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THE WESTERN CARPATHIAN FOREDEEP — DEVELOPMENT OF THE FORELAND BASIN IN FRONT OF THE ACCRETIONARY WEDGE AND ITS BURIAL HISTORY (POLAND)

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Abstract: The Early to Middle Miocene Carpathian Foredeep in Poland (PCF) developed as a peripheral foreland basin related to the moving Carpathian front. The subsidence of the basin was controlled both by the sediment and thrust-induced load. The main episodes of intensive subsidence in the PCF correspond to the period of progressive emplacement of the Western Carpathians onto the foreland plate, with exception of the "dormant" Carpathian frontal thrust during the "Middle Badenian" salinary event when a low subsidence or uplift took place. The important driving force of tectonic subsidence was the emplacement of the nappe load related to the subduction roll-back. During that time the loading effect of the thickening of the Carpathian accretionary wedge on the foreland plate increased and was followed by progressive acceleration of total subsidence. The mean rate of the Carpathian overthrusting, and north to north-east migration of the axis of depocentres reached 12 mm/a at that time. During the Late Badenian-Sarmatian time the rate of advance of the Carpathian accretionary wedge was lower 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 the successively younger deposits onto the foreland plate.

Key words: Miocene, Paratethys, Outer Carpathians, Carpathian Foredeep, lithostratigraphy, overthrusting, backstripping, subsidence, basin evolution.

Introduction

The Western Outer Carpathians were folded and thrust during the Early–Middle Miocene, when the oceanic or thinned continental crust of the Outer Carpathian flysch basin was subducted below the Central and Inner Carpathians (Alcapa and Tisza-Dacia microplates). The Early to Middle Miocene subduction was accompanied by the northeastward directed escape of the Alcapa microplate, and post-Middle Badenian eastward escape of Tisza-Dacia. At the front of the moving crustal fragments overthrusting of the Outer Carpathians and formation of the flexural foreland basin took place (Csontos et al. 1992; Meulenkamp et al. 1996; Oszczypko 1997; Kováč et al. in press). In the Polish part of the Outer Western Carpathians the relationship between the folded and thrust flysch deposits and the Miocene autochthonous molasse deposits has been very well recognized from deep boreholes in the belt 30–40 km wide (see Wdowiarz 1976; Oszczypko & Tomaś 1985; Oszczypko & Ślączka 1989; Żytko et al. 1989). There is a lot of evidence that overthrusting of the Western Carpathians onto the foreland plate was progressive (see Jurkova 1979; Oszczypko & Tomaś 1985) and could be palinspastically restored (Oszczypko & Ślączka 1985, 1989; Oszczypko 1996; Kováč et al. 1989, in press; Tari et al. 1997). The aim of this work is to describe the temporal and spatial relation between the subsidence within the foredeep basin and overthrusting of the orogenic wedge in the Polish segment of the Western Carpathians.

Since the fundamental paper of Price (1973), the development of the foreland basins has been regarded as a result of lithosphere flexure caused by the loading effect of the growing thrust belt. Although, the first modelling studies confirmed this concept (Beaumont 1981), later studies (e.g. in the Carpathians and Appenines) revealed that the topographic load is not always sufficient to explain the observed deflection of the foreland plate (see Royden & Karner 1984) and it must be connected with the deep subcrustal load of the downgoing plate (Krzywiec & Jochym 1997).

Regional setting

The Polish Carpathians are a part of the great arc of mountains, which stretches for more than 1300 km from the Vienna Forest to the Iron Gate on the Danube (Fig. 1A). In the west, the Carpathians are linked with the Eastern Alps and, in 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. 1B). Between the Inner and Outer Carpathians the Pieniny Klippen Belt (PKB) is situated. It is Tertiary strike-slip boundary, consinsting of a strongly tectonized terrain about 800 km long and 1–20 km wide (Birkenmajer 1986). The Outer Carpathians consist of stacked nappes and thrust-sheets which reveal different lithostratigraphy and structure (Figs. 1B, 2). The Outer Carpathians are composed of 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 — a Late Oligocene/Early Miocene accretionary wedge. The Magura Nappe is horizontally overthrust onto the Moldavides (Săndulescu 1988) — an

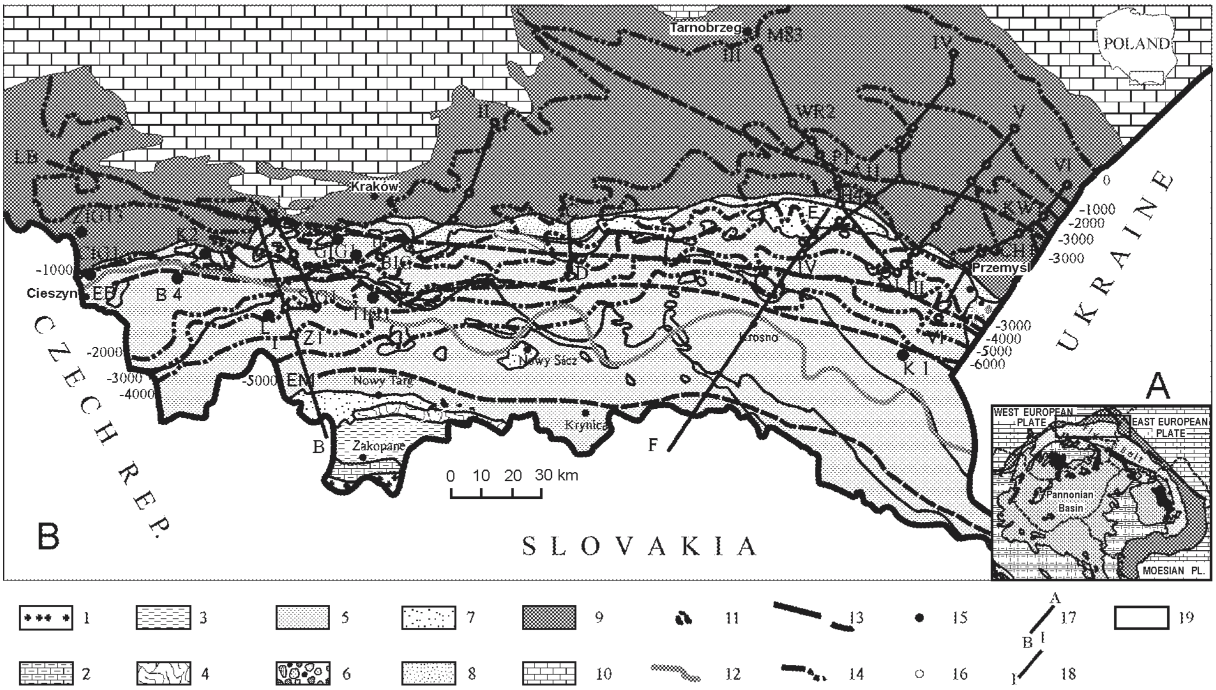

Fig. 1. A—Position of the Polish Carpathian Foredeep in the Carpathian-Pannonian region. **B**—Sketch-map of the Polish Carpathians and their foredeep (after Oszczypko 1997, supplemented); 1 — crystalline core of Tatra Mts., 2 — high and sub-Tatra units, 3 — Podhale Flysch, 4 — Pieniny Klippen Belt, 5 — Outer Carpathians, 6 — Stebnik Unit, 7 — Miocene deposits upon Carpathians, 8 — Zgłobice Unit, 9 — Miocene of the foredeep, 10 — Mesozoic and Paleozoic foreland deposits, 11 — andesites, 12 — northern extent of Lower Miocene, 13 — axis of subsidence (EM — Early Miocene, EB — Early Badenian, LB — Late Badenian, S — Sarmatian), 14 — isobath of Miocene substratum, 15 — selected boreholes, 16 — boreholes on the cross-section, 17 — geological cross-section, 18 — subsidence cross-section, 19 — study area.

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 Outer 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 (Oszczypko 1992), whereas the main decollement surfaces of the Moldavides are located in the Lower Cretaceous black shales. All the Outer Carpathian nappes are horizontally overthrust onto the Miocene deposits of the Carpathian Foredeep (see Oszczypko & Tomaś 1985; Żytko et al. 1989). However, along the frontal Carpathian thrust a narrow zone of folded Miocene deposits developed [Stebnik (Sambor-Rozniatov) and Zgłobice units (Figs. 1B, 3)]. The detachment levels of the folded Miocene units are connected with the Lower and Middle Miocene evaporites.

The basement of the Carpathian Foredeep represents the epi-Variscan platform and its cover (Oszczypko et al. 1989). The depth to the platform basement, recognized from boreholes, changes from a few hundred metres in the marginal part of the foredeep up to more than 7000 m beneath the Carpathians (Figs. 1B, 2, 3). The magneto-telluric soundings in the Polish Carpathians have revealed a high resistivity horizon, which is connected with the top of the consolidated-crystalline basement (Ryłko & Tomaś 1995; Żytko 1997). The depth of the top of the magneto-telluric basement reaches about 3–5 km in the northern part of the Carpathians, drops to approximately 15–20 km at its deepest point and then peaks at 8–10 km in the southern part. The axis of the magneto-telluric low coincides, more or less, with the axis of gravimetric minimum. South of the gravimetric minimum and, more or less parallel to the PKB, the zone of zero values related to the Wiese vectors, was recognized by geomagnetic soundings (Jankowski et al. 1982). This zone is connected with a high conductivity body occurring at the depth of 10–25 km and is located at the boundary between the North European Plate and the Central West Carpathian Block (Żytko 1997). 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 54 km towards the south and then, peaks along the PKB at 36–38 km (Aizberg et al. 1997).

Miocene deposits of the Carpathian Foredeep

Miocene deposits have been discovered both in the Outer Carpathians and in the Carpathian Foredeep. In the Outer Carpathians the Lower Miocene deposits were incorporated into the Moldavides accretionary wedge (Eggenburgian-Ottnangian, NN 2–3 zones). These deposits represent the youngest part of the flysch sequence.

The Polish Carpathian Foredeep (PCF) can be subdivided into two parts: outer and inner (Oszczypko 1982, 1997). The width of the outer foredeep (outside the Carpathians) varies between 30–40 km in the western segment and up to 90 km in the eastern part (Fig. 1B). The outer foredeep is filled up

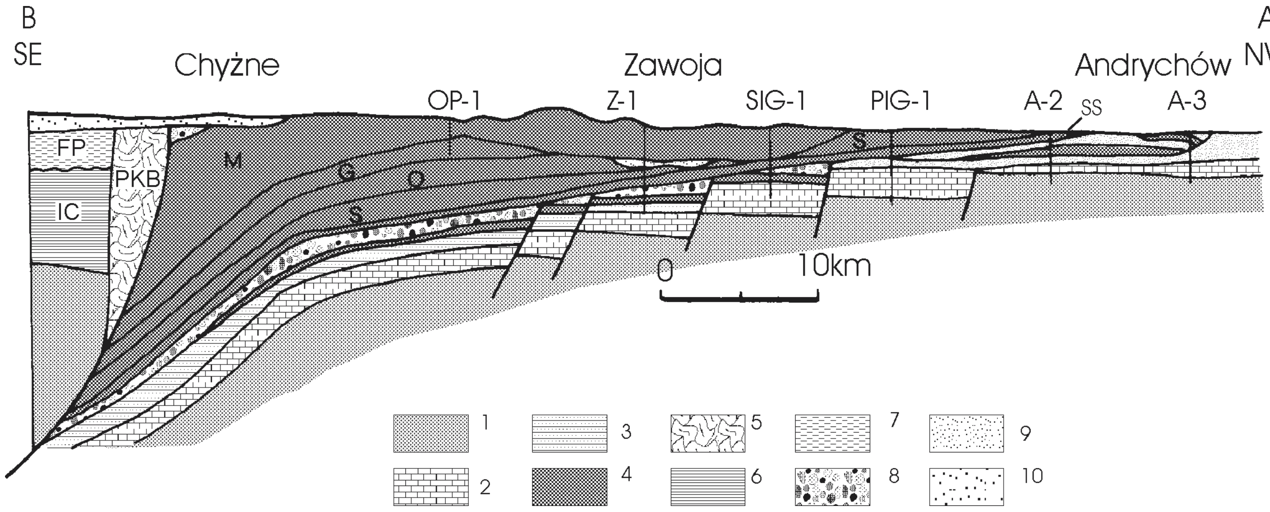

Fig. 2. Geological cross-section A–B (Andrychów-Chyżne, location see Fig. 1) through Polish Outer Carpathians (after Oszczypko 1997, supplemented); 1 — crystalline basement, 2 — Paleozoic, 3 — Paleogene, 4 — Outer Carpathians, 5 — Pieniny Klippen Belt, 6 — Inner Carpathian units, 7 — Podhale Flysch, 8 — Lower Miocene, 9 — Badenian, 10 — Upper Miocene. ***Abreviations:*** FP — Podhale Flysch, IC — Inner Carpathians, PKB — Pieniny Klippen Belt, M — Magura, G — Grybow, O — Obidowa-Slopnice, S — Silesian, SS — sub-Silesian units.

with Middle Miocene (Badenian and Sarmatian) marine deposits, which range from a few hundred metres in thickness in the northern-marginal part up to 3500 m in the south-eastern part. The inner foredeep, located beneath the Carpathian nappes, is more than 50 km wide (Figs.1B, 2, 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 1500 m. The Lower Miocene strata are mainly terrestrial in origin, whereas the Badenian and Sarmatian ones are marine.

The oldest autochthonous Lower Miocene strata, up to 1000 m thick, have been drilled by the Zawoja-1 borehole (Moryc1989; Połtowicz 1995). The lowermost portion of this sequence, 159 m thick, known as the Zawoja Fm. has recently been regarded as autochthonous Paleogene deposits (Oszczypko 1997), similar to those described from Southern Moravia (Picha 1979, 1996). The Zawoja Fm. is covered by a 260 to 370 m thick flysch-derived olistoplaque, referred to the Sucha Fm., and known from the: Sucha IG 1, Zawoja 1 and Lachowice 1, 2 boreholes (Figs. 1B, 2, 4; see also Ślączka 1977; Moryc 1989; Baran et al. 1997). In the Sucha IG 1 borehole this formation is composed of a few separate flysch olistoliths of varying age (Paleocene to Lower Cretaceous), showing connections with the Silesian and sub-Silesian successions (Ślączka 1977). In the Zawoja 1 borehole, the olistostrome formation is represented by a uniform sequence of dark, calcareous-free shales with rare intercalations of thin-bedded, very fine-grained sandstones. These deposists correspond to the Veřovice Shales and Lgota Formation of the sub-Silesian–Silesian units and 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 1997). In the Sucha-Zawoja area the age of the flysch olistoplaque development could be estimated as Ottnangian-Karpatian? (Garecka et al. 1996). This formation is overlapped by the Stryszawa Formation that reaches the thickness of 360–566 m (Fig. 4, see also Ślączka 1977; Moryc 1989). These deposits are composed of coarse to medium-grained, polimictic conglomerates with carbonate and locally gypsum-anhydrite cement. The thickness of these conglomerates varies from 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 Paleozoic basement of the Carpathian Foredeep, as well as from the front of the Carpathian nappes (see Moryc 1989). These conglomerates show features of alluvial deposits, passing upwards into variegated, conglomeratic-sandy-mudstone strata (Oszczypko 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 alluvial fan. The Stryszawa Fm. contains relatively frequent recycled flysch microfauna of the Lower Cretaceous–Oligocene age, showing a connection with the sediments of the sub-Silesian development (E. Malata pers. comm. 1997). 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) an assemblage which allows us to assume that its age is Eggenburgian–Ottnangian (N 5-N 6). This microfauna is representative for the middle-upper bathyal depths. There is a contradiction between the sedimentary record of the Stryszawa Fm., which reveals both shallow-water and/or terrestrial origin, and a deep-water character of microfauna. This suggests that the above-mentioned microfauna

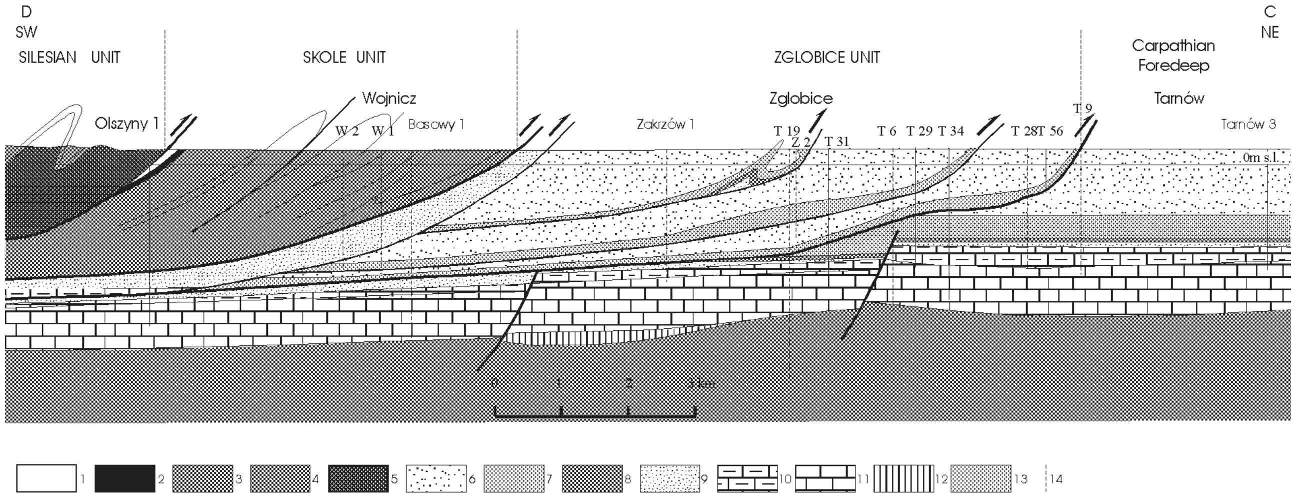

Fig. 3. Geological cross-section through marginal part of Polish Outer Carpathians (Olszyny-Tarnów, location see Fig. 1). ***Flysch Carpathians:*** 1 — Oligocene, 2 — Eocene, 3 — Senonian-Paleocene, 4 — Cenomanian-Senonian, 5 — Lower Cretaceous; ***Carpathian Foredeep (Badenian):*** 6 — Grabowiec Beds, 7 — Chodenice Beds, 8 — evaporites, 9 — Baranów Beds; ***Platform basement:*** 10 — Turonian-Senonian, 11 — Upper Jurassic, 12 — Lower Triassic, 13 — Lower Carboniferous, 14 — boreholes.

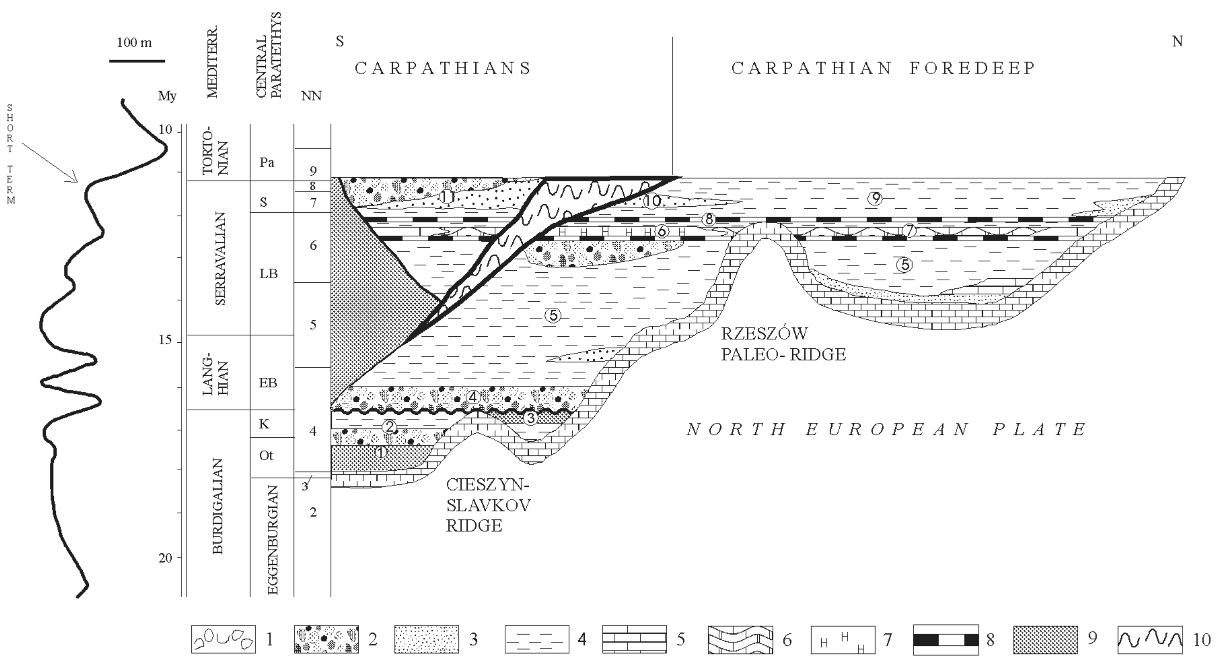

Fig. 4. Lithostratigraphic model of the Miocene deposits of the Polish Carpathian Foredeep (after Oszczypko 1997, supplemented); chronostratigraphy of the Central Paratethys after Steininger et al. (1990) and Rögl (1976), global see level oscilation after Haq et al. (1987). ***Lithology:*** 1 — pebbly mudstones, 2 — conglomerates, 3 — sandstones, 4 — siltstones & mudstones, 5 — limestones, 6 — gypsum & anhydrites, 7 — salts, 8 — tuffites, 9 — Outer Carpathians and flysch-derived olisthostroma, 10 — folded Miocene deposits. ***Lithostratigraphic units:*** 1 — Sucha Fm., 2 — Stryszawa Fm., 3 — Zamarski Mb. of Zebrzydowice Fm., 4 — Dębowiec Cgl., 5 — Skawina Fm. and Baranów Bds., 6 — Wieliczka Fm., 7 — Krzyżanowice Fm., 8 — Chodenice Bds., 9 — Grabowiec and Krakowiec Bds., 10 — Bogucice Ss., 11 — Nockowa Bds. and Bela Fm.; Ot — Ottnangian; K — Karpatian; EB — Early Badenian; LB — Late Badenian; S — Sarmatian; Pa — Pannonian.

was also recycled from the youngest (Lower Miocene) flysch strata?. Karpatian calcareous nannoplankton (NN 4 zone) has also been reported from the Stryszawa Fm. (Garecka et al. 1996). In the Bielsko-Cieszyn area, green-grey mudstones with intercalations of conglomerates occur (Bielsko and ? Zebrzydowice formations, see Buła & Jura 1983). These could be interpreted as a marine equivalent of the Stryszawa Fm. (see Garecka et al. 1996; Oszczypko 1997).

The Middle Miocene began with the extensive Early Badenian marine transgression which flooded both the foredeep and the marginal part of the Carpathians. In the foredeep, the Badenian[1] strata rest directly on the platform basement with the exception of the SE part of the inner foredeep, where they cover Lower Miocene deposits. Usually the "Lower Badenian" (Ney 1968; Ney et al. 1974) begins with a thin layer of conglomerates, however, in the western part of the

[1]The Badenian deposits in the outer part of the Polish Carpathian Foredeep are traditionally subdivided into "Lower Badenian" (sub-evaporite), "Middle Badenian" (evaporite), and "Upper Badenian" (supra-evaporite) beds. These subdivisions are in contradiction to recent nannoplankton and isotope investigations (see Fig. 4).

foredeep they attain a thickness of up to 100 m. The conglomerates pass upwards into dark, clayey-sandy sediments (Skawina Fm.). The thickness of 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 the Praeorbulina glomerosa Zone (N 8), but in the outer fordeep with the Orbulina suturalis (N 9 or N 10) Zone (Garecka et al. 1996; see also Oszczypko 1997). According to the nannoplankton studies, this formation belongs to the NN 5 zone, and in its uppermost part to the NN 6 zone (Andreyeva-Grigorovich 1994; see also Garecka et al. 1996). The radiometric age of a 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. com. 1997). The evaporitic horizon, traditionally regarded as "Middle Badenian" in age, either overlies these deposits or rests directly upon the platform basement. This horizon consists of rock salts, claystones, anhydrites, gypsum and marls (Figs. 4, 6). 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 (Gaździcka 1994; Peryt & Peryt 1994; Peryt et al. 1997, 1998), the age of the evaporitic horizon could be estimated as the NN 6/7 zone. The evaporatic horizon passes upwards into 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 3000 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 5000 m (see Andreyeva-Grigorovich et al. 1997). In the Kraków-Bochnia region at the top of the evaporitic horizon, silty-sandy deposits (Chodenice Beds) with a few intercalations of tuffites occur. The radiometric age of these tufites is around 12 Ma BP (Figs. 4, 6, see also Van Couvering et al. 1981).

The development of the folded Miocene units (Figs. 1, 3) 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 recognized at the front of the Skole Nappe SE of Przemyśl, as well as beneath this nappe (Ney 1968). The Stebnik Unit is composed of both Early (up to 2200 m thick, Ney 1968) and Middle Miocene, up to Sarmatian strata (Andreyeva-Grigorovich et al. 1997; Garecka & Olszewska 1997). In the Ukrainian Carpathians, folded Early Miocene molasses are known from the Boryslav-Pokuty as well as the Sambor-Rozniatov units (Andreyeva-Grigorovich et al. 1997). These deposits belong to the Stebnik and Balich formations. The Stebnik Fm., up to 3000 m thick, is composed of variegated clays with intercalations of sandstones and gypsum lenses. The formation contains Ottnangian, probably recycled foraminifers (see

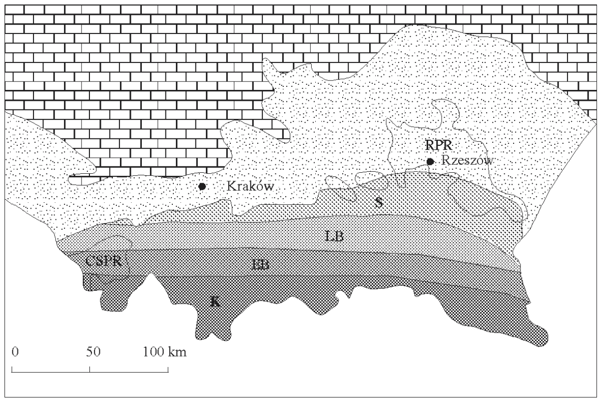

Fig. 5. Palinspastic sketch-map of the Polish Carpathians during the Karpatian (K), Early Badenian (EB), Late Badenian (LB) and after Late Sarmatian (S) (after Oszczypko 1997, supplemented); CSPR — Cieszyn-Slavkov Paleo-ridge, RPR — Rzeszów Paleo-ridge.

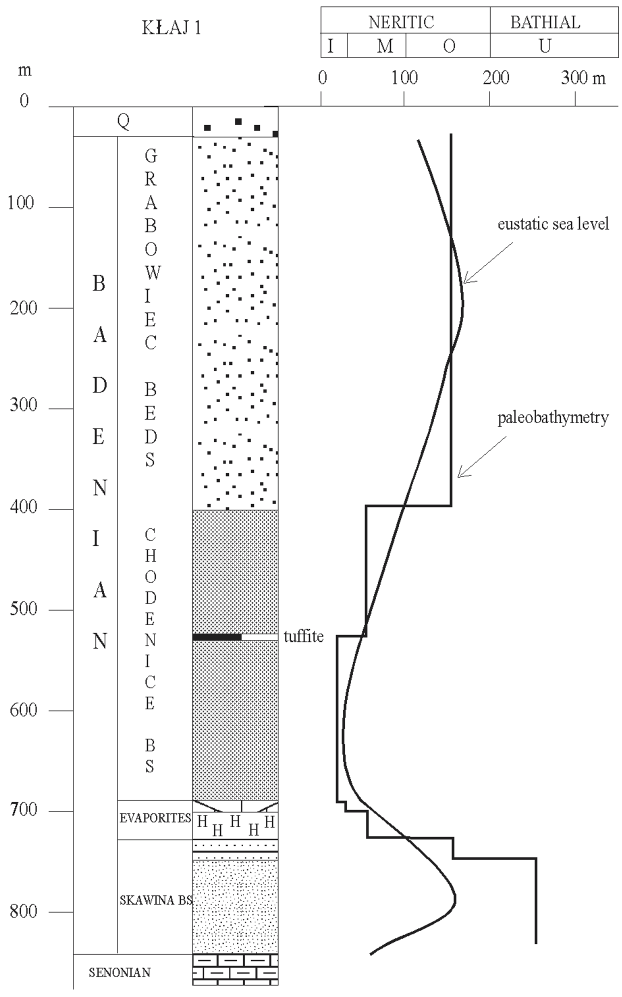

Fig. 6. Paleobathymetry (Gonera pers. inf., 1997) and sea level fluctuation (Haq et al. 1987) of the sedimentary record in Kłaj I borehole (for location see Fig. 1).

Stryszawa Fm.) and, Karpatian nannoplankton (Andreyeva-Grigorovich et al. 1997). The Stebnik Formation is overlain by the Balich Fm., up to 600 m thick and is represented by

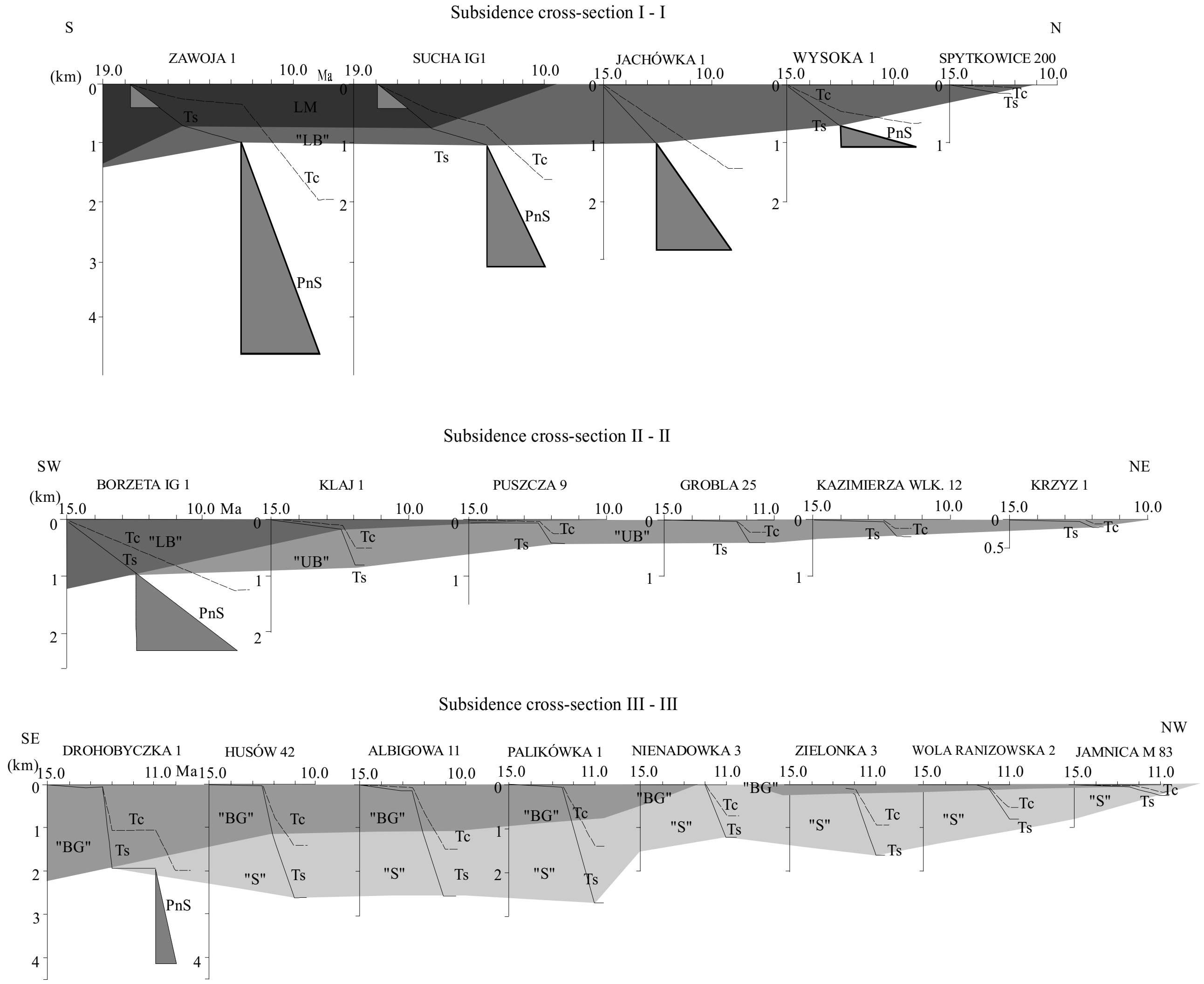

Fig. 7. Backstripped subsidence cross-sections I–III (after Oszczypko 1997, supplemented): Ts — "total" subsidence, Tc — "tectonic" subsidence, PnS — "postnappe subsidence", LM — Lower Miocene, "LB" — "Lower Badenian", "UB" — "Upper Badenian", "S" — "Sarmatian".

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 Karpatian (NN 4 zone), but in some localities the Early Badenian species *Preorbulina glomerosa* and *Orbulina universa* have been discovered (see Andreyeva-Grigorovich et al. 1995, 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 of the Skawina formations (Oszczypko 1997).

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) occur (Figs. 1B, 3). 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 (Fig. 2). The Zawoja 1 borehole reached the parautochthonous "Lower Badenian"? deposits beneath the Magura Nappe (Moryc 1989; Baran et al. 1997).

Multistage overthrusting of the Carpathian wedge

In the Polish segment, the relationship between the Outer Carpathian accretionary wedge and the Miocene molasse deposits has been very well recognised from deep boreholes as far as 30–40 km from the present-day Carpathian frontal thrust (see Wdowiarz 1976; Oszczypko & Tomaś 1985; Żytko et al. 1989). The surface of overthrust is of regular shape and rather gently inclined. In the Western Carpathians there is abundant evidence that the overthrust of the Carpathians onto the foreland plate was progressive (see Jurkova 1979; Oszczypko & Tomaś 1985; Oszczypko & Ślączka 1985, 1989; Oszczypko 1996; Kováč et

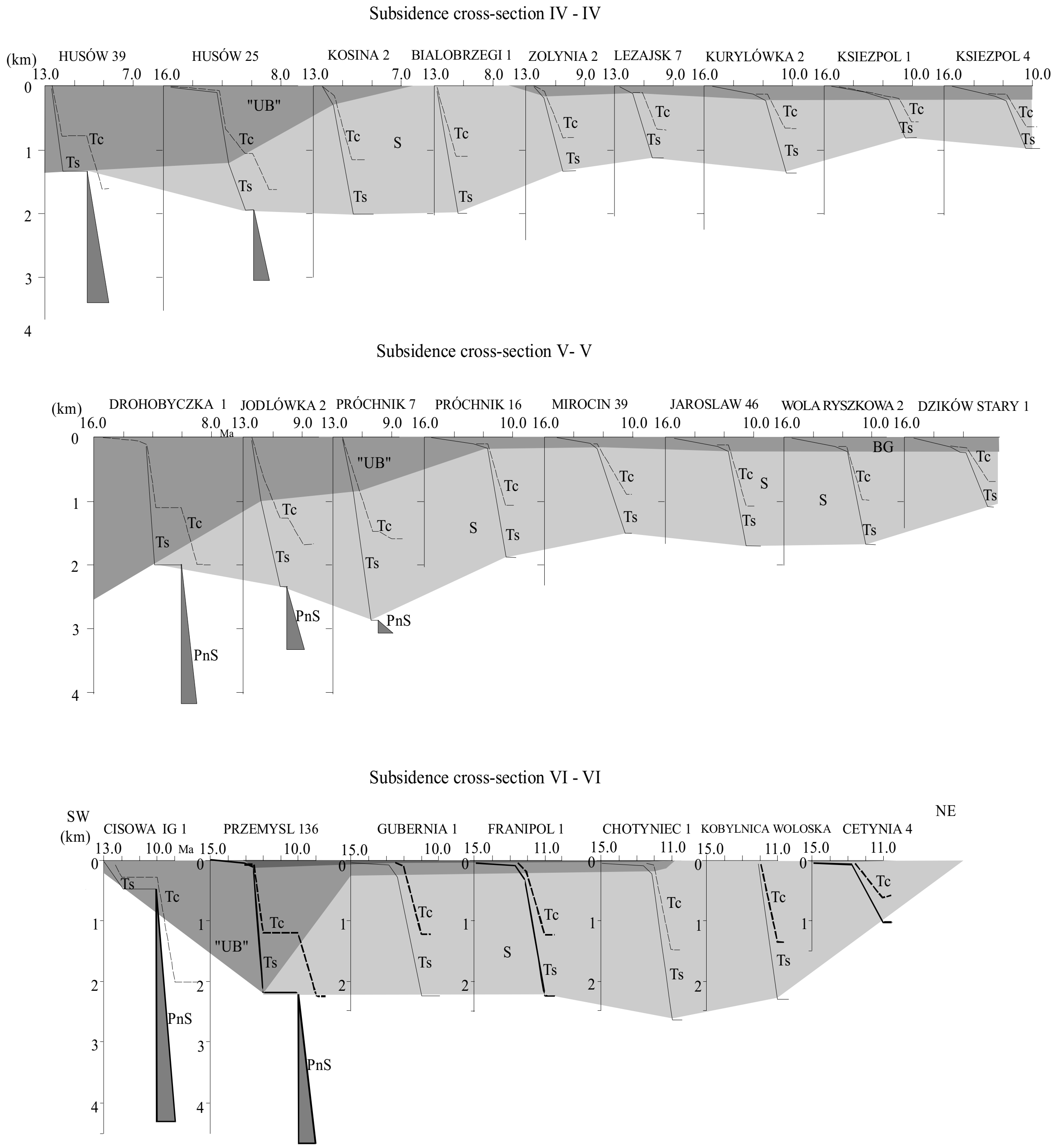

Fig. 8. Backstripped subsidence cross-section IV–VI (after Oszczypko 1997, supplemented). For explanation see Fig. 7.

al. 1989, in press). In the Polish Carpathians it is documented by the occurrence of the flysch-derived olistostromes in the autochthonous and parautochthonous Miocene strata of different ages and by the relation of the "Upper Badenian" autochthonous deposits to blind faults (Krzywiec 1997).

According to my estimation, the multistage overthrusting of the Polish Outer Carpathians took place during the following periods (Fig. 15): **1)** before deposition of the Stryszawa Fm. (after the Ottnangian and before the Karpatian); **2)** before the Early Badenian (the mean rate of these overthrustings could be estimated as 20 and 26 mm/a for the western and eastern parts of Polish Carpathian Foredeep respectively), **3)** during the Late Badenian (mean rate of overthrusting 9.5 and 7.5 mm/a); **4)** after the Sarmatian (rate of overthrusting 14.5 mm/a). The mean rate of the Carpathian frontal thrusting after the Karpatian could be estimated as 12 mm/a (see Oszczypko 1996). This value is comparable to the results of Roca et al. (1995) who have concluded that between the Middle Oligocene and Sarmatian times the mean rate of the Carpathian convergence reached 11–14 mm/a.

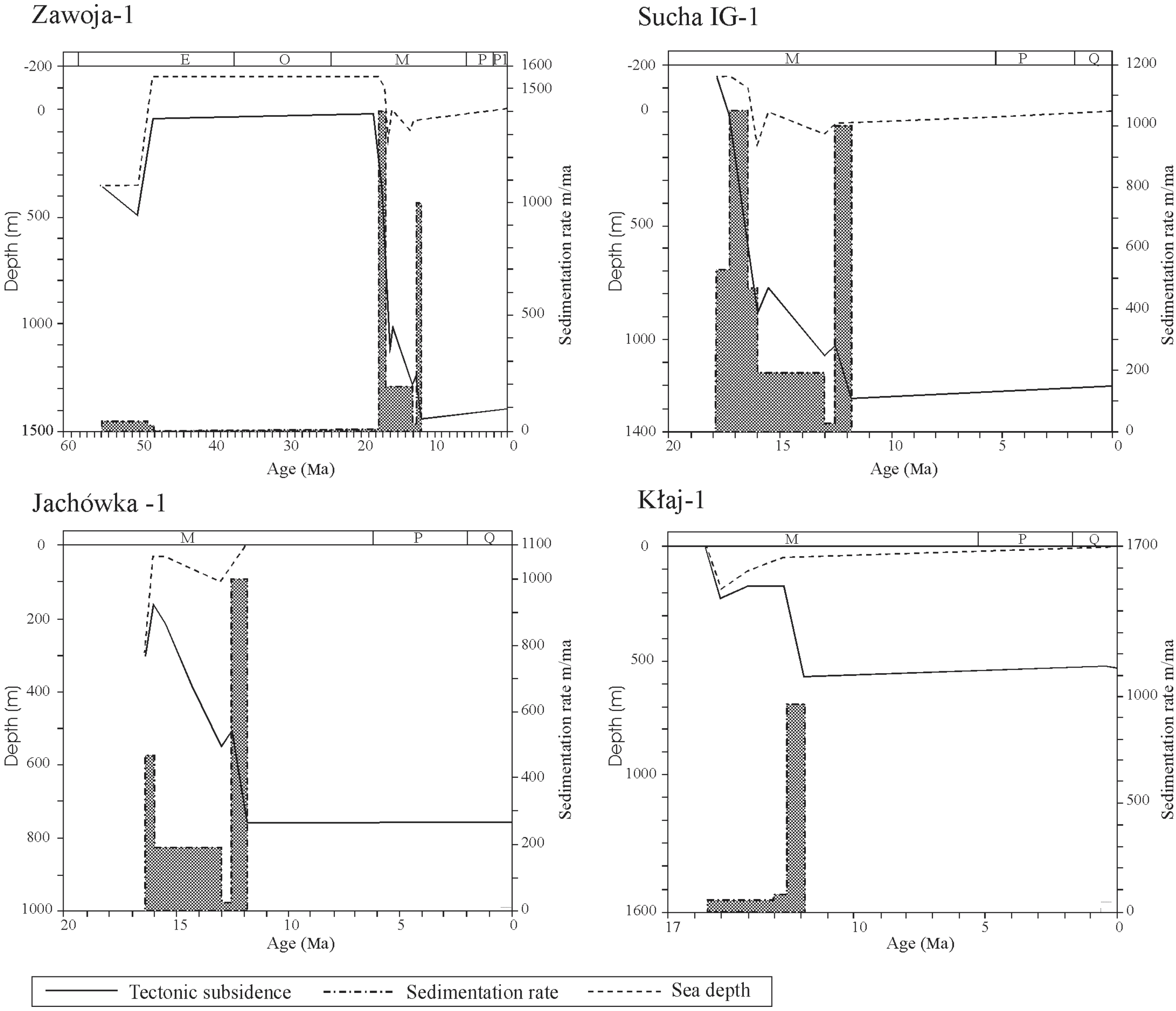

Fig. 9. Backstripped burial diagrams of the selected boreholes from the western part of PCF. The boreholes Zawoja1, Sucha IG1 and Jachówka1 with correction of the upper portion of the Middle Miocene deposits "eroded" by the the Carpathian overthrust, and without the "post-nappe subsidence".

The above mentioned rates of overthrusting of the Polish Outer Carpathians reflect oblique-northward convergence between the North European Plate and the Alcapa microplate, and are probably smaller than the rates related to the NE escape of the Alcapa block. If we considered that the unpublished Oszczypko and Ślączka palinspastic map of the Late Oligocene (in Csontos et al. 1992; see also Meulenkamp et al. 1996; Tari et al. 1997), which suggested 400 km of NE, post- Oligocene and prior to the Late Badenian motion of the Pieniny Klippen Belt, the rate of the Outer Carpathian overthrusting would reach about 40–50 mm/a. According to Meulenkamp et al. (1996) this motion of PKB corresponds to the 1160 km eastward lateral migration of the depocenters in the Carpathian Foredeep and to the 200 km post-Ottnangian displacement of the Alcapa Superunit relative to the Tisza-Dacia microplate.

Burial history of the Polish Carpathian Foredeep

In this contribution the burial history of the Polish Carpathian Foredeep (see also Oszczypko 1995, 1996, 1997) has been constructed on the basis of selected 40 wells, grouped in six sections, more or less perpendicular to the front of the Carpathians (Figs. 1B, 7–8). For computation purposes the numeric stratigraphy has been applied (Fig. 4). Taking into account that the new nannoplankton and radiometric data from the Badenian and Sarmatian deposits of the Polish Carpathian Foredeep do not correspond to the traditonal Paratethys scheme (see Steininger et al. 1988), the numerical stratigraphy was constructed for the purpose of this study (Fig. 4). It has been achieved by correlation of local stratigraphy with nannoplankton calibration (Gaździcka 1994; Peryt

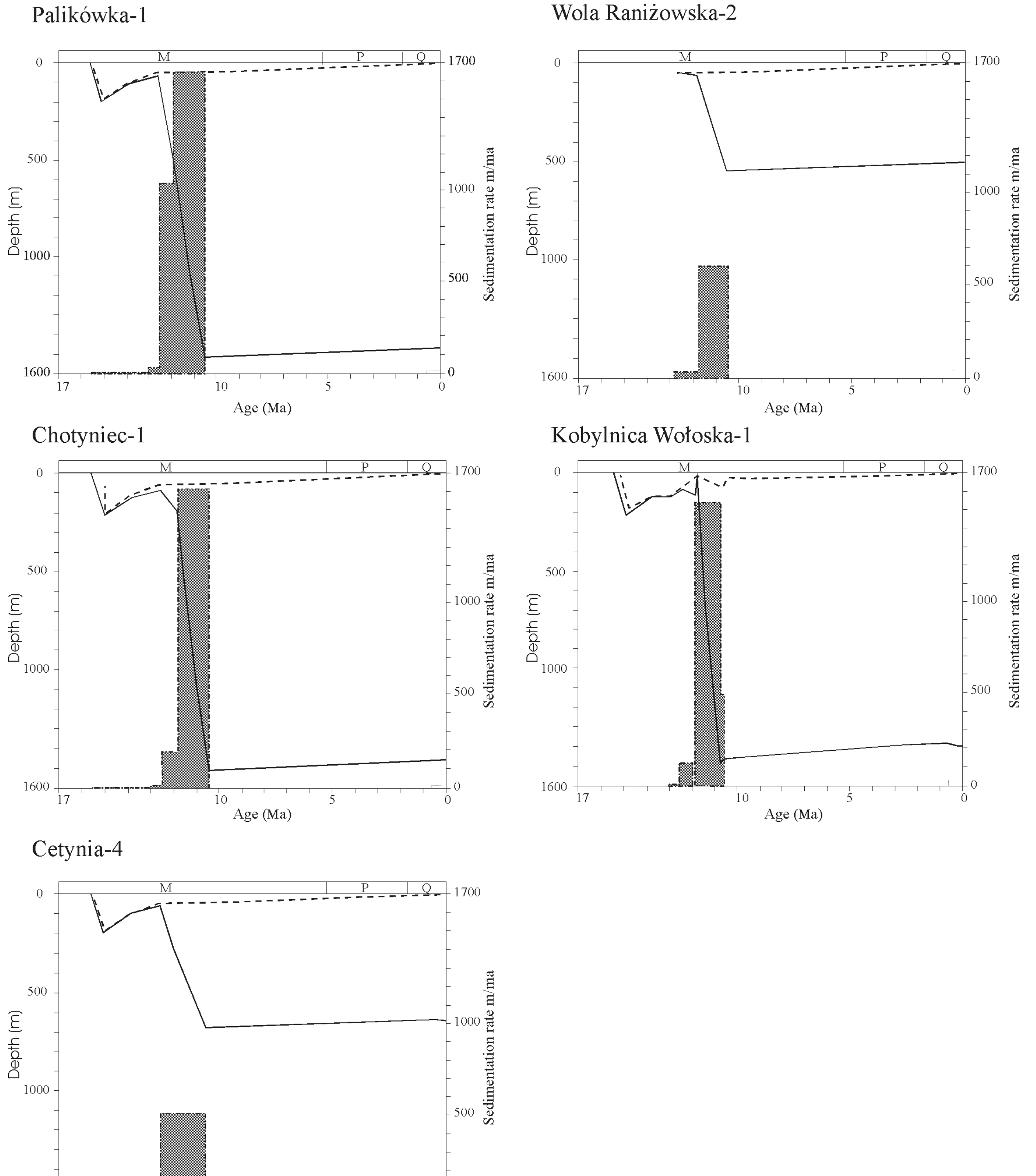

Fig. 10. Backstripped burial diagrams of the selected boreholes from the eastern part of PCF.

& Peryt 1994; Peryt et al. 1997, Andreyeva-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). Global (Berggren et al. 1995), regional (Central Paratethys) correlations (Steininger et al. 1990; Rögl 1996) and sea level chronology (Haq et al. 1987) have also been considered. According to the proposed numerical stratigraphy, the Badenian deposits of the Polish Carpatian Foredeep belong to the upper part of NN 4, NN 5, and NN6 zones, and represent the time span 16.4–11.8 Ma BP. The numerical age of the "Lower Badenian" in the inner western PCF has been accepted as 16.4–13.0 Ma BP. For the traditional subdivisions of the outer PCF, that is "Lower Badenian"-sub-evaporite, "Middle Badenian"-evaporite and "Upper Badenian"-supra-evaporite the following numerical ages have been accepted: 15.0–13.0, 13.0–12.5 and 12.5–11.8 Ma

BP respectively. The youngest deposits of the PCF belong to the "Sarmatian" (NN 7 and N8/9? zones) and probably represent the time interval 11.8–10.5 Ma BP.

The procedure of Van Hinte (1978), Sclater & Christie (1980), Angevine et al. (1990), and Allen & Allen (1992) has been used for computation of subsidence curves (see also Oszczypko 1995, 1997). The final diagrams have been produced using the PC program "SUBSIDE" (Hsui 1993). The program plots the decompacted depth versus time for the stratigraphic units, "tectonic" subsidence and rates of "tectonic" subsidence. The decompacted depth of the lowest unit describes the "total" subsidence curve. The "tectonic" subsidence represents basement subsidence corrected for the loading effect of sediments (see "backstripped tectonic subsidence using Airy isostasy", Allen & Allen 1992). Program "SUBSIDE" does not take into account corrections for variations in water depths and eustatic sea level fluctuations. For these computations the data from the published catalogues of boreholes drilled by the Petroleum Industry and partly by the Polish Geological Institute have been used. These data contain simplified lithostratigraphic profiles of the boreholes. In most of the wells located in the outer foredeep these profiles were represented by: the "Lower", "Middle" and "Upper" Badenian, Sarmatian and Quaternary deposits. For decompaction procedure the program uses surface porosity, porosity depth coefficients, and sediments grain density (see Sclater & Christie 1980 and Schmoker & Halley 1982). For a few boreholes located in the Carpathians (Figs. 7–8) the post-nappe load has been additionally regarded but without correction for "tectonic erosion" of subthrust strata. These calculations have allowed estimation of the general trends of subsidence and depth relation between "total" and "tectonic" subsidence. The "total" subsidence was more or less 1.7–1.8 times higher than the "tectonic" subsidence. For selected boreholes "tectonic" subsidence estimated by the program "SUBSIDE" has been compared with results obtained with the program "BasinMode1" which included paleobathymetry and eustatic sea level corrections (Figs. 9–10).

For paleobathymetry corrections the following data, based on quantitative proportion between benthic and pelagic foraminifers, have been accepted (Fig. 6, see also Gonera1994; Czepiec 1996; Kováč et al. 1993):

Numerical Age (Ma)										
17.8 – 17.2	17.2 – 16.4	16.4 – 16.0	16.0 – 15.5	15.5 – 13.8	13.8 – 13.0	13.0 – 12.6	12.6 – 12.5	12.5 – 12.0	12.0 – 11.8	11.8 – 10.0
Paleobathymetry (m)										
0	50	350	30	300	150	50	0	50	150	40

For the eustatic sea level corrections the short term curves have been used (Haq et al. 1987)

The final plots of the "tectonic" subsidence (in m) estimated by using both of the programs showed the following differences related to paleobathymetry and eustatic sea level fluctuations:

Boreholes	Klaj 1	W. Raniz. 2	Palikówka 1	Chotyniec 1	Cetynia 4
"SUBSIDE"	522	500	1440	1400	625
"BasinMod 1"	560	550	1520	1500	700
Δ (m)	-38	-50	-80	-100	-75

As it was expected, the "tectonic" subsidence obtained by "BasinMode1" is higher than that ploted by "SUBSIDE" but differences do not exceed 100 m. More distinctive differences are visible in the diagrams describing "tectonic" subsidence during the "Middle Badenian" evaporite deposition and just after that event (ca. 12.5 Ma BP).

For the three boreholes situated in the Carpathians (Fig. 1), the thickness of the upper portion of the Miocene deposits "tectonically" eroded by the Carpathian nappe has been restored. For these wells tectonic subsidence (m) has been computed with the help of "BasinMode1" program, then the obtained values have been compared with the post nappe "tectonic" subsidence (Figs. 7–8) plotted by "SUBSIDE".

Borehole	"BasinMode 1"	"SUBSIDE"	Δ (m)
Drohobyczka 1	1520	2000	-480
Sucha IG 1	1250	1600	-350
Zawoja 1	1450	2000	-550

These differences have shown the importance of the role played by the nappe load in the basement subsidence of the inner foredeep.

In the burial diagrams (Figs. 7–8, 9–10) four periods of intense subsidence are visible: the Early Miocene (Karpatian?), Early Badenian, Late Badenian and Sarmatian. The subsidence cross-sections describe formation and migration of the foreland basin from south-west towards north-east.

The Early Miocene (Karpatian?) and Early Badenian depocenters were situated (Fig. 1B) in the western inner foredeep, extending towards the Sambor-Rozniatov basin in the east (see also Oszczypko 1997). During these times, the axes of subsidence were more or less subparallel to the present-day front of the Carpathians (Fig. 1B). In the initial stage (Karpatian?) of the basin development, the rate of total subsidence (1000–1400 m/Ma) in the Czech and Polish segments was fully compensated by the rate of deposition (Fig. 9, see also Vass & Čech 1983 and Meulenkamp et al. 1996). This resulted in terrestrial and shallow marine? sedimentation. Towards the east (Sambor-Rozniatov basin) the rate of the total subsidence increased to at least 2000 m/Ma. The Early Badenian axis of subsidence was shifted at least 30–40 km (rate of migration 15–20 mm/a) north from its Early Miocene position (Fig. 1), whereas the northern margin of the basin moved to the north by 30 (W part) to 100 km (E part). It was related to the Langhian marine trangression. At that time, in the axial part of the basin, the rate of sedimentation reached 250 to 500 m/Ma in the Moravian segment (Vass & Čech 1983 and Meulenkamp et al. 1996) to 200 m/Ma (Fig. 9) in the Polish part. Simultaneously, in the area of the northern stable shelf of PCF the subsidence was extremely low (Figs. 7, 8) and the rate of sedimentation oscillated from a few dozen to 50 m/Ma (Fig. 10). This period of very low subsidence and accumulation is marked in the whole Central Paratethys foreland basins (see Meulankamp et al. 1996, Fig. 7).

From the Early Badenian (Langhian) marine transgression, the rate of subsidence was higher than the rate of deposition. This resulted in marine sedimentary conditions during the Badenian and Sarmatian times. The paleobathymetry of the Early Badenian basin varied from the upper bathyal depths in the axis of the basin to neritic (Fig. 6, see also Kováč et al. 1993), and littoral in the northern and southern (Carpathian) marginal part of the basin.

From the Serravalian (ca. 15 Ma BP) a gradual shallowing of bathymetry in the Carpathian foreland basin, coinciding with a gradual global fall of relative sea level, was observed. This caused the partial isolation of the basin, and initiated the Badenian (ca. 13.0–12.5 Ma BP) salinity crisis in shallow basin (inner-middle neritic? depths, Figs. 6, 10). For that period the diagrams of tectonic subsidence reveal a tendency to progressive uplifting of the sea floor, whereas the sedimentation rate varies from a few dozen metres/Ma in the area of sulphide facies up to ca. 50 m/Ma (Figs. 9–10) in the area of chloride facies. It is a very rough approximation because the episode of chemical accumulation could have been very short-lasting (25–35 Ka, see Garlicki 1968; Petrichenko et al. 1997) and the rates of subsidence/- sedimentation could have been one order higher, up to 500 m/Ma. After evaporite deposition (ca. 12.5 Ma BP), when the basin was the shallowest (Fig. 6, see also Gonera 1994; Kasprzyk 1993; Czepiec 1997) tectonic uplift of the foreland reached its maximum (Figs. 9–10). This resulted locally in a post-evaporite erosion of at least 50–100 m of evaporitic and sub-evaporitic deposits (see Rzeszów Paleoridge, Fig. 1, see also Komorowska-Błaszczyńska 1965). The subareal and/or areal erosion of the anhydrites before deposition of the Ratyn Limestone or before deposition of the Kosiv Fm. has also been reported from the Ukrainian part of the foredeep (see Peryt & Peryt 1994; Panow & Płotnikow 1996 and Andreyeva-Grigorovich et al. 1997). The middle Serravalian relative fall of the sea level could have caused a basinward shift of clastic sedimentation (Krzywiec 1997). A new period of intense subsidence was initiated during the Late Badenian. The depth of the Late Badenian sea oscillated between the outer neritic and inner neritic depths (Gonera 1994; Czepiec 1996). The subsidence took place both in the inner and outer foredeep (Fig. 1). In the eastern segment of the PCF, the axis of subsidence shifted 15 km (rate of migration 3.75 mm/a) north from the Early Badenian position, and was more or less in line with the present-day position of the Carpathians (Fig. 1). The highest rate of subsidence up to 2000 m/Ma was estimated in the SE part of PCF in the boreholes Przemyśl 136 and Drohobyczka 1, situated 10–15 km south of the Carpathian front. Towards the NW in the Rzeszów area (boreholes Husów 39, 25, 42, Albigowa 11 and Palikówka 1) rate of total subsidence reached about 1200–1300 m/Ma, whereas the rate of sedimentation oscillated around 1000 m/Ma (Figs. 8, 10). The slightly lower rates of subsidence and sedimentation are observed in the Tarnów and Bochnia areas. In the area effected by post-evaporitic erosion, for example “Rzeszów Island”, the Late Badenian deposits transgressively overlapped the Precambrian and Paleozoic basement. Towards the NE margin of the PCF, the rate of the Late Badenian subsidence and sedimentation decreased to 100–200 m/Ma. The Late Badenian subsidence continuously passed into Sarmatian subsidence, although the locations of depocentres were distinctly changed (Fig. 10). In comparison to their former position the Sarmatian depocenters were shifted 40–50 km (rate of migration 20–25 mm/a) towards the NE, and the axis of subsidence rotated clock-wise by up to 20 degrees (Fig. 1B, see also Oszczypko & Żytko 1987). The zone of the Sarmatian maximum subsidence was connected with the so-called “Wielkie Oczy Graben”. The total subsidence in this zone varied from 1500 m in its NE part up to 2500–3000 m in SE part (Figs. 8, 10), whereas the maximum values of tectonic subsidence reached 1300–500 m. Towards the northern margin of the PCF the total subsidence decreased to a few hundred metres. The high rate of the Sarmatian subsidence was compensated by the high rate of sedimentation, which reached 1500–1600 m/Ma (Fig. 10). During the Sarmatian the depth of the basin oscillated between outer neritic and littoral depths (Czepiec 1996). Towards SE, on the Ukrainian territory, where the Sarmatian deposits reached a thickness of up to 4000 m (see Andreyeva-Grigorovich et al. 1997), subsidence and the rate of deposition were higher. In Figs. 7–8 there are zones of abrupt increase of subsidence between boreholes Próchnik 7 and 16, Białobrzegi 1 and Zołynia 2 and Palikowka 1 i Nienadówka 3 connected with NW–SE trending faults (see also Oszczypko et al. 1989). In each case the hangingwall is located on SW side of the fault. According to Krzywiec (1997) the faults of the same direction investigated close to the Polish-Ukrainian boundary developed as synsedimentary normal faults. The calculated subsidence and sedimentation rates correspond very well with those published by Meulenkamp et al. (1996) for transects 9 (PCF) and 10 (Ukrainian segment). According to these authors the rates of maximum sedimentation of the Early Sarmatian deposits vary from 2440 m/Ma in PCF to 4440 m/Ma in the Ukrainian segment.

As a rule, with the above described exception for the Sarmatian time, the area of maximum 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 (see also Oszczypko & Ślączka 1989). During the Karpatian–Sarmatian time (7 Ma) the axis of maximum subsidence within the PCF moved about 85 km towards the north and northeast. The mean rate of migration of the axis of subsidence could be estimated at 12 mm/a (12 km/Ma). This rate is similar to the mean rate of the Carpathian overthrusting, and is lower than that of the pinch-out migration (13.8 mm/a). During the Late Badenian–Sarmatian time this resulted in the widening of the eastern part of PCF. A similar event was described by Homewood et al. (1986) from the Swiss Molasse Basin. The main episodes of intense subsidence in the PCF correspond to the periods of progressive emplacement of the Western Carpathians onto the foreland plate (Figs. 6, 15, see also Oszczypko 1997), whereas the “Middle Badenian” event of low subsidence or uplift is related to the period of “dormant” Carpathian frontal thrust (see also Meulenkamp et al. 1996). The distinct relationship between the periods of the Carpathian overthrusting and subsidence of the PCF suggests that the significant driving force of subsidence was the emplacement of the tectonic nappe load related to subduction roll-back. Each emplacement of the Carpathian front initiated a new period of subsidence (Fig. 15). 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),

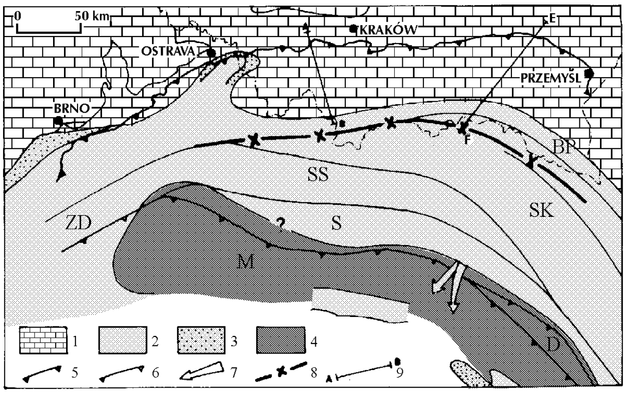

Fig. 11. Palinspastic sketch-map of the Carpathian Foreland Basin during the Early Burdigalian (Eggenburgian) (after Oszczypko 1997, supplemented). 1 — North European land; 2 — nerithic and bathyal deposition; 3 — shalow marine deposition; 4 — Carpathian land; 5 — recent Carpathian front; 6 — active thrust; 7 — possible sea-ways; 8 — zero line of Wises vectors; 9 — cross-section.

Transition from residual flysch basin to peripheral foreland basin

At the very beginning of the Early Miocene Outer Carpathian orogeny, the Magura and probably the Fore-Magura basins were folded and thrust towards the north. This period of folding, thrusting and erosion was postdated by the Eggenburgian transgression on the Magura Nappe in the Vienna Basin (Jiříček & Seifert 1990; Kováč et al. in press). In the more northern part of the Carpathian basin, the terminal flysch sedimentation persisted up to the Middle Burdigalian (Ottnangian — NN 3, see Krhovský et al. 1995; Andreyeva-Grigorovich et al. 1997; Koszarski et al. 1995; Ślęzak et al. 1995; Oszczypko 1997), when the upper part of the Krosno Fm. (Polyanytsa) was deposited (Fig. 11). The width of that basin before folding is still being discussed. 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 reached 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 the Pieniny Klippen Belt and the foreland reached 180 km (restored width of basin measuring 235 km, see Roca et al. 1995). For the same time the restored width of basin presented by Morley (1996) reached 290 to 350 km for the western and eastern part of the the Polish Outer Carpathians respectively.

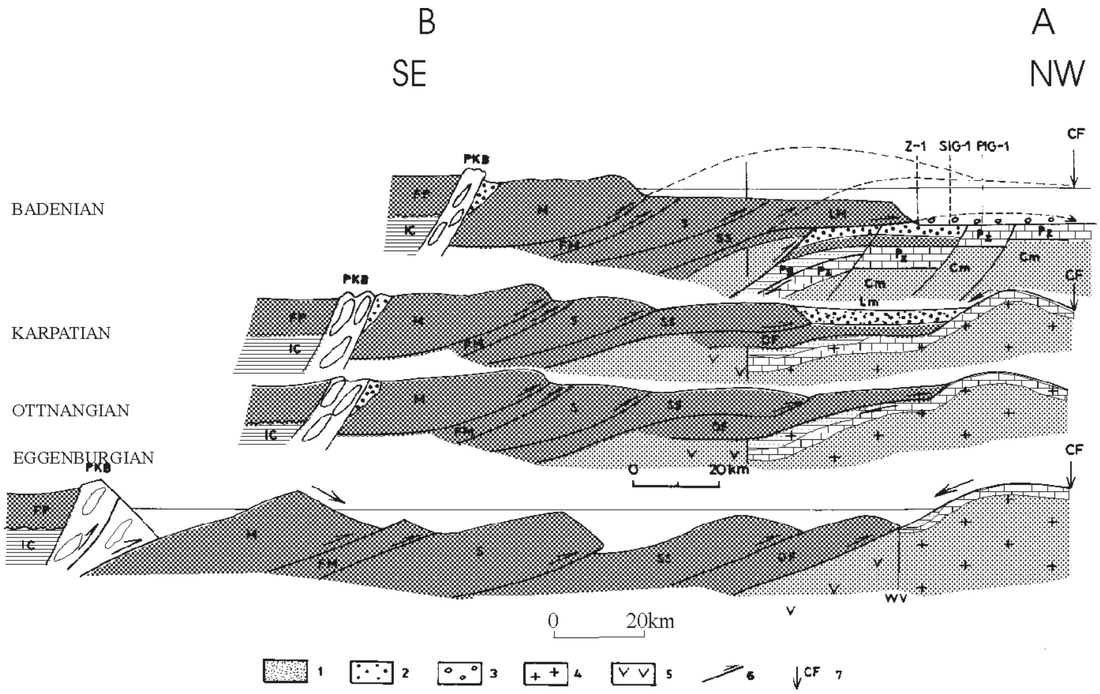

Fig. 12. Palinspastic cross-section through Polish Western Carpathians (Chyżne-Andrychów, after Oszczypko 1997, supplemented, for location see Fig. 1). 1 — fine-grained sediments, 2 — coarse-grained sediments, 3 — conglomerates, 4 — continental crust, 5 — thinned continental crust, 6 — thrust, 7 — present position of the Outer Carpathian front; 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 ?).

Royden (1993), Krzywiec & Jochym (1997), and Krzywiec (1997) 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 this extra "load" should be taken into account only during the early collisional history (see discussion in Miall 1995). However, it must be stressed that the temporal coincidence between thrust-related subsidence and the slab-pull mechanism of subsidence existed, and both of the processes were caused by the southwards subduction of the foreland plate.

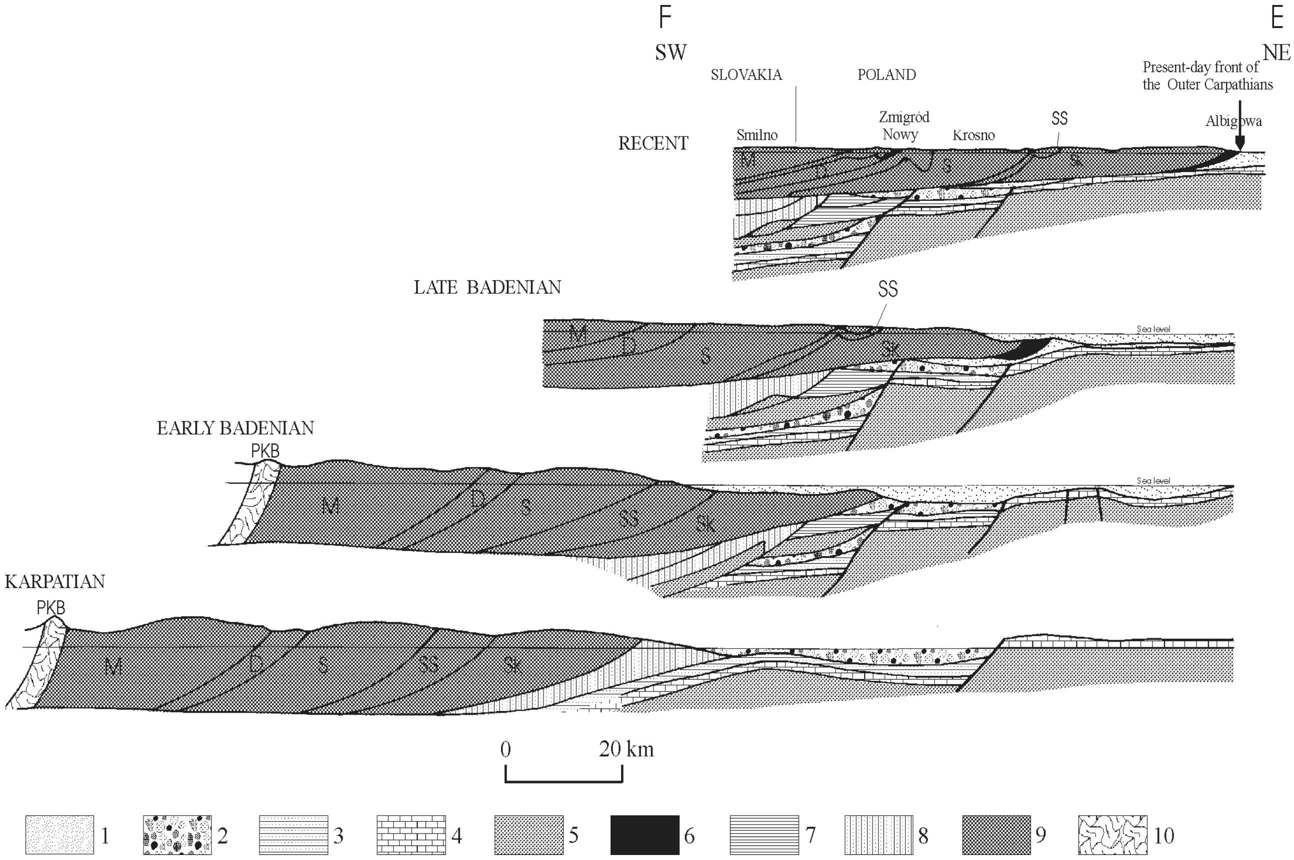

Fig. 13. Palinspastic cross-section through the Outer Carpathians E–F (Albigowa-Smilno, for location see Fig. 1). 1 — Badenian and Sarmatian, 2 — Ottnangian and Karpatian, 3 — Mesozoic and Paleogene, 4 — Paleozoic, 5 — Precambrian and Lower Cambrian, 6 — Zgłobice Unit, 7 — Stebnik Unit, 8 — Boryslav-Pokuty Unit, 9 — Outer Carpathian Units (M — Magura, D — Dukla, S — Silesian, SS — sub-Silesian and Sk — Skole units), 10 — Pieniny Klippen Belt.

During the Early Burdigalian, the Outer Carpathian residual flysch basin was probably narrower than the above mentioned values. According to my restoration (Figs. 12, 13) the width of this basin probably measured 100–150 km (Figs. 11, 12). In this restoration I have taken 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 both the eroded front of the Magura Nappe and uplifted parts of the basin (Fig. 12). At 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 (see Ślączka & Oszczypko 1987). During the Early Burdigalian the axial part of the basin reached bathyal depths. Contemporaneously with the residual flysch deposition a marine piggy back basin (?connected with the Vienna Basin) developed (Cieszkowski 1992, see also Kováč et al., in press) on the Magura Nappe along the Pieniny Klippen Belt strike-slip boundary (Figs. 11, 12).

The Western Outer Carpathians were folded and thrust during the Early/Middle Miocene, when the oceanic or thinned continental crust of the Outer Carpathian residual flysch basin was subducted below the overriding Carpathian orogene (Alcapa and Tisza-Dacia microplates). This was accompanied by the outward overthrusting and formation of the flexural foreland basin at the moving orogenic front, and partly on top of the orogenic wedge. Like other orogenic belts, the Outer Carpathians were progressively folded towards the continental margin. During the Ottnangian, the Late Krosno (Polyanytsa) 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 (Krhovský et al. 1995), evaporite of the Upper Vorotysche Fm. in Ukraine (Andreyeva-Grigorovich et al. 1997) and the Salt Fm. in Romania (see Micu 1982)]. This salinary crisis was followed by the Intra Burdigalian phase (Ottnagian compressive tectonic event), when the marginal part of the Outer Carpathians (Silesian, sub-Silesian and Skole units) was folded, overthrust and uplifted. The active thrust front of the Outer Carpathians moved to the Silesian/sub-Silesian and Skole units front (see Kováč et al. in press). The Carpathians overrode the platform and caused flexural depression of the foreland and uplift of a peripheral bulge (Cieszyn-Slavkov Paleoridge, Figs. 1, 12, 13) at that time. The flysch olistoplaque, recognized in the Sucha IG 1 and Zawoja 1 boreholes, probably records that period of overthrusting (Figs. 7, 15). From that moment, the Polish Carpathian Foredeep began to develop as a peripheral foreland basin related to the moving Carpathian front (Oszczypko 1997). The northern edge of the Late Burdigalian (Karpatian) molasse basin was located about

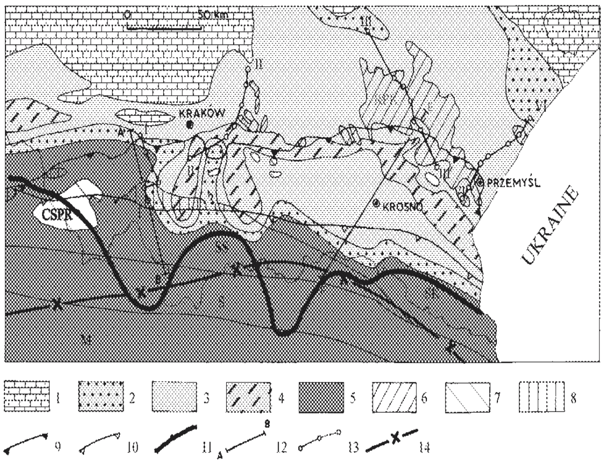

Fig. 14. Palinspastic sketch-map of the Carpathian Foreland Basin during Badenian salinary crisis (after Oszczypko 1997, supplemented). 1 — Małopolska Land, 2 — littoral facies, 3 — sulphate facies, 4 — chloride facies, 5 — Carpathian Land, 6 — area without evaporites, 7 — area without Miocene deposits, 8 — flysch-derived olistostromes, 9 — recent Carpathian front, 10 — the Early Badenian Carpathian thrust, 11 — southern extent of the Early Badenian transgression, 12 — cross-section, 13 — subsidence cross-section, 14 — zero line of Wises vectors.

20 to 50 km south from the present-day position of the Carpathian thrust (Figs. 1, 12, 13). The basin, partly developed on top of the advancing Carpathian front and on the platform, was dominated by terrestrial deposition and filled up mostly with sediments derived from the emerged platform and 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 1982)]. These deposits formed a clastic wedge along the Carpathians, comparable with the Lower fresh-water Molasse of the Alpine Foreland Basin. 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 (Figs. 5, 12–13). This caused an extra subsidence, which enabled transgression of the Early Badenian sea both onto the foreland plate and the Carpathians. The Early Badenian sea was relatively deep. According to paleoecological estimations (Kováč et al. 1993; Gonera 1994), the axial part of the basin reached upper bathial 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 1000 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 (Figs. 1B, 12–13). At the turn of the Badenian, the drop of the sea level caused regression in the Carpathians (Fig. 14). The lowstand level and climatic cooling (Demarq 1987) initiated a salinity crisis in the Carpathian foreland basin. The shallow (stable shelf) part of the evaporite basin (Fig. 14, see also Połtowicz 1993) was dominated by sulphate facies, whereas the deeper part, located along the Carpathian front, was occupied by chloride-sulphate facies. According to Kovalevich (1997), the paleobathymetry of the chloride sub-basin reached at least a few dozen metres. After the evaporite deposition the basement of the outer foredeep was uplifted (Figs. 9, 10) and a part of the foredeep was effected by erosion (e.g. Rzeszów Paleoridge, Fig. 1B). This event was followed by telescopic shortening of the Carpathian nappes (Intra Badenian compressive event, see also Kováč et al. in press). It is documented by at least 12 km of movement by the Magura and Fore Magura units in the relation to the Silesian Unit, and tectonic reduplication of the sub-Silesian Unit (Figs. 2, 12). During that period of compression the front of thrust belt shifted 20–30 km towards the NE. It was accompanied by the underthrusting of the Moldavides beneath the Magura and the PKB accretionary wedge (Fig. 2, see also Tomek & Hall 1993). In the southern part of the outer foredeep that compression event is documented by "blind faults" development (Krzywiec 1997). This resulted in the "Upper Badenian" very intense subsidence (Figs. 7–10, 15), collapse of the Rzeszów Paleoridge and a new marine transgression onto the Carpathians. The Sarmatian subsidence was also temporally related to this compressive event (Fig. 15), but the depocenter was located in the NE part of the basin, obliquely to the Carpathians. It is suggested that the loading effect of the nappe was not the only mechanism responsible for the Sarmatian

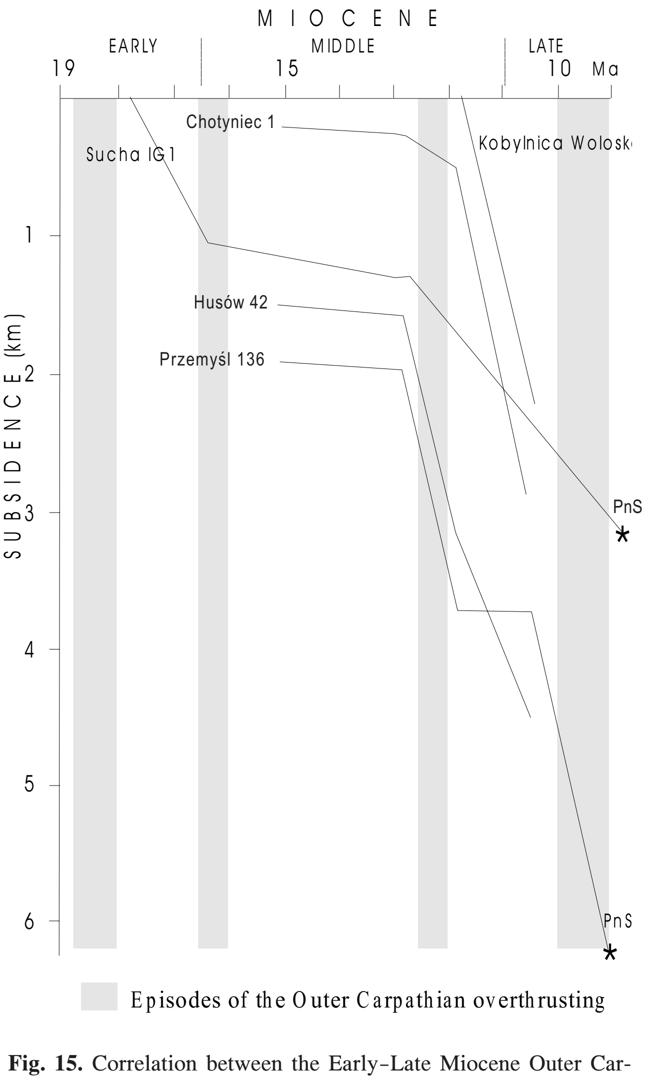

Fig. 15. Correlation between the Early–Late Miocene Outer Carpathian overthrusting and subsidence in the Polish Carpathian Foredeep.

subsidence (see Krzywiec 1997). In the course of the global Tortonian fall of the sea level (ca. 10.5 Ma BP) the sea retreated from the Carpathian foreland basin. This was followed by the last, about 30 km overthrust of the marginal Outer Carpathians towards the NE to their present-day position. This was accompanied by the post-nappe collapse of the Carpathian basement (Fig. 15). During the Pliocene erosion of the Outer Carpathians the isostatic uplifting of the Carpathians was initiated.

Conclusions

1) The Early to Middle Miocene subduction of the Outer Carpathian crust beneath the Alcapa and Tisza-Dacia microplates was accompanied by the outward overthrusting of the Flysch and Molasse Zone deposits and formation of the flexural foreland basin ralated to the moving Carpathian front. In the Polish Outer Carpathians the mean rate of the northwards overthrusting reached 12 mm/a, whereas in northeast direction this value was probably a few times higher (40–50 mm/a?).

2) The initial (Ottnangian-Karpatian) foreland basin, partly developed on the top of the advancing Carpathian front and on the platform, was dominated by terrestrial deposition. These deposits formed a clastic wedge along the Carpathians, comparable to the Lower fresh-water Molasse of the Alpine Foreland Basin. This was followed by the main period of the Middle Miocene marine deposition.

3) In the Polish Carpathian Foredeep, the periods of the Miocene subsidence were temporally and spatially related to the emplacement of the front of the Carpathians.

4) The important driving force of tectonic subsidence was the emplacement of the nappe load related to the subduction processes.

5) During the Early–Middle Miocene time, the loading effect of the thickening Carpathian accretionary wedge on the foreland plate increased and caused a progressive increase of the total subsidence, with exception of the "Middle Badenian" salinary crisis when the low subsidence or uplifting was related to the period of "dormant" Carpathian frontal thrust.

6) The Miocene convergence of the Carpathian wedge resulted in the migration of depocenters and onlap of the successively younger deposits onto the foreland plate.

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