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Subsurface structure and tectonic style of the NE Outer Carpathians (Poland) on the basis of integrated 2D interpretation of geological and geophysical images

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Abstract: Integration of the information from surface and subsurface geological exploration (maps and well sections) and results of geological reinterpretation of more than ten archival seismic sections and several dozen magnetotelluric soundings (MT; published and archival) implies a new structural picture of the Carpathian tectogene, interpreted to depths exceeding 10 km. The tectonics of nappes and their basement is illustrated by four regional cross-sections (derived from geological and petroleum-exploration traverses) and examples of detailed interpretation of zones with complicated structure, as well as results of testing the initial structural models with application of the balanced cross-section method and gravimetric modelling. In the tectonics, a complicated system of overthrusts and detachments of sedimentary covers (from their heterogeneous basement) represents a predominant feature. It induced, within particular nappes and tectonically altered structural-facies units, specific systems of narrow folds with diversified geometries. Broad folds of the intermediate structural stage, which are gently sloping in the hinterland of the nappes, were interpreted on the basis of geophysics as paraautochthonous elements. They cover deep-seated faults with large throws, which obliquely or subvertically dip to the SW and were distinguished in the basement on the grounds of extreme contrasts at the resistivity boundaries. Zones of dramatically low resistivities, which separate blocks of the uplifted basement, were interpreted as tectonic sutures with geometry rebuilt in the stage of the Neogene lithosphere subduction. Therefore, the structural layout of the sedimentary cover is characterized by more gently dipping nappe overthrusts of the sequential type and secondary, out-of-sequence thrust slices, most frequently imbricate ones. The flysch covers resting over the tectonic sutures, particularly in margins of inherited structural depressions, are characterized by more diversified tectonic style in comparison with peripheral, gently-sloping covers thrust over the flexural platform slope, and with steep slices and imbricate thrusts having consequent NE vergence. A specific type of dislocation is represented by flat inversional detachments (seismically documented) which are accompanied by disharmonic folding of "thin-skinned" structural elements. In the eastern part of the foreland of the Dukla overthrust, they form a developed system of backthrusts on the slope of a triangular structure superposed on a "shallower" tectonic suture of the basement; the system replaces sets of fault-propagation folds developed in the eastern part of this zone.

Key words: Western Carpathians, subsurface mapping, tectonics of Alpides, fold and thrust belt, structural interpretation, seismic sections, magnetotelluric soundings.

Introduction

The present state of growing knowledge of the tectonics and evolution of the Outer Carpathians is characterized by an unusual diversity of views, dominated by overabundance of new conceptions and interpretive schemes which sometimes depart from profound analysis of the recognized subsurface geological structure. In this context and in the light of progress in methods and scope of investigations, dimensioned cartographic images are an underestimated element for justification of conceptual models and investigation projects. One of the sources of evidence for this is the results from deep wells drilled into the eastern part of the Polish Carpathians, sections of which significantly depart from the assumed ones.

The coherent relation of surface cartographic images and well sections to geophysical models of subsurface tectonics of structures, particularly to seismic images of the geometry of folds in the cover, represents a fundamental problem in the construction of acceptable images of the complicated Carpathian tectonics. Interferential seismic records and their low quality, as well as the lack of regionally continuous reflectors, have resulted in a sceptical attitude towards the credibility of the seismic images from the Carpathian region, acquired through standard methods of field-data processing (e.g. Wdowiarz 1985).

Serious divergence is also found in the interpretation of the depth of occurrence and tectonics of the basement of allochthonous covers in the central zone of the fold and thrust belt. Compared with seismic refraction profiles, which document relatively regular and large-radius geometry of depressions in the basement, the results of several hundred magnetotelluric soundings (MT) carried out in this area have provided a much more complicated structural image.

Against the background of the interpretive implications outlined above, relatively little attention has been given to the influence of the disharmonic tectonics of structures in the cover and basement on the obtained geophysical images of the geological subsurface setting. This problem is crucial not only from the scientific point of view, but also for the credibility of

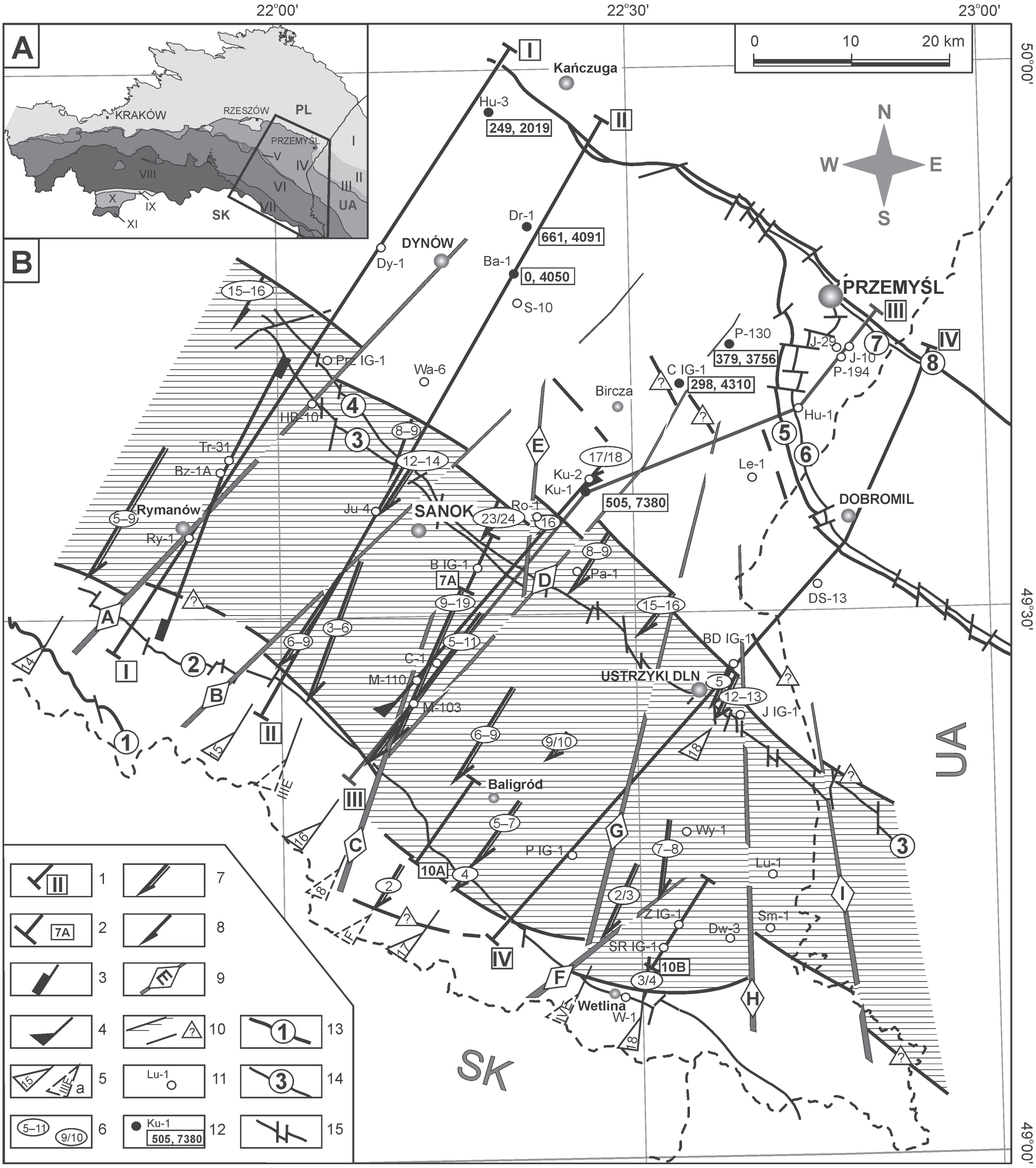

Fig. 1. A — Location of the study area (framed) within the Polish segment of the Alpides; geostructural elements and units: **I** — Carpathian Foredeep, **II** — Stebnik Unit, **III** — Boryslav-Pokuttya Unit, **IV** — Skole Unit, **V** — Sub-Silesian Unit, **VI** — Silesian Unit, **VII** — Dukla Unit, **VIII** — group of Magura units, **IX** — Pieniny Klippen Belt, **X** — Podhale Trough, **XI** — Tatra Mts. **B** — Structural sketch of the study area with location of presented 2D models and used profiles of magnetotelluric sounding. **1** — lines of regional cross-sections (traverses); **2** — lines of detailed cross-sections (not in line with the traverses) and numbers of figures that illustrate them; **3** — line of the balanced cross-section (Fig. 6); **4** — line of the seismic profile 34-15-96K tested through gravimetric modelling (Fig. 9); **5** — locations and numbers of magnetotelluric profiles (a — recorded by older-generation instruments — after Stefaniuk 2001 and Stefaniuk et al. 2002); **6** — numbers of magnetotelluric soundings (MT) which documented dramatic denivelations of the high-resistivity horizon (tectonic sutures of the basement); **7** — location of deep-seated tectonic sutures; **8** — location of "shallower" tectonic sutures; **9** — subsurface traces and denotation of probable transversal faults in the basement of the tectogene; **10** — extent of the zone of deep tectonic shears of the basement, a — interpolated traces of the above zone and probable tectonic shears (unformed–initial?); **11** — locations of deep wells; **12** — deep wells penetrating the Precambrian basement — numbers in parentheses determine thickness [m] of Miocene deposits under the Skole Nappe overthrust and depth [m] to the Precambrian basement; **13** — surface intersection traces of groups of structural-facies units; **14** — surface intersection traces of boundaries of particular nappes and units; **15** — surface intersection traces of faults which dislocate them.

petroleum-system modelling which requires as precise structural images as possible.

The aim of the paper is to present and to interpret two-dimensional images (mostly unpublished) of the subsurface structure of the Outer Carpathians, worked out by the author within the framework of the Polish-Ukrainian research project DWN/1818-1/2M 2005 entitled “Transfrontier studies of deep-seated geological structures in the marginal zone of the Carpathians from the point of view of the potential discovery and development of new oil and gas fields” (Capik et al. 2006). To reach the aim it was necessary to integrate the previous state of geological recognition, reinterpreted and supplemented by results of new investigations, with results of modelling of petroleum systems in the interfluve of the San River (Poland) and Stryi River (western Ukraine). Seven deep regional sections (so-called traverses) were the objects of this modelling. Of them, four western ones have been presented in this paper. The essential scope of the present paper has been confined to structural images of the eastern part of the Polish Carpathians (Fig. 1) and analysis of their tectonic style.

The new models of the subsurface structure have been constructed on the basis of the results of geological interpretation carried out for reprocessed archival seismic sections (Marecik et al. 2008) and MT soundings (Stefaniuk 2001, 2003; Stefaniuk et al. 2002), reinterpreted by the author. Compared with previously published cross-sections (e.g. Poprawa & Nemčok 1989; Kuśmierek 1990), the new interpretive options of the geological structure have been supported by “segments” of geological-geophysical images (at larger scales) and by testing of their correctness through the methods of balanced cross-sections and gravimetric modelling.

Geostructural background

The eastern segment of the Western Carpathians is characterized by discrepant setting of structural covers, which manifests itself by disappearance of the structural-facies units of the Magura Group and increment of units of the Marginal Group at the orogen front (Książkiewicz 1972; Oszczypko et al. 2008). They encircle so-called Middle Group units that attain the largest width in the borderland between Poland, Slovakia and Ukraine. The Middle Group is characterized by increased thickness of the youngest flysch members (Oligocene–Early Miocene) distinguished as so-called Menilite–

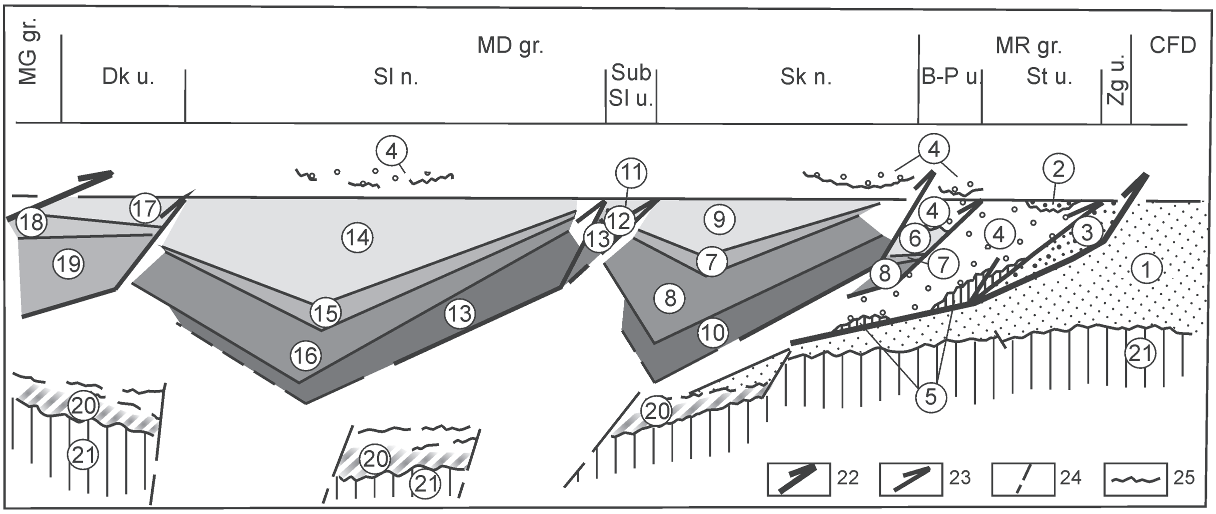

Fig. 2. Synthetic structural-lithostratigraphic model of the eastern part of the Polish Carpathians. **Geostructural elements and structural-facies units: MG gr.** — Magura Group of units, **MD gr.** — units and nappes of the Middle Group, **Dk u.** — Dukla, **Sl n.** — Silesian, **Sub Sl u.** — Sub-Silesian, **Sk n.** — Skole, **MR gr.** — units of the Marginal Group, **B-P u.** — Boryslav-Pokuttya, **St u.** — Stebnik, **Zg u.** — Zgłobice; **CFD** — Carpathian Foredeep. **Lithostratigraphic complexes.** ***Carpathian Foredeep and units of the Marginal Group*****: 1** — autochthonous molasse (Late Badenian–Sarmatian), **2** — postinversional cover (Late Sarmatian); *folded deposits* of the Early and Middle Miocene, **3** — of the Zgłobice Unit, **4** — of the Stebnik and Boryslav-Pokuttya units and patches of the transgressional cover that flatly overlies folded flysch deposits; *flysch deposits* (locally in the form of patches under the Skole Nappe overthrust), **5** — erosional patches of the flysch cover on the platform slope (Late Eocene–Oligocene), which were overthrust together with Stebnik molasses; *Boryslav-Pokuttya Unit* (Skole Series), **6** — Menilite Shales (Oligocene–Early Miocene), **7** — Popeli Beds, Variegated Shales and Hieroglyphic Beds (Eocene), **8** — Inoceramian Beds (Ropianka Fm, Senonian–Paleocene). ***Units of the Middle Group*****:** *Skole Nappe*: **7 and 8** — as above, **9** — Menilite-Krosno Series (Krosno Beds, Transition Beds and Menilite Beds, Oligocene–Early Miocene), **10** — Siliceous Marls, Dołhe Shales, Spas Beds, Bełwin Mudstones (Hauterivian–Turonian); *Sub-Silesian Unit*: **11** — Menilite Beds and Krosno Beds (Oligocene), **12** — Variegated Shales, Węglówka Marls (Senonian–Eocene), **13** — Lgota (Gaize) Beds, Veřovice Shales, Grodziszcze Sandstones and Cieszyn Beds (Valanginian–Cenomanian); *Silesian Nappe*: **13** — as above, **14** — Krosno Beds, Transition Beds and Menilite Beds (Oligocene–Eggenburgian), **15** — Hieroglyphic Beds and Ciężkowice Sandstones (Eocene), **16** — Istebna Beds, Godula Shales (Turonian–Paleocene); *Dukla Unit*: **17** — Krosno Beds, Transition Beds, Cergowa Beds and Menilite Shales (Oligocene), **18** — Variegated Shales, Przybyszów Sandstones, Hieroglyphic Beds (Eocene), **19** — Majdan Beds, Cisna Beds and Łupków Beds (Senonian–Paleocene). **Pre-Alpine basement of the Carpathian tectogene: 20** — deposits of the Early Mesozoic and Paleozoic (undifferentiated), **21** — Precambrian (Vendian–Early Cambrian?). **Graphical symbols: 22** — overthrusts which distinguish groups of units, **23** — overthrusts of particular nappes and units, **24** — faults in the basement, **25** — stratigraphic unconformities and sedimentary-erosional gaps.

Krosno Series (Jucha & Kotlarczyk 1958) that covers (together with older, Cretaceous–Oligocene flysch series) the deep-seated basement of the tectogene (Fig. 2). Denivelations of the basement are probably connected with the highest gradients of the lithosphere thickness variations within the Carpathian arc, between the Pannonian mantle diapir (approximately 60 km) and the platform slope (up to 200 km), according to seismological and magnetotelluric data (Konečný et al. 2002). These disproportions also become manifest in the Earth's crust thicknesses which are reflected in the Moho discontinuity position (Kuśmierek & Ney 1988; Bielik 1999). New and original results (Zeyen et al. 2002; Dérerová et al. 2006) confirm the above suggestions.

Probably the major part, if not the whole flysch cover, was detached from its original basement along thrusts that sheared bottom shale complexes of the Early Cretaceous, locally of the Eocene. Against this background, nappe covers, formed of thick turbidite sequences of the Late Cretaceous–Paleocene and Oligocene, should be discerned from tectonically disturbed structural-facies units with condensed thickness, which originated from paleoelevations (Kuśmierek 1990).

According to Konečný et al. (2002), at the junction of the Western and Eastern Carpathians, the slope of the subducting platform in the Karpatian–Early Badenian times was dislocated by an oblique deep-seated fracture directed SW–NE. The application of seismic tomography and thermal modelling, has enabled us to identify on the eastern side of this fracture a steeply dipping detached slab of the continental lithosphere, which was submerged in the asthenosphere under the Outer Carpathian arc.

In the author's opinion, geodynamic mobility of the lithosphere at the junction of the Western and Eastern Carpathians becomes evident as early as in the sedimentary stage, in the form of considerable facies and thickness variations of the Cretaceous–Eocene sandstone series, which in the Marginal Group were expressed most strongly in the Late Miocene. Undoubtedly, it had an effect in the form of the diversified tectonic style of allochthonous covers and implied their correlation in the transfrontier zone between Poland and Ukraine. This refers especially to the flysch — molasse units of the Marginal Group, which were formed in a late-geosynclinal relict subbasin (Kuśmierek 1984; Konečný et al. 2002). Thickness of molasses that filled the subbasin is dramatically reduced in the zone of the meridional bend of frontal folds and thrusts of the Middle Group, which is called the Przemyśl Sigmoid, conventionally accepted as the border between the Western and Eastern Carpathians (Świdziński 1971).

To NW of the Przemyśl Sigmoid only fragments of the Stebnik cover were preserved at the front and at the base of the Skole overthrust. Combining the tectogenesis of the Przemyśl Sigmoid with the above mentioned deep-seated fracture and taking into account the prominent discrepancy of the arrangement of the marginal thrusts, as well as the subordinate tectonic engagement of the Middle Miocene molasses in relation to the Early Miocene ones and to the flysch deposits, one should infer that the activity of this fracture did not reach the relict subbasin or it ceased in the Late Sarmatian.

Transversal deep-seated faults of the strike-slip fracture type, which dislocated zones of the buried basement and were identified by interpretation of the geophysical surveys and remote-sensing analyses (Kuśmierek 1990; Doktór et al. 1990), in the study area reveal a radial arrangement (Fig. 1) and are not directly reflected in the tectonics of the allochthonous covers, as the tectonics are dominated by ductile continuous deformations and thrusts induced by centripetal subduction of (rigid) blocks of the platform slope and their subsurface wedging (Kuśmierek 1996).

Criteria of integration of the geological and geophysical investigations

The recognition of the subsurface geological setting of the study area is very irregular. The marginal part of the Carpathians is best documented by wells and seismic profiles, which have been inspired by exploration for gas accumulations in the underlying Miocene molasses and by searching for a westward extension of deep-seated folds of the Boryslav-Pokuttya Unit. On the contrary, the worst is the recognition of the southeastern part where few deep wells have penetrated the thick cover of Oligocene deposits.

The study area is located in the central part of the "transfrontier" geological map of the Polish, Ukrainian and Slovak Carpathians on the scale of 1:200,000 (Jankowski et al. 2004), accepted as the input source of surface information, constrained in zones of complicated tectonics by cartographic images (published and archival) on larger scales.

The situations of the constructed cross-sections, oriented perpendicularly to fold strikes, were controlled by locations of deep wells and seismic profiles in such a way as to acquire a possibly uniform image of the geological setting between the Dukla Unit overthrust and the Carpathian Foredeep (Fig. 1). Construction of the geological-seismic cross-sections (originally scaled to 1:50,000) was based on geological interpretation of several dozen reprocessed archival seismic sections with digital recording, acquired by the "Geofizyka — Kraków Company" in the years 1977–1996, and a few made by the "Geophysical Exploration Company" (PBG) from Warsaw, as well as on geological reinterpretation of earlier sections with analog recording. Application of a modified procedure for seismic data processing in the ProMAX system (Marecik et al. 2008) significantly improved the quality of the seismic sections in terms of their dynamics and resolution.

Well sections which were not located on traces of the traverses or seismic sections were projected in accordance with the strikes of outcrops of lithostratigraphic complexes. In justified cases, tectonic interpretation of fragments of the well sections was corrected in order to receive better relation to cartographic and seismic images, among others through recalculation of measured (true) dips into apparent dips when a trace of a cross-section was oblique to the strikes of structures.

A fundamental criterion of construction of the geological-seismic cross-sections was acknowledgement of factual data in such a way as to secure consistence of the interpreted geometry of structures and dislocations with their intersection traces and well sections, and the highest degree of consistence with the pattern of reflectors. Lithostratigraphic identification of the reflectors could have been justified only by a few synthetic seismograms (Kuśmierek & Baran 2008) that could be generated for well sections possessing the necessary sets of geophysical measurements.

Structural-lithostratigraphic criteria of classification of the tectonostratigraphic units that form the eastern part of the Polish Carpathians, as well as the structural sequence of the covers, were compiled in Fig. 2, explanations of which ascribe sediments composing the covers to individual lithostratigraphic successions. During the construction of the geological-seismic cross-sections and regional traverses, characteristic thickness variation trends were ascribed to lithostratigraphic members, in order to scale most reliably the geometry of structures through using the available profiles and thickness maps (e.g. Kuśmierek et al. 1995). The most rapid (sometimes dramatic) thickness changes are characteristic of turbiditic deposits, as well as limbs of Oligocene synsedimentary folds and lithosomas of coarse-clastic Grodziszcze, Ciężkowice and Kliwa sandstones.

First-order objects of interpretation of the seismic sections were represented by images of the subsurface geometry of tectonic dislocations documented by surface mapping and/or well sections, that means strike-slip faults and thrusts of various orders, subsurface traces of which were approximated with the arc geometry. Tracing of them was not difficult, particularly on seismic sections which were characterized by good readability of reflectors. In this phase of interpretation, numerous subsurface dislocations were detected, which do not appear in the surface intersection image or have not been documented by mapping. Identification of stratigraphic unconformities in the basement of the tectogene and contouring of flysch elements (patches) within the Stebnik Unit caused greater difficulty and uncertainty.

Afterwards, the structural arrangement of the lithostratigraphic boundaries was introduced into the obtained image of the discontinuous tectonics, first of all on the basis of the geological information from sections of outcrops and wells, and on regional premises referring to particular zones or structural-facies units. In the seismic sections, best readable was the structural arrangement of flat-lying fold limbs, whereas zones of their hinges and intense continuous deformations were characterized by the interferential records of the wave field, controlled by known properties of the seismic imaging method.

The geological interpretation of the morphology and structure of the tectogene basement was based upon the results of magnetotelluric sounding realized by PBG Warsaw in the years 1975–1990 with the use of analog instruments, and next in the years 1997–2001 with the use of new-generation high-frequency instruments that made it possible to acquire information also on the resistivity distribution in sediments that build the allochthonous covers (Stefaniuk 2001, 2003; Stefaniuk et al. 2002).

In the first approximation, the lateral character of resistivity changes in geoelectric cross-sections can be ascribed to three hypsometric levels:

- the shallow level with low and medium (sporadically higher) values, strongly diversified and predominantly oblique (vergent) resistivity boundaries; according to the depth criterion, the level corresponds to the allochthonous covers;
- the intermediate level with variable thickness (from 0 to a few km), which is dominated by subhorizontal resistivity boundaries; the level corresponds to the Miocene autochthonous molasses and hypothetical paraautochthon of unidentified age;
- the deep level with extreme resistivity contrasts in the complexes which rest obliquely, often subvertically, with maximal resistivity values correlated with the Precambrian basement and with low values corresponding to younger (?) altered rocks.

The position of the base of the intermediate level corresponds to the hypsometry of refraction seismic horizons and it probably reflects the morphology of the Mesozoic, Paleozoic, and Precambrian basement. Identification of the top of this level is evident in seismic sections within the marginal part of the Carpathians as sharp boundaries of nappe thrusts over the autochthonous molasses. It causes, however, difficulty in the hinterland of the nappes (Lizoon & Zayats 1997) because of weakly diversified seismic image over the subhorizontal reflection system; the system suggests the occurrence of second-order detachments rather than hypothetical nappe overthrusts and even "junction" of the covers (?).

The results of the MT sounding were interpreted in different manners (e.g. Kuśmierek 1990; Ryłko & Tomaś 2005 and references therein), often conservatively (e.g. fig. 4 in Stefaniuk 2006) in relation to the complicated structural arrangement of

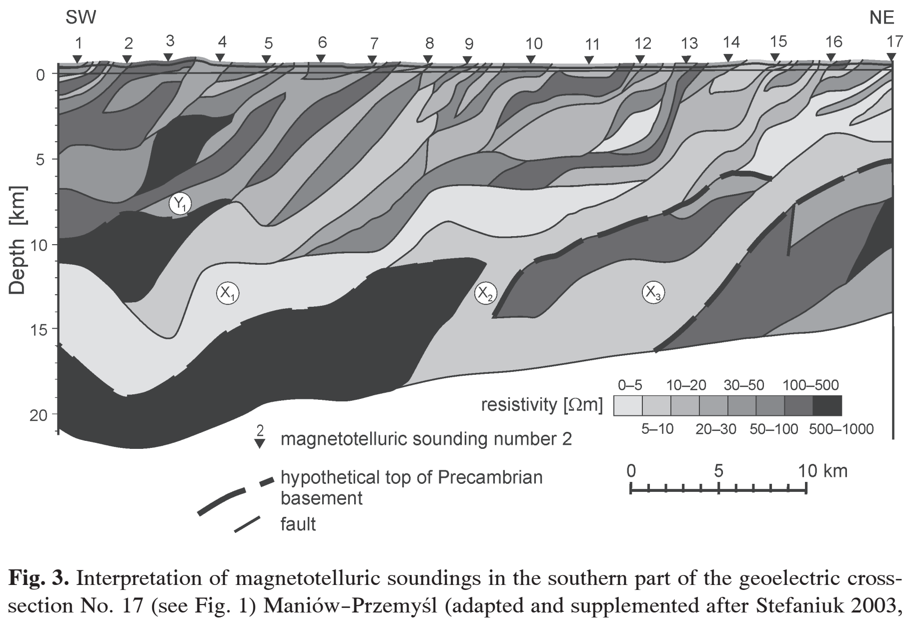

Fig. 3. Interpretation of magnetotelluric soundings in the southern part of the geoelectric cross-section No. 17 (see Fig. 1) Maniów–Przemyśl (adapted and supplemented after Stefaniuk 2003, with permission). Identification of tectonic sutures in the consolidated basement (according to the author): deep ones (x_1, x_2, x_3) and shallower one (y_1).

the resistivity boundaries of the deep level in the geoelectric cross-sections (Stefaniuk 2001, 2003).

Figure 3 presents an example of a probable location of compressional tectonic sutures, according to the author's interpretation, which are correlated with dramatic denivelations of the high-resistivity horizons. Their geometry and hypsometric position justify distinguishing deep and shallower sutures, the later (subordinate) are relatively "flatter" and most often occur in the margins of the zone of the buried basement of the tectogene (Fig. 1). Nevertheless, they are also contoured by high resistivity contrasts (Fig. 4) which suggest the presence of subhorizontal shears of the Precambrian basement separated by fragments of the "wedged" sedimentary cover (?).

The geometry and subsurface intersection of the postulated compressional sutures are undoubtedly disturbed by transversal faults, probable traces of which (Fig. 1) were determined on the basis of analysis of the geoelectric cross-sections, and structural and resistivity-distribution maps of the top of the basement (figs. 15 and 16 in Stefaniuk 2003). The idea of the tectonic sutures in the basement of the tectogene refers to the author's earlier publications (Kuśmierek 1990, 1996) and to

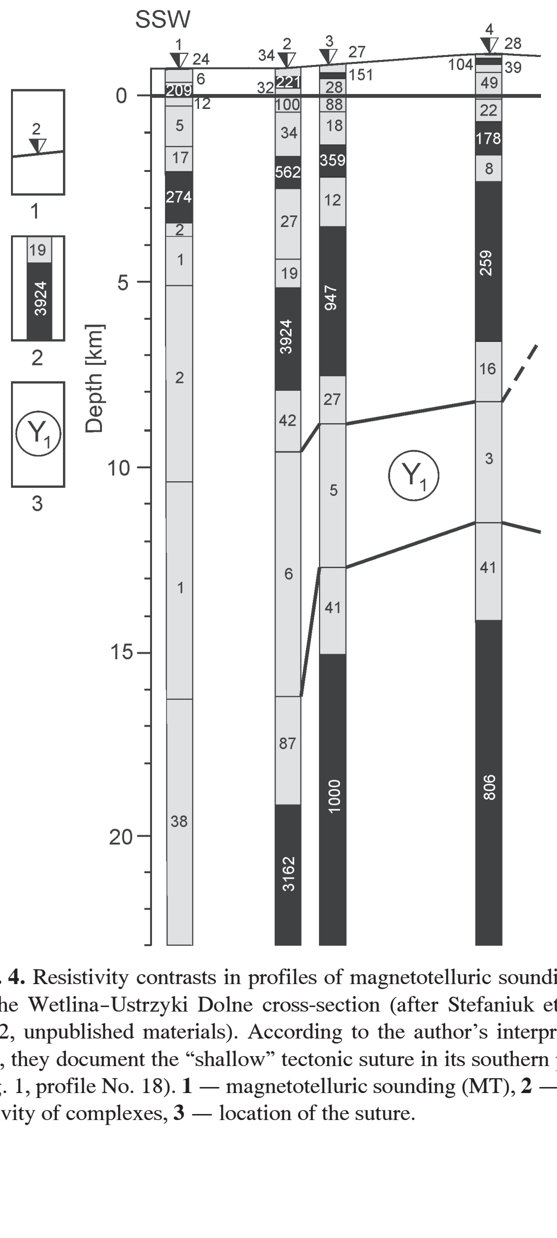

Fig. 4. Resistivity contrasts in profiles of magnetotelluric soundings in the Wetlina–Ustrzyki Dolne cross-section (after Stefaniuk et al. 2002, unpublished materials). According to the author's interpretation, they document the "shallow" tectonic suture in its southern part (Fig. 1, profile No. 18). **1** — magnetotelluric sounding (MT), **2** — resistivity of complexes, **3** — location of the suture.

the lithosphere model along the RP-X traverse (fig. 16 in Bielik 1999) with the suggested position of the northern megasuture located under the eastern part of the Polish Outer Carpathians.

Characteristic features of the geological structure and examples of its imaging

Integrated interpretation of the two-dimensional geological and geophysical images according to the criteria described above documents a new, more complicated picture of the tectonics of the flysch series (Fig. 5), particularly in zones of structural depressions which are characterized by the disharmonic style of surface (thin-skinned) and subsurface tectonic deformations. The detachments found in numerous seismic sections, among others in 31-19-94K (Fig. 5A), enabled the author to carry out more profound interpretation of complicated folds recognized in well sections, which do not appear in the surface cartographic image. The origin of these detachments is probably connected with the advanced stage of the tectonic compression, which is suggested by divergent directions of displacements (within their limbs). Some of these detachments may represent reactivated compressive reverse faults (Letouzey 1990); nevertheless, they belong to a younger generation of tectonic shears when compared with steeply dipping out-of-sequence overthrusts, traces of which they dislocate. Thrusts of the sequential type are most weakly imaged in their far hinterland, which is illustrated by an example of a hypothetical detachment of the Skole Nappe from the paraautochthon that occurs at depths exceeding 7000 m (Fig. 5A).

Complicated deformations are most frequently associated with inherited structural depressions in which predominantly thick series of the Krosno lithofacies deposits were preserved; the deposits reveal anisopachous thickness distributions in limbs of folds of the synsedimentary type. In order to date the development of these deformations as potential hydrocarbon traps, paleostructural models were constructed with application of the balanced cross-sections (Kuśmierek et al. 2001), among which one was oblique to the line of the traverse I (Fig. 1) and imaged development of folds and thrusts within the Silesian Nappe.

In the southern part of the nappe, the balancing results document development of synsedimentary thrusts of the imbricate type, which generated so-called fault-propagation folds, whereas in the eastern part, at the nappe front, detachment folds (Mitra 1986) were formed.

Unlike the widely used numerical options (e.g. Nemčok et al. 2006), a manual procedure of balancing was applied. The balancing was carried out for full thicknesses of the youngest sediments, that means also their thicknesses removed by erosion in the inversional stage (Fig. 6B, C), according to the complicated procedures described by Kuśmierek et al. (1995). The constructed models have proven that initial synsedimentary deformations were formed before the time of sedimentation of the Jasło Limestone stratigraphic member (Fig. 6A) and became intensified at the turn of Oligocene and Early Miocene, that is before sedimentation of the transgressive Middle Miocene molasses (Fig. 6C). They have also con-

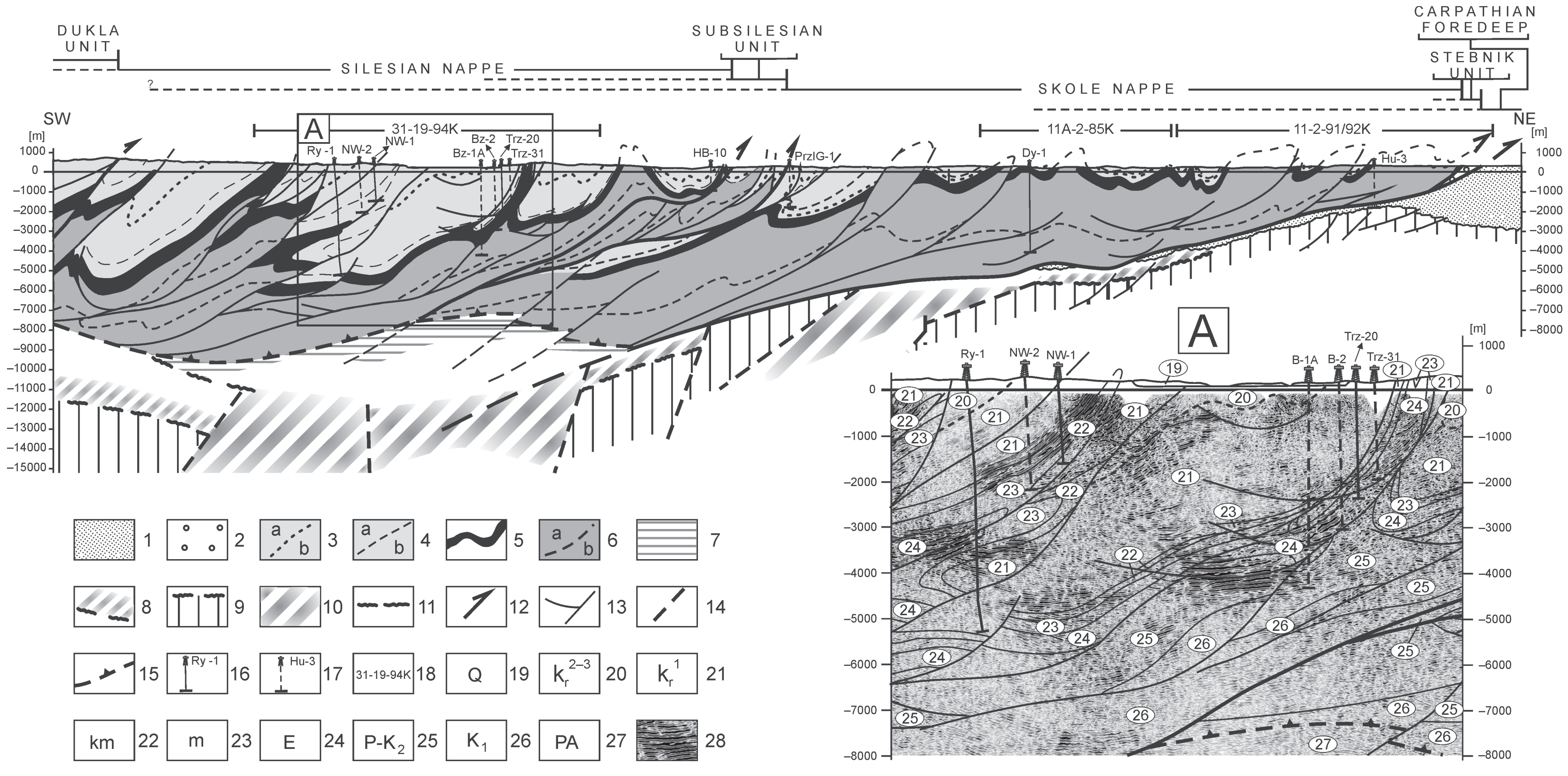

Fig. 5. Traverse I: Jaśliska–Husów. **1** — autochthonous molasses (Late Badenian–Sarmatian), **2** — folded molasses of the Stebnik and Zgłobice Units (Ottnangian–Early Sarmatian), undifferentiated; deposits of Oligocene–Early Miocene (Ol–M_1): **3** — position of the Jasło Limestone stratigraphic member (approximately 28 Ma), a — Supra-Jasło Complex (Ol_2–M_{1nj}), b — Sub-Jasło Complex (Ol_{1pj}), **4** — Oligocene lithofacies: a — Krosno (k_r), b — Menilite and Transition (m+km), **5** — Eocene deposits (E); **6** — Cretaceous–Paleocene deposits: a — Paleocene–Senonian (K_2–P), b — older (Sub-Senonian, K_1), **7** — subsurface structural elements of unidentified age (Paleogene–Late Mesozoic, pre-flysch?), gently sloping under nappe overthrusts (paraautochthon?), **8** — deposits of Early Mesozoic (Jurassic–Triassic?) and Paleozoic (undifferentiated), **9** — high-resistivity basement, Precambrian (Riphean–Vendian–Early Cambrian?), according to magnetotelluric sounding, **10** — low-resistivity lithostratigraphic complexes (recorded by magnetotelluric sounding) which separate uplifts of basement blocks — interpreted by the author as tectonic sutures (roots of nappes of the Middle and Marginal groups?), **11** — stratigraphic unconformities, **12** — nappe overthrusts, **13** — lower-order overthrusts (tectonic slices) and faults, documented by mapping, drilling and/or seismic, **14** — probable faults in the basement, with geometry interpreted by the author on the basis of magnetotelluric sounding, **15** — probable subsurface detachments of nappe covers from paraautochthonous elements, **16** — location and denotation of well section, **17** — well section projected onto the traverse plane, **18** — number of seismic section. **A** — seismic image of subsurface tectonics in the axial part of the Central Carpathian Synclinorium. **19** — Quaternary (Q); Silesian Series, lithostratigraphic complexes: Oligocene–Early Miocene deposits (Ol–M_1): **20** — Middle and Upper Krosno Beds (undifferentiated, k_r^{2-3}), **21** — Lower Krosno Beds (k_r^1), **22** — Transition Beds (km), **23** — Menilite Beds (m); older deposits: **24** — Eocene (E), **25** — Senonian–Paleocene (P–K_2), **26** — Early Cretaceous (Sub-Senonian, K_1); **27** — paraautochthon (PA?), **28** — seismic reflectors.

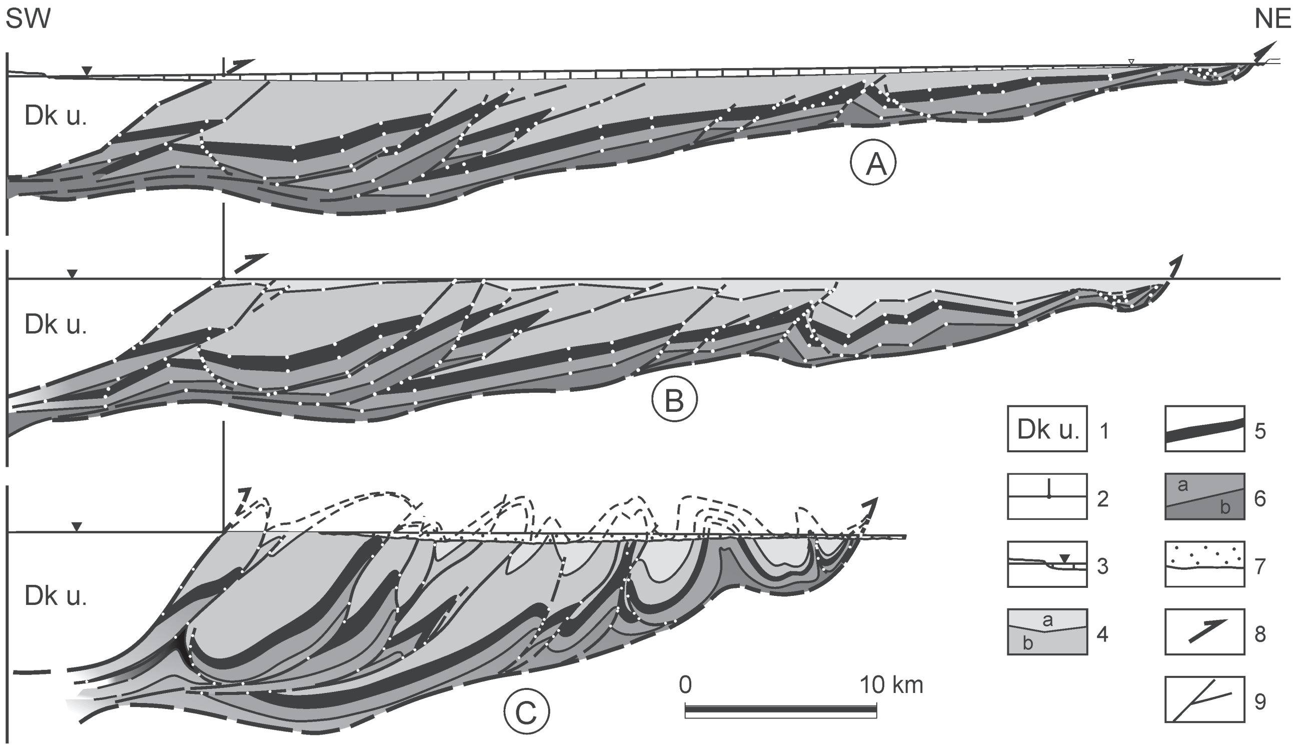

Fig. 6. Image of development of synsedimentary tectonic deformations during Late Oligocene–Early Miocene times obtained through application of the balanced cross-section method to the Silesian Nappe along the traverse I (Fig. 1) — according to unpublished materials (Kuśmierek, Maćkowski et al. 1996). Paleostructural models: **A** — during sedimentation of the Jasło Limestone stratigraphic horizon (approximately 28 Ma); **B** — in the final stage of sedimentation of the Krosno Lithofacies (Egerian?); **C** — in the stage preceding the final inversion of the Silesian Nappe (Late Karpatian–Early Badenian?). **1** — Dukla Unit, **2** — relative datum line of the paleostructural models, **3** — hypothetical sea level and paleomorphological profile of the Jasło Limestone basin (model A), **4** — lithostratigraphic complexes — Menilite-Krosno Series: **a** — Supra-Jasło Complex, **b** — Sub-Jasło Complex, **5** — Eocene deposits, **6** — Cretaceous–Paleocene deposits: **a** — younger (Senonian–Paleocene), **b** — older (Sub-Senonian), **7** — transgressive Miocene deposits, **8** — hypothetical position of nappe overthrusts, **9** — secondary overthrusts (tectonic slices) and synsedimentary faults.

firmed the correctness of tectonic interpretation of the present-day subsurface cross-section as the input for the balancing method.

Figure 7 presents the geological structure along the traverse II (Fig. 1). In its southern part, the seismic image documents common occurrence of typical fault- (thrust-) propagation folds, whereas its northern part is built up of structures with highly diversified origin and geometry. Specific features of tectonics at the front of the nappe overthrusts of the Middle Group were depicted in Fig. 7A and B. In the zone of the overthrust covers of the Silesian Nappe and Subsilesian Unit, the seismic image is weakly readable due to rapid changes of thickness and lithology of interfingering flysch members (of both the sequences) and their steep dips, which was recognized, among others, in the Bykowce IG-1 well section (Fig. 7A). These changes, in particular rapid wedging out of thick series of Paleogene sandstones, undoubtedly influenced the intensity of the tectonic deformations, typical also of the outcrops of this zone (Malata 1997).

A distinctive character of tectonic deformations is typical of the front of the Skole Nappe overthrust. At its base, tectonically altered fragments of the Stebnik cover occur, and in the zone of wedging out of the autochthonous Miocene molasses (encountered in the Bachórzec-1 well), flat tectonic shears in the Precambrian basement also dislocate the nappe base (Fig. 7B).

The northern part of the traverse III (Fig. 8) illustrates specific features of tectonics of the Marginal Group units and of the Skole Nappe front in the Przemyśl Sigmoid zone (Fig. 1). Long imbricated folds ("skybas") and tectonic slices of the Skole Nappe and wedging out Boryslav-Pokuttya Unit (Gluško 1968) are thrust over intensely folded older molasses of the Stebnik Nappe, which are dislocated by flat thrusts (Fig. 8A). The intensity of the tectonic deformations declines in the section of younger members building up the Stebnik cover that is locally overlain by transgressive conglomerates of the Late Miocene. A specific feature of the Stebnik Nappe tectonics in the borderland between Poland and Ukraine is represented by erosional patches of the youngest members of the Skole Series, encountered at the base of the nappe. The patches are detached and overthrust together with the covering molasses which rest with a sedimentary gap (Fig. 8A). Their extent was contoured in more than ten seismic sections (Kuśmierek & Baran 2008) on the basis of such criteria as continuity decline and/or angular unconformities of seismic reflections in the vicinity of the wells that encountered these patches.

The subsurface structure of the southern part of the traverse III (to S of the Kuźmina-1 well) has been well recog-

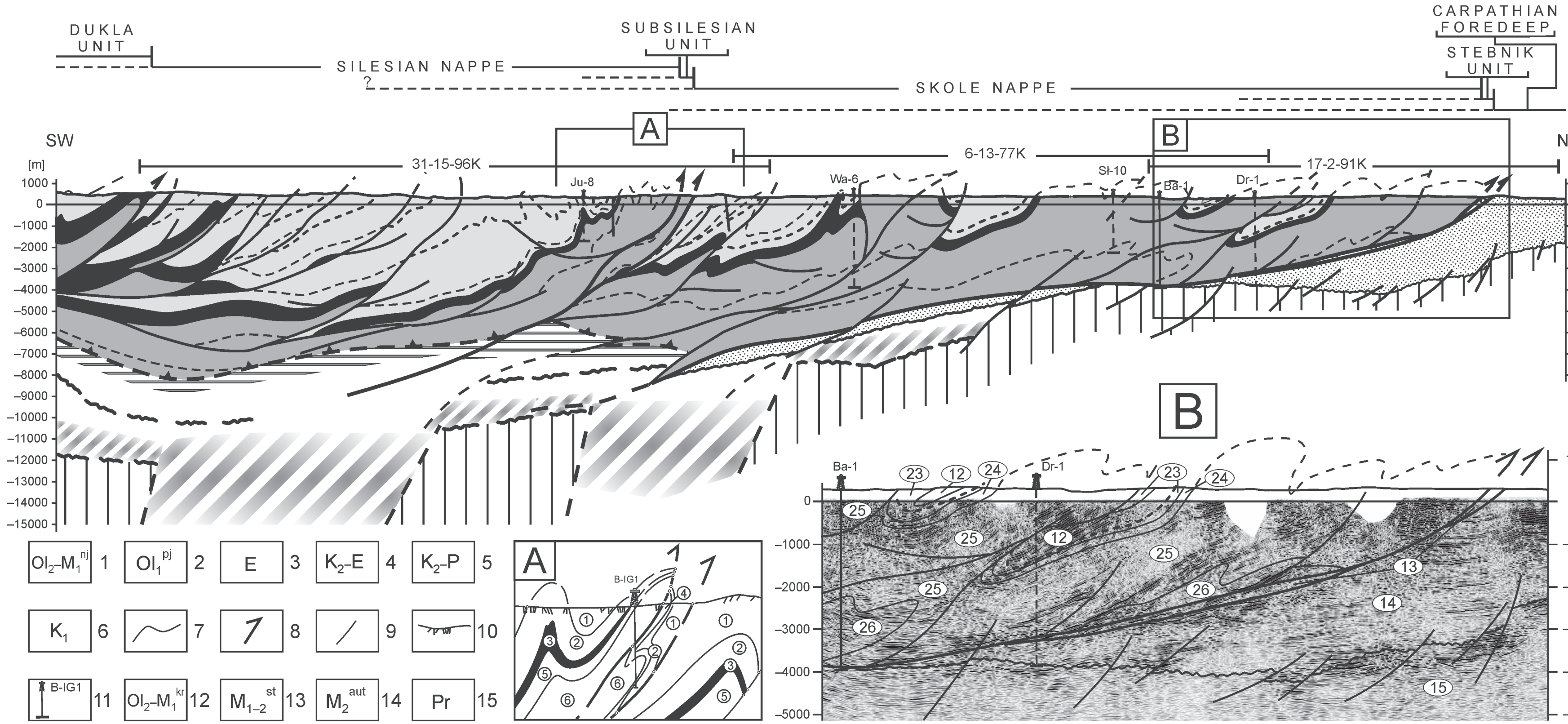

Fig. 7. Traverse II: Bukowsko–Łopuszka Wielka (Explanations as for Fig. 5). **A** — Tectonic style and thickness reduction trends of flysch covers in the Silesian overthrust zone — position of the cross-section was marked A (on the traverse) and its line was marked 7A (in Fig. 1). Lithostratigraphic complexes — Menilite-Krosno Series: **1** — Supra-Jasło Complex, **2** — Sub-Jasło Complex; **3** — Eocene deposits, **4** — Senonian–Eocene deposits in the Sub-Silesian Unit (undifferentiated), **5** — Senonian–Paleocene deposits, **6** — Early Cretaceous deposits (Sub-Senonian); graphical symbols: **7** — lithostratigraphic boundaries, **8** — nappe overthrusts, **9** — lower-order overthrusts (tectonic slices), **10** — dips of beds, **11** — well section. **B** — Seismic image of geometry of the overthrusts and wedging out autochthonous Miocene molasses in the marginal zone of the Carpathians. Allochthonous units; Skole Series — symbols of lithostratigraphic complexes: **12** — Krosno Lithofacies (Ol_2–M_1^{kr}, undifferentiated); Stebnik Unit and Zgłobice Unit: **13** — folded Miocene molasses (M_{1-2}^{st}, Late Karpatian–Early Sarmatian, undifferentiated); basement of the tectogene: **14** — autochthonous Middle Miocene molasses (M_2^{aut}, Late Badenian–Sarmatian, undifferentiated), **15** — Precambrian (Pr); explanation of the remaining lithostratigraphic symbols (m, E, P–K_2, K_1) — as for Fig. 5A.

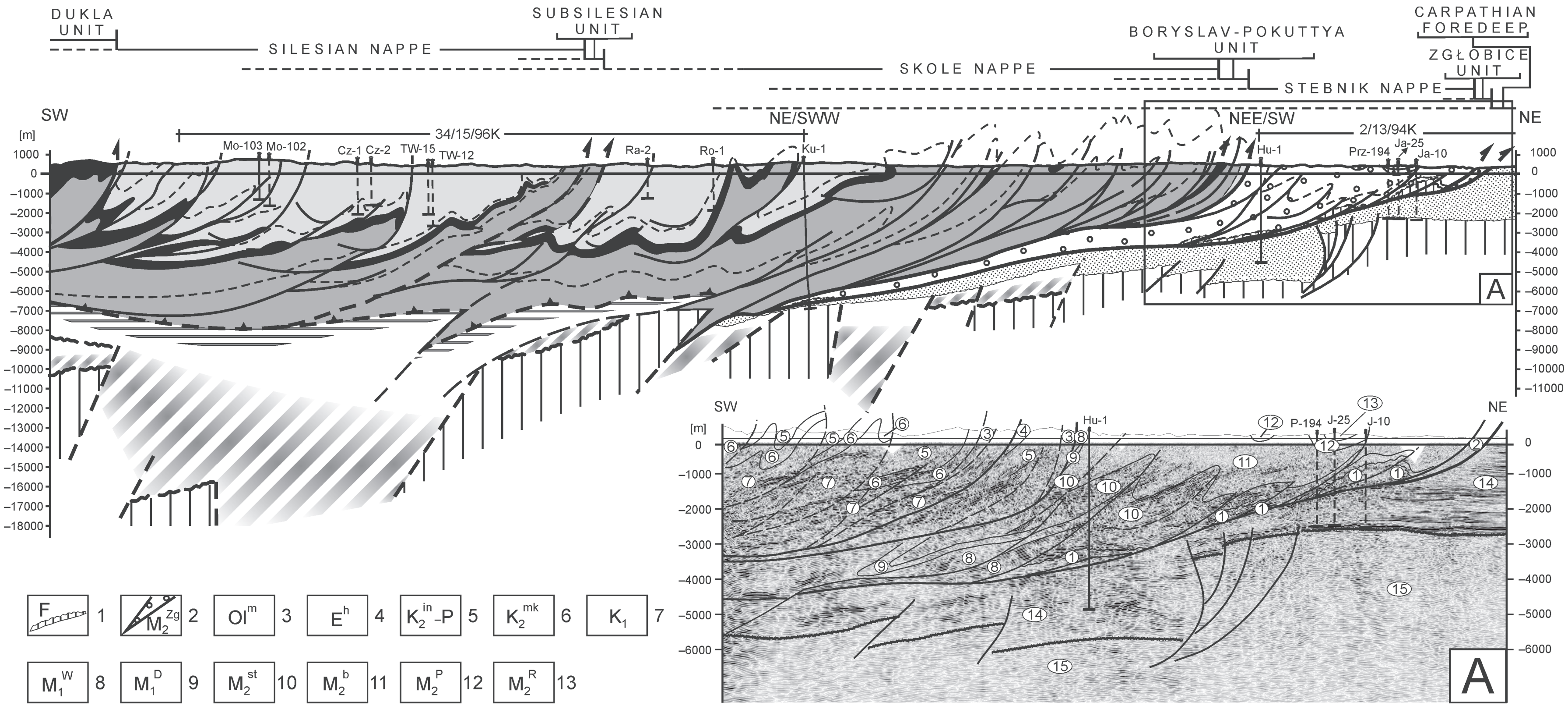

Fig. 8. Traverse III: Komańcza–Jaksmanice: **1** — erosional patches of the flysch cover on the platform slope at the base of the Stebnik Unit (F, Late Eocene–Oligocene), **2** — deposits of the Zgłobice Unit (M_2^{Zg}); remaining explanations as for Fig. 5 and cross-section A. **A** — Geological-seismic image of tectonics of the Marginal Group of allochthonous units and their basement in the borderland between Poland and Ukraine (after Kuśmierek & Baran 2008, reprinted with permission). Flysch lithostratigraphic complexes (of the Skole Nappe and Boryslav-Pokuttya Unit): **3** — Menilite Beds (Ol^m), **4** — Hieroglyphic Beds and Variegated Shales (E^h), **5** — Inoceramian Beds (Ropianka Fm, Senonian–Paleocene, K_2^{in}-P), **6** — Siliceous Marls (Turonian, K_2^{mk}), **7** — older Cretaceous deposits (Turonian–Hauterivian); folded molasses (Late Ottnangian–Early Sarmatian): **8** — Vorotyšča Beds (Saliferous Clay, M_1^W), **9** — Dubnik Conglomerate (M_1^D), **10** — Stebnik Beds (M_2^{st}), **11** — Balyč Beds (M_2^b), **12** — Przemyśl Beds (M_2^p), **13** — Radyč Conglomerate (M_2^R) — postinversional cover?

nized by the seismic profile 34-15-96K and MT (profile 16 in Fig. 1), running parallel to its line. In order to validate the MT results, which document huge denivelations of the Precambrian basement, and to carry out preliminary, working interpretation of the tectonics of the flysch cover, gravimetric modelling was conducted along its line (Fig. 1). After rather insignificant correction of rock densities, the modelling results have confirmed correctness of the interpretation of the subsurface geological structure, as “errors” of matching of the modelled gravitational effect with observed anomalies (measurement data — Fig. 9) were insignificant.

Along the traverse IV, which was worst documented by seismics (Fig. 10), the foreland of the Dukla Unit and Skole Nappe is characterized by the most complicated tectonics. The accepted interpretation of the specific tectonics in the so-called Bieszczady facies subregion (Kuśmierek 1979), which extends from the Dukla thrust up to the Otryt thrust (O–O in Fig. 10), has been supported by seismic documentation of the southern segment of the FII/I-74/75 profile (line 10A in Fig. 1) that crosses the outcrops of the oldest (in this part of the Carpathians) flysch formation members in the tectonic element called the Bystre scale (Ślączka 1959). Detailed mapping conducted by the author (Kuśmierek 1979) has documented that this element constitutes a frontal digitation of a fold overturned to the NE (of the pseudosyncline type), which is also revealed by the geometry of reflectors (Fig. 10A).

Occurrence of upturned rock series, combined with presence of tectonic windows and patches and backthrusts, was also noted in the Ukrainian part of so-called Fore-Dukla Zone, among others in the upper Uzh drainage basin (Danysh 1973).

Occurrence of backward thrust tectonic elements was also identified in the Polanki IG-1 (Fig. 10) and Suche Rzeki IG-1 (Fig. 10B) well sections. The structural arrangement of reflections in both the seismic sections, which accentuates the divergent, disharmonic structure of detached and tectonically reactivated structural elements, indirectly reflects the morphology of the basement.

The complicated tectonics of the internal synclinorium of the Skole Nappe, before the front of the Silesian overthrust, was recognized in the deep wells Jasień IG-1 and Brzegi Dolne IG-1. Its deep-seated elements are also imaged by the W00 70 276 seismic profile recorded by PBG (Fig. 10). The Jasień IG-1 well section documented a complex system of tectonic shears that do not appear in the surface structure. They dislocate steep and locally backward inclined folds devoid of the Lower Cretaceous deposits. The folds had been

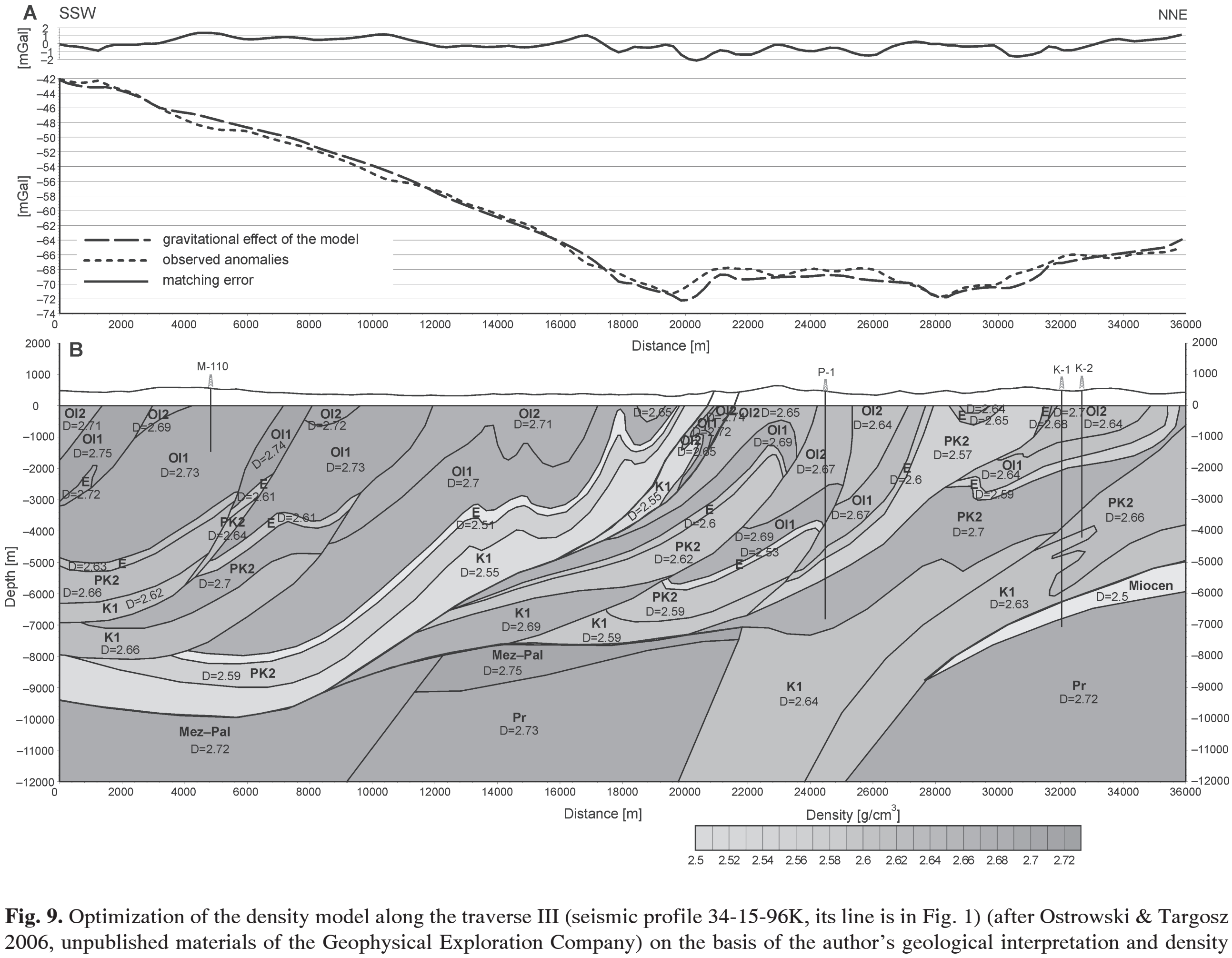

Fig. 9. Optimization of the density model along the traverse III (seismic profile 34-15-96K, its line is in Fig. 1) (after Ostrowski & Targosz 2006, unpublished materials of the Geophysical Exploration Company) on the basis of the author’s geological interpretation and density data. Lithostratigraphic explanations as for Figs. 2, 5, 7; remaining explanations — see the figure.

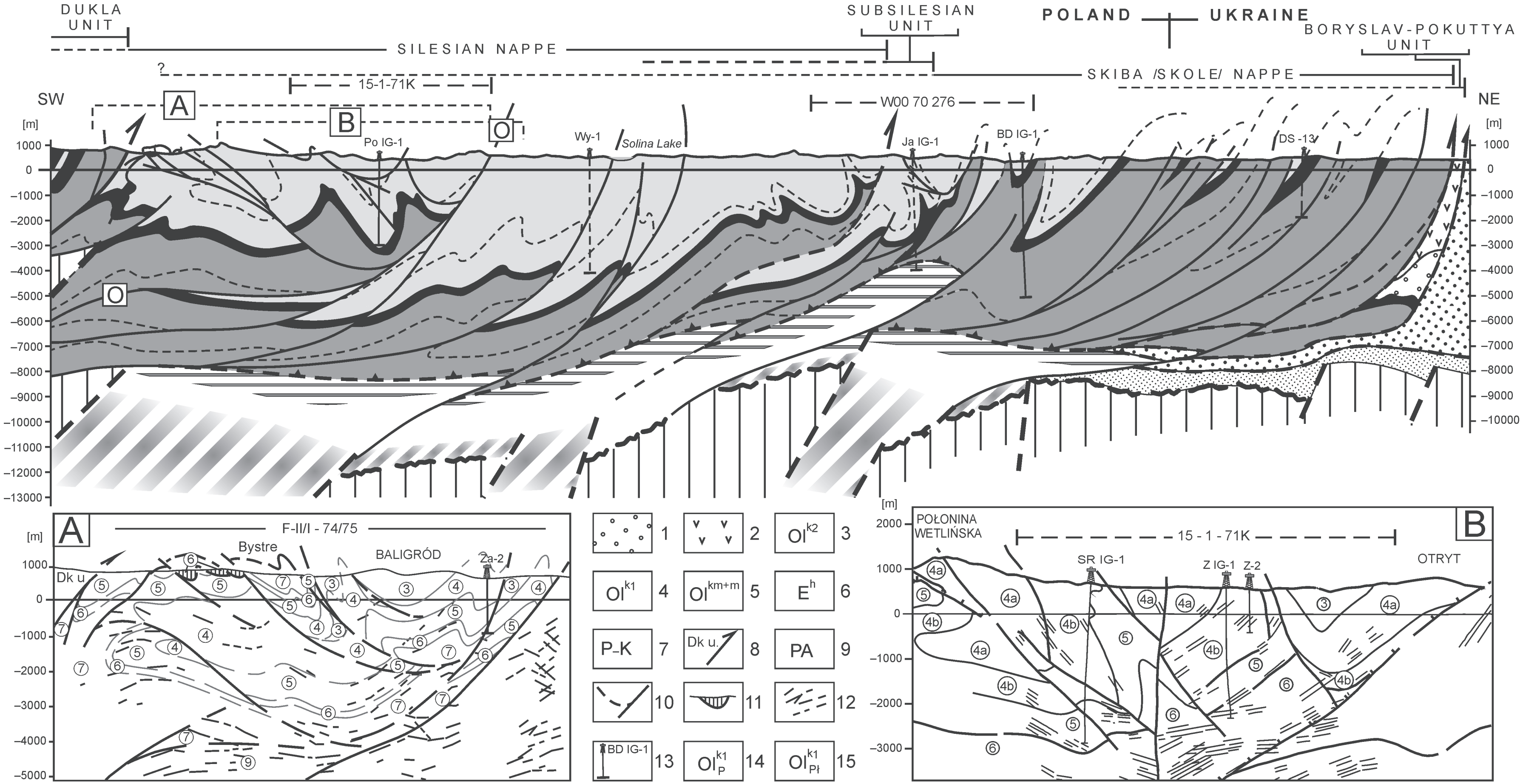

Fig. 10. Traverse IV: Cisna (Poland)–Chidnovichi (Ukraine); the Ukrainian part was corrected with unpublished materials of C. Zayats and P. Loziniak. Early Miocene folded molasses of the Boryslav-Pokuttya Unit: **1** — Poljanica Beds, **2** — Vorotyšča Beds (Saliferous Clay); remaining explanations as for Figs. 5, 8. **A** — Interpretation of tectonics of structures in the foreland of the Dukla Unit along the seismic section FII/I-74/75 (southern fragment; see Fig. 1, line 10A) on the basis of seismic documentation (Pepel, Bardadyn, Patryas — Geophysical Exploration Company, Warsaw 1974/75, unpublished materials) and cartographic-structural investigations (Kuśmierek 1979). Menilite-Krosno Series (Oligocene): **3** — Middle Krosno Beds (Ol^{k2}), **4** — Lower Krosno Beds (Ol^{k1}), **5** — Transition Beds and Menilite Beds (undifferentiated, Ol^{km+m}); older deposits: **6** — Eocene–Ciężkowice Sandstones, Variegated Shales and Hieroglyphic Beds (E^{h}), **7** — Paleocene–Cretaceous (undifferentiated Istebna Beds, Lgota Beds, Grodziszcze Sandstones, Cieszyn Beds, P-K), **8** — overthrust of the Dukla Unit (Dk u.), **9** — paraautochthon (PA?), **10** — overthrusts of lower orders and faults, **11** — erosional outliers of the thrust upper limb of the Iwonicz–Rudawka Rymanowska Fold, **12** — seismic reflections, **13** — well location and symbol. **B** — Interpretation of tectonics of structures in the southeastern part of the seismic section 15-I-71K (see Fig. 1, line 10B) on the basis of seismic documentation (Shöppl & Bednarz 1972, Polish Oil and Gas Company Kraków, unpublished materials) and cartographic-structural investigations (Kuśmierek 1979). Lower Krosno Beds (divided): **14** — sandstone complex (Ol_{P}^{k1}), **15** — sandstone-shale complex ($Ol_{Pł}^{k1}$); remaining explanations as for Fig. 10A.

detached from the underlying deep-seated fold with the Lower Oligocene sediments, 430 m thick, encountered at its top (Żytko 2004). This gently sloping fold, with dips predominantly from 5 to 7°, was interpreted as a paraautochthonous element documented by drilling (Fig. 10).

The northeastern part of the traverse IV — constructed on the basis of the Ukrainian geological atlas (Shakin et al. 1976) and corrected by new, unpublished materials of C. Zayats and P. Loziniak — illustrates, among others, developed thickness of folded molasses of the Boryslav-Pokuttya Unit, which overlie, with a sedimentary gap, deep-seated folds of the unit.

Regional diversification of the tectonic style

Considerable differentiation of the feature of the subsurface structures between southern and northern segments of particular traverses (Figs. 5, 7, 8, 10) justifies the usefulness of their separate analyses. Internal segments of the traverses — lying in the zone of compressional sutures in the tectogene basement (Fig. 1) with diversified hypsometry of its individual blocks and geometry and amplitudes of the deep-seated fractures dislocating them — are characterized by more differentiated types of structures in the cover. In their southern parts, at least to the system of transversal deep-seated fractures C–D–E (Fig. 1), sets of fault-propagation folds predominate; most frequently they are represented by stacked slices with tectonically reduced northern limbs overlapping the internal margin of the southern tectonic suture (Figs. 5, 7, 8). The system of backthrusts that appears in the southern part of the traverse IV (Fig. 10) is probably related to subsurface wedging of the uplifted basement blocks within the "shallower" tectonic suture, above which so-called triangle zones of the eastern sector of the Fore-Dukla Zone were formed (Roure et al. 1993). The origin of interpretive controversies concerning this sector is connected not only with the youngest phase of the compressional inversion of the structures (during which backward-vergent thrusts were formed; see Fig. 10A), but also with mutual relations between synsedimentary tectonic deformations and sedimentary structures on the northern slope of the Fore-Dukla uplift (Kuśmierek 1981).

The northern parts of the internal segment of the traverse IV are characterized by common occurrence of detachment folds with variable vergence, locally — backward vergence on slopes of the thrust nappe covers, among others above broad uplifts which can be interpreted as duplexes. Flat detachments of the type of compressional inversion faults — identified in seismic sections — are most often located in zones of structural depressions of the flysch cover, which are superposed on deep-seated compressional sutures. Sporadically they also occur in northern segments of the traverses I and II (up to the subsurface trace of the fracture B; see Fig. 1) as associated with disharmoniously folded structural elements (Figs. 5, 7).

The tectonic style of the external segments of the traverses, dominated by the flexural slope of the subducted platform, is characterized by a geometrically consequent system of thrusts dipping toward the southwest. Their amplitudes increase to the SE and they are intensified in the Przemyśl Sigmoid zone behind the trace of the fracture B where — at the external side of the zone of the compressional sutures — faults with smaller throws appear, which dislocate the slope of the platform basement (initial sutures? — Fig. 1). In the traverses I and II (Figs. 5, 7), the gently sloping Skole Nappe cover is dislocated by flat-dipping overthrusts and tectonic slices, and some synclinal structures are cut at the base by inversional detachments. In the traverses III and IV (Figs. 8, 10), a system of imbricate thrusts is developed, which separate structural elements of the "skyba" type and asymmetric geometry accentuated by wedging out of the youngest lithostratigraphic members of the Skole Series (preserved only in deeper synclines). In the near-surface zone, they are characterized by steeper dips and smaller amplitudes of displacements that sometimes decline or are compensated by deformations of the continuous type. From this it can be inferred that the early stage of their propagation could have preceded sedimentation of the youngest members of the Skole Nappe; the youngest members wedge out on the slope of the platform margin, which is shown by their thickness reduction combined with the tendency to change the lithofacies of the sediments toward successions of the platform type.

In the interpreted seismic sections, no deep-seated extension of the Boryslav-Pokuttya Unit at the base of the Silesian Nappe has been encountered. The prospects for discovering oil fields (of the Boryslav type) under the Przemyśl Sigmoid or in its southern margin had been linked with this conception (e.g. Wdowiarz & Jucha 1981 and references therein). The deepest well Kuźmina-1 (7541 m), drilled for this purpose, at the base of the Stebnik Unit encountered a detached block of flysch deposits (at the depth of 7062–7221 m) which were admitted to be olistoliths (Malata & Żytko 2006). However, in the author's opinion, it is a tectonically detached erosional outlier of the flysch cover (Fig. 8), lying in a structural position analogous to the previously described patches at the front of the Skole overthrust.

The most distinct differentiation of the tectonic style of individual structural-facies units along their strikes exists between the traverses III and IV. It reveals tectonic mobility of the transversal fractures (marked by letters from C to I in Fig. 1) which dislocate the tectogene basement in the hinterland of the Przemyśl Sigmoid and separate the northern and northeastern segments of the Carpathian arc.

Summary

Cartographic imaging of the subsurface structure of the Outer Carpathians tectogene is an underestimated element for recognition of the tectogene structure. Such imaging is crucial for profound interpretation of the complicated tectonics of the allochthonous flysch covers and their basement, and for reconstruction of scaled paleostructural models. Integrated interpretation of the two-dimensional cartographic and geophysical images, combined with well sections, has documented a new, more complicated picture of the subsurface structure in the eastern part of the Polish Carpathians, dominated by thrusts of the cover and deep-seated faults of the basement, which induced fold systems of various geometries and origins.

Acceptance of significant differentiation of the tectonic style between surface and subsurface structural elements of nappe covers and their heterogeneous basement has shaken the sceptical attitude towards the credibility of the seismic images and results of the MT interpretation in the Carpathian domain. Application of the modified methodology of processing of seismic data and their geological interpretation has specified subsurface traces of overthrusts and thrust faults, among others documenting the geometry of flat inversional detachments (that were previously unrecognized). Reinterpretation of the MT results justifies relating the oblique and subvertical resistivity boundaries with extreme contrasts to compressional sutures of the tectogene. Overlying gently-sloping structural elements in the nappe hinterland have been interpreted as paraautochthonous covers, which should be admitted to be a working hypothesis based upon geophysical premises and the author's interpretation of one of the deep well sections.

The interpretation of patches of the flysch cover at the base of the Stebnik Nappe overthrust, which is different from the commonly accepted, implies the advisability of revision of the previously published stereotyped paleogeographic models.

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