GEOLOGICA CARPATHICA, 51, 5, BRATISLAVA, OCTOBER 2000
281–300

RESULTS OF 2D BALANCING ALONG 20° AND 21°30' LONGITUDE AND PSEUDO-3D IN THE SMILNO TECTONIC WINDOW: IMPLICATIONS FOR SHORTENING MECHANISMS OF THE WEST CARPATHIAN ACCRETIONARY WEDGE

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(Manuscript received March 15, 2000; accepted in revised form June 20, 2000)

Abstract: The restoration of structures along two balanced cross sections through the West Carpathian accretionary wedge and the pseudo-3D restoration in the Smilno tectonic window area shows that various defined units are parts of the Magura and Silesian sedimentary successions. The shortened Magura and Silesian successions were detached at the base of the Upper and Lower Cretaceous sediments, respectively. The interpretation of the structural and sedimentological data places the Magura depositional area as the southwestern neighbour of the Silesian depositional area. Both areas were shortened during the Upper Eocene–Oligocene. The Magura area was shortened strongly owing to the collision between the Alpine orogen and the European Platform. The Silesian area was shortened gently due to the subduction of the oceanic plate attached to the European Platform. The Magura Unit was thrust over the Silesian sediments much later during the Miocene as an out-of-sequence oblique thrust. The Miocene shortening of the Magura Unit and the oblique closure of the Silesian portion of the basin caused a significant contribution to the orogen strike-parallel sinistral strike-slip faulting in the deformation of the accretionary wedge. The general shortening mode was a piggy-back process. Thrust geometries were created by both the fault-bend and fault-propagation folding. The frequent out-of-sequence thrusting is caused by the friction/erosion interplay. Variations in friction along the basal thrust include low friction, documented by subhorizontal veins with vertically grown fibers and long thrust sheets, medium friction, indicated by the duplexing, and high friction indicated by antiformal stacks. Basement steps along pre-existing rifting-related normal faults caused complications in the wedge geometry. The step perpendicular to the tectonic transport caused the development of the antiformal stack, the oblique step caused the sinistral transpression.

Key words: West Carpathian accretionary wedge, 2D and pseudo-3D structural balancing, deformation mechanisms, basin restoration.

Introduction

The Outer West Carpathian accretionary wedge (Fig. 1) was a focus for numerous studies in the sixties and seventies that presumed a fold and thrust-belt character (e.g. Maheľ 1973). The few recent balanced cross section projects (e.g. Roure et al. 1993; Roca et al. 1995) also assume that thrusting was a dominant mechanism. These balancing campaigns frequently used large scale map data (e.g. from Poprawa & Nemčok 1989) and a limited number of bore holes, but their objectives did not include studying the deformation mechanisms in detail.

Thrust sheets of the wedge comprise the fill of several basins. These basins include the Early Cretaceous rifts that evolved on a passive margin of the European Platform (e.g. Świdziński 1948; Książkiewicz 1960, 1962a, 1965, 1977), the Upper Cretaceous-Paleocene basins formed by basin inversion of earlier rifts (e.g. Suk et al. 1984 and references therein; Malkovský 1987; Schröder 1987) and the Eocene-Oligocene deep foreland basin (e.g. Poprawa & Nemčok 1989 and references therein; Winkler & Ślączka 1992).

This paper introduces regional balanced cross sections along Krakow-Zakopane and Bochnia-Kroscienko transects and the pseudo-3D balancing in the Smilno tectonic window area. Both transects and area balancing are based on detailed field data, seismic, magnetotelluric, bore hole data and data from published geological maps. The paper presents a calculation of the shortening and restoration of the original basin width along regional cross sections. The main aim of the paper is to use the data produced by balancing to examine mechanisms of the wedge deformation in detail. Time period names and related radiometric ages used for the Neogene and older periods are taken from the time-scale for the Central Paratethyan Neogene (Vass et al. 1987; Rögl 1996) and time-scale of Haq & van Eysinga (1998), respectively.

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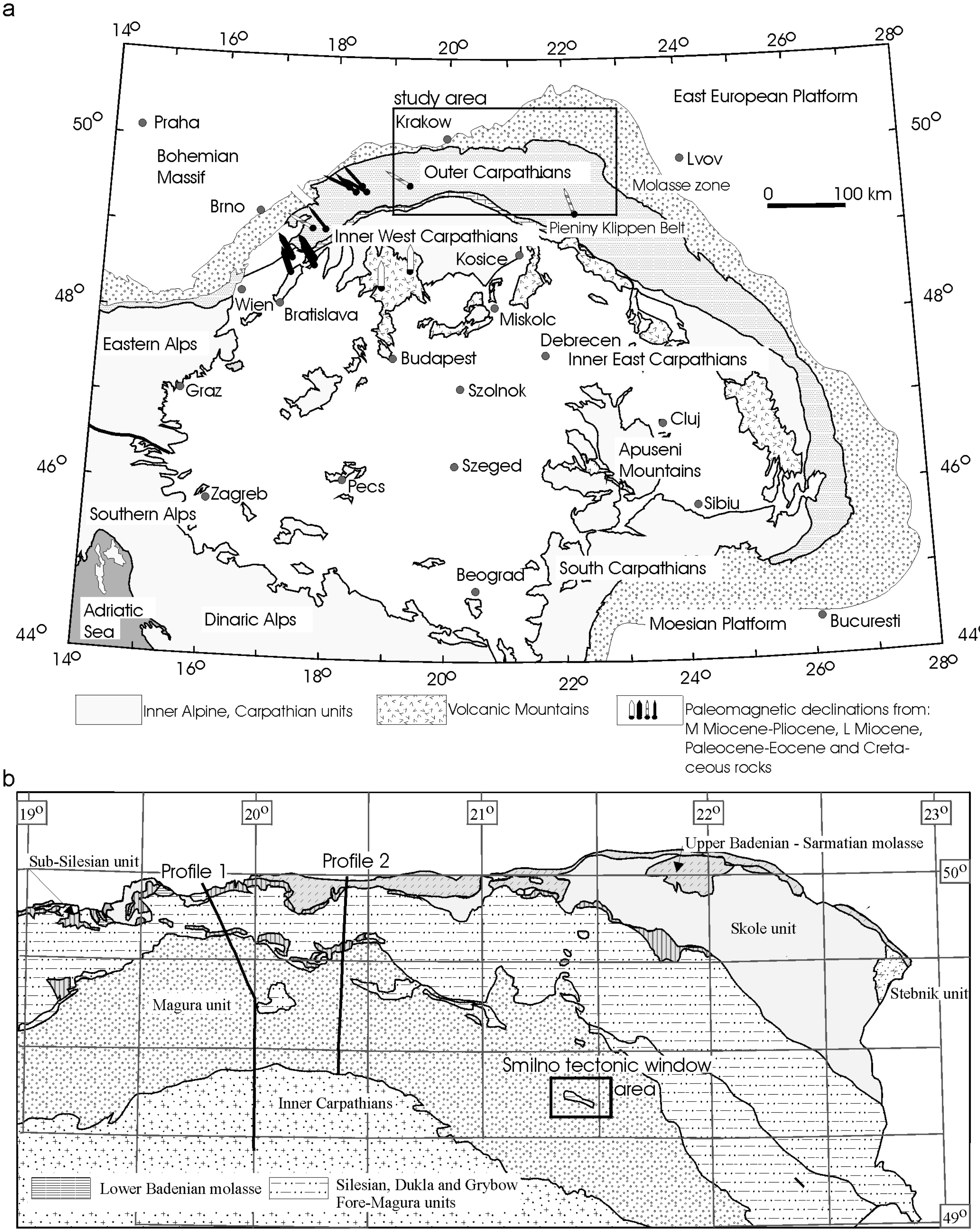


Fig. 1. a —Regional map of the Carpathian Arc showing major tectonic units and selected paleomagnetic data (modified after Royden & Báldi 1988; Săndulescu 1988; Túnyi & Kováč 1991; Krs et al. 1977, 1982, 1991, 1993; Koráb et al. 1981; Pătrascu et al. 1994; Márton & Márton 1989). The rectangle indicates location of figure b). **b** — Regional geological map of the eastern Outer Western Carpathians showing the location of regional balanced cross-sections (Figs. 5, 7) and key area (Fig. 2) (modified from Poprawa & Nemčok 1989).

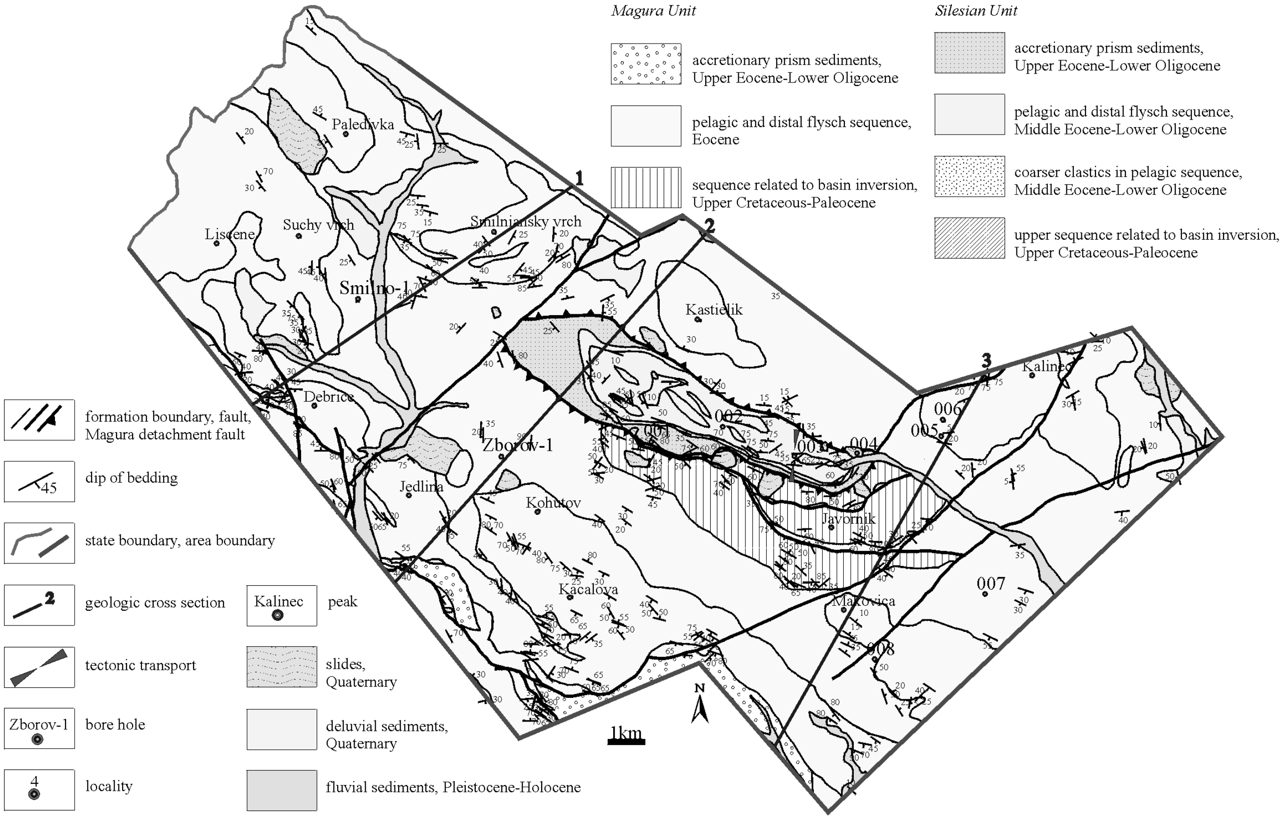


Fig. 2. The geological base map of the Smilno tectonic window used for the pseudo-3D balancing (modified after Nemčok 1990). The area is located in Fig. 1b.

Methods

Regional transects were located to be parallel to the tectonic transport. They cross the whole accretionary wedge, being pinned on the platform. Both profiles and a key area were mapped and checked in the field (Figs. 1, 2), using available 1:50,000 Polish and Slovak Geological Survey maps. The average density of field-check locations is one per each km of the profile. At each location, a GPS location was made, measurements of bedding attitude, sediment transport and structural features were taken, and samples for biostratigraphic analysis were taken. Most of available bore hole data and reflection seismic profiles were taken from the Amoco's confidential data package acquired together with an exploration concession.

In order to avoid difficulties during the 2D balancing, pinching and swelling facies and laterally changing facies were grouped in larger sequences to obtain suitable layered packages (Figs. 3, 4). Marginal facies and series related to potential intra-basinal highs belonging to the Subsilesian Nappe were grouped together with their basinal equivalents belonging to the Silesian Nappe (Fig. 3) in these packages. Sediments belonging to the Grybów, Obidowa-Slopnice and Dukla Units were grouped as in the case of the Silesian Nappe. Because the balancing has shown that they are the southern continuation of the Silesian sediments, they are enclosed as the southern part of resulting layers. This results in the sedimentary succession, which will be called the Silesian Succession in this paper. Some of Magura and Silesian layers, result of grouping, are diachronous, progressively younger toward the foreland and toward the east. Resulting sequences were named according to their age relationship to main evolutionary stages of the region, known from papers documenting rifting (e.g. Michalík & Soták 1990; Michalík 1990, 1991; Książkiewicz 1960, 1962a, b, 1965, 1977; Świdziński 1948; Sikora 1976; Rakús et al. 1990; Roth 1973; Jiříček 1981, 1982; Malkovský 1987; Hanzlíková & Roth 1965), basin inversion (e.g. Malkovský 1979, 1987; Betz et al. 1987; Bachman et al. 1987; Schröder 1987; Suk et al. 1984; Lamarche et al. 1999; Książkiewicz 1954, 1960, 1977; Nemčok 1971), Eocene relative tectonic quiescence (e.g. Książkiewicz 1957, 1960; Świdziński 1948) and the youngest accretionary wedge stage, that is syn-tectonic deposition fed directly by the advancing thrust belt (e.g. Świdziński 1948; Książkiewicz 1957, 1960; Książkiewicz & Leško 1959; Roth 1973; Rakús et al. 1990). Balancing, described later, have proved this division to be correct, as it was in cases of earlier balancing studies (Roure et al. 1993; Roca et al. 1995).

After the described preparation, all data readings were projected into profiles, together with bore hole, shallow reflection seismic and magnetotelluric data. The regional balanced

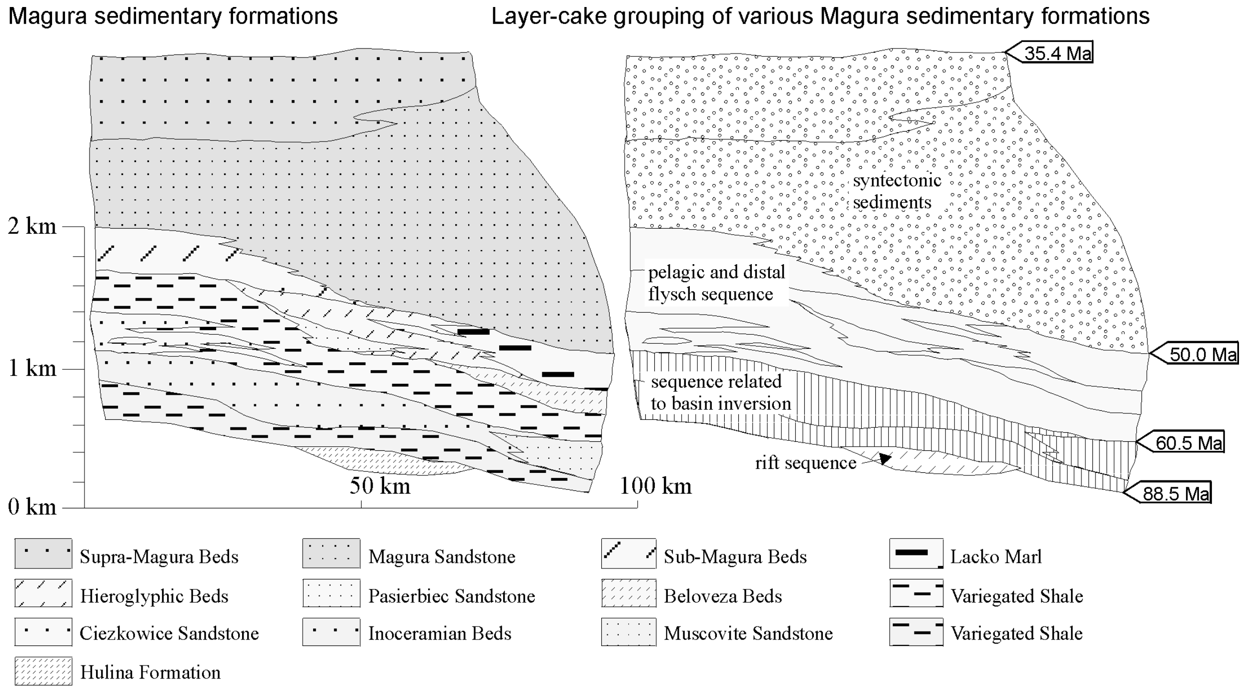


Fig. 3a. Example of grouping of sedimentary formations of the Magura Nappe (modified after Geroch et al. 1967) into the layered-cake sequence required by the balancing. Explanation in text.

cross sections were constructed using the Paradigm Geophysical GeoSec2D software. The pseudo-3D balancing in the Smilno tectonic window was made manually along three short cross sections. Structures interpreted in these cross sections and the surface were projected on to horizontal sections at 0 and −500 m altitude. Sediments from regional balanced cross sections were restored to their original undeformed state. The shortening was calculated from the comparison of the deformed and the undeformed state and the strain rate was determined from the shortening divided by the related time period in seconds.

Basin fill

Silesian Succession

The oldest continuous unit of the Silesian Succession above the basal décollement is the Valanginian–Hauterivian aged rifting-related sequence (Fig. 4). The basal parts of this sequence have a Tithonian age in the area further to the west of our profile. The succession in profile comprises shale, sandstone and limestone with a cumulative average thickness of 420 m. It unconformably overlaps its basement. The paleocurrent data from sandstone indicate a transversal sediment transport, coming from NW-SE striking intra-basinal highs and basin margins (Książkiewicz 1962b). This oldest rifting-related sequence is conformably overlaid by the Barremian-Aptian rift-related sequence comprising mostly shale, which was occasionally deposited below Calcium Compensation Depth (CCD). This sequence is also on average 420 m thick. It is conformably overlaid by the Albian-Cenomanian sediments which are also related to the rifting. They form a thin rhythmic distal flysch, on average 280 m thick. It was frequently deposited below CCD and has a longitudinal sediment transport.

The Turonian sequence related to the inversion of earlier rifts is conformable in some places and unconformable in other places, lying on rift related sequences. It consists of on average 280 m thick flysch sediments (Fig. 4), occasionally deposited below CCD. The Turonian sequence is overlain by a Senonian-Paleocene sequence related to the continuing basin inversion. The contact, in places conformable, in places unconformable, is characterized by a change from thin to thick rhythmic flysch (Książkiewicz 1960, 1962b). The NW-SE striking sediment transport was transversal, from margins and intra-basinal highs.

This basin-inversion related sequence is conformably overlaid by the Eocene distal flysch sequence with several sandstone bodies (Fig. 3). It is 0.45 to 1 km thick (Fig. 4).

The youngest parts of the Silesian Succession are formed by Oligocene syn-tectonic sediments that frequently unconformably overlie the older sequences described above. They consist of rhythmic flysch and sandstones on average 2.1 km thick (Fig. 4). Their sediment transport was transversal, mainly from the south where the ancestral Carpathian orogenic belt existed (see also Książkiewicz 1960, 1962b).

Major competent strata in the Silesian stratigraphic succession (Fig. 4) are the Senonian-Paleocene thick-rhythmic flysch sequence and the Oligocene flysch and sandstone sequence. The secondary competent strata is the Turonian flysch sequence. Incompetent sequences comprise the Valanginian-Hauterivian shale, sandstone and limestone sequence, the Barremian-Aptian shale sequence, the Albian-

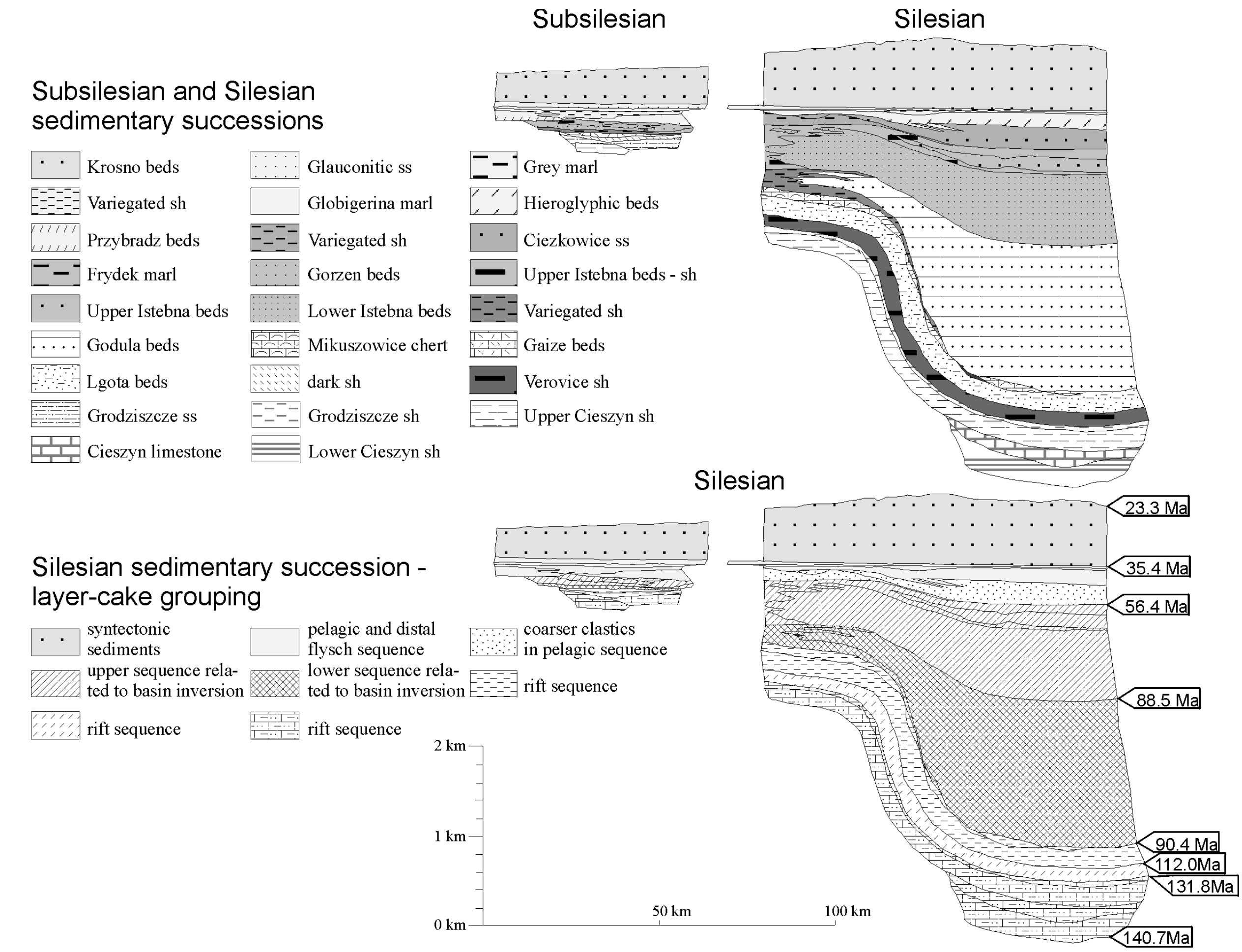


Fig. 3b. Example of grouping of sedimentary formations of the Silesian, Subsilesian Nappes into the layered-cake sequence required by the balancing (modified after Geroch et al. 1967). Explanation in text.

Cenomanian thin-rhythmic flysch sequence and the Eocene pelagic and distal flysch sequence.

Magura Succession

The oldest continuous unit of the Magura Succession above its basal décollement is the Senonian-Danian sequence related to an inversion of the Early Cretaceous rifts (Fig. 4). It comprises shale, sandstone and flysch facies and is on average 700 m thick. Measured sediment transport from the NE is transversal (see also Książkiewicz 1962b). Older sediments are present only locally, and are as old as Albian-Cenomanian (e.g. Mišík et al. 1985; Oszczypko 1992).

The Senonian-Danian sequence is conformably overlaid by the Thanetian-Ypresian pelagic and distal flysch sequence, that also contains several sandstone bodies (Fig. 3). It is on average 500 m thick (Fig. 4) and has a longitudinal paleotransport direction, with the exception of the uppermost portion.

The youngest parts of the Magura Succession are formed by mostly unconformably lying late Ypresian-Priabonian syn-tectonic sediments. They are on average 1.25 km thick (Fig. 4) and comprise a thick rhythmic flysch and sandstone. Their sediment transport was transversal.

The major competent strata in the Magura stratigraphic succession (Fig. 4) are the Senonian-Danian flysch sequence and the Lutetian-Priabonian flysch and sandstone sequence. The incompetent unit is the Thanetian-Ypresian pelagic and distal flysch sequence.

Balanced regional cross section 1

The cross section is pinned on the East European Platform and ends at the contact with the Pieniny Klippen Belt (Fig. 5). Normal faults in the basement and subthrust section below the wedge detachment fault have been interpreted from available reflection seismics (profiles 5-3-73K, 5-1-78K, 5A-1-78K) and magnetotelluric data (e.g. Rylko & Tomas 1995). There was no evidence regarding their inversion found in outcrop during this study. The mining activity in the Wieliczka area has documented evidence of the inversion (Poborski & Jawor 1989) in addition to the field studies of Cretaceous basins in the Bohemian Massif (e.g. Malkovský 1979, 1987; Betz et al. 1987; Bachman et al. 1987; Schröder 1987). Jurassic subthrust sediments cut by these faults do not indicate any distinct thickness changes along our profile (Fig. 5). Faults are overlain by

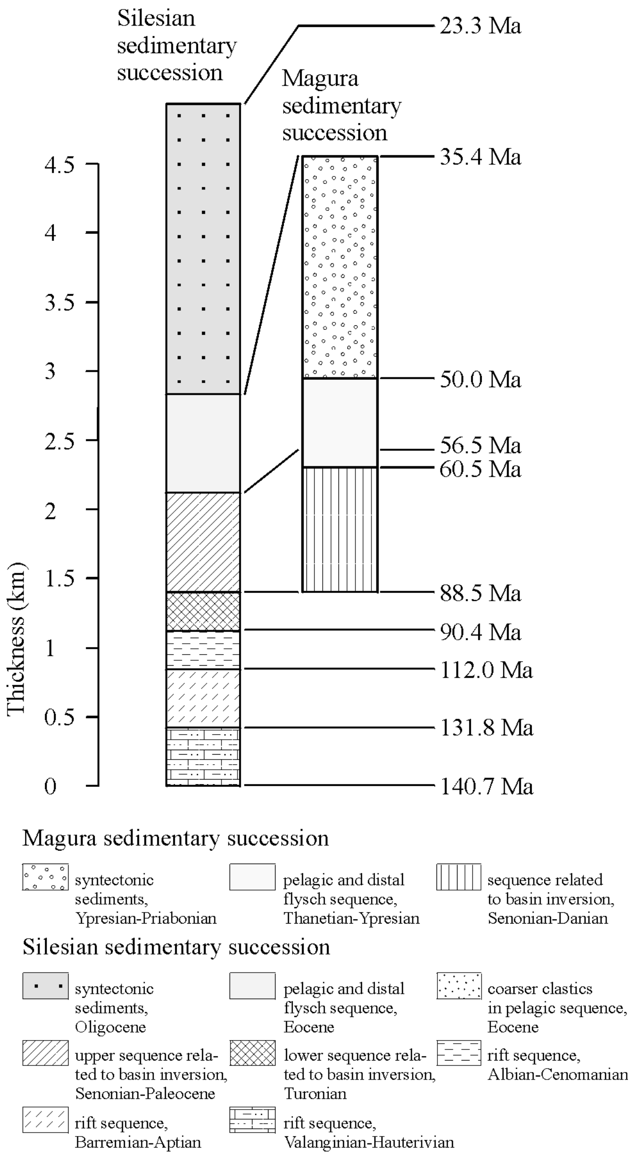


Fig. 4. Simplified lithostratigraphic column showing average thickness values for the Silesian and Magura Basin fill. Note that age limits for diachronous accretionary prism sedimentary sequence is given by onlap and end in the proximal and distal part of the wedge, respectively. The upper age limit of the underlying Eocene sequence is adjusted to this.

undeformed Neogene molassic sediments (Fig. 5). A small proportion of these sediments is accreted into a wedge. Upper Badenian sediments incorporated in the frontal part of the wedge indicate the age of the last thrusting. Behind these Badenian sediments, a wedge is formed by the 3.5–15 km wide Silesian thrust sheets. The first thrust sheet of the wedge in direction from the platform has an unconformable contact between the Oligocene and underlying Senonian-Paleocene sediments (Figs. 5, 6a). Its whole Eocene pelagic and distal flysch sequence is eroded off (Fig. 6a). A similar unconformity is present in the thrust sheet penetrated by the Tokarnia bore hole (Figs. 5, 6b). The restored cross section provides evidence for syndepositional thrusting of this sheet during the Oligocene (Fig. 6b,c). Silesian thrust sheets are mostly deformed by fault-bend folding (sensu Suppe 1983) associated with the post-Oligocene–Late Badenian development of the Carpathian accretionary wedge. The calculated shortening is 75 km, the original basin width is 131 km and the strain rate 8.8×10^{-16} s^{-1}.

The deformation of the Magura Nappe is different, being characterized by fault-propagation folding (sensu Suppe & Medvedeff 1984) (Fig. 5). Sheets are 4.5–12 km wide. Fault tips are usually present in the Eocene pelagic and distal flysch sequence. Unconformably lying and unfolded Middle Sarmatian transgressive facies of the Orava-Nowy Targ Basin (Cieszkowski 1992; Nagy et al. 1996) provides the upper time limit for the wedge deformation. The calculated shortening is 20 km, original basin width 64 km and strain rate 1.1×10^{-15} s^{-1}. An unrealistic thickness of the Thanetian-Ypresian pelagic and distal flysch sequence in the balanced cross section near Chabowka bore hole indicates a capability of balancing to find a mapping error in the survey map. The same is indicated in the restored cross section, which indicates a correct thickness in the neighbouring thrust sheets.

Balancing and restoration does not provide any direct evidence about the pre-Neogene shortening. However, the age of the youngest Magura sediments in its various parts indicate that the initial shortening of the Magura sedimentary succession took part during the late Eocene and Oligocene. The ages of the youngest Magura sediments further indicate a piggyback sequence of thrusting. Numerous observations of deformation bands, which were formed prior to Eocene sediments cementation, in the Krynica and Rača Nappe of the Magura nappe system serve as further evidence for pre-Neogene shortening (e.g. Świerczewska & Tokarski 1998; Tokarski & Świerczewska 1998).

The proximal half of the wedge in the restored cross section indicates a strike-slip component of the movement along thrusts because of the mismatch of restored sheets. The restored Silesian Basin geometry shows that lithofacies of the Subsilesian Unit, mapped separately in available survey maps, are either marginal facies of the Silesian Basin or facies of its intra-basinal highs. This restored geometry also shows that the basin originated in the Lower Cretaceous as a system of NW-SE trending horsts and grabens associated with the Early Cretaceous rifting that acted in the European Platform (e.g. Ziegler 1982; Malkovský 1987; Książkiewicz 1977).

Balanced regional cross section 2

The cross section is pinned on the European Platform and ends at the contact with the Pieniny Klippen Belt (Fig. 7). There have been several normal faults interpreted from the available reflection seismic data below the wedge. Their thrust reactivation is not visible from our cross section. Autochthonous Neogene sediments seal these normal faults and unconformably overlie the Upper Cretaceous and Jurassic sediments. Both the Jurassic and Cretaceous sediments are preserved in a rift, the fill of which was not incorporated into the Outer Carpathian accretionary wedge (Fig. 7).

The upper Badenian molassic sediments are the youngest sediments of the wedge. They are present in its frontal parts, where they unconformably overlie the Senonian-Paleocene

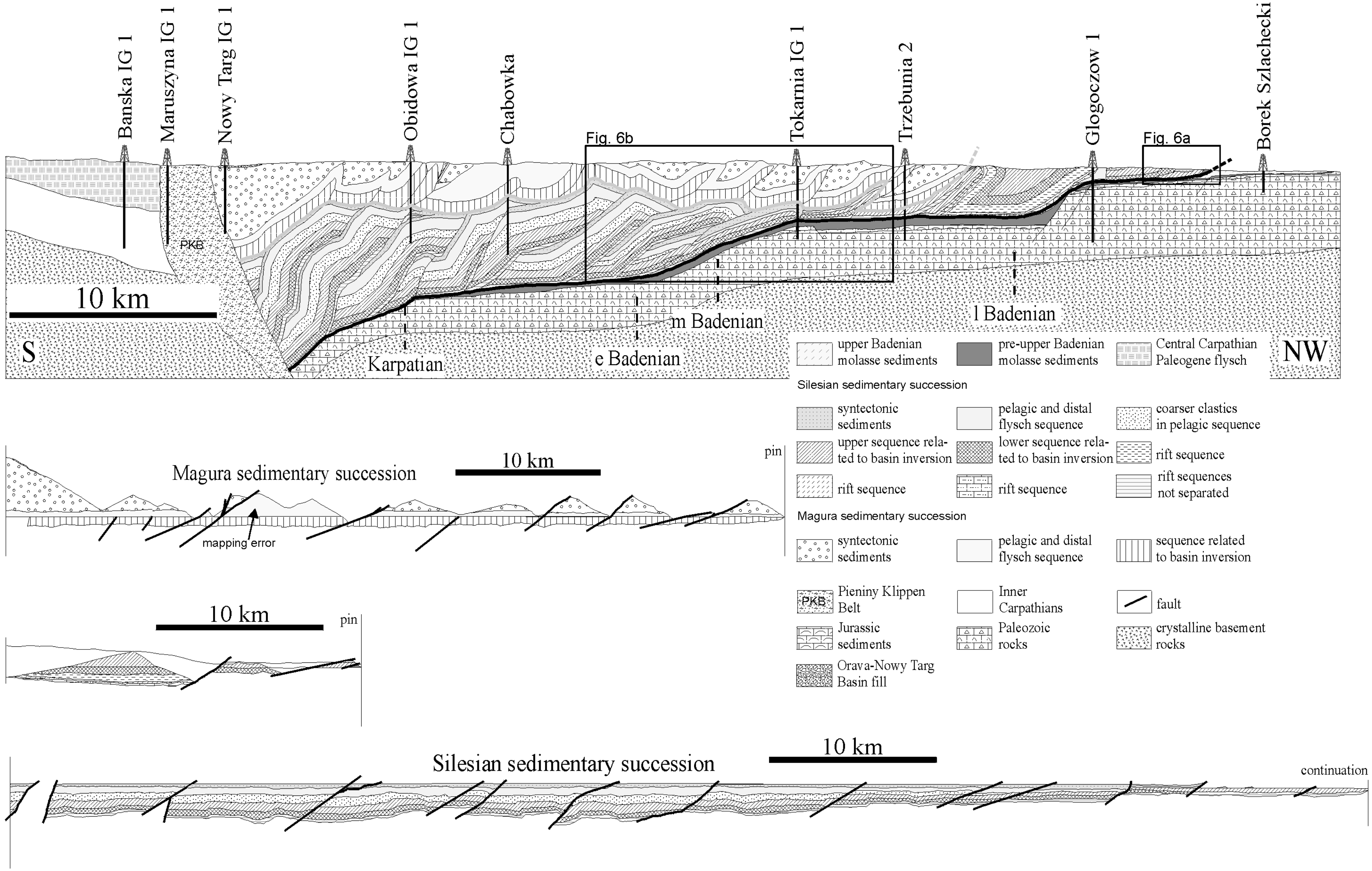


Fig. 5. Regional balanced and restored cross section 1. The location of the profile is shown in Fig. 1b. Thick gray and black lines indicate the detachment faults of the Magura Unit and Outer Carpathian accretionary wedge, respectively. Comment mapping error indicates the area where balancing indicates error, missing facies, in the geological survey map. Further explanation in text.

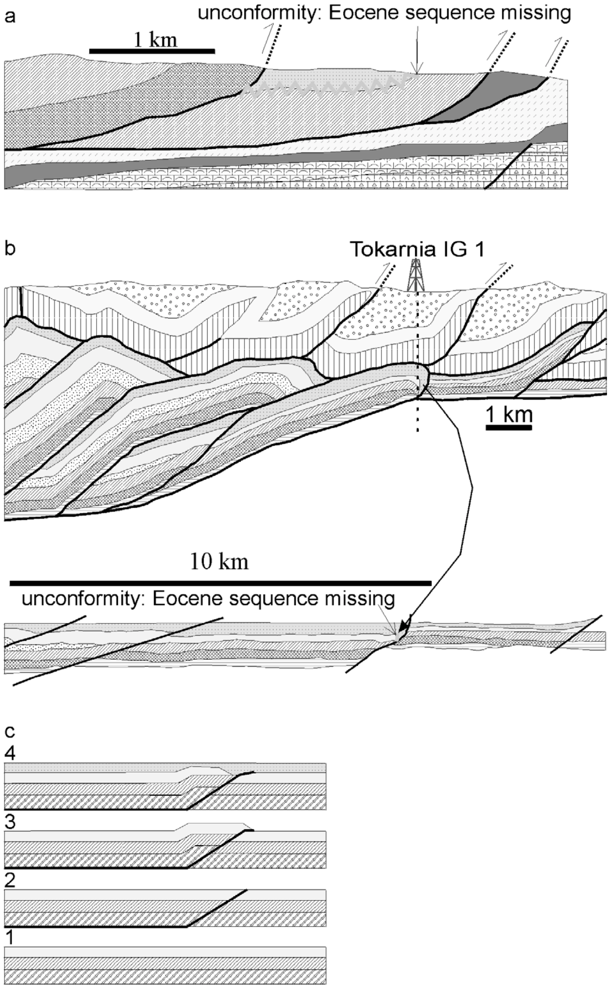


Fig. 6. a — Zoom on the frontal thrust sheet from regional balanced cross section 1 from Fig. 5. Explanation in Fig. 5. **b** — Zoom on the thrust sheet penetrated by the Tokarnia IG 1 bore hole from regional balanced and restored cross section 1 from Fig. 5. Explanation in Fig. 5. **c** — Cartoon illustrating tectonic scenario leading to missing of the Eocene sequence in the anticlinal area of the thrust sheet from Fig. b. Subsequent stages 1–4 indicate a pre-shortening Silesian Valanginian-Eocene sedimentary package (1), its detachment (2), thrust sheet formation (3) and syntectonic erosion in the anticlinal area and contemporaneous and subsequent Oligocene deposition (4).

sequence related to the basin inversion. Missing sediments indicate at least 0.6 km of the Lower Miocene erosional removal of the Silesian sediments before the molasse was deposited (Fig. 7). Molassic sediments are also present in the frontal parts of the wedge as they were accreted to its base (Fig. 7). Frontal thrust sheets of the wedge, comprised of the Silesian Basin fill, are 2.8–6.7 km wide. They were made by the fault-propagation folding. The décollement is located in the middle Badenian shale sequence with gypsum, like in profile 1. Subhorizontal veins with the fibrous gypsum are present close to the décollement (Fig. 8a). Fibers grew vertically in the direction of the minimum compressive stress σ_3 (Fig. 8b), indicating the fluid overpressure along the décollement. The data on the timing of this growth come from the location Bochnia (location 107) where sub-vertical fibers are sigmoidally bent (Fig. 9). Their bending indicates that their growth was coeval with the wedge displacement, which is determined to be toward the northeast direction (Fig. 9c). The other location inside the wedge close to its décollement is at Zglobice (location 106). It shows the shale duplexing, and sandstone boudinage within a shale horizon, E-W striking fold axes and randomly oriented gypsum veins indicating fluid overpressure (Fig. 10). This location is also deformed by a set of normal faults made by N-S extension roughly parallel to the regional compression (Fig. 10). Further back in the accretionary wedge, the Lakta bore holes 1, 3 and 27 allowed the determination of an unconformable contact of the Oligocene sediments with older sequences in the frontal part of the thrust sheet (Figs. 7, 11). The restored image of this thrust sheet (Fig. 11) indicates syndepositional thrusting coeval with and postdating a 1.1 km deep erosion of pre-Oligocene sequences. The rear of this thrust sheet is folded adjacent to the Magura sole thrust in its hanging wall. The immediate contact of the Magura and Silesian Units here is made by the Zegocina sinistral transpressional strike-slip fault zone. It brings a large portion of the oldest sediments to the surface in the form of the 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 normal fault in the autochthonous basement that is oblique to the cross section. 2.1–16.3 km wide buried Silesian thrust sheets form duplexes underneath the Magura thrust (Fig. 7). They are formed by fault-bend folding. The exception from the foreland-vergent duplex system is the Slopnice antiformal stack and the most proximal parts of the wedge. The Slopnice antiformal stack is formed by four sheets of various length, which are cut at the base of the 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). The proximal parts of the wedge have subvertical and overturned thrust faults. The calculated shortening of the Silesian Basin fill is 80 km (58 %). The restored basin width is of 137 km. The calculated horizontal strain rate is 8.9×10^{-16} s^{-1}. These values are similar to those from profile 1.

The shortening of the Magura Basin fill is 42 km (50 %) and results in an original basin width of 83 km and a strain rate of 1.7×10^{-15} s^{-1}. These values are different from those in profile 1 and will be discussed later. The Magura Unit shows evidence of the prevalent fault-bend folding. The Magura thrust sheets in the cross section are 3.6–12.1 km wide. The restored balanced cross section (Fig. 7) shows that the average length of thrust sheets in the frontal half of the unit is comparable with the average length of thrust sheets in the frontal half of the Silesian Unit. The Magura sole thrust is composed of a deformed zone up to 100 m thick. This zone varies in composition according to formations juxtaposed in the footwall and hanging wall. It either contains sandstone blocks of various sizes in a highly deformed shale fault gouge or it is formed by the tectonic breccia in a sandy matrix. The out-of-sequence movement of the Magura thrust is best documented by the

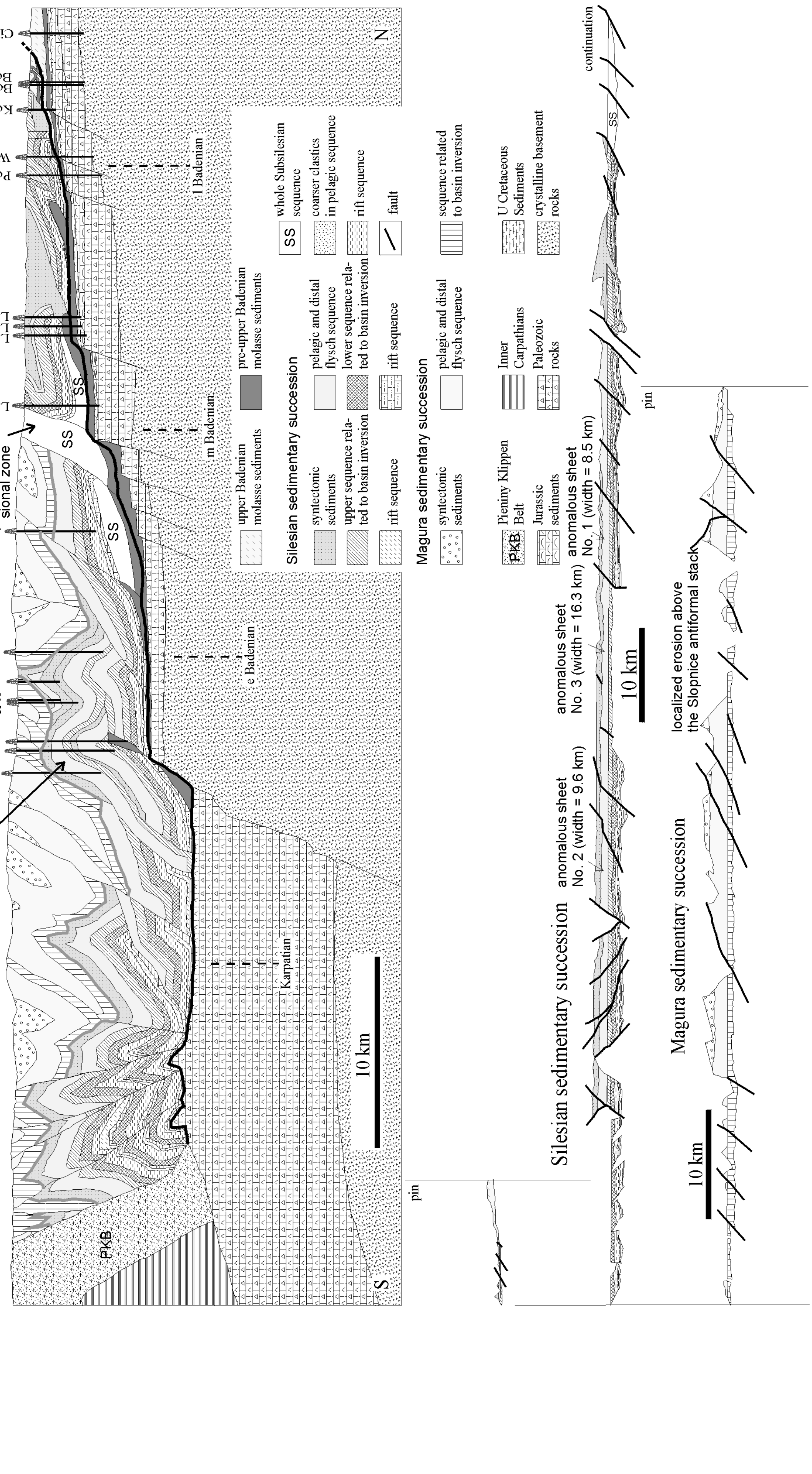


Fig. 7. Regional balanced and restored cross section 2. The location of the profile is shown in Fig. 1b. Thick gray and black lines indicate detachment fault of the Magura Unit and Outer Carpathian accretionary wedge, respectively. Explanation in text.

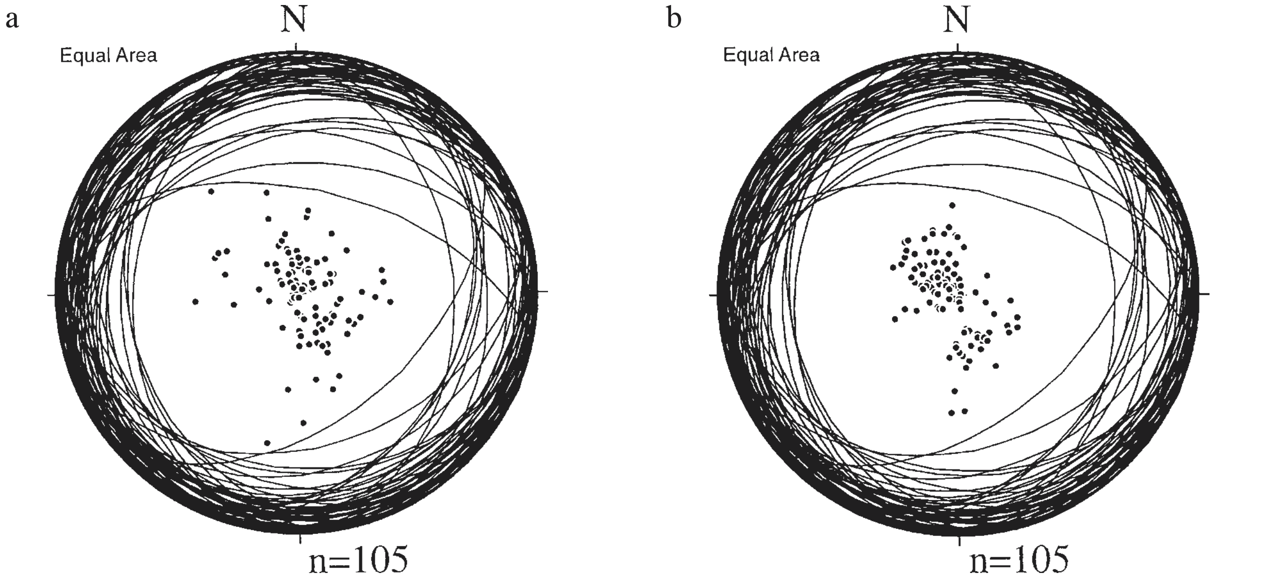


Fig. 8. a — Great circle and pole diagram of subhorizontal extensional veins filled by gypsum at location Bochnia (loc. 107) in a lower hemisphere stereonet. The veins are formed in the middle Badenian shale of the Wieliczka Formation. **b** — Scatter diagram of gypsum fibers vertically grown in veins, which are shown in a.

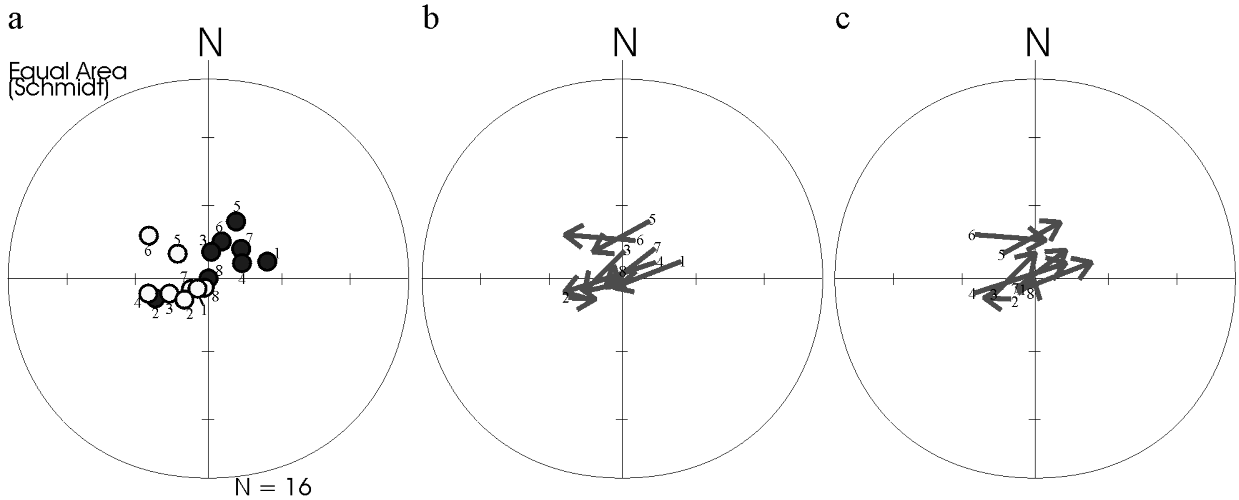


Fig. 9. a — Scatter diagram of gypsum fibers sigmoidally grown in subhorizontal extensional veins at location Bochnia (loc. 107) in a lower hemisphere stereonet. Numbers at points refer to certain fiber, the black dot indicates the orientation of the initial growth and the white dot shows the orientation of the late growth. **b** — Arrows indicate the change in orientation from the early stage of growth to the late stage of growth. **c** —Arrows indicate the accretionary wedge advance trajectories determined from the sigmoidal growth of gypsum fibers.

lower-middle Badenian molasse sediments penetrated by the Zawoja bore hole between the Magura and Silesian Units (Moryc 1989), 55 km to the west of our cross section.

The Smilno tectonic window area

Local cross sections 1, 2 and 3 through the Smilno tectonic window are pinned on the northeastern boundary of the studied area and end at the southwestern boundary (Figs. 2, 12). The structure of the area is made by a Magura Unit thrust over the Silesian duplexes. The Magura basal thrust zone is formed by a brecciated zone several hundred meters thick which is penetrated by the bore holes Smilno-1 and Zborov-1. Both bore holes found hydrocarbon accumulations in this brecciated zone (Leško et al. 1987; Wunder et al. 1991). The average strike of thrusts and fold axes in the area is NW-SE. The Magura Unit is, except thrusts and folds, deformed by two NE-SW striking sinistral strike-slip faults mapped by Nemčok (1990). The western one is located between local cross sections 1 and 3, and the eastern one runs through the local cross section 2. As shown by our balancing, the eastern strike-slip

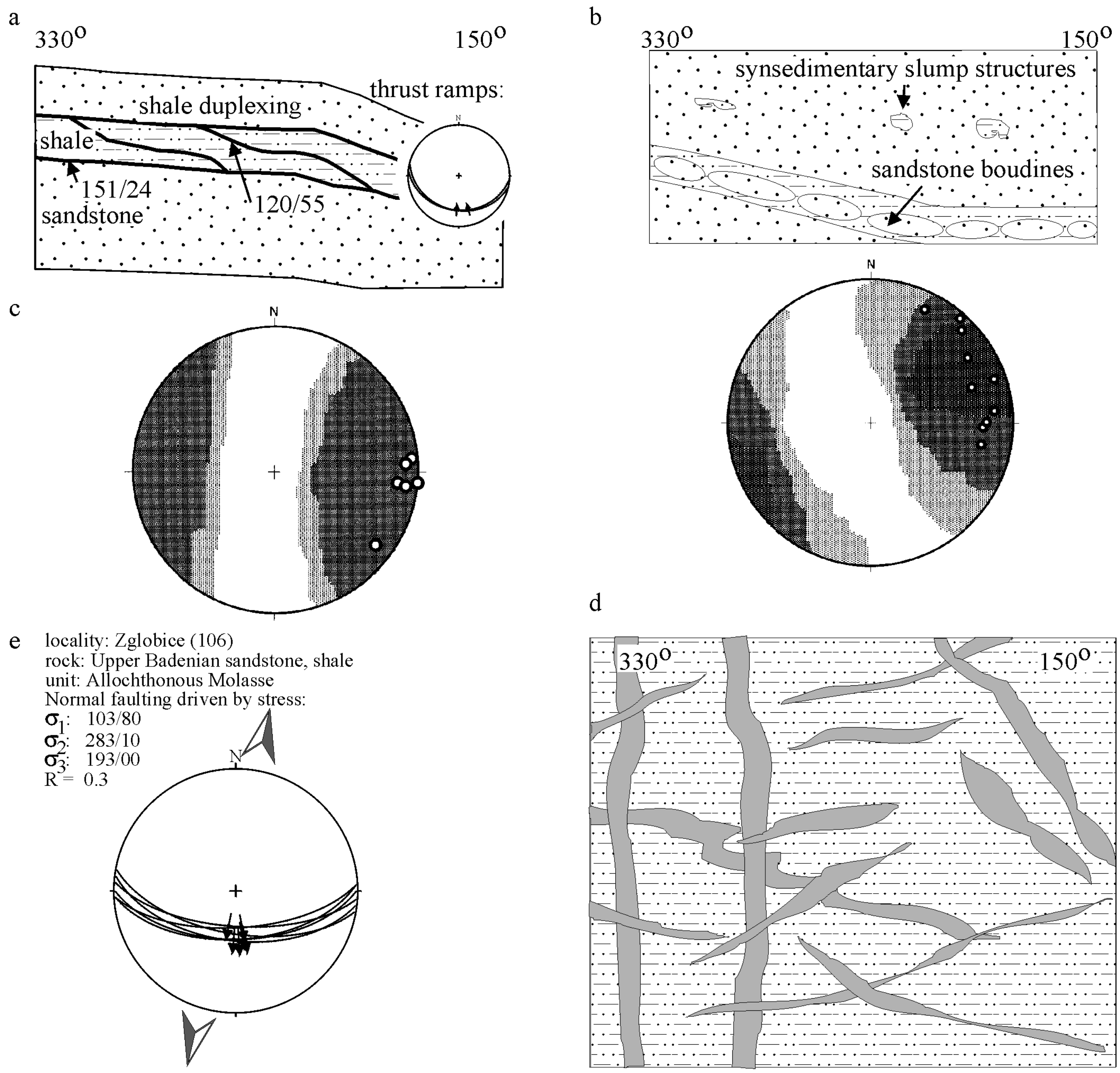


Fig. 10. a — Shale duplexing at the location Zglobice (loc. 106), situated 28 km to the east from regional profile 2, formed by the Upper Badenian Chodenice Formation that comprises sand/sandstone with shale intercalations. **b** — Sandstone boudines inside the shale horizon. Scatter diagram shows the orientation of pinch-out lines. **c** — Scatter diagram of all fold axes from the location. **d** — Detail of randomly oriented extensional veins filled by fibrous gypsum in the shale horizon. **e** — Great circle diagram of normal faults deforming the location with the stress state calculated by the program of Hardcastle & Hills (1991). Arrows show the direction of the extension.

fault ends in reality to the west of the local cross section 2. The area to the NE of its tip is deformed only by the folding and thrusting. The different northeastward displacement of the eastern and western parts of the Magura thrust sheets here are transferred by the sigmoidal bend of folds and thrusts, present to the northeast of this tear fault. The thrust sheets to the east of this transfer zone are located further northeastward than the same sheets present to the west of the bend. However, the shortening along cross sections to the east and west of the transfer zone does not differ significantly. The shortening along the western local cross section 1, calculated for the situation prior to the out-of-sequence thrusting above the uplifted Silesian sheet which is exposed in the window, is about 9.6 km (43.8 %). The shortening along the eastern local cross section 2 is about 13.1 km (51.6 %). The difference is the geometry of structures involved and the mechanism of shortening. The Magura thrust sheets, made of the Cretaceous-Paleocene basin inversion sediments underneath Eocene sediments in the local cross section 1, are much shorter than the Magura thrust sheets comprised of both the Cretaceous-Paleocene basin inversion

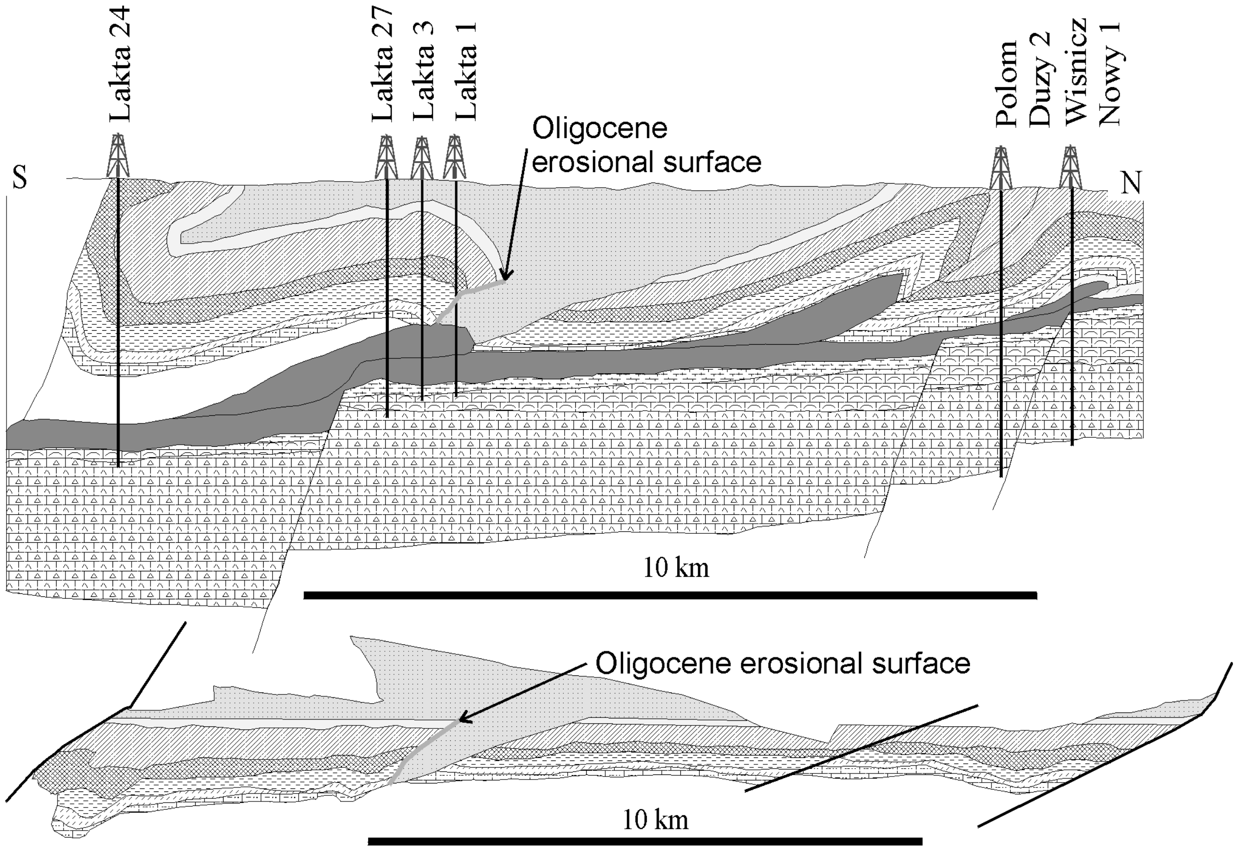


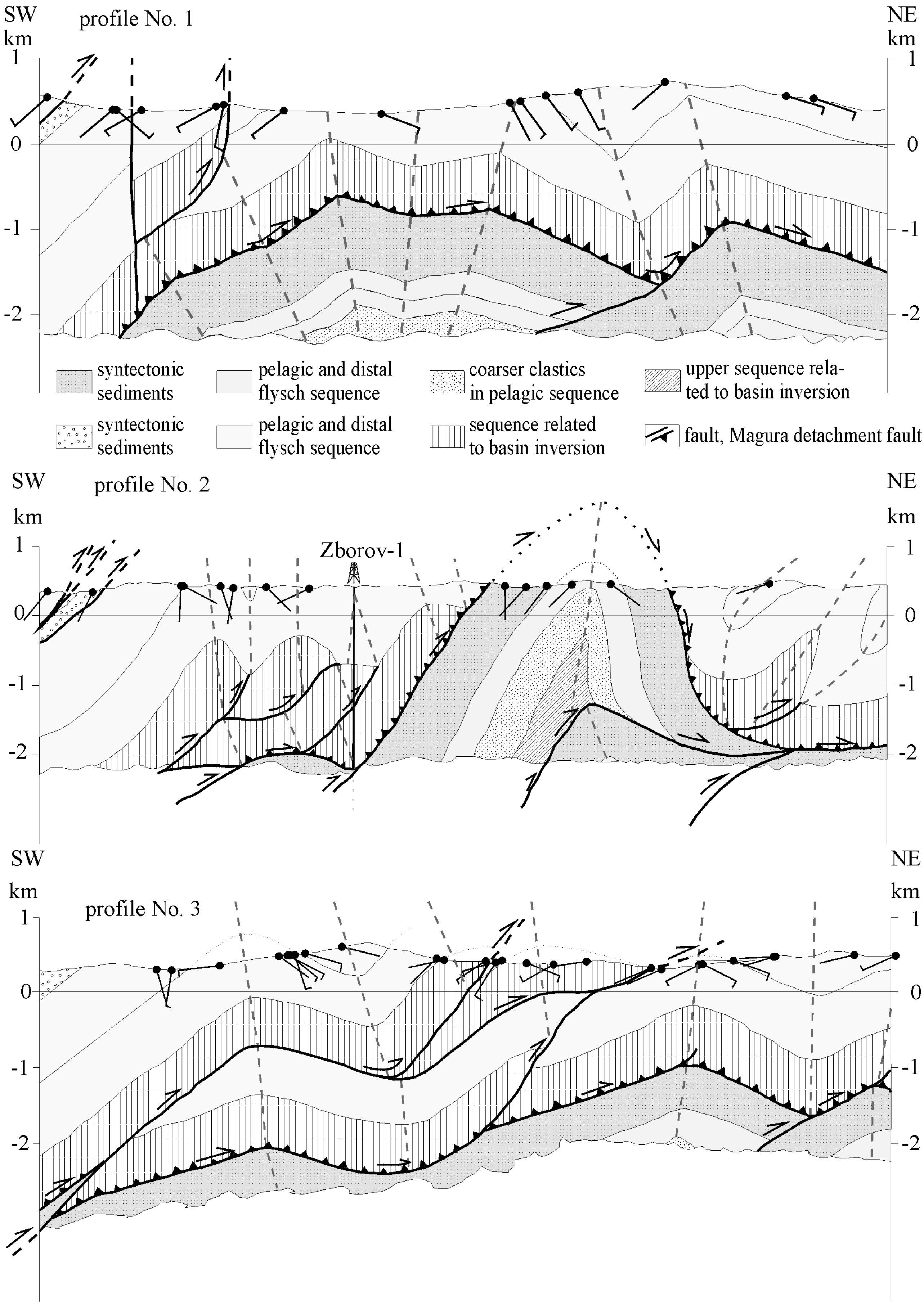
Fig. 11. Zoom on the thrust sheet penetrated by the Lakta bore holes from regional balanced and restored cross section 2 from Fig. 7. Explanation in Fig. 7. Figure shows missing Upper Cretaceous to Eocene sequences in the anticlinal area of the thrust sheet, indicating syntectonic erosion in the anticlinal area predating and coeval with Oligocene deposition.

and Eocene pelagic/distal flysch sediments in the local cross section 2. The former are 1.6–3.4 km wide and the latter 3.4–7.6 km wide. The Magura sheets with the Cretaceous-Paleocene sediments in the local cross section 1 are formed by the fault propagation and fault-bend folding. Their ramps end or tip at the base of the Eocene sequence which is partly detached. The separate movement of the Eocene sequence continued by the out-of-sequence thrusting, that is indicated by the complex geometry of the underlying Cretaceous-Paleocene sheets in the area of the bore hole Zborov-1. It is also indicated by an apparent 4.3 km extension of the Magura Cretaceous/Paleocene sequence above the uplifted Silesian sheet exposed in the window. This Silesian sheet is formed by the fault bend folding and placed at the top of the Smilno antiformal stack. The out-of-sequence build-up of the stack and the separate movement of the detached Eocene Magura sequence from its underlying Cretaceous/Paleocene sheets has created the seeming extension above the stack. The out-of-sequence thrusting above the Smilno antiformal stack is also indicated by the out-of-sequence folding of the syncline located in front of the stack and out-of-the-syncline thrust (sensu McClay 1992) (Fig. 12). The out-of-the-syncline thrust indicates the top-to-northeast displacement along the Magura thrust. The short Magura thrust sheet formed by the Cretaceous/Paleogene sediments in the local cross section 2 also indicates the out-of-sequence thrusting. The remaining sheets in the cross section are formed in the piggy-back thrusting sequence. Unlike sheets in the local cross section 1, all thrust sheets in the local cross section 2 are deformed by the fault-bend folding.

Local cross section 3 shows thrust sheets which are separated by a sinistral strike-slip fault from sheets described along local cross sections 1 and 2. This cross section indicates the smallest shortening in this area. It is about 3.9 km (24 %). The whole cross section shows only two sheets formed by the fault-bend folding. The northern sheet is very wide, roughly 12.6 km, in the profile. The southern thrust sheet is roughly 3.6 km wide in the cross section, but continues towards the SW. It is cut and displaced by a dextral strike-slip fault.

Thrust structures laterally change over short distances (Fig. 2). Two open anticlines with the interlimb angles of

Fig. 12. Local profiles across the Smilno tectonic window area (area located in Fig. 1b). Location of profiles is indicated in Fig. 2. Explanation in text. Small line perpendicular to bedding symbol shows the direction toward older stratigraphy. Note that not all bedding symbols are parallel to balanced solution. They were either ignored after calculation of kink bands, which honored the average value, or ignored after a check of parasitic folding.


SW
km
profile No. 1
NE
km
1
0
-1
-2
syntectonic sediments
pelagic and distal flysch sequence
coarser clastics in pelagic sequence
upper sequence related to basin inversion
syntectonic sediments
pelagic and distal flysch sequence
sequence related to basin inversion
fault, Magura detachment fault
SW
km
profile No. 2
NE
km
Zborov-1
SW
km
profile No. 3
NE
km

125° and 145° in the Magura Unit cut by the local cross section 3 in the surroundings of the Zborov-1 bore hole merge into a single anticline in the tectonic window area. This anticline has an acute interlimb angle. Its axial plane dips to the southwest. This tight anticline becomes open to the east of the window, having an interlimb angle of 130°. Similar lateral variations in the strike, geometry and number of thrust sheets can be observed to the NE and SW of this structure (Fig. 2).

Interpretation and discussion

Palinspastic implications from regional cross sections

The position of the Magura detachment fault in the Upper Cretaceous sediments in regional cross sections is much higher in the stratigraphic column than the position of the Silesian detachment fault, which is cut in the lowermost Lower Cretaceous sediments. It is physically impossible for a propagating detachment fault to jump down in the piggyback succession (see e.g. Mandl 1988). On the contrary, it tends to propagate upwards in the succession (e.g. Boyer & Elliott 1982; Suppe 1985). If the sediments of the Magura Unit were deposited to the south of the Silesian sediments, their décollement should propagate either in the Lower Cretaceous or older sediments, as it is implied from the mentioned physical laws and staircase geometry of the décollements in other orogenic belts (e.g. Rich 1934; Bally et al. 1966). The higher stratigraphic position of the Magura detachment than the Silesian detachment, thus, indicates that the Magura succession was not deposited to the south of the original position of the Silesian Succession as is generally accepted in the literature (e.g. Rakús et al. 1990). Sediments of the Magura and Silesian Nappes have to be originally southwestern and northeastern neighbours, respectively (Fig. 13a,b; Morley 1996). This determination of their positions takes into account the Neogene northeastward oblique thrusting of the Magura Unit (e.g. Nemčok et al. 1998), sinistral transpression in the western part of the Central Carpathian Paleogene Basin (CCPB) and compression in the eastern part of the CCPB (e.g. Nemčok et al. 1996), paleomagnetic declination data (Fig. 1a; Túnyi & Kováč 1991; Krs et al. 1977, 1982, 1991, 1993; Koráb et al. 1981; Pătrascu et al. 1994; Márton & Márton 1989), which indicate larger counterclockwise mass rotation in the western West Carpathian accretionary wedge than in its eastern part. Sediment transport data collected by numerous authors for the Magura sequences (e.g. Książkiewicz 1962b; Rakús et al. 1990; Fig. 13c) also indicate a northern source that was originally interpreted as the cordillera between the Magura and Silesian Basins. Accepting the northeastward transport of the Magura Nappe (Figs. 13a,b) this sediment source could only be the Bohemian Massif, located north of the original position of the Magura depositional area (Fig. 13a). When the Magura Nappe got to its present position by oblique out-of-sequence thrusting, transported paleocurrent indicators in their present position indicate the presence of a non-existing cordillera (Fig. 13c). This mistakingly interpreted cordillera was used earlier (e.g. Rakús et al. 1990 and references therein) as the justification for the separation of the Silesian Basin from the Magura Basin during the Eocene–Oligocene and gives them original pre-thrusted positions as northern and southern neighbours.

Two Silesian thrust sheets in Figs. 5, 6, 7, 11 indicate the initial thrusting in the Silesian depositional area to be as early as the Oligocene. This date of deformation indicates that Silesian sediments underwent initial shortening significantly earlier than when they were overthrust by the Magura Nappe in the Early-Middle Miocene. Magura out-of-sequence overthrust is proved by the presence of the lower-middle Badenian molassic sediments penetrated between the Magura and Silesian Nappes by the Zawoja 1 bore hole (Moryc 1989) located about 30 km to the west of the regional profile 1.

The restored Silesian sedimentary succession (Figs. 5, 7) shows that all ramps and flats of neighbouring thrust sheets match with each other. We observe thrust sheets mapped as belonging to the Grybow, Obidowa-Slopnice and Dukla Units as close neighbours originally. These thrust sheets form the southern continuation of the sedimentary succession present in the Silesian Unit mapped at surface. Their position in the southern marginal parts of this over 130 km wide basin with complex morphology justifies their slightly different facies. Restoration shows that they belong to the same basin (Figs. 5, 7). The restoration of the Subsilesian Unit also shows that it belonged to the same basin. Subsilesian facies are present in the northern margin and intra-basinal highs of the basin when restored in the cross section.

A relatively young, Early-Middle Miocene, out-of-sequence Magura overthrust is required to bring the Magura accretionary wedge together with the ALCAPA unit (sensu Csontos 1995) of the Inner Carpathians from its ancestral Eocene-Oligocene position in the present Eastern Alpine area (Fig. 13a,b). The Magura accretionary wedge thus moved eastward together with the ALCAPA and formed the ancestral accretionary wedge of the Carpathian orogen overriding the subducting oceanic slab attached to the European Platform. This eastward movement of the Outer Carpathian wedge involves, apart from thrusting, a distinct sinistral strike-slip component parallel to the strike of the wedge. It is documented in the southwestern parts of the restored Silesian Basin where the ramps and flats of neighbouring thrust sheets do not match exactly (Figs. 5, 7). They require balancing perpendicular to the cross section, which indicates strike-slip displacement. Indeed, a field check of some of them has shown sinistral strike-slip faulting parallel to the strike of the wedge. Orogen-parallel sinistral strike-slip faulting is also visible easily in the map of Kulka et al. (1985), indicated by NE-SW striking sinistral Riedel shears splaying off the Pieniny Klippen Belt into the wedge. Thrusting and sinistral strike-slip data in support of this same mechanism are known from the wedge areas further to the west (Nemčok et al. 1998). Further structural evidence of partitioned deformation include orogen-perpendicular thrusting and folding (e.g. Roca et al. 1995; Maheľ 1973) and large-scale orogen-parallel sinistral strike-slip faulting (e.g. Royden 1985; Royden et al. 1982; Marko et al. 1991). Larger sinistral rotation of paleodeclination data along the western margin of the ALCAPA and smaller sinistral rotation of these data along the northeastern margin (Túnyi & Kováč 1991; Krs et al. 1977, 1982, 1991, 1993; Koráb et al. 1981; Pătrascu et al.

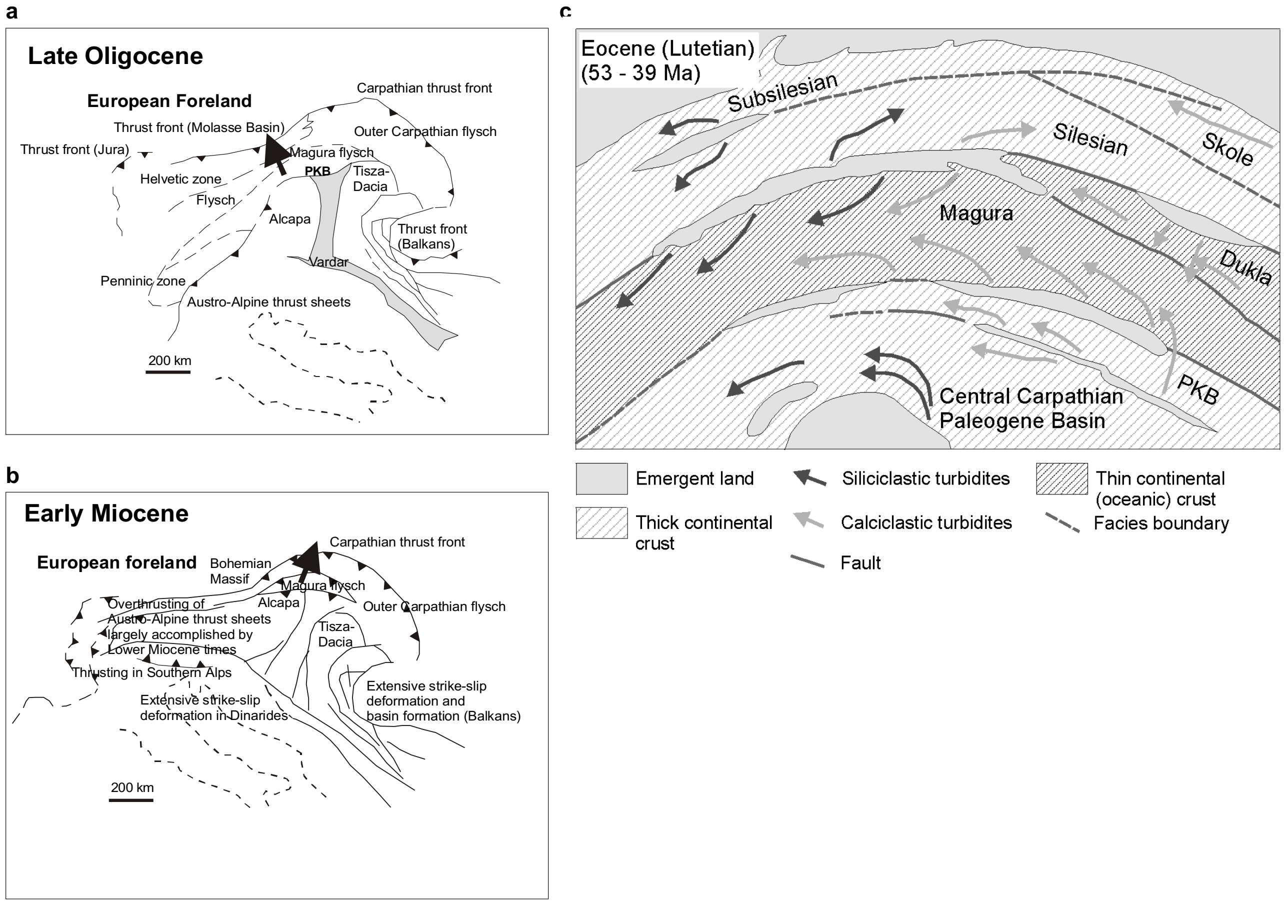


Fig. 13. a — Late Oligocene regional geological setting in the Alpine-Carpathian-Pannonian area (modified after Morley 1996). Thick arrow indicates convergence in the Alpine area. **b** — Early Miocene regional geological setting in the Alpine-Carpathian-Pannonian area (modified after Morley 1996). Thick arrow indicates convergence in the Carpathian area. Note that the advance of the Magura Unit to its new position requires its oblique advance. It is in accordance with predominant sinistral strike-slip faulting along its western part and predominant thrusting in its eastern part (e.g. Nemčok et al. 1998), larger paleomagnetically-indicated counterclockwise mass rotations in its western part and smaller counterclockwise mass rotations in its eastern part (e.g. Túnyi & Kováč 1991; Krs et al. 1977, 1982, 1991, 1993; Koráb et al. 1981; Pătrascu et al. 1994; Márton & Márton 1989). **c** — Sediment transport data for the Lutetian (modified from Rakús et al. 1990).

1994; Márton & Márton 1989; Fig. 1a) also support this mechanism. Other evidence from the Inner Carpathians about the eastward movement of the ALCAPA unit is discussed in detail by Csontos et al. (1992).

Thus the only plausible interpretation is to place the original Eocene position of the Magura sediments to the southwest of the Silesian sediments, in the area in front of the ancestral Eastern Alps-Western Carpathians. The Magura Unit then becomes a part of the Middle Eocene-Oligocene accretionary wedge of the Eastern Alpine-Carpathian orogen, which is known to be a coherent structural domain during this time (Royden & Báldi 1988). In such a case the Magura Unit can be correlated with the Rhenodanubian flysch of the Eastern Alps, as suggested earlier (e.g. Laubscher & Bernoulli 1982; Tollmann 1989). This further implies that the deposition of the Magura sedimentary succession happened from the Early Cretaceous to the Eocene, as based on analogy with the deposition of the Rhenodanubian flysch (e.g. Faupl 1975; Prey 1980). This would be in accordance with documented rare occurrences of the Albian-Santonian sediments in the Magura Unit (e.g. Mišík et al. 1985; Oszczypko 1992). This timing of the deposition is in accordance with the situation in the Silesian part of the basin, where the sedimentation started from the Lower Cretaceous (e.g. Geroch et al. 1967) and lasted longer than in the sedimentary succession, which became the Magura Unit (Fig. 4). The correlation of the Magura and Rhenodanubian flysch further implies that the Magura sediments underwent their initial shortening in the middle–late Eocene due to collision in their ancestral position, as based on the Rhenodanubian flysch data (e.g. Decker et al. 1993 and references therein). This is in accordance with our data and available data (Eliáš et al. 1990; Stráník et al. 1993), which show that the youngest Magura sediments in its western part are of middle–upper Eocene age. The age trend of youngest sediments along our cross section, from the middle Eocene sediments in the south to the upper Eocene sediments in the north, indicates a piggyback sequence of thrusting. A part of the Rhenodanubian-Magura sediments later became the northeastern part of the wedge, known as the already mentioned ALCAPA block (sensu Csontos 1995), which extruded eastward during the Miocene (e.g. Ratschbacher et al. 1991). The exact timing of the extrusion and the detailed geometry of the wedge is not firmly established. The extrusion of the Central Eastern Alps has been put into the broad late Oligocene–Miocene (30–14 Ma) interval (Ratschbacher et al. 1991). Since only the southeastern part of the shortened Rhenodanubian-Magura sediments became part of the extruding wedge together with the Central Eastern Alps, this would require erosion of the upper (southern) sheets, which had to be detached at the Lower Cretaceous level. Such a Lower Cretaceous stratigraphic level of the décollement is reported from the uppermost Rhenodanubian duplexes (Decker et al. 1993). A 3–4 km thick missing section of Magura burial, which would comprise missing thrust sheets detached at Lower Cretaceous level, might be indicated by abnormaly high outcrop vitrinite reflectance data from the Moravian part of the Magura Unit (Franců 1997, pers. commun.). The younger age of the extrusion than in the Central Eastern Alps is indicated in the Rhenodanubian flysch. The structural data (Decker et al. 1993) indicate a Miocene age. The West Carpathian data also indicate the younger timing of the ALCAPA block movement. They include paleomagnetic evidence for the Eggenburgian-Karpatian progressively decreasing counterclockwise mass rotation (Túnyi & Kováč 1991) and the Karpatian pull-apart opening of the Vienna Basin (Royden 1985), both along the northwestern boundary of the ALCAPA block, and an existence of lower-middle Badenian molassic sediments between the Magura and Silesian Units (Moryc 1989) along the northeastern boundary of the ALCAPA block.

The earlier collisional shortening of the sediments of the future Magura Unit explains why the calculated strain rate for the Magura Unit is higher than the strain rate calculated from the Silesian Unit sediments, which were shortened only due to subduction. Other evidence for large out-of-sequence movements of the Magura thrust is the Silesian thrust sheet from Fig. 6b. It was thrust during the deposition of Oligocene sediments (Fig. 6c). It was formed before the Miocene Magura Unit thrust over the Silesian Unit, during the time when deposition had finished in most parts of the ancestral Magura depositional area and the Magura Unit was involved in the Oligocene collision in its ancestral Alpine position to the southwest of the Silesian sediments. Deposition continued only in few remnant depressions (e.g. Nemčok 1961; Cieszkowski & Olszewska 1986).

Deformation of the wedge

Both regional cross sections (Figs. 5, 7) indicate that the West Carpathian accretionary wedge was shortened in general piggy-back mode. However, the buttressing effect of preexisting normal faults with greater throw caused two out-of-sequence thrusts in the regional profile 1, one to the south of the Obidowa IG 1 and the other near the Trzebunia 2 bore hole (Fig. 5) and several more along the regional profile 2, one called the Zegocina transpressional zone and the remaining ones in the rear third of the wedge (Fig. 7). The sinistral Zegocina transpressional zone is formed in the Silesian Unit in front of the Magura thrust by the displacement of a wedge that encountered an oblique buttress in the basement. Deformation brings the oldest wedge sediments to the surface in the form of small duplexes.

Early normal faults are related to the Lower Cretaceous rifting (e.g. Roure et al. 1993). None of them in our profiles indicates their inversion, observed in adjacent areas (e.g. Książkiewicz 1977; Malkovský 1979, 1987; Schröder 1987). However, an out-of-sequence thrusting caused by the inversion of basement structures is known from the Wieliczka area (Poborski & Jawor 1989), to the east of the frontal parts of our regional profile 1. Neogene molasse sediments overlie normal faults with smaller throw to the extent that they do not form any buttresses (Fig. 7).

Normal fault buttresses acted as frictional force concentrators during the shortening, reducing the critical width of the thrust sheet behind them, as observed in physical or numeric models (Nieuwland 1997, pers. commun.; Mandl 1988).

Areas with low basal shear stress had wide thrust sheets. Such Silesian sheets are present in the regional cross section 2 (Fig. 7). They are 8.5–16.3 km wide, while the average width is about 6 km. The first of them climbed over the buttress, which was far to the south from the present position of the Slopnice stack, if we restore it to its original position. Both the abruptly increased frictional force along its toe fault and the weight of the toe caused the out-of-sequence thrusting of the sheet No. 3 behind it. This one, apparently with very low basal shear stress, is by far the widest sheet. It has no rifting-related sediments and is much thinner than surrounding sheets. The reduced thickness should, however, result in a shorter length of sheets than in the case of surrounding thicker sheets (see e.g. Boyer 1995). Under these circumstances its length is even more anomalous.

Accreted in the wedge, the above mentioned sheets advanced toward the foreland until they encountered a normal fault with a stratigraphic omission of 2.3 km in the Slopnice area. Its increased friction caused the antiformal stack development. The out-of-sequence thrusting here is indicated by Neogene molasse sediments between sheets penetrated by the Lesniowka 2 well (Fig. 7). The increased friction in the antiformal stack drove the out-of-sequence movement of the third sheet behind it. This sheet was cut, together with its Magura roof thrust, forming a breaching thrust (sensu McClay 1992). Any larger out-of-sequence movement of this sheet was cancelled by the localized erosion above the antiformal stack (Fig. 7), which reduced the weight there and drove a new out-of-sequence thrust. Similar complex shortening/erosion interplay can be determined at the Smilno antiformal stack (Figs. 2, 12).

The thrust sheet width was also influenced by sediment thickness. It is visible in the restored frontal part of the Silesian sedimentary succession (Fig. 7) how the thickness and width of the first six thrust sheets progressively increase from north to south. This relationship is frequently modified by complex basin floor morphology. The Silesian detachment fault propagated inside the Lower Cretaceous shale and carbonate formations. Frontal Silesian sheets were later thrust above autochthonous Neogene sediments, where the décollement indicates a very low friction. This is shown by a minor accretion of Neogene sediments to the wedge (Fig. 7). It is also indicated by fact that each rear sheet overrides only the rear portion of its frontal neighbour (Fig. 7), as observed in the low-friction sand-box models (Nieuwland 1997, pers. commun.). As shown by subhorizontal gypsum veins with vertical fibers (Fig. 8a,b), the low friction can be attributed to cycles of the overpressure along the décollement. The syntectonic fiber growth is documented by their sigmoidal bending (Fig. 9a,b) coeval with advance of the accretionary wedge (Fig. 9c). The overpressure developed in compartments, which developed along the basal thrust when fluids were periodically trapped. Each overpressure cycle triggered a new episode of hydraulic fracturing and fluids moved along the décollement further toward the foreland, as shown by recent ring-shear experiments and deep sea drilling data (e.g. Knipe 1993; Brown et al. 1994). Parts of the basal thrust between overpressured compartments behaved as asperities, supporting the wedge against its collapse, as proved by Lay et al. (1982). Local extensional collapses in the wedge in the area of grown morphology and reduced basal friction are indicated by normal faulting (Fig. 10).

Low friction is also indicated along the Magura thrust, which mostly juxtaposes rather thicker rhythmic, competent flysch sequences of the Magura and Silesian Units. The overlying Magura sheets have the same lengths as Silesian sheets in the wedge front (Figs. 5, 7), where the existence of the fluid overpressure is proved by vein data (Figs. 8, 9, 10). The character of the Magura thrust is, however, different from the character of the basal thrust in the frontal parts of the wedge. It is formed by the thick brecciated zone, which varies in thickness up to several hundred meters. The proven occurrence of hydrocarbons in the breccia (Leško et al. 1987; Wunder et al. 1991) can explain the reduced friction by the potential for an increased fluid pressure. The reduced friction thus could be caused by migrating hydrocarbons that preserved the high porosity of the breccia until now.

The initial basal friction underneath the Magura Unit, before it was thrust over Silesian sheets, was not low. This is indicated by its deformation by fault-bend folding in its frontal parts (Fig. 7), similar to medium-friction sandbox models (Nieuwland 1997, pers. commun.). The underlying Silesian thrust sheets indicate variations in the basal friction from place to place. The fault-bend folding, as observed in sandbox models (Nieuwland 1997, pers. commun.), indicates a moderate friction and the antiformal stack indicates a high friction.

The erosion of the wedge varies from place to place. The total Neogene-Quaternary erosion, visible mainly in the restored cross section through the Magura sedimentary succession, progressively increases towards the hinterland, reaching a maximum value of 2.7 km (Fig. 7). The locally accelerated erosion modifies this general trend, for example up to 2.2 km above the Slopnice antiformal stack (Fig. 7).

The Smilno area shows that thrust and fold geometries change laterally over short distances (Figs. 2, 12). These changes are accommodated by the shorter strike-slip fault or sigmoidal structure and longer strike-slip fault in the case of smaller and larger difference.

Conclusions

1) The calculated shortening of the Silesian sedimentary succession is 75–80 km, the original basin width is 131–137 km and strain rate $8.8–8.9\times10^{-16}$ s^{-1}. The calculated shortening of the Magura sedimentary succession is 20–42 km, the original basin width 64–83 km and strain rate $1.1–1.7\times10^{-15}$ s^{-1}.

2) Both successions were northeastern and southwestern neighbours, the Magura succession located to the south of the Bohemian Massif and the Silesian succession to the east of it. The Magura Unit was shortened first during the Eocene–Oligocene and then emplaced as a nappe by a relatively young, Early–Middle Miocene, oblique out-of-sequence thrusting. This thrusting comprised a distinct strike-parallel sinistral strike-slip component.

3) The shortening of the Silesian sedimentary succession started already in the Oligocene, before the emplacement of the Magura Nappe. The Grybow, Obidowa-Slopnice and Dukla Units comprise facies which were deposited in the southern parts of the Silesian depositional area. Facies present in the Subsilesian Unit were deposited in intra-basinal highs and the northern margin of the same basin. The major deformation of the Silesian sedimentary succession is coeval with the emplacement of the Magura Nappe.

4) The general thrusting mode of the Outer Carpathian wedge is piggy-back. Out of-sequence thrusts were caused by the basement inversion that influenced the sequence of thrusting above them, the buttressing effect of the pre-existing structures, which locally increased basal friction and thus influenced the thrusting behind them, and the interaction of basal friction and localized erosion. A basement step perpendicular to the tectonic transport of the overlying wedge caused the development of an antiformal stack, while an oblique step caused the sinistral transpression.

5) The frontal parts of the basal thrust of the West Carpathian accretionary wedge experienced periods of the overpressure caused by migrating fluids. The Magura thrust also indicates the decreased basal friction, caused by increased fluid pressure, most probably due to migrating hydrocarbons.

6) The West Carpathian accretionary wedge indicates lateral changes in the structural style over short distances.

Acknowledgements: The work has been carried out with the financial support of the Amoco Prod. Co., Houston, and the follow up work was supported by the Alexander von Humboldt Fund and Slovak Geol. Survey Project MZP-513/96. MN wishes to thank Piotr Krzywiec, Nestor Oszczypko, Marek Cieszkowski, Zbygniew Paul, Antoni Tokarski, Jim R. Plomer, Andrzej Ślączka, Gary A. Taylor and Dick Nieuwland for help and valuable discussion. The authors wish to thank JN who cannot see the final result.

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