Geological Quarterly, Vol. 41, No. 4, 1997, p. 521–532

PROJEKT KBN PBZ 02-03

The Upper Cretaceous carbonate-dominated sequences of the Polish Lowlands

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(Received: 09.10.1997)

Four depositional systems have been distinguished basing on borehole data in the Late Cretaceous sedimentary basin of the Polish Lowlands: (1) pelagic carbonates system containing (a) limestone-opoka facies and (b) chalk facies, (2) pelagic clastics system, (3) siliciclastic shelf system, and (4) submarine fan system. The material collected from the Polish Lowlands and its interpretation was subsequently compared with the data from the marginal parts of the Late Cretaceous basin. All the data derived from both boreholes and outcrops have been compiled and the correlation of trends and geological events occurring in various areas of the basin gives a more complete picture of the Late Cretaceous sedimentary cyclicity. As a result of these investigations, two major cycles (K3 and K4) have been recognized. They are related to panregional tectonic events. Nine lower-order sedimentary cycles have been distinguished within them. Since the Early Palaeocene sedimentation is intimately connected with the Late Cretaceous basin, it has been necessary to include the youngest, Early Palaeocene cycle (Pc-I) terminating the Zechstein–Mesozoic evolution of the basin.

INTRODUCTION

Depositional systems and sedimentary cyclicity in the Late Cretaceous epicontinental sedimentary basin of the Polish Lowlands (Fig. 1) have been analysed on the basis of borehole data (cores, well logs) with additional information derived from outcrops in marginal parts of the basin. Out of hundreds of boreholes drilled over the territory of Poland, 6 boreholes have been selected and examined in detail (as exemplified in Fig. 2). They are most representative, relatively well cored and with good quality wireline log record (including gamma ray, neutron-gamma ray, resistivity, SP and, in a few cases, sonic log curves). Six of them are displayed in a correlation scheme (Fig. 3). Schematic diagram showing the succession of depositional systems, relationships between them and the transgressive-regressive cycles is also shown in Figure 4. The map constructed by M. Jaskowiak-Schoeneichowa and A. Krassowska (1988, modified by K. Leszczyński) shows the reconstructed primary (not decompacted) thickness of the Upper Cretaceous deposits and their maximum extent during the Turonian (Fig. 1).

It must be emphasized that the area dealt with in this paper is restricted to the Polish Lowlands and does not comprise the whole Late Cretaceous basin of Poland. Therefore, the depositional systems described hereto do not exhaust the full range of sedimentary environments represented within all Late Cretaceous sedimentary sequences. The studies conducted within the limits of this project do not embrace the areas such as the Sudetes and Central Polish Uplands from where deltaic, flysch and other sedimentary environments have been reported (e.g. J. Milewicz, 1973; S. Radwański, 1968, 1973).

In order to reconstruct the Upper Cretaceous cyclicity, the material collected from many boreholes drilled over the Polish Lowlands and then interpreted, was subsequently compared with the data from the marginal parts of the Late Cretaceous basin (S. Alexandrowicz, 1969; S. Cieśliński, 1976; M. Hakenberg, 1969, 1978; I. Heller, W. Moryc, 1984; M. Machalski, I. Walaszczyk, 1987; R. Marcinowski, 1974, 1980, 1996; R. Marcinowski, A. Radwański, 1983, 1989; J. Rutkowski, 1965; I. Walaszczyk, 1987, 1992). The analysis of its central parts does not bring enough information on transgressive-regressive cycles because of monotonous lithofacies of the Upper Cretaceous sequences in the central zones with gradual transitions from one rock type into another owing to a long distance from land areas and, most frequently, very low influence of shoreline shifts upon pelagic sedimentation.

Much attention has been paid to the occurrence of erosional surfaces, gaps, hardgrounds and phosphatic horizons. All the data derived from both boreholes and outcrops have

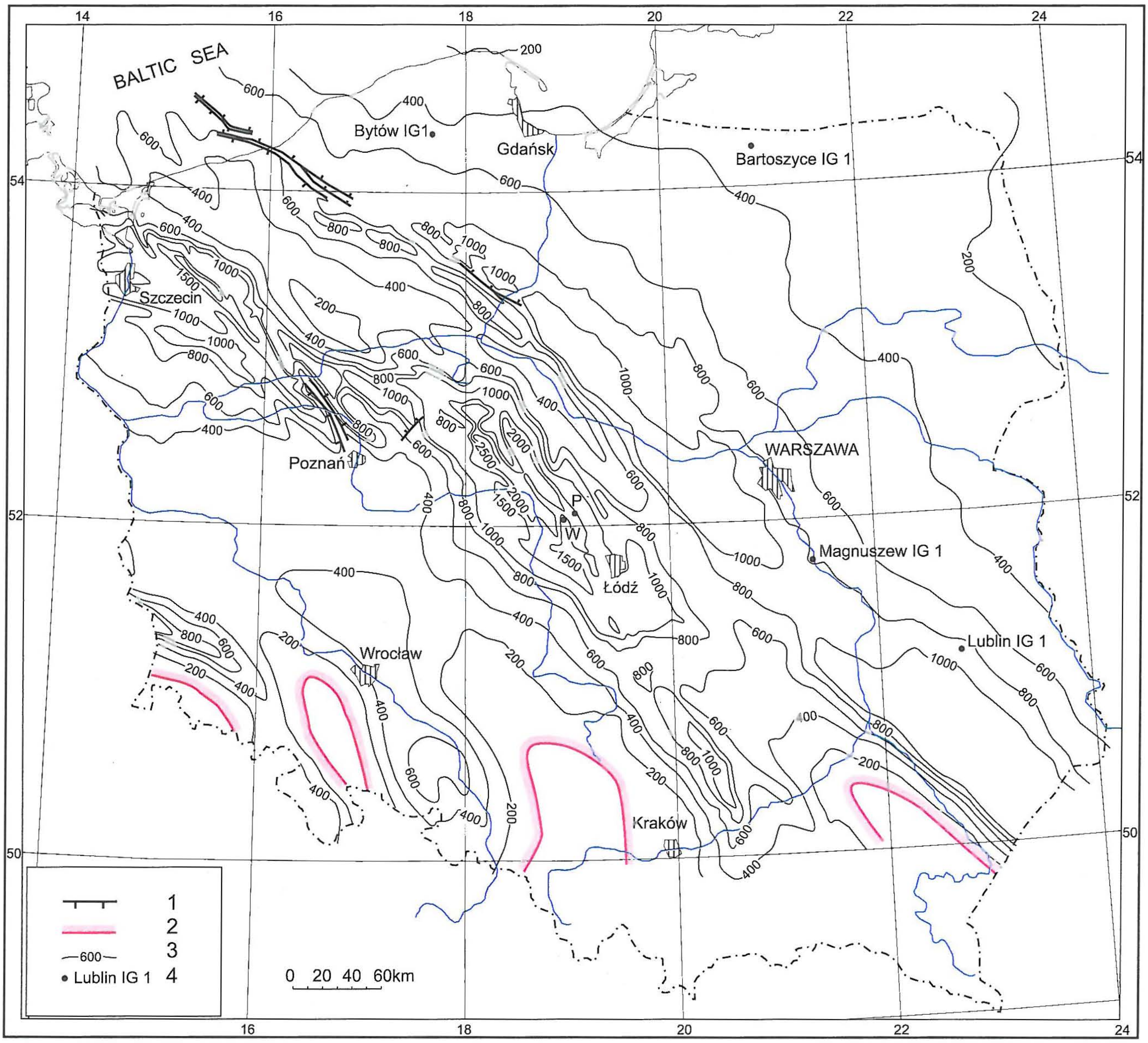

Fig. 1. Basinal framework of the Upper Cretaceous (including the Upper Albian) after M. Jaskowiak-Schoeneichowa and A. Krassowska (1988) modified by K. Leszczyński

1 — synsedimentary faults, 2 — maximum extent of basin (Turonian) (K3-IV), 3 — reconstructed primary isopachs, 4 — interpreted borehole sections (P — Poddębice PIG 2, W — Wartkowice 1)

Mapa paleotektoniczna kredy górnej (z albem górnym) według M. Jaskowiak-Schoeneichowej i A. Krassowskiej (1988) uzupełniona przez K. Leszczyńskiego

1 — uskoki synsedymentacyjne, 2 — maksymalny zasięg basenu (w turonie) (K3-IV), 3 — paleoizopachyty, 4 — interpretowane profile otworów wiertniczych (objaśnienia symboli patrz tekst angielski)

been compiled and the correlation of trends and geological events occurring in various areas gives a more complete picture of the sedimentary cyclicity in the Upper Cretaceous sequences. It must be stressed, however, that regional differences in a tectonic régime may have resulted in some deviations in the evolution of various parts of this basin.

PALAEOTECTONIC BACKGROUND

The reconstructed primary thickness distribution of the Upper Cretaceous deposits indicates that there was a zone of lower subsidence stretching SE–NW along the former Mid-Polish Trough (Fig. 1). Its formation started during the Late Turonian (M. Jaskowiak-Schoeneichowa, 1981; M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988; A. Krassowska,

1997) giving rise to the development of two troughs extending on both sides of this zone: the Szczecin–Mogilno–Uniejów–Nida Trough and Pomeranian–Płock–Lublin Trough. They showed much stronger and differentiated subsidence than the central belt at that time. The latter marked the initial stages of the Mid-Polish Swell regional uplift. In the Mogilno region the primary thickness of the Upper Cretaceous deposits could even exceed 2600 m (Wilczyn–Ślesin Depression). The central zone displayed a high mobility related to the synsedimentary growth of salt structures and activity of synsedimentary faults. Those processes resulted in a series of horsts, half-horsts, elevations and domes which came into existence during the Late Cretaceous tectonic evolution. They were accompanied by half-grabens and depressions of stronger subsidence. Outside the Szczecin–Mogilno–Uniejów–Nida Trough and Pomeranian–Płock–Lublin Trough, tectonically quiescent and low subsidence areas occurred (e.g. the Gorzów Block, stable cratonic areas of north-east Poland).

The maximum extent of the Late Cretaceous basin was during the Early and Middle Turonian (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988; A. Krassowska, 1997) (Fig. 1). Only in the southernmost parts there were persistent land areas.

STRATIGRAPHY

Giving a precise age to each Upper Cretaceous cycle boundary in borehole sections meets some difficulties. The frequency of ammonite, inoceramid and belemnite fossils in cores is usually poor. Foraminifera assemblages, although very useful for borehole stratigraphy (E. Gawor-Biedowa, 1984, 1997), only approximate the age of individual sequences. Only in fully cored boreholes, the subdivision into stages and, in some cases, sub-stages was possible. However, there is frequently little evidence for cyclicity in many of palaeontologically well documented boreholes (monotonous lithology, lack of lithological and stratigraphical marker horizons). The biostratigraphical subdivision of the Upper Cretaceous sequence, used in this paper (Tab. 1), is adopted from A. Błaszkiewicz (1997). It is supplemented (for the Turonian and Santonian) with I. Walaszczyk's (1992) studies for the Polish Uplands. Comprehensive nannoplankton investigations are still lacking for deep boreholes from the Polish Lowlands. They would certainly supply a lot of important stratigraphical data.

In view of scarcity of biostratigraphical data, a lithological-stratigraphical subdivision based upon both well log analysis and palaeontological data is commonly used. M. Jaskowiak-Schoeneichowa (1977, 1981) and A. Krassowska (1981, 1986) distinguished well log complexes for the Szczecin Trough and for the Lublin region respectively. It appears that such complexes may be regarded as chronohorizons and applied for stratigraphical purposes. However, they cannot be correlated with eustatic transgressive-regressive cycles because, particularly in the central parts of the basin, they are related rather to regional tectonic events of the Late Cretaceous inversion phase. Moreover, the uniform Upper Cretaceous lithological column and gradual transitions from one rock type into another, often make the correlations between different regions difficult.

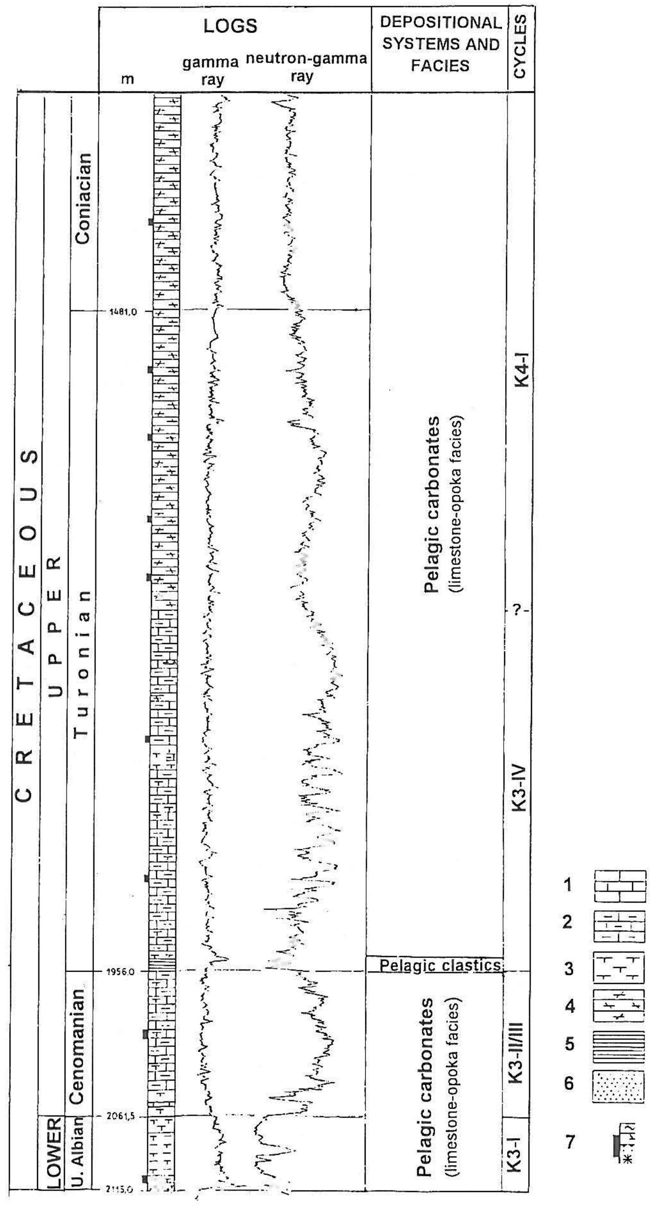

Fig. 2. Upper Albian through Turonian section in borehole Poddębice PIG 2
1 — limestones, 2 — marly limestones, 3 — marls, 4 — opokas, 5 — marly claystones, 6 — sandstones, 7 — cores

Profil albu górnego-turonu w otworze Poddębice PIG 2
1 — wapienie, 2 — wapienie margliste, 3 — margle, 4 — opoki, 5 — iłowce margliste, 6 — piaskowce, 7 — odcinki rdzeniowane

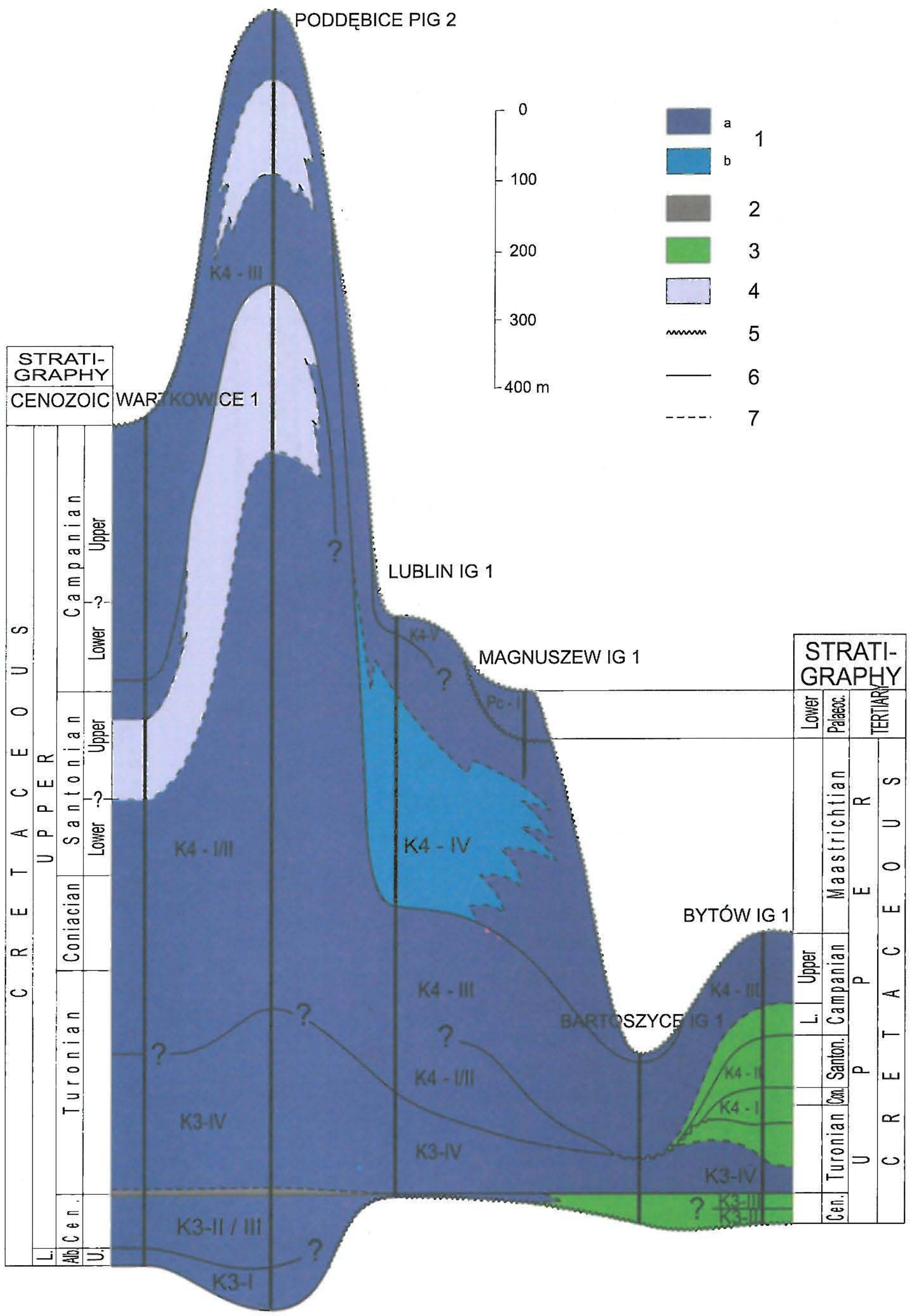

Fig. 3. Correlation of depositional systems and transgressive-regressive cycles between selected boreholes in the Upper Cretaceous sequences of Central Poland

1 — pelagic carbonates system (a — limestone-opoka facies, b — chalk facies); 2 — pelagic clastics system; 3 — siliciclastic shelf system; 4 — submarine fan system; 5 — erosional surfaces; 6 — boundaries between transgressive-regressive cycles; 7 — boundaries between depositional systems; other explanations see Fig. 2

Korelacja systemów depozycyjnych i cykli transgresywno-regresywnych górnej kredy centralnej Polski w wybranych otworach wiertniczych

1 — system węglanów pelagicznych (a — facje wapienno-opokowe, b — facje kredy piszącej); 2 — system klastyków pelagicznych; 3 — system szelfu silikoklastycznego; 4 — system podmorskich stożków piaszczystych; 5 — powierzchnie erozyjne; 6 — granice cykli transgresywno-regresywnych; 7 — granice systemów depozycyjnych; pozostałe objaśnienia patrz fig. 2

DEPOSITIONAL SYSTEMS

The following depositional systems have been recognized in the Upper Cretaceous: (1) pelagic carbonates system (containing limestone-opoka facies and chalk facies), (2) pelagic clastics system, (3) siliciclastic shelf system, and (4) submarine fan system.

PELAGIC CARBONATES SYSTEM

This system is associated with the great worldwide Late Cretaceous marine transgression. It occupies vast areas of the Polish Lowlands and, in many borehole sections of the central zone, is the only one distinguishable (Figs. 3, 4). Two main types of facies can be recognized within this system. These are (a) limestone-opoka facies and (b) chalk facies.

The limestone-opoka facies are chiefly represented by grey limestones (mudstones, skeletal wackestones, rarely packstones) and occur from the Late Albian through Maastrichtian. Marls and opokas (passing basinwards from sandy and silty to more clayey) were deposited in tectonically more active and differentially subsiding zones. Opokas became particularly predominant from the Late Turonian onwards.

Tectonically quiescent zones were the areas of chalk sedimentation represented by white pure chalk and marly chalk. These are located on both east and west extremes of the territory of Poland and are characterized by the occurrence of hardgrounds. Chalk facies have been recorded from the Turonian through Maastrichtian.

All the rock types commonly contain cherts and flints and frequently show silification. Parallel horizontal and flaser lamination is common.

Pelagic carbonates are rich in both macro- and microfossils. Most abundant are inoceramids, belemnites, sponges, brachiopods, ammonites, foraminifers and radiolarians. Echinoderms, corals, gastropods, bryozoans and others have also been reported. Calcareous nannoplankton is common particularly in chalk facies. Ichnofossils such as *Planolites*, *Thalassinoides*, *Ophiomorpha* and *Chondrites* have been noted from these deposits. Pelagic carbonates were deposited in relatively deep waters of open-marine shelf environments, below the wave base at depths of up to 200 m and perhaps even 500 m (*Research on Cretaceous...*, 1986).

PELAGIC CLASTICS SYSTEM

Pelagic clastics occur at the base of the Turonian showing a pronounced well-log marker over vast areas. They are correlated with the *Inoceramus labiatus* Zone (M. Jaskowiak-Schoeneichowa, 1981; M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988) (Figs. 2, 3 and 4). They are represented by dark grey, frequently black, compact marly claystones commonly showing fissility. Thin lamination and pyrite concentrations can be observed in places. Foraminifers and radiolarians are the most important fossils but rare inoceramid specimens have also been found. These sediments contain 5–46% of $CaCO_3$. Pelagic marly claystones were deposited during a short period of decreased carbonate productivity in similar water depth to that assumed for pelagic carbonates. They occur as a unit of up to several tens of metres in thickness.

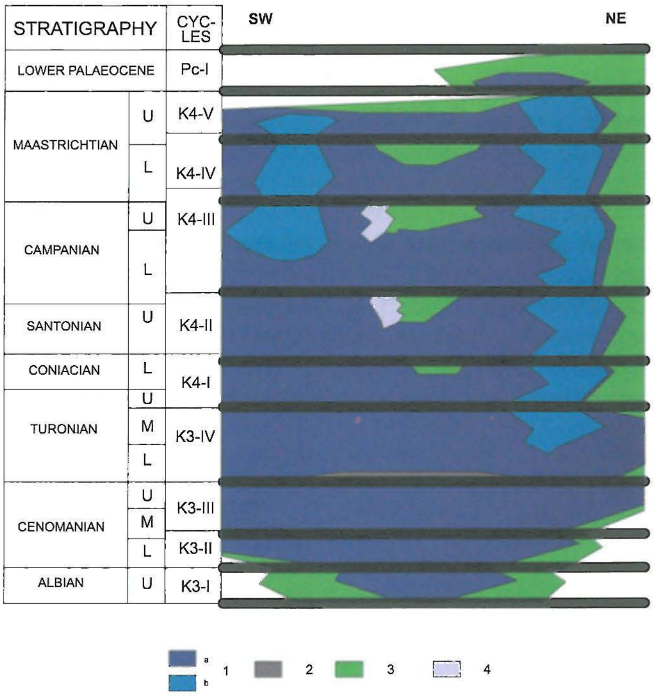

Fig. 4. Schematic diagram showing the succession of the Upper Cretaceous depositional systems and cyclicity along the line perpendicular to the basin depocenter

1 — pelagic carbonates system (a — limestone-opoka facies, b — chalk facies); 2 — pelagic clastics system; 3 — siliciclastic shelf system; 4 — submarine fan system

Schematyczny przekrój obrazujący następstwo systemów depozycyjnych w górnej kredzie wzdłuż linii prostopadłej do osi basenu

1 — system węglanów pelagicznych (a — facje wapienno-opokowe, b — facje kredy piszącej); 2 — system klastyków pelagicznych; 3 — system szelfu silikoklastycznego; 4 — system podmorskich stożków piaszczystych

SILICICLASTIC SHELF SYSTEM

This system is represented by clastic, usually calcareous rocks. These are grey very fine- to coarse-grained marly sandstones, siltstones and claystones. The carbonate content increases basinwards. All rock types contain glauconite (most abundant in sandstones) and phosphatic horizons. Fossils are mainly represented by inoceramids and foraminifers. Bioturbation is locally well developed. These deposits were accumulated in a shallow near-shore sub-littoral zone, mostly above the wave base. Siliciclastic shelf depositional system occupies a narrow belt fringing land areas and parts of the former Mid-Polish Trough in northwestern Poland which was uplifted above the wave base or even sea-level in the Santonian, Campanian and Maastrichtian (M. Jaskowiak-Schoeneichowa, 1981) (Figs. 3, 4). This system is best developed over a large area of the Pomeranian Trough and the Peribaltic Syneclise (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988). It comprises there a large part or the whole lithological column of the Upper Cretaceous sequence and is most common from the Turonian onwards.

SUBMARINE FAN SYSTEM

This system is represented by sandstones with graded bedding commonly occurring. The sediments usually contain no fossils but occasionally foraminifers have been found. The sandstones gradually pass upwards into sandy opokas, marls, siltstones and claystones with glauconite and further up into opokas and marls with typical pelagic features. Such sediments were deposited in the central parts of the Santonian and Campanian basin (Figs. 3, 4), near strongly active salt structure zones (e.g. near the Kłodawa and Damasławek diapirs, Mogilno–Łódź Trough). They are typical fan-shaped bodies formed by gravity flows and related to the increased morphological gradients at rapidly growing salt structures. Such strong halokinetic movements occurred during the first phase of the Late Cretaceous tectonic inversion (J. Sokołowski, 1966; R. Dadlez, S. Marek, 1997). Some areas of the Mid-Polish Swell, uplifted above the wave base or even sea-level, were undergoing erosion. The earlier deposited Upper and especially Lower Cretaceous rocks (first of all the sandstones of the Mogilno Formation) may have been the source of clastic sediments transported into deeper parts of basin to form submarine fans. This system is genetically strictly connected with siliciclastic shelf system interpreted to have locally occurred in the central zone (Fig. 4).

THE TRANSGRESSIVE-REGRESSIVE CYCLES

Two major transgressive-regressive cycles (K3 and K4) with lower-order minor cycles have been recognized in the Upper Cretaceous (Tab. 1). Since the Lower Palaeocene sedimentation which took place north-east of the line Kołobrzeg –Bydgoszcz–Rawa Mazowiecka–Biłgoraj was intimately connected with the demise of the Late Cretaceous basin, it has been necessary to include here the youngest, Lower Palaeocene cycle (Pc-I) terminating the Zechstein–Mesozoic evolution of the basin.

Cycle K3 begins with the great Late Albian transgression and is characterized by a rapidly and successively expanding sea area with relatively slow subsidence and a general transgressive trend from the Late Albian until Middle Turonian. Limestones are the most common rocks within these sequences.

Cycle K4 displays generally regressive trend with much stronger subsidence, and is largely controlled by the Late Cretaceous inversion processes. Opokas are predominant rocks in this cycle over vast areas of the Polish Lowlands.

Analysing the Upper Cretaceous rocks it is sometimes difficult to distinguish individual transgressive-regressive cycles in borehole sections located in the central parts of the Late Cretaceous basin due to:

— monotonous lithology (poor lithologic variability) with gradual transitions from one rock type into another owing to a long distance from land areas and, most frequently, very low influence of shoreline shifts upon pelagic sedimentation;

— significant role of regional tectonic events, including salt tectonics, related to the Late Cretaceous inversion;

— relatively poor coring (insufficient lithological and stratigraphical data).

In order to recognize the Upper Cretaceous cyclicity, some published information derived from outcrops in the marginal parts has been considered (S. Alexandrowicz, 1969; S. Cieśliński, 1976; M. Hakenberg, 1978; M. Machalski, I. Walaszczyk, 1987; R. Marcinowski, 1974, 1996; R. Marcinowski, A. Radwański, 1983, 1989; J. Rutkowski, 1965; I. Walaszczyk, 1987, 1992) and compared with borehole data from its central part (M. Jaskowiak-Schoeneichowa, 1979, 1981; M. Jaskowiak-Schoeneichowa, A. Krassowska, 1983; A. Krassowska, 1986). A particular attention has been paid to the occurrence of sedimentary and stratigraphic gaps, phosphatic horizons and hardgrounds which may have been related to sea-level changes (W. J. Kennedy, R. E. Garrison, 1975; J. M. Hancock, 1989; R. Marcinowski, 1996). In the Upper Cretaceous deposits of Poland, phosphatic horizons and hardgrounds have been observed in outcrops from the Upper Albian through uppermost Coniacian. They are correlated with regressive pulses and occur: in the middle Upper Albian, middle Middle Cenomanian, at the boundary between the *lamarcki* and *costellatus* Zones (Turonian) and in the uppermost Coniacian (I. Walaszczyk, 1987; R. Marcinowski, 1996).

The transgressive-regressive cycles recognized in the Polish Lowlands fairly well correspond with the Late Cretaceous sea-level curve compiled by J. M. Hancock (1989) in the British region with particularly distinct transgressive events of the early Late Albian, early Early Cenomanian, late Middle Cenomanian, Early Turonian and Late Turonian as well as strongly pronounced regressive events during the early Middle Cenomanian, earliest Turonian and Middle/Late Turonian (Fig. 5.).

K3-I — LATE ALBIAN

The transgressive phase of this cycle is distinctly marked over vast areas of the Polish Lowlands by the occurrence of glauconitic marly sandstones commonly with phosphatic nodules. They form a thin layer not exceeding a few metres in thickness (in central zones not more than 1 m) which yields belemnites such as *Neohibolites ultimus* (d'Orbigny), *N. minimus* (Miller) and *Parahibolites tourtiae* Weigner (S. Marek, M. Rajska, 1997). The basin was expanding as evidenced by a rapid vertical change from sandy to marly sedimentation with limestone intercalations at the top. Due to such a quick transgression, the only depositional system to be distinguished in the central zones, are the open-marine pelagic carbonates represented by limestone-opoka facies (Figs. 3, 4). Marginal zones are occupied by sandstones of siliciclastic shelf system. The upper boundary of this cycle is marked by hardgrounds and gaps which have been observed at the top of the Upper Albian deposits in the vicinity of Annopol-on-Vistula (S. Cieśliński, 1976; I. Walaszczyk, 1987), as well as by coarse-grained and conglomeratic facies occurring at the Upper Albian/Cenomanian boundary in the Nida Trough (M. Hakenberg, 1969, 1978) and Polish Jura (R. Marcinowski, 1974). In the central areas of the basin a very well pronounced lithological change from marls to limestones is regarded as the stratigraphical boundary between the Upper Albian and Cenomanian (documented by a number of fossils — M. Jaskowiak-Schoeneichowa, 1979, 1981; M. Jaskowiak-Schoeneichowa, A. Krassowska, 1983) and at the same time, the boundary between the cycles K3-I and K3-II.

K3-II — EARLY CENOMANIAN + EARLY MIDDLE CENOMANIAN AND K3-III — LATE MIDDLE CENOMANIAN + LATE CENOMANIAN

Sharp boundary between marls and limestones may suggest a further rapid expansion of the sea and the beginning of cycle K3-II. Its extent overstepped that of the previous one. Pelagic carbonates became widespread and occupied broad areas (Figs. 3, 4). In the narrow marginal parts they were replaced by shallow siliciclastic shelf system. Cycles K3-II and K3-III are separable in marginal parts of the basin. Within the Annopol-on-Vistula section hardgrounds are recorded at the top of the Lower-Middle Cenomanian sandy glauconitic marls with rapid increase in planktic foraminifers marking a sharp sea-level rise (I. Walaszczyk, 1987). The stratigraphic gap is thought to comprise there the *Acanthoceras jukesbrownei* Zone of the late Middle Cenomanian (R. Marcinowski, 1980). Over the large central parts of the Cenomanian basin, cycle K3-II together with cycle K3-III are represented by a single undifferentiated lithological complex of highly calcareous limestones. Only in the clastic shelf area (borehole Bytów IG 1, Fig. 3) two cycles are distinguishable in the Cenomanian sequence with a phosphatic horizon in its middle part which can probably be correlated with the Middle Cenomanian regressive pulse. However, no reliable palaeontological data have been obtained so far.

Specimens of the ammonite *Mantelliceras hyatti* Spath, characteristic of the *Mantelliceras mantelli* Zone have been found within deposits corresponding to the cycle K3-II. Bivalves such as *Inoceramus crippsi* Mantell, *I. scalprum* Boehm, *I. bohemicus* Leonhard, *I. virgatus* Schlüter and *I. pictus* Sowerby have been reported from the deposits correlated with cycle K3-III. Their stratigraphical ranges fall within the upper part of the Cenomanian corresponding to the *Acanthoceras rhotomagense* and *Calycoceras naviculare* Zones (A. Błaszkiewicz, 1997). At the Cenomanian/Turonian boundary in the Szczecin Trough and Gorzów Block as well as in north-east Poland, hardgrounds have been noted (M. Jaskowiak-Schoeneichowa, 1979, 1981). From the Annopol-on-Vistula section, discontinuity surfaces frequently expressed by hardgrounds or an omission surface are known (S. Cieśliński, 1976; I. Walaszczyk, 1987, 1992). The above-mentioned events may be correlated with another regressive phase and the beginning of the cycle K3-IV.

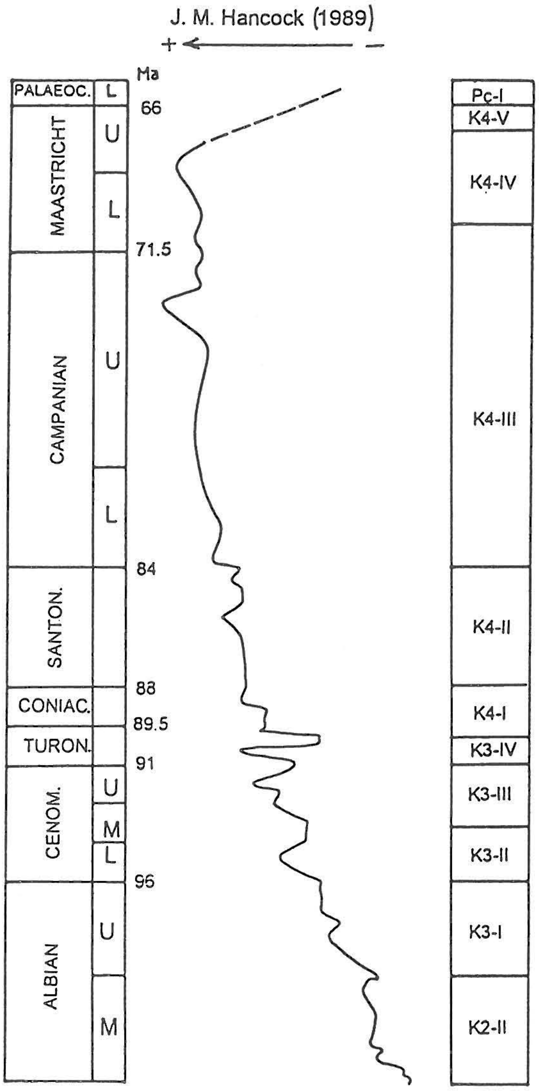

Fig. 5. Late Cretaceous transgressive-regressive cycles in Central Poland compared with sea-level changes in the British region (after J. M. Hancock, 1989)

Porównanie górnokredowych cykli transgresywno-regresywnych Polski centralnej ze zmianami poziomu morza na Wyspach Brytyjskich (według J. M. Hancocka, 1989)

K3-IV — EARLY AND MIDDLE TURONIAN

This cycle is characterized by successively increasing subsidence and the sea-level rise. The Late Cretaceous basin reached its maximum extent (Fig. 1) and its sediments overstepped all the older ones (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988). Almost the whole studied area is occupied by pelagic carbonates system with clastic deposits along its margins (Figs. 3, 4). Along with limestone-opoka facies, chalk sedimentation also appeared in eastern Poland. A complex of dark marly claystones (up to a few tens of metres thick)

Table 1

Subdivision of the Upper Cretaceous (including the Upper Albian and Lower Palaeocene) and sedimentary cyclicity in Central Poland

Chronostratigraphy		Cephalopod and bivalve zones		Transgressive-regressive cycles
Stage	Sub-stage	A. Błaszkiewicz (1997)	I. Walaszczyk (1992)	
Palaeocene	Lower			Pc-I
Maastrichtian	Upper	*Hoploscaphites constrictus crassus*		K4-V
		Belemnitella junior		K4-IV
	Lower	*Belemnella sumensis*		
		Belemnella lanceolata		K4-III
Campanian	Upper	*Nostoceras pozaryskii*		
		Didymoceras donezianum		
		Bostrychoceras polyplocum		
		Neancyloceras phaleratum		
	Lower	*Gonioteuthis quadrata*		
		Gonioteuthis granulataquadrata	*Sphenoceramus patootensiformis*	K4-II
Santonian	Upper	*Gonioteuthis granulata*	*Sphenoceramus pinniformis*	
	Middle	*Inoceramus cardissoides*	*Sphenoceramus cardissoides*	
	Lower			
Coniacian	Upper	*Inoceramus involutus*	*Megadiceramus subquadratus*	K4-I
			Volviceramus involutus	
	Middle		*Cremnoceramus crassus*	
			Cremnoceramus deformis	
	Lower		*Cremnoceramus brongniarti*	
			Cremnoceramus walterdorfensis	
Turonian	Upper	*Inoceramus schloenbachi*	*Mytiloides incertus*	
		Inoceramus costellatus	*Inoceramus costellatus*	
	Middle	*Inoceramus lamarcki*	*Inoceramus lamarcki*	K3-IV
			Inoceramus apicalis	
		Inoceramus labiatus	*Mytiloides hercynicus*	
	Lower		*Mytiloides labiatus*	
			Mytiloides kossmati	
Cenomanian	Upper	*Calycoceras naviculare*	*Mytiloides hattini*	K3-III
	Middle	*Acanthoceras rhotomagense*		K3-II
	Lower	*Mantelliceras mantelli*		
Albian	Upper	*Stoliczkaia dispar*		K3-I

representing pelagic clastics system occurs at the bottom of the Turonian over a vast area (Figs. 2, 3 and 4). Symptoms of shallowing, in the form of sedimentary and stratigraphical gaps or hardgrounds as well as the increasing content of clastic material in sediments, are visible in many borehole sections within the upper part of cycle K3-IV. This may be due to both the first phase of tectonic inversion in the axial part of the basin and the Late Turonian eustatic sea-level fall (J. M. Hancock, 1989; R. Marcinowski, 1996). Cycle K3-IV is characterized by the occurrence of *Inoceramus labiatus* Schlotheim and *I. lamarcki* Parkinson.

K4-I — LATE TURONIAN + CONIACIAN AND K4-II — SANTONIAN + EARLIEST EARLY CAMPANIAN

These two cycles are usually inseparable in the Polish Lowlands. They have been, however, recognized in the Miechów region (J. Rutkowski, 1965) and in the Polish Jura (R. Marcinowski, 1974; I. Walaszczyk, 1992). Pelagic carbonates are still predominant (Figs. 3, 4). In the clastic shelf area (borehole Bytów IG 1 — northern Poland, Fig. 3), the K4-I/K4-II boundary is marked by the appearance of medium- and coarse-grained sandstones with glauconite. In the central zones, the regressive phase of the cycle K4-II is marked by the increase in terrigenous material supply in the uppermost Santonian and lowermost Campanian deposits. Combination of the intensified uplift movements of the first phase of tectonic inversion in the central parts of the Late Cretaceous basin and the eustatic sea-level fall in the whole area at those times resulted both in the appearance of submarine fan system and the spreading of siliciclastic shelf deposits (Figs. 3, 4). Clastic deposits may have also be formed in the central parts of the basin as early as during the regressive stage of the cycle K4-I (Fig. 4). Upper Turonian rocks of cycle K4-I yield *Inoceramus costellatus* Woods and *I. schloenbachi* Böhm — index species in the Turonian zonation (A. Błaszkiewicz, 1997). Coniacian deposits are characterized by the occurrence of *I. involutus* Sowerby and *I. digitatus* Sowerby. The deposits correlated with the cycle K4-II are documented by *I. cardissoides* Goldfuss, *I. pachti* Arkhangelsky, *I. pinniformis* Willett, *I. patootensiformis* Seitz, *Gonioteuthis granulata* (Blainville) and the index taxon of the *Gonioteuthis granulataquadrata* Zone (lowermost Campanian). The K4-II/K4-III boundary can possibly be drawn between the *granulataquadrata* and *quadrata* Zones (A. Błaszkiewicz, 1997).

K4-III — LATE EARLY CAMPANIAN + LATE CAMPANIAN (?+ EARLIEST EARLY MAASTRICHTIAN)

Another considerable regression and the influx of terrigenous material into the basin took place during the Late Campanian (end of cycle K4-III). J. Rutkowski (1965) distinguished a sedimentary cycle in the Miechów region comprising the Late Campanian and earliest Maastrichtian. In the central zones, submarine fan system developed again (Figs. 3, 4). Close to the Campanian/Maastrichtian boundary, gaps and hardgrounds occur in the Płock Trough (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1983). These events may correspond to the Late Campanian and earliest Maastrichtian regressive phase. The reconstructed extent of this basin is apparently smaller compared with the previous one. Much of the Fore-Sudetic Monocline as far as the Cracow region was the land area (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988). Cycle K4-III is documented among others by ammonites *Bostrychoceras polyplocum* (Roemer), *Nostoceras pozaryskii* Błaszkiewicz and belemnites *Gonioteuthis quadrata* (Blainville), *Belemnitella mucronata* (Schlotheim). The K4-III/K4-IV boundary seems to run within the lowermost part of the Maastrichtian *Belemnella lanceolata* Zone.

K4-IV — EARLY MAASTRICHTIAN + EARLY LATE MAASTRICHTIAN

This cycle is characterized by the development of siliciclastic shelf system over much areas on one hand, and the limitation of pelagic sedimentation mainly to the western and eastern parts of Poland, on the other (Figs. 3, 4). The basin exhibits high mobility and therefore there are some areas where its extent slightly oversteps those of the older ones. The maximum extent of the basin was probably at the end of the early Late Maastrichtian (A. Krassowska, 1997). The presence of a sedimentary cycle comprising the upper part of the Lower Maastrichtian sequence was evidenced by J. Rutkowski (1965) in the Miechów region. In the Lublin region, cycle K4-IV is correlated by A. Krassowska (1986) with well log complex VA-C (based upon resistivity, gamma ray and SP logs), and terminates with hardgrounds recorded in the Late Maastrichtian in the vicinity of Kazimierz-on-Vistula (M. Machalski, I. Walaszczyk, 1987) and in the Lublin area (A. Krassowska, 1986). Cycle K4-IV is characterized by the following fossils: *Belemnella lanceolata* (Schlotheim), *B.* cf. *occidentalis* Birkelund, *Hoploscaphites constrictus constrictus* (Sowerby) and *H. tenuistriatus* (Kner). The K4-IV/K4-V boundary probably runs within the *Hoploscaphites constrictus crassus* Zone because the index species has been noted from both K4-IV and K4-V deposits (Lublin region, A. Krassowska, 1986).

K4-V — LATEST LATE MAASTRICHTIAN

In southeastern Poland (Lublin area) this cycle is correlated by A. Krassowska (1986) with well-log complex VD comprising the uppermost Maastrichtian. Its upper boundary is marked by sedimentary gaps, intraformational erosional surfaces and hardgrounds. Cycle K4-V is best recognizable only in the Lublin region (Fig. 3 — borehole Lublin IG 1) due to strong erosion which affected most of the Polish Lowlands area. Therefore, it is very difficult to estimate the extent of this basin and the distribution of depositional systems at that time. Of important fossils, some specimens of *Hoploscaphites constrictus crassus* (Łopuski) have been found within the deposits of cycle K4-V.

Pc-I — EARLY PALAEOCENE

After a considerable structural and facies reconstruction of the whole Late Cretaceous basin during the maximum inversion phase at the turn of the Cretaceous and Tertiary, the Early Palaeocene basin occupied only the northeastern part of the Polish Lowlands (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988). Strong influx of terrigenous material and the development of siliciclastic shelf system resulted from the increasing land areas. Pelagic sedimentation was confined to the axial parts which moved north-east to the Płock Trough at that time (M. Jaskowiak-Schoeneichowa, A. Krassowska, 1988) (Fig. 4). Facies analysis indicates further development of clastic shelf facies and the restriction of pelagic sedimentation area. The Lower Palaeocene deposits have been distinguished basing upon foraminifera investigations (E. Gawor-Biedowa, arch. materials) of which *Anomalina minor* Pożaryska et Szczechura, *Cibicidoides proprius* Brotzen and *C. succedens* (Brotzen) are important among others. Over the whole area, the upper boundary of this cycle is erosional.

CONCLUSIONS

1. The vast majority of the Lower Cretaceous deposits in the Polish Lowlands is represented by pelagic carbonates depositional system (containing limestone-opoka facies and chalk facies) which, in many borehole sections of the Polish Lowlands, is the only one recognizable. Pelagic clastics, siliciclastic shelf, and submarine fan systems have also been recognized.

2. After a maximum expansion of the basin during the Early and Middle Turonian, a considerable drop in sea-level and a change in tectonic régime took place.

3. Two major cycles related to panregional tectonic events (K3 and K4) composed of nine lower-order sedimentary ones have been distinguished. Since the Lower Palaeocene sedimentation is intimately connected with the Late Cretaceous basin, it has been necessary to describe the youngest, Lower Palaeocene cycle (Pc-I) terminating the Zechstein–Mesozoic evolution of the basin in the course of the terminal phases of its inversion. Boundaries between the cycles are determined by erosional surfaces, gaps, hardgrounds and phosphatic horizons.

4. Cycle K3 begins with the great Late Albian transgression and is characterized by a rapidly and successively expanding sea area with relatively slow subsidence and a general transgressive trend from the Late Albian until Middle Turonian.

5. Cycle K4 displays generally regressive trend with much stronger subsidence, and is largely controlled by the Late Cretaceous inversion processes. Opokas are predominant rocks in this cycle over vast areas of the Polish Lowlands.

6. Several transgressive-regressive events can be correlated with their counterparts in Western Europe: the early Late Albian, early Early Cenomanian, late Middle Cenomanian, Early Turonian, Late Turonian and Early Campanian transgressive phases as well as strongly pronounced regressive events during the early Middle Cenomanian, earliest Turonian and Middle/Late Turonian

Translated by the Author

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GÓRNOKREDOWE SEKWENCJE DEPOZYCYJNE NA NIŻU POLSKIM

Streszczenie

Analiza systemów depozycyjnych, cykliczności i rytmu sedymentacji w basenie kredy górnej Niżu Polskiego została oparta głównie na danych z otworów wiertniczych (rdzenie wiertnicze, kompleksowa analiza, interpretacja i korelacja geofizyki otworowej). Spośród dużej liczby wierceń do analizy systemów depozycyjnych i wydzielenia cykli transgresywno-regresywnych wybrano 6 otworów najbardziej reprezentatywnych, stosunkowo dobrze rdzeniowanych i z czytelnym zapisem geofizyki wiertniczej. Wykonano korelację otworową w celu przedstawienia położenia systemów depozycyjnych i ich wzajemnych relacji (fig. 3). Cykliczność i sukcesja systemów depozycyjnych zobrazowane zostały na syntetycznym przekroju schematycznym (fig. 4). Zasięg maksymalny basenu górnokredowego w turonie (cykl K3-IV) i paleomiąższość osadów górnej kredy przedstawiono na mapie (fig. 1).

Obok danych wiertniczych z Niżu Polskiego przeanalizowano materiał z szeregu prac dotyczących w dużej mierze stref marginalnych basenu. To pozwoliło na całościowe zestawienie i korelację trendów i zjawisk geologicznych ujawniających się w różnych częściach basenu, dając pełniejszy obraz rozwoju cykliczności w górnej kredzie. Regionalna specyfika reżimu tektonicznego często powoduje jednak odstępstwa od ogólnych tendencji w basenie.

Próbę wydzielenia cykli transgresywno-regresywnych podjęto uwzględniając występowanie powierzchni erozyjnych, luk sedymentacyjnych i stratygraficznych, twardych den oraz horyzontów fosforytowych mogących mieć związek ze względnymi wahaniami poziomu wód.

Wyróżniono cztery systemy depozycyjne: (1) węglanów pelagicznych morza otwartego (obejmujący facje wapienno-opokowe oraz facje kredy piszącej), (2) klastyków pelagicznych, (3) szelfu silikoklastycznego i (4) podmorskich stożków piaszczystych. Pozwoliło to sprecyzować cykliczność sedymentacji w basenie górnokredowym. Wyodrębniono dwa cykle wyższego rzędu: K3 zaczynający się transgresją w albie górnym i K4 związany z rejestrowanym globalnie spadkiem poziomu mórz w późnym turonie, zmianą reżimu tektonicznego w basenie i znacznym rozprzestrzenieniem opok. W obrębie tych dwóch cykli wyróżniono 9 cykli niższego rzędu oraz ostatni cykl kończący kredową ewolucję basenu i obejmujący paleocen dolny. Cykl K3 wykazuje ogólnie transgresywny trend z maksimum w dolnym i środkowym turonie i słabą jeszcze subsydencją. W cyklu K4 ogólny trend zmienia się na regresywny, a subsydencja znacznie wzrasta.