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Stages of development in the Polish Carpathian Foredeep Basin

Review article

Nestor Oszczypko[1]**, Marta Oszczypko – Clowes[1]†

1 *Institute of Geological Sciences, Jagiellonian University, 30-063 Kraków, Poland*

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Abstract: In southern Poland, Miocene deposits have been recognised both in the Outer Carpathians and the Carpathian Foredeep (PCF). In the Outer Carpathians, the Early Miocene deposits represent the youngest part of the flysch sequence, while in the Polish Carpathian Foredeep they are developed on the basement platform. The inner foredeep (beneath the Carpathians) is composed of Early to Middle Miocene deposits, while the outer foredeep is filled up with the Middle Miocene (Badenian and Sarmatian) strata, up to 3,000 m thick. The Early Miocene strata are mainly terrestrial in origin, whereas the Badenian and Sarmatian strata are marine. The Carpathian Foredeep developed as a peripheral foreland basin related to the moving Carpathian front. The main episodes of intensive subsidence in the PCF correspond to the period of progressive emplacement of the Western Carpathians onto the foreland plate. The important driving force of tectonic subsidence was the emplacement of the nappe load related to 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 axes of depocentres reached 12 mm/yr at that time. During the Late Badenian-Sarmatian, 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 depocentres and onlap of successively younger deposits onto the foreland plate.

Keywords: Polish Carpathian Foredeep • palaeogeography • nannofossil biostratigraphy • basin evolution

1. Introduction

The Western Outer Carpathians were folded and thrusted during the Late Early/Middle Miocene, when the oceanic or thinned continental crust of the Outer Carpathian flysch basin became 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 the Tisza-Dacia microplate. At the front of the moving crustal fragments, overthrusting of the Outer Carpathians and formation of the flexural foreland basin took place [1–4]. In the Polish part of the Outer Western Carpathians, the relationship between deformed deposits and the Miocene autochthonous foredeep deposits has been very well recognised by the deep boreholes in the zone 30-50 km wide ([3–8]). There is a lot of evidence that overthrusting of the Outer Western Carpathians onto the fore-

*E-mail: nestor.oszczypko@uj.edu.pl
†E-mail: m.oszczypko-clowes@uj.edu.pl

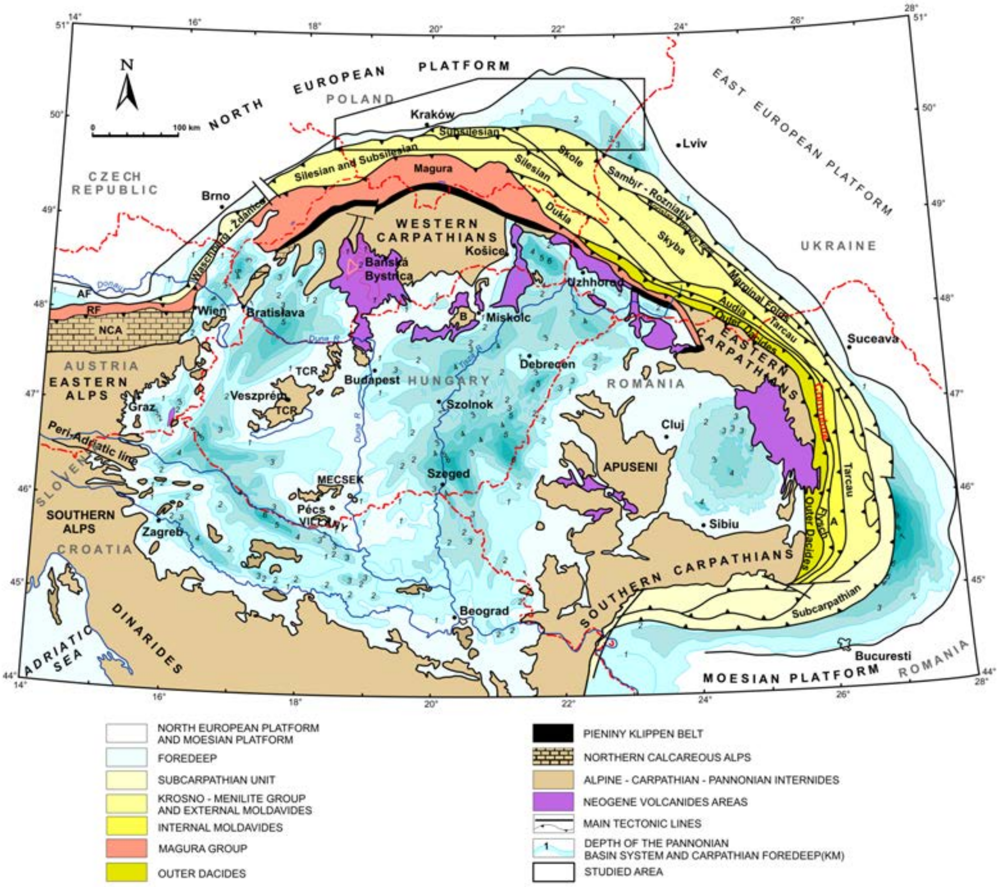

Figure 1. Geological map of the East Alpine-Carpathian-Pannonian basin system [3, 11]. Abbreviations: TCR - Trans-Danubian Ridge, B - Bükk Mts, NCA - Northern Calcareous Alps, RF - Rheno-Danubian Flysch, AF - Alpine Foredeep, VTF - Vienna Transform Fault (W-Carpathian Transfer Zone).

land plate was progressive [3, 4, 6, 7, 9, 10] and could be palinspastically restored [1, 7, 8, 11, 12]. The aim of this work is to describe the temporal and spatial relation between the subsidence, deposition and overthrusting of the orogenic wedge in the Polish segment of the Western Carpathians. This relationship has been known since the fundamental paper of [13], who showed that foreland basins could be formed by isostatic flexural subsidence of the lithosphere, accompanied by the spreading of the fold and thrust belt. In this concept, the development of the foreland basins has been regarded as the result of the lithosphere flexure caused by loading effect of the growing thrust belt. Although the first modelling studies confirmed this concept [14], the 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 [15, 16] and must be connected with deep subcrustal load of the downgoing plate [17, 18].

2. Regional setting

The Polish Carpathians are part of the great arc of mountains, which stretches for more than 1,300 km from the Vienna Forest in Austria to the Iron Gate on the Danube in Romania (Fig. 1 [11]). In the west, the Carpathians are linked with the Eastern Alps and in the east they pass into the Balkan orogenic belt. Traditionally, the Western Carpathians have been always subdivided into two distinct ranges. The Inner Carpathians are considered the older range and the Outer Carpathians the younger one (Fig. 1). The Pieniny Klippen Belt (PKB) is situated between the Central and Outer Carpathians . It is a Tertiary strike-slip boundary, which represents a strongly tectonized terrain about 800 km long and 1-20 km wide [19]. The Outer Carpathians are built up of stacked nappes and thrust-sheets which reveal different lithostratigraphy and structure (Figs. 1, 2). The Outer

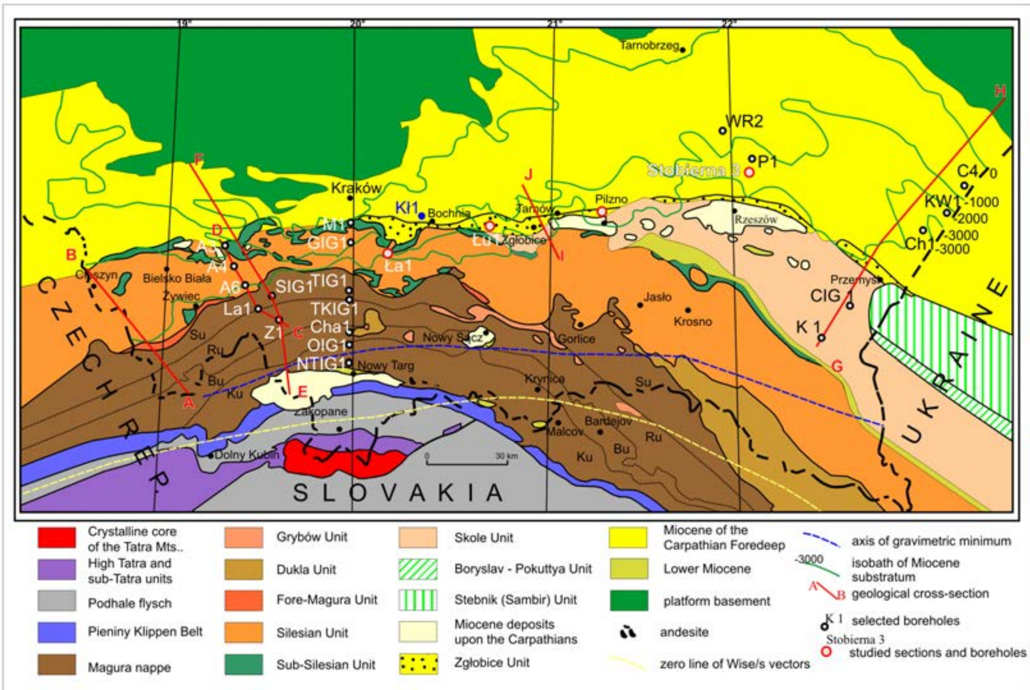

Figure 2. Sketch - map of the Polish Carpathians and their foredeep [3]. Abbreviations: Su- Siary, Ru- Rača, Bu- Bystrica, and Ku- Krynica subunits of the Magura Nappe. Boreholes: A 3 - Andrychów 3; A 4 - Andrychów 4; A 6 - Andrychów 6; La - Lachowice 1 Z 1 - Zawoja 1; SIG 1 - Sucha IG 1; ZIG 1 - Zakopane IG 1; BIG 1 - Bańska IG 1; NT IG1 - Nowy Targ IG 1; OIG 1 - Obidowa IG 1;Ch 1 - Chabówka 1; SB 1 - Skomielna Biała 1: Tk IG 1 - Tokarnia IG 1; TIG 1 - Trzebunia IG 1; GIG 1 - Głogoczów IG 1; M 1 - Mogilany 1; Kł 1 - Kłaj 1; Ła 1—Łapanów 1, Łu 1- Łukanowice 1, St-3, Stobierna 3, WR 2 - Wola Raniżowska 2; P 1 - Palikówka 1; K 1 - Kuźmina 1; CIG 1 - Cisowa IG 1; Ch 1 - Chotyniec 1; KW 1 - Kobylnica Wołoska 1; C 4 - Cetynia 4.
Main groups of tectonic units of the Outer Western Carpathians: Marginal Group (external): Borislav-Pokuttya, Stebnik (Sambir) and Zgłobice units; Middle Group (central): Grybów, Fore-Magura, Dukla, Silesian, sub-Silesian and Skole units and Magura Group (internal).

Carpathians are composed of the Late Jurassic to Early Miocene, mainly turbidite (flysch) deposits, completely uprooted from their basement (Figs. 2, 3). The largest and innermost unit of the Outer Carpathians is the Magura nappe - a Late Oligocene/Early Miocene accretionary wedge. The Magura nappe is flatly overthrust onto the Moldavides [3] - an Early/Middle Miocene accretionary wedge, which consists of several nappes: the Fore-Magura-Dukla group, Silesian, Sub-Silesian, Skole and Boryslav-Pokuttya units (Figs. 2, 3). 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-Senoniam variegated shales [3, 20], whereas 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 [3, 6]. However, along the frontal Carpathian thrust a narrow zone of folded Miocene deposits developed [Stebnik (Sambir) and Zgłobice units (Figs. 2, 3, 4)]. The detachment levels of the folded Miocene units are connected mainly with the Early and Middle Miocene evaporites.

The basement of the Carpathian Foredeep represents the epi-Variscan platform and its cover [3]. The depth to the platform basement, recognised by boreholes, changes from a few hundred metres in the marginal part of the foredeep up to more than 7,000 m beneath the Carpathians (Figs. 2, 3, 4). 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 [21]. The depth of the top of magneto-telluric basement reaches about 3-5 km in the northern part of the Carpathians, then 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 (Fig. 2). South of the gravimetric minimum and,

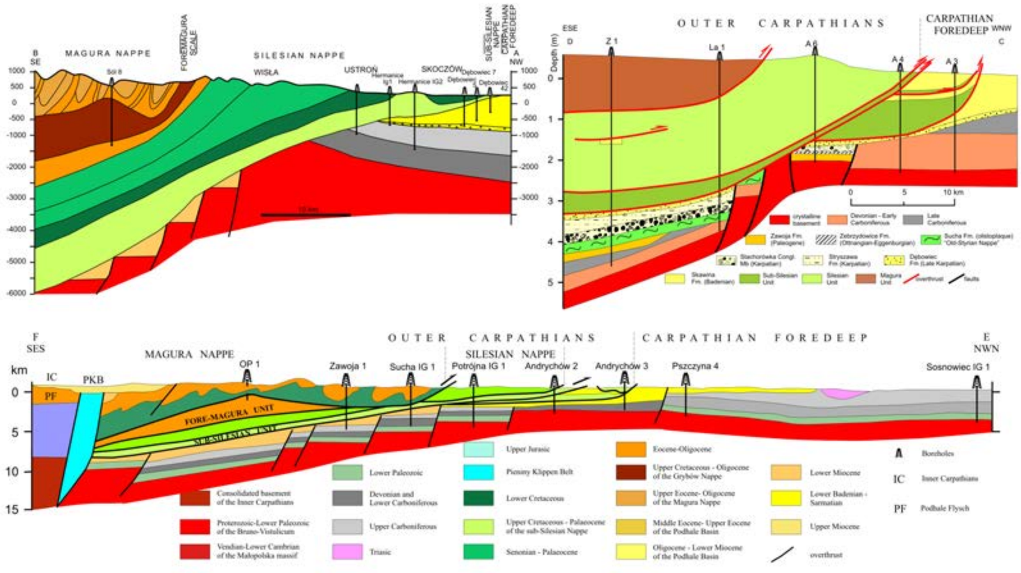

Figure 3. Geological cross-sections. A-B Dębowiec - Rycerka Dolna; C-D Andrychów - Zawoja [35,3 modified] , E-F Sosnowiec - Orawa [4, supplemented].

more or less parallel to the PKB, the zone of zero values related to of the Wiese vectors, was recognised by geomagnetic soundings [22]. This zone is connected with a high conductivity body occurring at a depth of 10-25 km and could be located at the boundary between the North European Plate and the Central West Carpathian Block [21]. In the Polish Carpathians, the depth to the crust-mantle boundary ranges from 37-40 km at the front of the Carpathians to 54 km towards the south, and then peaks along the PKB at 36-38 km [3].

3. Miocene sedimentary infill the Polish Carpathian Foredeep Basin

The Miocene deposits have been discovered both in the Outer Carpathians and in the Carpathian Foredeep (Fig. 2). In the Outer Carpathians, the Early Miocene deposits have been incorporated into the accretionary wedge as the youngest deposits of the flysch sequence (Eggenburgian-Ottnangian, NN 2-3 zone). The Polish sector of the Outer Carpathian accretionary wedge is locally transgressively overlain by the Middle Miocene marine and freshwater deposits.

The Polish Carpathian Foredeep (PCF), can be subdivided into two parts (Fig. 5), the outer and inner foredeeps [1, 3, 4, 23]. 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. 2). 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 the northern-marginal part, up to 3,000 m in the south-eastern part. The inner foredeep, located beneath the Carpathian nappes, is more than 50 km wide (Figs. 3,4) and is composed of Early to Middle Miocene autochthonous and allochthonous deposits. Preserved thickness of these deposits is still quite significant, up to 1500 m, although they have been subsequently tectonically eroded by the Carpathian nappes. The Lower Miocene strata are mainly terrestrial in origin, whereas the Midddle Miocene (Badenian and Sarmatian) ones are marine.

4. Inner Foredeep

The Lower Miocene deposits beneath the Carpathian nappes, overlapping the Proterozoic and Palaeozoic basement, have been drilled in the Bielsko, Cieszyn and Sucha Beskidzka areas (Figs. 3, 4, 5). The oldest autochthonous Lower Miocene strata, up to 1,000 m thick, have been drilled by the Zawoja-1 borehole [24–26]. The lowermost portion of this sequence, 159 m thick, is known as the Zawoja Fm. (Figs. 5, 6). The Zawoja Fm. is not homogenous. In general, this formation can be divided into three parts [25]. The lower conglomeratic part, 94 m thick,

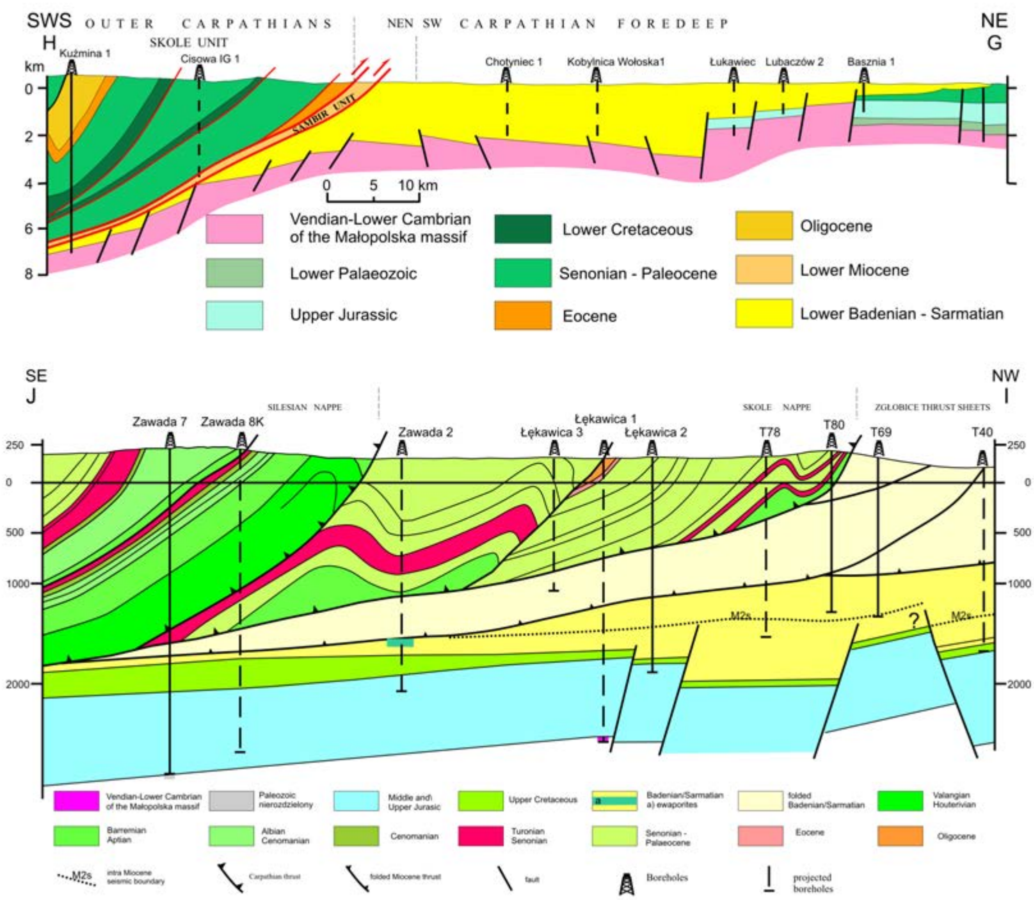

Figure 4. Geological cross-sections G-H Lubaczów - Kuźmina [4], I-J Tarnów-Zawada.

begins with a thick layer of grey-greenish to black matrix-supported conglomerates at the depth interval 4,825.5 - 4,815.0 m. These conglomerates, with sandy-silty, coalified flakes, are composed of well rounded clasts of quartz, quartzites, quartzitic sandstone and sporadic Palaeozoic rusty limestones derived from the Palaeozoic/ Proterozoic basement [27]. The conglomerates display a few fining and thining upwards sequences, 25 to 40 km thick. In core material, at the depth interval 4,751-4,759 m, a sub-vertically dipping mesoscopic anticline was pierced [27]. The anticline is composed of dark, parallel-laminated mudstones with thin sandstone intercalations. This flysch-derived olistolith is overlain by mudstone-conglomerate beds, ca. 9 m thick. The matrix of the conglomerates contains Palaeocene dinocysts (Gedl in [27]). In the lower part of the Zawoja Formation, in the silt-muddy matrix of the conglomerates, the agglutinated and planktonic Late Cretaceous -Middle Eocene foraminifera have been determined (Malata in [27]). Simultaneously, in the matrix of the basal portion of conglomerates, rich Eocene-Oligocene dinocysts have been found (Gedl in [27]).

The middle part of the Zawoja Formation, 42 m thick, is represented by a low-resistivity unit, represented by green calcareous - free siltstones with red irregular lamination or hematitic coating, containing the Lower Cretaceous (*Plectorecurvoides irregularis* Geroch, *Thalmannamina neocomiensis* Geroch and *Verneuilinoides neocomiensis* (Mjatluk) [25]) as well Upper Cretaceous *Globotruncana* s.l. and Eocene species *Saccaminoides carpathicus* Geroch and *Reticulophragmium ampelectens* (Grzybowski). The uppermost part of the Zawoja Formation is represented by a 23m thick package of conglomerates built from the eroded rocks of the lower plate.

The Zawoja Fm. is covered by a 260 to 370 m thick flysch-derived olistoplaque, referred to as the Sucha Fm., and known from the Sucha IG 1 and Zawoja 1 wells, and several other wells in the Lachowice area (Figs. 2, 3, 5, 6,

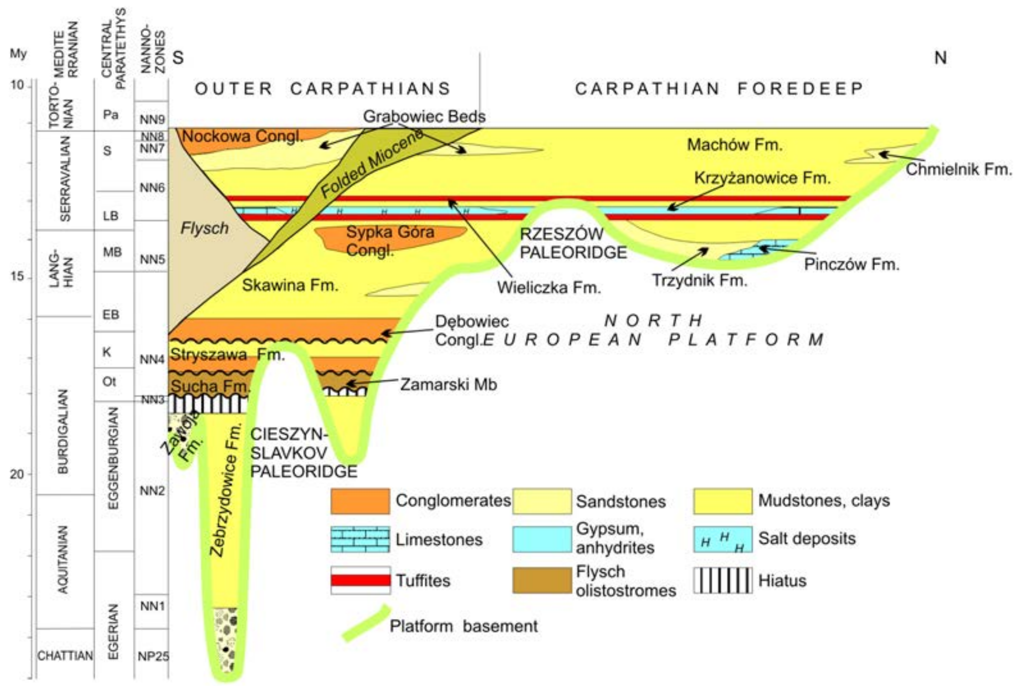

Figure 5. Lithostratigraphic model of the Miocene deposits in the Polish Carpathian Foredeep [3, supplemented]. Abbreviations: Ot - Ottnangian; K - Karpatian; EB - early Badenian; LB - late Badenian; S - Sarmatian; Pa - Pannonian.

see also [24–26, 28]). In the Sucha IG 1 borehole, this formation is composed of a few separate flysch olistoliths of various ages (Palaeocene to Early Cretaceous) that show a connection with the Silesian and Sub-Silesian successions [28]. 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 Verovice Shales and Lhota Formation of the sub-Silesian-Silesian nappes, and the Spas Shales of the Skole Nappe. The age of the black deposits from the Zawoja 1 borehole has been determined by Dinoflagellata studies as the Aptian-Late Albian [29]. In the Sucha - Zawoja area, the age of the flysch olistoplaque development could be estimated as the Ottnangian-Karpatian [30]. This formation is covered by the Stryszawa Formation that reaches the thickness of 360-566 m (Figs. 5, 6, see also [24, 25, 28]). These deposits are composed of coarse to medium-grained, polimictic conglomerates with carbonate and, locally, gypsum-anhydrite cement (Fig. 7-A). 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 [31]. The material of the conglomerates was derived both from crystalline Precambrian and sedimentary Palaeozoic basement of the Carpathian Foredeep, as well as from the front of the Carpathian nappes [24]. These conglomerates show features of alluvial deposits, passing upwards into variegated (Fig. 7-B), conglomeratic-sandy-mudstone strata [1]. The upper part of the Stryszawa Formation 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 Early Cretaceous - Oligocene age (Fig.7-C), having connection with the sediments of the sub-Silesian development [27]. In the Sucha IG-1 borehole [30, 32], the Lower Miocene (Ottnangian-Karpatian?) microfauna has been found in sporadic samples. The Eggenburgian-Ottnangian (N 5/N 6) assemblage has also been found by Gonera [27] in core material from the borehole Zawoja-1, at the depth of 4,271 - 4,278 m [27]. These foraminifera, characteristic for the middle-upper bathyal depths, are in contradiction with the sedimentary record of the Stryszawa Fm, which reveals shallow-water and/or terrestrial origin. This suggests that the above-mentioned microfauna might have been reworked from the Lower Miocene flysch strata. The Karpatian/Early Badenian calcareous nannoplankton (NN 4 zone) has also been reported from the Stryszawa Fm. [30].

In the Bielsko-Cieszyn, the Early Miocene strata de-

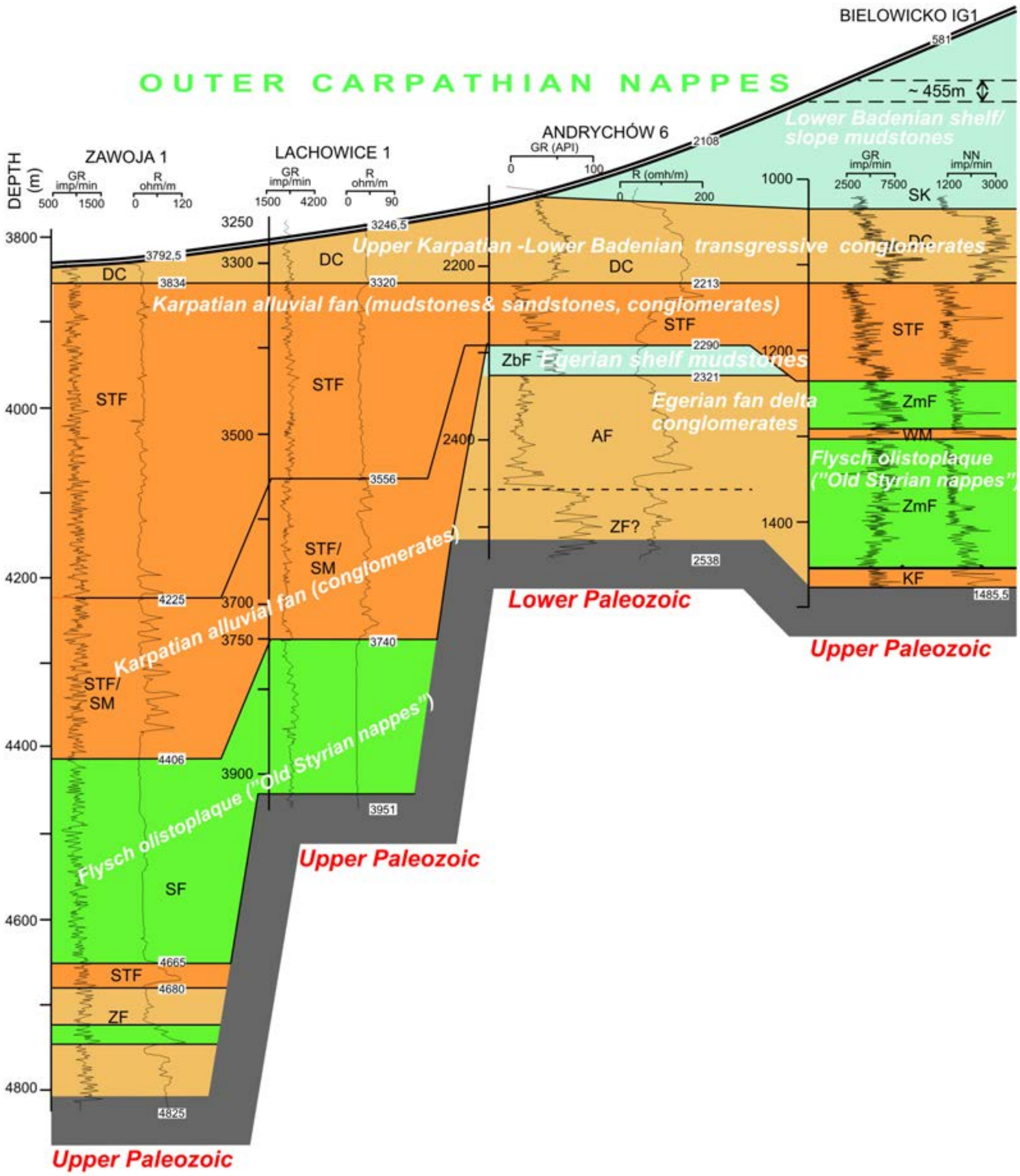

Figure 6. Well log cross-section of the subthrust Early Miocene to Early Badenian deposits of the Zawoja Andrychów Cieszyn area [35, modified)]. Abbrevations: ZF- Zawoja Formation (Oligocene- ? Lower Miocene), AF-Andrychów Formation (Egerian), ZBF- Zebrzydowice Formation (Egerian-Eggenburgian): flysch olistoplaque („Old Styrian nappe"): SF -Sucha Formation, ZmF - Zamarski Formation, STF -Stryszawa Formation (?Ottnangian -Karpatian), STF/SM -Stachorówka Conglomerate Member of the Stryszawa Formation, KF and WM- mainly flysch-derived conglomerates, DC - Dębowiec Conglomerate (? Upper Karpatian-Lower Badenian), SK - Skawina Formation (Lower Badenian).

posited above the Upper Carboniferous basement have been found in a few boreholes in a sub-thrust position. These strata belong to the Zebrzydowice Formation [33], composed of pelitic grey-greenish deposits of the Early Burdigalian (N5/N6) age [30]. The Lower Burdigalian (NN2-NN3) marine deposits were also discovered in NE Moravia [34]. These strata probably correspond with the Upper Egerian/Eggenburgian (NN1) dark marine mudstones (Figs. 5, 6, 7-D) bearing platform-derived conglomerates (Oligocene?) at the base, pierced by the Andrychów-6 borehole [35].

In the Cieszyn area, the Zebrzydowice Fm. is overlapped by the flysch olistoplaque (Zamarski Mb.) [33]. The Zamarski olistoplaque, composed of elements of the Sub-

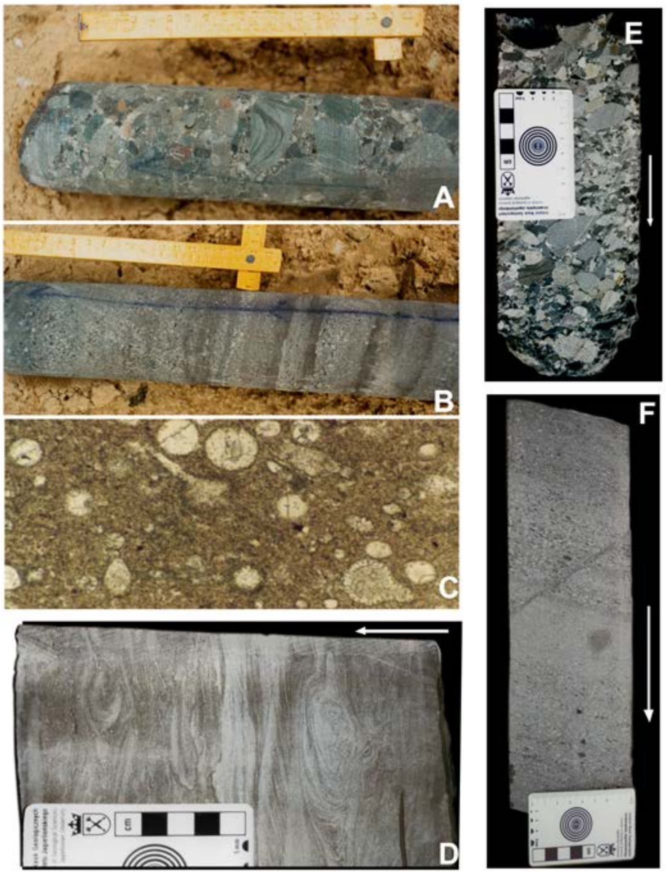

Figure 7. Typical lithofacies of the Lower/Middle Miocene of the PCF (inner foredeep). A - fine conglomerates of the Stachorówka Mb. of the the Stryszawa Fm. (Lower Miocene), Zawoja 1 borehole, core interval 4,301-4,309 m; B - thin-bedded sandstones and variegated mudstones of the Stryszawa Fm. (Lower Miocene), Zawoja 1 borehole, core interval 4,137-4,144 m; C - Mid-Cretaceous radiolarian microfacies, thin-section of the Stryszawa sandstone (Fig. 7B); D - thin-bedded fine-grained sandstone of the Zebrzydowice Fm. (Egerian) with hummocky-cross lamination and convolution at the top, Andrychów - 6 borehole, core interval 2,324-2,339 m; E - polimictic pebble conglomerate of the Stryszawa Fm., Andrychów - 6 borehole, core interval 2,213-2,219 m; F - granule conglomerates and coarse- to very coarse-grained sandstones of the Dębowiec Conglomerate (Early Badenian), Andrychów - 6 borehole, core interval 2,135-2,143 m.

Silesian Nappe, is 25-150 m thick.

The olistoplaque is covered by a 10-110 m thick layer of variegated conglomerates composed of flysch-derived clasts. These conglomerates resemble the Stryszawa Fm. from the Sucha-Zawoja area. In authors' opinion, all buried fragments of the Sub-Silesian succession (Sucha and Zamarski olistoplaques) are erosional remnants of the Old Styrian nappe, which was at least 25 km wide. According to [36], the Old Styrian overthrust was formed after the Karpatian age and before the deposition of "basal Badenian clastics", which are synonymous with the Dębowiec Conglomerates [37] in Poland. However, if we accept the new biostratigraphic data [30], then the age of Old Styrian thrusting should be regarded as intra-Karpatian.

In the Cieszyn -Bielsko-Sucha Beskidzka area, the upper part of the sub-thrust foredeep sequence is represented by a 40-90 m thick complex of the transgressive Dębowiec conglomerates and sandstones, which are composed of the Upper Carboniferous clasts (Figs. 5, 6, 7- F). These conglomerates pass upwards into the Skawina Fm. [38]. According to [30], both the Dębowiec conglomerates as well as the lowermost portion of the Skawina Fm. are of the Late Karpatian/Early Badenian age.

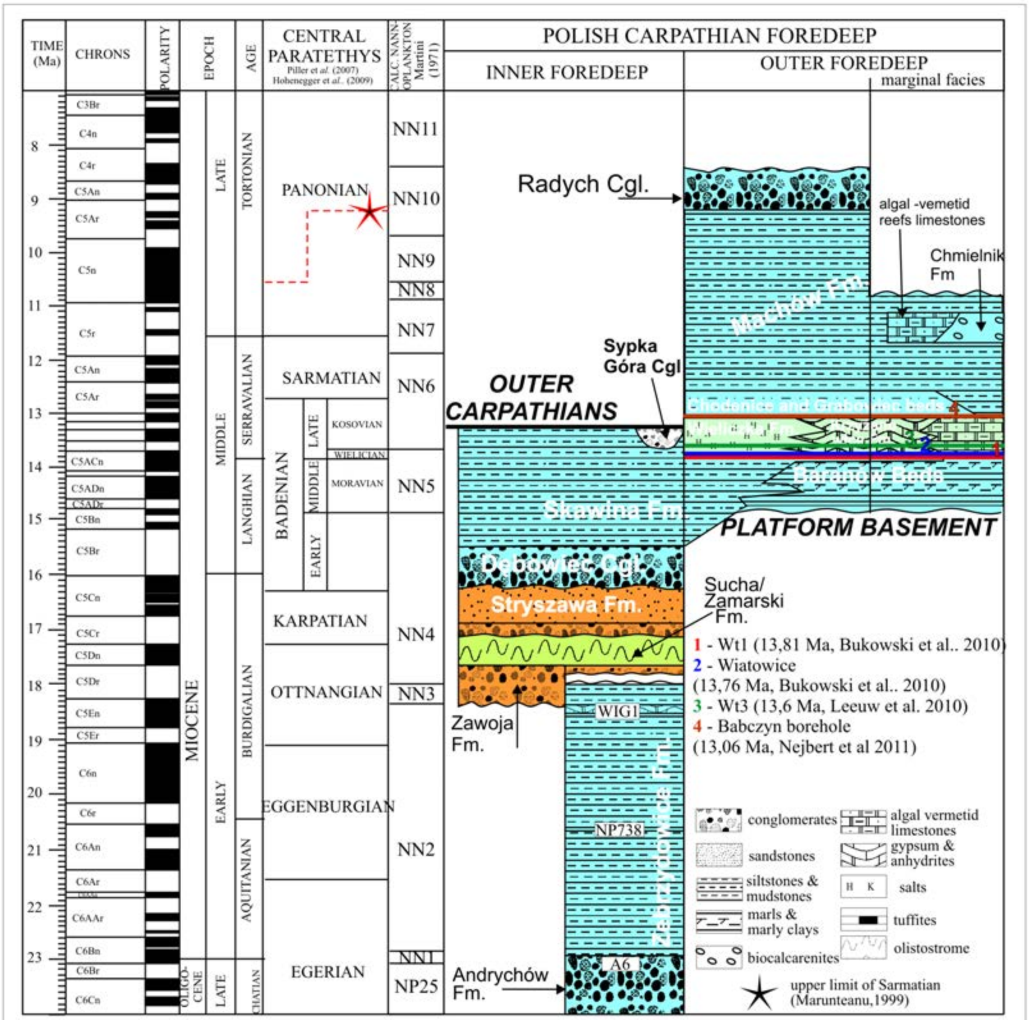

Figure 8. Stratigraphic scheme of the Miocene deposits of the Polish Carpathian Foredeep basin (compiled after Oszczypko [2, 4, 39, 40], suplemented).

5. Outer Carpathian Foredeep

5.1. Middle Miocene (Langhian and Serravallian)

The Middle Miocene began with the extensive Early Badenian marine transgression, which flooded both the foredeep and marginal part of the Carpathians (Figs. 6, 8). The Badenian deposits in the outer part of the Polish Carpthian Foredeep are traditionally subdivided into -Lower Badenian (sub-evaporitic), -Middle Badenian (evaporites), and -Upper Badenian (supra-evaporitic) beds. This subdivision is in strong contradiction with the recent Early/Middle Miocene integrated stratigraphy of the Central Paratethys [11, 40, 41]. The revised subdivion is as follows: Early Badenian (16.30-14.89 Ma), Middle Badenian -Moravian (Lower and Upper Lagenid Zone; 14.89-13.82 Ma), and Late Badenian (Wielician-13.82-13.65 Ma and Kosovian: Bullimine-Bolivine Zone - 13.65-12.73 Ma). In this scheme, the boundary NN4/NN5 at 14.89 Ma is located inside Helicoshaera amliaperta LO (15.50-14.53 Ma), while NN5/NN6 boundary (13.65 Ma) coincides with Sphenolithus heteromorphus LO. Subsequently, the Badenian/Sarmatian boundary is placed at 12.73 Ma.

The Badenian strata rest directly on the platform basement, except in the inner foredeep, where they cover the lower Miocene deposits. Usually, the "lower Badenian" [42, 43] begins with a thin layer of conglomerates; how-

Figure 9. Typical lithofacies of the Middle Miocene of the PCF (outer foredeep). A - dark-grey, laminated marly siltstones and marlstones, upper part of the Skawina Fm. (Badenian), Łapanów 1 borehole, core interval 1,588-1,594 m; B - dark-grey, laminated clystones and mudstones of the Chodenice beds (Badenian/Sarmatian) with sporadic intercalations of grey, very thin-bedded (up to 0.5 cm), very fine-grained sandstones. Sandstones sometimes display ripple-cross lamination, Łukanowice 1 borehole, core interval 1,132-1,139 m; C - dark-grey laminated silty heterolithes, with horizons of ripple-cross laminated very fine -grained sandstones and siltstones. Upper part of the Machów Fm. (Sarmatian), Stobierna-3 borehole, core interval 715-724 m; D - Early Sarmatian littoral cross-laminated lamy sands, marginal part of PCF, NE of Pińczów [4].

ever, in the western part of the foredeep the Dębowiec Conglomerates attain a thickness of up to 100 m. The conglomerates pass upwards into dark, clayey-sandy sediments of the Skawina Fm. The thickness of the "lower Badenian" deposits is variable, reaching up to 1,000 m in the western inner foredeep (Fig. 5), whereas in the remaining parts of the foredeep it rarely exceeds 30-40 m [43]. The sedimentation of the Skawina Fm. began in the inner foredeep with Praeorbulina glomerosa zone (N 8), whereas in the outer one with the Orbulina suturalis (N 9 or N 10) zone [1, 4, 30]. South of Kraków, the Skawina Formation has been pierced by the borehole Łapanów 1 (Fig. 2) beneath the Carpathian overthrust, at the depth of 1,458-1,765.5 m. This formation transgressively covers Jurassic limestones of the lower plate.

The core material is represented by dark-grey marly claystones and mudstones with sporadic intercalations of very fine-grained heteroliths (Fig. 9-A). From the 1,588 - 1,594 m depth interval, 14 samples for nannofossil research were collected. The autochthonous assemblage is represented by *Calcidiscus leptoporus* (Murray and Blackman), *Calcidiscus premacintyrei* Theodoridis, *Coccolithus miopelagicus* Bukry, *Coccolithus pelagicus* (Wallich), *Coronocyclus nitescens* (Kamptner), *Cyclicargolithus floridanus* (Roth & Hay), *Discoaster deflandrei* Bramlette & Riedel, *Discoaster exilis* Martini & Bramlette, *Discoaster variabilis* Martini & Bramlette, *Helicosphaera carteri* (Wallich), *Helicosphaera compacta* Bramlette & Wilcoxon, *Helicosphaera euphratis* Haq, *Helicosphaera intermedia* Martini, *Helicosphaera mediteranea*, *Helicosphaera valbersdorfensis*, *Pontosphaera multipora* (Kamptner), *Pontosphaera plana* (Bramlette & Sullivan) *Reticulofenestra minuta* Roth, *Reticulofenestra pseudoumbilica* (Gartner), *Sphenolithus moriformis* (Bronnimann & Stradner), and *Umbilicosphaera rotula*.

According to the standard zonation [44], LO of *Sphenolithus heteromorphus* marks the NN5/NN6 boundary. From the biostratigraphical point of view, the stratigraphic range of *Helicosphaera valbersdorfensis* is significant. It appears first in the highest part of NN5 and its last occurrence is near the NN6/NN7 boundary [45, 46]. Additionally, important is also the *Cyclicargolithus floridanus*, whose last common occurrence takes place in the middle part of NN7. It is also important the stratigraphic range of *Helicosphaera waltrans*, with last occurence just above the first occurrence of *Helicosphaera valbersdorfensis*. A very important species is *Sphenolithus abies* (but not observed in the assemblage), which is characteristic for the higher part of NN6 (cf. [46]).

Taking into account the lack of *Sphenolithus heteromorphus*, *Discoaster kuglerii*, *Helicosphaera waltrans* and *Sphenolithus abies*, and simultaneous presence of *Helicosphaera valbersdorfensis* and *Cyclicargolithus floridanus* it can be suggested that the assemblages may represent the lower part of NN6 Zone (Fig. 8).

According to the calcareous nannoplankton studies [47], the uppermost part of the sub-evaporitic Skawina Formation belongs to the boundary between NN5 and NN6 zones, although in the Bochnia and Kalush Salt Mine (Ukraine) only the NN6 zone was determined (Fig. 8).

The radiometric age of a tuffite from the uppermost part of the Skawina Fm. in the Wieliczka Salt Mine (WT-1, see also [47, 48]) has been determined (Ar/Ar) as 13.81+/−0.08 Ma [49]. Simultaneously, the age of Wiatowice tuffites located in the younger part of the Skawina Formation in the Gdów "embayment" has been determined (Ar/Ar) as 13.76±0.08 Ma [50].

The Upper Badenian evaporitic horizon either overlies these deposits or rests directly upon the platform basement. These Badenian (Wielician) evaporites belong to the lower part of the NN6 zone [47, 51, 52] and consist of rock salt, claystones, anhydrites, gypsum and marls. The Badenian evaporitic deposits in the PCF are included into two formations: the Krzyżnowice Formation (anhydrites) and Wieliczka Formation (salts) [53]. Between Wieliczka and Tarnów, the thickness of salts attains 70-110 m [48, 54] and decreases towards the east to a few dozen metres, whereas the thickness of gypsum and anhydrites commonly varies between 10 and 30 m [55, 56].

In the Bochnia Salt Mine, inside the Wieliczka Salt Formation (NN6 Zone after [47]), the WT-3 tuffite horizon, ca. 37 m above the top of the Skawina Fm., has been distinguished by [48]. The radiometric age of this tuffite has been determined at 13.60+/−0.07 Ma [49].

The evaporites are overlain by a sandy-silty series that are attributed to the Upper Badenian (Kosovian) and Sarmatian (Fig. 8) (see [58, 59]). These sand-silty deposits, known as the Machów Formation, with a thick sandstone complex at the base, range in thickness between a few hundred metres in the northern parts of the basin to 3,000 meters in the SE, close to the Polish/Ukrainian boundary. In the northern, marginal part of the PCF, the Late Badenian/ Sarmatian littoral carbonates and clastic deposits are well preserved [4].

In the Kraków-Bochnia region, at the top of evaporitic horizon (Wielician), the Upper Badenian (Kosovian) silty-sandy deposits of the Chodenice beds with a few intercalations of tuffites occur. The thickness of these deposits oscillates from 50-60 m on the SE periphery of Kraków to 300 m in the Wieliczka-Bochnia area. The radiometric age (Ar/Ar) of tuffites from the locality Chodenice near Bochnia has been determined as 13.62±0.10 Ma [50].

West of Tarnów (Fig. 2), folded deposits of the Chodenice beds have been pierced by the £ukanowice 1 borehole (Fig. 9 - B). These strata are represented by laminated marly clystones and mudstones with sporadic intercalations of thin-bedded sandstones. The nannofossil autochthonous assemblage (Fig. 10) from these beds is represented by: *Calcidiscus leptoporus* (Murray and Blackman), *Calcidiscus premacintyrei* Theodoridis, *Coccolithus miopelagicus* Bukry, *Coccolithus pelagicus* (Wallich), *Coronocyclus nitescens* (Kamptner), *Cyclicargolithus floridanus* (Roth & Hay), *Discoaster deflandrei* Bramlette & Riedel, *Discoaster exilis* Martini & Bramlette, *Discoaster variabilis* Martini & Bramlette, *Helicosphaera carteri* (Wallich), *Helicosphaera compacta* Bramlette & Wilcoxon, *Helicosphaera euphratis* Haq, *Helicosphaera intermedia* Martini, *Helicosphaera mediterranea*, *Helicosphaera valbersdorfensis*, *Pontosphaera multipora* (Kamptner), *Pontosphaera plana* (Bramlette & Sullivan), *Reticulofenestra minuta* Roth, *Reticulofenestra pseudoumbilica* (Gartner), *Rhabdosphaera sicca*, *Sphenolithus abies, Sphenolithus* moriformis (Bronnimann & Stradner), and *Umbilicosphaera rotula*.

The described nannofossil assemblage is lacking Discoaster kuglerii as well as *Sphenolithus heteromorphus* and *Helicosphaera waltrans*. At the same time, *Sphenolithus abies, Helicosphaera valbersdorfensis* and *Rhabdosphaera sicca* are present what suggests that the assemblage may represent the upper part of the NN6 Zone.

The Chodenice beds pass upwards into a sandy-clayey complex (Grabowiec beds) bearing a sandy lithosome (Bogucice sands) in the lower part [60]. The Bogucice sands are interpreted as a progradational complex of the lowstand systems tract, which developed within an incised valley and shelf-edge delta.

In the central part of the PCF, north of Rzeszów area, the Upper Badenian (Kosovian) deposits locally rest directly upon the platform basement, which is composed of the Upper Proterozoic-Lower Cambrian slates. In this area, the Upper Badenian-Sarmatian infill of the PCF displays two shallowing-upward deposition sequences. The lower sequence is represented by hemipelagic, turbiditic, lower deltaic and intra-deltaic deposits, while the upper sequence (Fig. 9 - C) displays upper deltaic and nearshore-to-estuarine facies [61].

The lower sequence has been supplied with siliciclastic material derived from erosion of the uplifted platform basement, while the upper part of the infill reflects sediment progradation from the south, from the erosional frontal part of the Carpathian accretionary wedge. The mentioned sequences contain different calcareous nannoplankton assemblages (see Oszczypko-Clowes in [61]). The lower sequence is represented by a moderately abundant nannofossil assemblage dominated by *Cyclicargolithus floridanus* and *Coccolithus pelagicus*, whereas *Helicosphaera carteri*, *Reticulofenestra pseudoumbilica* and *Sphenolithus moriformis* have been observed less frequently (Fig. 10). The lack of *Sphenolithus heteromorphus* Deflandre and *Discoaster kuglerii* Martini and Bramlette, and simultaneous presence of *Helicosphaera valbersdorfensis* and *Cyclicargolithus floridanus* it could be suggested that the assemblages may represent upper part of the NN6 Zone.

The upper sequence contains additionally *Calcidiscus macintyrei* and *Coccolithus miopelagicus* (>14µm). The FO of *Calcidiscus macintyrei* defines the lower boundary of the NN7 Zone [45, 46]. The youngest deposits have been pierced by the borehole Stobierna-3 at the depth of 715-724 m (Fig. 2, 9-C). According to the standard zonation [44, 62], FO of *Discoaster kugleri* marks the boundary between NN6 and NN7. However, the species is practically absent from high latitude areas, so it was suggested to use an alternative biostratigraphic event to determine the zone NN7 [45, 46]. The presence of C*occolithus miopelagicus* (>14µm) is essentially confined just to that interval, but its first occurrence is gradational [46].

More or less simultaneously with siliciclastic sedimentation in central and southern parts of PCF, the Late Badenian coralline algae-vermetid reefs and the early Sarmatian serpulid-microbialite reefs developed in the northeastern and eastern borders of the Carpathian Foredeep Basin in Poland and Ukraine [63]. Sarmatian detrital deposits are also known from the northern littoral part of PCF (Fig. 9-D).

The problem of the Badenian/ Sarmatian boundary in the PCF has been recently discussed by [64] on the basis of results of the Babczyn-2 borehole (east of Lubaczów), drilled in the NE part of the PCF (near the Polish-Ukrainian border). In this borehole, above 32 m evaporite gypsum of the Krzyżanowice Formation (Wielician), the 9.4-m-thick Pecten beds, related to post-evaporite Kosovian transgression, and 12.6-m-thick Sarmatian *Syndesmya* beds were drilled. The boundary between the *Pecten* and *Syndesmya* beds is more or less coincident with the appearance of the endemic Sarmatian foraminifer *Anomalinoides dividens* Łuczkowska. In the *Pecten* beds (3.4 m above the gypsum), a tuffite layer was found and dated (Ar40/Ar39) to an average age of 13.06 ± 0.11 Ma [64].

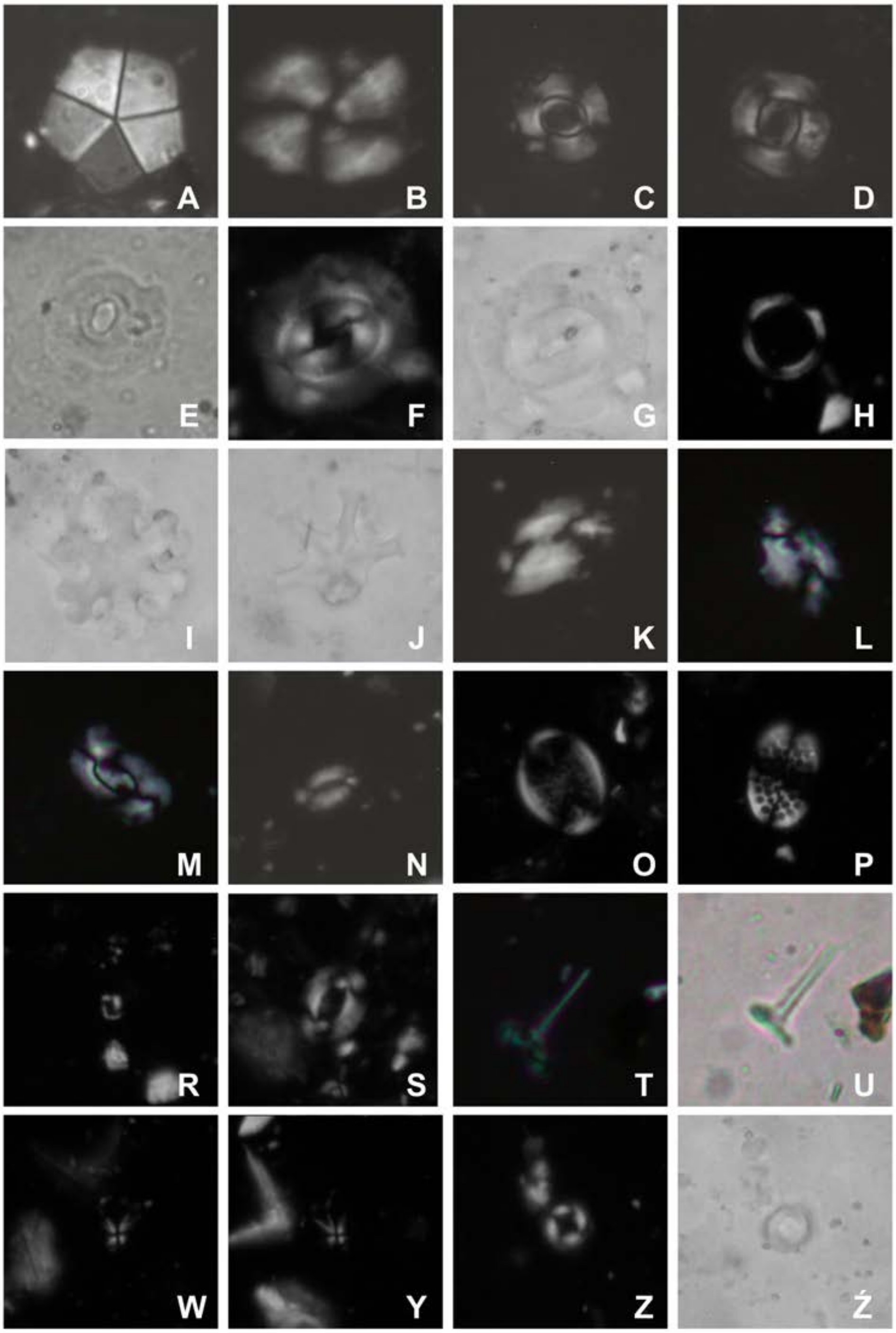

Figure 10. Badenian/Sarmatian typical nannofosil assemblages. A - *Braarudosphaera bigelowii* (Łukanowice-1; 1,132-1,139 m); B - *Calcidiscus leptoporus* (Chodenice beds, Zgłobice section); C, D, E - *Calcidiscus premacintyrei* (Łukanowice-1; 1,132-1,139 m); F, G - *Coccolithus miopelagicus* (Stobierna-3; 715-724 m, box I); H - *Coronocyclus nitescens* (Stobierna-3; 715-724 m, box I); I - *Discoaster deflandrei* (Stobierna-3; 715-724, box I); J - *Discoaster variabilis* (Stobierna-3; 834-843 m, box VIII); K - *Helicosphaera carteri* (Chodenice beds, Zgłobice section); L - *Helicosphaera carteri* (Łukanowice-1; 1,132-1,139 m); M - *Helicosphaera intermedia* (Chodenice beds, Zgłobice section), N - *Helicosphaera walbersdorfensis* (Łukanowice-1; 1,132-1,139 m); O - *Pontosphaera discopora* (Stobierna-3; 715-724 m, box I); P - *Pontosphaera multipora* (Stobierna-3; 715-724 m, box I); R - small *Reticulofenestra* (Stobierna-3; 715-724 m, box I); S - *Reticulofenestra pseudoumbilica* (Stobierna-3; 715-724 m, box I); T, U - *Rhabdosphaera sicca* (Chodenice beds, Zgłobice section); W, Y - *Sphenolithus abies* (Stobierna-3; 715-724m, box II); Z, Ż - *Umbilicosphaera rotula* (Stobierna-3; 715-724 m, box I).

Figure 11. Typical lithofacies of the Middle Miocene of the Zgłobice thrust sheets, Miocene erosional outliers in the Outer Carpathians and the northern marginal facies. A-B - poorly cemented sandstones of the Chodnice beds (Late Badenian - Late Badenian/Sarmatian); C - submarine slump, Chodnice beds (Late Badenian/Sarmatian); D - sandy mudstones with coalified flakes; A-D Dunajec River section at Zgłobice; E - mudstones and yellow-rusty siltstones of the Biegonice Fm., Kamienica Nawojowska River section at Nowy Sącz [69].

6. Folded Miocene deposits

Along the southern margin of the PCF, development of the folded Miocene units (Figs. 2, 3, 4) was strongly influenced by the configuration of the frontal Carpathian thrust fault and the depth to the basement [6, 7]. The Stebnik (Sambir) Nappe, that occurs along the front and beneath of the Skole Nappe SE of Przemyśl near the Polish-Ukrainian border [42], includes Lower and Middle Miocene deposits as young as the Sarmatian [47, 59, 65]. Between Przemyśl and Kraków, an up to 10-km-wide zone of folded Badenian and Sarmatian strata occurs along the Carpathian frontal thrust (Zgłobice thrust-sheets, [66]) that can be regarded as a continuation of the Stebnik (Sambir) Nappe [4, 59].

In the Pilzno-Bochnia area, structural position of the Zgłobice thrust-sheets has been recognised by numerous boreholes and seismic data. This is clearly visible on the cross-section (Fig. 4-B) through the marginal part of the Carpathians near Tarnów. On this cross-section, the folded Miocene Zone (Late Badenian-Sarmatian), up to 10 km broad, is composed of three thrust sheets, which are up to 1,000 m thick. These thrust sheets are flatly overthrust onto the autochthonous Miocene, divided by the M2s seismic boundary (evaporites) into the "sub-evaporite" and "supra-evaporite" Badenian strata. Towards the east, the thickness of folded Miocene deposits is drastically reduced by the overthrust of the Outer Carpathians.

At the Zgłobice outcrop there are exposed, in an overturned position, thick to medium bedded, poorly cemented sandstones passing upwards into the dark-grey marly mudstones of the Chodenice beds (Fig. 11- A-D). Samples collected from these beds contain a moderately abundant calcareous nannoplankton association belonging to the upper part of the NN 6 Zone (see discussion above).

The youngest deposits of the Zgłobice thrust-sheets have been recognised in the Pilzno area. These strata are composed of claystones and mudstones with sporadic sandy intercalations. They also contain few layers of tuffites. All collected samples contain the well diversified and abundant nannofossil association. The autochhtonous assemblage is represented by *Calcidiscus leptoporus* (Murray and Blackman), *Coccolithus miopelagicus* Bukry, *Coccolithus pelagicus* (Wallich), *Coronocyclus nitescens* (Kamptner), *Cyclicargolithus floridanus* (Roth & Hay), *Discoaster deflandrei* Bramlette & Riedel, *Discoaster exilis* Martini & Bramlette, *Discoaster variabilis* Martini & Bramlette, *Helicosphaera carteri* (Wallich), *Helicosphaera compacta* Bramlette & Wilcoxon, *Helicosphaera euphratis* Haq, *Helicosphaera intermedia* Martini, *Helicosphaera mediterranea*, *Helicosphaera valbersdorfensis*, *Pontosphaera multipora* (Kamptner), *Pontosphaera plana* (Bramlette & Sullivan), *Reticulofenestra minuta* Roth, *Reticulofenestra pseudoumbilica* (Gartner), *Sphenolithus moriformis* (Bronnimann & Stradner), and *Umbilicosphaera rotula*.

The described nannofossil assemblage is lacking both *Discoaster kuglerii* as well as *Calcidiscus premacintyrei*. The last common occurrence of Calcidiscus premacintyrei takes place just before the first occurrence of *Discoaster kugleri*, so it can be used to approximate the determination of the Zone NN7 [45]. The co-occurrence of *Sphenolithus abies*, *Helicosphaera valbersdorfensis* and *Coccolithus miopelagicus* (>14μm), followed by the absence of *Cacidiscus premacintyrei*, allowed us to assign all the samples to the Zone NN7. The tuffite horizons from the Pilzno area can probably be correlated with tuffites from Sułków Brickyard (near Wieliczka), located inside the NN6/7 Zone [47].

The youngest folded Miocene deposits of the PCF belonging to the NN8/NN9 Zone have been recognised [67] in sub-vertically dipping grey and green claystones in the Andrychów-section at the frontal Carpathian thrust (Fig. 3 C-D).

The same nannofossils, belonging to the NN8 and NN9 zones, have been identified in clayey-sandy deposits of the upper part of the Dashava Formation in the Western Ukraine [59]. These strata have been sampled in the Bonevychi and Mykhaylevychi sections of the Sambir/Stebnik Nappe, near the Polish boundary [59]. This formation is overlapped by the flysch-derived Radych, conglomerates, which record the youngest stage of the Sambir subbasin development at the front of the overriding Eastern Flysch Carpathians.

The Badenian and Sarmatian strata are also preserved as transgressive erosional outliers within the Polish Outer Carpthians. The southernmost occurrence (Fig. 2) of the Badenian (Kosovian)/Sarmatian marine sediments is known from the Nowy Sącz Basin (Fig. 2; [68, 69]). Both freshwater deposits, up to 650 m thick, with thin intercalatations of lignites (Fig. 11-E) as well as brackish and marine deposits with rich gastropods and bivalves, foraminera and calcareous nannoplankton are known from this basin. The autochthonous nannofossil assemblages are characterised by the presence of *Helicosphaera valbersdorfensis*, *Cyclicargolithus floridanus*, Sphenolithus abies, Helicosphaera stalis and also rare Calcidiscus premacintyrei. All these species can be attributed to the upper part of NN6 and lowermost part of NN7 zones (see discussion earlier) [69].

7. Stages of structural and depositional development of the Polish Carpathian Foredeep basin

Development of foredeep basins is generally regarded as resulting from flexural deformation of the lithosphere in response to its loading by a growing orogenic wedge [13, 14]. The Carpathian Foredeep Basin is a typical slab-loaded fore-arc foreland basin [70] that developed in front of the advancing Carpathians. The arcuate shape of the Carpathians and their foredeep (Fig. 1) was primarily controlled by the configuration of the margin of the European foreland plate [4]. The present-day width of the PCF's outer foredeep varies between 30-40 km in its western segment and 10 km in the Kraków area, up to 90 km on the Rzeszów meridian, and around 50 km along the Polish-Ukrainian state boundary (Fig. 2). Significant narrowing of the foredeep close to Kraków is related to the NW-SE trending foreland structures [42], whereas to the east erosional remnants of marine Miocene deposits can be found beyond the present-day margin of the foredeep, suggesting that its depositional margin was located farther to the north. According to our estimation [1–4], the multistage overthrusting of the Polish Outer Carpathians took place during the following periods:

1. before deposition of the Stryszawa Fm. (after

Ottnangian and before Karpatian) (early Styrian movements);

2. during the Late Badenian (?late Styrian movements);

3. after the Sarmatian.

The mean rate of the Carpathian frontal thrusting after the Karpatian could be estimated as 12 mm/yr [1, 2]. This value is comparable to the results of [71] who have concluded that between the Middle Oligocene and Sarmatian the mean rate of the Carpathian convergence reached 11-14 mm/yr.

8. Early Miocene transition from a residual flysch basin to the PCF

In the western part of the Polish Outer Carpathians (Cieszyn-Bielsko area), the Andrychów 6 borehole penetrated autochthonous Late Oligocene to Early Miocene deposits beneath the Carpathian nappes (Fig. 6). The basal portion of this sequence is composed of the fan-delta pebbly mudstones and conglomerates overlain by dark marine mudstones of the Egerian age [34]. Northward, these shelf mudstones are followed by the marine Eggenburgian (Ottnangian) grey-greenish marine clays of the Zebrzydowice Fm. [30] that reflect progressive flooding of the foreland basin. At the same time, this marine basin was probably linked with the Outer Carpathian residual flysch basin.

The Egerian-Ottnangian marine sedimentation [34] was followed by an intra-Burdigalian (late Ottnangian) uplift, folding and overthrusting of the Outer Carpathians onto the foreland platform. This was accompanied by the development of large-scale slides (olistoplaques and gravitational nappes; see Sucha and Zamarski formations) along the frontal parts of the Sub-Silesian Nappe [72]. By the late Ottnangian, the front of the orogen was located about 50 km south of its present-day position in the eastern parts of the PCF, whilst in the Cieszyn area gravitational nappes had more or less reached the present-day position of the Carpathian front (Fig. 12-A). During the initial stage (Ottnangian-Karpatian) of the inner foredeep development in the Czech and Polish segments [73, 74], subsidence and sedimentation rates were in balance, as shown by the accumulation of terrestrial and shallow marine series [1, 2, 75].

In the Zawoja 1 borehole (Figs. 3, 6), the fan-delta conglomerates of the Zawoja Formation with a small flysch olistolites are overlapped by thick flysch olistoplaque (Sucha Fm. [2, 24, 28]), while in the Cieszyn area the Early Miocene Zebrzydowice Fm. is overlain by the thick flysch olistoplaque of the Zamarski Fm. [32]. The Zamarski Fm. extends over at least 50 sq. km and consists of elements of the Sub-Silesian Nappe (Fig. 12A). This olistoplaque is also known as the "Old Styrian overthrust" from the marginal part of the Moravo-Silesian Carpathians [35].

Emplacement of the Sucha/Zamarski olistoplaques was followed by the Karpatian period of intense subsidence of the inner foredeep that probably affected also the frontal part of the Carpathian Nappe system. The inner foredeep was filled with the coarse alluvial fan deposits of the Stryszawa Formation that were derived both from the Carpathians as well as from emerged parts of the lower plate [1, 2, 4]. Its basal part consists of conglomerates containing components derived from both the Carpathians and emerging parts of the foreland platform [1, 2, 4]. Its basal part consists of conglomerates containing components derived from the Carpathian flysch as well as the Palaeozoic basement of the foreland. These conglomerates grade upward into sandstones, the carbonate and gypsum cement of which yielded Ottnangian-Karpatian nannoplankton (NN4 [30]), as well as reworked Lower Cretaceous to Early Miocene flysch foraminifera. The youngest recycled microfauna found in the Stryszawa Formation is of Eggenburgian-Ottnangian age and occurs also in the youngest strata of the Outer Carpathians [1].

The Early Miocene inner PCF Basin was at least 40 km wide and extended to the southeast into the Sambir Basin of the Western Ukraine [4, 58]. Deposition of the Stryszawa Formation was followed by erosion, which was caused by the uplift of the peripheral Cieszyn-Slavkov Palaeo-Ridge [1, 6, 10]. In Southern Moravia, this erosional period can be correlated with the discordance below the terminal Karpatian strata [76]. Erosion along the northern flank of the Cieszyn Slavkov Palaeo-Ridge was coupled with the development of normal faults bounding the W-E and NW-SE trending grabens (e.g., Bludowice-Skoczów Palaeovalley; [10]). During the Early Badenian, the axes of these extensional grabens migrated towards the NE.

9. Early/Middle Badenian opening of the basin

During the late Karpatian/early Badenian, SW-NE and NW-SE trending troughs developed in front of the "Old Styrian" thrust. Starting with the early Badenian (Langhian) marine transgression, subsidence rates ex-

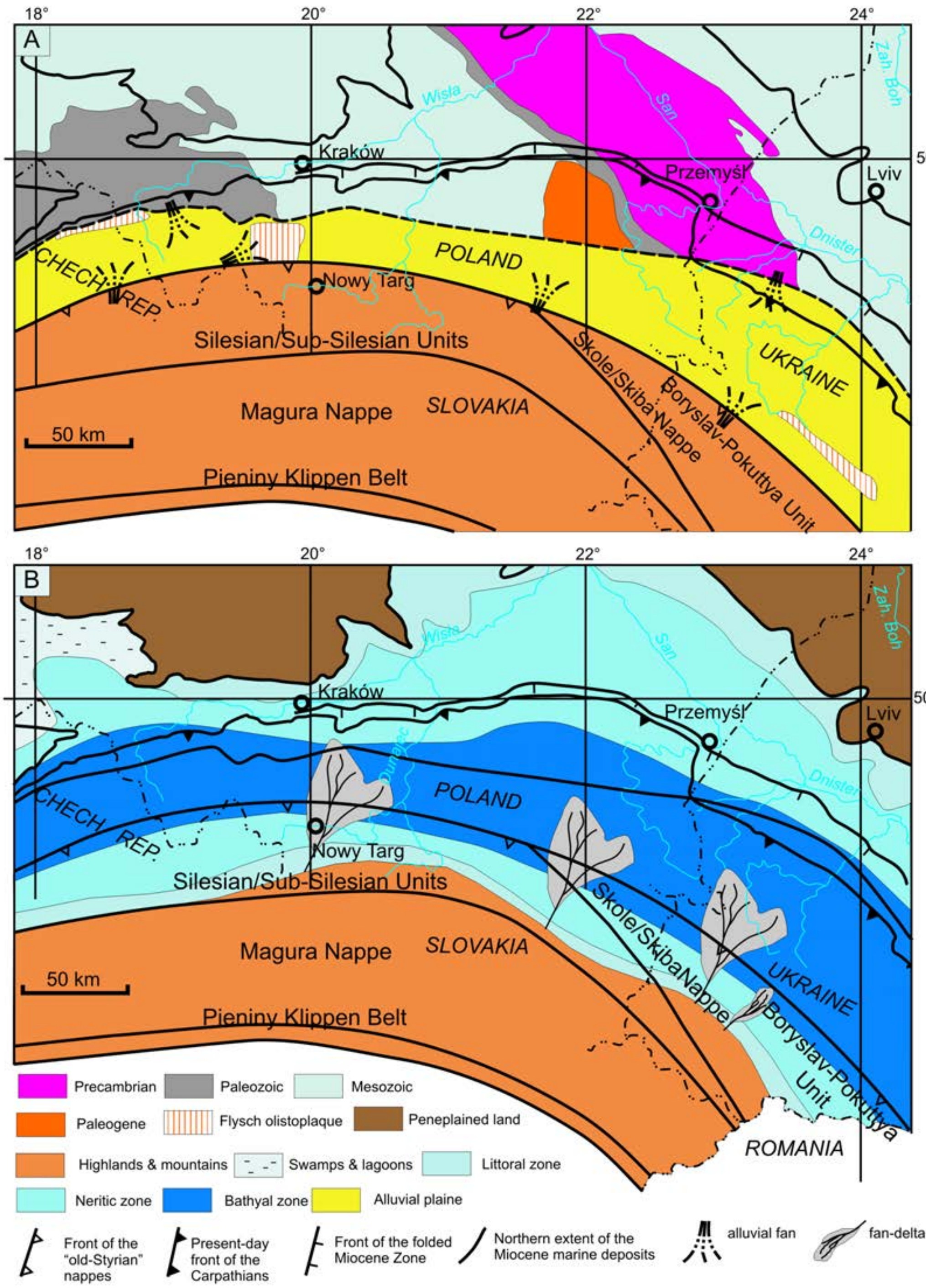

Figure 12. Karpatian (A) and Early Badenian (B) palinspastic palaeogeographic maps of the Polish Carpathian Foredeep [4, simplified].

ceeded sedimentation rates resulting in the establishment of marine environments that persisted during Badenian and Sarmatian times. The early Badenian, sedimentation rates in Moravia, in the axial part of the basin, reached 250 to 500 m/My in [75, 77] and 200 m/My in Poland [1, 2], whilst its northern stable shelf subsided very slowly with sedimentation rates ranking between a few dozens and 50 m/My [2]. During the Early Badenian, water depths varied in this basin between upper bathyal in its axial parts and neritic to littoral in its northern and southern (Carpathian) marginal parts (Fig. 12-B). During the Late Karpatian-Early Badenian, these subsiding grabens were being successively filled in with slope deposits (blocks of Carboniferous rocks), and the near-shore Dębowiec Conglomerate. The latter is 40-100 m thick and composed of Upper Carboniferous clasts [2, 4, 43]. In the external parts of the PCF, the transgressive conglomerates rest directly on the Palaeozoic basement of the foreland. This marine transgression reached both the foreland and the Carpathians. The Dębowiec conglomerates grade upwards into the marine clayey-sandy sediments of the Skawina Fm. that attains a thickness of up to 1,000 m in the western, internal parts of the basin, whereas elsewhere it rarely exceeds 30-40 m [44]. Deposition of the Skawina Fm. began in the internal parts of the foredeep with the Praeorbulina glomerosa Zone (N8), and in its external parts with the Orbulina suturalis Zone (N9 or N10). According to nannoplankton studies, the Skawina Fm. spans the NN 5 zone and extends into the Late Badenian NN 6 zone. This is documented both by previous studies [47] as well as our nannoplankton data from Łapanów1 borehole (this paper).

10. Late Badenian (Wielician) salinity crisis

Since the early Late Badenian, a gradual decrease in water depths can be observed in the Carpathian foreland basin that coincided with a eustatic gradual fall in sea level, as well as the late Styrian movements in the Outer Carpathian acretionary wedge. In the southern part of the foreland basin, this is manifested by deposition of flysch conglomerates on top of the Skawina Fm. These conglomerates were derived from erosion of uplifted marginal parts of the Outer Carpathians [78].

Deposition of evaporites in the northern marginal part of the PCF was preceded by shallowing water depths and cooling of marine waters [79]. The late Badenian sea level drop, climatic cooling, and northwards shifting of the Outer Carpathian front and partial isolation of the Carpathian foreland basin from the open seas resulted in a salinity crisis [2, 4?].

Taking into account new radiometric data [34, 48, 49, 63], the episodes of chemical precipitation in the PCF can be of relatively short duration - at least 75 Ky (see also previous works [53, 80]). In this period, sedimentation rates varied between 133-400 m/My in areas of sulphate facies and 933-1467 m/My in areas of chloride facies. The shallow (stable shelf) parts of the basin were dominated by sulphate facies (Fig. 13), whereas its deeper parts, located along the Carpathian front, were occupied by chloride-sulphate facies [55, 81–83]. According to [55], water depths in "the gypsum sub-basin were very shallow, zero to several metres whilst the halite sub-basin was estimated as less than 30-40 m deep".

During the deposition of the Wieliczka Salt Formation, the Carpathian orogenic front was still mobile, which is documented by the occurrence of flysch blocks in salts of the Wieliczka and Bochnia salt mines [84].

The termination of the Late Badenian (Wielician) salinity crisis in the Carpathian Foredeep in the western Ukraine (Kudryntsi section) has been documented by [85] as a major environmental change from hypersaline to open marine conditions.

At the end of evaporite deposition, when the basin was the shallowest [86, 87], tectonic uplift of the foreland resulted in the development of a regional unconformity, and in erosion of up to 50-100 m of evaporitic and sub-evaporitic deposits (Rzeszów Palaeo-Ridge). This erosional surface has also been reported from the Ukrainian part of the foredeep [88, 89].

11. Late Badenian -Sarmatian terminal basin

During the Late Badenian (late Styrian) compressional event, major shortening took place in the Carpathian thrust belt [1, 2]. This is documented by a displacement of at least 12 km of the Magura Nappe and Fore-Magura group of nappes relative to the Silesian Nappe, as well as by tectonic duplication of the Sub-Silesian Nappe. This shortening and uplift of the Carpathian nappe stack could be attributed to increased slab loading and acceleration of subsidence in the inner and outer foredeep. Simultaneosly, in the uplifted Outer Carpathian orogen pull-apart intramontane basins, e.g., the Nowy Sącz and Nowy Targ Orava basins [20, 69], began to develop.

This subsidence pulse represented the final stage in the evolution of the Polish-Ukrainian Carpathian foredeep basin. During the Late Badenian, in this area, the axis of subsidence shifted 15 km northward with respect to its early Badenian position (migration rate 3.75 mm/y), reaching approximately the present-day position of the Carpathian deformation front. The highest subsidence rate of up to 2,000 m/My was determined in the SE part of the PCF in the Przemyśl area [1, 4]. In the Rzeszów area, subsidence rates decreased whereas sedimentation rates oscillated around 1,500 m/My.

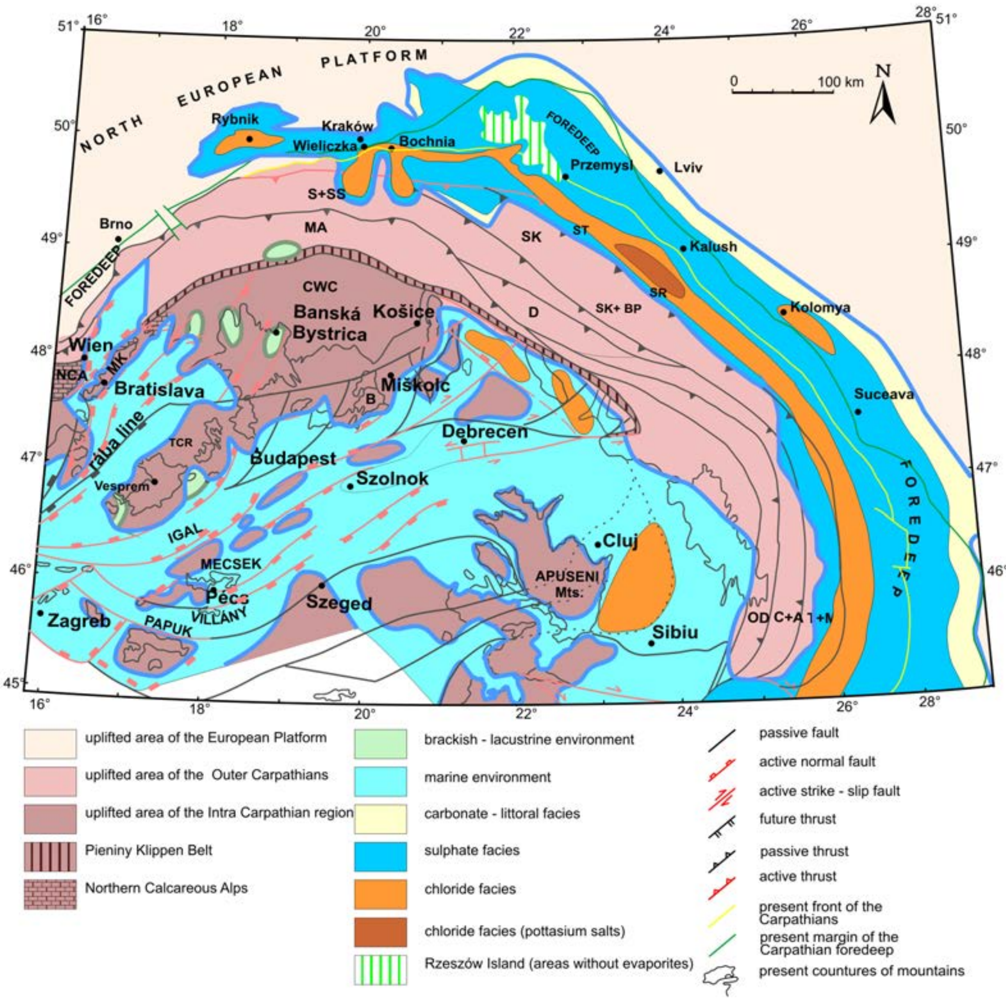

Figure 13. Late Badenian (Wielician) palinspastic palaeogeography of the Carpathian Foredeep and Transylvanian-Pannonian basin system [47, simplified]. Abbrevations: Outer Carpathians and Intracarpathian area: AC - Audia, Macla, Convolute Flysch nappes, BP - Borislav-Pokuttya Unit, CWC - Central Western Carpathians, D - Dukla Unit, MA - Magura Nappe, MF - Marginal Folds Unit; MK - Male Karpaty Mts., OD - Outer Dacides, SC - Subcarpathian Unit, SK - Skole Nappe, SR - Sambir Unit, SS - Subsilesian Unit, ST - Stebnyk Unit, T -Tarcau Nappe, TCR - Transdanubian Central Range, ZD - Ždanice Unit.

Towards the NE margin of the PCF, subsidence and sedimentation rates decreased to 100-200 m/My. Although the PCF basin continued to subside during the Badenian-Sarmatian transition, its depocentre shifted 40-50 km towards the NE whilst its axis rotated clock-wise by up to 20° [4, 90]. The zone of maximum Sarmatian subsidence coincides with the so-called "Wielkie Oczy Graben". Total subsidence in this zone varied between 1,500 m in its NE part and up to 3,000 m in the SE part, whereas tectonic subsidence reached a maximum of 1,500 m and decreased to a few hundred metres towards the northern margin of the PCF. The high Sarmatian subsidence rates were compensated by high sedimentation rates, reaching 1,700-2,400 m/My. Another centre of the highest subsidence was probably located along the contemporary front of the Carpathians. This subsidence centre persisted to the Late Sarmatian/Panonian time, as it is confirmed by the presence of the youngest marine deposits at the front of the present-day Carpathian margin [59, 67].

The Late Badenian (Kosovian) transgression was related to the last, but very intense phase of PCF subsidence that commenced around 13.65 Ma and ended ca. 10.5 Ma during the Sarmatian s.l. During this transgression, the outer and inner neritic conditions were established in the inner and outer parts of the foredeep [57, 86, 87], as well as in the marginal part of the Carpathians. The Kosovian

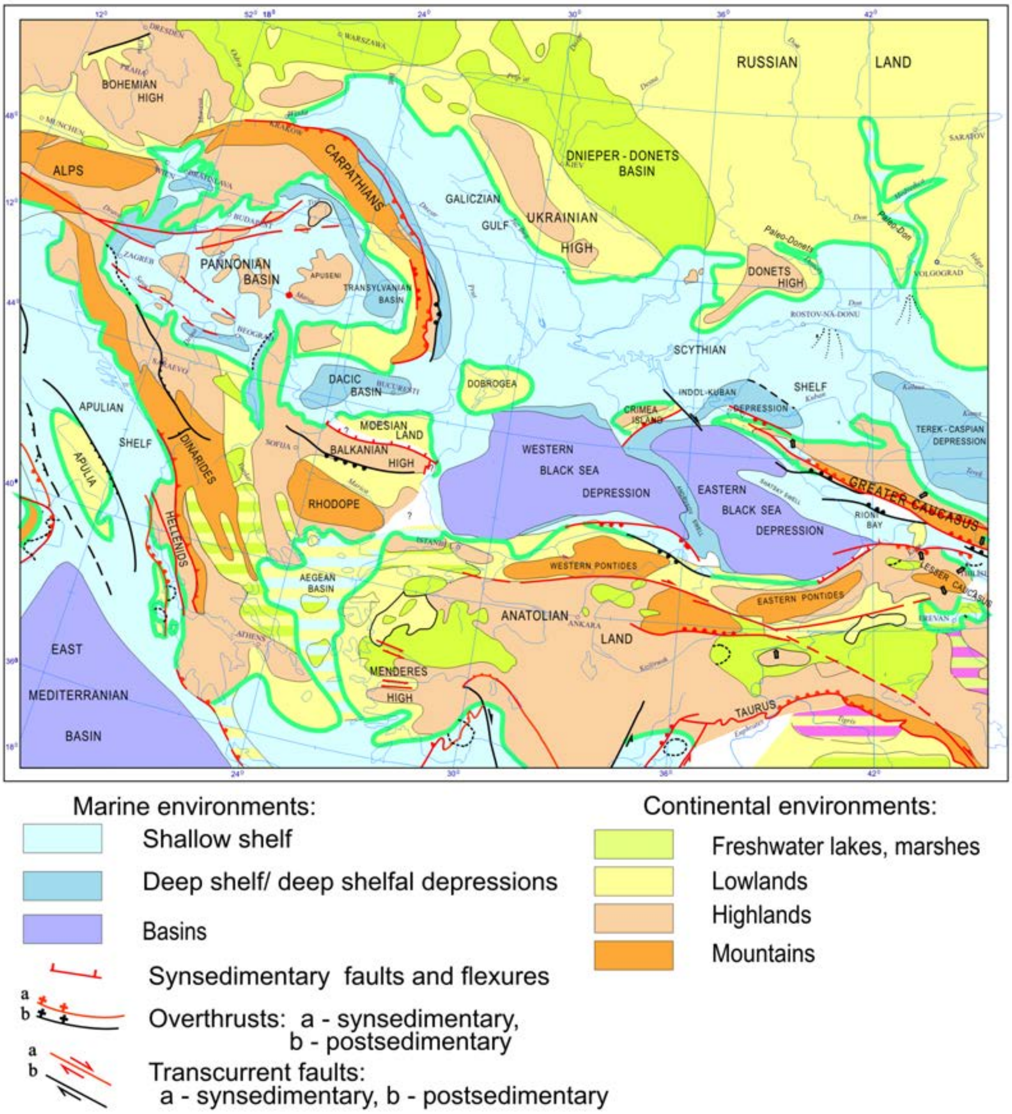

Figure 14. Palaeogeographic map of the Early Sarmatian (based on [93, 62], simplified).

flooding in the Polish and Ukrainian Carpathian Foredeep Basin represented the last marine transgression from the Mediterranean areas [63]. This is documented by the coralline algal-vermetid reefs from the Roztocze (Poland) and Medobory (Western Ukraine) hills. The Kosovian marine transgression flooded the marginal part of the Outer Carpathians, and along the present-day Dunajec River valley reached the Nowy Sącz Basin [20, 69].This marine connection was interrupted ca. 13.3 Ma, and since the Early Sarmatian the Carpathian foreland was occupied by a mixo-mesohaline (semi-marine) basin (Roztocze and Medobory serpulides reef), incidentally connected with the Mediterranean (Fig. 14, see also [63]).

In the outer part of the PCF the evaporites are covered by the Upper Badenian/ Sarmatian siliclastic sedimentary succession, known as the Machów Formation [53]. The maximum thickness of this succession is related to the present-day front of the Polish Outer Carpathians. Towards the north, the thickness of these deposits progresively decreases. Simultaneously, the thickness of the Machów Formation increases towards the east from a few hundred metres near Kraków up to 3,000 m north of Przemyśl. This succession displays a shallowing-upward trend of sedimentation and consists of hemipelagic, turbiditic and deltaic and nearshore-to-estuarine facies associations [61]. In the area located north of the Carpathian front near Rzeszów, the pre-Badenian (Precambrian) basement is characterized by strongly differentiated basement, with very deep (up to 1.5 km) palaeovalleys. In this area, the lower part of the late Badenian/Sarmatian succession was supplied from erosion of the platform sources, while the upper, part of succession was derived from the eroded of the Outer Carpathians nappes [61]).

In the Outer Carpathians, the Late Badenian/Sarmatian transgression overlaid fresh-water paludal deposits or rested directly on the flysch rocks [3].

During the entire period of the PCF evolution, the deepest part of the basin corresponded with the zone of maximum tectonic subsidence, located - as a rule - along the contemporary front of the migrating Carpathian accretionary wedge (Figs. 12-14). Finally, the present-day position of the Carpathian nappes was reached in post-Sarmatian time [1, 2, 5, 85, 91, 92].

12. Conclusions

1) The early Miocene folding, thrusting and inversion of the Outer Carpathians was traditionally referred to the Early Miocene Savian and Styrian orogenic phases. However, taking into account that the youngest flysch deposits of the marginal Zdanice, Skole-Skiba and Boryslav-Pokuttya units belong to the Ottnangian-late Early Burdigalian NN3 and NN4 calcareous nannoplankton zones, the onset of this deformation phase cannot be older than about 17 Ma. This corresponds with the intra-Burdigalian (Ottnangian/Karpatian) compressive tectonic event, referred to as the Early Styrian phase.

2) The intra-Burdigalian folding and uplift of the Outer Carpathians can be related to the north-eastward translation of Alcapa and Tisza-Dacia microplates in response to the roll-back of the Carpathian subduction slab and increasing collisional coupling of the Adriatic and European plates in the Alpine domain. In the Outer Carpathians, this was accompanied by north- and northeast-directed nappe transport and the development of the peripheral flexural Carpathian Foredeep along the advancing orogenic front.

3) The initial (Ottnangian-Karpatian) foreland basin, partly developed on 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 with the fresh-water Lower Molasse of the Alpine Foreland Basin. This was followed by the Early Badenian marine transgression and the main period of the Middle/Late Miocene marine deposition.

4) These open marine conditions were replaced temporally by the early Late Badenian salinity crisis typified by very high sedimentation rates.

5) In the Polish Carpathian Foredeep, the episodes of Miocene subsidence were temporally and spatially related to the emplacement of the front of the Carpathians, and the important driving force of tectonic subsidence was the emplacement of the nappe load related to subduction processes.

6) During the Early-Middle Miocene, the loading effect of the thickening Carpathian accretionary wedge on the foreland plate increased and caused a progressive increase of the total subsidence.

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

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