Large-scale tectono-sedimentary Middle Miocene history of the central and eastern Polish Carpathian Foredeep Basin — results of seismic data interpretation

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Abstract. Foredeep basins can be characterised by tectonic deformations related to two different tectonic regimes. Progressive propagation of the orogenic belt towards the foreland results in transmission of compressional stresses into the foredeep domain and in development of frontal zone of thrust-related folds within the foredeep sediments. These deformations often develop as growth folds. Another group of deformations is related to flexural extension of the top of the foreland plate. Development of these extensional deformations might be to some degree influenced by the pre-existing, older basement faults. Interpretation of dense coverage of seismic profiles from the central and eastern part of the Polish Carpathian Foredeep Basin (PCFB) provided well-documented examples of both compressional and extensional tectonic deformations. Also, large-scale depositonal pattern has been documented. It was concluded that central and eastern parts of the PCFB significantly differed in their Miocene tectonic and depositional history. In the central part of this basin growth fault-propagation folds and associated syntectonic fan deltas developed. Within the Mesozoic basement only minor normal faulting was detected and interpreted as reactivation of older normal faults. Large palaeovalleys mapped within the Mesozoic basement and filled by foredeep sediments were interpreted as erosional, tectonically-controlled features that developed after Cretaceous/Palaeogene inversion of the Polish Trough. In this part of the PCFB sediments were supplied from the south, from the Carpathians. In the eastern part of the PCFB a system of large normal faults exists with total throw in the range of 2–2.5 km. Their origin has been atributed to Miocene, flexure-induced reactivation of inherited Mesozoic rifting-related faults. Within the hangingwall of this system of normal faults several inverted faults were identified. It is proposed that their development was related to the combined effect of compressional stresses transferred from the Carpathian collision zone and extension due to reactivation of older large-scale faults. It was also concluded that during deposition of the foredeep sediments differential compaction-related faulting played important role. Upper Badenian–Sarmatian post-evaporitic sediments (Krakowieckie shales) are gently onlapping Middle Badenian evaporites towards the NW, and no progradational features have been identified. This seismostratigraphic configuration was interpreted as a result of gradual development of open marine environment after the Middle Badenian salinity crisis and re-establishment of the marine connections with the eastern Paratethys.

Introduction

Foredeep basins belong to the broad group of sedimentary basins that develop due to continental collision, formation of the thrust belts and progressive flexure of the continental lithospheric plate (Allen & Allen, 1990). They can be divided into two classes on the basis of their relation to the thrust belt. Retro-arc foredeep basins are located on the inner (in relation to the main thrusting trajectories) side of the thrust belt, and peripheral foredeep basins develop in front of the orogenic belt and directly overlie foreland (lower) plate.

Main features of the geological history of the foredeep basins include displacement of the zone of maximum subsidence towards the foreland of the migrating thrust belt, uplift, migration and erosion of the flexural forebulge, and consecutive onlapping of the foreland plate by foredeep sediments. Typical tectonic deformations encountered in foredeep basins are related to both compressional and tensional regimes. Due to foreland-directed propagation of the thrust belt older foredeep sediments become progressively involved in the thrust-related folding and usually form a strip of thrust and folded sediments in front of the main orogenic wedge. For example, a large part of the sedimentary infill of the Alpine foredeep basin, i.e. Molasse basin, was progressively incorporated in the Alpine orogenic wedge (Gorin et al., 1993; Pfiffner, 1986). Sedimentary and tectonic history of these basins often provides crucial information for dating of consecutive stages of deformation of the thrust belts. For example, synorogenic sediments, such as conglomerates or fan-deltas developed in front of active fault-related growing folds, provide information on the onset and particular stages of deformation within the orogenic belt (Blair & Bilodeau, 1988; Burbank et al., 1988; DeCelles et al., 1987, 1991; Medwedeff, 1989, 1992; Pivnik, 1990; Suppe et al., 1992), undeformed piggy-back foredeep sediments post-date last stages of thrusting movements (Ricci Lucchi 1986), also local and regional unconformities developed within the foredeep sedimentary infill are related to the tectonic movements within the thrust belt (Crampton & Allen, 1995; Sinclair et al., 1991). Tensional, generally thrust belt-parallel faults developed primarily within the foreland plate and related to its flexure form another group of typical upper crustal brittle deformations, often encountered in the foredeep basins (Bradley & Kidd, 1991; Harding & Tuminas, 1989). Slip component of these sets of faults is usually relatively small, as can be seen for example in the German Molasse basin (Bachmann & Mueller, 1992). Recently published studies on development of the Swiss Molasse basin stressed importance of the control exerted by reactivated foreland plate structures (inherited Mesozoic rifting-related faults) on the deposition of Tertiary foredeep sediments (Lihou & Allen, 1996). In general, however, relationship between inherited older foreland plate structures and depositional history of foredeep basin received much less attention.

Carpathian Foredeep basin, its development and regional setting

The Outer Carpathian thrust-and-fold belt consists of several imbricate thrust sheets or nappes built up of Cretaceous to Palaeogene flysch sediments and Miocene foredeep deposits, and is bounded to the north and east by the undeformed, youngest (Badenian to Sarmatian) flexure-related

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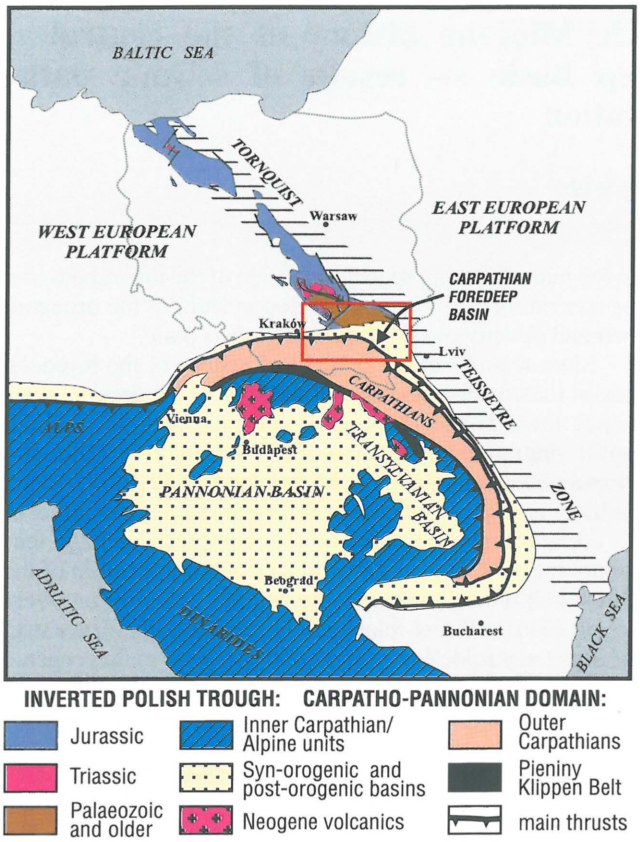

← **Fig. 1.** Location of the Polish Carpathian Foredeep Basin at the background of the general geological map of the central and eastern Europe. Note relationship between Polish segment of the Carpathians and large-scale tectonic grain of the foreland European plate: T-T zone and inverted Polish Trough (outlined by subcrops of Jurassic, Triassic and Palaeozoic rocks)

foredeep basin extending as far to the north as the Holy Cross Mnts (Fig. 1). Neogene development of the Carpathians was related to convergence of the European and African plates. This large-scale geodynamic process resulted in collision of the North Pannonia and Tisza units of the Intra-Carpathian domain with the European foreland plate, and was related to lateral eastward escape of North Pannonia unit from Alpine collision zone and slab-pull of the European plate due to subduction of oceanic or thinned continental crust (Csontos et al., 1992; Krzywiec & Jochym, 1996, 1997; Royden 1988, 1993; Royden & Baldi, 1988; Royden & Burchfiel, 1989; Royden & Karner, 1984; Sandulescu, 1988). This collision zone and related subduction of the foreland plate was imaged in details on the deep seismic reflection profiles (Tomek & Hall, 1993), and also suggested by gravity modelling studies (Bojdys & Lemberger, 1986; Lillie et al., 1994). The Polish Carpathian Foredeep Basin (PCFB) is a typical peripheral foredeep basin filled with synorogenic molasse sediments

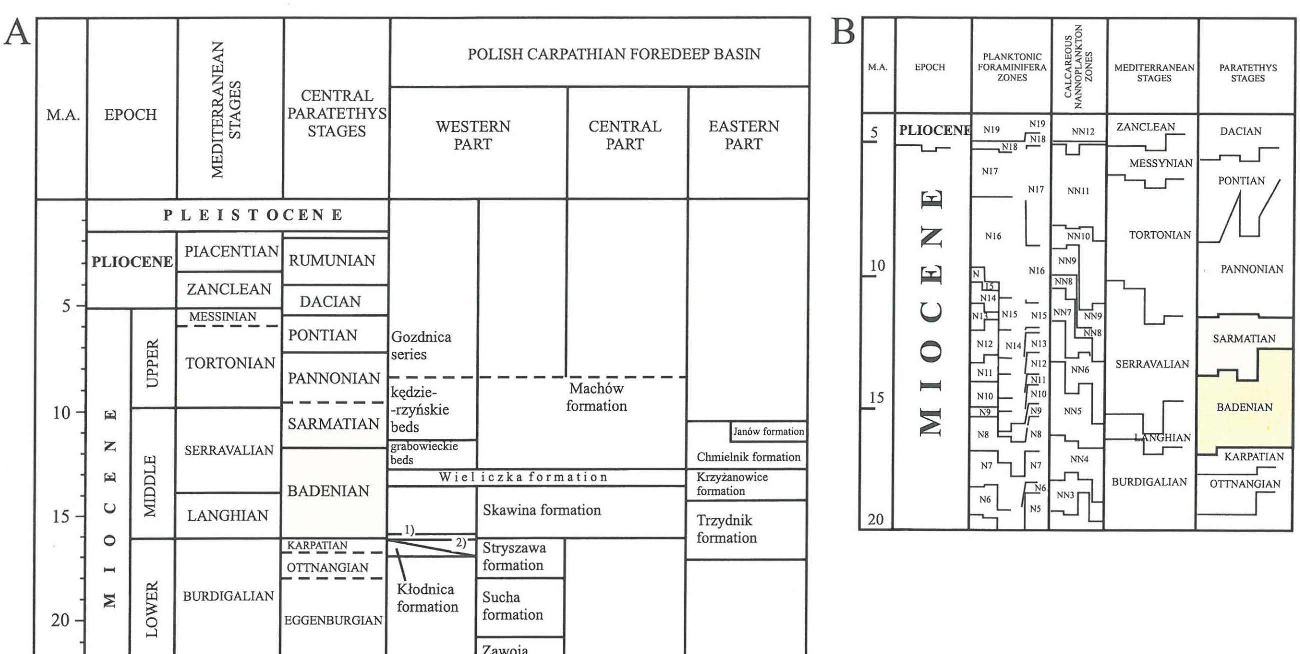

Fig. 2. A — stratigraphic column showing relationship between Central Paratethys and Mediterranean stages and main lithostratigraphic units defined in the PCFB (after Piwocki et al., 1996, simplified); B — stratigraphic table simplified after Berger (1992) that shows discrepancies among various authors as to the location of particular stratigraphic boundaries

that developed due to regional flexure of the European foreland lithospheric plate. It formed the most northern part of the Paratethys sea (Hamor, 1988). For correlation between Mediterranean and Paratethys stratigraphic stages see Fig. 2 and compare, for example, Berger (1992), Roegl (1996); see also discussion in subsequent paragraph. PCFB

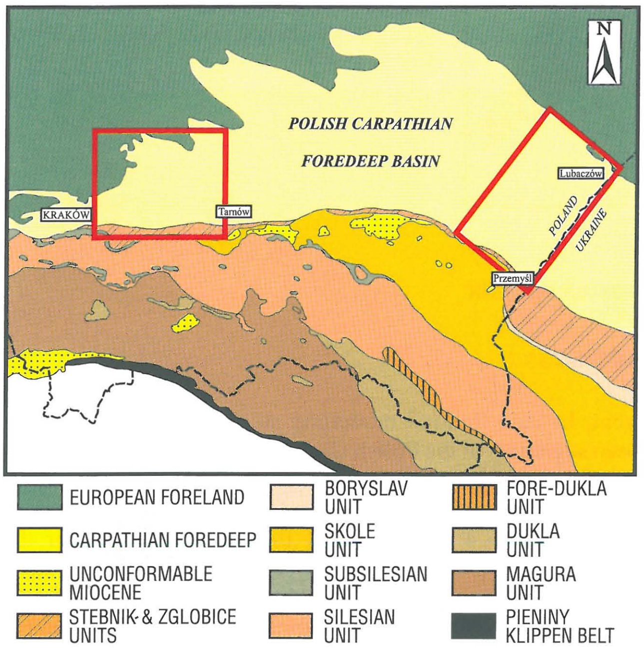

Fig. 3. Map of the Polish and West Ukrainian Carpathians and of their foredeep basin (after Żytko et al., 1989, supplemented). Red rectangles deliminate central and eastern parts of the PCFB

was initiated in Eggenburgian times due to the onset of thrust loading of the foreland plate, and lasted at least until Sarmatian times. Crustal shortening and evolution of the Carpathian foredeep basin was coeval with extensional and strike-slip tectonic regime within the intra-Carpathian domain (Pannonian Basin system) and development of back-arc basins (Csontos et al., 1992; Kovač et al., 1993, 1995). Extensive discussion on various aspects of development of the PCFB can be found in Ney et al. (1974), Oszczypko (1996), Oszczypko & Ślączka (1985, 1989), Oszczypko & Tomaś (1985) and Oszczypko & Żytko (1987).

Badenian and Sarmatian sediments that fill PCFB in front of the present-day Carpathians are built mainly of deltaic and turbiditic siliciclastic deposits and also include extensive Middle Badenian evaporites (rock salt, anhydrites and gypsum) which form excellent stratigraphic marker, also for seismic reflection data analysis. They were deposited in the so-called external zone of the PCFB (Ney et al., 1974). They were also partly involved in the thrust-and-fold deformations and now form a relatively narrow strip of deformed foredeep sediments in front of this part of the Carpathians (Zgłobice and Stebnik units; Fig. 3).

Evolution of the PCFB and architecture of the foreland European Plate

The Carpathian foreland plate can be divided into two major segments. In the east (mainly Ukraine) it belongs to the East European Platform that is characterised by 45 km thick crust, and made of Precambrian crystalline basement and undeformed Palaeozoic and Mesozoic sediments (Ziegler, 1990). In the west (Poland and Czech Republic)) the foreland plate of the Carpathian arc belongs to the epi-Vari-

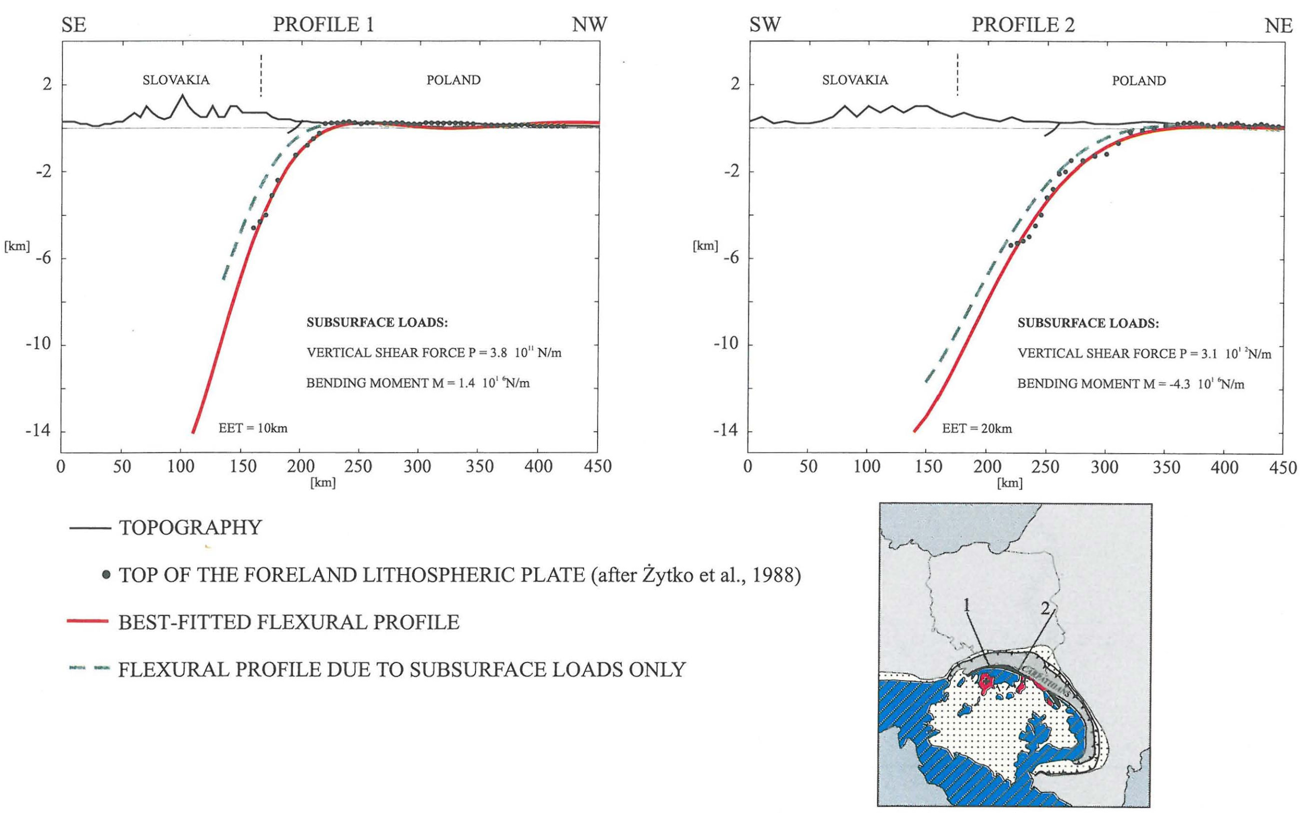

Fig. 4. Results of flexural modelling (elastic lithospheric plate of constant EET flexed under topographic and subsurface loads) for two profiles from western and eastern Polish Carpathians)

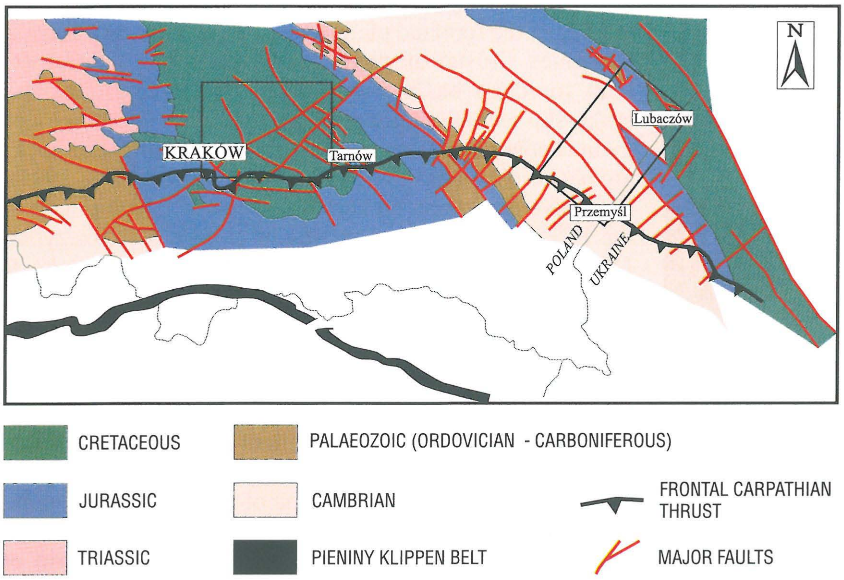

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Fig. 5. Map of the substratum of the Polish and West Ukrainian Carpathian Foredeep basin (after Oszczypko et al., 1989, supplemented by data from Izotova & Popadyuk, 1996; Kutek, 1994)

scan West European Plate characterised by 30–35 km thick crust (Guterch et al., 1986; Ziegler, 1990), consolidated during the Hercynian orogeny and covered by Mesozoic sediments. These two plates are divided by the Tornquist-Teisseyre Zone, i.e. major NW-trending basement discontinuity extending from the Baltic Sea across whole Poland, and beneath the Carpathian arc towards the Black Sea (Guterch et al., 1986; Ziegler, 1990; Fig. 1). Different age of consolidation and various crust thickness would suggest that rheological properties, and hence flexural response of the eastern and western segments of the Carpathian foreland plate related to slab-pull and thrust loading would be different. In fact, flexural modelling studies completed for the two segments of the Polish Carpathians suggest that they are characterised by different EET values: in the range of 8–15 km for the western segment, and 20–25 km for the eastern one. On Fig. 4 the results of flexural modelling for the western and eastern Polish Carpathians, presented after Krzywiec & Jochym (1997), show also dominance of subsurface loads (slab-pull mechanism) for both parts of the PCFB. Substratum of the PCFB is highly differentiated (Oszczypko et al., 1989; Fig. 5) what is connected to the pre-Neogene history of this area. Carboniferous and Permian disintegration of Hercynian Europe, followed by Me-

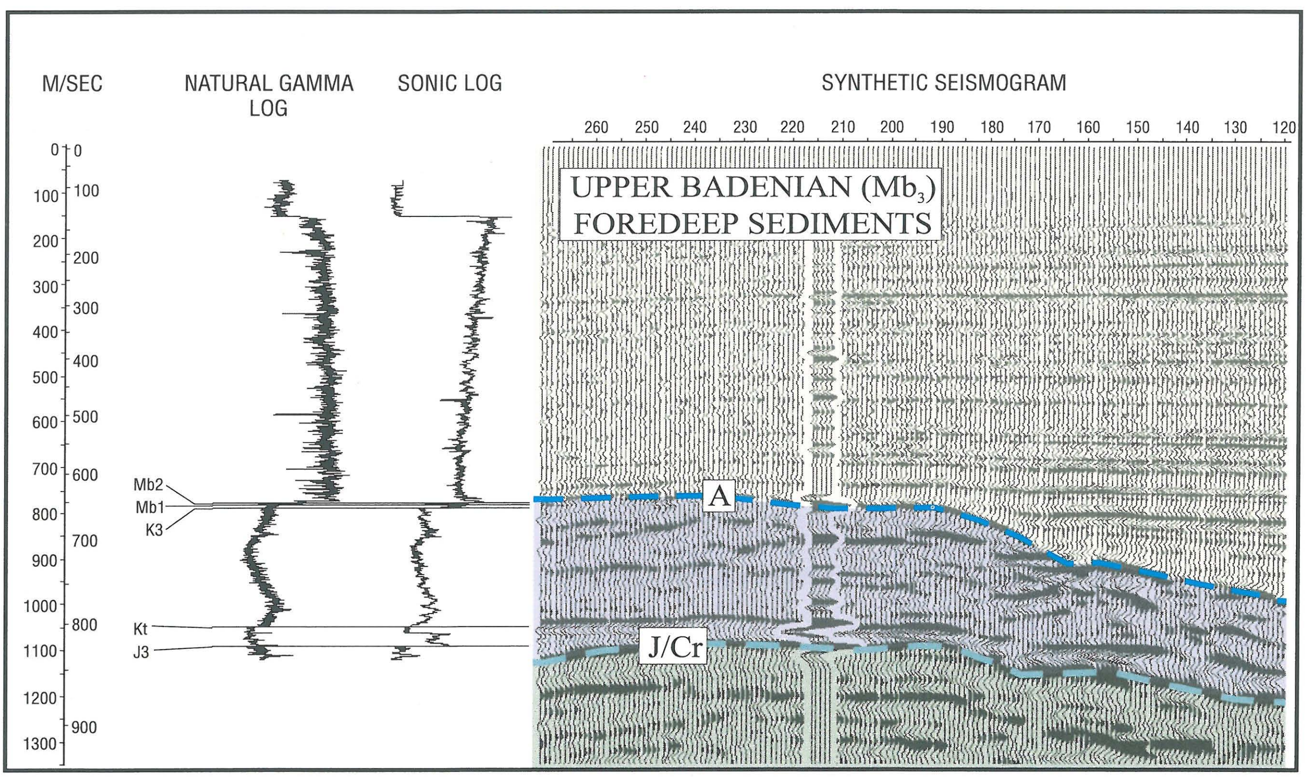


Fig. 6. Natural gamma log, sonic log, synthetic seismogram and its correlation with seismic profile for a typical well from the central part of the PCFB. Note thickness relationship between Lower Badenian (Mb1) siliciclastics and Middle Badenian (Mb2) evaporites, and generated synthetic seismogram. A: seismic horizon generated by Middle Badenian evaporites. See text for discussion

sozoic rifting, led to development of the Tethyan rift system with its important element, i.e. the Polish-Danish Trough (Dadlez et al., 1995; Pożaryski & Brochwicz-Lewiński, 1978; Pożaryski & Żytko, 1980; Ziegler, 1990). It extended at least as far as the present-day Carpathian thrust front in eastern Poland and western Ukraine (Hakenberg & Świdrowska, 1997; Kutek, 1994). During Late Cretaceous/Palaeogene times, the Mid-Polish Trough was inverted and uplifted what resulted in partial or total erosion of Mesozoic sedimentary cover. Tectonic grain of the Carpathian foreland plate related to this rifting and inversion tectonic activity generally follows the NW–SE direction and is oblique to the Carpathian arc and its foredeep basin, at least in the Polish segment (Fig. 1). It can be hypothesised that during the development of external (Badenian–Sarmatian) PCFB some form of reactivation of inherited NW–SE oriented structures of the foreland plate might have influenced foredeep basin formation.

Remarks on stratigraphy of the Miocene sediments of the PCFB

Vast literature exists on stratigraphy of the Carpathian foredeep sediments, as these sediments host numerous deposits of commercial interest, like rock salt, native sulphur or hydrocarbons, that have been exploited over the last centuries (see Siemiradzki, 1909 for summary of XIX century studies; also Alexandrowicz, 1965; Kirchner, 1956; Łuczkowska, 1958; Ney et al., 1974). For mapping and exploration purposes and during local sedimentological studies of outcrops a plethora of local "formations" or "beds" was established, and in most cases their exact lateral relationship is still not fully understood. Several papers on stratigraphy and evolution of the PCFB published recently (Alexandrowicz et al., 1982; Piwocki et al., 1996; Oszczypko, 1996) stress the fact that instead of trying to fit these local lithostratigraphic units to regional stratigraphic scheme, broadly defined formations comprising all local subdivisions should be used instead. Recently published studies of calcareous nannoplankton strongly suggest that all the deposits that fill PCFB in front of the Carpathians, and tradi-

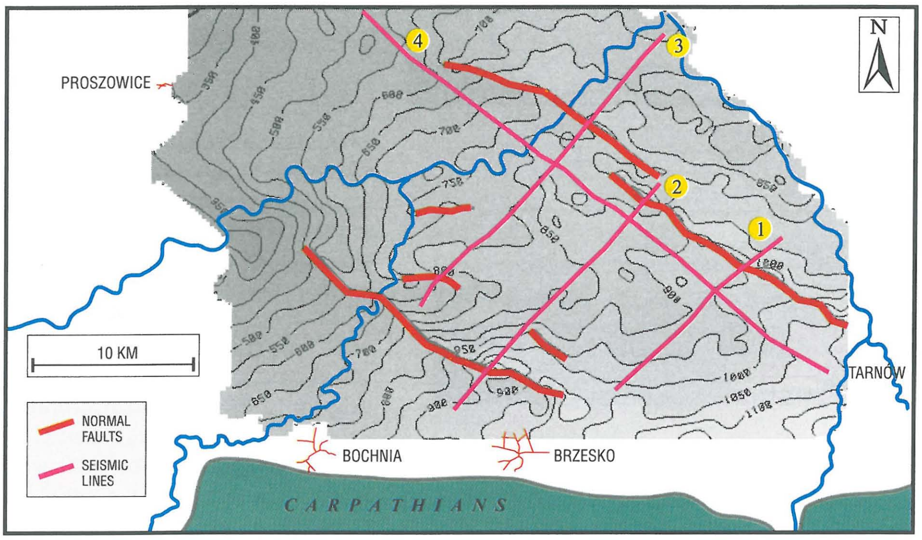


Fig. 7. Time structural map of the top of Jurassic in the central part of the PCFB

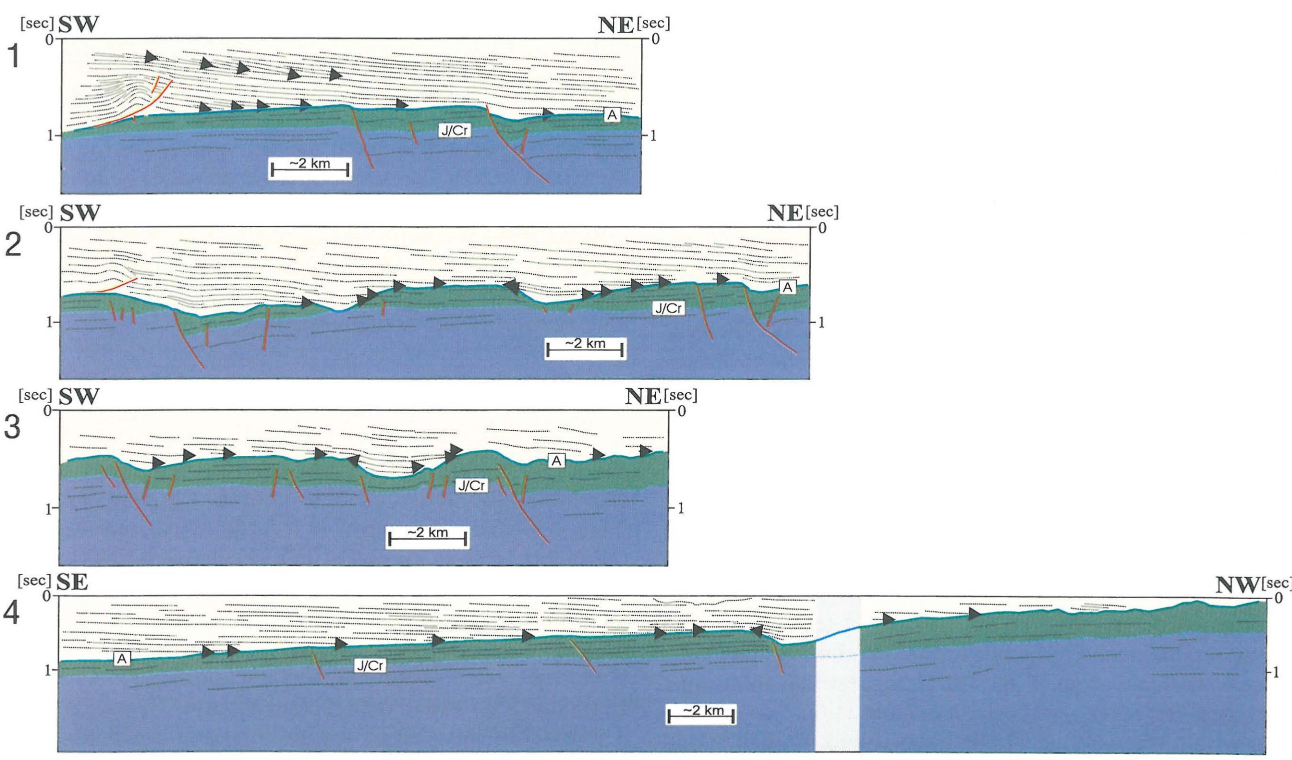


Fig. 8. Selected interpreted seismic time lines showing main tectonic features identified within the Mesozoic basement of the central part of the PCFB. For location see Fig. 7

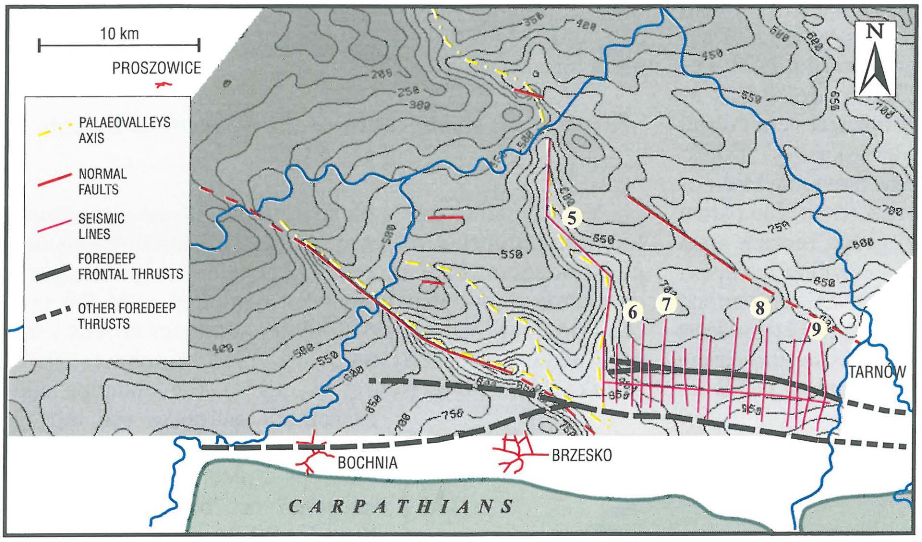


Fig. 9. Time-structural map of the evaporite horizon that can be regarded as a good approximation of the top of the pre-Miocene basement. Note large lows (palaeovalleys) developed within this basement and their relationship to normal faults. Compare their extent and tectonic pattern with the map of the J/Cr boundary

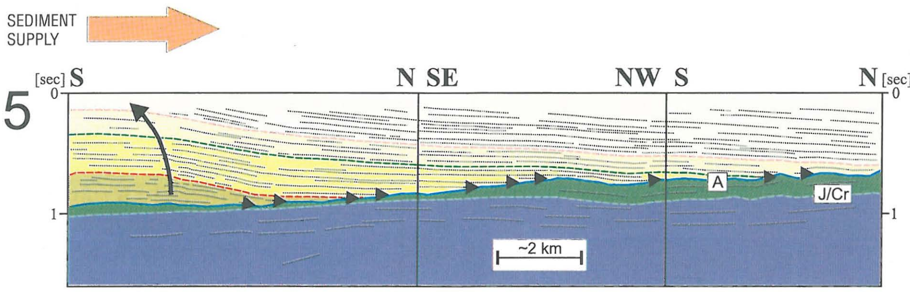


Fig. 10. Interpreted seismic line located along the axis of the morphological low (palaeovalley) cut within the Mesozoic basement. Note that Upper Badenian reflectors are generally inclined towards the north, but in vicinity of the Carpathians they become horizontal, thus forming large-scale clinoform sigmoidal pattern. No similar change of inclination can be observed within the Mesozoic section. Also note migration of the offlap-break (red arrow). Inferred direction of sediment supply was from the south. For location see Fig. 9

tionally regarded as Badenian to Lower Sarmatian in age, might be younger since they belong to the NN6–NN9 nannoplankton zones (Garecka & Olszewska, 1997; Gaździcka, 1994; see Oszczypko, 1996, for more detailed discussion). Some of the recently published papers stress ecological dependence of particular microfossil assemblages that were previously used for long-distance correlation, as well as their age-discrepancy in relation to other parts of the Central Paratethys sea (Szczechura, 1982, 1996). In the uppermost part of the Krakowieckie shales (Machów Formation), *Silicoplacentina (Thecamoebians)* characteristic for Pannonian has been recently identified (Paruch-Kulczycka, 1997). Inspection of published correlation schemes between Mediterranean and Paratethys stages shows that the exact location of particular boundaries greatly varies according to different authors. See, for example, Berger (1992) for very useful compilation of stratigraphic subdivisions for these two domains, showing important discrepancies between particular authors regarding location of stratigraphic boundaries, for example in the order of 2–3 Ma for Badenian/Sarmatian boundary (Fig. 2). Results of the all above mentioned recent stratigraphic studies of the PCFB sediments, coupled with radiometric ages obtained for tuff horizons (Van Couvering et al., 1981) suggest that traditional correlation of particular "beds" and "formations" distinguished within the external PCFB deposit with Badenian and Lower Sarmatian stages might be not correct and would require significant re-evaluation. All these together point to the fact that microfaunistically-defined and lithostratigraphic units and boundaries should be used with great caution. Therefore, during interpretation of the seismic reflection profiles no attempt has been made to correlate loosely defined biostratigraphic boundaries (for example Badenian/Sarmatian boundary) with seismic data. In subsequent paragraphs traditional stratigraphic ages (i.e. Lower, Middle and Upper Badenian and Sarmatian) will be used, however they should be regarded as working lithostratigraphic terms rather than correct chronostratigraphic connotations.

The main objectives of this paper can be defined as follows:

1) to describe two parts (central, between Kraków/Bochnia and Tarnów, and eastern, between Przemyśl and Lubaczów) of the PCFB in terms of dominant tectonic features and large-scale depositional pattern, mainly for the Upper Badenian–Lower Sarmatian (post-evaporitic) sedimentary section,

2) to interpret the above in terms of relationship between sedimentary processes and tectonic activity, like progressive thrusting of the Carpathian thrust belt and reactivation of inherited structures of the foreland plate.

Central (Bochnia–Tarnów) part of the PCFB

Central part of the PCFB is located between Kraków/Bochnia and Tarnów, and is bounded on the south by the Carpathian flysch nappes. In front of the Carpathian nappes there is a relatively narrow belt of the deformed foredeep sediments, called Zgłobice unit (Kotlarczyk, 1985), and farther to the north foredeep sediments did not suffer compressional deformation (Fig. 3). To the north, Miocene sediments are bounded by the outcrops of Mesozoic (mainly Cretaceous) series belonging to the sedimentary cover of the European Platform (SW part of the inverted Polish Trough). These sediments extend towards the south and form the basement of this part of the PCFB (Fig. 5).

In the central part of the PCFB Miocene foredeep sediments can be divided into three main lithological intervals that belong to the Skawina, Wieliczka and Machów Formations (Fig. 2). On Fig. 6 typical thickness relationship of these intervals with the aid of natural gamma and sonic logs are presented. A synthetic seismogram and its correlation with seismic profile is presented as well. It can be seen that Lower Badenian (Mb1) shales are usually too thin to be distinguished on seismic data. Throughout the study area these sediments are 10–40 m thick on the average (Jawor, 1970). The overlying evaporites (Mb2) are also relatively thin, in the order of 10–50 m (Jawor, 1970; Ney et al., 1974), but due to their increased seismic velocity they form an excellent seismic marker. Lower Badenian siliciclastics and Middle Badenian evaporites are present across all of the central part of the PCFB, and in most cases both these intervals can be correlated with one strong seismic reflector (Fig. 6). During seismic data interpretation it was assumed that this reflector effectively marked the boundary between Upper Badenian siliciclastics and Mesozoic basement. Upper Badenian siliciclastics are built up of sandstones and shales and they attain 1.5 km in the vicinity of the Carpathian front. In this area sandstone content is significantly higher, what indicates the Carpathians as the source area.

In order to assess influence of any older, basement tectonic deformations on deformations present within the Miocene foredeep section it was necessary to describe large-scale tectonic pattern of the Mesozoic basement. For this reason one seismic reflector was identified within the Mesozoic series and correlated across all of the study area. This reflector was correlated with the Jurassic/Cretaceous boundary (Fig. 6), identified in many wells in the study area. This boundary marks a transition from Jurassic carbonates to Cretaceous siliciclastics and subordinately carbonates, and is also related to erosional processes (Jawor, 1970).

During the completed interpretation a dense coverage of industry seismic reflection data was used. Their interpretation included identification of main tectonic features, correlation of several seismic horizons, and identification of unconformity-bounded seismic units of different size and extent.

Tectonic grain of the Mesozoic basement

Deformations of the top of the Jurassic were regarded as representative for the structural style of the Mesozoic series of this part of the PCFB, in particular for their post-Cretaceous history (Jawor, 1970). Its correlation and constructed time-structural map provided information on main tectonic features that often influenced development of the Miocene foredeep sediments. No attempt has been made to complete very detailed tectonic interpretation of the Mesozoic rocks, only main faults were correlated and mapped instead. Time-structural map of the Jurassic/Cretaceous boundary is presented on Fig. 7, and selected representative, interpreted seismic profiles are presented on Fig. 8. From their analysis it was concluded that main deformations developed within the Mesozoic basement included normal faults trending NW–SE, and also some minor antithetic faults. It is important to note that all these faults displace Mesozoic rocks towards the NE, and no major thickness changes that could be related to their significant synsedimentary activity are observed within the Mesozoic series. Based on all these features it was concluded that these faults developed during and after the Late Cretaceous/Palaeogene inversion of this part of the Polish Trough. This conclusion is compatible with the results of other more detailed studies based on well data (Jawor, 1970; Oszczypko & Tomaś, 1976).

Another very important feature related to the Mesozoic basement of the foredeep Miocene sediments are morphological lows (valleys) cut into the top of Cretaceous rocks. Their shape and extent are clearly marked by a strong reflector related to the overlying Miocene evaporites. On the presented interpreted seismic lines it can be observed that in most cases they are related to the normal faults described above. Their development and importance for the Miocene history of the study area will be described in the following section.

Sedimentation of the Miocene (Upper Badenian) foredeep deposits

The most striking seismic feature identified within the Badenian sediments that fill this part of the PCFB is a regional angular unconformity developed between the Middle Badenian evaporites and Upper Badenian siliciclastics (Fig. 8). All the Upper Badenian reflectors are strongly inclined towards the north, and the Middle/Upper Badenian unconformity is marked by numerous downlap seismic contacts. Particular seismic packages pinch-out towards the north. This pattern can be seen on all of the seismic lines from this part of the PCFB. This suggests that all the sediments deposited above the evaporites formed a large-scale clinoform. On several profiles located in close vicinity of the present-day Carpathian front it can be seen that Miocene reflectors change their inclination and become nearly horizontal (Fig. 10). No similar change of inclination can be observed within the Mesozoic basement. Therefore, it can be concluded that the observed large-scale seismic pattern of the foredeep sediments was not related to any tectonic movements like bending of the foreland plate but is due to depositional processes. The observed large-scale seismic pattern of the Upper Badenian sediments (Fig. 10) was interpreted as a large-scale sigmoidal configuration related to deltaic environment and sediment progradation from the Carpathians into the foredeep basin. Development of a wedge of clinoform-type reflectors due to delta progradation from the orogenic belt towards the foredeep basin is a common feature observed in the other collisional settings. For example, such an interpretation was offered for large-scale sigmoidal seismic configuration observed on numerous seismic lines in the Apenninic–Adriatic foredeep (Ori et al., 1986). More detailed analysis of configuration of seismic reflectors at the most southern part of several profiles (Fig. 10) showed that offlap-break migration can be observed. This suggests that the Upper Badenian foredeep sediments developed due to retrogradation of the entire deltaic system.

Such an interpretation has been recently confirmed by integrated seismic interpretation and studies of calcareous nannoplankton from core samples from this area (Krzywiec & Ślęzak, in preparation). Several wells were densely sampled along their entire length and the results of nannoplankton studies showed that all these sediments belong to NN5-6 nannoplankton zones. This conclusion is based on occurrences of the following taxa: *Helicosphaera californiana* Bukry, *H. carteri* (Wallich) Kamptner, *H. minuta* Mueller, *H. sp. aff. H. selli* Bukry & Bramlette, *Reticulofenestra pseudoumbilica* (Gartner) Gartner, *Thoracosphaera fossata* Jafar *and T. saxea* Stradner. Apart from the autochthonous Miocene taxa a large amount (up to 80%) of

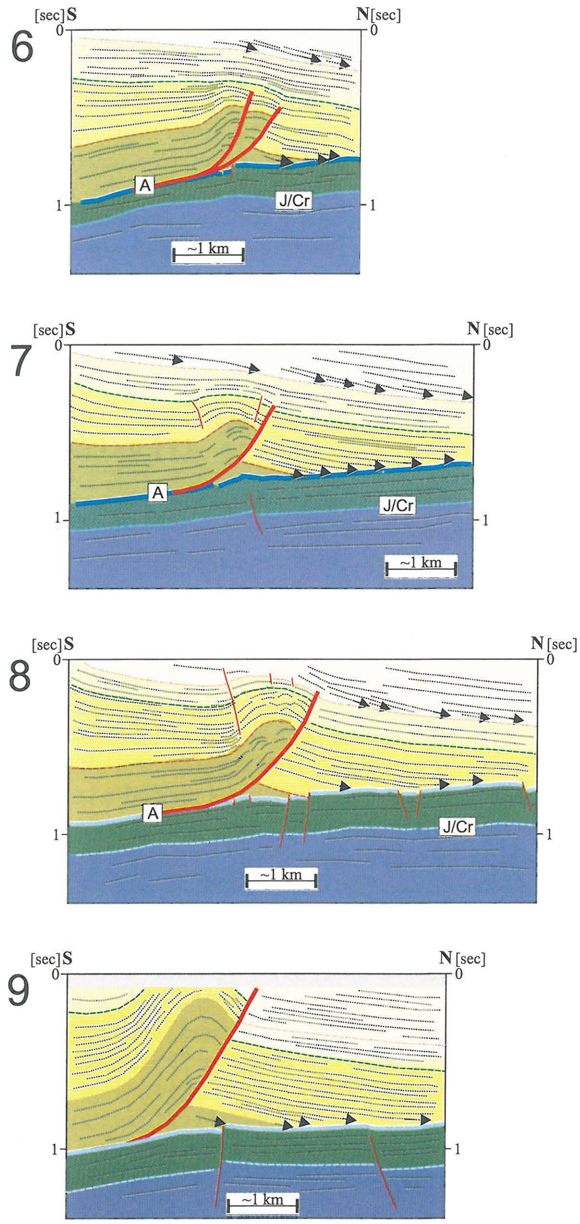


Fig. 11. Selected interpreted seismic lines located in the southern part of the central PCFB, showing foredeep thrust-related growth folds. For location see Fig. 10

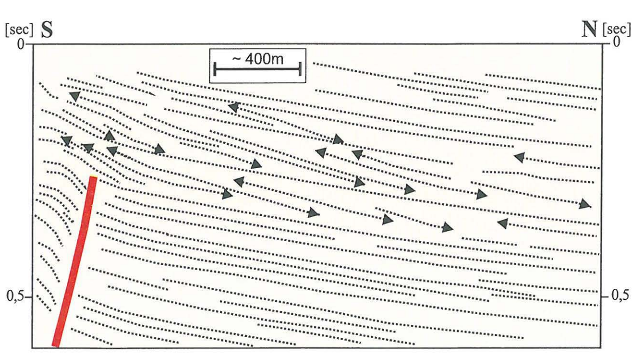


Fig. 12. Close-up of the small prograding clinoforms developed in front of the growth folds. They were interpreted as a seismic expression of the fan deltas derived from eroded thrust front

redeposited, older taxa was identified. They are mainly Middle and Upper Eocene, and Upper Oligocene, and also Lower Miocene, Palaeocene and Upper Cretaceous in age. Such a content of redeposited nannoplankton species clearly points to the Carpathians as the source of the studied sediments . No other source of such redeposited nannoplankton assemblages could be proposed but from the eroded flysch Carpathians.

In order to estimate the influence of older tectonic deformations developed within the Mesozoic basement on sedimentation of the foredeep sediments, structural map of the reflector related to the Middle Badenian evaporites was constructed (Fig. 9). Main features that can be observed on this map are prominent lows (palaeovalleys) cut into the Mesozoic rocks. Other features include normal faults oriented NW–SE. Comparison of this map and map of the top of the Jurassic (Fig. 7) shows that these lows follow main NW–SE faults developed within the basement. Only locally they depart from the dominant trend and are not related to any faulting (compare Figs. 8, 9).

The shape of these lows clearly suggests that they were supplying sediments generally from the north toward the south. Very similar features, filled by Palaeogene (foreland-derived) and Neogene (foredeep) sediments, were described in more western part of the Carpathian Foredeep, in the Czech part of this basin. They were interpreted as ancient, tectonically-controlled, submarine canyons of the Tethyan margin (Picha, 1974). In Poland, these morphological lows are filled only by Miocene foredeep sediments. Their development was clearly influenced by the pre-existing faults and only sub-ordinarily they developed as pure erosional features. It can be postulated that these valleys/canyons were incised during Palaeogene times due to tectonically-controlled erosion that followed inversion of the Polish Trough. No Palaeogene sediments were found in the study area, however, at their southern extension remnants of Palaeogene sediments have been recently found, as indicated by core studies from wells located in the vicinity of Rzeszów (Moryc, 1995). Upper Badenian sediments of the PCFB supplied from the eroded Carpathian nappes covered this morphologically diversified erosional surface and passively filled these palaeovalleys.

Tectonics and sedimentation in the southern segment of the central PCFB

In central part of the PCFB, in front of the Carpathian nappes, a relatively narrow belt of deformed foredeep deposits occurs (Zgłobice unit, Kotlarczyk, 1985; Fig. 3). This unit consists of several fault-and-fold structures of maximum width up to 10 km (Kirchner & Połtowicz, 1974). More than 20 closely spaced seismic profiles are located above the most frontal (northern) part of the Zgłobice unit, and some of them are presented on Fig. 11. They show lateral variations of the structural styles of interpreted structures. In order to interpret their development, three reflectors within the Miocene section were picked and correlated. Special attention was paid to thickness changes of particular seismic packages in relation to the development of thrust structures.

These structures represent typical fault-propagation folds that form and grow at the tip of propagating thrust faults (Suppe & Medwedeff, 1990). They occur where a ramp steps up from the decollement level and gradually

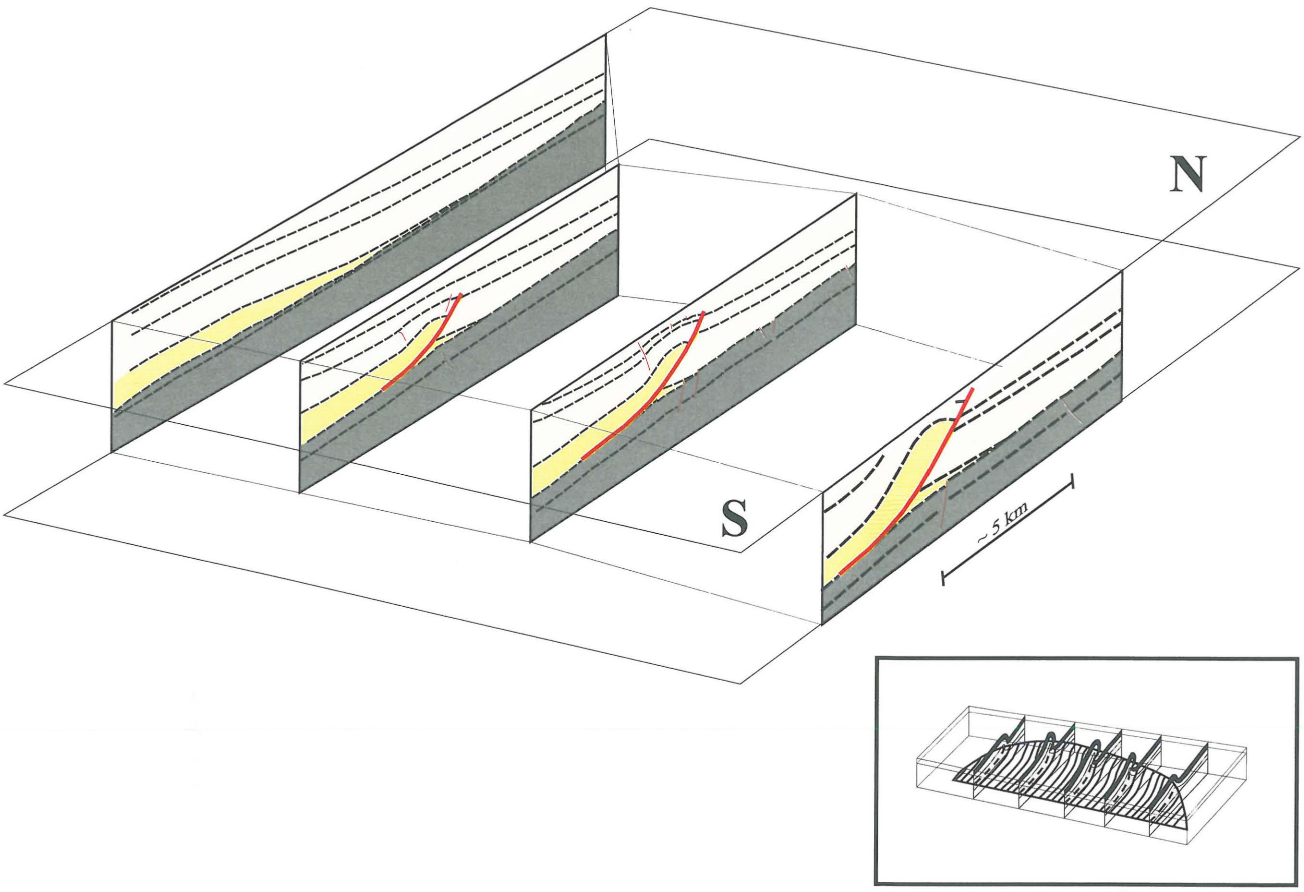


Fig. 13. Block-diagram showing lateral variations of the frontal thrust-related growth fold interpreted in the Carpathian Foredeep. The inset contains conceptual model of ideal self-similar thrust sheet after Fischer & Woodward (1992)

propagates upward and eventually deformation is being taken up by folding. Middle Badenian evaporites served as a favourable detachment level. Other tectonic features of these fold-related-folds include minor backthrusting and slight imbrication that resulted in the formation of a small imbricate fan system (Boyer & Elliot, 1982). They can also be called blind thrusts, as they do not cut to the surface (Dunne & Ferril, 1988). Comparison of thickness of the identified seismic packages clearly shows that these structures can be interpreted as typical growth structures, i.e. structures that developed during sedimentation (Medwedeff, 1989). Characteristic thickness changes include rapid thinning of sedimentary packages from the limbs towards the crest of the growth fold. Several onlapping and downlapping horizons were identified at both flanks of these folds, also their post-depositional rotation can be seen. The continuity of majority of reflectors above the crest of the fold and locally developed progressive unconformities suggest that due to the growth of these structures accommodation space was significantly reduced above their crests but no major erosion took place. Moreover, distinct fanninig of sediments can be seen in front of this fold. All the described features are typical for growth folds that frequently develop in the frontal part of orogenic belts. Very similar structures were described, for example, from the Apenninic foredeep basin (Artoni & Casero, 1997; Ori et al., 1986), and their development has also been successfully modelled by means of numerical modelling (Hardy et al., 1996). Another important feature related to the growth folds are fan deltas and conglomerates derived from eroded thrust front (Burbank & Verges, 1994; DeCelles et al., 1987, 1991; Medwedeff, 1989, 1992; Pivnik, 1990). In case of the fold-propagation folds developed in the central part of the PCFB, small prograding clinoforms were identified on many seismic lines in front of these folds. They were interpreted as a seismic expression of fan deltas that developed due to thrusting, folding and erosion (Fig. 12). Similar fan deltas were also described in outcrops (Doktor, 1983). Three-dimensional block-diagram based on selected interpreted seismic lines was constructed in order to visualise lateral variations of the identified fault-propagation fold (Fig. 13). It shows many characteristic features of the self-similar thrust sheet (Fischer & Woodward, 1992). Comparison of the extent of this fault-related fold with structural map of the evaporite horizon (i.e., approximately top of the basement; Fig. 9) suggests that its development was influenced by basement topography. In the area characterised by higher elevated basement (northern slope of the palaeovalley), stress accumulation related to buttressing effect led to development of frontal foredeep compressional structures. Towards the west, towards the centre of the palaeovalley, no buttressing effect occurred and hence growth fold did not develop.

Eastern (Przemyśl–Lubaczów) part of the PCFB

Eastern part of the PCFB is located between the Carpathian front to the south and outcrops of the Cretaceous rocks to the north, and is superimposed on the axial part of the inverted Polish Trough, i.e. the Małopolska Massif (Figs. 1, 3, 5). Inversion of the Polish Trough has resulted in complete

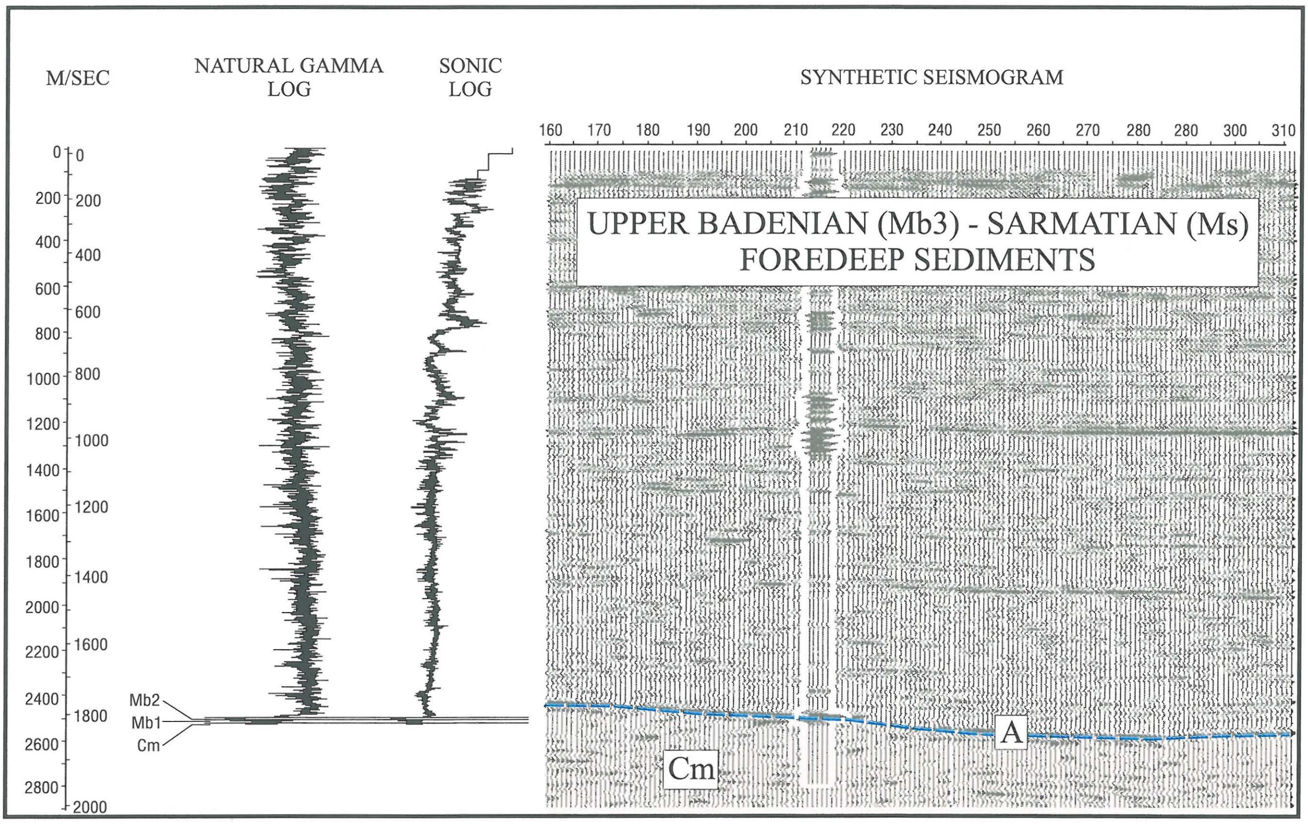
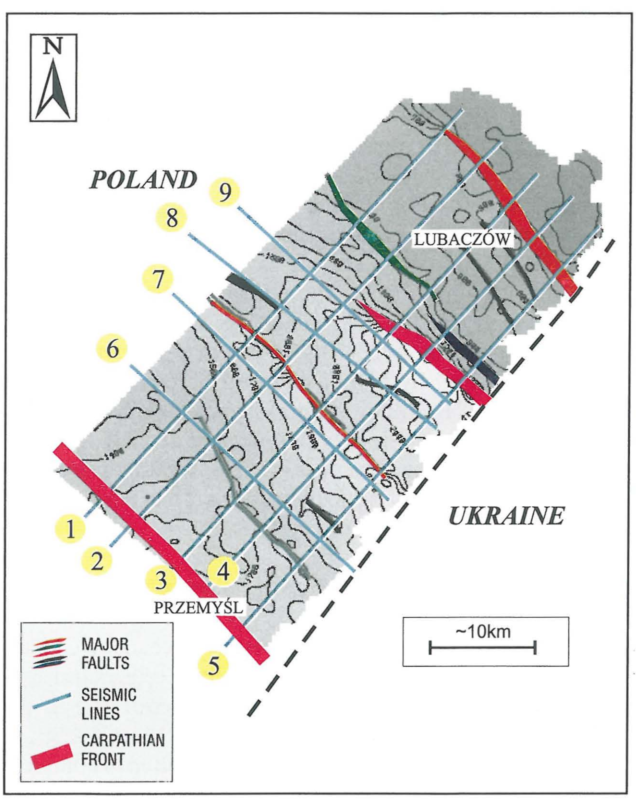


Fig. 14. Natural gamma log, sonic log, synthetic seismogram and its correlation with seismic profile for a typical well from the eastern part of the PCFB. Note significantly smaller thickness of the Lower Badenian (Mb1) siliciclastics and Middle Badenian (Mb2) evaporites in comparison with more than 2.4 km thick Upper Badenian/Sarmatian siliciclastics. Also note extremely monotonous natural gamma response of the Upper Badenian/Sarmatian shaly interval of the Krakowieckie shales. A — seismic horizon generated by Middle Badenian evaporites. See text for discussion

removal of the Cretaceous strata, and the Palaeozoic and Jurassic sediments forming basement of this part of the Carpathian foredeep are unconformably overlain by Miocene sediments (Dziadzio & Jachowicz, 1996; Głowacki et al., 1963, 1966; Izotova & Popadyuk, 1996; Karnkowski & Głowacki, 1961; Moryc, 1961; Oszczypko et al., 1989).



Similarly to the central part of the PCFB, Miocene sediments of the eastern part of this basin can be divided into three lithological intervals (Fig. 14) that include rather thin (20–30 m on the average) cover of transgressive conglomerates, sandstones and shales (traditionally regarded as Lower Badenian), and extensive, 10–20 m thick, evaporites (traditionally regarded as Middle Badenian in age). The evaporites are covered by very thick, up to 2.5 km, series of shales and sandstones (Ney et al., 1974). In the axial part of the eastern PCFB these siliciclastics, traditionally considered as Upper Badenian and Sarmatian, are built of the so-called Krakowieckie shales belonging to the Machów Formation (Fig. 2). Analysis of calculated synthetic seismogram (Fig. 14) shows that, similarly to the central part of the PCFB, Lower and Middle Badenian sediments can be correlated with the single strong reflector generated by evaporitic horizon. Time-structural map of this reflector was constructed (Fig. 15; compare also Oszczypko et al., 1989) using

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Fig. 15. Time structural map of the evaporite horizon in the eastern part of the PCFB

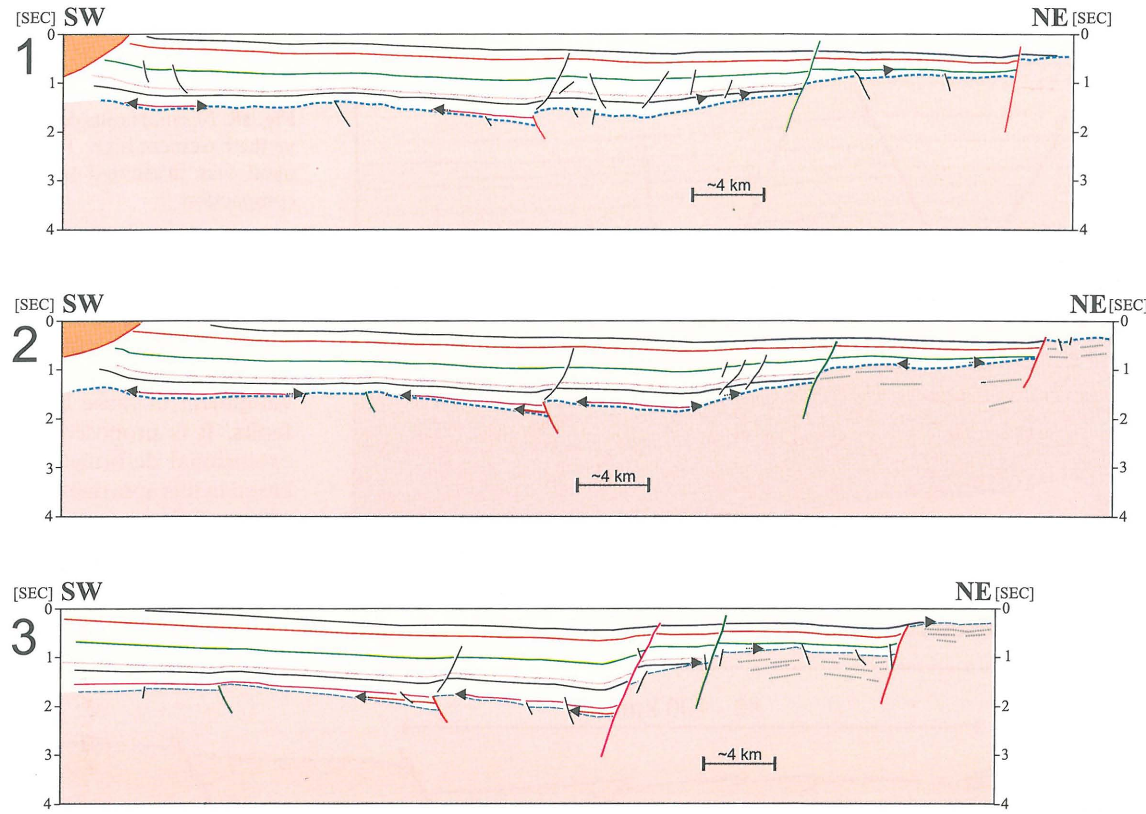

Fig. 16. Three regional (SW–NE) seismic lines located in the eastern part of the PCFB. For location see Fig. 15

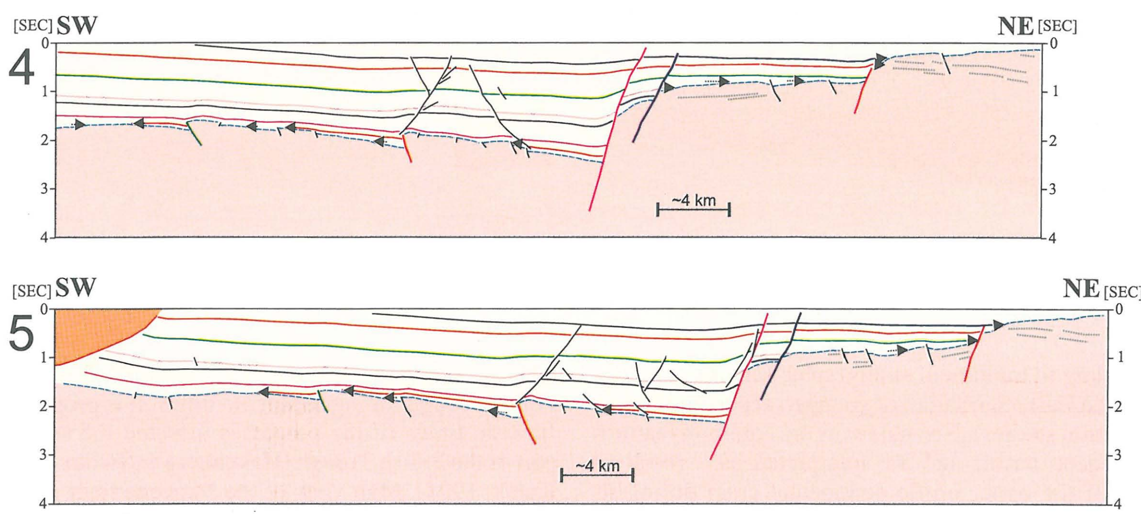

Fig. 17. Two regional (SW–NE) seismic lines located in the eastern part of the PCFB. For location see Fig. 15

dense coverage of the seismic profiles from the area between Przemyśl and Lubaczów. In order to present variations in tectonic and depositional style of this part of the PCFB, five SW–NE and four NW–SE regional seismic profiles have been constructed (Figs. 16, 17, 19). Within the Miocene foredeep sediments seven reflectors were chosen and correlated in order to assess their depositional and tectonic history. The basement of this part of the PCFB consists mainly of Cambrian and older rocks, and no seismic response was recorded from below the evaporite reflector. Therefore, most of the interpretation was solely based on configuration of the Miocene reflectors. Only within the footwall block of this fault system several reflectors related to Jurassic sedimentary cover that escaped post-Cretaceous erosion were identified.

Tectonics of the eastern PCFB

Based on the results of the seismic data interpretation it was concluded that main tectonic deformations developed in this area included large normal faults and smaller inverted antithetic faults present within the hangingwall block. Both hangingwall and footwall blocks are relatively uniformly covered by evaporites so, as they require relatively shallow environment for their formation, it was concluded that the onset of faulting can be dated as post-evaporitic (post-Middle Bade-

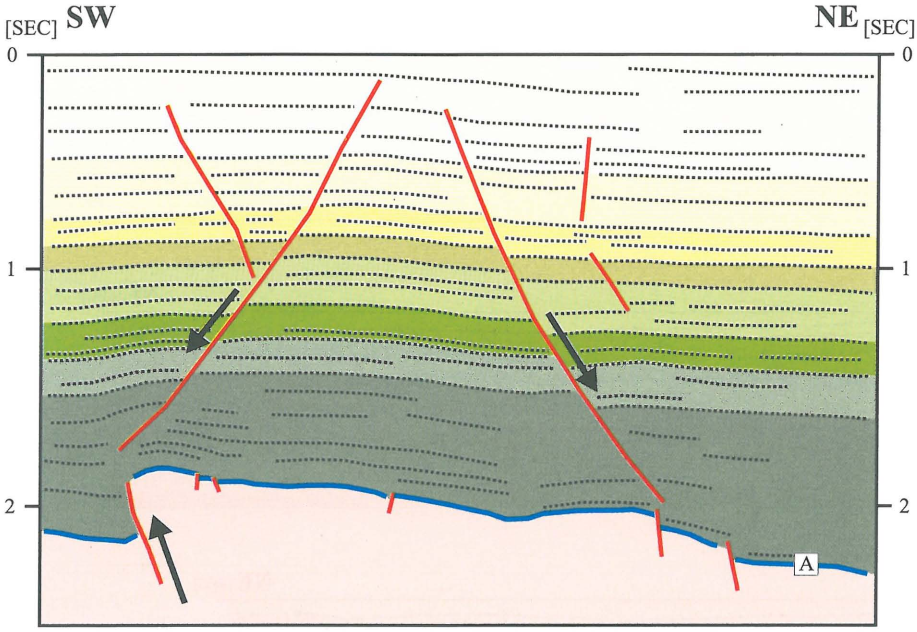

Fig. 18. Normal faults developed above the basement high. Their development was attributed to differential compaction

additional mechanism, apart from simple flexural extension, must be offered in order to explain the development of these large normal faults. It is proposed that brittle extensional deformation was focused in this area due to combined effect of flexure of the foreland Carpathian plate and related reactivation of older tectonic discontinuities. The area of Miocene

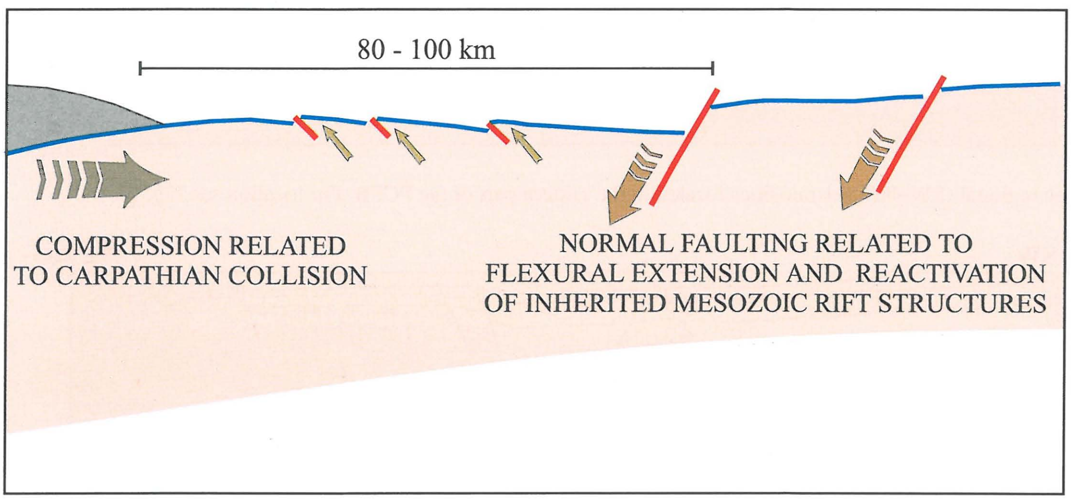

Fig. 19. Model for large-scale tectonic evolution of the eastern part of the PCFB. See text for explanation

nian according to traditional stratigraphic schemes, but possibly at least Early Sarmatian or younger, according to new nannoplankton studies). Normal faults are common features in the foredeep basins and are interpreted as a result of extension of the upper brittle continental crust during its flexure beneath the thrust belt (Bradley & Kidd, 1991). The majority of these faults are synthetic in relation to thrust loading, but antithetic faults are also common. Usually, slip component of such faults is not large and ranges from few meters to maximum few hundred meters close to the thrust front. Normal faults typically do not modify continuity of the tilt of the flexed foreland plate to a large extent (Harding & Tuminas, 1989). In case of the eastern PCFB quite different situation is present, since the identified faults are considerably larger and the total stratigraphic throw for evaporitic horizon is in order of 2–2.5 km. Recently, the zone of maximum tectonic subsidence is located some 30 km towards the foreland from the present-day thrust front, but it must be considered that during their formation the Carpathian front was located considerably further to the south, at least some 50–80 km from its present-day position (Oszczypko & Ślączka, 1989). Therefore, it was assumed that normal faulting belonged to the north-eastern border of the Polish Trough during Mesozoic times. It is proposed that in Jurassic times rifting processes affected the south-eastern part of the Polish Trough (Hakenberg & Świdrowska, 1997; Kutek, 1994). Map-view of the Miocene fault pattern (Fig. 15, also compare Oszczypko, 1989) resembles transfer zones typical for the active extensional settings (Morley et al., 1990). It can, therefore, be postulated that this inherited, rift-related Mesozoic fault pattern might have been reactivated during Miocene flexure of the foreland plate.

All the interpreted normal faults propagate into the Miocene foredeep section. Along the major normal faults significant thickness variations within the Miocene section were described and attributed to their Miocene syndepositional activity. However, it must be stressed out that, most probably, a large component of these thickness variations is also due to differential compaction above hangingwall and footwall, as in this area favourable conditions did exist for initiation of such a process. They included rigid basement and extremely thick package of soft rock (Krakowieckie shales) deposited above up- and downthrown sides of these faults. Recently published studies of differential compaction

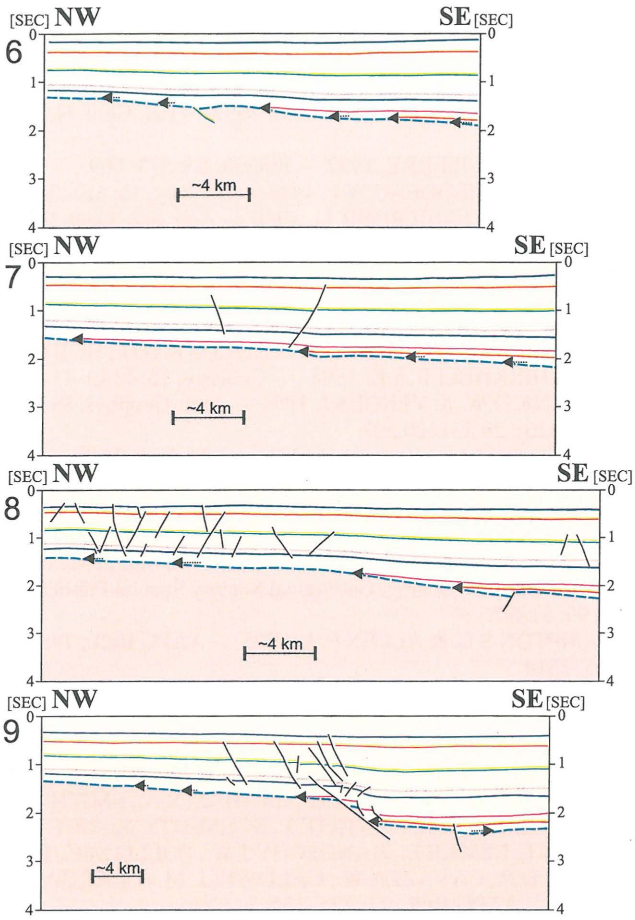

Fig. 20. Four regional (NW–SE) seismic lines located in the eastern part of the PCFB. For location see Fig. 15

above normal faults (Skuce, 1996) suggest that such a process could influence to a large degree thickness variations across normal faults, and can produce significant normal-drag above the hangingwall; a feature that can be clearly seen in proximity of the normal faults developed in the PCFB. Moreover, under certain conditions, differential compaction can produce secondary anticline above the normal fault. Such features are typically regarded as indicators of structural positive inversion of normal fault (Hayward & Graham, 1989). Gentle anticlines can be observed above normal faults in the PCFB, but on the basis of the above considerations they can not be directly related to structural inversion.

Thickness variations of Miocene packages, described across the major basement-involved normal faults, can be attributed both to their syndepositional activity and differential compaction. However, several compaction-related faults that developed solely due to the latter process, have also been identified. These faults (Fig. 18) developed above a basement high that was produced by inversion of antithetic faults within the hangingwall (the so-called Ryszkowa high, see discussion below).

Another very interesting tectonic feature, identified on many seismic profiles located in the eastern part of the PCFB, are sets of slightly inverted antithetic basement faults and associated folds developed within the Miocene sediments (Figs. 16, 17). They are characterised by gently inclined, nearly planar backlimb dips and short, hooked forelimbs. Such an inversion geometry is considered typical for rotated blocks (Coward, 1996; McClay & Buchanan, 1992). These basement blocks were most probably rotated shortly after deposition of evaporites, as they were unconformably onlapped by younger siliciclastics. Significant thinning of the sedimentary packages, at least at the lowermost part of the post-evaporitic succession, above their crests and slightly divergent onlap pattern above their backlimbs indicate that they developed as growth structures (Cartwright, 1989; McClay & Buchanan, 1992). Their development could also be related to the formation of backthrusts, i.e. hangingwall-vergent thrusts that were initiated by buttressing of compressional deformations by relatively steep surfaces of major normal faults (McClay & Buchanan, 1992). Development of reverse faults (backthrusts) within the hangingwall of a compressed normal fault has been also successfully modelled in sandbox experiments (Koopman et al., 1987).

Based on geometrical characteristics of the fault structures developed within the basement of the eastern PCFB it can be postulated that tectonic activity that affected the eastern part of the PCFB might have also included some strike-slip movements. Some of the deformations interpreted within the Cambrian basement are similar to pop-up structures (e.g., middle part of profile 1, Fig. 16). Such structures, often developed within the hangingwall of an inverted normal fault (McClay & Buchanan, 1992), are also indicative of strike-slip movements. Based on sandbox modelling studies it was postulated that the development of reverse faults and pop-up geometry within the hangingwall is related to compression at large angle to the faults. It can be expected that in case of the reactivated older, Mesozoic fault pattern such geometry might have existed because of regional obliquity of the Carpathian orogen and the NW–SE trending Polish Trough. Therefore, one might expect that some form of strike-slip movements did occur within the reactivated Cambrian basement. It should also be noted that the Miocene (Late Badenian–Sarmatian) tectonic activity at the northern edge of the PCFB (Roztocze region) has already been postulated on the basis of detailed field studies, and strike-slip component of these deformations has been suggested (Jaroszewski, 1977).

In order to explain the observed large-scale tectonic deformations within the basement and the sedimentary infill of the eastern part of the PCFB, the following model was proposed (Fig. 19). Shortly after deposition of the Middle (Upper?) Badenian evaporites large normal fault were activated at considerable distance (at least 80 km) from the thrust front. It is proposed that their development could be explained by reactivation of the inherited Mesozoic (Jurassic?) rift-related tectonic zone, due to combined effect of thrust emplacement and slab-pull. This zone was intrinsically weakened by Mesozoic extension related to the Polish Trough development and its subsequent inversion, hence focused Miocene extension related to the flexure of the Carpathian foreland plate. At the same time compressional stresses transferred from the Carpathian collision zone were buttressed against the pre-existing normal faults. The interplay of flexural extension and compressional deformations resulted in basement block rotation and/or formation of small-scale backthrusts. These inverted faults developed as growth structures. Later, due to significantly increased sediment loading, most of the deformation was taken up by normal faults. Secondary deformations include numerous compaction-related normal faults and sets of conjugate faults that dissect Miocene foredeep sedimentary infill. Some form of later inversion of main normal faults might have occurred, as gentle anticlines are observed above these large normal faults. However, they might also have been created by differential compaction above the hangingwall and footwall.

Depositional pattern of the eastern PCFB

Unlike in the central part of the PCFB no sediment progradation from the Carpathians was detected on the seismic profiles. Instead, gentle onlapping of the Middle Badenian evaporites by the Upper Badenian–Sarmatian fine-grained siliciclastics (Krakowieckie shales) can be seen on all seismic lines oriented SE–NW (Fig. 20). This feature was interpreted as an effect of a gradual, NW-directed marine ingression after the Middle Badenian salinity crisis that eventually led to the establishment of open marine connections with the eastern Paratethys.

Conclusions

The central and eastern parts of the PCFB can be characterised by very different large-scale tectonic and depositional styles. In the central part growth fault-propagation folds developed that influenced deposition of the foredeep sediments. The observed morphology of the Mesozoic basement originated due to tectonically-controlled erosion that followed inversion of this part of the Polish Trough. Only slight reactivation of basement normal faults in Miocene times did occur. The Upper Badenian foredeep sediments were supplied to this part of the PCFB by a deltaic system, today manifested by only partly preserved large-scale sigmoidal seismic pattern. The eastern part of the PCFB can be characterised by large normal faults dissecting both Palaeozoic basement and Miocene foredeep infill. Their development was interpreted as caused by Miocene reactivation of the inherited Mesozoic rift pattern. The identified tectonic features also include inverted antithetic faults that might have developed due to formation of hangingwall backthrusts or/and block rotation. It has been also proved that syndepositional compaction-related tectonic activity affected foredeep sediments. No sediment progradation can be observed in this part of the PCFB; instead, regional gentle NW-directed onlapping of the evaporite horizon by the Krakowieckie shales has been documented. These seismostratigraphic features have been interpreted as related to basin deepening that followed the salinity crisis, and re-establishment of marine connections with the eastern Paratethys.

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