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# Biostratigraphy and sequence stratigraphy of the Lower Cretaceous in the NW part of the Mid-Polish Trough

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By comparison with the Lower Cretaceous of central and SE Poland, that of NW Poland (the Pomeranian, Szczecin, and Mogilno-Łódź troughs) has scarce biostratigraphic data. But, despite the lack of Lower Cretaceous exposure in the NW Polish Lowlands, borehole data, including borehole-cores and geophysical logs, allow analysis of complete successions. We refine the stratigraphic units using parallel studies of ammonites, microfauna and calcareous nannoplankton collected from the same intervals, and by correlating age-defined intervals with geophysical logs. Ostracod zones F to A are documented by the presence of ostracod assemblages representing the interval between the Upper Tithonian (ostracod zone F) and the lower part of the Upper Berriasian (ostracod zones E to A). The fragmentary and poorly preserved ammonites allowed only for distinguishing the uppermost Middle and Upper Berriasian (Ryazanian), while the informal subdivisions from the central part of the basin could not be identified unequivocally. Nannoplankton recognized in the succession analysed was very rare due to shallow marine facies of the strata. Only one nannoplankton zone was recognized in the lower part of the succession studied: the CC2 *Stradneria crenulata* Zone (uppermost Middle and Upper Berriasian and lowermost Valanginian). An additional study only on nannoplankton enabled recognition of certain boreal taxa typical of the BC2 zone of the Uppermost Riazanian. Valaginian ammonites occur in core material located closer to the central part of the trough. Some planktonic foraminiferal species indicate the Lower Aptian. Some Upper Cretaceous nannoplankton zones were also recognized: the CC9 *Eiffellithus turriseiffeli* (Uppermost Albian to Lower Cenomanian) and UC0, UC1-2 and UC3 zones which correspond to the Upper Albian and Lower as well as Middle Cenomanian. The sequence stratigraphic interpretation was based on geophysical logs with the application of gamma-ray, neutron-gamma, spontaneous potential and resistivity logging, as well as caliper logging. These studies allowed recognition and correlation of sedimentary sequences within the part of the sedimentary basin analysed, characterized by a similar cyclic pattern of geological phenomena described using depositional sequences as in the central and SE part of the Polish Basin. Third-order depositional sequences with maximum flooding surfaces were distinguished. Effective correlation of depositional cycles with biostratigraphy and with the global sea level curve was demonstrated for several boundaries, confirming the applicability of this method for the Polish part of the the Central-European Basin. Other boundaries recognized that are not correlatable and shifted relative to Haq's curve may reflect autogenous factors (e.g., local tectonics) overlapping with the global changes controlled by allogenic processes.

Key words: Lower Cretaceous, ammonite, foraminifera, ostracod and nannoplankton biostratigraphy, depositional systems, sequence stratigraphy, relative sealevel changes, NW Poland.

## INTRODUCTION

This paper continues research performed by the same team in central and SE Poland (Gaździcka et al., 2003, 2006; Dziadzio et al., 2004).

The Lower Cretaceous sedimentary succession in the Polish Lowlands have so far been studied with regard to stratigraphy (e.g., Raczyńska, 1967, 1979b; Marek, 1968, 1969; Marek and Raczyńska, 1973), analysis of depositional systems, and cyclic sedimentation (Leszczyński, 1997). Formal biostratigraphic zones corresponding to the stratigraphic schemes presently used in Europe have been distinguished for the Valanginian of the Tomaszów Basin (Kutek et al., 1989; Dziadzio et al., 2004) and the Middle and Upper Albian of the Annopol area (Kutek and Marcinowski, 1996b). Informal stratigraphic units described as “Beds” have been distinguished for the uppermost Middle and Upper Berriasian (Ryazanain), Valanginian, Hauterivian (Marek, 1964, 1968, 1969, 1977, 1984 1997; Marek and Raczyńska, 1973, 1979; Raczyńska, 1979b; Marek and Shulgina, 1996; Marek and Rajska, 1997). Determination of sedimentary cyclicity without a precise stratigraphic framework and correct correlation of sedimentary sequences based on geophysical logs may, though, bring about serious errors.

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Analysis of sedimentary sequences and their correlation in central and SE Poland has allowed reconstruction of transgressive-regressive cycles related to eustatic sea level changes and indicated tectonic activity at the boundary between the East European Platform and the Mid-Polish Trough (Gaździcka et al., 2003, 2006; Dziadzio et al., 2004). These studies enabled determination of the precise stratigraphic position of particular Lower Cretaceous stratigraphic units; coupled with the analysis and correlation of borehole logs, these data help improve our knowledge of the geological evolution of the Polish Basin.

The lack of exposed Lower Cretaceous deposits in NW Poland necessitated the use of cores and borehole log data, which allowed the analysis of complete successions. However, for reliable results, geophysical logging needs to be calibrated using biostratigraphic data from cores. The precise determination of stratigraphic units is enhanced by the parallel analysis of different fossil groups (ammonites, microfauna, calcareous nannoplankton) collected from the same intervals. This enabled the precise correlation and distinction of sedimentary sequences within the part of the sedimentary basin analysed.

The classic area for Lower Cretaceous stratigraphy, encompassing the southern part of the Jura Mountains, selected Alpine units, and adjacent regions of southern France, belongs to the Tethyan domain. An independent stratigraphic scheme exists for the Boreal domain, based on different faunal assemblages (e.g., Kemper et al., 1981; Kutek et al., 1989; Ogg and Hinnov, 2012; Reboulet et al., 2018). The palaeogeographic position of the Polish Basin between the Tethys Ocean and the Boreal seas favoured mixing of the influences from both domains. This phenomenon is reflected perfectly in the Lower Cretaceous cephalopod, foraminifera, ostracod and calcareous nannoplankton assemblages. The Polish Basin, due to its mixed Mediterranean-Boreal aspect, has considerable significance for the correlation of stratigraphic schemes of the two palaeogeographic domains (Marcinowski and Wiedmann, 1985; Kutek et al., 1989; Kutek and Marcinowski, 1996a).

Nannoplankton stratigraphy has not previously been applied to the Lower Cretaceous succession of NW Poland. In this paper, the results of nannoplankton studies of sections in the NW Poland are sourced from an unpublished report by Gaździcka (2006). So far, many different nannoplankton schemes have been suggested for the Lower Cretaceous, from different regions and with the application of different criteria (e.g., Roth, 1973; Thierstein, 1976; Sissingh, 1977; Taylor, 1982; Perch-Nielsen, 1985; Jakubowski, 1987; Mutterlose, 1991). These proposals differ significantly from each other, partly because of the geographic variability of the nannoplankton assemblages, and partly by developments regarding the recognized stratigraphic ranges of particular calcareous nannoplankton taxa during the past few decades. The most significant studies regarding the Lower Cretaceous stratigraphy in the Polish Lowlands and its correlation with neighbouring areas are those by Mutterlose (1991, 1992) for the German Basin. The most recent subdivision of the Lower Cretaceous in the Boreal domain, based on material from the North Sea (Bown and Young, 1999), is very valuable; it correlates nannoplankton zones with orthostratigraphic ammonite zones both from the Boreal and Tethyan domains.

Another issue which still requires resolution is the palaeontological documentation of the Jurassic and Cretaceous boundary and its unequivocal determination in uncored intervals of sedimentary successions. In the Polish Lowlands, the Jurassic/Cretaceous boundary was, as in the entire Boreal domain, traditionally placed between the Volgian Stage, developed in the Purbeck facies, and the Ryazanian Stage represented by marine successions (e.g., Marek and Raczyńska, 1973; Dembowska and Marek, 1976; Marek et al., 1989; Grabowski et al., 2021). In the Tethyan domain, it was placed between the Tithonian and Berriasian. The base of the Berriasian is located in the Upper Volgian (Housa et al., 2007; Wimbledon et al., 2011; Bragin et al., 2013; Rogov, 2014; Wimbledon, 2014, 2017; Schnabl et al., 2015; Zakharov and Rogov 2020; Grabowski et al., 2021). There is thus need for a new stratigraphic interpretation of these stages in the successions from the NE Polish Lowlands. Moreover, the sedimentary facies across the Jurassic/Cretaceous boundary interval in the area, developed as shallow-marine clastic and evaporite deposits, does not allow direct application of the Tethyan scheme based on ammonites. Therefore, micropalaeontological methods have particular biostratigraphic significance.

This study determines. as precisely as possible, the stratigraphic position of particular Lower Cretaceous sedimentary successions in NW Poland, and correlates them at high-resolution with data from geophysical logs.

## GEOLOGICAL SETTING

The Early Cretaceous sedimentary basins of the Polish Lowlands developed along the margin of the East European Platform, and were oriented NW–SE (Dadlez et al., 1998). Their development was predominantly shaped by extension along the Teisseyre-Tornquist Line, that formed a zone with increased subsidence, known as the Mid-Polish Trough (Fig. 1).

Tectonic activity along the Mid-Polish Trough took place between the Permian and the end of the Cretaceous, with an extensional regime at least until the Albian (Kutek, 2001). The mobility of the basement rocks of the Mid-Polish Trough and of the marginal zone of the East European Platform significantly influenced sedimentation in the Early Cretaceous basins. The Kuyavian region showed the most intense tectonic activity, resulting in zones with enhanced subsidence and the simultaneous development of salt structures. The thickness of the Lower Cretaceous in central and SE Poland varies from several tens of metres to >500 m, with the highest values in the axial (central) part of the trough, successively diminishing towards its peripheries. In NW Poland, the thickness of the Lower Cretaceous varies from several tens of metres in the Pomeranian and Szczecin troughs to 650 m in the Kuyavian region (Marek, 1988; Leszczyński, 1998). Recognition of the primary thickness and extent of the sedimentary basins is hampered by later erosion, which took place at the end of the Early Cretaceous, before the Albian transgression, and after the inversion of the trough at the end of the Maastrichtian.

In NW Poland, the Lower Cretaceous sedimentary succession has a limited spatial extent and is usually relatively thin (Marek, 1988; Leszczyński, 1998). It generally represents shallow-marine settings, from marginally-marine marshy-lagoonal, to a shallow siliciclastic shelf (Leszczyński, 1997).

The Lower Cretaceous lithofacies, in the SE part of the basin, are dominated by carbonate deposits, whereas siliciclastic sedimentation prevailed in the central and NW part of the area.

Our research was focused on selected regions of NW Poland (Fig. 1), encompassing the northern part of the Mogilno Trough, and the Szczecin and Pomeranian troughs. The choice of study area reflects the limited outcrop of Lower Cretaceous strata and accessibility of archival geological data. Cores and geophysical logs were analysed from the following boreholes: Strzelno IG 1, Chociwel IG 1, Oświno IG 1, Człuchów IG 1 and Szczecin IG 1. Only geophysical logs from the Choszczno IG 1 borehole were analysed due to the lack of core material.

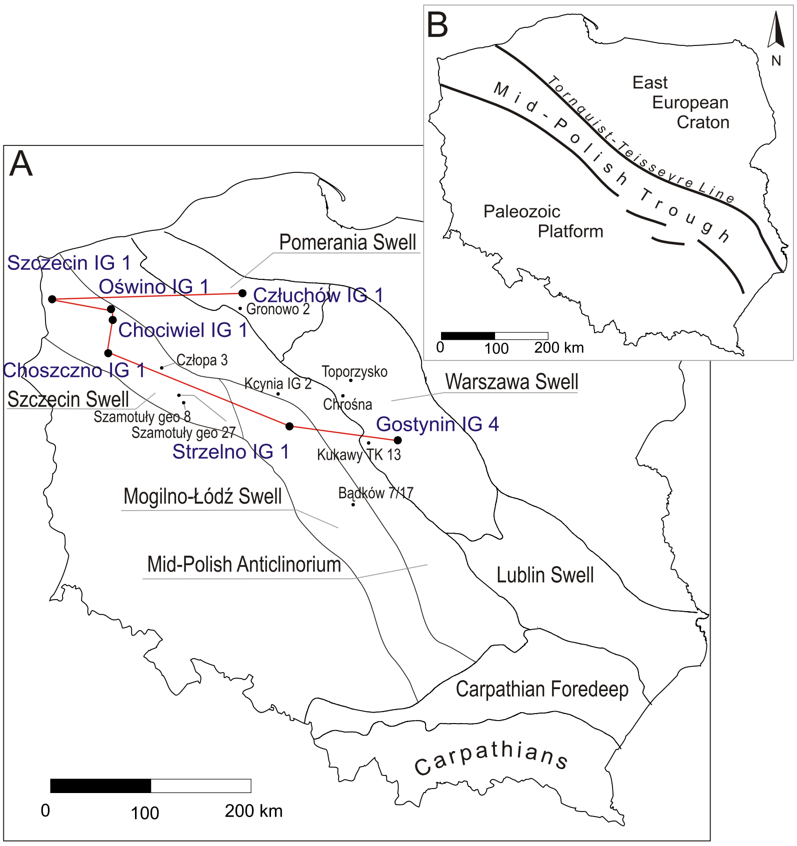

**Fig. 1A – location of the boreholes studied with line of cross-section, relative to the main geological structures (the supplementary boreholes are in smaller font); B – main tectonic structures**

Biostratigraphic analysis was supplemented by data from the following boreholes: Szamotuły geo 8, Gronowo 2, Człopa 3, Szamotuły geo 27, Toporzysko, Kukawy TK 13, Kcynia IG 2, Chrośna and Bądków 7/17 (Fig. 1). These analyses were correlated with earlier studies in central and SE Poland (Dziadzio et al., 2004).

## STRATIGRAPHY AND LITHOLOGY

In the lower parts of the Lower Cretaceous succession (uppermost Middle and Upper Berriasian/Ryazanian, Valanginian, Hauterivian), the stratigraphic subdivision is based on ammonites, and orthostratigraphic fauna for this interval (Marek and Raczyńska, 1973; Marcinowski and Wiedmann, 1985; Marek et al., 1989; Kutek et al., 1989; Marek and Rajska, 1997; Mitta and Ploch, 2012). The Lower Berriasian, developed in Purbeck-type facies and devoid of ammonites, was subdivided into ostracod zones (Bielecka and Sztejn, 1966; Marek et al., 1989). Micropalaeontological methods were applied to both the lower and upper parts of the Lower Cretaceous succession, especially in core data analysis (e.g., Moryc and Waśniowska, 1965; Sztejn, 1984, 1997). The presence of microfauna in some individual stages of the Lower Cretaceous have been recorded in several older studies on the geology of the northwestern part of the Polish Lowlands (Dadlez and Dembowska, 1965; Dembowska, 1973a, b; Raczyńska, 1979a, 1987). Bielecka and Styk (1973), Sztejn (1973, 1977) and Bielecka (1975), also referred to the microfauna of the Lower Cretaceous in descriptions of boreholes from this part of the Polish Lowlands. The occurrence of foraminifera in the upper part of the Lower Cretaceous in NW Poland was described by Sztejn (1984). The presently used lithostratigraphic subdivision of the Lower Cretaceous in the Polish Lowlands was developed by Raczyńska (1979b) and Marek and Raczyńska (1979).

The Lower Cretaceous stratigraphy in the northwestern part of the Polish Lowlands has been poorly documented palaeontologically, therefore its subdivision was traditionally based on lithological correlation with the central part of the basin (Raczyńska, 1967, 1971, 1973, 1987; Dembowska and Marek, 1976). Without the use of stratigraphically-calibrated geophysical logs, such interpretation was problematic. Besides lithology, the correlation of certain sedimentary sequences has been based on microfauna and in some cases also on ammonites. The Lower Cretaceous in the NW part of the Polish Lowlands has been correlated with the central part of the basin in the Kuyavian area, where the strata are best documented.

Due to problems with their subdivision in the NW part of the Polish Lowlands, the Berriasian (Ryazanian) to Lower Valanginian interval in the study area was treated as one unit. A few Berriasian ammonites representing *Berriasella*, *Surites*, *Euthymiceras* and *Himalayites* were by analogy with the Kuyavian area assigned to the “beds with *Riasanites*, *Himalayites* and *Picteticeras*” and “beds with *Surites*, *Euthymiceras* and *Neocosmoceras*” (Marek and Rajska, 1997). Revision of ammonites of the genus *Riasanites* indicates the presence of *Riasa-*

*nites swistowianus* and *Riasanites rjasanenis*, i.e., index taxa of biohorizons applied in the Central Russian Basin (Mitta and Ploch, 2012), in the Kuyavian area and the NW part of the Polish Basin. There may also be the *tzikwinianus* Zone (Mitta and Ploch, 2012), but further study is needed to confirm this zone.

In the general scheme for the epiplatform area of Poland, the lowermost Valanginian has so far been referred to as the "beds with *Platylenticeras*, *Neocomites* and *Karakaschiceras*" (Marek, 1997). An informal sand-dominated unit referred to as the "Middle Valanginian" was distinguished above. This was termed the "beds with *Polyptychites*" based mainly on their occurrence between the "beds with *Platylenticeras*" and "beds with *Dichotomites* and *Saynoceras*" (Marek, 1997). Only detailed studied outcrop in Wąwał in Tomaszów Mazowiecki (Kutek et al., 1989; Dziadzio et al., 2004) have allowed recognition of the ammonite zones.

The Lower Valanginian of NE Polish Lowlands has been documented by ammonites of the genus *Platylenticeras*. The *Platylenticeras* species in the Polish Basin migrated from the German Basin (Dziadzio et al., 2004) with corresponding similarity of taxonomy. Comparison with material from central Russia is needed. The microfaunal assemblage is not diverse enough for differentiating between the Berriasan (Ryazanian) and Lower Valanginian, which are developed mainly as siltstones and sandstones.

The deposits of informal unit, the "Middle Valanginian", are composed of sandstones, often with carbonized plant detritus. They represent lacustrine, and locally marshy environments. Their stratigraphic interpretation was based on their sandy character and their position between Lower Valanginian strata and deposits assigned to the Upper Valanginian and Lower Hauterivian (Raczyńska, 1967).

No ammonites have been found in the Upper Valanginian and Lower Hauterivian of NW Poland. The stratigraphic position of these beds is based on lithological correlation and similarities of foraminiferal and bivalve assemblages, mainly with the Kuyavian area. The strata include mainly siltstones and claystones. Both substages have been treated jointly due to the difficulties in determining the boundary between them, which has been interpreted conventionally (Raczyńska, 1967).

The microfossils found so far poorly document the Hauterivian substages (Mamczar, 1986; Sztejn, 1997), and so the Upper Hauterivian substage has also been distinguished conventionally. It is characterized by two lithological units: a lower one comprising sandstones with siltstone interbeds and an upper one including sandy-glauconite, sandy-clay, and clay deposits (Raczyńska, 1967).

Scarce and biostratigraphically insignificant microfossils (Mamczar, 1986; Sztejn, 1997), have been found in deposits assigned to the Barremian, Aptian, Lower and Middle Albian. They consist of quartz sands with glauconite and are overlain by Upper Albian marls, which in their basal part are sandy-marly and contain phosphatic concretions. Their stratigraphic position was determined based on their location between the Upper Hauterivian and Upper Albian successions (Raczyńska, 1967).

The lithostratigraphic scheme for the Polish Lowlands was modified by Marek (1997). The subdivision includes both formal units (formations, members), as well as informal units treated at formation level. A formal lithostratigraphic subdivision for the Lower Cretaceous has been introduced for central and NW Poland (Kuyavian area), and an informal subdivision for SE Poland. In the study area, distinguishing both formal and informal units is difficult. Infrequent fossils rarely allow for correlation with central Poland where the stratigraphic subdivisions were developed. Lithological changes within individual sedimentary successions in relation to the stratotype sections pose an additional problem.

In the Kuyavian and Pomeranian areas, the oldest clay-marly deposits of the Lower Cretaceous are distinguished as the Skotniki Member of the Kcynia Formation, encompassing carbonate-clastic deposits with evaporites developed in Purbeck-type facies. The Skotniki Member includes marly claystones with interbeds of *Cyrena* lumachelles. The stratigraphic position of this unit is based on ostracods, Zone A (Marek and Rajska, 1997) of the upper part of the Lower or Middle Berriasian (Dziadzio et al., 2004) or lowermost Berriasian (Leszczyński, 1997) and the Middle Volgian – lowermost Berriasian (Grabowski et al., 2021). The succession above the Skotniki Member, dominated by clay deposits with some sandy limestones and sandstones, is determined as the Rogoźno Formation including the Kajetanów, Zakrzew and Opoczki members. The Kajetanów Member, lacking ammonites, is assigned to the upper part of the Lower Berriasian (Marek and Rajska, 1997). Siliciclastic deposits of the Zakrzew Member contain a mixed Mediterranean-Boreal ammonite assemblage. They have been referred to as "beds with *Riasanites*, *Himalayites* and *Picteticeras*" and may be correlated with the *rjasanensis* Zone from the Central Russian Basin and with the Tethyan *occitanica* and *boissieri* (lower part) zones even in the Polish Lowland lacking index species of these Tethyan zones, which encompass the Middle and Upper Berriasian (Marek and Rajska, 1997; Mitta and Ploch, 2012). Based on ammonites, the Opoczki Member was assigned to the Upper Berriasian ("beds with *Surites*, *Euthymiceras* and *Neocosmoceras*") and lowermost Valanginian ("beds with *Platylenticeras*, *Neocomites* and *Karakaschiceras*") (Marek and Rajska, 1997).

Alternating sandy and clay-sandy deposits above the Opoczki Member are distinguished as the Bodzanów Formation. Based on ammonites occurring in the central part of the Polish Basin, its age was determined as the upper part of the Lower Valanginian ("beds with *Polyptychites*"). The Włocławek Formation, corresponding to the Upper Valanginian ("beds with *Dichotomites* and *Saynoceras*") and the Lower ("beds with *Endemoceras*") and Upper Hauterivian ("beds with *Simbirskites*"), encompasses alternating clay-siltstone and sandy deposits. The Włocławek Formation comprises the Wierzchosławice, Gniewków and Żychlin members. The formation is a formal unit with well-defined boundaries and a stratotype area (Raczyńska, 1979). Ammonite zones (Boreal – *robustum*, *heteropleurum*, *polytomus-crassus* and *triptychoides*; Mediterranean – *petransiens* and *verrucosum*) and nannoplankton zones (PN2 *Triquetrorhabdulus shetlandensis*, PN3 *Calcicalthina oblongata*, PN4 *Eiffellithus striatus* and PN5 *Conusphaera rothii*) have been distinguished in the Valanginian of the central part of the Polish Basin (Kutek et al., 1989; Dziadzio et al., 2004). Three ammonite zones, i.e., *noricum*, *amblygonium* and *gottschei*, and four nannoplankton zones, i.e., PN6 *Eprolithus antiquus*, PN7 *Perissocyclus plethotretus*, PN8 *Tegulalithus septentrionalis* and PN9 *Tegumentum octiformis*, were assigned to the Hauterivian (Dziadzio et al., 2004).

The upper Lower Cretaceous (Barremian, Aptian and Lower Albian) was assigned to the formal Mogilno Formation (Raczyńska, 1979) and includes sands and sandstones of variable grain size, commonly coarse-grained. This unit is also tripartite, with two members dominated by sandy deposits (Pagórek and Kruszwica Members) separated by a clay unit (Gopło Member). Stratigraphic revision of the central part of the Polish Basin has allowed nannoplankton zones to be established for the first time and indicates microfaunal assemblages characteristic of the upper part of the Lower Cretaceous. These include the Barremian PN10 *Nannoconus abundans* and PN11 *Broinsonia matalosa* zones, and the Aptian PN12 *Farhania varolii* and PN13 *Eprolithus floralis* zones (Dziadzio et al., 2004).

Intense research undertaken in recent years, including this study, is focused on refining the Lower Cretaceous stratigraphic subdivision in the Polish Lowlands based on newly acquired stratigraphic data and their correlation with the application of geophysical logs in neighbouring areas, as well as new research techniques, such as sequence stratigraphy. These studies have resulted in a high-resolution Lower Cretaceous subdivision in the central and SE part of the Polish Lowlands (Dziadzio et al., 2004). Our study is a continuation of this research by the same research team, focused on the NW part of the Polish Basin.

## MATERIAL AND METHODS

The project included palaeontological analysis of ammonite, foraminifera, ostracod and calcareous nannoplankton assemblages and simultaneous detailed analysis of geophysical logs of selected boreholes: Człuchów IG 1 (Pomeranian Swell), Szczecin IG 1 (Szczecin Swell), Oświno IG 1 (Szczecin Swell), Chociwel IG 1 (Szczecin Swell), Choszczno IG 1 (Szczecin Swell) and Strzelno IG 1 (Mogilno-Łódź Swell; Fig.1). The selection of boreholes used in this study was based on the presence of uppermost Jurassic and Lower Cretaceous strata and their availability in the cores. In some cases, the lack of continuous lithological successions, the restricted number of cores covering short intervals, and poor core yield were substantial drawbacks. The results were used to distinguish biostratigraphic zones and thus indicate the stratigraphic position of particular sedimentary intervals. The most important palaeontological results are shown non photographic plates, distributional charts of selected boreholes, and a stratigraphic scheme proposed for the successions studied (Figs. 2–4 and Appendix 1*).

Ammonites were collected from the the Strzelno IG 1 and Oświno IG 1 boreholes. Additional material from the Szamotuły geo 8, Gronowo 2, Człopa 3, Szamotuły geo 27, Toporzysko, Kukawy TK 13, Kcynia IG 2 Chrośna and Bądków 7/17 boreholes (Fig. 1) came from the collection of Prof. S. Marek, housed in the Geological Museum of the Polish Geological Institute – National Research Institute.

Microfauna from four boreholes: Człuchów IG 1, Strzelno IG 1, Chociwel IG 1 and Oświno IG 1 was analysed. Samples weighing 0.5–0.8 kg each were collected for micropalaeontological studies based on foraminiferal and ostracod assemblages. The samples were taken from fully cored intervals and their resolution depended on the core diameter and lithological variability (on average every metre, sometimes more closely). Hard rocks were disintegrated with glauber salt, whereas soft rocks were rinsed with water. The material obtained was sieved through a very fine mesh (0.1 mm), due to which the obtained micropalaeontological material was rich, including small foraminifera species which so far have not been described from the Lower Cretaceous of Poland. A *Nikon* binocular was used to view the foraminifera and ostracod assemblages. Photographs were made using a scanning electron microscope (SEM) in the Laboratory of Microscopic Photography of the PGI-NRI.

Samples for nannoplankton analysis were collected from the cores of Chociwel IG 1, Oświno IG 1, Człuchów IG 1, Strzelno IG 1 boreholes, and additional material was sourced from the Kcynia IG 2 borehole. Seventy samples were analysed, of which only 19 contained calcareous nannoplankton. The samples were usually collected from the same horizons as the material for micropalaeontological analysis and those yielding ammonite fossils. The studied succession not containing calcium carbonate with the only exception. Due to the relatively low nannoplankton content in the strata analysed, a concentration method based on centrifuging the fraction containing coccoliths (0.5–30 μm) was applied. Multiple, fast (30 s) centrifuging was used. Samples from deposits containing abundant clay minerals were first subjected to ultrasonic treatment. The analyses were conducted in an *Olympus BH-2* polarization optical microscope with phase contrast. Smear slides were prepared according to the standard technique (Perch-Nielsen, 1985; Bown and Young, 1999). The material analysed usually contained very low amounts of calcareous nannoplankton. More abundant and diverse assemblages were noted in selected sections of the Kcynia IG 1 and Chociwel IG 1 borehole cores. Nannoplankton is typically poorly preserved in the material analysed, which hampers taxonomic identification, and the diagnostic features of the coccoliths are visible only in polarised light.

Geophysical logs from 6 boreholes (Appendix 1), which according to archival data encompass the Lower Cretaceous, were analysed. Two correlative cross-sections were constructed. The cross-section (Appendix 1) running along the line of the Strzelno IG 1, Choszczno IG 1, Chociwel IG 1, Oświno IG 1, Szczecin IG 1 and Człuchów IG 1 boreholes presents the current state of knowledge on the Lower Cretaceous stratigraphy. The material was collected from published data, profiles of the boreholes 6, 11, 41, 42 and 43 (Raczyńska, 1972, 1973, 1977a, b; Jaskowiak-Schoenaichowa, 1973, 1977, 1978; Dembowska, 1977b) at the Polish Geological Institute, and borehole reports.

The second cross-section runs along the same line, but begins from the Gostynin IG 4 borehole, the stratigraphy of which was analysed by Dziadzio et al. (2004) and which provides an initial scheme for the study area.

The results of study of the biostratigraphy and geophysical logs, including borehole and core descriptions, were analysed and correlated. All data were depicted on the correlatory cross-sections and a new stratigraphic framework was prepared for the Lower Cretaceous strata. Material from two boreholes, Szczecin IG 1 and Człuchów IG 1, could not be analysed satisfactorily. The stratigraphic subdivision here was based on lithological similarities and geophysical logs eholes. The basic set of geophysical curves including: gamma-ray (GR), neutron-gamma (NEGR), spontaneous potential (SP) and resistivity (RES) logs was analysed. Various measurement sets made in different years precluded application of one curve set, which would similarly characterise lithological successions of the same age. Most logs were normalised and recalculated to pseudoAPI units. For correlation and depiction, the following sets were used:

- GR-NEGR (or GR-RES);
- SP-RES.

For the interpretation of sequences and depositional tracts in the Lower Cretaceous succession, sequence boundaries (SB); transgressive surfaces (TS); flooding and maximum flooding surfaces (FS /MFS) were distinguished.

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* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1631

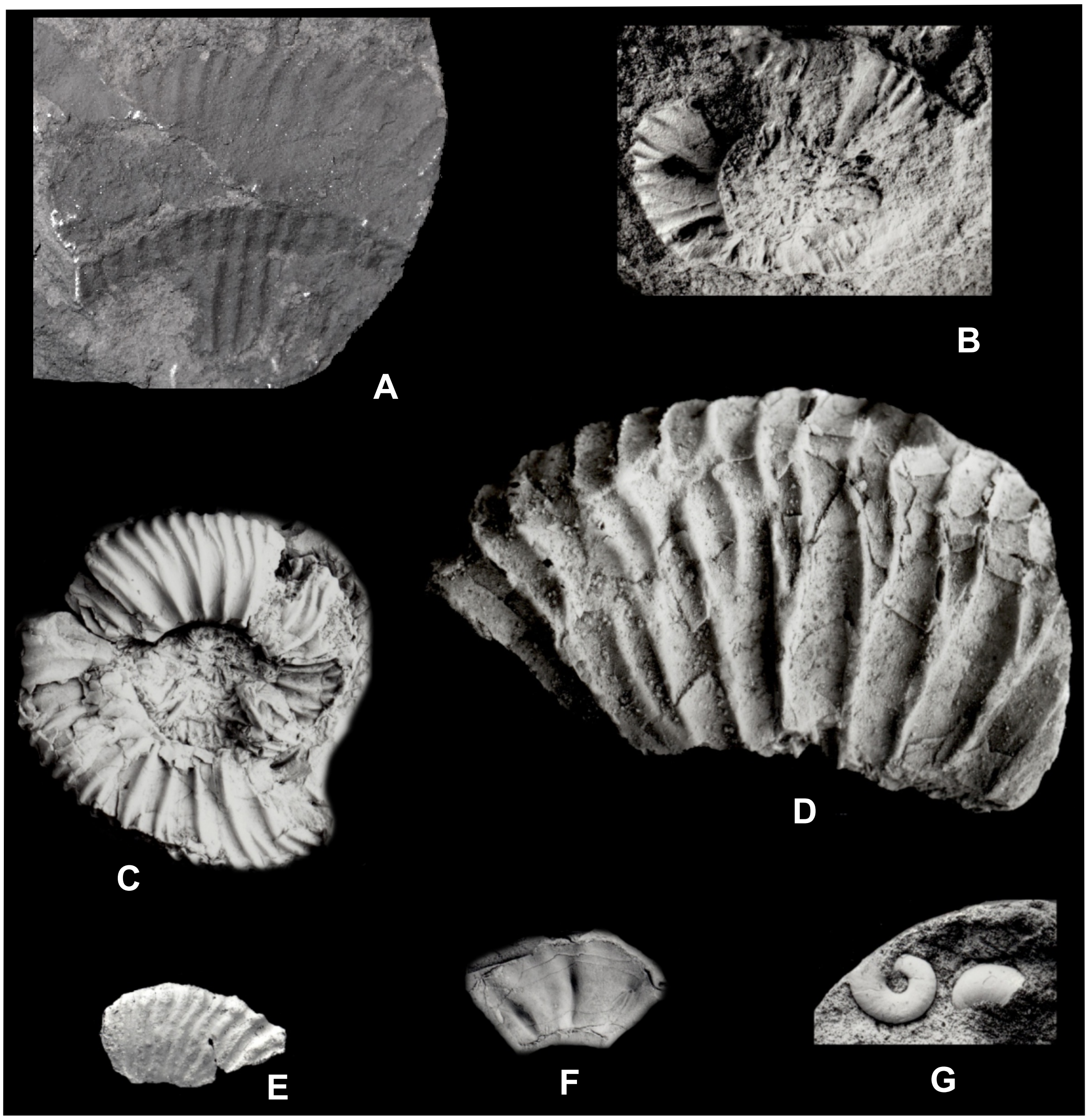

**Fig. 2A – (?)berriasellid, Muz. PIG 1671.II.14, Strzelno IG 1, depth 1336.2 m, uppermost Middle and Upper Berriasian; B – *Himalayites* cf. *breveti* (Pomel), Muz. PIG 1665.II.5, Oświno IG 1, depth 1526.2 m, uppermost Middle and Upper Berriasian, "Beds" with *Riasanites, Himalayites* and *Picteticeras*; C – *Surites* sp., Muz. PIG 1652.II.64, Oświno IG 1, depth 1522.4 m, Upper Berriasian, "Beds" with *Surites, Euthymiceras* and *Neocosmoceras*; D – *Berriasella* sp., Szamotuły geo 8, Muz. PIG 1652.II.13, 14, depth 646.0 m, Middle and Upper Berriasian; E – *Neocosmoceras* sp., Muz. PIG 1669.II.1, Gronowo 2, depth 340.5 m, Upper Berriasian, "Beds" with *Surites, Euthymiceras* and *Neocosmoceras*; F– *Platylenticeras* sp., Muz PIG 1665.II.52, Człopa 3, depth 529.0 m, Lower Valanginian; G – juvenile ammonites, Muz. PIG 1665.II.104, Kukawy TK 13, depth 1597 m, Upper Valanginian**

## RESULTS OF BIOSTRATIGRAPHIC ANALYSIS

### AMMONITES

Ammonites are relatively uncommon in the Lower Cretaceous succession of NW Poland and are usually poorly preserved. They occur mostly in the Berriasian (Ryazanian) and Valanginian. The low number of specimens did not allow for complete analysis of the Lower Cretaceous ammonite assemblages. For this reason, the study material was supplemented with ammonite faunas from other boreholes in the area, specimens of which can be found in the collections of Prof. Sylwester Marek, housed in the Geological Museum of PGI-NRI.

Particular zones are related to the Mediterranean and Boreal schemes in respect of these changing ammonite assemblages, and so the ammonite biostratigraphic scheme is presented for both domains.

Comparative studies of the collections of *Riasanites* specimens have confirmed the occurrence of *Riasanites rjasanensis* (Nikitin) in Poland (referred to as *Riasanites* sp. nov. by Mitta and Ploch, 2012), which was found in the Kcynia IG 2 borehole, depth interval 273.8 m (Muz. PIG 1652.II.21; Mitta and Ploch, 2012: pl. 1, fig. 4), Chrośna borehole, depth interval

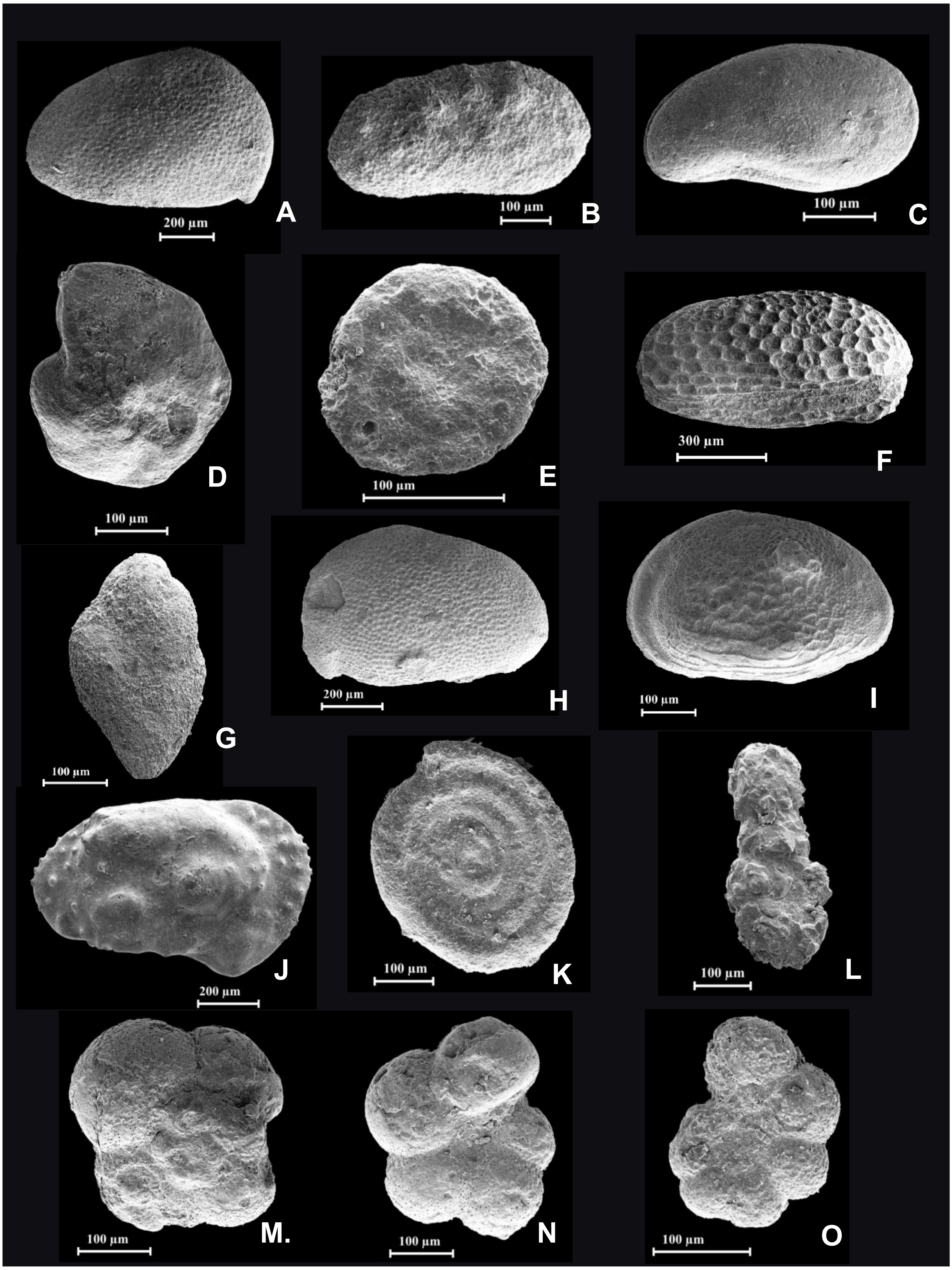

**Fig. 3A** – ***Cypridea tumescens praecursor*** **Oertli, Strzelno IG 1, depth 1398.0 m, Lower Berriasian (ostracod zone C); B** – ***Rhinocypris jurassica*** **(Martin), Strzelno IG 1, depth 1398.0 m, Lower Berriasian (ostracod zone C); C** – ***Damonella*** **sp., Strzelno IG 1, depth 1405.0 m, Lower Berriasian (ostracod zone ?C); D** – ***Lenticulina nodosa*** **(Reuss), Strzelno IG 1, depth 1359.0 m, Upper Berriasian (Ryazanian); E** – ***Glomospira irregularis*** **(Grzybowski), Strzelno IG 1, depth 1281.5 m, Valanginian; F** – ***Macrodentina mediostricta*** **Maltz, Oświno IG 1, depth 1577.0 m, Upper Tithonian (ostracod zone F); G** – ***Eoguttulina liassica*** **(Strickland), Oświno IG 1, depth 1577.0 m, Upper Tithonian (ostracod zone F); H** – ***Cypridea praealta invencula*** **Sztejn, Oświno IG 1, depth 1532.0 m, Middle Berriasian (ostracod zone B); I** – ***Klieana kujaviana*** **Bielecka et Sztejn, Oświno IG 1, depth 1532.0 m, Middle Berriasian (ostracod zone B); J** – ***Protocythere propria emslandensis*** **(Bartenstein et Burii), Oświno IG 1, depth 1518.0 m, Upper Berriasian (Ryazanian); K** – ***Ammodiscus*** **sp., Oświno IG 1, depth 1350.0 m Aptian; L** – ***Ammobaculites*** **sp., Oświno IG 1, depth 1350.0 m, Aptian; M, N** – ***Blefuscuiana infracretacea*** **(Glaessner), Oświno IG 1, depth 1350.0 m, Aptian; O** – ***Praehedbergella*** **sp., Oświno IG 1, depth 1350.0 m, Aptian**

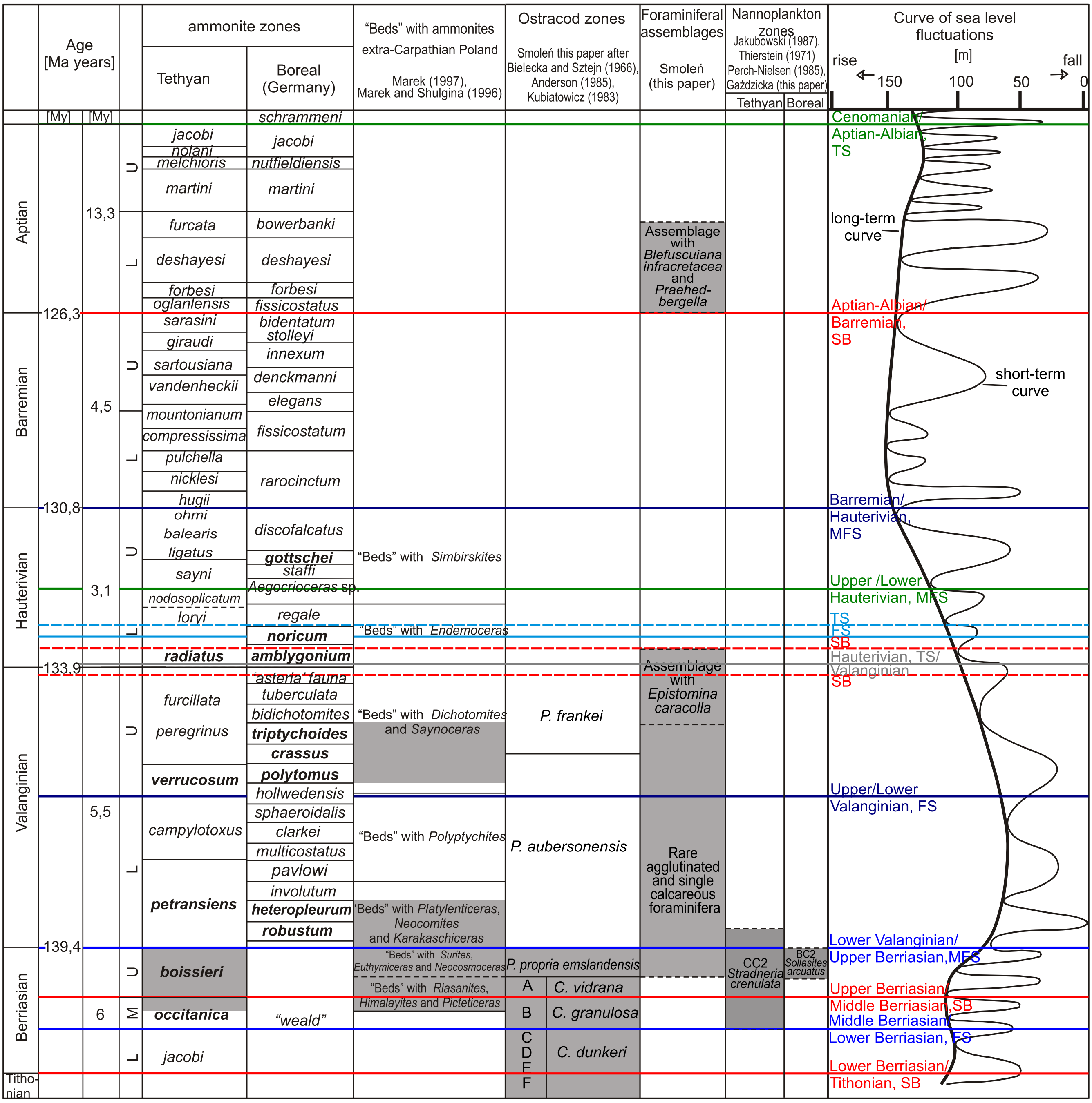

**Fig. 4. Comparison of Lower Cretaceous ammonite, foraminifer, ostracod and nannofossil zonations, and stratigraphic scheme proposed for the study sequences**

Ammonite zonation after Kemper et al. (1981), Kutek et al. (1989), Ogg and Hinnov (2012), and Reboulet et al. (2018), and long-term and short-term sea level curves after Haq (2014); in grey – zones and beds established in this paper

167.2–167.5 m, (Muz. PIG 1652.II.33; Mitta and Ploch, 2012: pl. 1, fig. 5). Mitta and Ploch (2012) also determined *Riasanites swistowianus* (Nikitin) from the Bądków 7/17 borehole, depth interval 209.0–215.0 m (Muz. PIG 1652.II.35; Mitta and Ploch, 2012: pl. 1, fig. 1), and Chrośna borehole, depth interval 167.2–167.5 m (Muz. PIG 1652.II.32; Mitta and Ploch, 2012: pl. 1, fig. 2). The latter species is indicative of the *swistowianus* biohorizon (*Riasanites rjasanensis* Zone) in the Russian Basin (Mitta, 2007).

Rare and fragmentarily preserved Berriasian (Ryazanian) ammonites have been found in the northern part of the basin (Table 1).

The Berriasian ammonite fauna in the study area is generally rare and poorly preserved. Due to strong compaction of the specimens, taxonomic assignment is problematic.

Valanginian ammonites are rarely recovered from boreholes studied in NW Poland. Lower Valanginian faunas occur in boreholes located closer to the central part of the basin, but

Table 1

**Distribution of the ammonite taxa**

| Borehole | Depth [m] | Species | Museum number | Figure | Stage |
|---|---|---|---|---|---|
| Strzelno IG 1 | 1336.2 | (?) berriasellid | Muz. PIG 1671.II.14 | Fig. 2A | Upper Berriasian |
| Oświno IG 1 | 1522.0 | *Surites* sp. | Muz. PIG 1652.II.64 | Fig. 2C | |
| Oświno IG 1 | 1523.0 | (?) *Surites* sp. | not storaged at the Museum | | |
| Oświno IG 1 | 1526.1 | *Himalayites* cf. *breveti* (Pomel) | Muz. PIG 1665.II.5 | Fig. 2B | |
| Szamotuły geo 8 | 646.0 | *Berriasella* sp. | Muz. PIG 1652.II.13, 14 | Fig. 2D | |
| Gronowo 2 | 340.5 | (?) *Neocosmoceras* sp.<br>(?) *Euthymiceras* sp. Raczyńska, (1967: tab. 1, fig. 5) | Muz. PIG 1669.II.1 | Fig. 2E | |

have not been analysed in this project; the specimens are housed in the Geological Museum of PGI-NRI. A juvenile form of *Platylenticeras* (Muz. PIG 1665.II.52; Fig. 2F) was found in the Człopa 3 borehole at a depth of 529.0 m. A specimen determined as *Platylenticeras* (Raczyńska, 1973), collected from the Szamotuły geo 27 borehole at a depth of 337.5 m, cannot be revised because it is poorly preserved and its taxonomic assignment is problematic.

Specimens described as *Saynoceras verrucosum* found in the Toporzysko (depth 486.2 m; Muz PIG 1665.II.103) and Kukawy TK 13 boreholes (depth 1597 m; Muz. PIG 1665.II.104; Fig. 2G) are juvenile forms with a smooth conch without any diagnostic features. They cannot be identified to species level because juveniles of numerous species have the same form.

Ammonite faunas representing "beds with *Endemoceras*" and "beds with *Simbirskites*", described from the central part of the basin (Marek, 1997; Raczyńska, 1979) and upper parts of the Lower Cretaceous, has not been found in the study area.

## MICROFAUNA

In the current study, the micropalaeontological analysis of the borehole core material allows revision of the biostratigraphy of some sedimentary sequences and of the position of some stratigraphical units. This concerns especially the older deposits in the "Purbeckian facies". The ostracods found in the "Purbeckian facies" analysed helped identify local ostracod zones F to A (after Bielecka and Sztejn, 1966) which have been distinguished in the Polish Basin. In this study, the stratigraphical position of ostracod zones F–A was demonstrated and the stratigraphical scheme established in central Poland (Dziadzio et al., 2004) was confirmed (Fig. 4). According to this scheme, the "Purbeckian"-type sequences should be correlated at least with the uppermost Tithonian to lower part of the Upper Berriasian

In the study area, deposits from the Jurassic/Cretaceous boundary interval of the "Purbeckian facies" are preserved in the Strzelno IG 1 and Oświno IG 1 boreholes. Zone F marks the beginning of the "Purbeckian facies". Assemblages typical of zone F were recognized in the Oświno IG 1 borehole (depth range 1546.0–1577.5 m). They are characterized by mixed marine and brackish-marine taxa with the following ostracod species typical for this zone such as *Macrodentina mediostricta* Maltz (Fig. 3F), *Protocythere* cf. *serpentina* (Anderson), *Procytheropteron* cf. *brodiei* (Jones) and representatives of the genera *Darwinulla*, *Damonella*, *Cypris*, *Paranotacythere* and *Schuleridea*. Foraminifera are represented by a few specimens of *Eoguttulina liassica* (Strickland) (Fig. 3G), *Spirillina infima* (Strickland), *Palaeomiliolina egmontensis* (Lloyd), *Bellorusiella turica* Gorbatchik and *Lenticulina* sp. In Strzelno IG 1, the lower part of the succession analysed (depth 1462.0 m), detrital, partly dolomitized limestones yielded unidentified ostracods, *Clypeina* algae and foraminifera such as *Melathrokerion eospiralis* Gorbathik and *Pseudocyclammina lituus* (Yokoyama) (Table 2). An ostracod assemblage characteristic of zone E was found in the Strzelno IG 1 borehole at a depth of 1419.5 m, in a marly shale interlayer within anhydrite deposits. This zone is marked by the occurrence of the species *Cypridea inversa* Martin, together with other, long-ranging, ostracod species (Table 2). The ostracod zones D and C were identified only in the Strzelno IG 1 borehole at depth interval 1398.0–1405.0 m. These zones are characterized by occurrence of other *Cypridea*, such as *Cypridea tumescens praecursor* Oertli (Fig. 3A), *Cypridea binodosa binodosa* Martin, and by long-ranging ostracod taxa such as *Rhinocypris jurassica* (Martin) (Fig. 3B) and *Damonella* sp. (Fig. 3C and Table 2). Ostracod zone B was clearly documented only in the Oświno IG 1 borehole. At a depth of 1532.0 m, in marls with the bivalve *Cyrena,* the characteristic taxa of ostracod zone B such as *Cypridea praealta iuvencula* Sztejn (Fig. 3H) and *Klieana kujaviana* Bielecka and Sztejn (Fig. 3I) were found together with other, long-ranging, ostracod species. The uppermost part of the "Purbeckian"-type deposits contains brackish and marine ostracods of zone A. This zone was identified only in the Strzelno IG 1 borehole. At a depth of 1378.5 m, Bielecka (1975) noted the presence of *Klieana kujaviana* Bielecka and Sztejn and higher, at 1376.0 m, *Pachycythereidea compacta* (Wolburg) (Table 2). The Oświno IG 1 borehole does not have the brackish-marine deposits of ostracod zone A. Directly above the deposits with ostracods of zone B, at depth 1518.0 m, only a marine microfauna is present. It is represented by individual speciments of the calcareous foraminifer *Lenticulina* cf. *nodosa* (Reuss) and a few agglutinated taxa as well as marine ostracods which indicate the ostracod *Protocythere propria emslandensis* Zone, distinguished in the uppermost Berriasian deposits in central Poland (Dziadzio et al., 2004). In the Strzelno IG 1 borehole, marine deposits were documented at depth 1359.0 m, including the foraminifera *Eoguttulina witoldi* Sztejn, *Pseudonodosaria humilis* (Roemer), *Lenticulina* cf. *nodosa* (Reuss) (Fig. 3D), *Epistomina* sp., *Haplophragmoides concavus* (Chapman), *Ammobaculites* sp., and ostracods of the genera *Protocythere* and *Cytherella* (Table 2). Such associations have been described in the boreholes from central Poland (Sztejn, 1969; Dziadzio et al., 2004; Grabowski et al., 2021) in the *rjasanensis* Zone.

Table 2

**Distribution chart of the microfauna in the uppermost Tithonian and Berriasian in the Strzelno IG 1 borehole**

| Stage | | Ostracod stratigraphy | Depth | Ostracoda | | | | | | | | | | | | | | | | | Foraminifera | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *Cypridea inversa* Martin | *Klieana alata* Martin | *Damonella pygmaea* (Anderson) | *Scabriculocypris* cf. *trapezoides* | *Cypridea lata polonica* Sztejn | *Cypridea tumescens praecursor* Oertli | *Cypridea* cf. *binodosa binodosa* Martin | *Cypridea valdensis praecursor* Oertli | *Damonella ellipsoidea* (Wolburg) | *Rhinocypris jurassica* (Martin) | *Damonella* sp. | *Darwinulla* sp. | *Fabanella* sp. | *Klieana kujaviana* Bielecka and Sztejn | *Pachycythereidea compacta* Wolburg | *Protocythere* sp. | *Cytherella* sp. | *Melathrokerion eospiralis* Gorbathik | *Pseudocyclammina lituus* (Yokoyama) | *Eoguttulina witoldi* Sztejn | *Pseudonodosaria humilis* (Roemer) | *Lenticulina* cf. *nodosa* (Reuss) | *Epistomina* sp. | *Haplophragmoides concavus* (Chapman) | *Ammobaculites* sp. |
| Berriasian | Upper | | 1359.0 | | | | | | | | | | | | | | | | x | x | | | x | x | x | x | x | x |
| | | B+A | 1376.0 | | | | | | | | | | | | | | x | x | | | | | | | | | | |
| | | | 1378,0 | | | | | | | | | | | | | | x | | | | | | | | | | | |
| | | | 1380.0 | | x | | | | | | | | x | x | | | | | | | | | | | | | | |
| | | | 1388.0 | | x | | | | | | x | x | | | | | | | | | | | | | | | | |
| | M | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Lower | D+C | 1400.0 | | x | | | x | x | x | x | x | x | x | x | x | | | | | | | | | | | | |
| | | | 1405.0 | | x | | | x | x | x | x | x | x | x | x | x | | | | | | | | | | | | |
| | | E | 1419.5 | x | x | x | x | | | | | | | | | | | | | | | | | | | | | |
| T | | | 1446.0 | | | | | | | | | | | | | | | | | | x | x | | | | | | |

T. – Tithonian, M. – Middle Berriasian

In the Valanginian–Middle Albian interval, microfauna is present only at certain depths (Appendix 1). It is mostly represented by long-ranging foraminifera, mainly agglutinated taxa. In the Valanginian, microfauna was noted only in the Strzelno IG 1 and Człuchów IG 1 boreholes (Appendix 1). In the Człuchów IG 1 borehole, a rather low-abundance foraminiferal assemblage occurs at a depth of 705.0 m. It comprises agglutinated forms such as *Haplophragmoides cushmani* Loeblich and Tappan, *H. concavus* (Chapman), *Glomospirella gaultina* (Berthelin), *Ammodiscus* sp. and *Trochammina* sp. In the Strzelno IG 1 borehole, in depth interval 1234.0–1281.6 m, there are scarce foraminifera assemblages with *Glomospira irregularis* (Grzybowski) (Fig. 3E), *Trochammina kcyniensis* Sztejn, *H. concavus* (Chapman), *Ammobaculites* cf. *eocretaceous* Bartenstein and Brand, *Proteonina difflugiformis* Brady, *Haplophragmoides cushmani* Loeblich and Tappan, *Lenticulina* sp., *Lenticulina subalata* (Reuss), *Reophax* sp. and *Trochammina* sp. In the higher part of the Strzelno IG 1 borehole in the depth interval 1226.0–1234.0 m, more calcareous foraminifer appear in claystones with high-Fe concretions. Here, foraminiferal assemblages with *Epistomina caracolla* was distinguished (Fig. 4), which in addition to *Epistomina caracolla* (Roemer) also contain taxa such as *Lenticulina subalata* Reuss, *Epistomina* sp., *Vaginulinopsis humilis* Reuss, *Glomospirella gaultina* (Berthelin), *Proteonina* sp. and *Reophax* sp. The micropalaeontological documentation does not constrain the age of these rocks. Similar foraminiferal assemblages were noted in central and southeastern Poland in the Valanginian and lowermost Hauterivian deposits (Dziadzio et al., 2004). The upper part of the Lower Cretaceous also includes scarce microfossils. Foraminifera are sporadically present in the Człuchów IG 1 and Chociwel IG 1 boreholes. Assemblages composed of agglutinated taxa have no stratigraphic significance. A foraminiferal assemblage with *Blefuscuiana infracretacea* and *Praehedbergella* sp. (Fig. 4) is present in the Oświno IG 1 borehole at a depth of 1350.0 m in dark siltstones. The index species *Blefuscuiana infracretacea* (Glaessner) (Fig. 3M, N) points to an Aptian age. The foraminiferal assemblage mentioned above, in addition to the index species, also includes another planktonic species, *Praehedbergella* sp. (Fig. 3O), rare calcareous forms representing the genera *Lenticulina* and *Epistomina.* and also agglutinated taxa such as *Ammodiscus* sp. (Fig. 3K), *Ammobaculites* sp. (Fig. 3L) and other of genera: *Haplophragmoides*, *Trochammina*, *Proteoina*, and *Glomospira.*

## CALCAREOUS NANNOPLANKTON

The stratigraphically oldest coccolith assemblage was found in the Strzelno IG 1 borehole core, in the clay-siltstone interval at a depth of 1314.0 m. It includes rare and poorly preserved, low-diversity calcareous nannoplankton: *Cyclagelosphaera margerelii* Noël, *Diazomatolithus lehmanii* Noël, *Nannoconus* sp., *Retacapsa angustiforata* Black, *Rotelapillus laffittei* (Noël), and *Watznaueria barnesiae* (Black). The taxonomic composition of the coccolith assemblage from the

Table 3

**Distribution of calcareous nannoplankton taxa within the Kcynia IG 2 borehole section**

| Calcareous Nannoplankton species | *Anfractus harrisonii* | *Conusphaera rothii* | *Crucibiscutum salebrosum* | *Cyclagelosphaera argoensis* | *Diazomatolithus lehmanii* | *Haqius circumradiatus* | *Lithraphidites carniolensis* | *Retacapsa angustiforata* | *Sollasites arcuatus* | *Sollasites horticus* | *Staurolithites mitcheneri* | *Tegumentum stradneri* | *Tetrapodorhabdus coptensis* | *Watznaueria barnesae* | *Watznaueria biporta* | *Watznaueria britannica* | *Watznaueria fossacincta* | *Zeugrhabdotus erectus* | *Zeugrhabdotus diplogrammus* | Nannoplankton zones Perch-Nielsen (1985); Bown et al. (1999) | | Lithostratigraphy | Stage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth [m] | | | | | | | | | | | | | | | | | | | | | | | |
| 253 | | | | | | | X | X | X | | | | | X | | | X | | | CC2 *Stradneria crenulata* | BC2 *S. arcuatus* | Rogoźno Formation | Upper Berriasian |
| 255 | | X | | | | | | | X | | | | | | | | X | | | | | | |
| 260 | X | | X | X | X | X | X | X | | | X | X | X | X | X | X | | | X | | | | |
| 264 | | | | | X | | X | X | X | | | | | | | | X | | | | | | |
| 268 | | | | | X | | | | | | | | | | | | X | | | | BC1 *R. angustiforata* | | |
| 270 | | | | X | X | | X | | | | X | | | X | X | X | | X | | | | | |
| 275 | | | | X | X | | | | | | | | | | | | X | X | | | | | |
| 278 | | | | | | | | | | | | | | | | | | | | | | | |

Strzelno IG 1 borehole core allows recognition of the CC2 *Stradneria crenulata* (Thierstein, 1971; nom. corr. Perch-Nielsen, 1985) standard nannoplankton zone. This horizon encompasses the uppermost part of the Middle Berriasian, the Upper Berriasian and the lowermost Valanginian (Perch-Nielsen, 1985). It is thus a rather long interval, and the low diversity of the coccolith assemblage does not allow determination of the precise stratigraphic position of the succession analysed.

More abundant and taxonomically diverse assemblages of calcareous nannoplankton have been noted in the Kcynia IG 2 borehole located on the Kuyavian-Pomeranian Swell, to the north-west of Strzelno. An 80-m series of grey and dark grey claystones and marly shales with intercalations of marls and siltstones with siderite, pyrite concretions, and accumulations of calcareous mollusc shells was studied in the succession of this fully cored borehole. This complex occurs above a 130 m thick series of Purbeck-type facies, encompassing shallow-marine limestones, gypsum and anhydrite, as well as dark bituminous shales, capped by a thin horizon of fresh-water deposits representing the Wealdian. The transgressive cycle begins with clayey marls with *Cyrena* bivalves, ostracods and agglutinated foraminifera. The nannoplankton assemblages document the stage of basin development when the coastline was clearly shifted landwards. The nannoplankton assemblages are dominated by representatives of the genus *Watznaueria*: *W. barnesiae* (Black), *W. biporta* Bukry, *W. britannica* (Stradner), and *W. fossacincta* (Black). Tethyan or cosmopolitan species are also common: *Cyclagelosphaera argoensis* Bown, *Haqius circumradiatus* (Stover), *Diazomatolithus lehmanii* Noël, *Lithraphidites carniolensis* Deflandre and *Retacapsa angustiforata* Black. They are accompanied by Boreal taxa, such as *Crucibiscutum salebrosum* (Black), *Sollasites arcuatus* (Black), *S. horticus* (Stradner et al.) and *Zeugrhabdotus erectus* Deflandre. The taxonomic composition of the nannoplankton assemblages allows recognition of the Upper Berriasian (Ryazanian) BC2 *Sollasites arcuatus* Boreal nannoplankton zone (Jakubowski, 1987; Table 2). This zone encompasses a short stratigraphic interval (from the first to the last appearance of *S. arcuatus*) and corresponds to the upper part of the CC2 *Stradneria crenulata* standard nannoplankton zone (Thierstein, 1971; Perch-Nielsen, 1985), distinguished in the Tethyan domain.

Nannoplankton zone BC 2 is correlated with the ammonite *albidum* Zone corresponding to the uppermost Ryazanian in the Boreal domain (upper part of the Tethyan *boissieri* Zone; Fig. 4).

An additional study only on nannoplankton was done for the higher part of the boreholes mainly to add to the few nannoplankton records from Lower Cretaceous deposits in the NW part of the Mid-Polish Trough and to obtain more biostratigraphic information. Abundant but poorly preserved calcareous nannoplankton with traces of strong chemical corrosion were noted in dark grey marls of the Chociwel IG 1 borehole core at a depth of 2323.7 m. The assemblage is dominated by coccoliths of the species *Watznaueria barnesiae* (Black), accompanied by *W. biporta* Bukry and *Cyclagelosphaera margerelii* Noël. The species *Eiffellithus monechiae* Crux, *E. turriseiffeli* (Deflandre), *Prediscosphaera columnata* (Stover) and *Prediscosphaera spinosa* (Bramlette and Martini) indicate the CC9 *Eiffellithus turriseiffeli* standard nannoplankton zone and the corresponding BC27 (Bown et al., 1999) and UC0 (Burnett, 1999) Boreal nannoplankton zones (Table 4 and Appendix 1).

This interval ranges from the first occurrence (FO) of *E. turriseiffeli* and the FO of *Corollithion kennedyi* Crux. It is corre-

Table 4

**Distribution of calcareous nannoplankton taxa within the Chociwel IG 1 borehole section**

| Calcareous nannoplankton species<br>Depth [m] | *Axopodorhabdus albianus* | *Broinsonia enormis* | *Calculites percensis* | *Cyclagelosphaera margerelii* | *Cyclagelosphaera reihardtii* | *Eiffellithus turriseiffeli* | *Eprolithus floralis* | *Haqius circumradiatus* | *Helenea chiasta* | *Lithraphidites carniolensis* | *Prediscosphaera columnata* | *Rhagodiscus splendens* | *Tranolithus orionatus* | *Watznaueria barnesae* | *Watznaueria biporta* | *Zeugrhabdotus diplogrammus* | *Zeugrhabdotus erectus* | *Zeugrhabdotus scutula* | *Braarudosphaera africana* | *Crucicribrum anglicum* | *Thoracosphaera thoracata* | *Gartnerago nanum* | *Gartnerago theta* | *Helicolithus trabeculatus* | *Kamptnerius magnificus* | *Manivitella pemmatoidea* | *Nnannoconus* sp. | *Corollithion kennedyi* | *Prediscospaera cretacea* | *Rhagodiscus angustus* | *Biscutum constans* | *Reoagulum parvidentatum* | *Acenolithus cenomanicus* | *Gartnerago segmmentatum* | Nannoplankton Zones | Perch-Nielsen (1985), Burnett (1999) | Amonite Zonation | Stage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2266.5 |  |  | X | X | X |  | X | X | X |  |  |  |  |  |  |  | X | X | X |  |  | X |  |  |  |  |  | X |  |  | X | X |  | X | CC9 *Eiffellithus turriseiffeli* | UC3 | *Rotomag.* | Cenomanian Middle |
|  | X | X | X |  | X | X | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2268.5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  | X |  |  | X | X |  |  |  |  |  |  |  | X | X | X | X |  |  | X |  |  |  |  | X |  |  |  |  |  | X |  | UC1-2 | *Mantelli* | Lower |
| 2288.5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | X | X | X |  | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2301.5 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | X |  | X |  |  | X | X |  |  |  | X |  | X |  | X | X | X | X |  | X |  |  |  |  |  | X |  |  |  |  | X | X |  | UC0 |  |  |
| 2304.5 | X | X | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2317.0 |  |  | X |  | X | X |  | X | X |  |  | X | X |  |  |  | X | X | X |  | X | X | X | X |  |  |  |  |  | X | X |  | X | X |  |  | *Dispar* | Upper Albian |
| 2323.7 |  |  | X |  |  |  | X | X | X |  |  | X |  | X | X |  | X | X | X |  | X | X | X |  |  | X |  | X |  | X | X | X | X |  |  |  |  |  |
|  |  | X | X | X | X |  | X | X | X |  |  | X |  | X | X |  | X | X | X |  | X | X | X | X |  | X | X |  |  |  |  |  |  |  |  |  |  |  |
|  |  | X | X | X | X |  | X | X | X |  | X | X | X | X |  | X | X | X |  | X | X | X | X |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

lated with the *dispar* ammonite zone and the lower part of the *mantelli* Zone, ranging from the uppermost Albian to the lowermost Cenomanian (Fig. 4). A nannoplankton assemblage of similar taxonomic composition to that noted above, indicating the uppermost Albian, occurs in light grey marls at a depth of 2317.0 m. In turn, the overlying ~10 m thick succession can be described as transitional between the Albian and Cenomanian, corresponding to the previously distinguished Vraconian Stage. This term was used for a marly facies with *Aucellina* shells ("*Aucellina marls*") that is widespread in Europe and is characterized by the gradual disappearance of Albian taxa (nannoplankton, foraminifera and macrofauna) and the appearance of Cenomanian taxa *Aucellina gryphaeoides* (Sow.) while other forms described as *Aucellina* sp. have been noted in marls occurring in depth interval 2304.4–2320.2 m of the Chociwel IG 1 borehole core (Jaskowiak-Schoenaichowa, 1977).

Representatives of the *Gartnerago* genus, i.e., *G. nanum* Thiersten and *G. theta* (Black), appear from a depth of 2304.5 m in the nannoplankton assemblages; the FO of *Corollithion signum* Stradner was noted at a depth of 2301.5 m. The appearance of *G. nanum* documents the Albian/Cenomanian boundary, because the FO of this species was observed above the boundary between the *dispar* and *mantelli* zones, i.e., in the lowermost Cenomanian. The species *Corollithion kennedyi* Crux (zonal marker – Burnett, 1999) was noted at a depth of 2288.5 m, which allowed recognition of the subsequent UC1 nannoplankton zone corresponding to the Lower Cenomanian (Appendix 1). In turn, samples from depth levels of 2268.5 and 2266.5 m contain calcareous nannoplankton assemblages pointing to the Middle Cenomanian-UC3 Boreal nannoplankton zone, subzone UC3b. The taxonomic composition of the nannoplankton assemblages with *Acenolithus cenomanicus* Black and the lack of *Gartnerago theta* (Black) point to the lower part of the Middle Cenomanian, corresponding to the *rhotomagense* ammonite zone.

A similar case was observed in the Oświno IG 1 borehole core, located also in the Szczecin Trough, in which 18 samples were studied in depth interval 1285.5–1542.3 m. Calcareous nannoplankton appear in grey marls at a depth of 1287.0 m, and the taxonomic composition of the assemblage with *Corollithion kennedyi* Crux and *Gartnerago theta* (Black) points to the Lower Cenomanian, UC1 nannoplankton zone. A sample from a depth of 1285.5 m contains a more abundant coccolith assemblage with *Acaenolithus cenomanicus* Black, documenting the Middle Cenomanian UC3 nannoplankton zone (Appendix 1). The Tethyan species *Microrhabdulus decoratus* Deflandre, whose FO marks the lower boundary of the CC10 standard nannoplankton zone encompassing the upper part of the Lower Cenomanian, has not been recorded in any of the two borehole cores analysed.

## ANALYSIS OF GEOPHYSICAL LOGS

The most complete Lower Cretaceous successions occur in the Strzelno IG 1 and Oświno IG 1 boreholes. The remaining boreholes are characterized by fragmentary and much reduced successions; the reduction refers to the lower part of the Lower Cretaceous, e.g., in the Choszczno IG 1 and Chociwel IG 1 boreholes. Analysis of geophysical logs shows that it is very difficult or in some cases impossible to distinguish also the upper stages of the Lower Cretaceous as done by previous researchers on the same dataset. The fragmentary stratigraphic data do not allow for unequivocal subdivision of the Cretaceous in the Szczecin IG 1 and Człuchów IG 1 boreholes, where almost complete Lower Cretaceous successions have been recognized. Comparison of the position of the stage boundaries with geophysical logs indicates that they do not have similar characteristics.

A detailed list of depths of particular stages in the boreholes analysed is shown in Table 5.

## DISCUSSION

### SIGNIFICANT BOUNDARIES DISTINGUISHED DURING THE ANALYSIS

The boundary between the **Tithonian** and **Berriasian** in the study area and in the central part of the Polish Lowlands occurs at the base of the >30 m thick series of carbonate-sulphate deposits described by Gaździcka (1996) and Dziadzio et al. (2004).

The boundary is thus of regional character, as in the central part of the Polish Lowlands in the Warsaw Trough. Similarly, as in the south of Poland, it may represent a sequence boundary combined with a relative sea level fall, and is clearly noted on geophysical logs (see Dziadzio et al., 2004). The boundary is placed in this interval in the Strzelno IG 1 borehole, as in the Gostynin IG 4 borehole. The lower unit assigned to the Upper Tithonian is carbonate-marly-dolomitic.

The **Lower Berriasian** is represented by alternating clay-carbonate-sulphate deposits identified by core data. Towards the NW they are replaced by marly-carbonate deposits, with oolitic limestones in the lower part of the Lower Berriasian, as in the SE of the basin in the Białobrzegi IG 1 borehole (Dziadzio et al., 2004).

The carbonate-sulphate deposits in the vicinity of Oświno are overlain by marly deposits (~6 m thick), as in the vicinity of Gostynin. Most probably the equivalents of these deposits are 2 m thick in the Strzelno IG 1 borehole. This change in facies, as in southern Poland, may suggest the beginning of the transgression as early as in the Early Berriasian. A transgressive surface may be present there. These deposits probably continuously pass into the Middle Berriasian.

The base of the **Middle Berriasian** was placed by analogy with the central part of the Polish Lowlands. It can be related with a transgressive surface, clearly identified on geophysical logs (see Dziadzio et al., 2004).

A highstand systems tract is probably developed above this boundary in the part of the Polish Lowlands analysed; it encompasses a thin (~8–15 m) Middle Berriasian succession. The Middle Berriasian strata include dark grey marly shales interbedded with bioclastic limestones as in the region of Oświno.

The **Upper Berriasian** was recognized in the Strzelno IG 1 and Oświno IG 1 boreholes. The Middle/Upper Berriasian boundary was placed at the base of a lower-range sequence, whose lowstand systems tract and transgressive systems tract includes the Upper Berriasian. The boundary is determined similarly as in the southern part of the Polish Lowlands. A more complete and surprisingly thick (74 m) succession in the study area was recognized in the Strzelno IG 1 borehole, where it is developed as a series from shallow-marine limestones with *Cyrena* through a sandy clays to clays and clayey siltstones with horizons of *Exogyra* fauna, pyritized bioturbation infills and sideritic concretions at the top, within which lies a maximum flooding surface marking the boundary between the Berriasian and Valanginian. The boundary is placed exactly in the same location as in the southern part of the Polish Lowlands. The large thickness of the Upper Berriasian in the study area is of high significance. Comparative analysis with existing data on the Lower Cretaceous indicates that this is the first case of such substantial thickness in the Berriasian in NW part of the Polish Trough. It may be interpreted as a channel infill or an incised shelf valley.

Table 5

**Depth of the Lower Cretaceous stratigraphic boundaries in the boreholes based on lithological similarities and geophysical logs**

| Borehole/stratigraphic interval | Strzelno IG 1 | Choszczno IG 1 | Chociwel IG 1 | Oświno IG 1 | Szczecin IG 1 | Człuchów IG 1 |
|---|---|---|---|---|---|---|
| Cenomanian/Turonian | 952.5 | 936.0 | 2243.0 | 1257.0 | 1492.0 | 574.0 |
| Aptian-Albian/Cenomanian TS | 1037.2 | 982.0 | 2325.3 | 1293.0 | 1543.2 | 621.0 |
| Barremian/Aptian-Albian SB | 1143.8 | | | 1335.0 | 1563.6 | 656.5 |
| Hauterivian/Barremian MFS | 1155.5 | | | 1354.5 | 1569.4 | 662.2 |
| Lower/Upper Hauterivian MFS | 1190.7 | 982.0 | 2345.5 | 1411.5 | 1576.5 | 680.0 |
| Valanginian/Hauterivian TS | 1229.0 | 1000.0 | 2345.5 | 1448.0 | 1584.9 | 684.5 |
| Lower/Upper Valanginian FS | 1281.24 | | | 1478.4 | | |
| Berriasian/Lower Valanginian MFS | 1318.0 | | | 1516.0 | 1609.0 base of the Valanginian | 705.5 base of the Valanginian |
| Middle/Upper Berriasian SB | 1391.0 | | | 1527.0 | | |
| Lower/Middle Berriasian FS | 1399.0 | | | 1541.5 | | |
| Tithonian/Lower Berriasian SB | 1442.0 | | | 1560.0 | | |
| Base of the Cretaceous | 1442.0 | 1000.0 | 2345.5 | 1560.0 | 1609.0 | 705.5 |

FS – flooding surface, MFS – maximum flooding surface, SB – sequence boundary, TS – transgressive surface

The Berriasian/Valanginian boundary was placed at the maximum on the gamma-ray log. A higher average of the gamma value is interpreted as being due to deeper sedimentary environments (e.g., Van Wagoner et al., 1990; Mitchum et al., 1993; Dziadzio et al., 2004; Moradi et al., 2019). Gradual deepening of the Berriasian sedimentary basin took place up to this boundary; it is also visible in the facies record and and in the retrogradational character of the geophysical logs.

Considerable thicknesses of the **Valanginian** succession were noted in the Strzelno IG 1 (~90 m) and Oświno IG 1 (~70 m) boreholes. A distinct dichotomy can be observed on geophysical logs within the clastic Valanginian deposits in the study area; based on core data and borehole logs, it is regarded as progradational in character. Of the same mode is the Lower Valanginian in the Warsaw Trough area, where parasequences are observed on geophysical logs and in core data.

The lower part of the succession includes clays and clay-siltstones, often with laminae and siderite layers, whereas the upper is sandy in character. In the middle part of the succession is the boundary between the Lower and informal "Middle Valanginian" within clays with sideritic concretions, where it can be linked with marine flooding (probably of a lower range than in the Gostynin area). Therefore, the Upper Valanginian succession in the study area indicates deposition during shallowing of a highstand systems tract. The sequence boundary which occurs in the SE part of the Polish Lowlands may also be present here in the lower part of the Upper Valanginian at the base of a sandy series, in the Strzelno IG 1 borehole at a depth of 1265 m, just above the flooding surface. This is confirmed by concretions and clay clasts in the base of the sandstones in the Strzelno IG 1 borehole, and by sandstones at a depth of ~1474 m in the Oświno IG 1 borehole.

In the topmost part of the lowstand systems tract, there is a transgressive surface (TS) in the Oświno IG 1 borehole, which may be the boundary between the **Valanginian** and **Hauterivian**, as in the Warsaw Trough. Based on palaeontological data, this boundary is placed within a clay series in the Strzelno IG 1 borehole, which may indicate stratigraphic continuity between the Valanginian and Hauterivian, and a more basinal part of the succession. Near Szczecin and Człuchów, deposits of this age were distinguished by analogy with the facies record and geophysical logs. However, they have not been subdivided there into the Lower and Upper Valanginian.

Above the transgressive surface, which in the Strzelno IG 1 borehole may coincide with flooding, begins a transgressive systems tract characterized in the entire area of the Polish Lowlands by the presence of strongly bioturbated clay shales, dispersed Fe ooids and glauconite (Gostynin IG 4 and Strzelno IG 1 boreholes).

In the Strzelno IG 1 borehole, as in the Gostynin IG 4 borehole and the SE part of the Polish Lowlands, a second-order sequence boundary occurs in the lower part of the **Lower Hauterivian** succession. Based on core data and borehole logs, a flooding surface and transgressive surface may be distinguished slightly higher up. This suggest rather unstable sedimentary conditions of the Lower Hauterivian caused by global sea-level changes or local tectonic conditions, and the strata recording these phenomena were probably deposited within a shallow clastic shelf. They are dominated by a clastic facies of fine- and very fine-grained sandstones, siltstones and claystones, interbedded with laminae or dispersed Fe and sideritic concretions, as well as Fe ooids. The succession is strongly bioturbated with pyrite-filled trace fossils. A maximum flooding surface has been recognized at the top of these deposits. It separates the Lower Hauterivian from the Upper Hauterivian deposits.

The **Lower Hauterivian**, although characterized by incomplete successions, probably occurs in the Choszczno IG 1 and Chociwel IG 1 boreholes, where it directly overlies Jurassic strata. Rocks of this age have also been correlated in the Szczecin IG 1 and Człuchów IG 1 boreholes, but based only on geophysical logs and lithological data.

The Upper Hauterivian is dominated by sandstones deposited during a lowstand systems tract. The highstand systems tact, which in the Strzelno IG 1 and Oświno IG 1 boreholes is very thin, corresponds to a much thicker one in the vicinity of Gostynin (Dziadzio et al., 2004). In both cases, the sandy facies is replaced by a clay facies upwards, which points to the retrogradational character of sedimentation in the Late Hauterivian.

The Hauterivian/Barremian boundary is recorded in the geophysical logs as a maximum on the gamma-ray curve corresponding to a maximum flooding surface. It is clearly identified in all boreholes in the study area and across the entire Polish Lowlands (Dziadzio et al., 2004).

Deposits of **Barremian** age were deposited during a highstand systems tract. They include fine-grained deposits formed within a shallow shelf. The top of these deposits marks a sequence boundary with sandstones of **Aptian–Albian** age.

Based on available data, it is not possible to subdivide this interval into separate stages. As in Dziadzio et al. (2004), they are treated as one unit. Additional boundaries, which may indicate oscillations of basin depth as in the case of the Gostynin to Białobrzegi area (Dziadzio et al., 2004), cannot be distinguished due to the lack of characteristic anomalies in the borehole logs. The largest thickness of these deposits was noted in the Strzelno IG 1 borehole (113 m). They include fine- and medium-grained quartz sands/sandstones with glauconite, often with coarser grains, which are well-sorted, washed out, and occasionally with dispersed clay and coalified material.

Based on available core data and material from the southern part of the Polish Lowlands (Dziadzio et al., 2004), the most probable sedimentary setting was a clastic shelf characterized by a high subsidence rate. Such sedimentation took place from the Warsaw Basin to the Oświno IG 1 borehole area, reaching 42 m in the Pomeranian Trough, of which sandstones comprise 20 m, being replaced by siltstones higher up in the succession. Small thicknesses of deposits of this age occur in the Szczecin IG 1 and Człuchów IG 1 boreholes. Strata of this age were not noted in the Chociwel IG 1 and Oświno IG 1 boreholes, where the Lower Hauterivian is directly overlain by the Cenomanian.

The topmost part of the Aptian-Albian interval is characterized by mass accumulations of glauconite and phosphorites, sometimes represented by large granules. Their presence may point to a maximum flooding surface and indicate that the deposits were formed on a transgressive surface. Above, sandstones are abruptly replaced by marls. The MFS, probably documenting the **Early Cenomanian** transgression, is recorded by two maxima on the gamma-ray log.

## STRATIGRAPHY AND DEPOSITIONAL SEQUENCES

The most complete Lower Cretaceous successions in the Pomeranian Basin occur in the Strzelno IG 1 and Oświno IG 1 boreholes. A slightly different case occurs in the remaining boreholes, where complete successions are missing e.g., the Choszczno IG 1 and Chociwel IG 1 boreholes, in which only the Lower Hauterivian is likely to be present. The strongly reduced Lower Cretaceous succession (reduction refers to the same stages) in the Szczecin IG 1 and Człuchów IG 1 boreholes, which are located in the same line with the Oświno IG 1 borehole, is difficult to understand. However, a comparison of the material analysed with that described by Dziadzio et al. (2004) shows that a similar cyclicity of sedimentation reflected in depositional sequences is preserved in other parts of the Polish Basin. Moreover, the Pomeranian Trough, consisting of a series of small blocks separated by faults, shows various vertical movements. Block mobility during sedimentation caused local variability in the subsidence of individual stages and formations and increase in stratigraphic-erosional gaps (Dadlez, 1983).

Third-order sequences and superordinate cycles, probably second-order sequences, can be distinguished in the entire Lower Cretaceous succession in the Pomeranian Basin.

The first sequence encompasses ~12 My, occurs at the **Tithonian/Berriasian** boundary, and is biostratigraphically documented by ostracods, marked by geophysical logs showing SB features and can be related to the global sea level fall determined on Haq's curve.

The stratigraphy of the lowermost interval studied belonging to the "Purbeckian facies" is based only on ostracod biostratigraphy (zones F to A). In this study, the position of the F to A ostracod zones was determined and the stratigraphic scheme established for central Poland by Dziadzio et al. (2004) was confirmed. According to this scheme, the "Purbeckian"-type sequences should be correlated at least with the uppermost Tithonian to the lower part of the Upper Berriasian. The interval encompassing ostracod zones F to B was hitherto assigned to the Upper Jurassic – the uppermost Middle Tithonian and the Upper Tithonian (Marek et al., 1989; Marek, 1997) – or to the Upper Volgian (Sztejn, 1991). The lowermost Lower Cretaceous – Berriasian deposits were considered as Ryazanian brackish-marine strata with ostracods of Zone A and an ammonite-bearing member of the Rogoźno Formation (Marek and Rajska, 1997). Recent joint geophysical and palaeontological analysis of the Lower Cretaceous of the Polish Lowlands has indicated significant changes in the subdivision of the Jurassic/Cretaceous boundary interval (Olszewska, 1999; Zdanowski et al., 2001; Gaździcka et al., 2003; Dziadzio et al., 2004; Grabowski et al., 2021). The boundary interval, previously attributed to the Upper Tithonian (Upper Portlandian or Upper Volgian in older reports), according to the latest biostratigraphic subdivision, largely represents the Lower Cretaceous.

In this study, the lower part of the "Purbeckian" deposits where ostracod taxa of zone F were recognized (Oświno IG 1 borehole) are referred to the latest Tithonian. Probably the Upper Tithonian can also be applied to the lower part of the sequences studied in the Strzelno IG 1 borehole which yielded foraminifera, ostracod and *Clypeina* algae. Micropalaeontological documentation does not determine the age of these strata. Nevertheless, these sequences may be assigned to the Upper Tithonian based on the presence of the foraminifera *Melathrokerion eospiralis* (Gorbathik) and *Pseudocyclammina lituus* (Yokoyama). Similar faunal assemblages recognized in the Ropczyce series in the Carpathian Foredeep represent the Upper Tithonian (Olszewska, 1999, 2001; Zdanowski et al., 2001). The upper part of the "Purbeckian" succession with ostracod assemblages of zones E through A is assumed to be of the Berriasian age. The vertical variations in ostracod assemblages in the boreholes studied enabled correlation of the "Purbeckian"-type deposits with similar sequences in central Poland (Dziadzio et al., 2004; Grabowski et al., 2021), and also with Dorset in southern England and with the Lower Saxony Basin in Germany (Anderson, 1985; Allen and Wimbledon, 1991; Schneider et al., 2018). The "Purbeckian" deposits with the ostracod taxa of zone F may be considered as equivalent to the lowermost part of the Lulworth Formation in Dorset and the upper part of OM4 (Munder Formation) in the Lower Saxony Basin. This is indicated by the co-occurrence of similar ostracod assemblages which are characterized by the mixed marine and brackish–marine taxa. Such assemblages are noted in an ammonite-barren interval at the top of the Jurassic in northwestern Europe (e.g., Anderson, 1985; Horne, 1995, 2009; Elstner and Mutterlose, 1996; Wilkinson, 2008; Wilkinson and Whatley, 2009). The ostracod zones E, D and C correspond to the pre-Middle Purbeck in Dorset. The ostracod zones E to C correspond also to the Katzberg Member (OM5) and the lower part of the Serpulit Member (OM6) of the Munder Formation in the Lower Saxony Basin (Anderson, 1985; Allen and Wimbledon, 1991; Elstner and Mutterlose, 1996; Arp and Mennerich, 2008; Schneider et al., 2018). This is indicated by the co-occurrence of the ostracods *Cypridea inversa* Martin, *C. tumescens praecursor* Oertli, *C. binodosa binodosa* Martin and others. In central Poland (Dziadzio et al., 2004), ostracod zones E, D and C were correlated with the English Lower Berriasian *C. dunkeri* Zone. The upper part of the "Purbeckian"-type deposits in NW Poland which consists of ostracod zones B and A seems to be equivalent to the upper part of the Serpulit Member (OM6) in the Lower Saxony Basin and perhaps the lower Middle Purbeck of the Lulworth Formation in Dorset. However, due to the different nature of the ostracod fauna, this correlation is difficult to establish. In central Poland, ostracod zone B is correlated with the English *Cypridea granulosa* Zone of the Middle Berriasian, while ostracod zone A was distinguished in the lower part of the Upper Berriasian and was correlated with the English *Cypridea vidrana* Zone (Dziadzio et al., 2004). In the marine deposits with ammonites above strata of the "Purbeckian" sequences, ostracods of the *Protocythere propria emslandensis* Zone were recorded. This ostracod zone is known in the Upper Berriasian (Ryazanian) in central Poland (Dziadzio et al., 2004) in the marine deposits with ammonites of the genera *Riasanites* and *Surites* and in the Lower Valanginian of the Tomaszów Syncline (Kubiatowicz, 1983).

Two informal stratigraphic units have been distinguished in the Berriasian in the central part of the basin: "beds with *Riasanites*, *Himalayites* and *Picteticeras*" and "beds with *Surites*, *Euthymiceras* and *Neocosmoceras*" (Marek, 1964, 1968, 1969, 1977, 1984, 1997; Marek and Raczyńska, 1973, 1979; Marek and Shulgina, 1996). The lower unit is supposed to correspond to the Tethyan *occitanica* and lower *boissieri* zones, and the English *kochi* and *icenii* zones, whereas the upper is the equivalent of the Tethyan upper *boissieri* Zone and the English *stenomphalus* and *albidum* zones (Marek et al., 1989; Marek and Shulgina, 1996; Marek, 1997). Berriasian ammonites are rare and poorly preserved in the study area, due to which the taxonomic assignment of certain specimens is problematic. Baraboshkin (1999) questioned the determination of *Riasanites rjasanensis* (Nikitin) from Poland. However, comparative studies of collections of *Riasanites* specimens have revealed occurrence of *Riasanites rjasanensis* (Nikitin) in central Poland (*Riasanites* sp. nov. in Mitta and Ploch, 2012: Kcynia IG 2 – borehole, depth 273.8 m, Muz. PIG 1652.II.21; Chrośna borehole, depth 167.2–167.5 m, Muz. PIG 1652.II.33). *Riasanites swistowianus* (Nikitin) has also been recognized (Bądków 7/17 borehole, depth 209.0–215.0 m, Muz. PIG 1652.II.35; Chrośna borehole, depth 167.2–167.5 m, Muz. PIG 1652.II.32), suggesting connections with the Russian Basin of the *Riasanites swistowianus* Subzone (*Riasanites rjasanensis* Zone) earlier than hitherto considered for the *Surites spasskensis* Subzone (*Riasanites rjasanensis* Zone) (Sasonova, 1977). *Riasanites swistowianus* (Nikitin) has been found outside of the Russian and Polish basins mainly in the Mangyslak region, which may suggest a direct connection between the Russian and Polish basins (Mitta and Ploch, 2012). In the Northern Tethys, *Riasanites* cf. *swistowianus* (Nikitin) has been figured from the famous Stramberk succession (Vašíček and Skupien, 2016: fig. 7B, C; Vašíček et al., 2017: fig. 6D, E), and may have migrated there from the Polish Basin. Thus, revision of Polish material supports the concept of a direct connection between the Boreal and Tethyan basins through the Polish Trough since the earliest Ryazanian. Detailed revision of *Surites* may allow determination of other Ryazanian zones.

The entire Berriasian ammonite assemblage has not yet been revised; nevertheless, its Mediterranean character with periodical influence from the Russian Platform is clear (Mitta and Ploch, 2012). Assignment of the Mediterranean specimens from the Polish Basin is questionable, as indicated by information acquired from the French researcher Camille Frau (2017); accordingly, the existing assignments of Tethyan forms are incorrect because it is not possible to allocate such poorly preserved specimens to any species. Due to the fragmentary character and poor preservation of the specimens, it is not possible to confirm the presence of both informal units in the study area. The ammonite specimens obviously document the Ryazanian.

The basal part of the Lower Cretaceous, developed in marine facies both in the Tethyan and Boreal domains, is characterized by relatively low-diversity calcareous nannoplankton assemblages. In the Strzelno IG 1 borehole, in samples located above Upper Berriasian ammonites and ostracod zone A, an assemblage of calcareous nannoplankton indicative of the CC2 *Stradneria crenulata* (Thierstein, 1971; nom. corr. Perch-Nielsen, 1985) standard nannoplankton zone occurs (Fig. 4). It encompasses the uppermost Middle and Upper Berriasian and the lowermost Valanginian (Perch-Nielsen, 1985). Its index species *Retecapsa angustiforata* (formerly *Stradneria*) appears in the Tethyan domain in the lower part of the *occitanica* ammonite zone (lowermost Middle Berriasian), and in the Boreal domain as late as the uppermost Middle Berriasian (basal part of Upper Ryazanian; Bown et al., 1999). In the Polish Lowlands, as in the Boreal domain, this species occurs from the uppermost Middle Berriasian (basal part of Upper Ryazanian), as indicated by calcareous nannoplankton from the Gostynin IG 1 borehole (Dziadzio et al., 2004). In the Southern and Eastern Carpathians of Romania, this species is noted also in the upper part of the Middle Berriasian (Melinte and Mutterlose, 2001).

Assemblages of calcareous nannoplankton in the Kcynia IG 2 borehole allow recognition of the uppermost Ryazanian BC2 *Sollasites arcuatus* Boreal nannoplankton zone (Jakubowski, 1987), corresponding to the upper part of the CC2 *Stradneria crenulata* standard nannoplankton zone (Thierstein, 1971; Perch-Nielsen, 1985) distinguished in the Tethyan domain. Nannoplankton zone BC2 is correlated with the upper part of the Tethyan ammonite *boissieri* Zone (Fig. 4) and with the Boreal ammonite *albidum* Zone corresponding to the uppermost Ryazanian. In the Oświno IG 1 borehole, located in the Szczecin Trough, despite the presence of ammonites representing the genera *Himalayites*, *Surites* and possibly *Berriasella*, and indicating the Berriasian (in depth 1522–1536 m), calcareous nannoplankton were not observed, probably due to secondary decalcification of the deposits.

The Upper Berriasian ostracod, ammonite and nannoplankton assemblages document a stage of basin development when the coastline was clearly shifted landwards. The maximum flooding surface is determined at the Berriasian/Valanginian boundary, earlier described by Dziadzio et al. (2004) and may be allocyclic. It can be correlated with global changes in the sea level (Fig. 4 and Appendix 1).

The **Valanginian** to **Barremian** deposits include scarce microfossils and are mostly characterized by long-ranging foraminifera, mainly agglutinated taxa. In the study area, the biostratigraphy of the Valanginian to Barremian successions is based on comparison with the Lower Cretaceous deposits in central Poland where a detailed biostratigraphy has been established (Dziadzio et al., 2004).

Although more nannoplankton species appear from the beginning of the Late Valanginian, and this diversity continues upwards throughout the Early Cretaceous, calcareous nannoplankton have not been recorded in the overlying Lower Cretaceous succession in NW Poland. In the Pomeranian Trough (Człuchów IG 1 borehole), the lowermost Cretaceous is represented by shallow shoreface facies, including mainly coarse clastic deposits with large amounts of organic matter of terrestrial origin (Leszczyński and Waksmundzka, 2013). According to these authors, the sedimentary succession of the Valanginian and Hauterivian (Bodzanów and Włocławek formations) represents a deltaic setting. In this part of the basin, sedimentation was dominated by influx of terrigenous material from the Fennoscandian Shield (the Cassubian land – Marek, 1997), and thus there were no favourable conditions for the development of phytoplankton, particularly coccolithophores.

A first-order sequence boundary is determined in the lower part of the Upper Valanginian succession and refers to the flooding surface (FS) earlier described by Dziadzio et al. (2004), but its rank is difficult to determine.

The second sequence encompasses ~10 my and occurs between the sequence boundary (SB) in the lower part of the Upper Valanginian and the boundary marking the subsequent sequence in the lower part of the Aptian (or base of the Aptian), with a maximum flooding surface at the Hauterivian/Barremian boundary. The Valanginian/Hauterivian boundary is transgressive and is correlated with a global sea level rise on Haq's curve. The Lower/Upper Hauterivian boundary is interpreted as a maximum flooding surface (MFS) and is correlated with a global sea level fall. The Hauterivian/Barremian boundary is MFS-like and can be correlated very well with the global sea level rise. The **Barremian/Aptian and Albian?** boundary (interpreted as SB) does not correlate with a sea level rise determined on Haq's curve (Fig. 4).

The third sequence, as in the Warsaw and Lublin troughs, may encompass the **Aptian-Albian** interval (strongly reduced in the study area) and terminate with the sequence boundary at the base of the Turonian.

In the study area, **Aptian** deposits were documented in the Oświno IG 1 borehole at a depth of 1350.0 m in dark siltstones. Here a foraminiferal assemblage with *Blefuscuiana infracretacea* and *Praehedbergella* sp. was distinguished (Fig. 4). The index species *Blefuscuiana infracretacea* (Glaessner) points to the Aptian. Such an assemblage was described in the Białobrzegi IG 1 borehole (as an assemblage with *Hedbergella infracretacea*) from the Lower Aptian (Dziadzio et al., 2004) and also from the Lower Aptian of Germany in dark marls referred to as the Hedbergella marls (Rückheim and Muterllose, 2002).

In NW Poland where marine sedimentation during the Early Cretaceous was restricted to a narrow zone (Mid-Polish Trough), conditions favouring the development of planktonic organisms took place in the Late Albian. Marine transgression resulted in the appearance of planktonic organisms such as phytoplankton (including coccolithophores) and planktonic foraminifera. Assemblages of coccolithophores appear in marly siltstones and marls capping the siliciclastic series in the Chociwel IG 1 (depth 2305.0–2323.0 m) and Oświno IG 1 (depth 1285.0–1287.0 m) boreholes. Their taxonomic composition allows for determination of the CC9 *Eiffellithus turriseiffeli* standard nannoplankton zone or the Boreal UC1-2 zone. The CC9 zone encompasses the **uppermost Albian** and the **Lower Cenomanian**. The British UC1-2 zone covers a narrower interval, i.e., the Lower Cenomanian corresponding to the *mantelli* and *dixoni* zones. Strata corresponding to the CC9 zone in the Chociwel IG 1 and Oświno IG 1 boreholes, besides *Eiffellithus turriseiffeli* (Deflandre) from the uppermost Albian, contain the species *Corollithion kennedyi* Crux and *Gartnerago segmentatum* (Stover), which appear for the first time in the Lower Cenomanian. Therefore, the sedimentary succession discussed should refer to the Lower Cenomanian and not to the Albian as previously considered Jaskowiak-Schoenaichowa (1977).

## TETHYAN *VERSUS* BOREAL TAXA

The Lower Cretaceous succession of NW Poland yields calcareous nannoplankton assemblages containing a large number of species characteristic of the Tethyan domain. They include *Lithraphidites*, *Rhagodiscus*, *Tranolithus* and *Watznaueria* (Thierstein, 1973; Wagreich, 1992). The thermophilic species *Watznaueria barnesiae* (Black) is a dominating element of all samples from the Lower Cenomanian (Chociwel IG 1 and Oświno IG 1 boreholes). It is accompanied by forms with lower (ecological) thermal requirements and species typical of the Boreal domain: *Eiffellithus turriseiffeli* (Deflandre) and *Prediscosphaera cretacea* (Arkhangelsky). However, Boreal taxa are less abundant than Tethyan taxa. Thermophilic species commonly occur also in the Upper Berriasian (Strzelno IG 1 and Kcynia IG 1 boreholes). The presence of abundant and taxonomically diverse nannoplankton assemblages, as well as their composition in the Upper Berriasian, Upper Albian and Cenomanian, points to possible warmer episodes in the climate of the Early Cretaceous. Also, the Berriasian ammonite assemblages contain a number of genera characteristic of the Tethyan domain though of uncertain identity due to their poor preservation. The ammonite fauna from the central Russia indicates Boreal influences and the same mixed character of Berriasian assemblages. The abundant occurrence of Tethyan species in the Polish epicontinental basin points to its opening towards the Tethys Ocean, as well as palaeocurrent directions which shifted water masses from the south to the north, transporting these planktonic organisms.

## GLOBAL SEA LEVEL CHANGES IN THE LOWER CRETACEOUS: LOCAL *VERSUS* GLOBAL CYCLICITY

In the study area, located in the NE part of the Mid-Polish Trough (excluding the Gostynin IG 4 and Człuchów IG 1 boreholes, see the location map, Fig. 1), a number of chronostratigraphic boundaries were determined, relating to sequence boundaries (SB), flooding boundaries and transgression surfaces, significant for determining the development of the Polish Basin in the Early Cretaceous. Figures 4 and Appendix 1 clearly show that some of the boundaries are regional and with high probability they can be associated with global sea level changes and may be allocyclic, but most boundaries are likely mixed, both allocyclic and autocyclic. The Tithonian/Berriasian boundary is marked by geophysical logs showing SB features which coincides with the appearance of ostracods of the ostracod E zone. It can be related to the global sea level fall determined on Haq's curve. Another boundary found in most of the boreholes relates to the Lower/Middle Berriasian boundary. It is determined by a flooding surface (FS) that correlates with a global sea level fall on Haq's curve, which may suggest its local character. It may also be the boundary coincident with a SB. The Middle/Upper Berriasian boundary is SB-like, but is at a global sea level maximum on Haq's curve. The maximum fall of the global sea level on Haq's curve occurs slightly earlier (in the upper part of the Middle Berriasian), thus it may be caused by autogenous factors. In the Upper Berriasian, additional sequence boundaries, flooding surfaces or even transgressive surfaces can be determined, but they cannot be widely traced, occurring locally in the Strzelno IG 1 and Oświno IG 1 boreholes. Changes corresponding to the global sea level fluctuations are shown in Figure 4. The Berriasian/Valanginian boundary corresponding to Haq's curve is determined by a MFS. The Lower/Upper Valanginian boundary in the interpretation shown refers to a flooding surface but its rank is difficult to determine. Based on Haq's curve, this interval may be interpreted as a global sea level fall, but within this process sea level may change many times by minor amounts. Therefore, it can be inferred that there is a consistency in the record overlapping by autogenous processes. The Valanginian/Hauterivian boundary in the study area is a transgressive one and is correlated with a global sea level rise on Haq's curve. It is preceded by a locally distinguished sequence boundary (e.g., in the Gostynin IG 4 and Strzelno IG 1 boreholes). The Lower/Upper Hauterivian boundary is interpreted as a MFS. This boundary is correlated with the global sea level fall determined at that time. The local succession between the Valanginian/Hauterivian and Lower/Upper Hauterivian in the Strzelno IG 1 borehole is thicker, and minor boundaries were marked there (cf. Appendix 1), which are absent in other boreholes (Choszczno IG 1, Chociwel IG 1), or have a significantly reduced thickness (e.g., Szczecin IG 1, Człuchów IG 1), which indicates very local changes in the development of deposits of this age range. The Hauterivian/Barremian boundary is MFS-like and correlates very well with a global sea level rise on Haq's curve. Importantly, in the Choszczno IG 1, Chociwel IG 1 boreholes there is a lack of Hauterivian and Barremian deposits, and in the Gostynin IG 4, Szczecin IG 1, Człuchów IG 1 boreholes their thickness is significantly reduced. The boundary of the Barremian/Aptian/Albian? is interpreted as a SB, which significantly differs from the interpretation in Haq's curve, as it is located at the point where the maximum depth of the basin occurs. Such a situation may be related to inaccuracies of the research as well as to the autogenous processes that delayed it compared to the global sea level rise. The Aptian/Albian (?)strata have a significant thickness in the Gostynin IG 4 and Strzelno IG 1 boreholes, but were not determinated in the Choszczno IG 1, Chociwel IG 1 boreholes, and have reduced thickness in the Oświno IG 1, Szczecin IG 1 and Człuchów IG 1 boreholes. Based on the borehole data, it is not possible to determine changes of global sea level (distinction of deposit sequences) in the Aptian deposits. Haq's curve shows significantly fluctuating global sea level changes, which are difficult to interpret, for example, in the Gostynin IG 4 and Strzelno IG 1 boreholes, despite the large thickness of these deposits. Therefore, the phenomena we described in the central part of the Polish Basin may not show a similar development across the entire area. The large variations in thickness and stratigraphy, even between closely located boreholes, may indicate a significant influence of local tectonics in this part of the Early Cretaceous sedimentary basin.

## CONCLUSIONS

The material analysed shows a cyclicity of sedimentation similar to that seen in depositional sequences of the central and

SE Polish Lowlands, described previously by the present authors. In the succession studied, third-order sequences, superordinate cycles, and probably second-order sequences can be distinguished.

The lower part of the succession studied, which consist of the Purbeckian-type facies (Strzelno IG 1 and Oświno IG 1 boreholes), can be dated only by means of ostracods (ostracod zones F to A) as uppermost Tithonian (ostracod zone F) to the lower part of the Upper Berriasian (ostracod zones E to A). The uppermost Tithonian deposits (ostracod zone F) are equivalents of the lowermost part of the Lulworth Formation in Dorset and the upper part of the OM4 (Munder Formation) in the Lower Saxony Basin. Deposits with ostracod zones E, D and C correspond to the pre-Middle Purbeck in Dorset and also to the Katzberg Member (OM5) and the lower part of the Serpulit Member (OM6) of the Munder Formation in the Lower Saxony Basin. The upper part of the Purbeck-type deposits in NW Poland, which includes ostracod zones B and A, seems to be the equivalent of the upper part of the Serpulit Member (OM6) in the Lower Saxony Basin and possibly the lower Middle Purbeck of the Lulworth Formation in Dorset.

In the Berriasian, two informal stratigraphic units distinguished in the central part of the Polish Basin: "beds with *Riasanites*, *Himalayites* and *Picteticeras*" (*occitanica* and lower *boissieri* zones) and "beds with *Surites*, *Euthymiceras* and *Neocosmoceras*" (upper *boissieri* Zone) have also been found in NW Poland. *Riasanites swistowianus* (Nikitin) indicates the basal part of the *Riasanites rjasanensis* Zone and suggests an earlier than hitherto considered connection with the Russian Basin. Calcareous nannoplankton assemblages allow recognition only of individual nannoplankton zones. The CC2 *Stradneria crenulata* standard nannoplankton zone encompassing the uppermost Middle and Upper Berriasian and lowermost Valanginian was distinguished. The index species *Retecapsa angustiforata* (formerly *Stradneria*) appears in the Tethys domain in the *occitanica* ammonite zone (lowermost Middle Berriasian).

The Upper Berriasian assemblages of ostracod, ammonite and nannoplankton also document a transgressive systems tract visible in the sequences. A maximum flooding surface is determined at the Berriasian/Valanginian boundary.

A first-order sequence boundary was determined in the lower part of the Upper Valanginian succession. A second sequence occurs between the sequence boundary in the lower part of the Upper Valanginian and the boundary marking the subsequent sequence in the lower part of the Aptian (or base of the Aptian), with a maximum flooding surface at the Hauterivian/Barremian boundary.

A third sequence may encompass the Aptian-Albian interval and terminate with the sequence boundary at the base of the Turonian.

The CC9 *Eiffellithus turriseiffeli* standard nannoplankton zone and the Boreal UC1-2 zone, encompassing the uppermost Albian and Lower Cenomanian, have been determined. Because the intervals analysed also yield forms found only in the Lower Cenomanian, therefore strata previously assigned to the Albian are considered to represent the Lower Cenomanian.

In the study area, global changes in sea level are only partly recognized. For the Lower Cretaceous deposits, only the following boundaries may be allocyclic and can be correlated with the global changes in the sea level: the Tithonian/Berriasian boundary (SB boundary type), the Berriasian/Valanginian (MFS boundary type), the Lower/Upper Valanginian boundary (with low correlation), the Lower/Upper Hauterivian boundary (interpreted as a MFS); the Hauterivian/Barremian boundary (MFS boundary type) correlates very well with Haq's sea level curve; the Barremian/Aptian-Albian? boundary (interpreted as a SB) does not correlate with the sea level rise determined on Haq's curve. The remaining boundaries are most likely autogenic and are probably related to block tectonic activity controlling both sedimentation and erosion, hence the facies and thickness differentiation of the successions studied.

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