The Early–Middle Miocene Carpathian peripheral foreland basin (Western Carpathians, Poland)

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Abstract: The Early to Middle Miocene Carpathian foredeep developed as a peripheral foreland basin ralated to the moving Carpathian front. The subsidence of the basin was controlled both by the sediment and thrust-induced load. The main driving force of tectonic subsidence was the emplacement of the nappe load. During the Early–Middle Miocene time the loading effect of the thickening Carpathian wedge on the foreland plate increased and caused a progressive increase of the total subsidence. The mean rate of the Carpathian overthrusting reached 7.7–12.3 mm/a at that time. During the Late Badenian–Sarmatian time the rate of advance of the Carpathian wedge was probably less than that of pinch-out migration and, as a result, the basin widened. The Miocene convergence of the Carpathian wedge resulted in the migration of depocenters and onlap of successively younger deposits onto the foreland plate.

Regional setting

The Polish Carpathians are a part of the great arc of mountains, which stretch for more than 1,300 km from the Vienna Forest to the Iron Gate on the Danube. In the west, the Carpathians are linked with the Eastern Alps and on the east they pass into the Balkan chain. Traditionally, the Western Carpathians have always been subdivided into two distinct ranges. The Inner Carpathians are considered the older range and the Outer Carpathians the younger one (Fig. 1). The Inner Carpathians contact along the Tertiary strike-slip boundary with the Pieniny Klippen Belt (PKB), which is a strongly tectonized terrain about 800 km long and 1–20 km wide (Birkenmajer, 1986). The PKB is separated from the Outer Carpathians by the Miocene sub-vertical strike-slip fault (Birkenmajer, 1986). The Outer Carpathians are built up of stacked nappes and thrust-sheets which reveal different lithostratigraphy and structure. The Outer Carpathians are composed of the Late Jurassic to Early Miocene mainly turbidite (flysch) deposits, completely uprooted from their basement.

The largest and innermost unit of the Outer Carpathians is the Magura nappe — an Early Oligocene accretionary wedge (Oszczypko, 1992). The Magura nappe is flatly overthrust onto the Moldavides (Sandulescu, 1988) — an Early/Middle Miocene accretionary wedge, which consists of several nappes: the Fore-Magura-Dukla group, Silesian, Sub-Silesian, Skole and Boryslav–Pokuty units. In the Flysch Carpathians the main decollement surfaces are located at different stratigraphic levels. The Magura nappe was uprooted from its substratum at the base of the Turonian–Senonian variegated shales (Malinowa Fm.). The second important detachment level is located at the base of the Lower Eocene variegated shales (Łabowa Fm.). The Fore-Magura group of units shows several detachment layers, i.e., in the Upper Cretaceous distal flysch deposits through Oligocene black shales. The main decollement surfaces of the Moldavides are located in the Lower Cretaceous black shales. All the Outer Carpathian nappes are flatly overthrust onto the Miocene deposits of the Carpathian Foredeep (see Oszczypko & Tomaś, 1985 and Żytko et al., 1989). However, along the frontal Carpathian thrust a narrow zone of folded Miocene deposits was developed [Stebnik (Sambor–Rozniatov) and Zgłobice units] The detachment levels of the folded Miocene units are connected with Lower and Middle Miocene evaporites. From the west to east, the front of the Polish Flysch Carpathians is built up by more and more external units. This is the result of discrepancy between the main direction of overthrusting and structural trending of the basement.

The basement of the Carpathian Foredeep represents the epi-Variscan platform and its cover (Oszczypko et al., 1989). The present-day structure of the basement was formed during the Late Alpine continental collision (Fig. 2). The depth to the platform basement, recognised by boreholes, oscillates from a few hundred metres in the marginal part of the foredeep up to more than 7,000 m beneath the Carpathians.

The magnetotelluric soundings in the Polish Carpathians have revealed a high resistivity horizon, which is connected with the consolidated-crystalline basement (Ryłko & Tomaś, 1995; Żytko, 1997). The depth of the magnetotelluric basement varies from 3–5 km in the northern part of

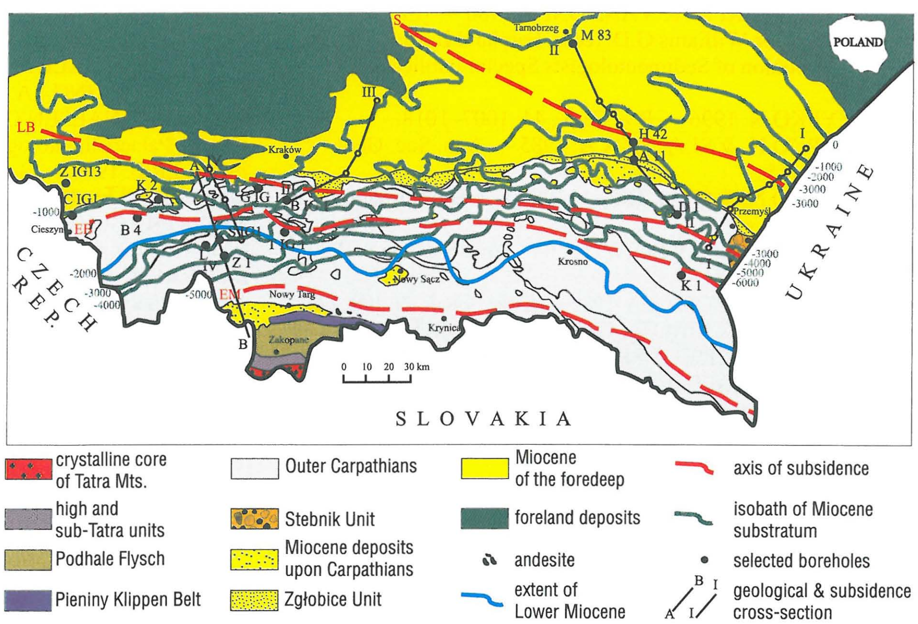

Fig. 1. Sketch-map of the Polish Carpathians and their foredeep (after Oszczypko, 1996, supplemented); EM — Early Miocene, EB — Early Badenian, LB — Late Badenian, S — Sarmatian

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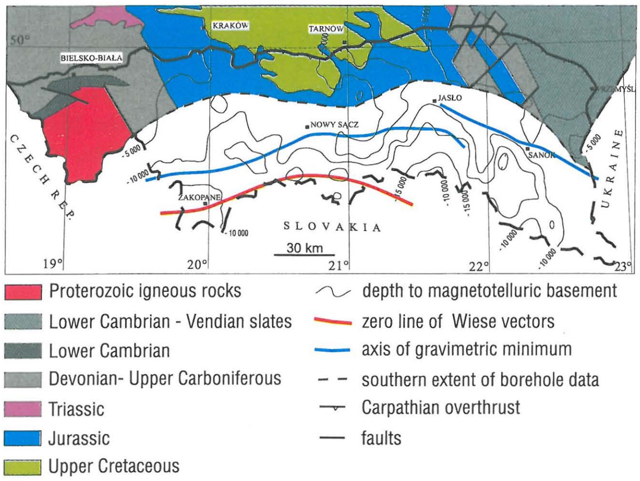
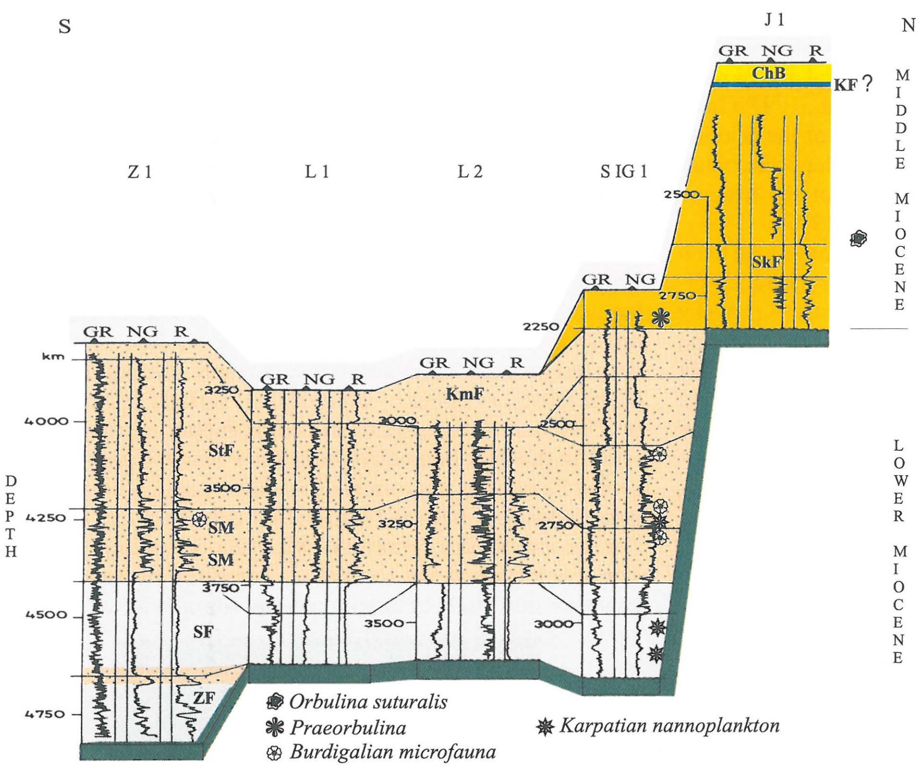


Fig. 2. Sketch map of the platform basement of the Polish Outer Carpathians (after Oszczypko, 1996)

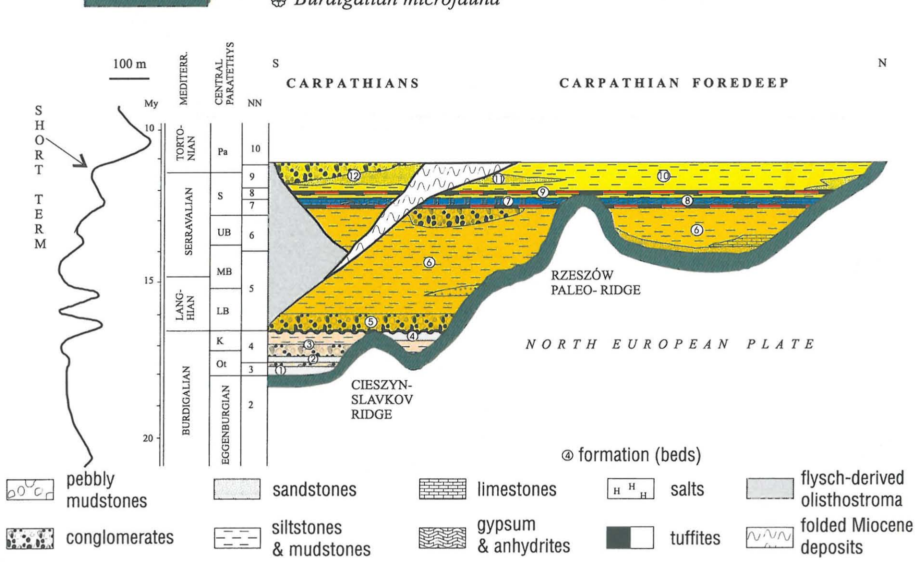
the Carpathians, dips to approximately 15–20 km at its deepest point and then peaks at 8–10 km in the southern part. The axis of the basement coincides, more or less, with the axis of gravimetric minimum (Fig. 2). South of the gravimetric minimum and, more or less parallel to the PKB, the zone of zero values related to of the Wiese vectors was recognised by geomagnetic soundings. This zone is connected with a high conductivity body occurring at a depth of 10–25 km and is located at the boundary between the North European Plate and the Central West Carpathian Block (Żytko, 1997), which is the northern tip of Apulia (Adriatic) Plate. In the Polish Carpathians, the depth to the crust-mantle boundary ranges from 37–40 km at the front of the Carpathians and increases to 50 km towards the south and, then, peaks along the PKB at 36–38 km.

Miocene deposits of the Outer Carpathians and Carpathian Foredeep

The Miocene deposits have been discovered in both the Outer Carpathians and in the Carpathian Foredeep. In the Outer Carpathians the Lower Miocene deposits were incorporated into the Moldavides accretionary wedge. These deposits represent the youn-



← **Fig. 3.** Log cross-section of the sub-thrust Miocene deposits (Zawoja–Sucha area, Polish Western Carpathians); lithostratigraphic correlation after Ślączka (1977), Moryc (1989), Połtowicz (1995), supplemented; ZF—Zawoja Fm., SF — Sucha Fm., StF — Stryszawa Fm., SM — Stachorówka Conglomerate Mb., KmF — Komorowice Fm. (Dębowiec Cgl.), SkF — Skawina Fm., KF — Krzyżanowice Fm. (anhydrite), ChB — Chodenice beds; biostratigraphy after Strzępka (1981), Połtowicz (1995), Garecka et al. (1996) and Gonera (pers. comm., 1997)



← **Fig. 4.** Lithostratigraphic model of Miocene deposits of the Polish Carpathian Foredeep (after Oszczypko, 1996); chronostratigraphy of the Central Paratethys after Steininger et al. (1990) and global sea level oscillations after Haq et al. (1987); lithostratigraphic units: 1 — Zawoja Fm., 2 — Sucha Fm., 3 — Stryszawa Fm., 4 — Zamarski Mb. of Zebrzydowice Fm., 5 — Dębowiec Cgl., 6 — Skawina Fm. and Baranów Bds., 7 — Wieliczka Fm. (salts), 8 — Krzyżanowice Fm. (anhydrites), 9 — Chodenice Bds., 10 — Grabowiec and Krakowiec Bds., 11 — Bogucice Ss., 12 — Nockowa Bds. and Bela Fm.; Ot — Ottnangian, K — Karpatian, LM — Lower Miocene, LB — Lower Badenian, MB — Middle Badenian, UB —Upper Badenian, S — Sarmatian, Pa —Pannonian gest strata of the flysch sequence. In the Silesian and Skiba (Skole) units of the Ukrainian Carpathians the Oligocene–Miocene boundary is located above the horizon of Jasło (Holovets) Limestone (see Andreyeva-Grigorovich et al., 1997). In the Silesian unit above that horizon lies the middle and upper part of the Krosno Formation, whereas in the Skole and Boryslav–Pokuty units the Upper Menilite and Polanitsa Formations are represented. The youngest deposits of the Boryslav–Pokuty unit belong to the Vorotyshche Formation which records the transition from flysch deposits to evaporites (gypsum and rock salt). Locally, this formation is intercalated with a very thick sequence of Sloboda and Dobrotiv conglomerates bearing the footprints of vertebrates and birds (deltaic deposits?).

The age of the youngest deposits of the Ukrainian Carpathians has been determined as the Early–Middle Burdigalian (Eggenburgian–Ottnangian -NN 2-3). The identical age of the Krosno Formation has been reported from the Silesian Unit in Poland (Ślęzak et al., 1995). According to Koszarski et al. (1995), in the Krosno Fm. of the Skole unit, the following calcareous nannoplankton zones have been recognised: NP 24/25 (Late Oligocene), NN 1, NN 2, NN 3, NN 4 (Early Miocene), and NN5 (Early–Middle Badenian), which seems to be impossible, according to all known geological and biostratigraphic data (see Andreyeva-Grigorovich et al., 1997; Garecka & Olszewska, 1997). In the southern part of the Silesian Unit near Gorlice, the Lower Miocene marine deposits containing flysch blocks, derived from the front of the Magura Nappe, have been recently found (Jankowski, 1997).

The flysch-derived olistostrome deposits have also been reported from the sub-Silesian unit near Andrychów (Wójcik et al., 1996). The Ždanice and Pouzdrany units (Krhovsky et al., 1995) of the Southern Moravia (Czech Rep.) contain Early Miocene (NN 1 and NN 2 zones) marine, marly deposits which are overlain by the Krosno-like strata without biostratigraphic evidence (Ottnangian?). Probably the Lower Miocene? strata have also been discovered by Cieszkowski (1992) in the Orava area (Magura nappe, SW Poland), but their relationship to the Magura nappe is still not clear. These deposits could be an equivalent to those of the Lower Miocene in the Vienna Basin.

The Polish Carpathian Foredeep (PCF) can be subdivided into two parts, the outer and inner ones (Oszczypko, 1982). On the Polish territory the width of the outer foredeep (outside the Carpathians) varies between 30–40 km in the western segment and it is up to 90 km in the eastern part (Fig. 1). The outer foredeep is filled up with the Middle Miocene (Badenian and Sarmatian) marine deposits, which range from a few hundred metres in thickness in its northern-marginal part, up to 3,500m in the south-eastern part. The inner foredeep, located beneath the Carpathian nappes, is more than 50 km wide (Fig. 1, see also Oszczypko & Ślączka, 1989) and is composed of Lower to Middle Miocene autochthonous deposits. Although these deposits were tectonically eroded by the Carpathian nappes, their preserved thickness is up to 1,500 m. The Lower Miocene strata are mainly terrestrial in origin, whereas the Badenian and Sarmatian ones are marine. In the Polish Carpathians, the oldest Lower Miocene strata that record the transition from flysch to molasse development of the foreland basin, have not been recognised yet. These deposits, associated with the Boryslav–Pokuty and Pouzdrany basins, are probably buried beneath the Carpathians, somewhere in the magnetotelluric depression (Fig. 2, see also Żytko, 1965).

The oldest autochthonous Lower Miocene strata, up to 1, 000 m thick, have been pierced by the Zawoja-1 borehole (Moryc,1989; Połtowicz, 1995). These deposits, 159 m thick, are known as the Zawoja Fm. (Figs. 3, 4 see Moryc, 1989). The formation is not homogenous and differs from the bottom towards the top. The bottom of this formation is represented by dark matrix-supported conglomerates, passing upward into folded and faulted (slump folds?), dark laminated mudstones (Fig. 5) and dark-grey pebbly mudstones (Fig. 6), covered by green, calcareous-free siltstones with red irregular lamination or haemathite coating. The top of the siltstones is cut by an erosional surface and covered by 25 metres of coarse-grained, matrix supported conglomerates. In the dark laminated mudstones scarce Upper Cretaceous–Paleocene microfauna has been found, whereas the green siltstones with red lamination contain poor, Middle Eocene arenaceous forams (E. Malata, pers. comm. 1997). The lower part of the formation, deposited by subaqueus cohesive flow and containing chaotic slump bodies, passes

Fig. 5. Folded and faulted, dark laminated mudstones and siltstones (borehole Zawoja-1, Zawoja Fm., depth 4751–4759 m)

Fig. 6. Quartz and quartzite dominated dark pebbly mudstone (borehole Zawoja-1, Zawoja Fm., depth 4736–7745 m)

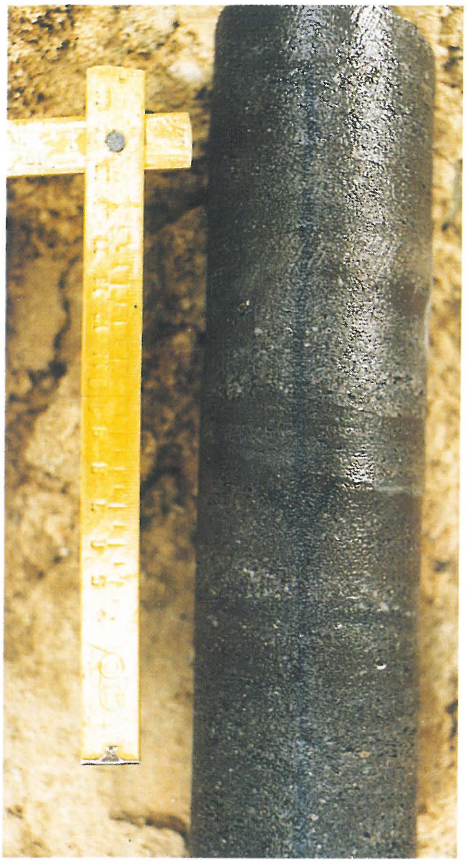


Fig. 7. Medium to coarse-grained, matrix supported sandstone with intercalation of brick-reddish mudstones (borehole Zawoja-1, Stryszawa Fm. (Karpatian?), depth 4137–4144 m)

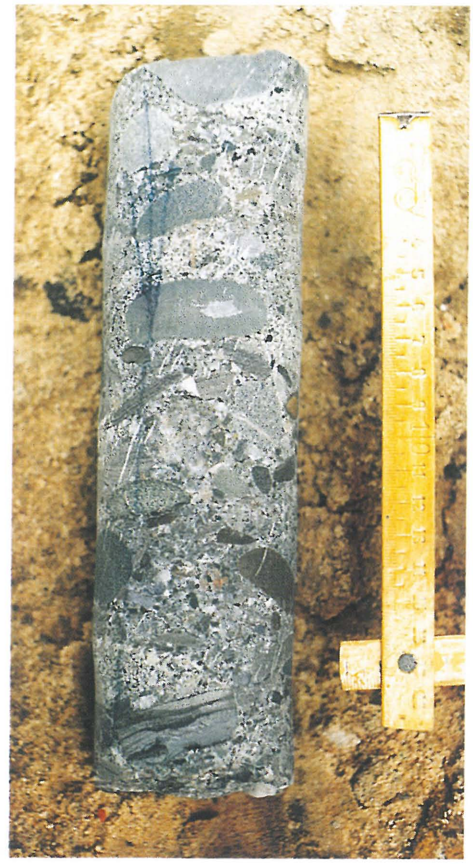


Fig. 8. Coarse conglomerate, rich in flysch-derived clasts, with carbonate-anhydrite cement (borehole Zawoja-1, Stryszawa Fm. (Karpatian ?), Stachorówka Mb, depth 4225–4228 m)

upward into low-density distal turbidites and green-red hemipelagites(?). Sedimentological features of these deposits show their similarity to the Paleogene canyon deposits known from northernmost marginal facies of the Paleogene Tethys (Southern Moravia, see Picha, 1979, 1996). The lithological and micropaleontological observations suggest that during the Late Cretaceous/Paleocene and Eocene times this basin revealed a close similarity to the Skole development. In this view, the so called "outer flysch" from the Wadowice area (see Książkiewicz, 1977) may also be connected with this sequence. These conclusions partly contradict Moryc's (1989) opinion, who regards the whole Zawoja Fm. as autochthonous molasse deposits.

According to my suggestion, only the uppermost part of the Zawoja Fm. shows molasse development (Fig. 3). The Zawoja Fm. is covered by a 260 to 370 m thick flysch-derived olistoplaque (Moryc, 1989; Baran et al., 1997). The olistoplaque described by Ślączka (1977) as the Sucha Fm. is known from the: Sucha IG-1, Zawoja-1 and Lachowice 1 and 2 (Figs. 1, 3, see also Ślączka, 1977 and Moryc, 1989), as well as Lachowice 3a boreholes (Baran et al., 1997). In the Sucha IG-1 borehole this formation is composed of a few separate flysch olistoliths, differing in age (Paleocene to Lower Cretaceous, see Ślączka, 1977). The material of the olistoliths shows connection with both the Silesian as well as sub-Silesian succession (Liszkowa, 1977). In the Zawoja-1 borehole the formation is represented by a uniform sequence of dark, calcareous-free shales with sporadic intercalations of thin-bedded, very fine-grained sandstones. These deposists corespond with the Veřovice Shales and Lgota Formation of the sub-Silesian-Silesian units. There also is close similarity to the Spas Shales of the Skole unit. The age of the black deposits from the Zawoja-1 borehole has been determined by the Dinoflagellata studies as the Aptian–Late Albian (Gedl, in press). The lower part of the black shales reveals Albian arenaceous microfauna (E. Malata, pers. comm., 1997). In the borehole considered, within the upper portion of the Lower Cretaceous strata, an isolated fragment of red shales (Upper Cretaceous–Eocene, E. Malata, pers. comm., 1997) has been found. In the Sucha–Zawoja area the flysch olistoplaque is overlapped by the Stryszawa Formation (Fig. 3, see also Ślączka, 1977; Moryc, 1977) which is composed of terrigenous deposits, probably terrestrial in origin that reach a thickness of 360–566 m (Fig. 3). These deposits are composed of coarse to medium-grained, polimictic conglomerates (Stachorówka Member, see Ślączka, 1977; Moryc, 1989) with carbonate and, locally, gypsum-anhydrite cement (Fig. 7). The thickness of these conglomerates varies between 140 m (Sucha IG-1) to 229 m (Lachowice 2), rising up to 650 m in borehole Ślemień-1 (Baran et al., 1997) The material was derived both from the crystalline and Palaeozoic basement of the Carpathian Foredeep, as well as from the front of the Carpathian nappes (see also Moryc, 1989). It should be stressed out that the conglomerates pierced in Ślemień-1 borehole are very rich in carbonate clasts, derived from the Palaeozoic platform basement (Baran et al., 1997). The Stachorówka Conglomerate Member shows features of alluvial deposits, passing upwards into variegated, conglomeratic-sandy-mudstone strata. (Fig. 8, see also Palensky et al., 1995). The granule conglomerates, and very coarse to medium grained sandstones are usually thin to medium-bedded. Conglomerates and

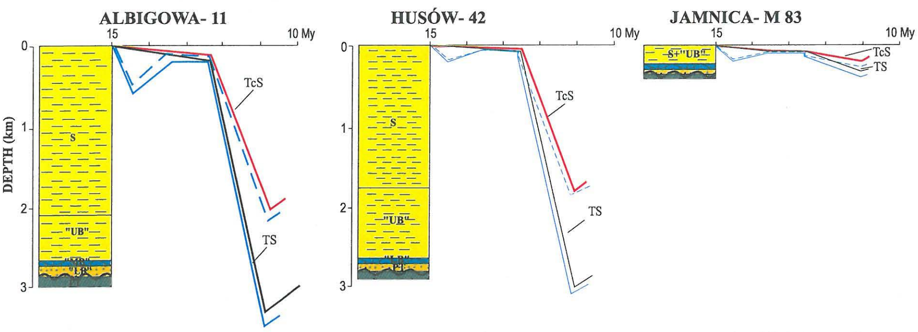


Fig. 9. Miocene geohistory diagrams of the outer foredeep; PT — Proterozoic, "LB" — "Lower Badenian", "MB" — "Middle Badenian", "UB" — "Upper Badenian" and S — Sarmatian, Tc — tectonic subsidence, Ts — total subsidence

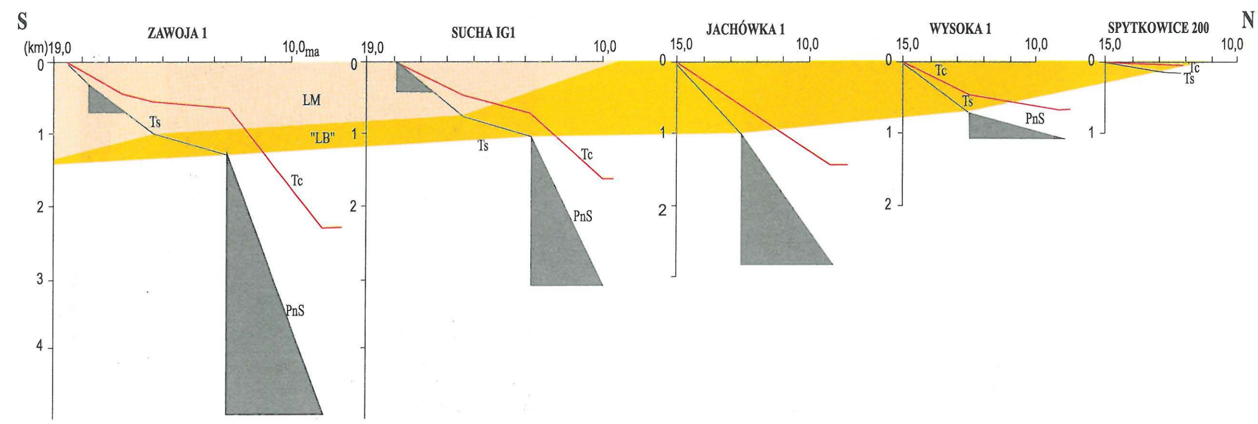


Fig. 10. Subsidence cross-section IV–IV

which flooded both the foredeep and marginal part of the Carpathians. In the foredeep, the Badenian** strata rest directly on the platform basement, except of the SE part of the inner foredeep, where they cover Lower Miocene deposits. The Lower Badenian (Kuciński et al., 1975; Ney, 1968; Ney et al., 1974) begins with a thin layer of conglomerates (up to 200 m in the western part of foredeep), passing upwards into dark, clayey-sandy sediments (Skawina Fm). The thickness of

sandstones are rich in matrix, often red coloured by iron oxides (Fig. 8). The cement is carbonatic and gypsum-anhydritic one (A. Lucińska, pers. comm., 1997). The upper part of the Stryszawa Formation (Bielsko Mb according to Moryc, 1989) is 210 to 240 m thick. This part of the formation was probably deposited as an aluvial fan. The Stryszawa Fm. contains relatively frequent recycled flysch microfauna of the Lower Cretaceous–Oligocene age, showing connection with the sub-Silesian development (E. Malata, pers. comm. 1997). The microfauna is both agglutinated as well as planktonic one. In the Sucha IG-1 borehole (Strzępka, 1981; Garecka et al., 1996), the Lower Miocene (Ottnangian–Karpatian?) microfauna has been found in the sporadic samples. Recently, M. Gonera (pers. comm., 1997) has found in the borehole Zawoja-1 (depth 4271–4278 m) the assemblage which allows one to make assumption that its age is Eggenburgian–Ottnangian (N5-N6). This microfauna is representative for the middle-upper bathyal depths (see also Kovač et al., 1993). There is contradiction between sedimentary record of the Stryszawa Fm. which reveals shallow-water and/or terrestrial origin, and deep-water character of microfauna. This suggests that the above-mentioned microfauna was also recycled from the youngest (Lower Miocene) flysch strata(?).

The Karpatian (NN 4) calcareous nannoplankton has also been reported from the Stryszawa Fm. (Garecka et al., 1996). In the Bielsko–Cieszyn area there occur green-grey mudstones with intercalations of conglomerates (Bielsko and Zebrzydowice Formations, see Kuciński & Nowak, 1975 and Buła & Jura, 1983) which could be interpreted as a marine equivalent of the Stryszawa Fm. (see Garecka et al., 1996; Oszczypko, 1996). The Middle Miocene began with the extensive Early Badenian marine transgression

the Lower Badenian deposits is variable, reaching up to 1000 m in the western inner foredeep, whereas in the remaining parts of the foredeep it rarely exceeds 30–40 m (see Ney et al., 1974). The sedimentation of the Skawina Fm. began in the inner foredeep with *Preorbulina glomerosa* zone (N 8), whereas in the outer one with the *Orbulina suturalis* (N 9 or N 10) zone (Kuciński et al., 1975; Szotowa, 1975; Garecka et al., 1996; see also Oszczypko, 1996). According to the nannoplankton studies, this formation belongs to NN 5 zone, and in the uppermost part to NN 6 zone (Andreeva-Grigorovich, 1994; see also Garecka et al., 1996). The radiometric age of tuffite from the uppermost part of the Skawina Fm. in the Wieliczka Salt Mine (WT-1, see Bukowski & Szaran, 1997) has been determined as 12,5±0,9 Ma BP (M. Banaś & K. Bukowski, pers. comm., 1997). The evaporitic horizon, traditionally regarded as Middle Badenian in age, either overlies these deposits or rests directly upon the platform basement. The horizon consists of rock salts, claystones, anhydrites, gypsum and marls (Figs. 4, 15). Between Wieliczka and Tarnów the thickness of salts attains 70–110 m (Garlicki, 1968; Bukowski & Szaran, 1997) and decreases towards the east to a few dozen metres, whereas the thickness of gypsum and anhydrites commonly varies between 10 and 30 m. According to nannoplakton investigations (Peryt & Peryt, 1994; Gaździcka, 1994; Karoli et al., 1994), the age of the evaporitic horizon could be estimated as the NN 6/7 zone. The evaporitic horizon passes upwards into

**The Badenian deposits in Poland are traditionally subdivided into Lower Badenaian (sub-evaporite), Middle Badenian (evaporite), and Upper Badenian (supra-evaporite) beds. The subdivision is in contradiction to the recent nannoplankton and isotope investigations (see Fig. 4)

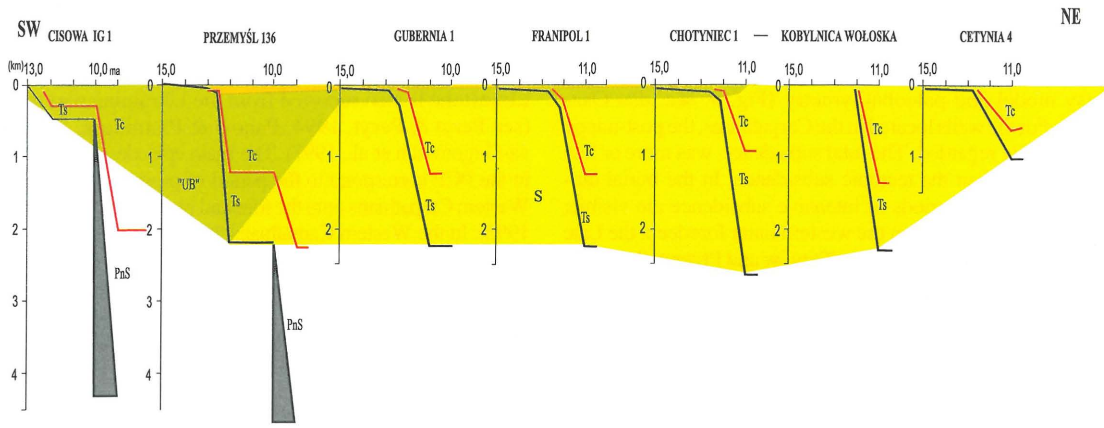


Fig. 11. Subsidence cross-section I–I

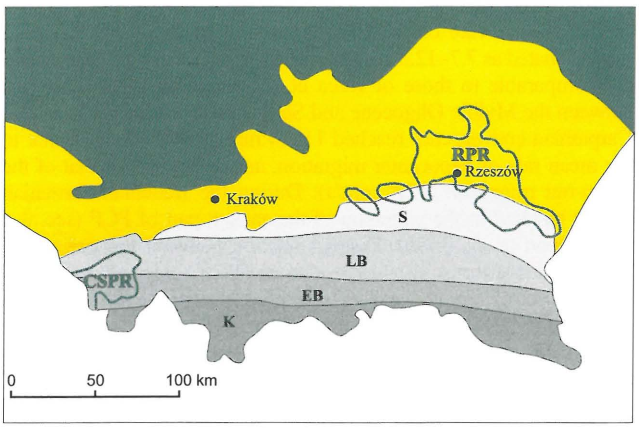


Fig. 12. Palinspastic sketch-map of the Polish Carpathians during the Karpatian (K), Early Badenian (EB), Late Badenian (LB) and after Late Sarmatian (S) (after Oszczypko, 1996); CSPR — Cieszyn–Slavkov paleo-ridge, RPR— Rzeszów paleo-ridge

the Upper Badenian–Sarmatian (NN 8/9 zone, see Gaździcka, 1994) sandy-silty deposits with a thick sandstone complex at the base. Their thickness ranges from a few hundred metres in the Tarnów area up to 3,000 meters near Przemyśl. In the Rzeszów area these deposits rest directly on the platform basement. In the Ukrainian part of the foredeep the thickness of the Upper Badenian–Sarmatian deposits reaches up to 5,000 m (see Andreyeva-Grigorovich et al., 1997). In the Kraków–Bochnia region at the top of evaporitic horizon there occur silty-sandy deposits (Chodenice beds) with few intercalations of tuffites. The deposits overlying the tuffites are rich in radiolarian assemblages (see Barwicz, 1996). The radiometric age of these tuffites is around 12 Ma BP (Fig. 4, see also Van Couvering et al., 1981). The development of the folded Miocene units (Fig. 1) in the Polish Carpathian Foredeep was strongly controlled by both the slope of the Carpathian overthrust surface and the depth of the platform basement (Oszczypko & Tomaś, 1985).

The Stebnik (Sambor–Rozniatov) unit has been recognised at the front of the Skole nappe SE of Przemyśl, as well as beneath this nappe (Ney, 1968; Garecka & Olszewska, 1997). The Stebnik unit is composed of both the Lower (up to 2 200 m thick, see Ney, 1968) and Middle Miocene strata (up to the Sarmatian, see Andreyeva-Grigorovich et al., 1997; Garecka & Olszewska, 1997). In the Ukrainian Carpathians, the folded Lower Miocene molasses are known from Boryslav–Pokuty as well as Sambor–Rozniatov units (Andreyeva-Grigorovich et al., 1997). These deposits belong to the Stebnik and Balich formations. The Stebnik Fm., up to 3,000 m thick, is composed of variegated clays with intercalations of sandstones and gypsum lenses. The formation contains the Ottnangian foraminifers and, probably, Karpatian nannoplankton(see Andreyeva-Grigorovich et al., 1977). The Stebnik Formation is overlain by the Balich Fm., up to 600 m thick and it is represented by grey and green-grey limy clays with intercalations of sands and sandstones. In the lower part of the formation, the intercalations of pink clays and argillites are observed. The nannoplakton studies determine the age of the formation as the Karpatian (NN-4), but in some localities the Early Badenian species *Preorbulina glomerosa* and *Orbulina universa* have been discovered (see Andreyeva-Grigorovich et al., 1997; see also Garecka & Olszewska, 1997). The Balich Fm. is overlain by the Badenian and Sarmatian strata. The Stebnik Fm. could be compared with the Stryszawa Fm., whereas Balich Fm. is probably an equivalent of the Bielsko and partly Skawina Formations.

Between Przemyśl and Kraków, along the Carpathian frontal thrust, a narrow zone (up to 10 km) of folded Badenian and Sarmatian deposits (Zgłobice unit, see Kotlarczyk, 1985) occurs (Fig. 1). The Badenian and Sarmatian strata are also preserved as erosional outliers in the Polish Outer Carpathians. The southernmost occurrence of the Upper Badenian/Sarmatian marine sediments is known from the Nowy Sącz Basin (Oszczypko et al., 1992). In the Cieszyn–Wadowice area, the Lower and Upper Badenian ? deposits are incorporated into the sub-Silesian and Silesian units. The Zawoja-1 borehole reached the parautochthonous Lower Badenian? deposits beneath the Magura Nappe (Moryc, 1989; Baran et al., 1997).

Burial history

The burial history of the Polish Carpathian Foredeep (see Oszczypko, 1995, 1996) was constructed on the basis of selected wells grouped in four sections, more or less perpendicular to the front of the Carpathians (Figs 1, 9–11). For computation purposes the numeric stratigraphy has been applied. This stratigraphy was constructed through correlation of local stratigraphy with nannoplankton calibration (Peryt & Peryt, 1994; Gaździcka, 1994; Andreeva-Grigorovich et al., 1995, 1997; Garecka et al., 1996) and rare radiometric data (Van Couvering et al., 1981; M. Banaś & K. Bukowski, pers. comm., 1997), as well as with global correlations (Berggren et al., 1995; Steininger et al., 1990) and sea level chronology (Haq et al., 1987).

The procedure of Van Hinte (1978), Sclater and Christie (1980), Angevine et al. (1990), and Allen & Allen (1992) has been used for computation (see also Oszczypko, 1996). The final diagrams have been produced using the PC program "SUBSIDE"

(Hsui, 1993). The program plots the total subsidence curve of the decompacted sediments and tectonic subsidence. For selected boreholes backstripped subsidence was corrected using simplified Airy isostasy model and paleobathymetry (Fig. 9, see also Oszczypko, 1996). For the wells located in the Carpathians, the post-nappe load was additionally regarded. The total subsidence was more or less 1.7–1.8 times higher than the tectonic subsidence. In the burial diagrams (Figs. 9–11) three periods of intensive subsidence are visible: the Karpatian (Early Badenian) in the western inner foredeep, the Late Badenian in the inner foredeep between Tarnów and Przemyśl, and the Sarmatian in the outer foredeep between Rzeszów and Przemyśl (Fig. 11). During the Karpatian–Badenian times, axes of subsidence were more or less subparallel to the Carpathian front, whereas the Sarmatian axis was clock-wise rotated by up to 20 degrees (Fig. 1, see also Oszczypko & Żytko, 1987).

As a rule, the maximum of subsidence was located at the front of the Carpathians. The subsidence took place not only on the foreland plate but also on the marginal part of the Carpathian accretionary wedge (Fig. 13, see also Oszczypko & Ślączka, 1989).

During the Karpatian–Sarmatian the axis of subsidence was shifted about 80 km outwards. The mean rate of the emplacement could be estimated as 10–12 mm/a. In the Polish foredeep, both the Karpatian–Early Badenian and Late Badenian subsidence reached 1.5 to 2. 0 km, whereas the Sarmatian subsidence was 2.5–3.0 km (Fig. 11). Towards the SE subsidence increased and in the Ukrainian sector reached 3.5 and 4.0 km, during the Early Miocene and Sarmatian, respectively (see Andreyeva-Grigorovich et al., 1997). In the initial stage (Karpatian) of molasse development the rate of subsidence was fully compensated by the rate of deposition. It resulted in terrestrial and shallow marine? sedimentation. Since the Early Badenian (Langhian) marine transgression, the rate of subsidence was higher than the rate of deposition. It resulted in marine sedimentary conditions during the Badenian and Sarmatian times. The paleobathymetry of the Badenian–Sarmatian basin varied from the upper bathyal depths during the Early Badenian to littoral-lagoonal depths during the salinity crisis. It was probably followed by nonmarine conditions, and then by the outer neritic and inner neritic depths during the Late Badenian and Sarmatian, respectively (Gonera, 1994; Kasprzyk, 1993; Czepiec, 1997). The Late Badenian subsidence was preceded by the Badenian salinity crisis when the rates of subsidence and deposition were extremely low. This resulted locally in a post-evaporite, elastic rebound of the foreland plate, and in erosion of at least 50–100 m of evaporitic and sub-evaporitic deposits (see Rzeszów Paleoridge, Figs. 1, 4, 15, see also Komorowicz-Błaszczyńska, 1965; Połtowicz, 1997). The subareal erosion of the anhydrites before deposition of the Ratyn Limestone is also reported from the Ukrainian part of the foredeep (see Peryt & Peryt, 1994; Panow & Płotnikow, 1996 and Andreyeva-Grigorovich et al., 1997). The main episodes of intensive subsidence in the PCF correspond to the period of progressive emplacement of the Western Carpathians onto the foreland plate (Fig. 12, see also Oszczypko, 1996). In the Western Carpathians there is abundant evidence that overthrust of the Carpathians onto the foreland plate was progressive (see Jurkova, 1979; Oszczypko & Tomaś, 1985; Oszczypko & Ślączka, 1985, 1989; Oszczypko, 1996).

According to my estimation, the multistage overthrusting of the Polish Outer Carpathians took place during the following periods:

1) before deposition of the Stryszawa Fm. (after Ottangian and before Karpatian),

2) before the Early Badenian,

3) during the Late Badenian, and after the Sarmatian (4).

The mean rate of the Carpathian frontal thrusting could be approximated as 7.7–12.3 mm/a (see Oszczypko, 1996). These values are comparable to those of Roca et al. (1995) who conclude that between the Middle Oligocene and Sarmatian times the mean rate of Carpathian convergence reached 11–14 mm/a. This rate is similar to the mean rate of depocenter migration, and is lower than that of the pinch-out migration (13,8 mm/a). During the Badenian-Sarmatian time it resulted in the widening of the eastern part of PCF (see also Homewood et al., 1986). Distinct relation between the periods of Carpathian overthrusting and subsidence of PCF suggests that the main driving force of subsidence was the emplacement of the tectonic nappe load. Each emplacement of the Carpathian front initiated a new period of subsidence. During the Early–Middle Miocene time the loading effect of the thickening Carpathian wedge on the foreland plate increased and caused a progressive increase of the total subsidence. However, Royden & Karner (1984), Royden (1993) and Krzywiec & Jochym (1997) have suggested that the supracrustal load was inadequate to explain the observed deflexion of the foreland plate in the Carpathians and postulated the existence of an additional subsurface "load" on the subducted plate. According to other authors, however, this extra "load" could be taken into account only during the early collisional history (see discussion in Miall, 1995).

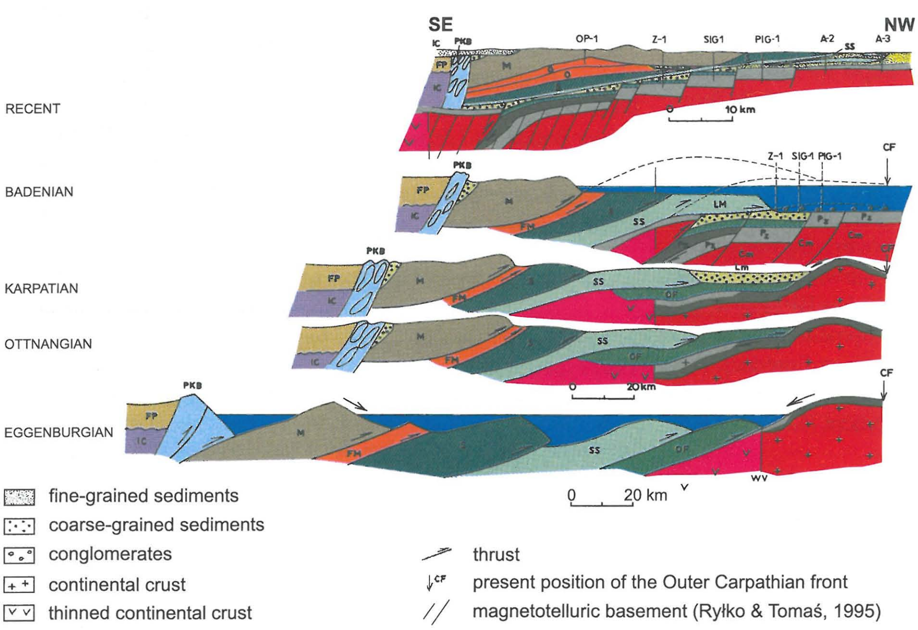


Fig. 13. Palinspastic cross-section through thePolish Western Carpathians (Chyżne–Zawoja–Andrychow); IC — Inner Carpathians, FP — Podhale Flysch, PKB — Pieniny Klippen Belt, M — Magura nappe, FM — Fore-Magura unit, S — Silesian unit, SS — sub-Silesian unit, OF — "Outer Flysch" (Skole unit ?)

Basin evolution

The Outer Carpathian basin, located along the nothern margin of the Tethys, was probably partly developed on an oceanic or thinned continental crust (Birkenmajer, 1986). Similarly to other orogenic belts, the Outer Carpathians were progressively folded towards the continental margin. At the very beginning, the Magura and probably the Fore-Magura basins were folded and thrust towards the north after the Middle Oligocene and before the Early Burdigalian (Eggenburgian–NN 1). This period of folding, thrusting and erosion is postdated by the Eggenburgian trasngression on the Magura nappe in the Vienna Basin (Wessely, 1993). In the more northern part of the Carpathian basin, the terminal flysch sedimentation persisted up to the Middle Burdigalian (Ottangian–NN 3, see Melinte, 1995;

Andreyeva-Grigorovich et al., 1997; Ślęzak et al., 1995; Oszczypko, 1996), when the upper part of the Krosno Fm. was deposited (Figs. 13, 14). The width of the Outer Carpathian Flysch basin before folding is still under discussion. It is related to the amount of the Neogene shortening and character of the basement crust. Recently published balanced cross-sections try to aproximate these values. According to Roure et al. (1993), in the eastern part of the Polish Carpathians, between the inner part of the Silesian unit and the foreland, the minimun amount of Neogene shortening reaches 130 km (restored width measuring 190 km). In another cross-section (Brzesko–Nowy Targ), the minimum amount of the Middle Oligocene to Late Sarmatian shortening between Pieniny Klippen Belt and the foreland reaches 180 km (restored width of basin measuring 235 km, see Roca et al., 1995).

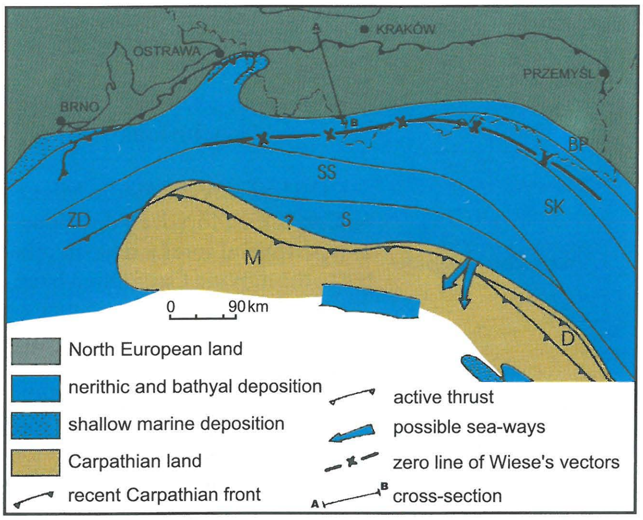


Fig. 14. Palinspastic sketch-map of the Carpathian Foreland Basin during the Early Burdigalian (Eggenburgian) (after Kovač et al., 1989 and Oszczypko & Ślączka, 1989; supplemented); M —Magura unit, D —Dukla unit, S — Silesian, SS — Silesian, Zd — Ždanice, SK — Skole, and BP —Boryslav–Pokuty sub-basins

During the Early Burdigalian, the Outer Carpathian flysch basin was probably narrower than that cited above (Figs. 13, 14) and the restored width of the basin probably measured 100–150 km. This restoration takes into account that the Magura basin was already folded at that time and that the intrabasinal source areas were tectonically reduced. As a result, the bulk of the material must have been derived from the eroded front of the Magura nappe and uplifted parts of the basin (Fig. 14). During that time a sizeable amount of the eroded and reworked flysch material was transported by debris flows from uplifted sub-marine highs and deposited in the basin. During the Early Burdigalian the axial part of the basin reached bathyal depths. Contemporaneously with residual flysch deposition, a marine piggy back basin (?connected with the Vienna Basin) was developed (Cieszkowski, 1992) on the the Magura nappe along the Pieniny Klippen Belt strike-slip boundary.

During the Ottnangian, the Late Krosno (Polanitsa) basin shifted towards the north (Ždanice unit-Czech Rep., Boryslav–Pokuty unit-Ukraine, and Marginal Folds unit-Romania), and finally underwent dessication [(Krepice Fm. in Moravia (Krhovsky et al., 1995)], evaporites of the Upper Vorotyshche Fm. in the Ukraine (Andreeva-Grigorovich et al., 1997) and the Salt Fm. in Romania (see Micu, 1982)]. Following the evaporitic sedimentation (Middle Burdigalian), the Carpathian Foredeep began to form simultaneously with the folding, overthrusting and inversion of the Outer Carpathians (Oszczypko & Ślączka, 1989). The Carpathians overrode the platform and caused flexural depression of the foreland and uplift of a peripheral bulge (Cieszyn–Slavkov Paleoridge, Figs. 1, 13) at that time. The flysch olistoplaque, recognised in the Zawoja-1 borehole, probably records that period of overthrusting. From that moment the Carpathian Foredeep began to develop as a peripheral foreland basin related to the moving Carpathian front. The northern edge of the Late Burdigalian (Karpatian) molasse basin was located about 20 to 50 km south from the present-day position of the Carpathian thrust (Figs. 1, 13). The basin, partly developed on top of the advancing Carpathian front, was dominated by the terrestrial deposition and filled up mostly with products derived from the emerged platform, as well as those from the front of the Carpathians (Stryszawa Fm. (Poland), Dobrotiv and Stebnik Formations (Ukraine), and red beds in Romania (Magiresti and Hirja beds, see Micu,

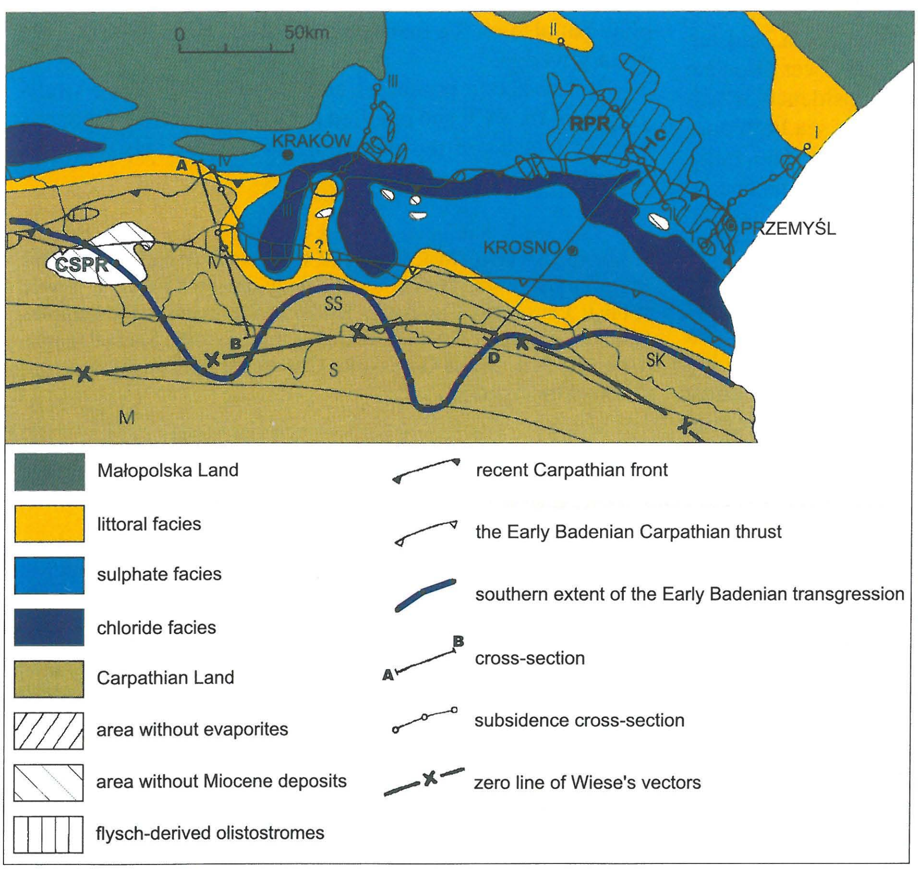


Fig. 15. Palinspastic sketch-map of the Carpathian Foreland Basin during Badenian salinity crisis (after Oszczypko & Ślączka, 1989 and Połtowicz, 1993; suplemented)

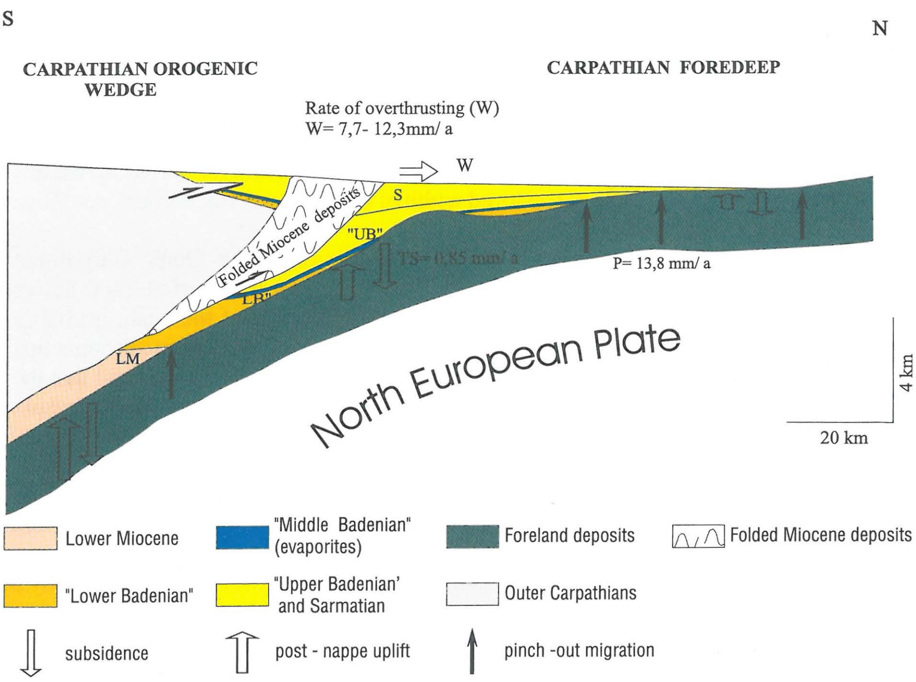


Fig. 16. Paleodynamic model of the Polish Carpathian Foredeep — middle part (after Oszczypko, 1996); TS —mean total subsidence mm/a, P —rate of pinch-out migration mm/a

1982). These deposits formed a clastic wedge along the Carpathians, comparable with the fresh-water Lower Molasse of the Alpine Foreland Basin. In the Zawoja (Figs. 1, 3, 10) area, the Early Miocene total subsidence reached at least 1,500 m (1.0 mm/a), increasing up to more than 2,000 m (2.0 mm/) towards the east (Sambor–Rozniatov Basin, see Oszczypko, 1996). At the end of the Early Miocene, the front of the Carpathians shifted 15 km towards the north, and the Silesian/sub-Silesian units partly overthrust Lower Miocene molasses (Fig. 13). This caused an extra subsidence, which enabled transgression of the Early Badenian sea both onto foreland plate and the Carpathians (Fig. 15). The Early Badenian sea was relatively deep. According to paleoecological estimations (Kovač et al., 1993; Gonera, 1994), the axial part of the basin reached upper bathyal depths at that time. The Early to Middle Badenian deposits reveal highly differentiated thicknesses, from a few dozen metres in the outer foredeep up to more than 1,000 m in the inner one. At that time, the axis of subsidence was located 20 to 40 km south of the present position of the Carpathian frontal thrust (Fig. 1). At the turn of the Badenian and Sarmatian, the drop of the sea level caused regression in the Carpathians (Fig. 15). The lowstand level and climatic cooling (Demarq, 1987) initiated salinity crisis in the Carpathian foreland basin. The shallow part of the evaporite basin (Fig. 15, see also Połtowicz, 1993) was dominated by sulphate facies, whereas deeper part, located along the Carpathian front, was occupied by chloride-sulphate facies. According to Kovalevich (1997), the paleobathymetry of the chloride subbasin reached at least few dozen metres. The fall of sea level after evaporite deposition probably resulted in viscoelastic relaxation of the platform crust, and caused uplift and erosion of the Rzeszów paleo-ridge (Oszczypko, 1996). After the salinity crisis, telescopic shortening of the Carpathian nappes took place and the front of the thrust belt shifted 20–30 km towards the NE. This resulted in the "Upper Badenian" subsidence up to 1,500 m (Figs. 9, 11), collapse of the Rzeszów paleo-ridge and a new marine transgression onto the Carpathians. The Sarmatian depocenter was located in the NE part of the basin, obliquely to the Carpathians. The rate of total subsidence was relatively high, up to 3.0 mm/a. At the end of the Sarmatian the Carpathians moved towards the NE and reached present-day position. It was followed by the regional regression of the sea and elastic rebound of the lithosphere (isostatic uplift of the Carpathians, Fig. 16).

Conclusions

1) The Early to Middle Miocene Carpathian foredeep developed as a peripheral foreland basin related to the moving Carpathian front.

2) The Miocene subsidence of the PCF was controlled both by the sediment and thrust-induced load.

3) The main driving force of tectonic subsidence was the emplacement of the nappe load.

4) Each emplacement of the Carpathian front initiated a new period of tectonic subsidence.

5) During the Early–Middle Miocene time the loading effect of the thickening Carpathian wedge on the foreland plate increased and caused a progressive increase of the total subsidence.

6) The subsidence took place not only on the foreland plate but also on the marginal part of the Carpathian accretionary wedge.

7) The above processes controlled the Miocene stratigraphy of the PCF and resulted in the migration on depocenters, as well as in the onlapping of successively younger deposits onto foreland plate.

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