GEOLOGICA CARPATHICA, OCTOBER 2006, 57, 5, 355–370

Tertiary development of the Polish and eastern Slovak parts of the Carpathian accretionary wedge: insights from balanced cross-sections

MICHAL NEMČOK[1], PIOTR KRZYWIEC[2], MAREK WOJTASZEK[3], LÍVIA LUDHOVÁ[4],
RICHARD A. KLECKER[5], WILIAM J. SERCOMBE[5] and MIKE P. COWARD[6†]

[1]✉EGI, University of Utah, 423 Wakara Way, Suite 300, Salt Lake City, UT 84-108 Utah, USA; mnemcok@egi.utah.edu
[2]Polish Geological Institute, Rakowiecka 4, PL-00-975 Warszaw, Poland
[3]Institute of Geological Sciences, Jagiellonian University, Oleandry 2A, PL-30-063 Krakow, Poland
[4]Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina, SK-842 15 Bratislava, Slovak Republic
[5]Amoco Prod. Co., P.O. Box 4381, Houston, TX 77210, USA
[6]Ries-Coward Associates, LtD., 70 Grosvenor Road, Caversham, Reading RG4 0ES, UK

(Manuscript received March 11, 2005; accepted in revised form March 16, 2006)

Abstract: During Eocene–Sarmatian, a Polish-eastern Slovak portion of the Outer West Carpathian accretionary wedge was deformed in front of the ALCAPA terrane. This portion advanced into the area of the subducting remnant Carpathian Flysch Basin, a large oceanic tract left in front of the Alpine orogen. Western parts of the wedge were characterized by a noticeable lack of involvement of thick-skin thrusting and by a predominant development of fault-propagation folds. Eastern parts of the wedge were characterized by the involvement of thick-skin thrusting, triangle zones and back-thrusts. The frontal portion of the wedge was characterized by a décollement formed along the shale and gypsum formations of the Badenian molasse sediments, which resulted in the increased width of the thrust sheets. Forelandward thinning of foreland basin sediments indicates that the portion of the European Platform attached to the subducting oceanic lithosphere flexed underneath the advancing Carpathians as early as the Eocene. Oligocene sediments record syn-depositional thrusting by abrupt thickness changes over short distances. Younger periods of the thrusting are documented by the Eggenburgian–Karpatian piggy-back basin carried by thrust sheets in the frontal portion of the ALCAPA terrane, the Early Miocene age of the youngest sediments in the central portion of the wedge and involvement of the middle Badenian molasse sediments in the frontal portion of the wedge. The end of the shortening is documented by the lower Sarmatian end of the strike-slip fault activity behind the wedge, by the middle Sarmatian transgression over the deformed wedge in the Orava-Nowy Targ Basin, which is located in the rear portion of the wedge, and by the Sarmatian undeformed sediments sealing the wedge front. The existence of the forebulge in front of the advancing Carpathians is documented by local Eocene, Oligocene and Lower Miocene unconformities in the frontal portion of the wedge.

Key words: Western Carpathians, development mechanism, structural style, balanced cross-sections.

Introduction

While Tertiary development reconstructions of the entire Carpathian-Pannonian region have resulted in a relatively accepted scenario (e.g. Balla 1984; Royden 1988; Royden & Báldi 1988; Horváth 1993; Csontos 1995; Haas et al. 1995; Meulenkamp et al. 1996; Nemčok et al. 1998; Bada 1999), several basic problems remain for the reconstruction of the Carpathian accretionary wedge. The effects of the mechanical stratigraphy, the presence of pre-thrusting structures, the syn-tectonic deposition, erosion, and fluid flow on the Carpathian wedge mechanics and dynamics require further research.

The Carpathian accretionary wedge was formed during the Tertiary by NE- and E-ward migration and accretion occurring in front of advancing microplates (e.g. Balla 1984; Kovács 1987; Royden & Báldi 1988; Kovács et al. 1989; Csontos et al. 1992; Haas et al. 1995). During this process, the remnant Carpathian Flysch Basin (rCFB), which was floored by oceanic and thinned continental crust placed between the orogen, the West and East European Platforms and the Moesian Platform, was consumed (e.g. Royden & Báldi 1988). The major driving force for the accretionary wedge was the subduction roll-back (e.g. Royden et al. 1982) and deformation of the wedge in the west was influenced by the eastward lateral mass extrusion from the Eastern Alps, as noted by Neubauer & Genser (1990) and Ratschbacher et al. (1991).

Earlier research of the Carpathian accretionary wedge defined ancestral basins, sediments of which are accreted in a present-day wedge. These sediments include sediments of Early Cretaceous rifts evolved on a present-day margin of the West European Platform (e.g. Swidziński 1948; Książkiewicz 1960, 1962b, 1965, 1977a; Lucińska-Anczkiewicz et al. 2002; Poprawa et al. 2002a,b; Grabowski et al. 2004; Oszczypko 2004), sediments of Upper Cretaceous-Paleocene basins formed by an inversion of earlier rifts (e.g. Suk et al. 1984 and references therein; Krzywiec 2002; Poprawa et al. 2002a; Oszczypko 2004 and references therein) and sediments of the Eocene-

Oligocene deep foreland basin (Winkler & Ślączka 1992; Poprawa et al. 2002a,b). This distinction was tested and put into tectonic continuum by earlier balanced cross-section campaigns (e.g. Roure et al. 1993, 1994; Roca et al. 1995; Behrmann et al. 2000). The existence of Early Cretaceous horsts and younger intra-basinal sources in the West Carpathian accretionary wedge sedimentary record (e.g. Książkiewicz 1960; Roure et al. 1993, 1994; Oszczypko & Oszczypko-Clowes 2002) and their non-existence in the East Carpathian accretionary wedge sedimentary record (e.g. Stefanescu & Melinte 1996) indicate the progressive deepening of the rCFB from NW to SE (see also Ryłko & Adam 2005).

Two modern attempts have been made for the described basin system to be palinspastically restored, however, they either lack balanced cross-sections made from detailed geological maps (Morley 1996) or cover the whole region by only a few balanced cross-sections (Ellouz & Roca 1994). No attempts have used kinematic data from the western half of the wedge to constrain their interpretation.

The balanced cross-sections and kinematic and paleomagnetic data in the western half of the Carpathian accretionary wedge would assist in answering fundamental unsolved questions, such as questions on the transformation of the convergence from the rear into both internal wedge deformation and advance, the role of the out-of-sequence thrusting, the nature of both erosion/shortening and deposition/shortening coupling, basement/cover deformation interplay and basal friction role in the thrusting.

The intent of this paper is not to address all of the outlined open problems, but rather to characterize the Tertiary mechanics of the Polish-east Slovak portion of the Carpathian accretionary wedge. This paper is based on the five regional balanced cross-sections to provide determination of wedge shortening and advancing during the Tertiary.

Methods

Five balanced cross-sections have been constructed from the West European Platform to the Inner Western Carpathians (Fig. 1). Data constraints for balancing are provided by magnetotelluric and gravity data (e.g. Pospíšil pers. com., 1994; Ryłko & Tomaś 1995), reflection seismic profiles (e.g. profiles 5-3-73K, 5-1-78K, 5A-1-78K), boreholes, our own outcrop data and data from available geological maps. Seismic data imaged structural architecture in the thinner portion of the wedge and the location of the basal décollement underneath the whole wedge. Magnetotelluric

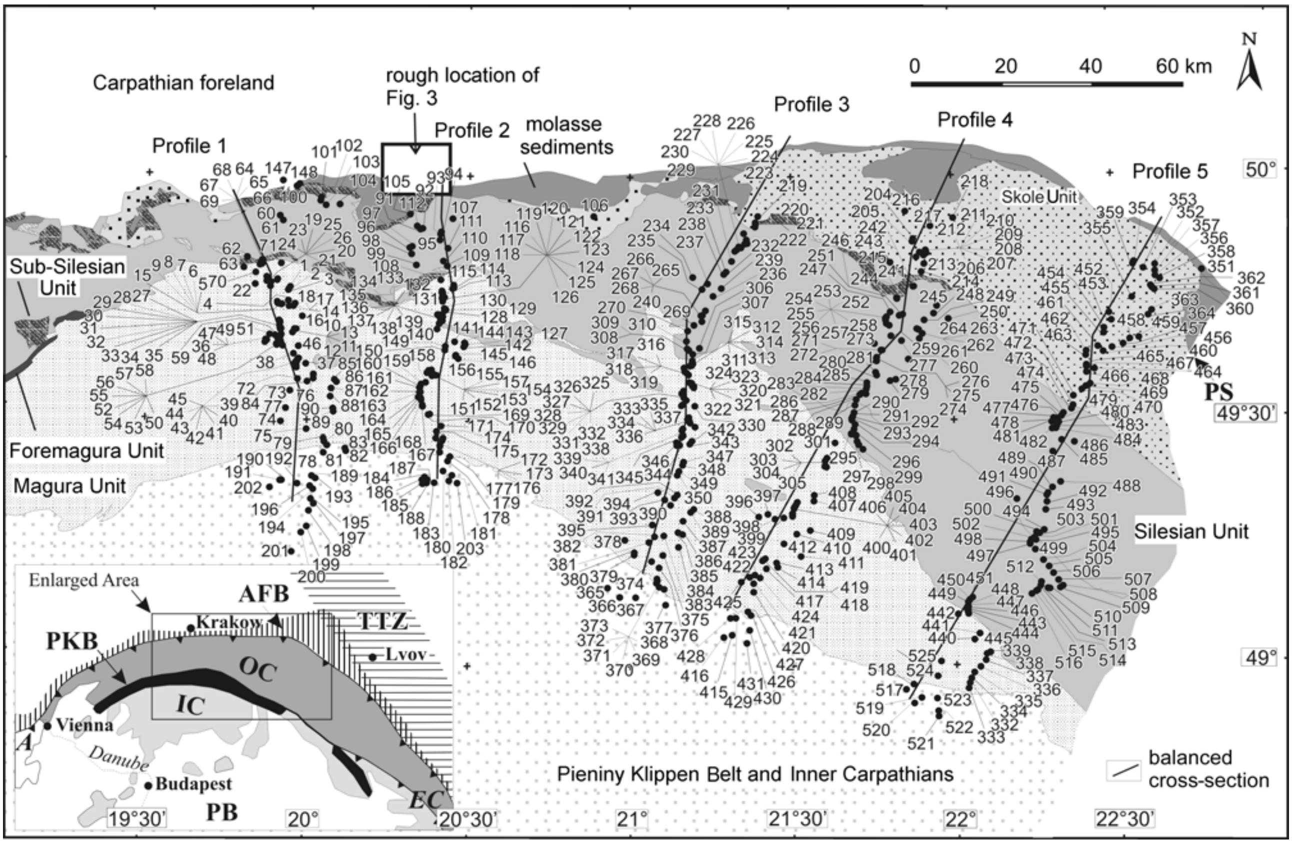

Fig. 1. A map of the Outer West Carpathian accretionary wedge between a longitude of E19° and E23° and with a location of balanced cross-sections and locations of kinematic studies. The inset shows the whole of the Western Carpathians. **AFB** are the autochthonous Miocene molasse sediments of the foreland basin, **TTZ** is the Tornquist-Teisseyre Zone, **OC** are the Outer Carpathians, **IC** are the Inner Carpathians, **EC** are the Eastern Carpathians, **PKB** is the Pieniny Klippen Belt, **A** are the Alps and **PB** is the Pannonian Basin. The seismic profile in Fig. 3 is parallel to the frontal portion of the second profile and located to the west of it. It is not precisely located for confidentiality reasons.

data were particularly suitable for the determination of the top of the crystalline basement, even under the rear portion of the wedge. Gravity data constrained geometries of structural highs and depressions below the thicker half of the wedge and boreholes constrained structural architecture in the upper 3–6 km of the wedge.

Dip domain and kink band analyses were made manually from seismic, borehole and outcrop data in order to exclude local complexities, such as lower-order folding or slumps. This cleaning resulted in thrust geometries constructed without complexities, which are smaller than the visualization capability of regional balanced cross-sections. This consideration was of special importance, because the obtained fold geometries cleaned from small-scale complexities comprised fault-bend folds (Suppe 1983), fault-propagation folds (Suppe & Medwedeff 1984) and their evolutional combinations (e.g. Mitra 1990). Their axial planes and bounding faults provided constraints for line balancing. Construction was done using Paradigm 2D GeoSec, in direction from pin lines towards the orogenic hinterland as well as from the surface down. Pin lines for the Magura and Silesian Units were located in the very front. Volume preservation was simulated by the area preservation within each cross-section. Deformed cross-sections were tested for area preservation by restoring them to their undeformed state using the flexural slip algorithm.

Mechanical stratigraphy

Figure 2 shows the complete and grouped lithostratigraphy of sediments present in the studied part of the Carpathian accretionary wedge. The complete lithostratigraphy is presented according to its division to the Skole, Sub-Silesian, Silesian, Dukla and Magura Units (Gucik et al. 1962; Bieda et al. 1963) and is slightly modified. Various facies have been grouped together to obtain the layered-cake stratigraphy required by balancing (Fig. 2). This grouping is not a simplification of the input data, because any separate facies can be located again after balancing is done. The Magura facies are grouped separately and the facies of all other units are grouped to the "Silesian Unit" because they were deposited in a system of neighboring basins and highs. The Silesian Unit will be used in this sense in the whole paper.

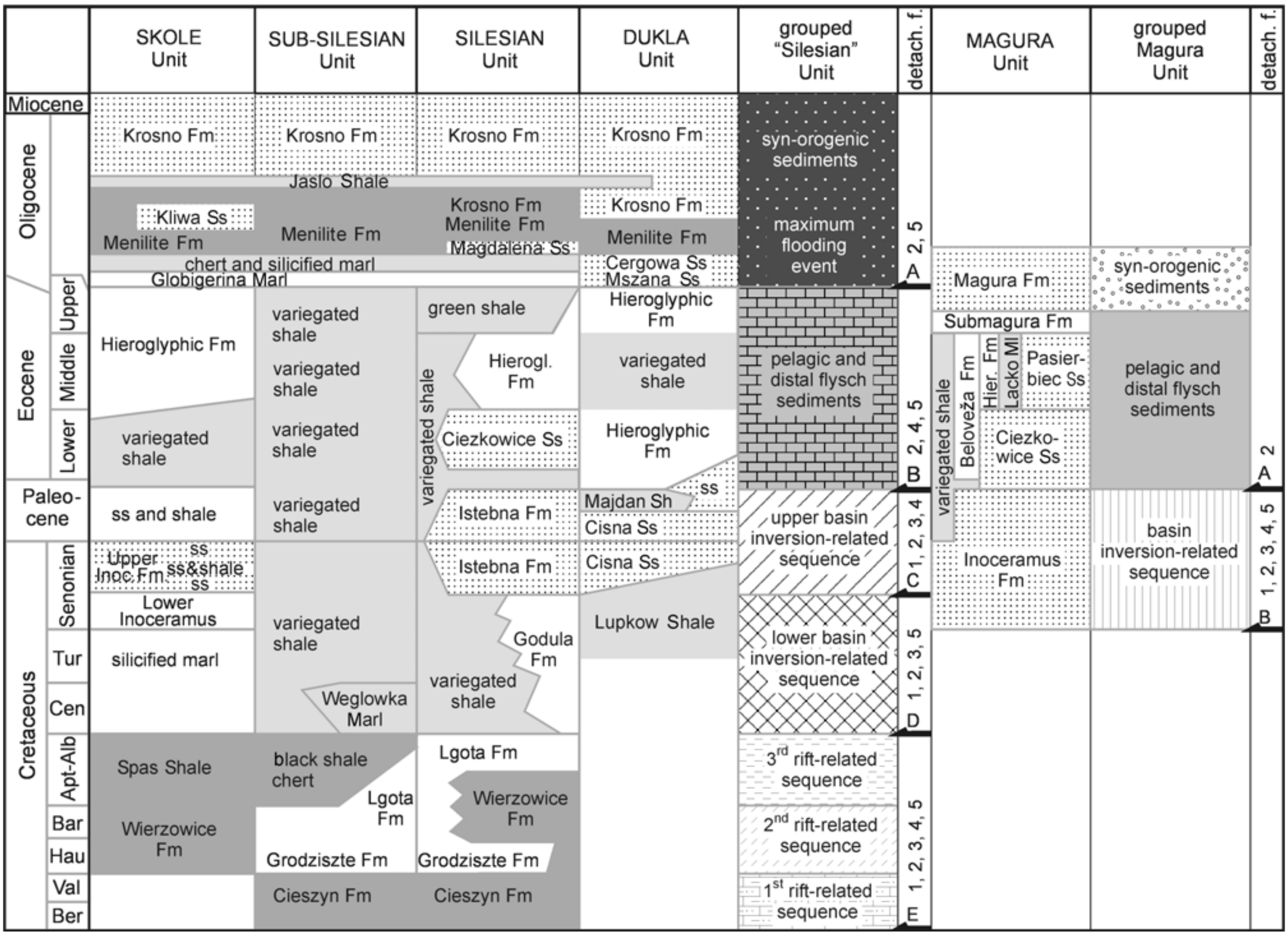

Fig. 2. The lithostratigraphy of the Outer West Carpathian accretionary wedge (modified after Gucik et al. 1962; Bieda et al. 1963). The numbers next to the detachments indicate the presence of the detachment at certain cross-section. Cross-sections numbered from west to east refer to locations in Fig. 1. The dark grey colour highlights hydrocarbon source rocks, the light grey highlights shale and marl and the dotted pattern highlights sandstone dominated facies. Further explanation is in text.

The Magura Unit is divided into three sequences (Fig. 2). The oldest sequence, a basin inversion-related sequence, forms a relatively competent layer characterized mainly by flysch sediments with abundant sandstone layers. The intermediate sequence, a pelagic and distal flysch sequence, can be characterized as an incompetent layer, due to the abundance of shale and thin rhythmic flysch, whether or not it locally contains larger sandstone bodies. The most competent sequence is the youngest one that was formed by sandstone-dominated syn-orogenic sediments.

The basal décollement is formed at the base of the Inoceramus Formation (B in Fig. 2). Less important local detachments have been observed in our balanced cross-sections at the base of the pelagic and distal flysch sediments (A in Fig. 2).

The Silesian Unit is divided into seven sequences (Fig. 2). The lowest three, divided in more detail for better visualization of Lower Cretaceous rifts (e.g. Nemčok et al. 2001), form generally incompetent layers due to their high shale content, despite a certain content of carbonate facies. Their incompetence is further enhanced by potential fluid-releasing clay mineral transformation and hydrocarbon generation. Primarily, the Spas, Wierzowice (Veřovice) Shale and parts of the Cieszyn (Tešín) Formation are known as potential source rocks (e.g. Bessereau et al. 1996). The lower basin inversion-related sequence is somewhat between an incompetent and competent layer, comprising a true mixture of different rheologies. The upper basin inversion-related sequence represents the lowermost competent layer, as it is supported by the Cisna Sandstone or sandstone-prevailing parts of the Istebna or the Inoceramus flysch. The following pelagic and distal flysch layer is an incompetent layer despite the local presence of larger bodies of the Ciezkowice Sandstone. The layer of syn-orogenic sediments includes sediments of the maximum flooding event, the Globigerina Marl and the Menilite Formation that reside on the bottom of the layer. Menilite Formation is the proven source rock in the region (Ziegler & Roure 1996), which can potentially change its rheology during the fluid expulsion. The upper parts of syn-orogenic sediments are generally competent, as represented by the Krosno flysch that comprises the larger proportion of sandstone.

The basal décollement is formed in shaly parts of the Cieszyn Formation and in the Wierzowice Shale (E in Fig. 2). Detachments at the base of both inversion-related sequences are locally frequent (C, D in Fig. 2). A less important local detachment has also been observed in our cross-sections at the base of both pelagic and distal sediments and syn-orogenic sediments (A, B in Fig. 2).

Balanced cross-sections

All balanced cross-sections are pinned on the West European Platform and end in the Pieniny Klippen Belt, with the exception of profile 1, which goes further to the Central Carpathian Paleogene (Podhale) Basin.

Profiles 1 and 2

Figures 5 and 7 in Nemčok et al. (2000), which show profiles 1 and 2, respectively, indicate four and nine normal faults below the wedge. They were constrained by magnetotelluric imaging (Ryłko & Tomaś 1995) and reflection seismic profiles 5-3-73K, 5-1-78K, 5A-1-78K. None of the two profiles shows a distinct thickening of Jurassic-Lower Cretaceous or Tertiary sediments towards these normal faults, which would indicate their relationship to Jurassic-Early Cretaceous rifting or the Tertiary flexure of the underlying plate, with exception of Jurassic wedge between third and fourth normal faults from north in profile 2. However, location 100 documents the same system of NW-SE striking normal faults, which deform the Oxfordian limestone and are overlapped by the Senonian marl, providing the evidence for Early Cretaceous rifting. The mining in the Wieliczka area between profiles 1 and 2 has documented the Neogene inversion of NW-SE striking normal faults (Poborski & Jawor 1989) in addition to far field and along-strike evidence from the Bohemian Massif to the west of our study area for their Late Cretaceous-Paleocene inversion (e.g. Malkovský 1979, 1987; Bachman et al. 1987; Betz et al. 1987; Schröder 1987).

Jurassic and Upper Cretaceous sediments of grabens underneath the thrustbelt are unconformably overlain by Neogene sediments, a small portion of which is accreted in the thrustbelt. Missing sediments underneath the unconformity in profile 2 indicate at least 0.6 km of the Lower Miocene erosional removal of the Silesian sediments before the molasse was deposited (Fig. 7 in Nemčok et al. 2000).

The youngest Neogene sediments of the thrustbelt have late Badenian age. They are present in frontal parts of profile 2 (Fig. 7 in Nemčok et al. 2000), where they unconformably overlie the Senonian-Paleocene upper basin inversion sequence. They belong to a relatively narrow belt of deformed foredeep deposits (Książkiewicz 1977c) called Zgłobice Unit (Kotlarczyk 1985), detached along middle Badenian evaporites. The fold-and-thrust structures of this unit include a small imbricated fan system consisting of mostly blind thrusts (sensu Boyer & Elliot 1982; Dunne & Ferrill 1988; Fig. 3) and minor backthrusting. They developed as growth structures. This is documented by a significant thinning of Badenian sedimentary packages from the limb towards the crest of the growth fold as well as intra-Badenian angular unconformities related to the thrust-induced rotation of depositional surfaces. In front of the fold-and-thrust structures of the Zgłobice Unit, above the M3 seismic horizon, which could be approximately correlated with the Badenian/Sarmatian boundary (Krzywiec et al. 1995), several stacked small-scale prograding wedges are observed on seismic data. These wedges were interpreted as fan deltas, derived from the eroded thrust front. In addition, similar Sarmatian fan deltas were described in several outcrops from the vicinity of the Carpathian front (Doktor 1983).

Although both profiles include the décollement fault, which is cut to the surface, several reflection seismic profiles from the vicinity of the profile 2 indicate buried thrustbelt front (Fig. 3). Fig. 3 also indicates that sedi-

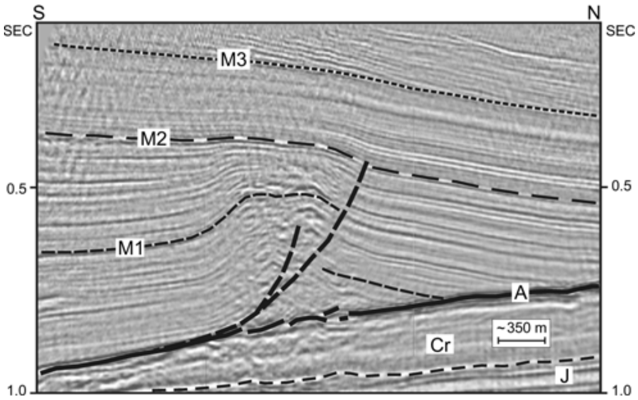

Fig. 3. A seismic reflection profile 27-7-92K crossing the frontal Carpathian thrust developed within the Miocene foredeep sediments. See explanation in Fig. 1 for location. The vertical scale indicates two-way travel time in seconds. Note the thickness reduction of foredeep sediments within the hinge of the interpreted fault-propagation fold pointing to its syn-depositional growth. **A** indicates the seismic horizon related to middle Badenian anhydrites (approximately the top of the pre-Miocene basement), **M1** and **M2** are intra-Badenian horizons, **M3** probably indicates the Badenian/Sarmatian boundary (from Krzywiec et al. 1995) and **J** and **Cr** show Jurassic and Cretaceous sediments. See text for further explanations.

ments deposited at about Badenian/Sarmatian boundary or a bit older overlie the frontal anticline.

Frontal thrust sheets of the thrustbelt in profiles 1 and 2 are 0.7–2 and 1.2–1.9 km thick, and 3.5–15 and 2.8–6.7 km wide, respectively. These sheets have been made by fault-propagation folding (sensu Suppe & Medwedeff 1984) and thrust over the shale and gypsum formations of the middle Badenian autochthonous molasse.

Sub-horizontal veins with the fibrous gypsum exist in close proximity to the décollement within the shale sequence at location 107 and indicate fluid overpressure (Nemčok et al. 2000). The other location inside the wedge that is close to its décollement is location 106. It shows shale duplexing and sandstone boudinage within shale horizons, E-W striking fold axes and randomly oriented gypsum veins, indicating fluid overpressure (Nemčok et al. 2000).

Frontal thrust sheets of the wedge contain unconformable contact between the Oligocene and underlying Senonian-Paleocene sediments. The entire Eocene pelagic and distal flysch sequence is frequently eroded off.

The immediate contact of the Magura and Silesian Units in profile 2 is made by the Zegocina sinistral transpressional strike-slip fault zone, which was studied at locations 113–127. The fault zone itself is shown in the balanced cross-section 2 as the undifferentiated Sub-Silesian sequence (Fig. 7 in Nemčok et al. 2000). This is because the distinction of each small strike-slip duplex, mapped by Burtan & Skoczylas-Ciszewska (1964b) was not possible. The W-E sigmoidal orientation of strike-slip duplexes indicates a sinistral transpression, which is documented at locations 114, 116 and 120 by kinematic data. This fault zone brings a large portion of the oldest sediments to the surface in strike-slip duplexes. These duplexes comprise both marginal and basinal facies of the Silesian Basin fill. The zone is formed above a large NE-SW striking fault in the autochthonous basement that is oblique to the cross-section.

Silesian thrust sheets buried under Magura thrust in profiles 1 and 2 are 2–8.3 and 2.1–16.3 km wide, and formed in 1–2.3 and 1.1–3.9 km thick sections, respectively. The shortening value and restored width of the Silesian Unit along profiles 1 and 2 are 75 and 80 km, and 130 and 137 km, respectively. The only exception from their foreland vergency is the Slopnice antiformal stack and the most proximal parts of the wedge. The Slopnice antiformal stack is formed by four sheets of various widths, which are cut at the base of Lower Cretaceous, Upper Cretaceous and Eocene. The overlapping ramp anticlines of the stack do not have coincident trailing branch lines and the Magura sole thrust above them is corrugated. The complex structure of the stack rules out its sequential development (e.g. Boyer & Elliott 1982; Butler 1982), particularly the presence of pre-upper Badenian sediments located among two of its thrust sheets. Proximal parts of the wedge contain subvertical and overturned thrust faults.

The deformation of the Magura Nappe is characterized by fault-propagation folding (Figs. 5 and 7 in Nemčok et al. 2000). Sheets in profiles 1 and 2, formed in 0.9–4.2 and 0.5–3.5 km thick sections, are 4.5–12 and 3.6–12.1 km wide, respectively. Fault tips are usually present in the Eocene pelagic and distal flysch sequence and the basal detachment of the Magura Unit is folded and offset by numerous out-of-sequence thrusts in profile 2.

The out-of-sequence movement of the Magura thrust is best documented by the existence of the lower-middle Badenian molasse sediments between the Magura and Silesian Units, discovered in the Zawoja borehole (Moryc 1989), which is located 55 km to the west of cross-section 2. These sediments were deposited on top of the shortened Silesian Unit and were later thrust over by the Magura Unit.

The amount of shortening and original width of the Magura Unit in profiles 1 and 2 is about 20 and 42 km, and 64 and 83 km, respectively. The timing of the end of shortening is provided by the middle Sarmatian transgressive facies of the Orava-Nowy Targ Basin, which lies on the Magura Unit (Cieszkowski 1992; Nagy et al. 1996).

Balancing does not provide any direct evidence regarding pre-Neogene shortening. However, the age of the youngest Magura sediments (Table 1) indicates that the initial shortening of the Magura sedimentary succession took part during the Late Eocene and Oligocene. The ages of the youngest Magura sediments (Table 1), younger in a northerly direction, further indicate a piggy-back sequence of thrusting. Numerous observations of deformation bands, which were formed prior to Eocene sediment lithification in the Krynica and Rača Nappes of the Magura nappe system, serve as added evidence for pre-Neogene shortening (e.g. Świerczewska & Tokarski 1998; Tokarski & Świerczewska 1998).

The proximal half of the wedge in the restored cross-section 1 indicates a strike-slip component of the movement along thrusts. This is because of the mismatch of restored sheets, which requires additional restoration in a map view for the horizontal component of the displacement (Nemčok

Table 1: The age of the syn-tectonic deposition along balanced cross-sections. **Profile 1:** 1 — Burtan (1964); 2 — Burtan & Szymakowska (1964); 3 — Badak (1964a); 4 — Watycha (1964a); 5 — Badak (1964b); 6 — Watycha (1964b). **Profile 2:** 1 — Burtan & Skoczylas-Ciszewska (1964a); 2 — Burtan & Skoczylas-Ciszewska (1964b); 3 — Paul (1978). **Profile 3:** 1 — Koszarski et al. (1965); 2 — Koszarski & Kucinski (1966); 3 — Koszarski (1967); 4 — Koszarski & Żytko (1967); 5 — Sikora (1964); 6 — Nemčok (1990). **Profile 4:** 1 — Kucinski & Nowak (1965); 2 — Ślączka (1963); 3 — Ślączka (1964); 4 — Nemčok (1990). **Profile 5:** 1 — Gucik et al. (1979); 2 — Wdowiarz et al. (1988); 3 — Gucik (1983); 4 — Ślączka & Żytko (1978); 5 — Nemčok (1990). The boundaries between Magura nappes in all of the referred maps were modified according to Poprawa & Nemčok (1989). An alternative end age of the syn-tectonic deposition along profile 4 is given as: Late Eocene-Early Oligocene (*3 — author 3). An alternative onset age of this deposition is given as: Profile 1: intra-Late Eocene (*3 — author 3); Profile 2: intra-Late Eocene (*2 — author 2); Profile 3: Late Eocene/Early Oligocene boundary (*1, 3, 4 — authors 1, 3, 4); Profile 5: Middle Eocene (*2 — author 2); Late Eocene/Early Oligocene (*2 — author 2).

Age	Magura Nappe System			Dukla Nappe	Silesian Nappe	Sub-Silesian Nappe	Skole Nappe
	Krynica Nappe	Bystrica Nappe	Rača Nappe				
Profile 1							
Oligocene					1	1	
Upper Eocene		3, 4	2, *(3)				
Middle Eocene	4, 5, 6						
Profile 2							
Oligocene					1, 2	1, 2	
Upper Eocene			3, *(2)				
Middle Eocene	3	3					
Profile 3							
Lower Miocene							
Oligocene					1, 2, 3, 4, 5	3	1, 2
Upper Eocene		6	6, *(1,3,4)				
Middle Eocene	6						
Profile 4							
Lower Miocene							
Oligocene				2, 3	2		1
Upper Eocene		4	4, *(2, 3)				
Middle Eocene	4						
Profile 5							
Lower Miocene							
Oligocene				1, 2, 4	1, 2, 4	1	1, 3
Upper Eocene		5	5				
Middle Eocene	5						

et al. 2000). Our field check showed a strike-slip component of the displacement along some of these fault contacts (locations 74–76, 114, 116, 120, 135, 137, 138, 165, 180, 189, 193), which is in agreement with some Polish Geological Survey maps (e.g. Kulka et al. 1985).

Profile 3

Figure 4 shows eight major normal faults related to Early Cretaceous rifting. Their timing is based on the thickness relations between Paleozoic and Mesozoic sediments on horsts and grabens. The first six faults are located underneath the frontal part of the wedge. There was no evidence of their later inversion that was found by balancing. The first four of them apparently caused ramp location in the overriding wedge. They are overlain by undeformed Neogene autochthonous molasse. The seventh and eighth large normal faults are present under the rear portion of the wedge (Fig. 4). Both of them have been reactivated by thrusting, as indicated by the balancing that was constrained by the top-basement surface, which was taken from interpreted magnetotelluric (Ryłko & Tomaś 1995) and gravimetric data (Pospíšil, pers. com. 1994). The balanced profile, however, does not allow determining, whether they have been reactivated by Late Cretaceous-Paleocene basin inversion or only by younger shortening during the development of the West Carpathian accretionary wedge. The younger shortening is apparent from their propagation through the overlying wedge and their out-of-sequence character (Fig. 4). The frontal portion of the wedge accreted small volumes of the Neogene molasse sediments. The youngest of them are of Badenian–early Sarmatian age. The frontal half of the wedge comprises Silesian sediment section in 4.3 to 18.6 km wide thrust sheets. This increased width, in comparison with profiles 1 and 2, is caused by the dramatic thickness increase of the Cretaceous portion of the sedimentary section in the unit defined as Skole (located in Fig. 1), which caused a strength increase. Its maximum thickness is 3.6 km. Most of these sheets, formed by fault-propagation folding, were thrust over incompetent formations of the autochthonous molasse (Fig. 4). Two preserved fault tips are located inside the Upper Cretaceous section, one at the base of the syn-tectonic sediments. The syn-tectonic sediments show large thickness variations, which are due to erosion of shortened structures and the existence of complex topography during their deposition.

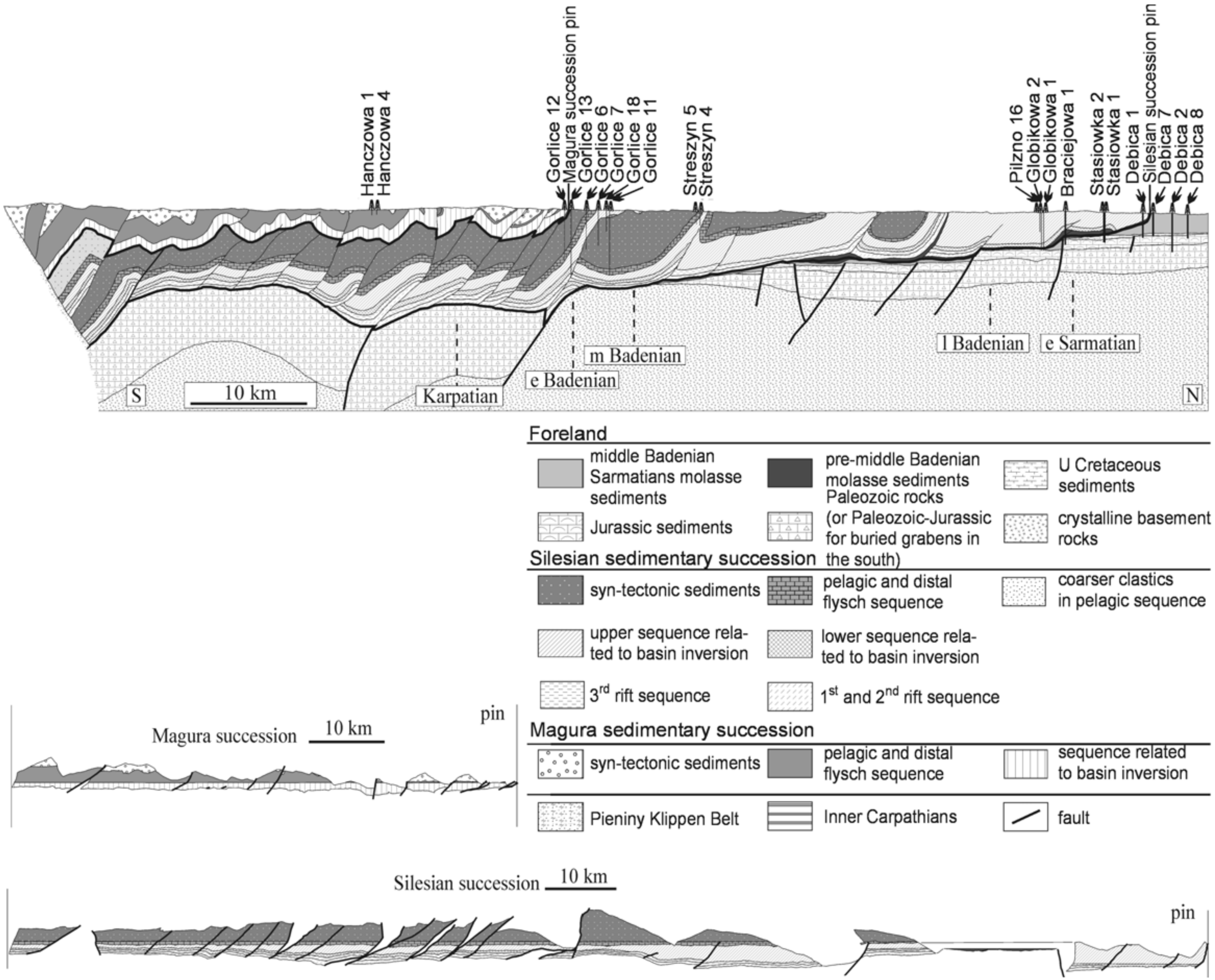

Fig. 4. A balanced and restored cross-section No. 3. The thick dashed vertical line indicates the southernmost extent of autochthonous molasse sediments of an indicated age, located below the accretionary wedge and inferred from well penetrations in the broader area. The layers of the Magura and Silesian sedimentary section are those introduced in Fig. 2 as a result of grouping facies. Molasse sediments are divided into groups of pre-middle Badenian and middle Badenian–Sarmatian. The vertical scale equals the horizontal scale.

The rear half of the wedge has a more complex structure, which includes thick-skin tectonics, buried Silesian duplexes and an overlying Magura Unit (Fig. 4). Basement-involved thrust blocks are 13 and 27.4 km wide and their bounding ramps cut through the wedge to the surface in an out-of-sequence fashion. Buried Silesian thrust sheets, formed in 3.6–4.6 km thick sections, are 3.6 to 10 km wide. They are relatively short in the area located behind the step in the basement of the Gorlice area (Fig. 4). Their ramps are cut through the whole section. The original width and amount of shortening along this profile reaches 168 and 74 km, respectively.

The structural architecture of the Magura Unit is developed by fault-propagation folding and the basal detachment of the Magura Unit is folded. Thrust sheets, made of 1.1–3.9 km thick sections, are 2.9 to 12.9 km wide. Two preserved fault tips are located inside the sequence related to basin inversion; one is located at the base of the pelagic and distal flysch sequence (Fig. 4). The total shortening and initial width of the unit is 18 and 66 km, respectively.

Balancing does not provide any direct evidence regarding pre-Neogene shortening. However, dramatic thickness variations of syn-tectonic sediments may indicate complex topography created by initial thrusting.

Profile 4

There are ten major normal faults related to Early Cretaceous rifting present below the wedge (Fig. 5). Their timing is based on the analogy with previous profiles and thickness relations of Paleozoic-Jurassic sediments in grabens and on horsts, although the origin by flexural bending cannot be ruled out for the first seven faults. The first seven normal faults are located under the frontal third of the accretionary wedge. None of them indicate a younger inversion. They are buried by Neogene autochthonous molasse sediments. The second and third normal faults coincide with ramp location in the overlying wedge. The remaining normal faults, interpreted from gravity and magnetotelluric data, are much larger than the first seven faults (Fig. 5). They have been inverted by younger thrusting. This balanced cross-section does not allow us to determine whether they were inverted during the Late Cretaceous–Paleocene basin inversion or during the Neogene development of the accretionary wedge. The Neogene reactivation can be implied from the out-of-sequence character of their extensions located within the wedge (Fig. 5).

The frontal part of the wedge incorporates a small volume of the Neogene molasse, lower Sarmatian being the youngest. Thrust sheet widths in the frontal third of the wedge are affected by thickness changes in the pre-Eocene part of the sedimentary section. The thick section, which has a thickness of about 1.92 km, forms thrust sheets that are 5.5–7.1 km wide. The thin section, located at both the southern and the northern sides of the thick section, has a thickness of only about 0.5 km and forms thrust sheets only 0.55–1.65 km wide. Fault-propagation folding formed most of the thrust sheets north of the Zyznow 1 well (Fig. 5). They were thrust over incompetent Neogene sediments. Four fault tips are located in the middle of the upper sequence related to basin inversion. One fault tip is located inside the pelagic and distal flysch sequence. The frontal six ramps propagated upward into Neogene sediments that were deposited in a piggy-back basin and carried on top of the first five thrust sheets. This is the only profile with preserved frontal thrust sheets. The remaining profiles show these structures as deeply eroded. The five frontal thrust sheets of profile 4 have preserved several local unconformities, which are described later in chapter "The timing of deformational events".

The remaining two thirds of the wedge have a more complex structure, including two levels of buried duplexes in the Czarnorzeki area, an antiformal stack and two triangle zones with back-thrusting in the Zboiska area and the Magura Unit above Silesian buried duplexes (Fig. 5). The comparison of Figs. 4 and 5 indicates that basement-involved thrusting affected more frontal parts of the European Platform than it did in profile 3. Each basement block-bounding ramp continues into the overlying wedge in an out-of-sequence fashion (Fig. 5). In addition, each of them causes a complexity in overlying structures. A comparison of Silesian thrust sheets buried underneath the Magura Unit with those in front of the Magura Unit indicates distinct thickness changes of the syn-tectonic sediments. It indicates a complex topography produced by initial thrusting during the deposition of syn-tectonic sediments (see Nemčok et al. 2000).

The basement involved thrust blocks are 11.8, 23 and 47.4 km wide. Silesian thrust sheets buried underneath the Magura Unit, about 1.7 km thick, are 1.6–8.2 km wide. The shortening value and original width of the Silesian Unit equals 183 and 304 km, respectively. The structures of the overlying Magura Unit are formed by both fault-bend and fault-propagation folding. Two fault-propagation folds have the tips of their ramps located inside the pelagic and distal flysch sequence. The ramps of fault-bend folds are either cut up to the present surface or cut up to the base of the syn-tectonic sediments (Fig. 5). The basal detachment of the Magura Unit is folded. Thrust sheets of the 0.5–3.2 km thick Magura section are 1.6–8.7 km wide. The shortening value and original width of the Magura Unit is 35 and 85 km, respectively.

Profile 5

Figure 6 shows five major normal faults related to Early Cretaceous rifting below the wedge, as indicated by the thick Paleozoic-Jurassic sediments preserved in grabens. The flexural origin of the first three faults, however, cannot be ruled out. The first two normal faults are located in front of the Kuźmina borehole. Their later inversion is not evident from the balanced cross-section. They do not coincide with ramps in the above wedge and are overlain by the autochthonous Neogene molasse. The three remaining normal faults are much larger than the first two and are located below the central part of the wedge (Fig. 6). The third and fifth normal faults show evidence of their thrust reactivation. The Neogene timing of thrust reactivation is indicated by their out-of-sequence character, i.e. their propagation through the overlying wedge (Fig. 6). There is no evidence allowing us to

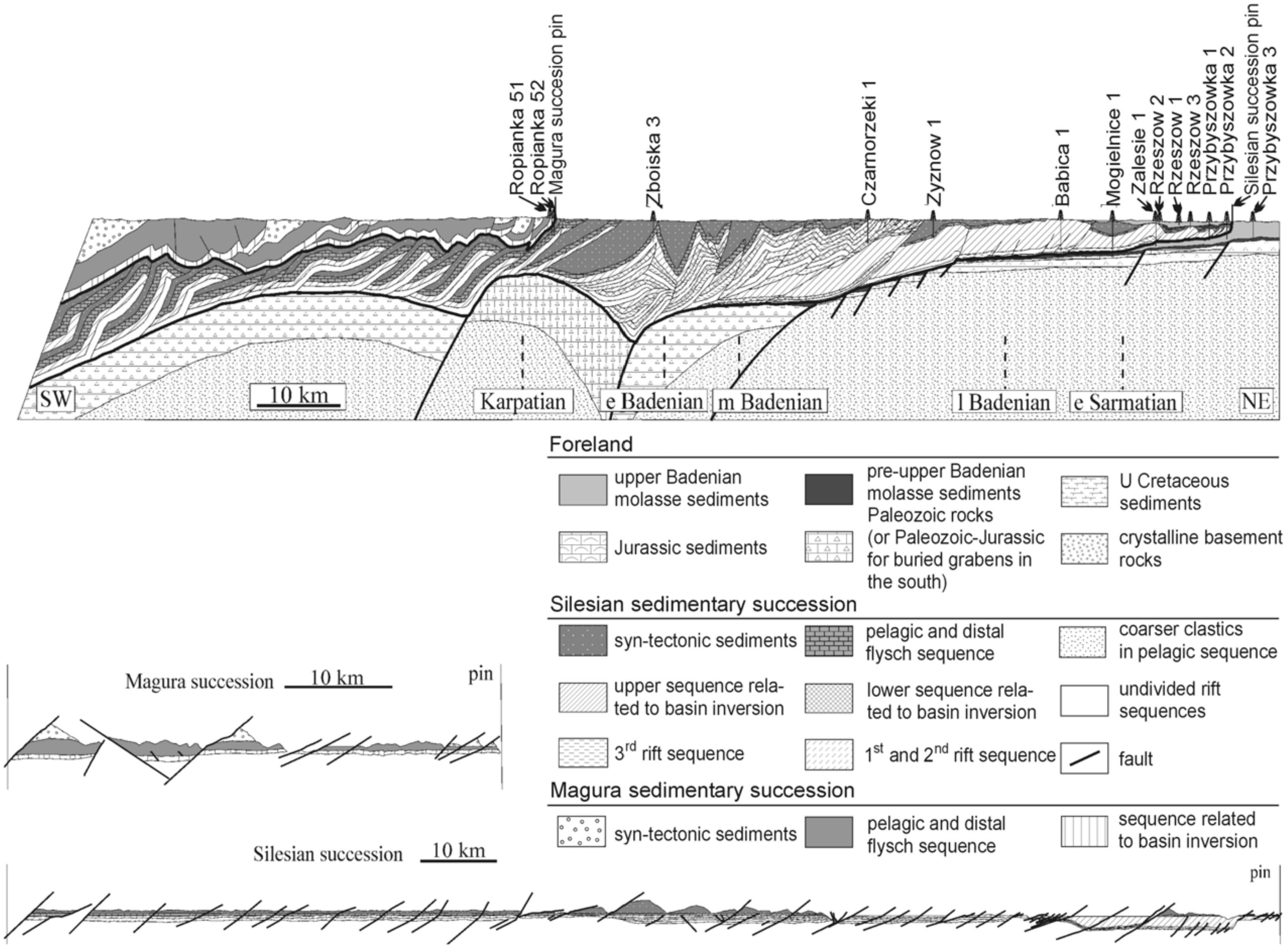

Fig. 5. A balanced and restored cross-section No. 4. Explanations are same as in Fig. 4. Molasse sediments are divided into groups of pre-upper Badenian and upper Badenian. The vertical scale equals the horizontal scale.

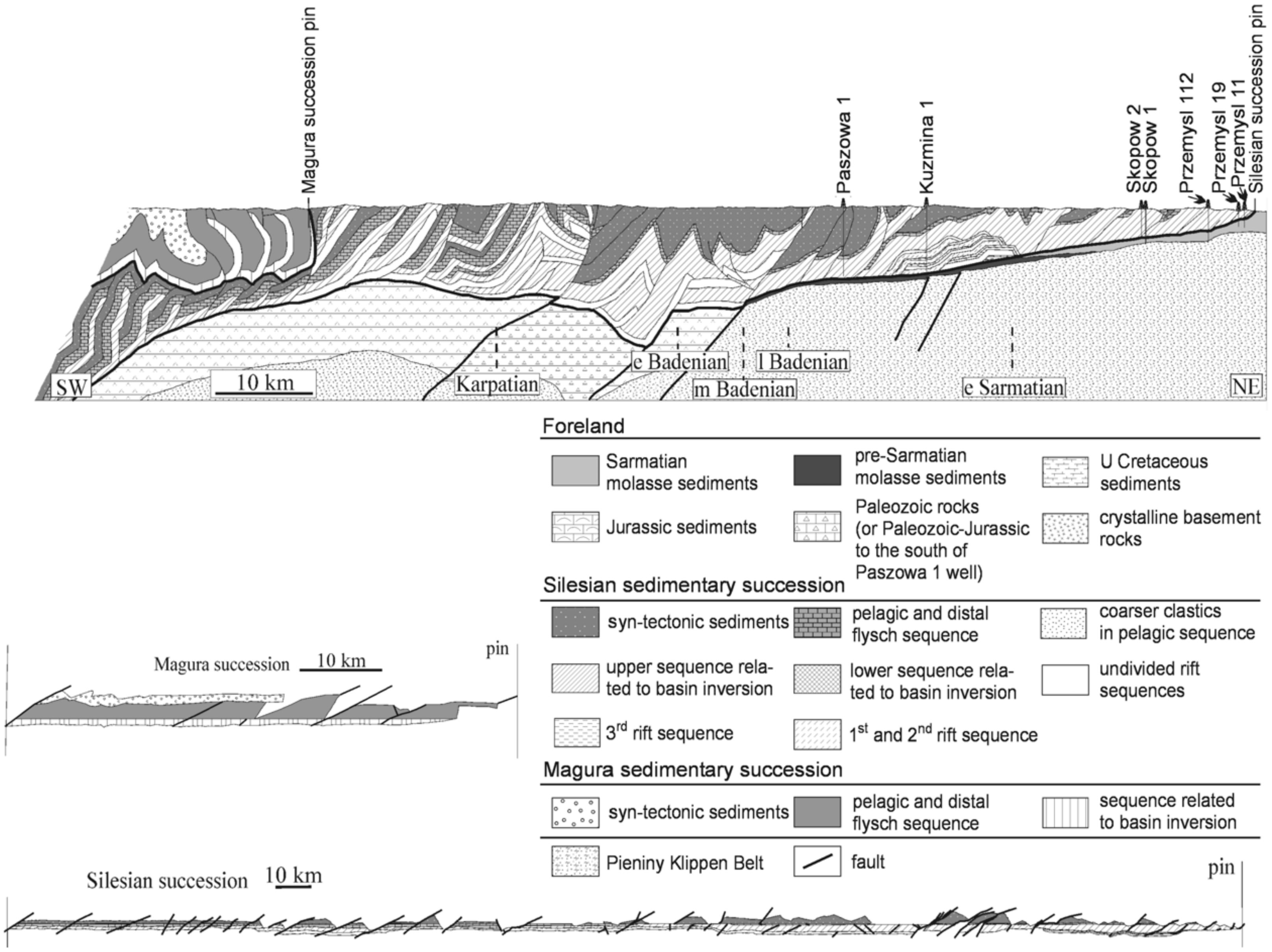

Fig. 6. A balanced and restored cross-section No. 5. Explanations are same as in Fig. 4. Molasse sediments are divided into groups of pre-Sarmatian and Sarmatian. The vertical scale equals the horizontal scale.

determine whether the thrust reactivation took part also during the Late Cretaceous–Paleocene time period.

The frontal half of the wedge comprises Silesian sediment sections in 2.1 to 26.4 km wide thrust sheets. This increased width, in comparison with profiles 1, 2 and 4, is caused by the thickness increase of the Cretaceous sedimentary section in the Skole Unit, which allows for increased strength. Its maximum thickness is 3.6 km, which is identical with profile 3.

The frontal part of the wedge was thrust over less competent middle Badenian–Sarmatian facies of the autochthonous molasse. Due to a deep erosional level, only three of the frontal thrust sheets show evidence of fault-propagation folding. Two preserved fault tips are located at the base of the Eocene section. The variable thickness of thrust sheets is related to various widths. Thrust sheets with a width of 7.1–26.4 km have a thickness close to the maximum value and contain both Lower and Upper Cretaceous sections. The thickness of the 2.1–8.6 km wide thrust sheets ranges between 1.4 and 2.1 km. The Lower Cretaceous section is not present in these short thrust sheets and the thickness of the Upper Cretaceous section is frequently reduced (Fig. 6). There are four buried Lower Cretaceous duplexes in the Kuźmina borehole area.

The rear portion of the wedge has a more complex structure, which includes triangle zones, back-thrusts in the Silesian section and dramatic thickness and thrust sheet width changes (Fig. 6). Triangle zones with back-thrusts are formed in the hanging walls of reactivated and upward-extended normal faults that were originally located underneath the wedge. Two of the normal faults reactivated by thrusting are propagated through the whole overlying wedge to the surface. Both hanging walls bring considerably older sediments than sediments in footwalls do to the present surface. Basement-involved thrust blocks are 7.4, 17.4 and 36.8 km wide. Silesian thrust sheets and duplexes in this part of the wedge, formed in 2–4.3 km thick sections. They are 3.6 to 15.7 km wide with the exception of one 30 km wide thrust sheet. Thrust sheet ramps are cut through the whole section. Some indicate fault-propagation folding, while others indicate fault-bend folding. One back thrust is propagated all the way to the surface; two others die out in basal parts of the Oligocene-Lower Miocene syn-tectonic sediments (Fig. 6). The total shortening and original width of the Silesian Unit reaches 222 and 349 km, respectively.

The shortening of the Magura Unit produces mostly overturned thrust sheets (Fig. 6). There is no evidence regarding the mechanism of folding, due to a deep erosion level. Thrust sheets of this 2.5–4.25 km thick section are 8 to 20.75 km wide. The basal detachment is folded. The initial width and shortening of the Magura Unit is 41 and 18 km, respectively.

The timing of deformational events

The following text summarizes available published evidence for the activity span of the thrustbelt activity, such as the age of basal post-orogenic sediments, activity span of syn-orogenic lateral ramps, age of syn-orogenic deformation, age of the youngest sediments accreted in the thrustbelt front, age of the youngest sediments located below the décollement fault, and ages of syn-orogenic erosional events:

1 — The youngest sediments in the Central Carpathian Paleogene (Podhale) Basin, located behind the wedge, have Oligocene–earlier Early Miocene age. They indicate the lowermost limit for the onset of syn-orogenic erosion (e.g. Čverčko 1975; Cieszkowski & Olszewska 1986; Oszczypko et al. 1992; Cieszkowski 1992; Soták et al. 2001; Janočko et al. 1998).

2 — The Čelovce Formation, the fill of the Eggenburgian-Karpatian piggy-back basin carried by thrust sheets of the Central Carpathian Paleogene (Podhale) Basin, indicates continuous syn-depositional thrusting. Together with other Lower Miocene sediments from northern parts of the East Slovak Basin, it indicates continuous shortening during this time period (Nemčok & Nemčok 1994; Nemčok et al. 1995, 1998).

3 — The Muráň strike-slip fault in the orogenic hinterland, which accommodated inhomogeneous thrusting of the Carpathian accretionary wedge, is sealed by the lower Sarmatian volcanics. It provides the upper bracket on the wedge activity (Fusán et al. 1967; Sperner 1996).

4 — The Pieniny Klippen Belt, which formed at the zone of contact of the Carpathian accretionary wedge and the orogenic hinterland, is sealed by undeformed lower Sarmatian volcanics (Birkenmajer 1986; Pécskay et al. 1995; own structural checking). It provides the upper bracket on the wedge shortening.

5 — Upper Badenian autochthonous molasse sediments seal the frontal thrust of the Carpathian accretionary wedge along profile 1. This indicates the end of wedge shortening in this area (Burtan 1964; Burtan & Skoczylas-Ciszewska 1964a,b; Burtan & Szymakowska 1964; own structural checking). The shortening in the area shown in profile 2 was slightly younger than in the area shown by profile 1, as it has the latest Badenian up to most probably the earliest Sarmatian age, as indicated by syn-tectonic fan deltas present in front of the Zgłobice Unit (Krzywiec 1997, 2001).

6 — The accretionary wedge is thrust over middle Badenian autochthonous molasse sediments along profiles 1 and 2. It puts the lower bracket on the time interval of the last wedge activity in this region (Książkiewicz 1960; own structural checking).

7 — The age of the undeformed basal transgressive facies of the Orava-Nowy Targ Basin, which lies on the rear portion of the Carpathian accretionary wedge along profile1, is middle Sarmatian. It indicates the upper bracket on the age of the last thrusting (Cieszkowski 1992; Nagy et al. 1996; own structural checking).

8 — The Krosno Formation lies on the Istebna Formation above an erosional contact in the frontal portion of profiles 1 and 3. This provides the upper bracket of Oligocene age on the forebulge erosion timing in this area.

9 — Eocene pelagic and distal flysch sediments lie on the Istebna Formation above an erosional contact in the front of profile 1, providing the upper constraint of Eocene age on erosion in this area.

10 — The Krosno Formation is eroded off and missing above the originally underlying Eocene pelagic and distal flysch sediments in relatively frontal parts of profile 2. This provides the lower bracket on the erosion timing in this area.

11 — Lower Badenian molasse sediments lie on the Istebna Formation above a local erosional contact along profile 2, providing the upper constraint on erosion in this area.

12 — The unconformity between the Godula Formation and the overlying Eocene pelagic and distal flysch sediments along profile 4 indicates erosion related to basin inversion, which took part during the Late Cretaceous–Paleocene.

13 — Numerous observations of deformation bands, which were formed prior to the Eocene sediments' cementation in the Krynica and Rača Nappes of the Magura nappe system, serve as evidence for pre-Neogene shortening (e.g. Świerczewska & Tokarski 1998; Tokarski & Świerczewska 1998).

14 — The frontal parts of profile 4 indicate that syn-tectonic Lower Miocene molasse sediments are unconformable over Oligocene–Lower Miocene syn-tectonic Krosno sediments, but later folded together with them.

They have to be merged with evidence of youngest ages of sediments accreted in various structures of the thrustbelt in its different portions, compiled from available surface geological maps and listed in Table 1.

Restored balanced cross-sections further provide us with evidence of rapid thickness changes characteristic for syn-orogenic deposition reacting to growth of various structures. They also allow us to see, which restored layers can be characterized by the wedge profile, indicating the proximity of the flexural bulge by pinching out and orogenic loading by thickening. The following text summarizes the evidence along five studied cross-sections:

1 — In profile 1 (Fig. 5 in Nemčok et al. 2000), the Middle-Upper Eocene syn-orogenic sediments of the Magura Unit are strongly thinning toward the foreland. The syn-orogenic sediments of Middle Eocene–Early Oligocene age in profile 4 probably form a wedge, but it is an uncertain interpretation due to erosion (Fig. 5). These sediments look lens-shaped in profile 5 (Fig. 6).

2 — The Eocene pelagic and distal flysch layer of the Magura Unit is lens shaped in profile 5 (Fig. 6), and lens-shaped to slightly thinning toward the foreland in profile 1 (Fig. 5 in Nemčok et al. (2000)). It is clearly thinning toward the foreland in profiles 2, 3 and 4 (Fig. 7 in Nemčok et al. 2000, and Figs. 4, 5).

3 — The Eocene pelagic and distal flysch layer of the Silesian Unit is clearly thinning toward the foreland in profile 1 (Fig. 5 in Nemčok et al. 2000). It is less distinctively thinning in profile 2 (Fig. 7 in Nemčok et al. 2000) and lens shaped to slightly thinning toward the foreland in profiles 3, 4 and 5 (Figs. 4, 5, 6).

4 — The Oligocene syn-orogenic sediments have varying thicknesses that can be interpreted as syn-depositional shortening in profiles 1 and 2 (Figs. 5, 7 in Nemčok et al. 2000). Oligocene-Lower Miocene syn-orogenic sediments in profile 4 probably form a forelandward thinning sequence, but the interpretation is uncertain due to erosion (Fig. 5).

Discussion

Interpretations of the 1 — palinspastic relationship of the Magura and other Outer Carpathian sediments, 2 — continuity of sediments previously grouped into Silesian, Sub-Silesian, Skole, Dukla, Grybów and Obidowa-Slopnice Units, 3 — out-of-sequence young Magura emplacement, 4 — basic structural style and mechanisms and 5 — original shape of the remnant Carpathian Flysch Basin, confirm previously published results (e.g. Roure et al. 1993, 1994; Ellouz & Roca 1994; Roca et al. 1995; Nemčok et al. 1999, 2000, 2001) and expand the knowledge regarding the whole wedge to the east of the Kraków-Zakopane line. The timing of the youngest main thrust movements determined along our profiles is in agreement with earlier papers (e.g. Jiříček 1979 and references therein; Nemčok et al. 1998 and references therein). There is a general trend of west-to-east younging of terminal thrusting along the Carpathian arc, which is of late Badenian age in the west of our study area and of Sarmatian age in the east of our study area. There are few new local evidence for Pannonian strata underneath the wedge in the Andrychów region of the Polish Western Carpathians (Wójcik & Jugowiec 1998; Wójcik et al. 1999). We understand them as local complexities in the overall younging trend of terminal thrust movements.

The new results or results differing slightly from earlier observations include 1 — the timing of initial shortening, 2 — the strike-slip component along thrusts in the rear and western portion of the wedge, and 3 — the timing of the flexural basin development.

The timing of the initial shortening of sediments accreted in the Outer Carpathian wedge can be improved either by studies of syn-sedimentary deformation or by balancing. Both methods suggest an earlier initiation of shortening than previously understood; Late Eocene-Oligocene in the Magura Unit and Early–Middle Miocene in the other Outer Carpathian Units (e.g. Książkiewicz 1957, 1960; Książkiewicz & Leško 1959; Roth 1973; Suk et al. 1984; Sandulescu 1988; Eliáš et al. 1990; Stráník et al. 1993; Ellouz & Roca 1994; Oszczypko 1998, 1999). The pronounced forelandward thinning of Middle Eocene–Upper Eocene and Lower Eocene layers of the Magura Unit in restored balanced cross-sections indicate the onset of shortening earlier than was thought before. This is in agreement with recent syn-sedimentary deformation studies in the Magura Unit (Świerczewska & Tokarski 1998; Tokarski & Świerczewska 1998), which determined the onset of shortening as early as Eocene. Restored balanced profiles 1 and 2 (Figs. 5, 7 in Nemčok et al. 2000) indicate initial shortening in the Silesian Unit as early as Oligocene, based on the syn-tectonic erosion of growth folds and the erosion timing in the forebulge region. This reconstruction was allowed in this study by the access to more detailed data, especially when compared to earlier balancing studies (e.g. Roure et al. 1993, 1994; Roca et al. 1995). The Oligocene age of the initial shortening in the units now located in front of and below the Magura Unit agrees with the thickness reduction observations shown in papers that have focused on details of hydrocarbon fields (e.g. Kruczek 1968; Kuśmierek 1994).

The strike-slip component of the displacement in the western part of the Outer Western Carpathians is indicated in the rear portion of the wedge, not only along the Pieniny Klippen Belt, as it was interpreted earlier (e.g. Birkenmajer 1986; Roca et al. 1995). The restored profiles 1 and 2 (Figs. 5, 7 in Nemčok et al. 2000) indicate a strike-slip component by misfit of neighbour thrust sheets. Some of these "thrust" contacts were checked in field. They show strike-slip component, which was indicated by sub-horizontal or oblique striations at outcrops such as locations 180 and 186. These data suggest that the Pieniny Klippen Belt was not a low friction zone along which the northeastward movement of the Inner Western Carpathians and a radial shortening of the Outer West Carpathian accretionary wedge would be decoupled. On the contrary, mapped arrays of strike-slip faults, that we had determined to be sinistral, are present within the rear portion of the wedge, as shown by the map of Kulka et al. (1985). The lack of strike-slip components on restored profiles 3, 4 and 5 (Figs. 4–6) is in accordance with their general eastward decrease along the orogen strike (Nemčok et al. 1998) and controlling stress regimes (Gayer et al. 1998).

Conclusions

1 — The basal décollement of the Magura Unit is formed along the Upper Cretaceous sediments. Local less important detachments are formed at the base of the pelagic and distal flysch sediments. The basal décollement of the Silesian Unit (grouping together the Skole, Sub-Silesian, Silesian, Dukla, Grybów and Obidowa-Slopnice Units in this paper) is developed along the Lower Cretaceous strata. Detachments along the bases of both basin-inversion-related sequences are locally frequent. Local unimportant detachments are formed along the base of both pelagic and distal flysch sediments and syn-tectonic sediments. The Magura Unit includes a sedimentary section that cannot be directly matched to the sedimentary section accreted in underlying units. Various units in front of and under the Magura Unit can be matched by balancing as neighbours in their original depositional area, because hanging wall and footwall geometries of adjacent thrust sheets in balanced cross-sections fit. Although their syn-rift sections may restore as separate bodies, syn-inversion and especially younger sediments run across the boundaries of Dukla, Obidowa-Slopnice, Grybów, Silesian, Sub-Silesian and Skole Units.

2 — The largest amount of the thrust structures along studied profiles was developed by fault-propagation folding. The second largest population of thrust structures includes fault-bend folds. The rest is formed by triangle zones, back-thrusts and basement-involved thrusts.

3 — Age distribution of the youngest Magura sediments in space indicates a piggy-back thrusting mode of the Late Eocene–Oligocene age. Balanced profiles 1 and 2 suggest that the initial shortening, in units in front of and under the Magura Unit, started as early as in Oligocene.

4 — Profiles 1 and 2 indicate a strike-slip displacement component of the Miocene, shortening in their rear portions along thrust planes and along sides of several salients. Profiles 3, 4 and 5 do not indicate a strike-slip displacement component of the Miocene shortening.

5 — Profiles 1 and 2 do not show any evidence for the Miocene thick-skin tectonics, reactivating the Early Cretaceous normal faults below the Outer Carpathian accretionary wedge.

6 — Profiles 1, 2 and 3 do not comprise any triangle zones and back-thrusts driven by buttressing from steps formed by failed rifts underneath the thrustbelt.

7 — Profiles 4 and 5 contain antiformal stacks, triangle zones and back-thrusts.

8 — Profiles 3, 4 and 5 indicate Miocene thick-skin tectonics, reactivating Early Cretaceous normal faults below the Outer Carpathian accretionary wedge.

9 — Boundary faults of the basement-involved thrusts along profiles 3, 4 and 5 cut the thin-skin wedge all the way to the present-day surface as young out-of-sequence thrusts.

10 — The detachment fault of the Magura Unit is frequently folded and offset by younger ramps, what can be seen at several locations along profiles 1, 2 and 4, and numerous locations along profile 3.

11 — Profiles 1 and 3 indicate orogenic loading of the flexural basin and forebulge shift forelandward by the fact that the Eocene sediments, which would be otherwise located between overlying Oligocene Krosno Formation and underlying Upper Cretaceous–Paleocene Istebna Formation of the Silesian section, are missing.

12 — Younger episodes of the forebulge shift forelandward and younger episodes of the wedge advance are indicated by Lower Miocene sediments that are unconformable over an Oligocene-Eggenburgian Krosno Formation and their subsequent shortening along profile 4.

13 — The onset of the flexural basin development is indicated by forelandward-thinning sediments of the syn-orogenic, pelagic and distal flysch layers in the Magura Unit. It is as young as Early Eocene.

14 — The onset of the flexural basin development is indicated by forelandward-thinning sediments of the Eocene pelagic and distal flysch layers in the units in front of and below the Magura Unit. The syn-orogenic sediments of these units are eroded too deeply for this determination. However, their thickness variations indicate syn-depositional shortening.

Acknowledgments: The paper was made within the framework of the EUROPROBE-PANCARDI group projects. The work of MN, MW, LL and MPC was carried out under the financial support of the Amoco Prod. Co., Houston and later it was carried out under support of the Alexander von Humboldt Fund and the Slovak Geol. Survey Project MŽP-513-96. PK wishes to thank Polish Oil and Gas Company for the access to seismic data of the foredeep basin and Komitet Badań Naukowych (Committee for Scientific Research) for funding (Grant No. 9 S602 010 06). The authors are grateful to numerous scientists of the PANCARDI group for the discussions. The authors thank Jacek Grabowski for a friendly review. The Carpathian seismic and magnetotelluric data access was from the proprietary data set owned by Amoco Prod. Co., and was used for exploration purposes. Authors wish to thank MPC who cannot see the final result.

References

Bachmann G.H., Müller M. & Weggen K. 1987: Evolution of the Molasse Basin (Germany, Switzerland). *Tectonophysics* 137, 77–92.

Bada G. 1999: Cenozoic stress field evolution in the Pannonian Basin and surrounding orogens. Inferences from kinematic indicators and finite element modelling, *Ph.D. Thesis, Vrije University,* Amsterdam, 1–204.

Badak J. 1964a: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-88D Czarny Dunajec. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Badak J. 1964b: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-88B Rabka. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Balla Z. 1984: The Carpathian loop and the Pannonian basin: a kinematic analysis. *Geophys. Transactions* 30, 4, 313–353.

Behrmann J.H., Stiasny S., Milička J. & Pereszlényi M. 2000: Quantitative reconstruction of orogenic convergence in the Northeast Carpathians. *Tectonophysics* 319, 111–127.

Bessereau G., Roure F., Kotarba A., Kusmierek J. & Strzetelski W. 1996: Structure and hydrocarbon habitat of the Polish Carpathians. In: Ziegler P.A. & Horváth F. (Eds.): Peri-Tethys Memoir 2. Structure and prospects of Alpine basins and forelands. *Mém. Mus. Nat. Hist. Natur.* 170, 343–373.

Betz D., Führer F., Greiner G. & Plein E. 1987: Evolution of the Lower Saxony Basin. *Tectonophysics* 137, 127–170.

Bieda F., Geroch S., Koszarski L., Książkiewicz M. & Żytko K. 1963: Stratigraphie des Carpathes externes polonaises. *Bull. Inst. Geol.* 181, 5–174.

Birkenmajer K. 1986: Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Stud. Geol. Pol.* 80, 7–32.

Boyer S.E. & Elliott D. 1982: Thrust systems. *Amer. Assoc. Petrol. Geol. Bull.* 66, 1196–1230.

Burtan J. 1964: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-76B Myslenice. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Burtan J. & Skoczylas-Ciszewska K. 1964a: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-77B Bochnia. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Burtan J. & Skoczylas-Ciszewska K. 1964b: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-77D Limanowa. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Burtan J. & Szymakowska F. 1964: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-76D Osielec. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Butler R.W.H. 1982: The terminology of thrust structures. *J. Struct. Geol.* 4, 239–245.

Cieszkowski M. 1992: Marine Miocene deposits near Nowy Targ, Magura Nappe, Flysch Carpathians (South Poland). *Geol. Carpathica* 43, 339–346.

Cieszkowski M. & Olszewska B. 1986: Malcov beds in the Magura Nappe near Nowy Targ, Outer Carpathians, Poland. *Ann. Soc. Geol. Pol.* 56, 53–71.

Csontos L. 1995: Tertiary tectonic evolution of the Intra-Carpathian area: a review. In: Downes H. & Vaselli O. (Eds.): Neogene and related magmatism in the Carpatho-Pannonian region. *Acta Vulcanol.* 1–13.

Csontos L., Nagymarosy A., Horváth F. & Kováč M. 1992: Tertiary evolution of the intracarpathian area: a model. *Tectonophysics* 208, 221–241.

Čverčko J. 1975: Preliminary report about results of the deep structural well Prešov-1. *Mns. Geofond,* Bratislava (in Slovak).

Doktor M. 1983: Sedimentation of Miocene gravel deposits in the Carpathian Foredeep. *Stud. Geol. Pol.* 68, 2, 1–107.

Dunne W.M. & Ferrill D.A. 1988: Blind thrust systems. *Geology* 16, 33–36.

Eliáš M., Schnabel W. & Stráník Z. 1990: Comparison of the Flysch Zone of the Eastern Alps and the Western Carpathians based on the recent observations. In: Minaříková D. & Lobitzer H. (Eds.): Thirty years of geological cooperation between Austria and Czechoslovakia. *ÚÚG,* Prague, 37–46.

Ellouz N. & Roca E. 1994: Palinspastic reconstructions of the Carpathians and adjacent areas since the Cretaceous: a quantitative approach. In: Roure F. (Ed.): Peri-Tethyan platforms. *Technip*, Paris, 51–78.

Fusán O., Kodym O., Matejka A. & Urbánek L. 1967: Geological map of ČSSR, scale 1:500,000. *Ústřední Ústav Geologický,* Praha (in Czech).

Gayer R.A., Hathaway T.M. & Nemčok M. 1998: Transpressionally driven rotation in the external orogenic zones of the Western Carpathians and the SW British Variscides. In: Holdsworth R.E., Strachan R.A. & Dewey J.F. (Eds.): Continental transpressional and transtensional tectonics. *Geol. Soc. London, Spec. Publ.* 135, 253–266.

Grabowski J., Krzemiński L., Nescieruk P., Paszkowski M., Szydło A., Pécskay Z. & Wójtowicz A. 2004: New data on the age of teschenitic rocks (Outer Carpathians, Silesian Unit) — results of the K-Ar dating. *Przegl. Geol.* 52, 40–46.

Gucik S. 1983: Regional geological map of Poland. Map 1026-Krzywcza. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Gucik S., Koszarski L., Książkiewicz M., Nowak W., Sikora W., Szymakowska F., Ślączka A. & Żytko K. 1962: Stratigraphic table of the Cretaceous and early Tertiary deposits in the Polish External Carpathians, Geological Atlas of Poland. Stratigraphic and facial problems. *Państw. Inst. Geol.,* Warszawa, Fascicle 13, 14, 2 maps, 1 table.

Gucik S., Paul Z., Ślączka A. & Żytko K. 1979: Geological map of Poland. B map without Quaternary sediments. Map Przemysl, Kalnikow (1:200,000). *Państw. Inst. Geol.,* Warszawa (in Polish).

Haas J., Kovacs S., Krystyn L. & Lein R. 1995: Significance of Late Permian–Triassic facies zones in terrane reconstructions in the Alpine–North Pannonian domain. *Tectonophysics* 242, 19–40.

Horváth F. 1993: Towards a mechanical model for the formation of the Pannonian basin. *Tectonophysics* 226, 333–357.

Janočko J., Hamršmíd B., Siráňová Z. & Jacko S. 1998: Suprafan and channel-and-levee deposits near Tichý Potok, Levoča Mts. (Central-Carpathian Paleogene Basin, Slovakia). *Slovak Geol. Mag.* 4, 3–15.

Jiříček R. 1979: Tectogenic developmentof Carpathian arc during Oligocene–Neogene. In: Maheľ M. (Ed.): Tectonic profiles of Western Carpathians. *GÚDŠ*, Bratislava, 205–215 (in Czech).

Koszarski L. 1967: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-79C Rzepiennik 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Koszarski L. & Kucinski T. 1966: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-79A Tuchow 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Koszarski L. & Żytko K. 1967: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-79D Jaslo 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Koszarski L., Kucinski T. & Szymakowska F. 1965: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-79B Pilzno 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Kotlarczyk J. 1985: Geotraverse Kraków–Baranów–Rzeszów–Przemysl–Komańcza–Dukla. Guide to excursion 4. *XIII Congress of* *the Carpatho-Balkan Geological Association,* Poland, Kraków, 21–32.

Kovács S. 1987: Plate tectonic position of the basement of the Great Hungarian Plain and its connections. *Spec. Publ. Hung. Acad. Sci. Comm.*, Szeged, 17–29.

Kovács S. et al. 1989: The Tisza superunit was originally part of the northern (European) margin of Tethys. In: Rakús M., J. Dercourt & Nairn A.E.M. (Eds.): Evolution of the Northern Margin of Tethys. *Mém. Soc. Geol. France, Nouvelle Ser.*, 81–100.

Kruczek J. 1968: Structural framework of the oil accumulation in the field Bóbrka–Rogi. *Biul. IG,* Warszawa 215 (in Polish).

Krzywiec P. 1997: Large-scale tectono-sedimentary Middle Miocene history of the central and eastern Polish Carpathian Foredeep Basin — results of seismic data interpretation. *Przegl. Geol.* 45, 10, 2, 1039–1053.

Krzywiec P. 2001: Contrasting tectonic and sedimentary history of the central and eastern parts of the Polish Carpathian Foredeep Basin — results of seismic data interpretation. In: Cloetingh S., Nemčok M., Neubauer F., Horváth F. & Seifert P. (Eds.): The hydrocarbon potential of the Carpathian-Pannonian region. *Mar. Petrol. Geol.* 18, 1, 13–38.

Krzywiec P. 2002: Mid-Polish Trough inversion — seismic examples, main mechanisms, and its relationship to the Alpine-Carpathian collision. In: Bertotti G., Schulmann K. & Cloetingh S. (Eds.): Continental collision and the tectonosedimentary evolution of forelands. *European Geophys. Soc. Spec. Publ. Ser. 1,* 151–165.

Krzywiec P., Łuczkowska E., Sadowska A. & Ślęzak J. 1995: Depositional model of the central part of the Carpathian Foredeep Basin, S Poland — results of integrated bio- and seismostratigraphic study. *XV Congress Carpatho-Balkan Geol. Assoc., Athens, Spec. Publ. Geol. Soc. Greece* 4, 3, 1113–1118.

Książkiewicz M. 1957: Geology of the Northern Carpathians: *Geol. Rdsch.* 45, 369–411.

Książkiewicz M. 1960: Description of the paleogeography of the Polish Flysch Carpathians. *Prace Inst. Geol.* 33, 209–231 (in Polish).

Książkiewicz M. 1962a: Geological atlas of Poland. Stratigraphic and facial problems. *Inst. Geol.,* Warszawa, 14 sheets.

Książkiewicz M. 1962b: Sur quelques analogies lithostratigraphiques entre les Carpathes roumaines et polonaises. *Bull. Acad. Pol. Sci.* 10, 11–17.

Książkiewicz M. 1965: Les cordilléres dans les mers crétacées et paléogénes des Carphates du Nord. *Bull. Soc. Géol. France* 7, 443–454.

Książkiewicz M. 1977a: Plate motion hypothesis and Carpathian development. *Ann. Soc. Geol. Pol.* 47, 321–353 (in Polish).

Książkiewicz M. 1977b: The tectonics of the Carpathians. In: Pozaryski W. (Ed.): Geology of Poland. *Wydawnictwo Geol.,* Warsawa, 476–620.

Książkiewicz M. 1977c: The tectonics of the Carpathians. In: Pożaryski W. (Ed.): Geology of Poland, IV. *Tectonics* 476–620.

Książkiewicz M. & Leško B. 1959: On the relation between the Krosno and Magura-Flysch. *Bull. Acad. Pol. Sci.* 7, 773–780.

Kucinski T. & Nowak W. 1965: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M 34-80 B Strzyżów 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Kulka A., Rączkowski W., Żytko K., Gucik S. & Paul Z. 1985: Regional geological map of Poland. Map 1050 Szczawnica-Krościenko. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Kuśmierek J. 1994: Evolution of the central Carpathian oil basin — quantitative interpretation. In: Roure F., Ellouz N., Shein V.S. & Skvortsov I. (Eds.): Geodynamic evolution of sedimentary basins. *International Symposium,* Moscow, 281–303.

Lucińska-Anczkiewicz A., Villa I.M., Anczkiewicz R. & Ślączka A. 2002: ^{39}Ar/^{40}Ar dating of alkaline lamprophyres from Polish Western Carpathians. *Geol. Carpathica* 53, 45–52.

Malkovský M. 1979: Tectonogenesis of the platform cover of the Bohemian Massif (in Czech). *Knihovnička ÚÚG* 53, 1–176.

Malkovský M. 1987: The Mesozoic and Tertiary basins of the Bohemian Massif and their evolution. *Tectonophysics* 137, 31–42.

McKenzie D.P. 1978: Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.* 40, 25–32.

Meulenkamp J.E., Kováč M. & Cícha I. 1996: On Late Oligocene to Pliocene depocenter migrations and the evolution of the Carpathian-Pannonian system. *Tectonophysics* 266, 301–317.

Mitra S. 1990: Fault-propagation folds: geometry, kinematic evolution, and hydrocarbon traps. *AAPG Bull.* 74, 921–945.

Morley C.K. 1986: A classification of thrust fronts. *AAPG Bull.* 70, 1, 12–25.

Morley C.K. 1996: Models for relative motion of crustal blocks within Carpathian region, based on restorations of the outer Carpathian thrust front. *Tectonics* 15, 885–904.

Moryc W. 1989: Miocene of the West Carpathian foreland in the Bielsko-Kraków zone. *Refer. Sesji Krakow 30.3.1989. Mat. Konf., Komis. Tekt. Komit. Nauk Geol. PAN,* 170–198.

Nagy A., Vass D., Petrík F. & Pereszlényi M. 1996: Tectonogenesis of the Orava Depression in the light of latest biostratigraphic investigations and organic matter alteration study. *Slovak Geol. Mag.* 1, 49–58.

Nemčok J. 1990: Geological map of the Pieniny, Čergov, Lubovňa Mts. and Ondava. Mts Scale 1:50,000, sheets 2. *SGÚ/GÚDŠ,* Bratislava (in Slovak).

Nemčok M. & Nemčok J. 1994: Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians. *Tectonophysics* 239, 81–109.

Nemčok M., Keith J.F. Jr. & Neese D.G. 1995: The Central Carpathian Paleogene Basin, West Carpathians. *ESRI Occasional Pub. 11A: Slovakian Geology, ESRI USC,* Columbia, 43–62.

Nemčok M., Pospíšil L., Lexa J. & Donelick R.A. 1998: Tertiary subduction and slab break-off model of the Carpathian-Pannonian region. *Tectonophysics* 295, 307–340.

Nemčok M., Coward M.P., Sercombe W.J. & Klecker R.A. 1999: Structure of the West Carpathian accretionary wedge: insights from cross section construction and sandbox validation. *Physics and Chemistry of the Earth* 24, 659–665.

Nemčok M., Nemčok J., Wojtaszek M., Ludhová L., Klecker R.A., Sercombe W.J., Coward M.P. & Keith J.F. 2000: Results of 2D balancing along 20° and 21° longitude and pseudo-3D in the Smilno tectonic window: implications for shortening mechanisms of the West Carpathian accretionary wedge. *Geol. Carpathica* 51, 281–300.

Nemčok M., Nemčok J., Wojtaszek M., Ludhová L., Oszczypko N., Sercombe W.J., Cieszkowski M., Paul Z., Coward M.P. & Ślączka A. 2001: Reconstruction of Cretaceous rifts incorporated in the Outer West Carpathian wedge by balancing. In: Cloetingh S., Nemčok M., Neubauer F., Horváth F. & Seifert P. (Eds.): The hydrocarbon potential of the Carpathian-Pannonian region. *Mar. Petrol. Geol.* 18, 39–64.

Neubauer F. & Genser J. 1990: Architektur und Kinematik der östlichen Zentralalpen: eine Übersicht. *Mitt. Naturwiss. Ver. Steiermark* 120, 203–219.

Oszczypko N. 1998: The Western Carpathian Foredeep — development of the foreland basin in front of the accretionary wedge and its burial history. *Geol. Carpathica* 49, 6, 415–431.

Oszczypko N. 1999: The Neogene dynamics of the Polish Carpathians and their Foreland. *Technika Poszukiwa Geol* 38, 82–83.

Oszczypko N. 2004: The structural position and tectonosedimentary evolution of the Polish Outer Carpathians. *Przegl. Geol.* 52, 780–791.

Oszczypko N. & Oszczypko-Clowes M.A. 2002: Newly discovered Early Miocene deposits in the Nowy Sącz area (Magura Nappe, Polish Outer Carpathians). *Geol. Quart.* 46, 117–133.

Oszczypko N., Olszewska B., Ślęzak J. & Strzępka J. 1992: Miocene marine and brackish deposits of the Nowy Sącz Basin (Polish Western Carpathians); new lithostratigraphic and biostratigraphic standards. *Bull. Polish Acad. Sci., Earth Sci.* 40, 83–96.

Paul Z. 1978: Regional geological map of Poland, Map 1034 Łącko.

Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Poborski J. & Jawor E. 1989: On sub-Carpathian tectonics in the Krakow area. *Przegl. Geol.* 6, 308–312 (in Polish).

Poprawa D. & Nemčok J. 1989: Geological atlas of the Western Outer Carpathians and their Foreland. *PIG Warszawa/GÚDŠ Bratislava/ÚÚG Praha.*

Poprawa P., Malata T. & Oszczypko N. 2002a: Tectonic evolution of the sedimentary basins of the Polish part of the Outer Carpathians in the light of subsidence analysis (in Polish). *Przegl. Geol.* 50, 1092–1108.

Poprawa P., Malata T., Oszczypko N., Słomka T. & Golonka J. 2002b: Subsidence versus deposition — quantitative analysis for the Polish Outer Carpathian basins. *Proceedings of the XVII Congress of the Carpatho-Balkan Geol. Assoc., Bratislava, September 1–4, 2002. Geol. Carpathica* 53, 1–7.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O. 1991: Lateral extrusion in the Eastern Alps, part 2: structural analysis. *Tectonics* 10, 2, 257–271.

Roca E., Bessereau G., Jawor E., Kotarba M. & Roure F. 1995: Pre-Neogene evolution of the Western Carpathians: constraints from the Bochnia–Tatra Mountains section (Polish Western Carpathians). *Tectonics* 14, 855–873.

Roth Z. 1973: Outer West Carpathians. In: Mahel' M., Roth Z., Jaroš J., Vozár J. & Haško J. (Eds.): Tectonical structures of the West Carpathians: Guide to Excursion A. *X Congress of Carpathian-Balkan Geol. Assoc., GÚDŠ,* Bratislava, 20–24.

Roure F., Roca E. & Sassi W. 1993: The Neogene evolution of the outer Carpathian flysch units (Poland, Ukraine and Romania): kinematics of a foreland/fold-and-thrust belt system. *Sed. Geol.* 86, 177–201.

Roure F., Kuśmierek J., Bessereau G., Roca E. & Strzetelski W. 1994: Initial thickness variations and basement — cover relationship in the Western Outer Carpathians (SE Poland). In: Roure F., Ellouz N., Shein V.S. & Skvortsov I. (Eds.): Geodynamic evolution of sedimentary basins. *International Symposium,* Moscow, 255–279.

Royden L.H. 1988: Late Cenozoic tectonics of the Pannonian basin system. In: Royden L.H. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *Amer. Assoc. Petrol. Geol. Mem., Amer. Assoc. Petrol. Geol.,* Tulsa 27–48.

Royden L.H. & Báldi T. 1988: Early Cenozoic tectonics and paleogeography of the Pannonian and surrounding regions. In: Royden L.H. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *Amer. Assoc. Petrol. Geol. Mem., Amer. Assoc. Petrol. Geol.,* Tulsa 1–16.

Royden L.H., Horváth F. & Burchfiel B.C. 1982: Transform faulting, extension and subduction in the Carpathian-Pannonian region. *Geol. Soc. Amer. Bull.* 73, 717–725.

Ryłko W. & Adam T. 2005: Basement structure below the West Carpathian–East Carpathian orogen junction (eastern Poland, north-eastern Slovakia and western Ukraine). *Geol. Carpathica* 56, 29–40.

Ryłko W. & Tomaś A. 1995: Morphology of the consolidated basement of the Polish Carpathians in the light of magnetotelluric data. *Geol. Quart.* 39, 1–16.

Sandulescu M. 1988: Cenozoic tectonic history of the Carpathians. In: Royden L.H. & Horváth F. (Eds.): The Pannonian Basin. A study in basin evolution. *AAPG Mem.* 45, 17–26.

Schröder B. 1987: Inversion tectonics along the western margin of the Bohemian Massif. *Tectonophysics* 137, 93–100.

Sikora W. 1964: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-91A Gorlice 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Ślączka A. 1963: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-92A Zmigród 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Ślączka A. 1964: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-92C Tylawa 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Ślączka A. & Żytko K. 1978: Regional geological map of Poland. B map without Quaternary sediments Lupków 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Soták J., Pereszlényi M., Marshalko R., Milička J. & Starek D. 1996: Sedimentology and hydrocarbon habitat of the submarine-fan deposits of the Central Carpathian Paleogene Basin (NE Slovakia). *Mar. Petrol. Geol.* 18, 87–114.

Sperner B. 1996: Computer programs for the kinematic analysis of brittle deformation structures and the Tertiary tectonic evolution of the Western Carpathians (Slovakia). *Tuebinger Geowissenschaftliche Arbeiten,* Tuebingen A/27, 1–120.

Stefanescu M. & Melinte M. 1996: Cretaceous–Early Miocene subsidence and the related source and reservoir rocks in the Moldavids. In: Wessely G. & Liebl W. (Eds.): Oil and gas in Alpidic thrustbelts and basins of central and eastern Europe. *EAGE Spec. Publ. EAGE,* 197–200.

Stráník Z. Dvořák J., Krejčí O., Müller P., Přichystal A., Suk M. & Tomek Č. 1993: The contact of the North European Epivariscan Platform with the West Carpathians. *J. Czech Geol. Soc.* 38, 21–30.

Suk M., Blížkovský M., Buday T., Chlupáč I., Cícha I., Dudek A., Dvořák J., Eliáš M., Holub V., Ibrmajer J., Kodym O., Kukal Z., Malkovský M., Menčík E., Műller V., Tyráček J., Vejnar Z., Zeman A. & Svoboda J. 1984: Geological history of the territory of the Czech Socialist Republic. *Czech Geol. Surv.,* Prague, 1–396.

Suppe J. 1983: Geometry and kinematics of fault-bend folding. *Amer. J. Sci.* 283, 684–721.

Suppe J. & Medwedeff D.A. 1984: Fault-propagation folding. *GSA Bull., Abstr. with Programs* 16, 670.

Świdziński H. 1948: Stratigraphical index of the Northern Flysch Carpathians. *Bull. Panstw. Inst. Geol.* 37, 1–128.

Świerczewska A. & Tokarski A. 1998: Deformation bands and the history of folding in the Magura nappe, Western Outer Carpathians (Poland). *Tectonophysics* 297, 73–90.

Tokarski A.K. & Świerczewska A. 1998: History of folding in the Magura nappe, Outer Carpathians, Poland. In: Rossmanith H.P. (Ed.): Mechanics of jointed and faulted rocks. *Balkema,* Rotterdam, 125–130.

Watycha L. 1964a: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-89A Mszana Górna. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Watycha L. 1964b: Regional geological map of Poland (Quaternary sediments omitted). Region of the Carpathians and their foreland. Map M34-89C Nowy Targ. Scale 1:50,000, 1 sheet. *Inst. Geol.,* Warszawa (in Polish).

Wdowiarz S., Zubricki A. & Frystak-Wolkowska A. 1988: Regional geological map of Poland. Map 1040-Rymanov 1:50,000. *Inst. Geol.,* Warszawa (in Polish).

Winkler W. & Ślączka A. 1992: Sediment dispersal and provenance in the Silesian, Dukla and Magura flysch nappes (Outer Carpathians, Poland). *Geol. Rdsch.* 81, 371–382.

Wójcik A. & Jugowiec M. 1998: The youngest member of the folded Miocene in the Andrychów region (S Poland) (in Polish with English summary). *Przegl. Geol.* 46, 763–770.

Wójcik A., Szydło A., Marciniec P. & Nescieruk P. 1999: The folded Miocene of the Andrychów region (in Polish). *Biul. Państw. Inst. Geol.* 387, 191–195.

Ziegler P.A. 1982: Geological atlas of Western and Central Europe. *Elsevier,* Amsterdam, 1–130, 40 plates.

Ziegler P.A. & Roure F. 1996: Architecture and petroleum systems of the Alpine Orogen and associated basins. In: Ziegler P.A. & Horváth F. (Eds.): Peri-Tethys memoir 2; Structure and prospects of Alpine basins and forelands. *Mém. Mus. Nat. Hist. Natur.* 170, 15–45.