, **10** — variegated clayey-marly deposits of late Palaeocene–Eocene, **11** — older sequences of the Menilite-Krosno Series (Oligocene), **12** — a–younger sequences of the Menilite-Krosno Series, b–Polyanytsya and Vorotyshche Beds, undivided (Eggenburgian–Ottnangian), **13** — Pre-Alpine basement (Precambrian–Meso-Palaeozoic), **14** — epicontinental (near-shore) deposits of the Skole Series: a–Eocene, b–Oligocene–lower Miocene, **15** — Miocene molasse (undivided): older–Stebnik Beds (Ottnangian–Karpatian, early Badenian?), b–younger (Badenian–early Sarmatian) – Balychi, Skawina (– Przemyśl), Bohorodchany, Tyras (Wieliczka), Chodenice and Grabowiec (Kosiv) Beds, **16** — intraformational conglomerates with fragments of rocks from: a–basement, b–flysch, **17** — evaporites, **18** — erosion of deposits. **Chronohorizons: mg** — Globigerina (Sheshory) Marls, **wj** — Jasło (Holovetsko) Limestones. **Characteristic lithofacies: a** — Kuźmina Sandstones, **b** — Spas Sandstones, **c** — Siliceous Marls, **d** — thick-bedded Inoceramian (–Stryi) Sandstones, **e** — Jamna Sandstones, **f** — Vyhoda Sandstones, **g** — Hieroglyphic Sandstones, **h** — Boryslav Sandstones, **i** — Kliwa Sandstones, **j** — Menilite Sandstones, Cherts and Marls, **k** — Krosno Beds, **l** — Polyanytsya Beds, **m** — evaporites, Vorotyshche Beds (Peri-Carpathian Salt-bearing Formation), **n** — Sloboda (Dubnik) Conglomerates, **o** — (younger) Wieliczka evaporites (–Kalush evaporites, Tyras Beds), **p** — Dobromil (–Radych) Conglomerates.

systems define the hinge of the flexural slope of the platform basement.

Transverse, oblique-slip faults striking SW–NE (subordinately S–N and SE–NW) and offsetting the pre-Alpine basement, which were identified on the basis of interpretations of geophysical survey results and remote-sensing analysis (e.g., Doktór et al. 1990; Kuśmierek 1990), are reflected only indirectly in the tectonics of the allochthonous nappes by changes in strikes (Kuśmierek & Baran 2008; Kuśmierek 2010). Nevertheless, they had an important influence on differentiation of the thickness and structural style of the nappes.

Tectonostratigraphic sequence of flysch and molasse formations in the frontal thrust zones: interpretative implications

Based on the contributions mentioned in Section "*The fold and thrust belt"* and on descriptions and chronostratigraphic correlations of geological processes contained in the publications of Gofstein (1964), Jiříček (1979), Dolenko et al. (1985), Kruglov et al. (1985), Petryczenko et al. (1994), Garecka & Olszewska (1997), and Poprawa et al. (2004), a model of the succession of the flysch and molasse deposits, tied to the tectonic regime that controlled their development (Fig. 3), was constructed in order to systematize the lithostratigraphic characteristics of formations distinguished in the geological cross-sections. Chronostratigraphic correlation of the deposits in the transfrontier zone of the Western and Eastern Carpathians presented a considerable difficulty in the light of rapid changes in thickness and lithology and differences in dating, encountered in a number of Polish and Ukrainian publications, such as Kotlarczyk (1988), Petryczenko et al. (1994), and Garecka & Olszewska (1997).

Graphical synthesis of the tectonostratigraphic sequences in the NE front of the Outer Carpathians (Fig. 3) has revealed several important relationships. Firstly, expansion of stratal units toward the platform slope was associated with pinching out of thick-bedded sandy series and interfingering of typical deep-marine turbidites with: epiplatform near-shore deposits during the late Palaeogene (so-called outer flysch in the Western Outer Carpathians), with evaporitic deposits (in the Eastern Outer Carpathians) locally with covers of near-shore conglomerates composed of exotics during the late Miocene; and then with marine deposits of the younger molasse. Secondly, the direction of that expansion can be confirmed by the increasing age of exotics (olistoliths, clasts) originating from erosion of older and older (toward NE) outcrops of the platform slope, from Jurassic and Upper Cretaceous rocks in sections of the Skole Series to the Palaeozoic quartzites and Precambrian phyllites in the early Miocene conglomerates (Ney 1968; Vjalov et al. 1981; Kotlarczyk 1988). Thirdly, intrabasinal synsedimentary uplifts triggered lateral changes in the thickness and lithofacies of deposits, particularly the extents of individual sedimentary successions, that impacted the distribution of Tertiary nappes in the Eastern Carpathians (e.g., Vjalov et al. 1981).

The diversified architecture of the eastern part of the Polish Carpathians and the western part of the Ukrainian Carpathians reflects the diachronism of the final phases of sedimentation of the flysch and molasse deposits, tectonic deformation, and the post-orogenic inversion of the orogen, in general manifested by:

- in the western part, transgression of the younger molasse onto folded and denudated (by subaerial, synkinematic? erosion; Świderski 1952; Kuśmierek 1990) rocks of the Skole Nappe before the Middle Miocene;
- in the eastern part, continuous sedimentation of the flysch–molasse deposits (locally washed out), thrust and folded in the final stages of their deposition (the Middle–Late Miocene).

Variation of the geological structure along the front of the NE segment of the Carpathians

Interpretation of the subsurface structure along the cross-sections

The locations of the transversal geologic cross-sections with the best documented subsurface structure of the frontal zone of the orogen in the eastern part of the Western

Carpathians (Fig. 4) and the western part of the Eastern Carpathians (Fig. 5) are presented in Fig. 1. Their traces were chosen to make use of the recent seismic reflection lines shot by Geofizyka — Kraków in the years 1991–2010 (sporadically, also older ones), running perpendicularly to structural strikes, and to the locations of deep wells, which were projected into the planes of the cross-sections.

For construction of the cross-sections, the fundamental criterion was to honour all the data in such a manner that the interpreted geometry is consistent with surface outcrops, seismically defined boundaries, well penetrations, and recognized trends of changes in distinct sedimentary formations (e.g., Kuśmierek et al. 1991–1994; Kuśmierek et al. 2009). The considerable improvements in acquisition and processing of seismic profiles, expressed by their better resolution and fidelity, was especially important for imaging the complex geometry of overthrusts and nappes, thrust imbricates and detachment folds which do not manifest themselves in the near-surface zone (Kuśmierek 2010).

In the Ukrainian Carpathians, interpretation of the subsurface structure in the northeastern fragment of cross-section VI (Fig. 5B) has been based on tectonic maps of so-called horizontal cuts at 3000, 5000 and 7000 m b.s.l. (Gluško & Kruglov 1986), as a consequence of the unavailability of the source documentation regarding the results of geophysical surveys and deep wells (Kuśmierek et al. 2009).

As illustrated by the enclosed cross-sections (Figs. 4 and 5), the tectonics of the allochthonous cover is most complicated in zones with deeply buried basement, which are characterized on magnetotelluric data by extreme resistivity contrasts and their unconformable positions (Kuśmierek 2010), which better synthesize the geometry of the resistivity boundaries, without going into the detailed description contained in the quoted paper. The cover is also characterized by great changes in thickness of the Oligocene–Lower Miocene successions (as a result of their syntectonic deposition), with the tendency to pinch out on structural elevations of the frontal zone of the Skole Nappe.

The thickness of the Skole Nappe decreases toward the platform margin as a result of the depositional pinch-out of the Lower Cretaceous sequences and pre-Badenian erosion (Figs. 1 and 4A, B). The geometry of the sole thrusts (frontal detachments) of the Skole Nappe and the Marginal Group units is generally unaffected by the faulted basement geometries (e.g., Wdowiarz 1976).

In the zone of shallow basement, the dips of thrusts are generally subhorizontal but become slightly steeper over depressions in the basement (Fig. 5), whereas further landward, their shape becomes complicated within tectonic sutures located in the foreland of the Silesian nappes as a result of subsurface wedging of displaced tectonic blocks.

In the Western Carpathians, the anticlinorium of the Skole Nappe is characterized by imbricate structures with roughly E–W strikes (Fig. 1). These are thrust over tectonically altered fragments of the allochthonous molasse of the Marginal Group (Fig. 4) and locally covered by outliers of the transgressive younger parautochthonous Miocene molasse (Fig. 1).

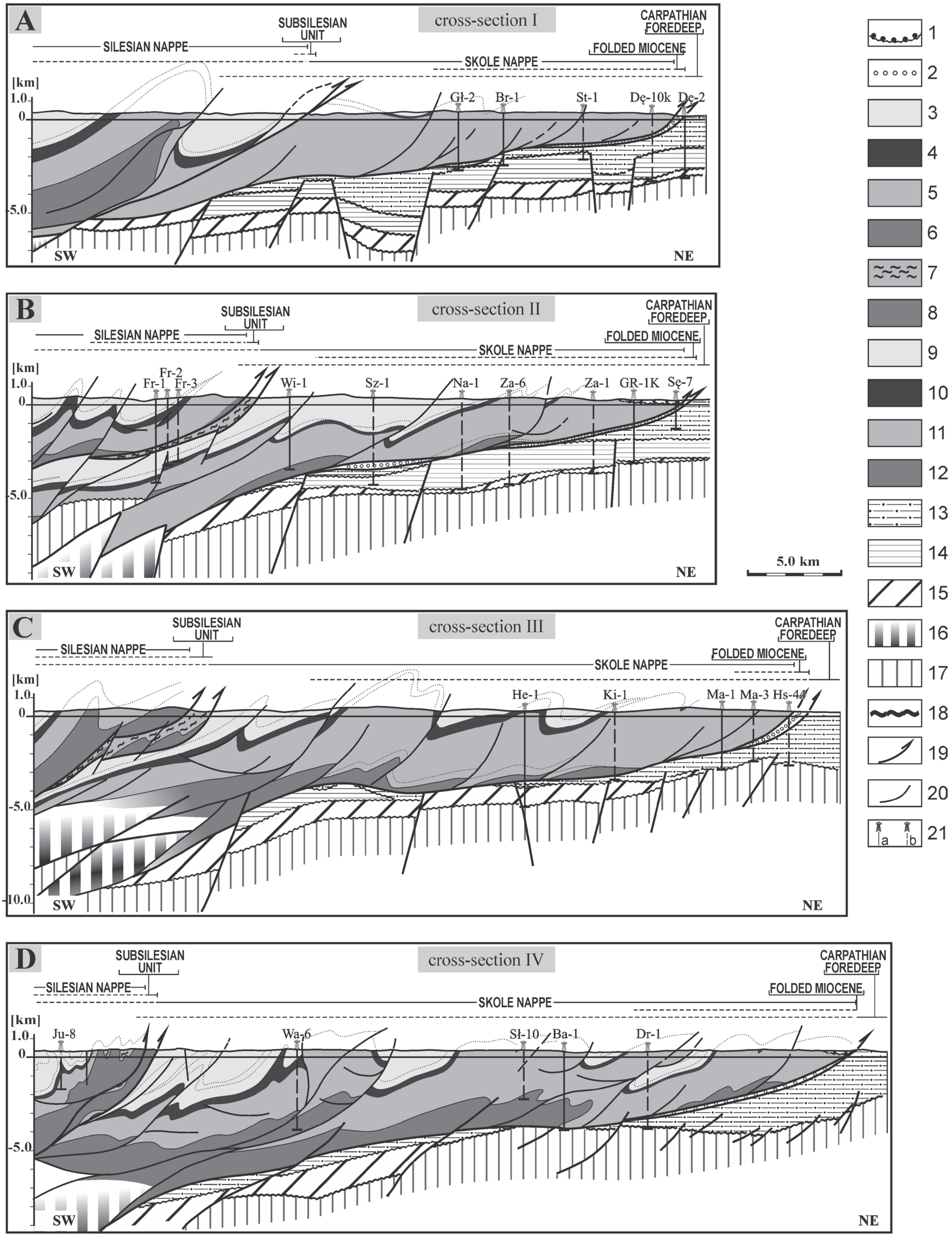
The changes in strikes of the marginal folds and thrusts of the Skole Nappe in the Przemyśl Sigmoid are accompanied by an intense reorganization of the orogenic front. To the SE of that zone, the tectonics of the Skole Nappe anticlinorium is dominated by a system of more closely spaced imbricate thrusts which separate structural elements of the "skyba" type, that is with the asymmetric geometry accentuated by pinchouts of the youngest flysch series, preserved only in deep synclines (Fig. 5). Also the stratigraphic section of the Boryslav-Pokuttya Nappe that pinches out laterally into the Przemyśl Sigmoid zone demonstrates the severe thickness reduction of the flysch deposits (Fig. 5A) in relation to their prolongation in the Ukrainian Carpathians (Fig. 5B), where above the structural depression of the pre-Tertiary basement, flat-lying disharmonic folds were formed.

Isolated erosional outliers of the epiplatform Palaeogene facies, which are unconformably underlying (with a stratigraphic gap) the Miocene molasse and were encountered by several wells (e.g., in the Hu-1 deep well, Fig. 5A), presumably determine the NE extent of the Palaeogene deposits in the Skole succession (Kuśmierek & Baran 2008). These deposits have not been found at the bottom of the Stebnik (Sambir) Nappe in the Ukrainian Carpathians (Fig. 5B) where the thickness of folded molasse exceeds 5000 m, although their occurrence cannot be excluded (Burov et al. 1969) at depths exceeding the ranges of the wells drilled.

Specific features of the tectonics of the Miocene molasse

In order to elucidate the complicated tectonostratigraphic relationships between the allochthonous/parautochthonous cover and the autochthonous series of the Carpathian

Fig. 4. Geological cross-sections (I–IV) through the frontal zone of the Western Carpathians, eastern part. **Allochthonous and parautochthonous cover: 1** — parautochthonous molasse (Badenian – early Sarmatian) transgressively overlying folded flysch series, **2** — folded molasse of the Stebnik Nappe (Ottnangian–Karpatian, early Badenian?) and Zgłobice Unit (Badenian–early Sarmatian), undivided; **Skole Series: 3** — deposits of the Menilite-Krosno Series (Oligocene–early Miocene), **4** — Hieroglyphic Beds and Variegated Shales (late Palaeocene–Eocene), **5** — Inoceramian Beds (Senonian–early Palaeocene) and Siliceous Marls (Turonian), undivided, **6** — Cretaceous deposits (Hauterivian–Turonian); **Subsilesian Series: 7** — Variegated Shales and Marls (Senonian–Eocene), **8** — Lower Cretaceous (sub-Senonian) deposits; **Silesian Series: 9** — Menilite-Krosno Series (Oligocene), **10** — Hieroglyphic Beds, Variegated Shales and Ciężkowice Sandstones (late Palaeocene–Eocene), **11** — Istebna Beds (Senonian–early Palaeocene), **12** — Lower Cretaceous (sub-Senonian) deposits, Lgota Beds, Veřovice Beds and Cieszyn Beds. **Autochthonous covers: 13** — Badenian – Sarmatian molasse (undivided), **14** — Mesozoic (undivided), **15** — Meso-Palaeozoic (undivided), **16** — Palaeozoic (undivided), **17** — Precambrian (Riphean–Vendian, Early Cambrian?). Graphical symbols: **18** — stratigraphic unconformities, **19** — nappe overthrusts, **20** — lower-order thrusts and other faults, **21** — wells: a–in the cross-section plane, b–projected onto the cross-section.


A
cross-section I
SUBSILESIAN UNIT
SILESIAN NAPPE
SKOLE NAPPE
FOLDED MIOCENE
CARPATHIAN FOREDEEP
[km]
1.0
0
-5.0
Gł-2
Br-1
St-1
Dę-10k
Dę-2
SW
NE
B
cross-section II
Fr-1
Fr-2
Fr-3
Wi-1
Sz-1
Na-1
Za-6
Za-1
GR-1K
Sę-7
C
cross-section III
-10.0
He-1
Ki-1
Ma-1
Ma-3
Hs-44
D
cross-section IV
Ju-8
Wa-6
Sł-10
Ba-1
Dr-1
5.0 km
1
2
3
4
5
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7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
a
b

Foredeep, the authors constructed three selected cross-sections through the front of the Carpathian overthrust at larger scales (Fig. 6A, B and C), as well as their detailed correlation between well penetrations (Fig. 7).

Cross-section A (Fig. 6), located to the west of the Wisłoka river valley (Fig. 1), illustrates the occurrence of the Upper Badenian deposits in three structural positions (from south to the north) as:

- the top parautochthon that is overlying (with a stratigraphic gap) the Cenomanian–Palaeocene deposits of the Skole Series but concordantly folded (?) and thrust together with them (the ŁG-1 well);

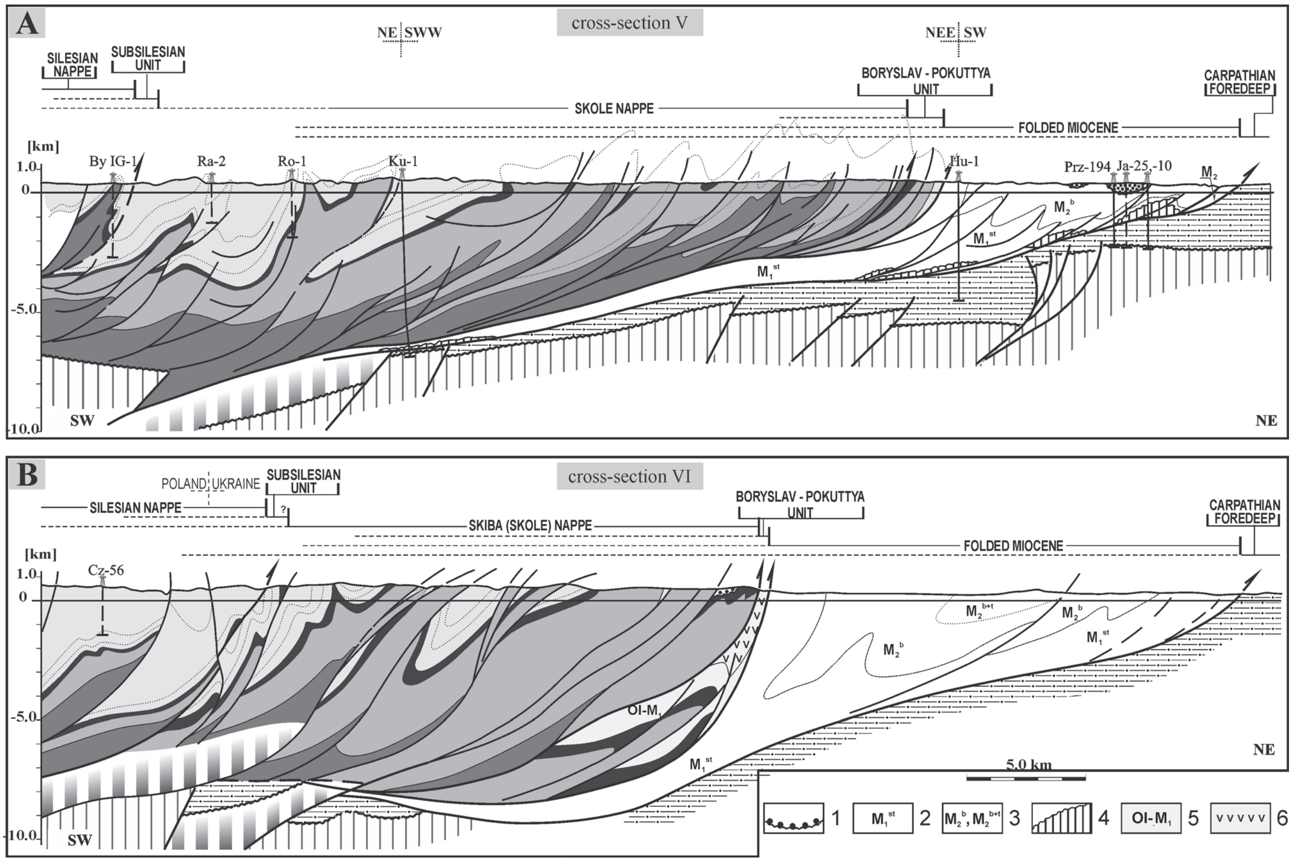
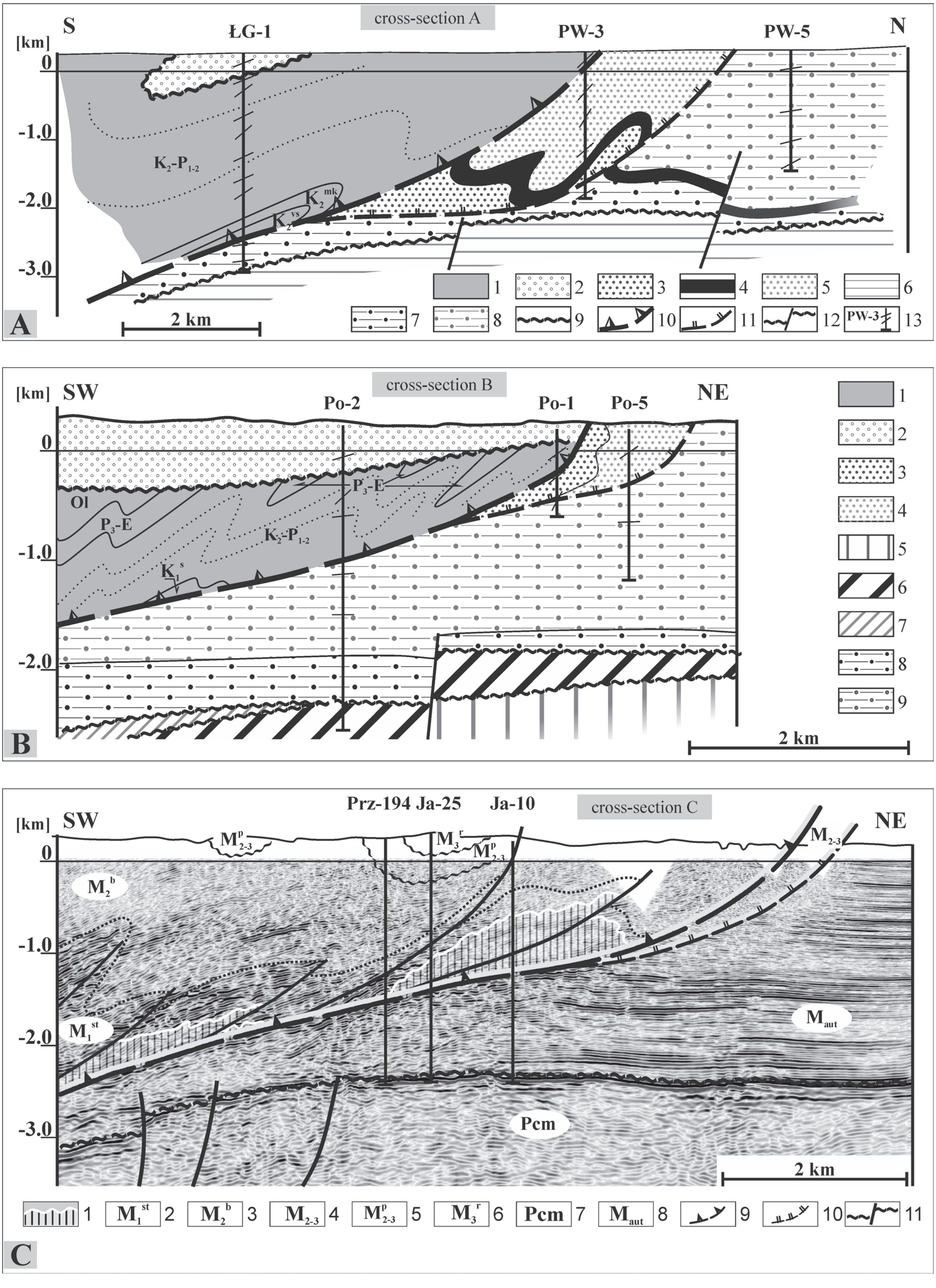


Fig. 5. Subsurface geological cross-sections (V–VI) through the frontal zone of the Eastern Carpathians, western part. **Allochthonous and parautochthonous cover: 1** — parautochthonous molasse (=Radych and Dobromil Conglomerates; late Badenian–early Sarmatian) transgressively overlying folded deposits of the Stebnik and Skyba nappes. **Folded molasse of the Stebnik (Sambir) Nappe: 2** — M_1–older (Ottnangian?–Karpatian) Stebnik Beds (M_1^{st}); **3** — M_2–younger (Badenian–lower Sarmatian) Balychi Beds (M_2^{b}) and Bohorodchany and Tyras Beds (M_2^{b+t}); **4** — erosional outliers of flysch subfacies of the Skole Series (Palaeogene). **Boryslav-Pokuttya Nappe: 5** — Menilite and Polyanytsya Beds, undivided (Ol–M_1), **6** — Vorotysche Beds (Eggenburgian). For remaining explanations see Fig. 4.

Fig. 6. Detailed cross-sections (A, B and C) through the outermost parts of the frontal thrusts. **A** — Łęki Górne–Pogórska Wola (after Jednorowska & Moryc 1967, slightly modified); **B** — Zalesie–Pobitno (tectonics of flysch series after Ney 1968, of Miocene molasse after Komorowska-Błaszczyńska (1971), with adaptation); C — Przemyśl–Jaksmanice (from Fig. 5A, with more details).
ad A/ **Skole Nappe: 1** — flysch deposits: Variegated Shales (Cenomanian) K_2^{vs}, Siliceous Marls (Turonian) K_2^{mk}, Inoceramian Beds (Senonian–Palaeocene) K_2-$P_{1\text{-}2}$; parautochthon: **2** — upper Badenian–lower Sarmatian; **folded Miocene: 3** — lower Badenian, **4** — evaporites, **5** — upper Badenian–lower Sarmatian; **autochthon: 6** — Upper Cretaceous marls and limestones, **7** — lower Badenian, **8** — upper Badenian–lower Sarmatian; **9** — stratigraphic unconformities, **10** — overthrust of the Skole Nappe, **11** — overthrust of folded molasse, **12** — faults, **13** — well penetrations with measured dips of strata.
ad B/ **Skole Nappe: 1** — flysch deposits: Spas Shales (Early Cretaceous) K_1^{s}, Inoceramian Beds (Senonian–Palaeocene) K_2-$P_{1\text{-}2}$, Hieroglyphic Beds and Variegated Shales (late Palaeocene–Eocene) P_3-E, Menilite-Krosno Series (Oligocene) Ol; **parautochthon: 2** — Badenian–lower Sarmatian; **folded Miocene: 3** — upper Badenian, **4** — lower Sarmatian; **autochthon: 5** — Precambrian, **6** — Devonian, **7** — Carboniferous, **8** — upper Badenian, **9** — lower Sarmatian. For the remaining symbols, see Fig. A.
ad C/ **Stebnik Nappe: 1** — erosional outliers of flysch subfacies of the Skole Series; **folded molasse: 2** — Stebnik Beds M_1^{st}, **3** — Balychi Beds M_2^{b}; **Zgłobice Unit: 4** — upper Badenian–lower Sarmatian $M_{2\text{-}3}$; **post-tectonic cover (parautochthon): 5** — Przemyśl (Skawina) Beds $M_{2\text{-}3}^{p}$, **6** — Radych Conglomerates M_3^{r}; **autochthon: 7** — Precambrian Pcm, **8** — undivided Miocene molasse (M_{aut}); **9** — overthrust of the Stebnik Nappe, **10** — overthrust of the Zgłobice Unit, **11** — thrust slices and faults. For the remaining symbols, see Fig. A.


cross-section A
S
ŁG-1
PW-3
PW-5
N
[km]
0
-1.0
-2.0
-3.0
K$_2$-P$_{1-2}$
K$_2$^{mk}
K$_2$^{vs}
1
2
3
4
5
6
7
8
9
10
11
12
PW-3
13
A
2 km
cross-section B
[km]
SW
Po-2
Po-1
Po-5
NE
0
-1.0
-2.0
Ol
P$_3$-E
K$_2$-P$_{1-2}$
K$_1$^{s}
1
2
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4
5
6
7
8
9
B
2 km
Prz-194 Ja-25
Ja-10
cross-section C
[km]
SW
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M$_{2-3}$^{p}
M$_3$^{r}
M$_{2-3}$
M$_2$^{b}
M$_1$st
M$_{aut}$
Pcm
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-1.0
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M$_1$st 2
M$_2$^{b} 3
M$_{2-3}$ 4
M$_{2-3}$^{p} 5
M$_3$^{r} 6
Pcm 7
M$_{aut}$ 8
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C

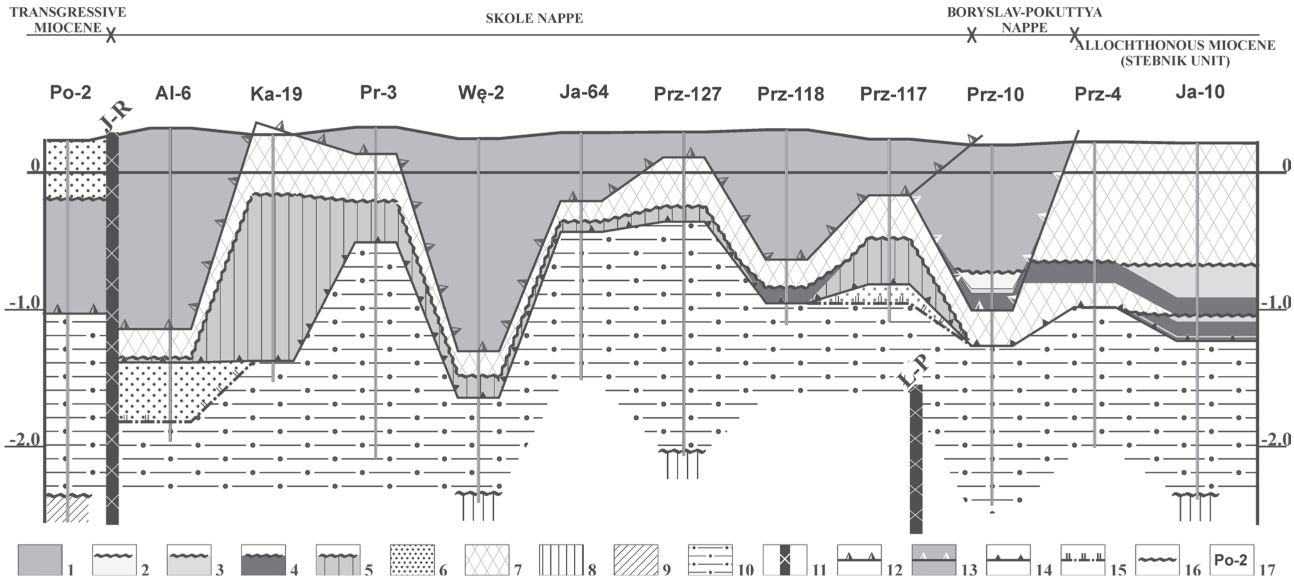

Fig. 7. Correlation of "flysch elements" in sections of the allochthonous Miocene in the frontal zone of the Polish Carpathians (eastern part). **Allochthon of the Skole and Boryslav-Pokuttya nappes: 1** — Inoceramian Beds (Late Cretaceous–Palaeocene); **outliers of the flysch subfacies of the Skole Series: 2** — Polyanytsya Beds (early Miocene), **3** — Menilite Beds (Oligocene), **4** — Variegated Shales (Eocene), **5** — Inoceramian Beds (Late Cretaceous–Palaeocene); **allochthonous and posttectonic Miocene: 6** — Zgłobice cover (late Badenian–early Sarmatian), **7** — Stebnik cover (Ottnangian–Karpatian); **autochthon: 8** — Precambrian, **9** — Devonian, **10** — Miocene (Badenian–early Sarmatian); **11** — transverse zones of deep-seated faults (J–R, Ł–P), **12** — overthrust of the Skole Nappe, **13** — overthrust of the Boryslav-Pokuttya Nappe, **14** — overthrust of the Stebnik Nappe, **15** — overthrust of the Zgłobice Unit, **16** — stratigraphic unconformities, **17** — symbols of well penetrations.

- a parautochthonous Miocene fold (at the front of the Skole Nappe overthrust), thrust over the autochthonous deposits of the Carpathian Foredeep (the PW-3 well) with the thrust amplitude on the order of 1 km;
- the subhorizontal autochthon, somewhat tectonically disturbed at depth (the PW-5 well), with basal lower Badenian deposits overlying (with a stratigraphic gap) the Upper Cretaceous marls (the ŁG-1 well).

Krzywiec et al. (2014) presented an alternative interpretation of the geological structure of the thrust front in the Pogórska Wola area (Fig. 1, cross section A), based on interpretation of a seismic 3D survey. In the southern segment of the seismic time section (fig. 10 in Krzywiec et al. 2014) — with the course similar to that of the cross section from our Fig. 6A — the quoted authors plotted (with a question mark) a backthrust that suggested a tectonic character of the unconformable position of the Miocene sediments on the Skole Nappe. Such interpretation conflicts with profiles of the early Badenian known from numerous wells (e.g., Połtowicz 1993), at the base of which there are sandstones and conglomerates with fragments of flysch rocks and sedimentary breccia of these rocks (Rajchel 1988), which indicate a transgressive origin of this surface. It is generally gently sloping, except for frontal thrusts where it was folded together with the Skole Nappe (Fig. 6A) during deposition of the Miocene synorogenic sediments.

Cross-section B (Fig. 6) is located in the eastern part of so-called Rzeszów Embayment (Fig. 1). The embayment is built up of the thickest preserved transgressive Miocene cover, with thicknesses exceeding 1000 m in the Mo-1 well (Wdowiarz 1976). In cross-section B, the upper and lower Badenian subhorizontal strata are unconformably overlying the tightly folded flysch series of the Skole Nappe (of Early Cretaceous–Oligocene age). In reality, the Badenian deposits that "drape" the flysch formations (the Po-2 and Po-1 wells) in the frontal zone were folded together with the transgressional surface during sedimentation of the lower Sarmatian deposits (the Po-5 well), resulting in overturned Miocene/flysch fold thrust onto the lower Sarmatian–upper Badenian autochthonous deposits which in turn unconformably overlie Devonian rocks (the Po-2 well).

Cross-section C (Fig. 6), located on the eastern side of the Przemyśl Sigmoid, represents the style of the geological structure of the Eastern Carpathians (Fig. 1A). This cross-section is an enlarged fragment of section V (Fig. 5A) and illustrates the geological interpretation of the northern part of the seismic section 2-13-94 K (originally scaled to 1:50,000), adapted from Kuśmierek & Baran (2008). The visualization aims at presenting the "internal structure" of the Stebnik Nappe and its relation to the overthrust nappes, the tectonics of the Carpathian Foredeep, and the structural situation of so-called "deep-seated flysch elements" (Ney 1968) that in fact represent erosional outliers of flysch deposits in the epiplatform facies (after Kuśmierek & Baran 2008) which rest at the base of the Stebnik molasse. Those outliers, encountered by the Ja-10, Ja-25 and Hu-1 wells (in the cross-section plane), are bounded by a surface of the Early Miocene erosion. In the seismic image, they are expressed by: decline of the reflector continuity; angular discordance; and different dynamics of their record in relation to the overlying molasses.

The flysch elements within the allochthonous Miocene cover were penetrated in different structural positions, delineated by stratigraphic discontinuities or overthrusts (Fig. 7), in the following forms:

- in the western zone, as eroded folds of the front of the Skole Nappe overlain by the transgressive cover of the Badenian–lower Sarmatian deposits and sometimes thrust over folded deposits of that same cover (see 6B, Po-1 well), which is distinguished as the allochthonous Zgłobice Unit (Kotlarczyk 1988, Połtowicz 2004);
- in the central part, as erosional outliers of the Cretaceous–Palaeocene, unconformably overlain by deposits of the lower Miocene (Eggenburgian?, Ottnangian–lower Badenian), distinguished as the allochthonous Stebnik Nappe (Unit) (Kotlarczyk 1988, Połtowicz 2004), and locally underlain by folded outliers of the Zgłobice Unit (in the Al-6 and Prz-117 wells);
- in the eastern part (the Eastern Carpathians), as the youngest sequence of flysch deposits (Eocene–lower Miocene) at the bottom of the overthrust Upper Cretaceous deposits belonging to the Boryslav-Pokuttya Nappe (the Prz-10 well?), and as erosional outliers unconformably overlain by the Stebnik molasse, thrust together with them over the autochthonous deposits of the Carpathian Foredeep (the Prz-4 and Ja-10 wells) (Kuśmierek & Baran 2008).

The palinspastic image of the tectonic evolution of flysch and molasse subbasins

Reconstruction criteria for the palinspastic framework

The image of the precompressional configuration of the subbasins in the NE segment of the Outer Carpathians during the Late Tertiary was obtained through palinspastic projection of the following folded and thrust surfaces of:

- the base of the Menilite-Krosno Series (Oligocene) in cross-sections of the Silesian, Subsilesian, Skole and Boryslav-Pokuttya nappes, which is correlated with the stratigraphic horizon of the Globigerina Marls (Sheshory Marls), approximately 34 Ma BP;
- the base of the Balychi Beds in cross-sections through the Stebnik Nappe, approximately 16 Ma BP (after Garecka & Olszewska 1997), assuming that it determines the boundary between the Early and Middle Miocene (Gradstein et al. 2004), although in older papers those beds were dated as Karpatian (Ney 1968; Petryczenko et al. 1994).

The authors assumed the relative reference line for the palinspastic projection to be the trace that connects the points of intersection of the base of the Oligocene deposits with the Dukla Overthrust surface, which were marked in 7 regional cross-sections (traverses I, III-VIII, Fig. 1), not included in this paper. They were chosen from a larger set of traverses, constructed by the authors and originally scaled to 1:50,000 or 1:100,000 (Kuśmierek et al. 2009; Górecki 2013) in such a way that their traces are perpendicular to fold strikes and evenly distributed in the reconstructed part of the Outer Carpathians (Fig. 1). Some of the segments (NE) are coincident with traces of the geological cross-sections (Fig. 4A, C, D and Fig. 5A) and the generalized structural models of the traverses IV and V were previously published (Kuśmierek 2010, figs. 7 and 8).

The cross-sections that illustrate the subsurface geological structure of the Ukrainian Carpathians along traverses VI (the NE part), VII and VIII (Kuśmierek et al. 2009) were constructed on the basis of geological maps (Shakin et al. 1976; Gluško & Kruglov et al. 1986; Burov et al. 1986; Jankowski et al. 2004; Kuzovienko et al. 2004) and publications (Danysh 1973; Gluško et al. 1984; Kolodij et al. 2004).

In order to reconstruct the configurations of the subbasins (Figs. 8 and 9), the lengths of stratigraphic boundaries were measured with an opisometer (in the cross-sections), ascribing them to particular nappes (tectonofacies units). The lengths of the straightened lines in directions consistent with their general vergence determined the original widths of sedimentation zones of particular nappes in the traces of the traverses.

Potential inaccuracies in constructing the palinspastic framework of the subbasins may arise from:

- neglecting the influence of the varied bathymetry (subsidence of the bottom) on the reduction of widths of sedimentation zones;
- assuming (*a priori*) that the age of structural offsets (thrusts, imbrications of folds, faults) was younger than the time of: (a) deposition of the guiding lithostratigraphic boundaries; and (b) formation of the subsurface line of the Dukla Thrust intersection with the basal surface of the Oligocene strata.

The second of these may include a potential error (on the order of several hundred metres to a few kilometres) in the eastern part of the Dukla Thrust, where synsedimentary tectonic movements in the foreland occurred as early as the early Oligocene (e.g., Kuśmierek & Baran 2013), possibly involving also the Dukla Nappe after the deposition of the Globigerina Marls (Fig. 3). The time of the initial shortening of the Krosno lithofacies deposits in the sedimentation zone of the Silesian nappes as early as the early Oligocene has been suggested by results of balancing cross-sections (Kuśmierek 2010, fig. 6A). It can also be confirmed by data from the literature, which were compiled by Nemčok et al. (2006, table 1).

Selection of the subsurface edge of the Dukla Thrust as the relative reference line for the palinspastic projection — taking account of its coincidence with the line of zero values of the Wiese vector — enables indirect tying of the Outer Carpathian cover to the potential zone of their collision with the Inner Carpathian zones (Figs. 8 and 9).

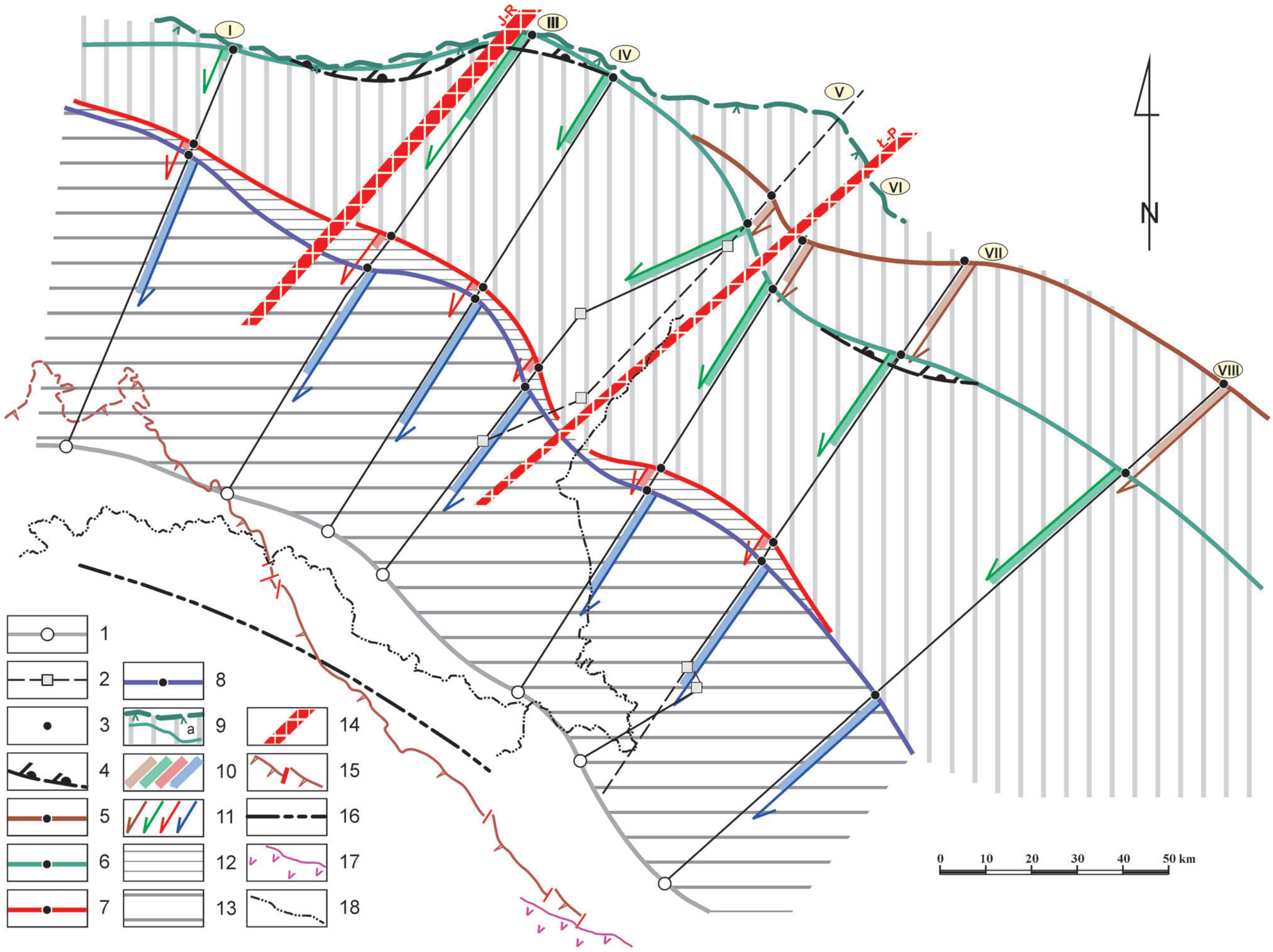

Fig. 8. Palinspastic reconstruction of the tectonic evolution of the NE segment of the Outer Carpathians during the Oligocene–Early Miocene. **1** — relative reference line of palinspastic reconstruction and traces of its projection in the planes of regional traverses, **2** — actual segments of traverses V and VII before geometrical correction of their deviation from directions perpendicular to strikes of structures, **3** — points documenting extents of sedimentary areas, **4** — SW extent of older Miocene molasse (Eggenburgian–Karpatian) overlying, with sedimentary continuity or with local stratigraphic gaps, the flysch deposits of the Skole succession; maximum northeastern extents of sedimentation of: **5** — Boryslav-Pokuttya Nappe, **6** — Skole Nappe, **7** — Subsilesian Nappe, **8** — Silesian Nappe; **9** — sedimentation zones of the Skole succession: a–in a near-shore facies to NE of the sedimentation area of the Skole and/or Boryslav-Pokuttya nappes, **10** — magnitude of narrowing of sedimentation areas of particular nappes, **11** — subhorizontal magnitude of basement displacement of particular nappes, **12** — sedimentation zone of the Subsilesian succession, **13** — sedimentation zone of the Silesian succession, **14** — zones of deep-seated faults (fractures), active before the middle Miocene; present-day locations of: **15** — Magura overthrust, **16** — zero values of the Wiese vector, **17** — volcanic cover, **18** — state borders.

The pre-orogenic configuration of the flysch subbasins and the magnitude of tectonic displacement during the Oligocene–Early Miocene

Basic parameters that scale the palinspastic models of the tectonic evolution in the NE segment of the Outer Carpathians (Figs. 8 and 9) are compiled in Table 1. They were derived from measurements and calculations in the planes of traverses I, III and IV in the Western Carpathians and traverses V, VI, VII and VIII through the Eastern Carpathians. Values from column 1 of each nappe (Table 1) and their sums document (in the scale of Fig. 8) the precompressional widths of sedimentation zones of particular nappes and their maximum extents to the NE. In Fig. 8, the dashed lines denote the extrapolated extents of the sedimentation of:

- the Skole succession of deposits in the epiplatform facies, located NE (or N) of the sedimentation zone of the Skole Nappe and/or the Boryslav-Pokuttya Nappe;
- older Miocene molasse (Eggenburgian–Karpatian) overlying, with sedimentary continuity (or with a local stratigraphic gap), the deposits of the Skole succession, in essence — their SW extent ascribed to the palinspastic projection of the early Oligocene.

In the frontal zone of the Outer Carpathians, the age of final tectonic deformation can be calibrated by the age of the syntectonic deposition of molasse (e.g., Jiříček 1979). In contrast, only indirect premises are available for the foreland zone of the Dukla Nappe, which indicate formation of synsedimentary folds as early as in the early Oligocene (Kuśmierek & Baran 2013).

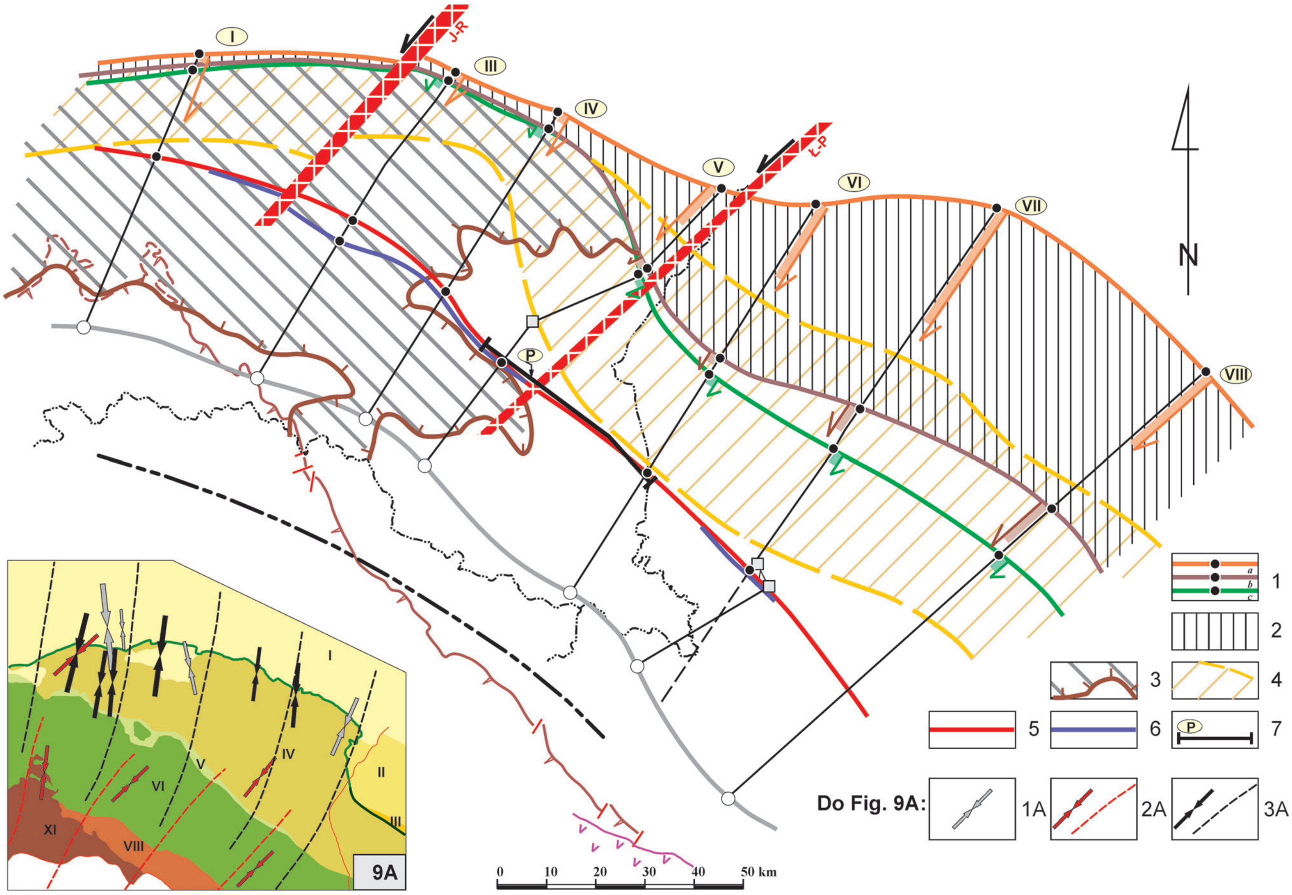

Fig. 9. Palinspastic reconstruction of the tectonic evolution of the NE segment of the Outer Carpathians in the beginning of the Middle Miocene and magnitude of displacements during Middle Miocene–Quaternary times. **1** — points documenting the NE extents of: a–sedimentation of allochthonous Miocene molasse, b–Boryslav-Pokuttya Nappe, c–Skole Nappe, **2** — sedimentation area of allochthonous Miocene molasse; present-day locations of: **3** — maximum extent of transgression of the middle Miocene molasse on nappes in the Western Carpathians, **4** — allochthonous molasses thrust over the autochthonous deposits of the platform slope; locations of overthrusts of: **5** — Subsilesian Nappe, **6** — Silesian Nappe; **7** — line of the longitudinal geologic cross-section (P). For the remaining explanations, see Fig. 8.
Inset A. Directions of the greatest horizontal stresses (S_{Hmax}) on the basis of borehole breakout data (after Jarosiński 2006), for: **1A** — autochthonous Miocene molasse in frontal zone of the Carpathians, **2A** — overthrust of the Carpathian flysch and folded Miocene molasses, **3A** — sub-Tertiary basement.

Subtraction of values from columns 1 and 2 of Table 1 yields the total magnitude of shortening of each nappe (in kilometres, column 3), presented as vectors in Figs. 8 and 9. This is illustrated for the Silesian succession (the Silesian and Subsilesian nappes) by the sums of the overall lengths of the thickened lines of the vectors of subhorizontal tectonic displacements, and for the Skole succession those lengths refer only to the Oligocene–early Miocene stratigraphic interval.

The total lengths of the vectors illustrate the magnitude of subhorizontal displacements of the consolidated basement of the nappes (Table 1, column 5). According to the assumption (see the previous section of the text), they were calculated as the sum of the magnitude of stratal shortening within each imbricate (column 3) and the heave of the intervening thrusts and faults. As dip angles of subsurface faults (“compressional sutures”) increase to vertical ones, their horizontal component decreases to zero.

The magnitude of shortening during the Oligocene–early Miocene does not show any marked variation within sedimentation zones of the Silesian succession (Table 1, Fig. 8). It varies more in the sedimentation area of the Skole succession, mostly in zones of strike changes of the Skole and Boryslav-Pokuttya subbasins, associated with the Jasło–Rzeszów (J–R) and Łupków–Przemyśl (Ł–P) deep-seated fractures (Fig. 8), locations of which were determined on the basis of premises from the regional analysis of the recent tectonics of the Outer Carpathians (e.g., Doktór et al. 1990; Kuśmierek 1990). Consequently, the arrangement of the nappes in the NE segment of the Outer Carpathians was influenced by the configuration of the flysch subbasins as early as in the Oligocene–early Miocene.

The total magnitude of subhorizontal displacement of the front of the accretionary prism, determined as the overall vector lengths (Fig. 8), is characterized by substantial differences along strike:

Table 1: Measured parameters of the magnitude of subhorizontal tectonic displacements of the allochthonous cover and its consolidated basement (CB) in regional geological traverses through the NE Outer Carpathians in the Late Tertiary

Number of traverse	NAPPES AND STRUCTURAL – FACIES UNITS OF THE OUTER CARPATHIANS																												
	Silesian Nappe (Krosno zone)					Subsilesian Nappe (Unit)					Skole / Skiba Nappe					Boryslav-Pokuttya Nappe					Stebnik / Sambir Nappe and Zgłobice Unit					The whole traverse			
	Sedimentary cover				CB	Sedimentary cover				CB	Sedimentary cover				CB	Sedimentary cover				CB	Sedimentary cover				CB	Sedimentary cover			CB
	Width of the sedimentation zone [km]	Present-day width of outcrops [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]	Width of the sedimentation zone [km]	Present-day width of outcrops [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]	Width of the sedimentation zone [km]	Present-day width of outcrops [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]	Width of the sedimentation zone [km]	Present-day width of outcrops [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]	Width of the sedimentation zone [km]	Present-day width of outcrops [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]	Width of the sedimentation zone [km]	Magnitude of shortening [km]	Percentage of shortening [%]	Magnitude of displacement [km]
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	3	4	5
W E S T E R N C A R P A T H I A N S																													
I	69,0	37,4	31,6	45,8	34,4	>2,5	0,7	>1,8		>9,5	22,0	19,6	>2,4	>0,9	>10,7						2,1*	0,7	1,4	66,7	14,0	>95,6	37,2	>39,9	68,6
III	58,1	31,3	26,8	46,1	33,7	8,5	5,1	3,4		14,2	53,8	31,1	22,7	44,2	37,1						2,2[2]	0,8	1,4	63,6	7,0	122,6	54,2	44,3	92,0
IV	60,3	28,9	31,4	52,1	35,6	2,5	0,7	1,8		9,5	53,9	36,8	17,1	31,7	19,7						2,4[3]	0,6	1,8	75,0	9,1	119,1	52,1	43,7	73,5
E A S T E R N C A R P A T H I A N S																													
V	51,4	23,9	27,5	53,5	32,4	5,2	1,4	3,8	73,0	7,4	60,5	32,2	28,3	46,8	29,2	7,9	1,4	6,5	82,3	9,2	22,3	12,4	9,9	44,4	15,8	147,3	76,0	51,6	94,0
VI	52,2	26,8	25,4	48,7	31,2	5,7	1,1	4,6	80,7	7,3	46,2	19,8	26,4	57,1	28,3	12,7	2,8	9,9	52,0	15,2	37,0	19,7	17,3	46,7	20,0	153,8	83,6	54,4	105,3
VII	58,9	27,4	31,5	53,5	36,3	4,8	1,6	3,2	66,6	8,0	49,9	26,1	23,8	47,7	28,0	24,9	7,8	17,1	68,7	26,2	49,2	21,8	27,4	55,7	31,3	187,7	103,0	54,9	129,8
VIII	61,8	32,8	29,0	46,9	37,9						73,0	35,4	37,6	51,5	38,2	29,1	5,8	23,3	80,0	33,9	42,1	21,2	20,9	49,6	21,5	206,0	110,8	53,4	131,5

*,2,3 according to cross-sections V, III, I (Połtowicz 2004; Figs. 6 and 9)

- in the Western Carpathians, 35.8–49.6 km for the sedimentary cover and 54.6–78.1 km for the consolidated basement;
- in the Eastern Carpathians, 55.3–74.2 km and 68.9–92.1 km, respectively.

The above ranges of values suggest dismemberment of the subducted platform slope into lithosphere blocks with variable directions and magnitude of displacement.

Interference of the allochthonous and parautochthonous covers in the Outer Carpathians during the Middle Miocene

Figure 9 is a palinspastic model of the tectonic evolution from the middle Miocene to Quaternary. It shows the extent of sedimentation zones of the allochthonous and parautochthonous Miocene molasse and the locations of frontal thrusts of the Skole and Boryslav-Pokuttya nappes at the end of the early Miocene, preceding the final inversion of the orogen (Fig. 3). During this interval, differences between the Western and Eastern Carpathians became marked.

The strikes of subbasins of the Marginal Group in the Eastern Carpathians follow the system of NW–SE oriented deep-seated faults that affect the SW slope of the East European Platform (Samojluk 1976a), namely the Tornquist-Teisseyre Zone (Picha 2011). Oblique interference of the T-T zone with the deep-seated fractures of the West European Platform manifests itself by minimum values of the gravity field (Zayats 2013) in the NE segment of the Outer Carpathians.

The differentiation of subbasin configurations between the Eastern and Western Carpathians during the Middle Miocene is manifested in their structural position and the width and magnitude of subhorizontal displacements of the sedimentary cover and its basement (Fig. 9). The difference of extreme values of tectonic displacement of the sedimentary cover exceeding 25 km (e.g., in the traverses III and VII, Fig. 9) supports the thesis that the folding and thrusting were diachronous along the front of the orogen toward the SE (Jiříček 1979), which means that in the eastern traverses (VII and VIII, Fig. 1) the final stage could have ended over 2 Ma later. The undeformed transgressive Badenian molasse on the folded nappes of the Middle Group in the Western Carpathians shows that the final phase of contraction in this area was no younger than the early Sarmatian, and it probably took place in subaerial conditions associated with the "cannibalism" of older deposits (Kuśmierek 1990).

In basement uplifts of the Western Carpathians (Fig. 4), the magnitude of shortening of the sedimentation zone of the allochthonous molasse was controlled primarily by the magnitude of slip on the detachments. In the Eastern Carpathians, however, it was dominated by development of continuous deformation as seen in cross-sections of the Boryslav-Pokuttya and Stebnik nappes (Figs. 5B and 9, Table 1 — columns 3 and 5).

The maximum extent of transgression of the Miocene molasse onto the flysch nappes (Fig. 9) was reconstructed on the basis of unpublished data from Urbaniak (in: Kuśmierek 1986) and of Kuśmierek et al. (1991-1994), as well as publications of Połtowicz (1993). Because this molasse forms the parautochthonous cover, its extent was reflected in the recent topography of the orogen, not the magnitude of tectonic displacements in the marginal zone of the Western Carpathians, which were dominated by thrusts in the base of the flysch (Fig. 9, Table 1 — column 5). The authors also plotted the extent of the younger and older folded molasse, thrust over the younger, autochthonous molasse of the Carpathian Foredeep. The minimum southern (southwestern) extent of their occurrence was determined by interpolation of well data and/or interpretation of the geometry of overthrusts in the planes of the traverses.

A synthesis of the palinspastic reconstruction of the tectonic evolution in the NE segment of the Outer Carpathians during the Late Tertiary is illustrated by the sums of the parameters calculated for whole traverses (Table 1). The ranges of values emphasize differences between the Western Carpathians and Eastern Carpathians, respectively in:

- the reconstructed widths of sedimentation zones: 95.6–122.6 km and 147.3–206.0 km;
- the magnitude of shortening: 37.2–54.2 km and 76.0–110.8 km;
- the percentage of shortening: 39.9–44.3 % and 51.6–54.9 %;
- the magnitude of basement displacements: 68.6–92.0 and 94.0–131.5 km.

The broad interval of geological time for the tectonic evolution during the Late Tertiary (34–12 Ma) for the whole segment of the Outer Carpathians located to the NE of the Dukla Overthrust, implies low average shortening rates, for example, 3.11–5.98 km/Ma for subhorizontal displacements of the basement. Nevertheless, when taking into account migrations (in time and space) of the folding and thrusting, real rates of shortening could be several times higher, for example, during the Late Oligocene–Early Miocene for the Middle Group nappes and during the Middle Miocene for the Marginal Group; for example, in the traverse VII it could exceed 10 km/Ma (Fig. 9).

The tectonic activity of the front of the Polish Outer Carpathians during the Pliocene–Quaternary involved relatively minor thin-skinned deformation (Zuchiewicz 2001). There were also long-wave oscillatory uplifts (Gofstein 1964; Kuśmierek et al. 1985), induced by the isostatic effects of "erosional unloading". Nevertheless, recent measurements on drill cores have revealed compressional stress (Jarosiński 2006), with the principal compressive stress subhorizontal and deviated a few to more than ten degrees from the interpreted displacement directions ascribed to the traces of the traverses (Fig. 9A).

The kinematic model of the orogenesis

To illustrate the model of the orogenesis of the frontal zone of the Outer Carpathians, successive stages of the tectonic evolution were reconstructed in geological cross-section V (Fig. 5A) through the Przemyśl Sigmoid (Fig. 1). The stages, in millions of years (I–IV in Fig. 10), were scaled using the magnitude of the subhorizontal tectonic displacements (Figs. 8 and 9) and the vertical component of tectonic movement of the Skole Nappe, namely subsidence of the base Oligocene in stage II, and with the amount of syntectonic erosion in stage III and the postinversional erosion in stage IIIa, which were interpolated on the basis of reconstructed maps (after Kuśmierek et al. 1995).

Having (for the Skole Nappe) the quantified values of the subhorizontal and vertical components of tectonic movement, the authors made a diagram of the rate and directions of the tectonic movements (resultant vectors, Fig. 10A) in the plane of the cross-section. The diagram shows, for successive stages of the evolution, both the change in the rate of movement and the oscillation of the movement vectors. It is suggested that in the early Oligocene (stage I-II), the palaeotectonics of the subbasins reflected the disintegration of the platform slope into blocks with variable subsidence and even local uplift due to block rotation, with the initial subduction taking place in the zone of the Subsilesian Swell (to SW of the cross-section). The increase in the rate of tectonic displacement in stage II-III, with the subhorizontal component still dominant, records the major phase of the subduction process during the Late Oligocene–Early Miocene, which manifests itself by the formation of thrust nappe and synsedimentary folds together with subaerial erosion of their uppermost parts (model II and Fig. 3). At the same time, the synclinorium of the Skole Nappe, located over the zone of the "subsurface wedging" of crustal blocks (model IV), was characterized by a higher degree of tectonic subsidence and continuous, more asymmetric deformation (Fig. 5A) in comparison with the anticlinorium (as shown by the different lengths and directions of the vectors **s** II-III and **a** II-III in Fig. 10A).

Model IIIa (Fig. 10) illustrates the amount of the postinversion erosion, as shown by the vertical component of the vector III-IV which has a positive value in Fig. 10A. The subvertical trajectory of the vector represents the superposition of the decline of compression with the isostatic uplift of the orogen during Miocene–Quaternary times (Fig. 3).

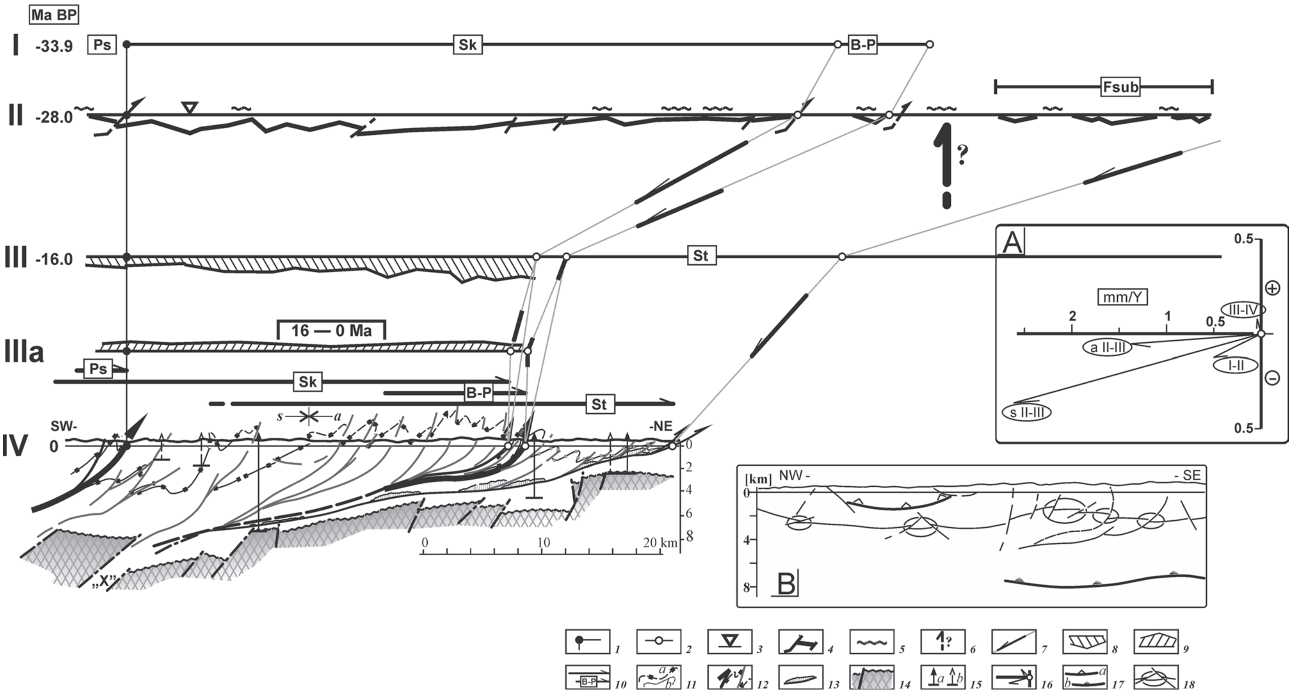

Fig. 10. Kinematic model of the tectonic evolution of the nappes of the Outer Carpathians in the Przemyśl Sigmoid zone. **I–IV** — Sections that image successive stages of the tectonic evolution: **I** — width of sedimentation zone of the Skole Nappe (Sk) and Boryslav-Pokuttya Nappe (B-P) during deposition of the chronohorizon of Globigerina (Sheshory) Marls; Ps — Subsilesian Nappe: **1** — start of the palinspastic framework correlated with the intersections of the base of the Menilite Beds with the basal thrust of the Subsilesian Nappe, **2** — points documenting the widths of sedimentation zones; **II** — as above, during deposition of the chronohorizon of Jasło (Holovetsko) Limestones: **3** — hypothetical sea level, **4** — hypsometry of the base of the Menilite Beds (Oligocene) and location of probable synsedimentary dislocations, **5** — probable zones of subaerial erosion, **6** — probable location of synsedimentary uplifts of the basement, **7** — interpolated magnitude and direction of tectonic displacements of points correlated with location of overthrusts (in the stage II–III), F_{sub}–interpolated sedimentation zone of the Skole succession deposits, in the near-shore (epicontinental) subfacies; **III** — as above, during deposition of the base of Badenian deposits, ~16.0 Ma (younger molasse), correlated with the beginning of sedimentation of the Balychi Beds; **estimated amount of erosion: 8** — syntectonic erosion, **9** — postinversion (terrestrial) erosion in the stage III–IV; **IV** — present-day tectonic model (according to Fig. 5A): **10** — vertical projections of nappe covers (extents of interference), **11** — geometry of chronostratigraphic boundaries: a–base of Oligocene, b–base of Badenian, **12** — traces of nappe overthrusts and minor thrusts, **13** — erosional outliers of flysch deposits of the Skole succession in the epicontinental subfacies, **14** — top of the consolidated basement (Precambrian) and faults that offset it, **15** — well sections: a–in the cross-section plane, b–projected onto the cross-section; "x"–deep-seated fracture skirting the southern extent of the platform type? basement; extents of synclinorium (s) and anticlinorium (a) of the Skole Nappe.
Inset A: 16 — diagram showing rates and directions of tectonic movements in successive stages of evolution of the Skole Nappe in the Late Tertiary; for the stage II–III, measured separately for **a** (anticlinorium) and **s** (synclinorium) of the Skole Nappe;
Inset B: Tectonic sketch of the longitudinal geologic cross-section P through the internal synclinorium of the Skole Nappe (the cross-section line is in Figs. 1 and 9). **17** — overthrusts of nappes: a–Subsilesian, b–Skole, **18** — thrust faults that offset the base of the Oligocene.

The propagation of the tectonic deformations as a result of the subduction of the platform slope is reflected by the consistent vergence of the overthrusts, which is characteristic of this process. They juxtaposed the imbricated "skybas" in the section of the Skole Nappe with the Boryslav-Pokuttya and Stebnik nappes at its base. The degree of the tectonic interference between the flysch and the flysch and molasse covers was illustrated (Fig. 10, model IV) to accentuate the analogy with the palinspastic projection (Fig. 9).

In light of the oroclinal geometry of the deformed sedimentary covers (Figs. 8 and 9), the convergent directions of the subhorizontal tectonic displacements inevitably resulted in compression also along the strikes of folds. This is illustrated, for example, by the longitudinal cross-sections in the form of thrust faults (Fig. 10B) which "shorten" the deformed surfaces. Their occurrence is a strong argument supporting the proposed model of the orogenesis of the fold and thrust belt.

Summary and discussion of results

1. The arc of the Outer Carpathians, created by thrusting and folding, overlies faulted segments of the European Platform lithosphere, bounded to the SW by the collision zone with altered, thinned lithosphere of a mantle diapir (Konečný et al. 2002). The lithosphere underlies the Carpathian Internides and back-arc basins, and that zone is identified with zero values of the Wiese vector (Jankowski et al. 1979). The basement of sedimentary basins of the Outer Carpathians was successively shortened during the Late Tertiary along deep-seated faults (Kuśmierek 2010) during its subduction (together with gravitational? subsidence) including original uplifts in the basement which separate the West Carpathian subbasins (Książkiewicz 1965). Convergence of the continental plates of the lithosphere was compensated in the collision zone by diapiric uprise of the mantle (Konečný et al. 2002).

2. Thrusts and folds of the sedimentary cover, detached from the subducted basement blocks, propagated toward the frontal zone of the Outer Carpathians and were subjected to telescopic shortening. The variable geometry of the zone was influenced by the pre-orogenic morphology of the basement of the sedimentary basins, including transverse oblique-slip fractures. The strike of the outer compressional suture that delineates the extent of the flexural platform slope in the area of the Polish Carpathians — the geoelectric signature of which was different in nature from the remobilized basement of the Externides in their central and southern parts (Stefaniuk et al. 2009, fig. 6; Kuśmierek 2010) — correlates (in the first approximation) with the axis of the gravitational minimum.

3. The sedimentary cover detached from its basement is characterized by distinct styles of: tectonic deformations (particularly the relatively weak syntectonic successions); the morphology of sedimentary basins; the sediment thicknesses and lithologies; and the geometry and amplitude of thrusts (Kuśmierek & Ney 1988). These have been illustrated by subsurface cross-sections through the frontal zone of the NE segment of the Outer Carpathians (Figs. 4, 5 and 6). In zones of shallow basement, the structural style of the allochthonous cover is dominated by thrust imbricates detached on sole thrusts, with the geometry becoming more complicated in the zone of the outer compressional suture. The style and consistent vergence of the thrust faults record their compressional origin (e.g., Wdowiarz 1976; Książkiewicz 1972).

4. The influence of deep-seated faults in the basement, which terminate upward beneath the sole thrusts (e.g., Kuśmierek & Baran 2008), manifests itself by changes in strike and modifications of the tectonics of the allochthonous cover, and particularly by their discrepancy in the Przemyśl Sigmoid zone, associated with the NW margin of the Transcarpathian Depression in the basement. The western part of the Eastern Outer Carpathians, which overlies that depression, is characterized by an increasing thickness of the nappes and of the whole lithosphere (Dérerová et al. 2006) and a thorough reorganization of the frontal zone of the orogen. This includes the system of imbricate thrusts that separate structural elements of the "skyba" type (Fig. 5), as well as the sedimentary continuity of flysch — molasse successions with their horizontal interfingering with the Stebnik molasse and autochthonous foredeep molasse (Petryczenko et al. 1994), apart from local stratigraphic gaps (washouts) and thrusts that offset the lithostratigraphic boundaries.

5. The tectonostratigraphic identification of depositional systems in the zone of frontal thrusts (Figs 2, 5, 6 and 7) is a basic source of information necessary for deciphering the Tertiary evolution of the Outer Carpathians (e.g., Krzywiec 2006) and it implies their direct connection with the architecture of the platform margin.

6. Profiles of the Miocene sedimentary successions of the frontal cover in the Western Outer Carpathians, thrust onto the Małopolska Block basement, are generally discontinuous on account of their deposition during subduction of the platform slope. The direction of subduction varied obliquely relative to the strikes of the nappes (Jiříček 1979; Ellouz & Roca 1994; Kuśmierek 1996), which is why the tectonostratigraphic relationships of the Miocene successions with Cretaceous–Palaeogene (flysch) formations and younger (or coeval) autochthonous molasse are complicated (Figs. 2, 3, 6 and 7). As a consequence, the Miocene deposits occur in various tectonostratigraphic positions (Figs. 6 and 7):

- the oldest of them form the upper members of the Krosno Beds of the flysch succession, preserved, for example, in the synclinorium of the Skole Nappe (Kotlarczyk 1988);
- the younger ones (and coeval ones) transgressively overlay (with a stratigraphic gap increasing toward the NW?) the epicontinental flysch facies but are thrusted and folded with them; for example, the flysch cores of the Bochnia folds (Tortonian, Książkiewicz 1972) and so-called "flysch elements" of the Stebnik succession in the Przemyśl Sigmoid zone (Kuśmierek & Baran 2008);
- the youngest ones (early Badenian–early Sarmatian) transgressively overlie the nappes of the Middle Group; in the frontal thrust zones they form synsedimentary folds and thrusts — locally with underlying flysch strata (Komorowska-Błaszczyńska 1971) – distinguished as the Zgłobice Unit (Kotlarczyk 1985) and thrust onto the younger (or coeval) autochthonous molasse (late Badenian–middle/late Sarmatian) of the Carpathian Foredeep (Ney 1968; Porębski & Oszczypko 1999).

Attempts have been made to link the occurrence of the epicontinental flysch-type lithofacies at the bottom of the Miocene molasse, or patches of such lithofacies that are interstratified with them, with the concept of gravity flows (Połtowicz 2004, Oszczypko et al. 2008); but such an option has no justification in the compressional style of the frontal zone of the orogen (e.g., Florek et al. 2004) or in its pre-Badenian morphology. Instead, the gravity sliding could comprise the zone of the epicontinental flysch facies, which covered the platform slope that was uplifted before the middle Miocene.

7. The gradual reduction of thickness and decreasing age of the autochthonous Miocene molasse toward the zone of the outer suture in the basement — which was cut by sole thrusts that propagated synchronously with deposition of the uppermost members (Figs. 4 and 5) — undermine the reliability of interpretations that suggest occurrence of allochthonous molasse on the southern side of the suture (e.g., Nemčok et al. 2006), which had been linked with presence of an internal basin of the Carpathian Foredeep, currently reaching up to the upper San river basin (?, Ney et al. 1974).

8. The tectonic evolution of the central-outer belt of the Outer Carpathians during the Late Tertiary — palinspastically reconstructed to two time intervals (Figs. 8 and 9,

Table 1) — was characterized by the variable arrangement of sedimentation zones of the frontal nappes, which appeared as early as in the early Miocene (Fig. 8), and by the increasing magnitude of subduction of the platform slope, which was accompanied by growth of the accretionary prism with increasing thickness of the deformed Miocene molasse. The convergent subduction direction of the basement blocks induced a conformable direction of the tectonic transport of the deformed sedimentary cover — namely toward the SW in the palaeogeographic projection — however, as a result of thrust propagation (detached from basement), moving in the opposite direction shown by the vergence of thrusts and folds. The magnitude of the movements is scaled by values of the horizontal component of subducting segments of the basement; shortening of the segments was increasing with their vertical rotation that triggered gravitational subsidence.

9. Potential inaccuracies in images of the palinspastic framework of the precompressional configuration of the subbasins in Figures 8 and 9 (apart from those mentioned in chapter "*Reconstruction criteria for the palinspastic framework"*) can be attributed to dating of the tectonic deformation stages in view of the diachronism of folding and thrusting movements and the time of initiation of backthrust faulting in internal zones of synclinoria.

10. Application of the traditional (opposite) procedure of palinspastic reconstruction (Kay 1945) — locating the basins of the Outer Carpathians in the area of the Pannonian mantle diapir (e.g., Unrug 1979) — requires an unacceptable distortion of their geometry because of the oroclinal nature of the fold and thrust arc (Khain et al. 1977; Kruglov et al. 1985) documented by detailed analysis of the palinspastic projection (Kuśmierek 1988). The opposite kinematic model for the formation of the accretionary wedge, deformed at the front of the ALCAPA terrane and moving to the N or NE (e.g., Nemčok et al. 2006) implies the controversial original location of the Carpathian sedimentary basins.

11. Application of the cross-section balancing technique for imaging the tectonic evolution of the fold and thrust belt during the Late Tertiary is complicated by the syntectonic character of deposition of the youngest sediments, associated with processes of their deposition and synkinematic erosion, which requires quantification of anisopachous primary thicknesses through reconstruction of the magnitude of erosion (Kuśmierek et al. 1995; Kuśmierek 2010, fig. 6). This problem has often been neglected, and this has had an impact on the reliability of the presented models (e.g., Nemčok et al. 2006). Cross-sections balanced without balancing of the highly variable thicknesses of synorogenic sediments revealing a diachronous pattern of lithofacies boundaries should not be a basis for drawing the tectogenetic conclusions, in particular based on a kinematic model of only single traverse (e.g., Gągała et al. 2012).

12. The above problem can be overcome through application of the palinspastic method, which allows precise imaging of the precompressional configuration of sedimentation areas and magnitudes of reduction of their original widths, under the following conditions:

- exact interpretation of the tectonics of folds and thrusts of isochronous boundaries in a few cross sections perpendicular to strikes of the folds;
- application of an appropriate reference line of the palaeogeographic model and a proper direction of "unfolding", and compensation of the horizontal component of amplitudes in planes of discontinuous dislocations formed after sedimentation of marker stratigraphic horizons.

13. Marked influence on modification of the tectonic style and stratigraphic inventory of nappes was exerted by transverse zones of deep-seated strike-slip faults, which were distinguished in Figures 8 and 9 from an undoubtedly more extensive set of transverse faults (Kuśmierek 2010) because they manifested themselves by changes in strikes of marginal flysch and molasse subbasins.

14. Discriminating between ductile deformations and brittle deformations, exposed by Gągała et al. (2012), is of significance when analysing the disharmonious setting of local structures. In the regional context, however, the tectonic style disharmony is more dependent on location of sediments subjected to deformation, and on pinching out of thick series of synorogenic deposits in zones of basement depression, in sections of which compressional structures are often associated by gravitational deformations with disharmonious tectonics (Kuśmierek 1979), improperly located in the recent geological map of the Outer Carpathians (Jankowski et al. 2004).

15. The kinematic model of the orogenesis (Fig. 10), constrained by the horizontal and vertical components of tectonic movements, depicts the variable rates and directions in successive stages of the evolution, with its initial phase in the early Oligocene (Fig. 10A). Zones of disruption and "subsurface wedging" (Roure et al. 1990) of tectonic blocks of the platform slope were characterized by a greater intensity of deformation, and the decline of the shortening was accompanied by the isostatic uplift. The convergent direction of movement in relation to the oroclinal geometry of the subbasins also induced strike-parallel shortening (Fig. 10B).

16. The differentiation of the geological structure of the Western and Eastern Outer Carpathians — reflected by the different arrangement of the nappes and Miocene parautochthonous covers (Fig. 9) — was influenced by rotation of subducting lithospheric blocks resulting from the convergent displacement (with collateral transpressional? interfingering; Kuśmierek 1990) and by the magnitude of the subduction and the basement relief. As distinct from the uplifted Małopolska Block beneath the Western Outer Carpathians, the western part of the Eastern Outer Carpathians is superimposed on the Transcarpathian Depression in the basement, which separated the Western Carpathian and Transylvanian mantle diapirs (Naumenko 1984). The influence of the advanced subduction of the basement in that part of the Outer Carpathians is manifested by the occurrence of Neogene volcanics in the hinterland, accompanied by a detached and sunken lithospheric slab (Konečný et al. 2002). The differentiation of the evolution from NW to SE of the central-outer belt of the Outer Carpathians during the Late Tertiary (34–12 Ma) is reflected by the large variation of measured parameters (Table 1):

- the total width of sedimentation zones: 95.6–206.0 km
- the magnitude of shortening: 37.2–110.8 km
- the percentage of shortening: 39.9–54.9 %
- the magnitude of basement displacement: 68.6–131.5 km
- the average shortening rate: 3.11–5.98 km/m.y. (with the maximum value in the late Oligocene–early Miocene, probably exceeding 10 km/m.y. in the traverse VII).

The parameters above are different from the ones determined by balancing of one traverse with a different subsurface interpretation and conceptual kinematic model (Behrmann et al. 2000; Gągała et al. 2012). The reconstructed width of the sedimentation zone and the magnitude of the basement displacements in the plane of that traverse (Table 1, traverse V) are relatively smaller than the values given by Roure et al. (1993) based on a hypothesis of a maximum dimension of the subthrust basement (Roure et al. 1994, fig. 11).

When comparing the above parameters we should keep in mind that the data in Table 1 and images in Figs. 8 and 9 are scaling only the subhorizontal component of tectonic displacement, unlike balanced cross-sections which sum up the values of both components of the displacement.

The significant differences in the structure of the frontal zone of the Western and Eastern Outer Carpathians, which have evoked different criteria for their classification by Polish and Ukrainian geologists, do not undermine the homogeneous model of the orogenesis for the whole NE segment of the Outer Carpathians.

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