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Possibility of sequence stratigraphic subdivision of the Zechstein in the Polish Basin

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Applying the Exxon method for sequence distinction, four depositional sequences can be distinguished in the Polish Zechstein, out of which the first commenced during the deposition of the upper portion of the Rotliegend and the fourth continued up to the lower portion of the Buntsandstein. In our opinion the Exxon approach is not a significant step in understanding the principles controlling the Zechstein basin evolution during the deposition of carbonate and evaporite-dominated, lower and middle parts of the Zechstein. The fourth depositional sequence commences with evaporite deposits of LST, but afterwards a general change of sedimentary regime occurred and the uppermost part of the Zechstein is dominated by terrigenous-evaporite lithofacies. Because it is not possible to distinguish typical depositional sequences in the Zechstein terrigenous-evaporite lithofacies, it was decided to distinguish climatic sequences. Despite of fundamental differences between the origin of climatic and eustatic sequences, they have an important common feature; their boundaries are isochronous.

INTRODUCTION

The Zechstein is a specific megafacies developed in the latest Permian during its last 5–7 Ma. The Zechstein sediments originated in a shallow, vast epicontinental marine basin extending over Central Europe. This basin had a very reduced connection with the Upper Permian open sea which occupied the site of the present Barents Sea. Connection was through a narrow strait between Greenland and the Scandinavian Peninsula in their palaeogeographic position. This over 1000 km long strait was formed due to tectonic activity of the Greenland–Norwegian Sea rift. The isolation of the Zechstein basin was accentuated by the existence of a possible barrier in the Viking Graben the mobility of which could have been responsible for periodical interruptions in connection with the Upper Permian sea.

The majority of the Zechstein sediments were formed during transgressive-regressive carbonate-evaporitic cycles embracing cyclothems from PZ1 to PZ3, and the uppermost Zechstein cyclothems from PZ4a to PZ4e — during terrigenous-evaporitic climatic cycles reflecting climatic changes from humid to arid.

Factors directly responsible for the existence of transgressive-regressive cycles are not well known. Questions whether they are related to the eustatic movements of the Late Permian ocean or rather to the local activity of the barrier in the Viking Graben yet await convincing answers. Considering the isolation of the Zechstein basin, only the most intensive transgressive impulses could assumingly be related to global eustatics whereas lower order oscillations could have been due to local factors.

Proposing a new sequence stratigraphy for the Polish Zechstein Basin the present authors discuss the possibility of replacing or complementing the traditional cyclothem approach. In search of convincing arguments and solutions of the existing problems we have benefited from the experience of our predecessors from the English (M. E. Tucker, 1991) and German (C. Strohmenger *et al.*, 1996*b*; C. Strohmenger, C. Strauss, 1996) Basins. Therefore, in this paper the Exxon method has been adopted for the distinction of sequences. Special attention is focused on the upper part of the Zechstein, as it is just the Polish Basin where the most complete and best known sequence representing the decline of Zechstein deposition exists.

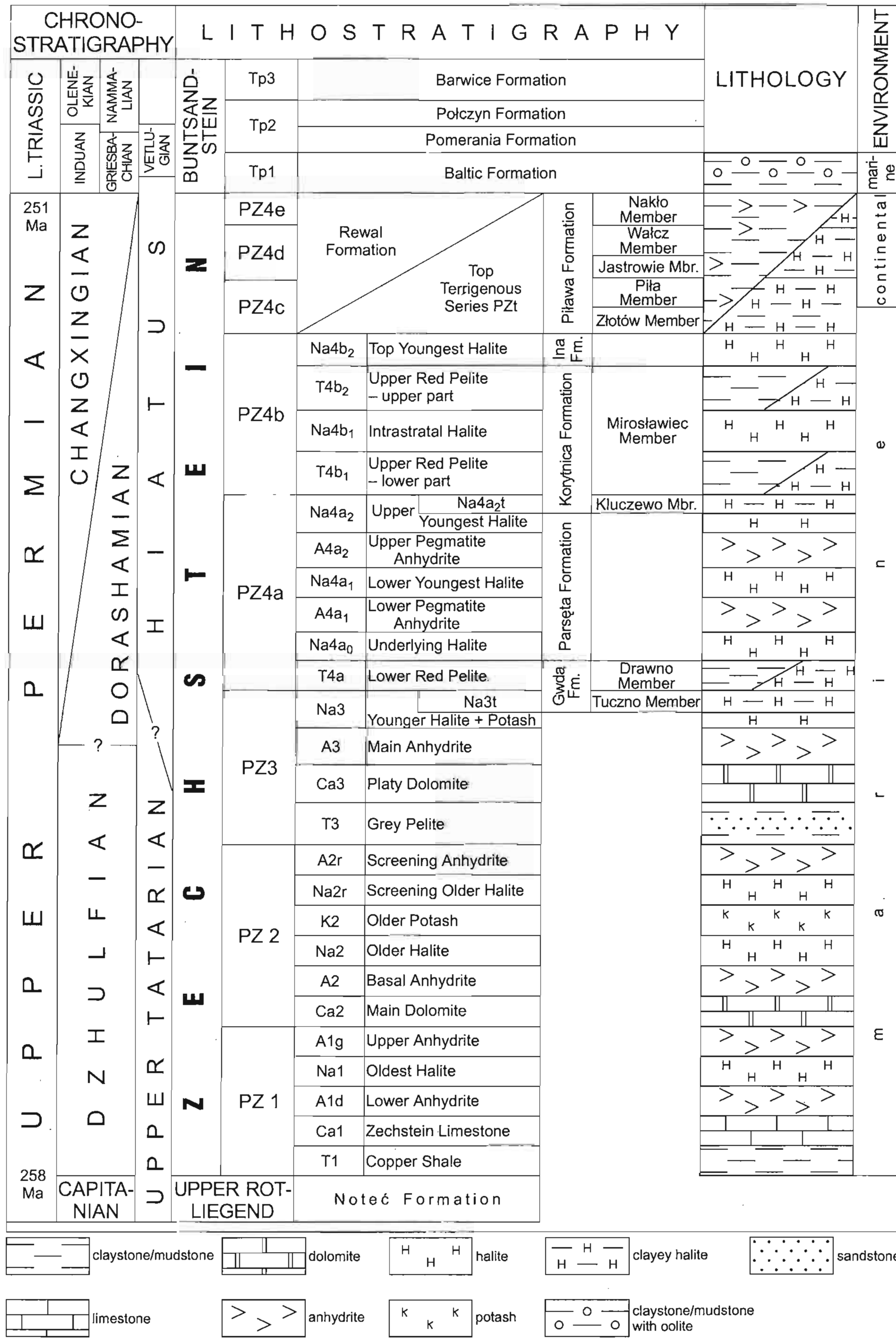


Fig. 1. Zechstein stratigraphy in the Polish Zechstein Basin

Stratygrafia cechsztynu w polskim basenie cechsztyńskim

Lithostratigraphy: Polish Basin (R. Wagner, 1994)						Sequences: Polish Basin (R. Wagner, T. M. Peryt, this paper)		German Basin (C. Strohmenger *et al.*, 1996*b*)	English Basin (M. E. Tucker, 1991)
Lower Buntsandstein Tpl			Baltic Formation			LST/TST		?	?
ZECHSTEIN / Zechstein 4			Rewal Formation/Top Terrigenous Series PZt			LST	PZS4-C 3 / PZS4-C 3.3	ZS 8	ZS 7
	PZ4e			Nakło Member	Piława Formation		PZS4-C 3.3		
	PZ4d			Wałcz Member			PZS4-C 3.2		
				Jastrowie Member					
	PZ4c			Piła Member			PZS4-C 3.1		
				Złotów Member					
	PZ4b	$Na4b_2$	Top Youngest Halite		Ina Fm.		PZS4-C 2		
		$T4b_2$	Upper Red Pelite – upper part	Mirosławiec Member	Korytnica Formation				
		$Na4b_1$	Intrastratal Halite						
		$T4b_1$	Upper Red Pelite – lower part						
	PZ4a	$Na4a_2t$	Upper Youngest Clay Halite	Kluczewo Member			PZS4-C 1		
		$Na4a_2$	Upper Youngest Halite		Parsęta Formation		PZS 4		
		$A4a_2$	Upper Pegmatite Anhydrite					?	
		$Na4a_1$	Lower Youngest Halite					ZS 7	
		$A4a_1$	Lower Pegmatite Anhydrite						ZS 6
		$Na4a_0$	Underlying Halite						
		T4a	Lower Red Pelite	Drawno Member	Gwda Formation				
Zechstein 3 PZ3		Na3t	Younger Clay Halite	Tuczno Member					ZS 5
		Na3 ‹K3›	Younger Halite (Younger Potash)					ZS 6	
		A3	Main Anhydrite						
		Ca3	Platy Dolomite			HST	PZS 3	ZS 5	ZS 4
		T3	Grey Pelite			mfs / TST			
Zechstein 2 PZ2		A2r	Screening Anhydrite						
		Na2r	Screening Older Halite						
		K2	Older Potash			LST			
		Na2	Older Halite					ZS 4	
		A2	Basal Anhydrite						
		Ca2	Main Dolomite			HST	PZS 2	ZS 3	ZS 3
Zechstein 1 PZ1		A1g ‹BrA1›	Upper Anhydrite / Anhydrite Breccia			mfs / TST			
		Na1	Oldest Halite			LST		ZS 2	
		A1d	Lower Anhydrite						
		Ca1	Zechstein Limestone			HST	PZS 1	ZS 1	ZS 2
		T1	Copper Shale			mfs / TST			ZS 1
		Zp1	Basal Conglomerate			LST/TST			

Fig. 2. Stratigraphy of the Polish Zechstein Basin comparing lithostratigraphy (Zechstein cyclothems PZ1 to PZ4) with Zechstein depositional sequences in Poland, Germany and England

LST — lowstand systems tract, TST — transgressive systems tract, HST — highstand systems tract, mfs — maximum flooding surface

Korelacja stratygrafii sekwencyjnej cechsztynu w basenach polskim, niemieckim i angielskim na tle litostratygrafii basenu polskiego

LST — ciąg systemowy niskiego stanu względnego poziomu morza, TST — ciąg transgresywny, HST — ciąg systemowy wysokiego stanu względnego poziomu morza, mfs — powierzchnia maksimum transgresji

TECTONIC, PALAEOGEOGRAPHIC AND CLIMATIC CONTROLS OF ZECHSTEIN SEDIMENTATION

The Polish Zechstein Basin was situated in the eastern part of the vast Central European Basin and constituted its natural closure. It was more than 1000 km away from the narrow strait in the Viking Graben (N part of the North Sea) through which intermittent connection existed with the Upper Permian open sea.

The Polish Zechstein Basin was flanked by three vast continents: the Scandinavian continent in the north, the vast peneplenized East European continent in the east and the morphologically diversified Caledonian and Variscan massifs in the south.

The main structural features of the Zechstein basin are older and were formed at the beginning of the Upper Rotliegend time when, after a long-lasting uplift and lack of sedimentation, subsidence commenced in the area of the future Upper Permian basin. Most probably this was thermal subsidence (P. A. Ziegler, 1990; R. Wagner, 1994) related to crustal extension (rifting) (R. Dadlez *et al.*, 1995). Thus, the factor chiefly responsible for the origin of the Upper Rotliegend basins was a tensional stress pattern which produced listric faults bordering the depositional basins. These processes, though with lesser intensity, continued into the Zechstein. The Zechstein sea transgression coincided in time with strong subsidence impulses as a result of which the sea transgressed the limits of the Upper Rotliegend basins.

The Zechstein sea invaded the Central European Permian continental basins most probably in the latest Permian (R. Wagner, 1994) i.e. in the lowermost Dzhulfian according to the stratigraphic division in the Tethys area or the upper portion of the Upper Tatarian in the Russian Platform (Fig. 1). The age of the Zechstein transgression precludes the relationship to major transgressive events of the Permian ocean because during this time regressive trends were predominant. The Zechstein transgression was most likely a local event caused by tectonic activity of the Greenland–Norwegian Sea rift and strong thermal subsidence impulses.

Several large tectonic units occur in the basement of the Polish Zechstein Basin. The northeastern part of the basin extended over a rigid Precambrian Craton and the southwestern part over mobile Palaeozoic–Caledonian and Variscan Platforms. The specific position of the Polish Basin with respect to both palaeogeography and tectonics significantly controlled the distribution of facies and thickness of the Zechstein sediments. It differed substantially from the other Zechstein basins, particularly from the German and English Basins (R. Wagner, 1994). Firstly, by the vastness of carbonate platforms — the up to 130 km wide Zechstein Limestone platform on the Precambrian Craton and the up to 150 km wide Main Dolomite on the Variscan Platform. Secondly, by the presence of halite throughout the PZ1 basin including its centre. Thirdly, by the occurrence of evaporites in the axial part of the depositional basin.

The thickness differentiation of the Zechstein sediments in the Polish Basin resulted from the mobility of the basement (R. Wagner *et al.*, 1980; R. Wagner, 1988, 1994). In the area of the Precambrian Craton the average subsidence was minor — 50 m/Ma approximately. The maximum subsidence i.e. about 300 m/Ma which was responsible for the formation of the depocentre in the Polish Zechstein Basin took place in a specific tectonic zone between the Teisseyre-Tornquist (T-T) fractures in the north-east and the Variscan front in the south-west. This enabled the deposition of a 1500 m thick evaporitic series and, as a consequence, the formation of Europe's most complete Zechstein sequence. The Variscan Platform was distinctive by a slightly weaker but very differentiated subsidence (from 80 to 160 m/Ma) depending on the geological structure of the Variscan orogen.

Zechstein deposition proceeded in a shallow intracontinental sea in an arid climate. With a reduced connection with the Upper Permian open sea, such climate permitted the deposition of thick evaporitic series in the three oldest cyclothems — PZ1, PZ2 and PZ3. These are carbonate-evaporitic cyclothems wide-spread throughout the Zechstein basin. They are distinctive by the presence of a carbonate horizon at the base of each cyclothem. Carbonates precipitated from seawater of normal, average salinity (Ca1) or of higher salinity (Ca2 and Ca3). In each cyclothem the carbonate horizons are overlain by evaporitic series indicative of progressive evaporation (R. Wagner, 1994).

The carbonate-evaporitic cyclothems originated in transgressive-regressive cycles of varying intensity and duration. The transgressive members were related to the supply of new sea-water. The most intensive inflows produced carbonates, the less intensive ones — carbonate-sulphate rocks. The regessive members originated at a significantly restricted inflow or a complete lack of new sea-water. Most anhydrites as well as halite and K-Mg salts were formed under such conditions. Terrigenous rocks are extremely scarce but their amount increases slightly in the marginal parts of the basin.

Such a course of deposition was possible under a stable and dry climate. Obviously the degree of aridity was variable and more arid periods (e.g. PZ2) alternated with less dry ones (e.g. PZ3). But generally speaking the climate was very dry.

At the close of the PZ3 cyclothem the climate changed substantially into more and more humid. In the latest Zechstein humid periods alternated with dry ones which, with the increasingly reduced connection with the Permian open sea, became the main factor responsible for the depositional cyclicity in the Zechstein basin. Most likely the break of connection between the Zechstein basin and the Late Permian open sea was due to the global regression in the latest Permian. There were distinct changes in the nature of Zechstein deposition. Carbonates disappeared completely and a new type of terrigenous-evaporitic cyclothems came into being. In humid periods terrigenous and terrigenous-saline sediments (the so-called zubers) originated whereas during arid periods evaporites, mainly rock salt, local K-Mg salt and minimum amounts of anhydrite were laid down. When connection with the open sea was disrupted in the lowermost part of the PZ4 subcyclothem (R. Wagner, 1987*a*, *b*, 1991; G. Czapowski, 1990), in the shrinking continental salt pan clayey-saline series were deposited in humid periods and clayey rock salt in the drier ones. Terrigenous sedimentation related to the fluvial environment prograded on the shores of the salt lake.

ZECHSTEIN SEQUENCE STRATIGRAPHY — REVIEW OF CONCEPTS

Traditionally the Zechstein Group is being divided into evaporitic cycles reflecting — in principle — progressive evaporation: at the base of a cycle occur sediments formed in a normal marine environment, followed by sediments indicative of increasing salinity thus reflecting both climatic changes and a more and more reduced connection between the Zechstein basin and the global ocean. Noteworthy is that the environmental changes within the individual Zechstein cycles were oscillatory in nature and resulted in the cyclicity (frequently of regional extent) of both carbonate and evaporitic deposition. Good examples are cycles recognized in the Zechstein Limestone (T. M. Peryt, 1984; T. M. Peryt, T. S. Piątkowski, 1976), in the Lower Anhydrite (G. Richter-Bernburg, 1985; J. C. M. Taylor, 1980) or in the Main Dolomite (T. M. Peryt, K. Dyjaczyński, 1991).

In 1991 M. E. Tucker suggested a new approach to Zechstein stratigraphy which he believed to provide a more balanced depositional image, as the concept of evaporitic cycles was based on changes in the central part of the basin, while the concept of sequence stratigraphy included the centre as well as the marginal parts of the basin. On the other hand, A. C. Kendall and G. M. Harwood (1996) pointed out that sequence stratigraphy can be safely applied to basin-marginal evaporites, as they constitute only a part of a larger facies mosaic and are affected by sea-level changes in somewhat similar ways to laterally contiguous sediment.

According to M. E. Tucker (1991) natural stratigraphic gaps occur at the base of evaporites and not at the base of carbonates (as assumed in the evaporitic cycles concept) and therefore carbonates are not naturally related to the overlying evaporites. In M. E. Tucker's opinion after a relative fall of the sea-level, the sequences commenced with evaporites formed as marginal lowstand gypsum wedges (e.g. Hartlepool Anhydrites, EZ1) or as basin center halite fills (Fordon Evaporites, EZ2). These evaporites grade upwards into carbonates deposited on shallow-water platforms surrounding the basin as transgressive and highstand systems tracts. Seven depositional sequences have been distinguished by M. E. Tucker (1991) in NE England and the adjoining North Sea area (Fig. 2).

I. G. Goodall *et al.* (1992) pointed out that the duration of the entire Zechstein (5–7 Ma according to M. Menning, 1995) lies within the extent of III order eustatic cycles (1–10 Ma) which would suggest that the sequences described by M. E. Tucker (1991) are in fact IV order sequences (*sensu* R. M. Mitchum, J. C. Van Wagoner, 1991). However, considering the period of 0.1–0.2 Ma for IV order cycles, it is evident that M. E. Tucker's seven sequences do not represent all potential eustatic cycles of the Zechstein deposition. I. G. Goodall *et al.* (1992) are of the opinion that the lower part of the Zechstein dominated by carbonates is related to a III order sea-level rise while the upper one (M. E. Tucker's sequences 5–7) originated during a III order fall. M. E. Tucker (1992) in turn noted that, considering the deposition rate of shallow-water carbonates (averaging 60 m/Ma — W. Schlager, 1981), the Zechstein carbonate formations would represent one million years or more each. Therefore the 4 sequences (ZS1–ZS4) distinguished previously (M. E. Tucker, 1991) should be related to III order sequences.

The three upper sequences described by M. E. Tucker (1991) — thin and evaporite-dominated — can be parasequences of one III order sequence (M. E. Tucker, 1992). The Zechstein sequence regarded as a whole — more carbonatic at the base and more evaporitic at the top — could according to M. E. Tucker (1992) have originated during II order sea-level rise and fall respectively.

On the basis of multidisciplinary studies of the Main Dolomite in particular and the surrounding evaporites of the southern margin of the German Zechstein Basin in the area of the Weser and Ems rivers, C. Strohmenger *et al.* (1996*a*) firstly divided this part of the Zechstein into sequences and parasequences. As, unlike M. E. Tucker (1991), C. Strohmenger *et al.* (1996*a*) did not authomatically correlate the evaporites with the lowstand systems tract (LST) and the carbonates with the transgressive systems tract (TST) and highstand systems tract (HST), their sequence stratigraphy differs in several important aspects from M. E. Tucker's (1991) proposal. Of substantial significance is the presence of LST sediments recognized in the upper portion of the Main Dolomite. Thus, like M. E. Tucker (1991) for the equivalents of the Zechstein Limestone in England, sequence boundaries were also placed within the carbonates (Main Dolomite). Of equal importance was the conclusion that the Z1 evaporites are chiefly TST sediments (and not LST as envisaged by M. E. Tucker, 1991). Later, C. Strohmenger *et al.* (1996*b*) presented a new division of the upper part of the Zechstein into stratigraphic sequences.

SEQUENCE STRATIGRAPHY OF THE POLISH ZECHSTEIN

There are several significant differences between the Polish Zechstein area and areas studied by the authors of the sequence concept and these differences entail a different way of looking at the Zechstein division. First and foremost the

PZ1 Upper Anhydrite is very distinctive and traceable throughout the Polish area. Secondly, the upper portion of the Zechstein is developed as evaporitic-terrigenous cycles. Thirdly, detailed studies of the evaporites permitted in some instances a precise correlation clarifying the relationship between evaporites classified into different stratigraphic units (T. M. Peryt, A. Kasprzyk, 1992; T. M. Peryt *et al.*, 1996*a*). And fourthly, the proposed division is based on results from the entire Polish Zechstein Basin thus enabling the distinction between local and regional factors.

Noteworthy is that the order of the distinguished stratigraphic sequences remains enigmatic. According to M. Menning (1995) the Zechstein represents the last 5–7 Ma of the Permian. During that time evaporites (Castille and Salado) being related to II order LST (Ochoan–Early Triassic supersequence) were laid down in the North American Permian Basin (M. Cecchi *et al.*, 1995). For this time interval not more than two (M. Cecchi, 1993) or three (C. A. Ross, J. R. P. Ross, 1987) III order sequences are being distinguished. Moreover, sea-level variations typical of III order cycles is 10–100 m (6–8 m for IV order cycles) and as sea-level changes of various orders overlap each other and, in addition, some of them are non-cyclic, these changes are in fact of different magnitude, different duration and different cyclicity. All this causes additional and serious difficulties in identifying the order of sea-level changes (C. A. Ross, J. R. P. Ross, 1995).

FIRST DEPOSITIONAL SEQUENCE PZS1

In the Polish part of the basin the Zechstein deposition commenced with overflooding of the Rotliegend desert basin as a result of subsidence caused by rifting combined with sea-level rise. This initial transgression of the Zechstein sea is evidenced by reworked Weissliegend sandstones and Zechstein conglomerates (Fig. 3).

TST sediments are represented by the Basal Limestone grained carbonates and Kupferschiefer. However, considering the low deposition rate of the Kupferschiefer the latter can be regarded as belonging to a condensed section. Also the major part of the Zechstein Limestone sediments — excluding the thin set of peritidal sediments occurring in the uppermost part of the Zechstein Limestone — is treated as HST. Maximum flooding surface (mfs) of the first sequence occurs in the lower part of the Zechstein Limestone.

Unlike in the English area where in many places the equivalents of the Zechstein Limestone are divided into two parts by the peritidal Hampole Beds, both in Poland (e.g. T. M. Peryt, 1984, 1989; W. Śliwiński, 1988; M. Magaritz, T. M. Peryt, 1994) and Germany (Ch. Pöhlig, 1986; J. Paul, 1991) in some part of the basin (the margin of the carbonate platform, the shoals in the basin centre) two (or more — W. Śliwiński, 1988) sets of peritidal layers appear within sediments representing a deeper depositional environment. There are two possible explanations of these evident sea-level changes: (1) we are in fact looking at two sequence boundaries, the peritidal sediments being LST sediments or (2) we are dealing with lower order sea-level changes. At the moment there is no convincing argument to solve this problem. Nevertheless, the present authors are in favour of the second possibility and believe that the alternating sub- and peritidal sediments correlated both on the marginal carbonate platform and in the shallower parts of the basinal zone (T. M. Peryt, 1986*a*) are indicative of IV order sequences within the first Zechstein sequence.

SECOND DEPOSITIONAL SEQUENCE PZS2

The second sequence commences with a thin (20–30 cm) layer of carbonate-sulphate laminites (T. M. Peryt, T. S. Piątkowski, 1977) followed by sulphates and subsequently by chlorides: halite and local potash salt. The Lower Anhydrite and the Oldest Halite are LST sediments. This is reflected in the evaporite facies pattern of the second sequence confined to the central — though very broad — basinal zone. In the peripheral part of the basin, on the margin of the carbonate platform a system of sulphate platforms and adjoining chloride basins developed showing a wide spectrum of mainly subaqueous facies (G. Czapowski, 1987; G. Czapowski *et al.*, 1993; T. M. Peryt, 1994). Evaporite deposition is distinctive by cyclicity controlled by changes of depth as well as salinity (T. M. Peryt *et al.*, 1992). Characteristic of the sulphate platforms slopes is the presence of turbidites, the source of detrital material being coeval to grass-like selenites building sulphate platforms (T. M. Peryt *et al.*, 1993; T. M. Peryt, 1994); in the deeper parts of the basin laminated anhydrites were laid down typical also of the central part of the basin (T. M. Peryt *et al.*, 1996*a*).

During evaporite deposition in the more central zone of the basin, the major part of the Zechstein Limestone platform rose above the water-level and was affected by karstification. At the close of the formation of the upper portion of the Oldest Halite also the sulphate platforms found themselves above the water-level. In the peripheral part of the basin the distinctive Anhydrite Breccia overlies the Zechstein Limestone sediments. This breccia is a TST sediment while the overlying massive anhydrites in the peripheral parts of the basin represent HST. It is with the massive anhydrites that mfs of the second sequence is connected. According to T. M. Peryt *et al.* (1996*a*), the lower portion of the Upper Anhydrite in the

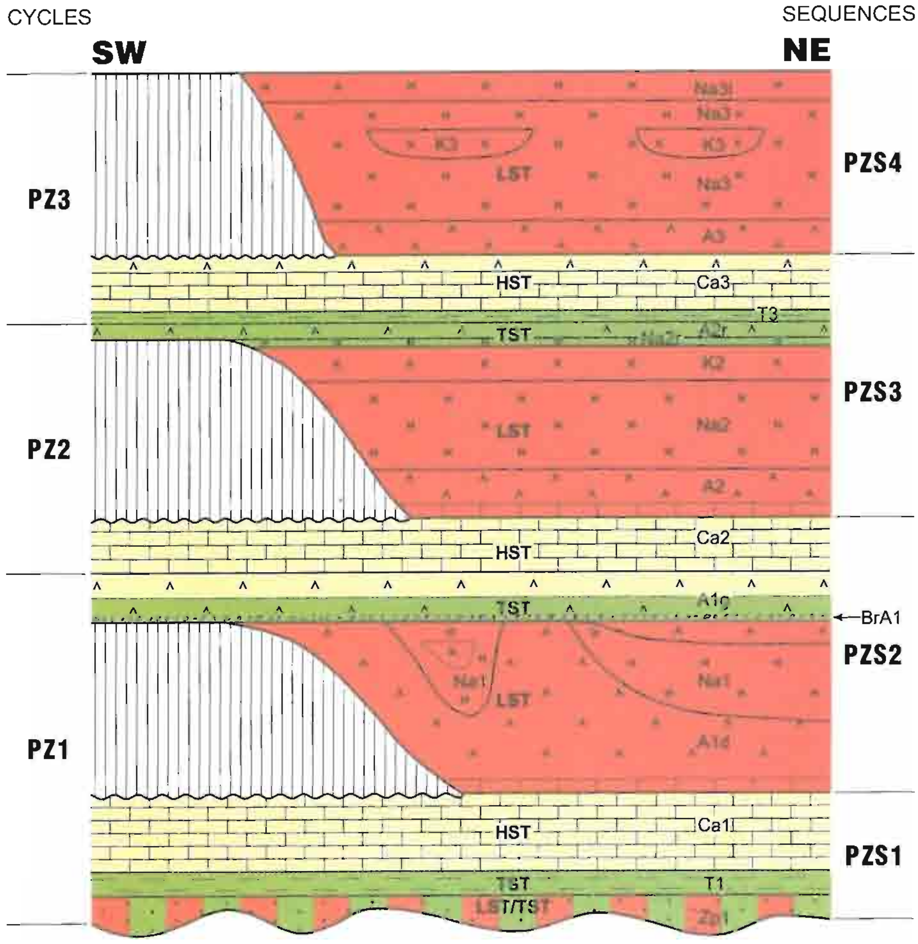


Fig. 3. Polish Zechstein chronostratigraphy and depositional sequences PZS1 to PZS4
Abbreviations as in Fig. 2

Chronostratygrafia polskiego cechsztynu i sekwencje depozycyjne PZS1–PZS4
Objaśnienia jak na fig. 2

peripheral part of the basin is TST while the middle and upper portions are HST. In the uppermost part of the Upper Anhydrite locally occurs nodular anhydrite (e.g. T. M. Peryt, 1990; A. Kasprzyk, 1992) being a diagenetic facies related to the fall of brine level; this facies is superimposed on earlier, mainly subaqueous depositional facies. In the transitional zone between the basin centre and its margins the part of Upper Anhydrite below the anhydrite breccia is a LST sediment which is followed by a TST sediments and subsequently by HST sediments. In the basin centre exclusively TST sediments have been recognized (Fig. 3).

At the close of Upper Anhydrite deposition the sea-level fell (according to T. M. Peryt, 1992, by several tens of metres) and the evaporite platform of PZ1 cycle was once again subaerially exposed thus permitting karstification of the Upper Anhydrite well documented in the Puck Bay area (T. M. Peryt *et al.*, 1992). Karstification has been also recognized by C. Strohmenger *et al.* (1996*a*) and related to the third sequence boundary. Although in fact this boundary can be treated as a sequence boundary covered by evident TST sediments (e.g. T. M. Peryt, 1992), the present authors believe that it should rather be regarded as a result of lower order sea-level oscillations analogous to those recognized later during Main Dolomite deposition. With this approach the major part of the Main Dolomite represents HST with well developed local cyclicity (e.g. T. M. Peryt *et al.*, 1989, 1990; T. M. Peryt, K. Dyjaczyński, 1991; T. M. Peryt, P. A. Scholle, 1996) reflecting sea-level oscillations similar to those occurring in the Zechstein Limestone.

C. Strohmenger *et al.* (1996*a*) put the sequence boundary in places of rapid transitions from sub- to peritidal facies which is quite frequently recorded on slopes of the Main Dolomite carbonate platforms. A well documented Polish example of such a rapid transition is the Puck Bay area where basinal facies sediments are overlain by peritidal sediments (phase D according to T. M. Peryt, 1986*b*, fig. 9D). Consequently, the upper portion of the Main Dolomite in the zone of the carbonate platform slope can be treated as the beginning of LST deposition of the next, third Zechstein sequence.

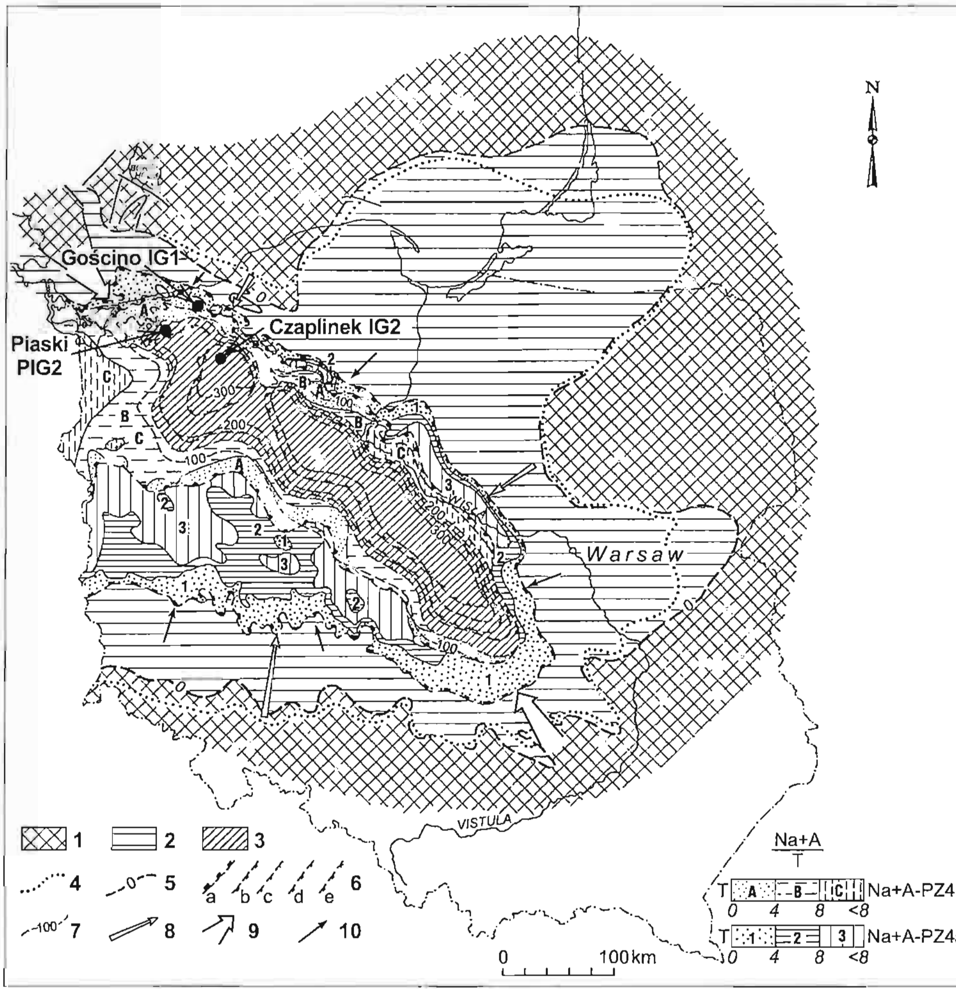


Fig. 4. Location of selected boreholes on the map of palaeofacies and palaeothicknesses of the Zechstein 4 (PZ4) in the Polish Zechstein Basin (after R. Wagner, 1994)

1 — areas of erosion, 2 — clastic facies, 3 — zuber facies, 4 — original extent of cyclothem PZ3, 5 — presumed original extent of clastic facies, 6 — extent of subcyclothems (a — PZ4a, b — PZ4b, c — PZ4c, d — PZ4d, e — PZ4e), 7 — palaeoisopachs of cyclothem PZ4, 8 — directions of regression, 9 — main direction of clastic transport, 10 — secondary directions of clastic transport; classification diagrams: T — terrigenous rocks, Na+A — chloride and sulphate rocks, (Na+A)/T — evaporation index, 1–3 — lithofacies classes in subcyclothem PZ4a, A–C — lithofacies classes in subcyclothem PZ4b

Położenie wybranych otworów wiertniczych na tle paleofacji i paleomiąższości cechsztynu 4 (PZ4) polskiego zbiornika cechsztyńskiego (według R. Wagnera, 1994)

1 — obszary denudacyjne, 2 — facje klastyczne, 4 — facja zubrów, 4 — pierwotny zasięg cyklotemu PZ3, 5 — przypuszczalny pierwotny zasięg facji klastycznych, 6 — zasięgi subcyklotemów (a — PZ4a, b — PZ4b, c — PZ4c, d — PZ4d, e — PZ4e), 7 — paleoizopachyty cyklotemu PZ4, 8 — kierunki regresji basenu morskiego, 9 — główne kierunki transportu materiału terygenicznego, 10 — podrzędne kierunki transportu materiału terygenicznego; diagramy klasyfikacyjne: T — skały terygeniczne, Na+A — skały chlorkowe i siarczanowe, (Na+A)/T — współczynnik ewaporacji, 1–3 — klasy litofacjalne w subcyklotemie PZ4a, A–C — klasy litofacjalne w subcyklotemie PZ4b

THIRD DEPOSITIONAL SEQUENCE PZS3

The Main Dolomite platform was risen above the water level. The general pattern of the evaporite facies of the third sequence in general representing LST is close to that of the second sequence: in the peripheries of the Main Dolomite platform occurs a Basal Anhydrite wedge formed in a subaqueous facies (T. M. Peryt *et al.*, 1996*b*) while the basin centre is taken up by halite and potash salt (G. Czapowski *et al.*, 1991*a*). Local sulphate lagoons situated behind the Main Dolomite barrier zone can be treated as equivalent of shallow-water carbonates covering the slope sediments of the carbonate platform, as postulated by C. Strohmenger *et al.* (1996*b*) for the German Zechstein. The Screening Anhydrite as well as Grey Pelite to which mfs is related are TST sediments. This transgressive nature is particularly well recognized in the Łeba Elevation (G. Czapowski *et al.*, 1991*b*). The Grey Pelite sediments represent a condensed section. The lower portion of the Platy Dolomite is made up of HST sediments. Considering the fact that in the southern part of the Polish Zechstein Basin shallow-water oolitic sediments overlie subtidal micrites (e.g. T. M. Peryt, 1988), one may assume that the former

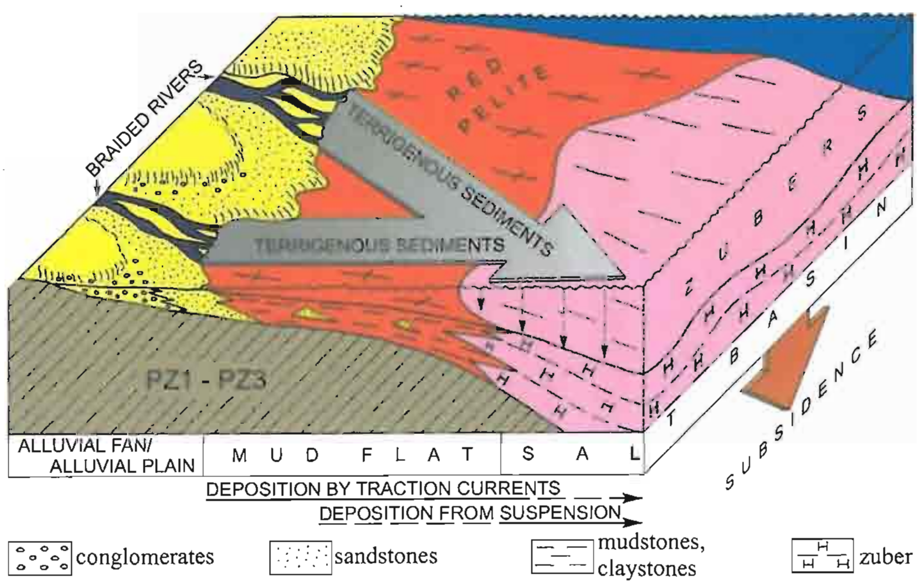


Fig. 5. Zuber sedimentation model (after R. Wagner, 1994)

Model sedymentacji zubrów (według R. Wagnera, 1994)

represent LST of the next, fourth depositional sequence. In this case the sequence boundary would lie within carbonates. It is possible, however, that the sequence boundary occurs in the lowermost part of the Main Anhydrite at the boundary between the laminated anhydrite (HA3 according to O. Bornemann, 1987) and streaky anhydrite (HA4).

FOURTH DEPOSITIONAL SEQUENCE PZS4

The upper part of the Main Anhydrite and all younger sediments to the Zechstein top are LST sediments.

In the uppermost part of the Younger Clay Halite Na3t of the PZ3 sedimentation in the Zechstein basin has changed substantially. Carbonates have disappeared completely (with the exception of a part of the English Basin where thin carbonates — Upgang Formation — occur). Sulphates have been confined to individual thin horizons. Within the halites both carbonates and sulphates are replaced by terrigenous strata of considerable correlational value throughout the Zechstein basin. As mentioned before all this was due to serious climatic changes. The stable arid climate in the carbonate-terrigenous cyclothems has been replaced by alternating humid and dry periods with a general trend toward more humid climate.

With the disappearance of carbonates and sulphates their sedimentary structures directly evidencing bathymetric changes can no longer be examined. The Zechstein clastics are predominantly fine-grained (claystones and mudstones/siltstones), strongly contorted by plastic halite and, much to the disadvantage of possible studies, almost uncored in boreholes. No evidence exists to distinguish typical eustatic cycles. The appearance of terrigenous horizons within evaporites points to more intense precipitation and the presence of river network supplying material to the basin. This is thus a factor completely unrelated to bathymetry or to transgressive cycles. Therefore, a separate lithostratigraphic division has been set up in Poland distinguishing one climatic cyclothem PZ4 divided into five subcyclothems from PZ4a to PZ4e reflecting climatic changes (R. Wagner, 1987*a*, *b*, 1991, 1994) (Fig. 1). This has been done not only to emphasize the genetical difference from cyclothems PZ1, PZ2 and PZ3 but also to show the contrast in time needed for their deposition. Most probably deposition of terrigenous-evaporitic subcyclothems was very rapid and the sedimentation time of the entire cyclothem PZ4 is comparable with that of one carbonate-evaporite cyclothem.

Deposition of terrigenous-evaporite sediments of the cyclothem PZ4 was very differentiated (Fig. 4). Three basic facies zones can be distinguished:

TERRIGENOUS AREA

These sediments were formed chiefly in humid periods on the peripheries of the evaporitic basin in fluvial environments and intracontinental sabkha (G. Pieńkowski, 1989, 1991). In dry periods thin layers of fine-clastic sediments were laid down or depositional gaps existed. Stratigraphically these sediments are equivalent of the Rewal Formation and the Top Terrigenous Series.

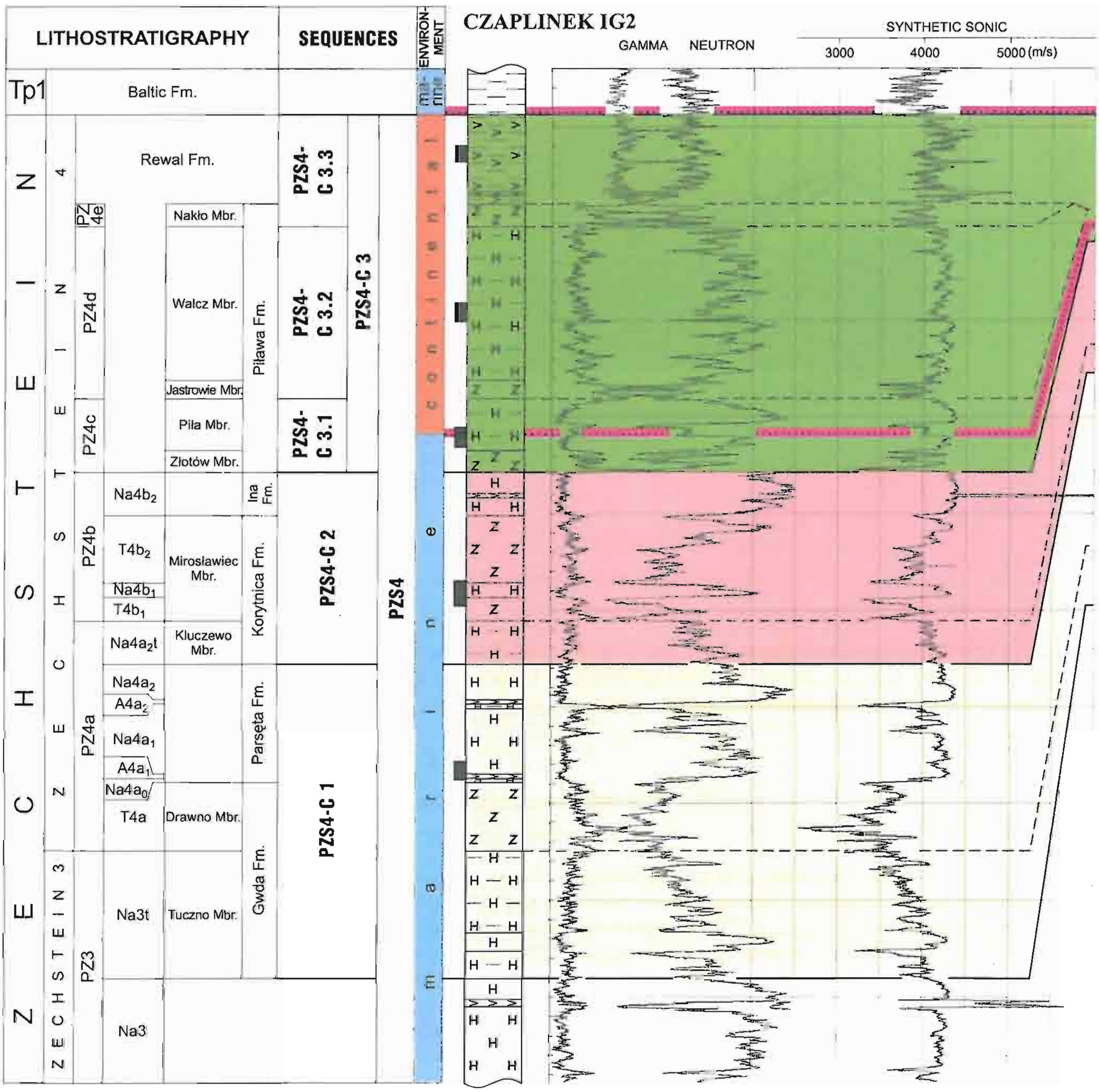


Fig. 6. Correlation of climatic sequences in the Polish Zechstein Basin

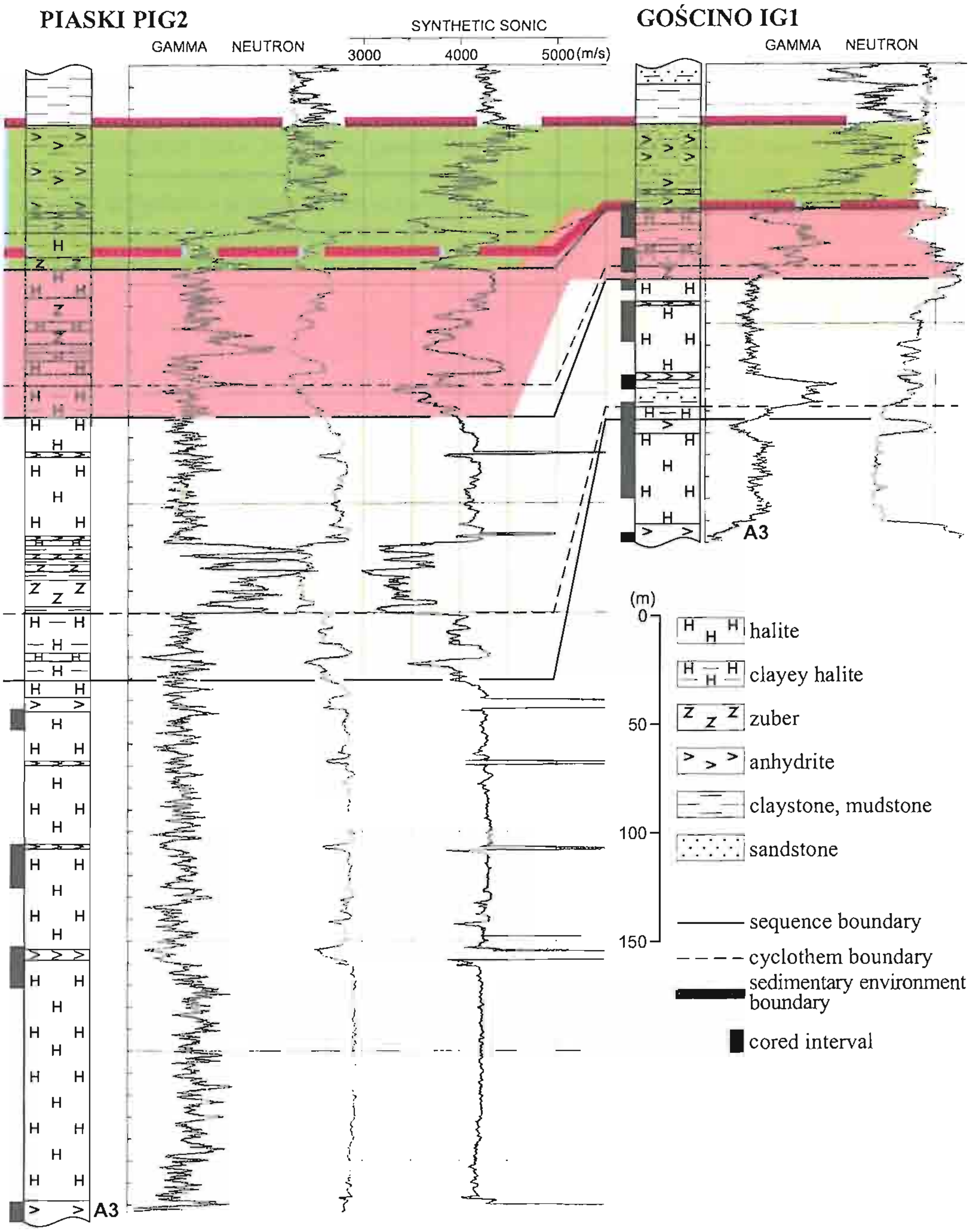
Abbreviations as in Fig. 2

CLAYEY-EVAPORITE AREA

These sediments were formed in the outer part of the evaporitic basin. In humid period red claystones and siltstones and subordinate sandstones were formed in a mud flat environment. Stratigraphically these sediments correspond to the Lower Red Pelite T4a (Fig. 1) and to the Upper Red Pelite T4b. Dry periods produced thin anhydrite layers (A4a$_1$, A4a$_2$) and halite of subcyclothems PZ4a and PZ4b.

ZUBER AREA

These sediments were formed in the axial part of the evaporitic basin in the Mid Polish Trough. In humid periods red claystone with subordinate siltstone representing the distal part of the bottom currents alternated with halite contaminated with terrigenous pelite deposited from suspension (Fig. 5). Stratigraphically these sediments are equivalent of the Gwda and Korytnica Formations as well as of the Złotów, Jastrowie and Nakło Members of the Piława Formation (Fig. 1). In dry periods evaporites have been deposited — predominantly



Korelacja sekwencji klimatycznych w polskim basenie cechsztyńskim

Objaśnienia jak na fig. 2

halite of the Parsęta and Ina Formations and clayey halite of the Piła and Wałcz Members of the Piława Formation. A separate formal division (Fig. 1) has been created for this specific lithofacies, as its correlation with clayey-evaporite sediments proved difficult.

A distinctive feature of the terrigenous-evaporite cyclothems was the shrinkage of the evaporite basins in increasingly young stratigraphic members and a simultaneous progradation of terrigenous sediments toward the basin centre.

As evidenced by a high bromine content in halites, sediments of Cyclothems PZ4a and PZ4b have been laid down in a marine environment. During the PZ4c Subcyclothem the environment changed into a salt lake without any connection with the sea. In the Piława Member formed in a dry period the bromine content in its lower part is 84 ppm and drops rapidly upwards to less than 20 ppm (R. Wagner, 1987*a*, *b*, 1991, 1994; G. Czapowski, 1990). Such low bromine contents are distinctive of halites precipitated in continental salt lakes. In younger subcyclothems — PZ4d and PZ4e the amount of bromine does not exceed 20 ppm.

The specific zuber lithofacies occurs also outside the Polish Basin in the northern part of the German Basin in the Helgoland and Lower Elbe Basins (G. Best, 1989).

As mentioned previously, there is no evidence of bathymetric changes in cyclothem PZ4. The type of sedimentation and relatively small thickness are indicative of a generally shallow-water environment and lowstand regime. There is thus no justification to distinguish typical eustatic sequences and, consequently, to apply concept of the sequence stratigraphy in this case.

A modification of sequence stratigraphy is proposed by introducing climatic sequences (Fig. 6). According to climatic cyclostratigraphy, lithological changes result from climatic changes. Despite substantial genetical difference between the eustatic and climatic sequences, they have one very significant feature in common — their isochronous boundaries. This is because changes of water-level in the basin as well as very pronounced climatic changes occurred simultaneously over vast areas and resulted in lithological differences.

The distinction of climatic sequences provided the possibility of a chronostratigraphic division of the Upper Zechstein. On the assumption that terrigenous or terrigenous-saline sediments were formed in humid periods and evaporites in dry periods, three climatic sequences were distinguished.

CLIMATIC SEQUENCE PZS4-C1

This sequence encompasses sediments formed in the oldest climatic cycle corresponding to the first major change from humid to arid climate (Figs. 7, 8).

The thickness of terrigenous sediments deposited during humid periods varies from 2 to 40 m depending on the distance from the provenance area and local activity of the fluvial system. In cyclothem stratigraphy these sediments correspond to the Lower Red Pelite T4a. The arid climate persisting in the upper part of PZ3 cyclothem gradually changes into humid. This process was reflected in sedimentation of a thin (a few to a dozen or so metres) halite layer with terrigenous intercalations. In the outer part of the basin this layer occurs beneath the Lower Red Pelite and is termed Younger Clay Halite (Na3t). In the basin centre where the Red Pelite is missing, this layer shows an increased thickness and is termed the Tuczno Member.

In the central part of the Polish Basin the Red Pelite is missing. There was no break in evaporite sedimentation and the supply of terrigenous material was not that intense. Zubers of the Drawno Member were formed attaining the maximum thickness of 36 m. The bromine content in pure halite averages 130 ppm (R. Wagner, 1987*b*; G. Czapowski, 1988).

The return of the arid climate impeded terrigenous sedimentation and evaporite sedimentation set in. As evidenced by sharp lithological boundaries often exhibiting features of erosional surfaces, this change was very rapid. Thus a small depositional gap may be assumed and the overlying evaporites can represent a transgressive system. This applies to the Underlying Halite ($Na4a_0$) and the transgressively overlying Lower Pegmatite Anhydrite ($A4a_1$). Further up in the sequence the Lower Youngest Halite ($Na4a_1$) occurs separated by the Upper Pegmatite Anhydrite ($A4a_2$). Similar evaporites occur in the basin centre and are termed the Parsęta Formation. Did the Lower Youngest Halite ($Na4a_1$) form under a highstand system? There is no univocal reply to this question. We can only assume that after the probable transgression of the Underlying Halite and Lower Pegmatite Anhydrite the water-level in the basin rose. The upper part of evaporites of sequence PZS4-C1 was most likely formed at lowstands, as evidenced by local K-Mg salts known from the English and German Basins (D. B. Smith, A. Crosby, 1979; G. Best, 1989).

The Upper Youngest Halite ($Na4a_2$) terminates evaporite sedimentation of the arid period and at its top the upper boundary of the sedimentary sequence PZS4-C1 has been placed.

With respect to cyclothem stratigraphy, the climatic sequence PZS4-C1 is equivalent to the uppermost layers of cyclothem PZ3 — Younger Clay Halite (Na3t) and Tuczno Member as well as subcyclothem PZ4a, excluding the Upper Youngest Clay Halite ($Na4a_2t$) and its equivalent in the basin centre — the Kluczewo Member.

The different placement of lithostratigraphic boundaries and climatic sequences results from genetical differences. By distinguishing a climatic depositional sequence the beginning of climatic changes is recorded, while lithostratigraphic boundaries are placed in instances of pronounced lithological changes, thus at the culmination of climatic change.

CLIMATIC SEQUENCE PZS4-C2

This sequence includes sediments formed in the second cycle of climatic changes from humid to arid. The lower sequence boundary has been placed at the base of the Upper Youngest Clay Halite ($Na4a_2t$). In cyclothem stratigraphy this is the uppermost horizon of cyclothem PZ4a. Like in sequence PZS4-C1, also here the lower sequence boundary is shifted with respect to cyclothem boundary. The 4 to 18 m thick Upper Youngest Clay Halite ($Na4a_2t$) is built of halite intercalated with red pelite and knotty anhydrite. Like in sequence PZS4-C1, the presence of this halite is indicative of increasing humidity. Its equivalent in the basin centre is pelitic halite of the Kluczewo Member.

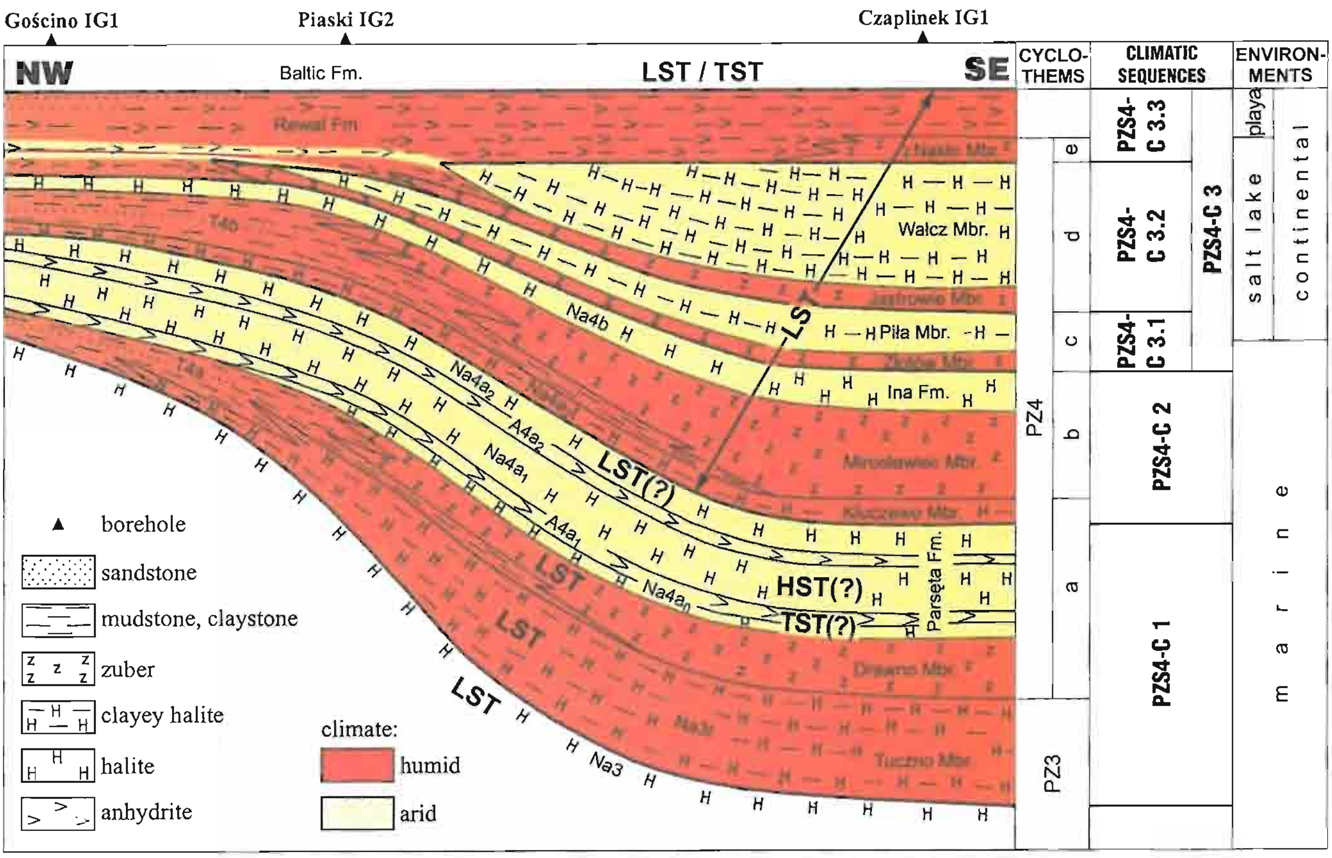


Fig. 7. Climatic depositional sequences (PZS4-C1–PZS4-C3) comparing the lithostratigraphical profile of the NW part of the Polish Zechstein Basin
Abbreviations as in Fig. 2

Klimatyczne sekwencje depozycyjne (PZS4-C1–PZS4-C3) na tle profilu litostratygraficznego NW części polskiego basenu cechsztyńskiego
Objaśnienie jak na fig. 2

With a strong increase of humidity evaporite deposition was interrupted and terrigenous deposition commenced. The Upper Red Pelite (T4b) is laid down, its thickness being from several to 40 m (R. Wagner, 1994). In its middle part the Upper Red Pelite is divided by a 0.5 to 4 m thick halite layer of regional extent. The Intrastratal Halite ($Na4b_1$) points to a short-lived climatic oscillation. The bromine content in the peripheral northern part of the basin was found to be 14 to 38 ppm. In the basin centre the Upper Red Pelite does not occur. Equivalent of these sediments are 25 to 55 m thick zubers of the Mirosławiec Member. The bromine content in halites from the zubers ranges from 30 to 90 ppm and is usually more than 50 ppm indicating the marine origin of the halites. In the zubers of the Mirosławiec Member occurs also 3 to 10 m thick Intrastratal Halite ($Na4b_1$). The bromine content in its lower part is high (83–130 ppm) and drops upwards to 20–47 ppm.

The climatic change from humid to arid was probably rapid and could be recorded by a short depositional gap (Fig. 8). In the dry period of the second climatic cycle a thin — 1.5 to 12.0 m — halite layer was formed (the Top Youngest Halite $Na4b_2$). Its equivalent in the basin centre is the slightly thicker (13.5–21 m) halite of the Ina Formation.

Halite is distinctive by its high purity; it does not contain any clay admixtures, by which it contrasts sharply from the under- and overlying zubers. The bromine content has been examined only in the northern periphery of the basin and found to vary from 22 to 83 ppm.

The evaporites of sequence PZS4-C2 had a much smaller extent than those of PZS4-C1.

Compared with the lithostratigraphic division, the sediments of sequence PZS4-C2 include in the lowermost part the Upper Youngest Clay Halite ($Na4a_2t$) and the Kluczewo Member — ascribed to subcyclothem PZ4a — as well as the entire subcyclothem PZ4b. The upper sequence boundary follows the lithostratigraphic boundary most probably due to a rapid climatic change accompanied by a depositional gap.

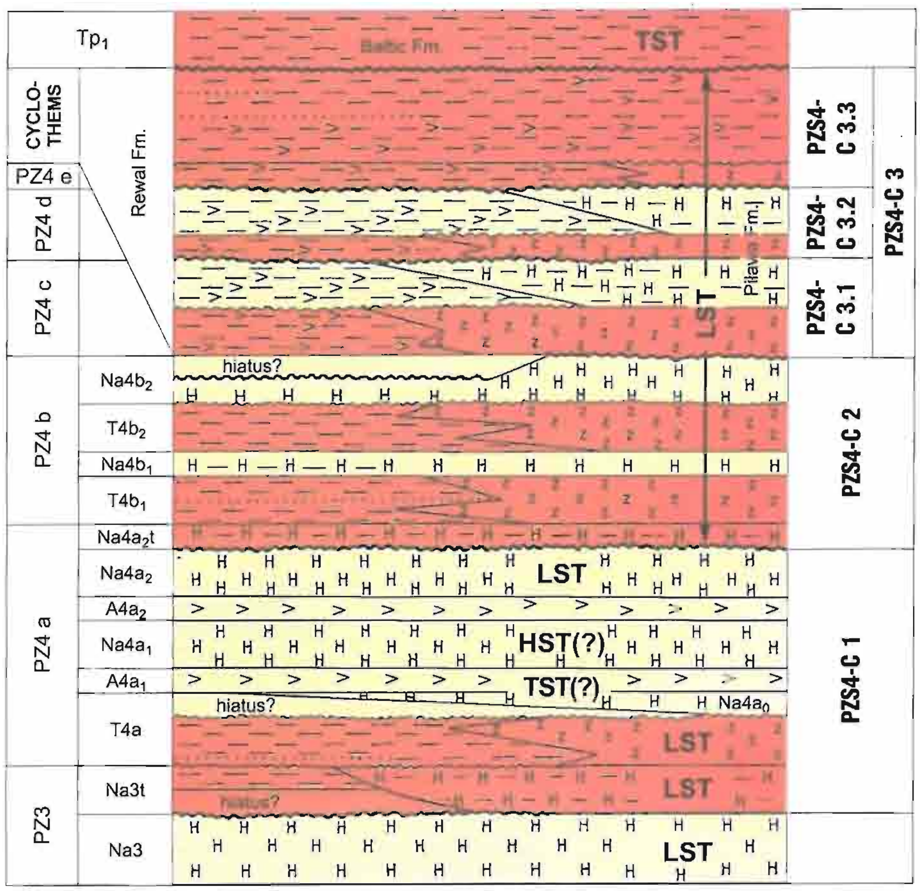


Fig. 8. Climatic depositional sequences (PZS4-C1–PZS4-C3) comparing the chronostratigraphical profile of the NW part of the Polish Zechstein Basin
Abbreviations as in Fig. 2

Klimatyczne sekwencje depozycyjne (PZS4-C1–PZS4-C3) na tle profilu chronostratygraficznego NW części polskiego basenu cechsztyńskiego
Objaśnienia jak na fig. 2

CLIMATIC SEQUENCE PZS4-C3

This sequence includes sediments formed in the third cycle of climatic oscillation with a humidity higher than during PZS4-C1 and PZS4-C2.

In the youngest climatic sequence the difference between sediments deposited in humid periods and those formed in arid periods are not that contrasting. Most likely the climate was more humid and the drier periods produced halite with clay admixtures, as terrigenous deposition continued, though with reduced intensity. Three parasequences — PZS4-C3.1, PZS4-C3.2 and PZS4-C3.3 — corresponding to three lower order climatic oscillations have been distinguished in sequence PZS4-C3 (Figs. 4, 7, 8).

PARASEQUENCE PZS4-C3.1

After the dry period of sequence PZS4-C2 the climate rapidly turned to humid. The zubers of the Złotów Member overlie the Top Youngest Halite (Na4b2) forming a sharp boundary. They are rather thin (from 5.5 to 17.5 m) and their extent is limited to the depocentre of the Polish Basin. In absence of core no bromine determinations could have been completed.

In the dry period slightly clayey halite of the Piła Member have been deposited. As opposed to evaporites of dry periods of older climatic sequence, terrigenous deposition was not terminated but only reduced. The thickness of the Piła Member evaporites is from 5.5 to 26.5 m.

During sedimentation of the Piła Member clayey halite the depositional environment in the Polish Zechstein Basin changed substantially. In the lower portion of the halite the bromine content is 21 to 84 ppm thus indicative of a marine environment. In the upper part of this halite the bromine content distinctly drops to less than 20 ppm. These values seem to indicate continental salt lakes without any connection with the marine basin. With reference to the lithostratigraphic division, parasequence PZS4-C3.1 is equivalent of subcyclothem PZ4c.

PARASEQUENCE PZS4-C3.2

Sediments of this parasequence occur in the depocentre of the Polish Zechstein Basin only and their extent is smaller than that of parasequence PZS4-C3.1. In the humid period 3 to 14.5 m thick zubers of the Jastrowie Member have originated. In the dry period considerably thicker — from 28.5 to 82.0 m — clayey halite of the Wałcz Member were laid down. In halite of both members the bromine content is low — several to a dozen or so ppm. Lithostratigraphically this parasequence is equivalent of subcyclothem PZ4d.

PARASEQUENCE PZS4-C3.3

These are the youngest Zechstein sediments recognized in the Polish Zechstein Basin and most probably in the entire Central European Basin (R. Wagner, 1994). This parasequence is asymmetric and contains sediments formed in an increasingly humid climate. In the basin centre red mudstone and claystone alternate with clayey halite of the Nakło Member. The thickness of these sediments ranges from 12 to 21.5 m. Bromine content in the halites is less than 10 ppm. Upwards they grade into terrigenous deposits of the Rewal Formation formed in a playa environment (Fig. 8). The upper boundary of parasequence PZS4-C3.3, being also the upper boundary of sequence PZS4-C3, has been placed where transgressive terrigenous sediments of the Baltic Formation appear. The Baltic Formation represents the oldest part of the Lower Buntsandstein. In the lithological profile this boundary is being placed where distinctive sedimentary structures of wave-generated heteroliths appear. A transgressive event (G. Pieńkowski, 1989, 1991) reversed the regressive trend persisting in the latest Zechstein. A vast intracontinental basin was formed the extent of which exceeded that of the Zechstein basin (A. Szyperko-Teller, W. Moryc, 1988). As evidenced by palaeomagnetic data (J. Nawrocki *et al.*, 1993), this transgression was most probably synchronous with the global transgression of the earliest Triassic (Griesbachian).

With reference to cyclothem stratigraphy the climatic parasequence PZS4-C3.3 is equivalent of subcyclothem PZS4e and of the uppermost part of the Rewal Formation and the Top Terrigenous Series.

CORRELATION OF CLIMATIC SEQUENCES WITH COEVAL DEPOSITIONAL SEQUENCES IN THE WESTERN PART OF THE ZECHSTEIN BASIN

This correlation applies to sediments formed in terrigenous-evaporite cyclothems according to lithostratigraphic terminology i.e. in the upper part of the Zechstein recording a period when regressive trends were predominant in the basin. Sedimentation proceeded in shrinking evaporitic basins accompanied by progradation of terrigenous sediments toward the centres. In the latest Zechstein time the small evaporitic basins were completely isolated and the connection with the Late Permian sea was disrupted. Under these conditions and with a shallow- and frequently extremely shallow-water depositional regime, the Zechstein basin became more and more differentiated. Sub-basins of slightly differing depositional conditions were formed.

The palaeogeographical situation creates substantial difficulties in correlating these sediments, particularly with respect to the distinguished depositional sequences. Outside the Polish Basin depositional sequences have been distinguished in the English (M. E. Tucker, 1991) and in the German (C. Strohmenger *et al.*, 1996*b*) Basins. In each of the two basins two sequences have been described in this time interval, ZS6 and ZS7 in the English and ZS7 and ZS8 in the German Basin not only differently numbered but also having different boundaries.

In the English Basin sequence ZS6 commences with terrigenous sediments (Carnallitic Marl) interpreted as LST sediment. In the German Basin the lower boundary of sequence ZS7 is placed further down within halite (Na3) correctly interpreted as LST sediment. In the Polish Basin the lower boundary of the first climatic sequence PZS4–C1 has an intermediate position — in the uppermost part of Younger Halite (Na3), but is based on totally different genetical criteria (Fig. 2). The Red Pelite (T4) in the German Basin is interpreted, similar to the English Basin, as LST sediment. The depositional environment of Pegmatite Anhydrite (A4) is envisaged differently: as TST in the German Basin and as HST in the English Basin. This difference results probably from the presence of a thin carbonate layer (Upgang Formation) beneath A4 in the English Basin believed to be a TST sediment. As the Upgang Formation has a very restricted extent even in the English Basin, such interpretation seems to be rather questionable. A local occurrence seems likely.

The environment of the Youngest Halite has a completely different interpretation. In the English Basin the entire halite horizon (Sneaton Halite Formation) together with the K-Mg salts (Sneaton Potash Member) occurring in halite has been defined as LST. Consequently, the boundary between sequences ZS6 and ZS7 has been set at the top of Pegmatite Anhydrite (Sherburn Anhydrite Formation). In the German Basin, on the other hand, the lower part of the Youngest Halite is understood as HST sediment while the upper part as LST. Thus, the boundary between sequences ZS7 and ZS8 was placed within the Youngest Halite and it is close to the analogous boundary in the Polish Basin (Fig. 2).

Which opinion is more reliable? There is no convincing evidence, the more so that the occurrence of K-Mg salts in the English Basin may be a local phenomenon which does not reflect the saturation of marine water throughout the Central European Basin.

The upper boundaries of the upper sequences in both basins, ZS8 in the German and ZS7 in the English have been set at the Permian/Triassic boundary, although based on completely different interpretations. This results from the following considerations. In the English Basin sequence ZS7 commences with the Youngest Halite (Na4) understood as a LST sediment. The overlying terrigenous layer (Sleights Siltstone) was also deposited in LST. The succeeding thin anhydrite (Littlebeck Anhydrite Formation) is interpreted as TST and the terrigenous series (Roxby Formation) occurring above it as HST. This is a highly unconvincing interpretation. The terrigenous sediments, beginning with Sleights Siltstone are equivalent of the Rewal Formation together with the Top Terrigenous Series (R. Wagner, 1986). Sedimentological studies have proved that their depositional environments, fluvial — sabkhas-playa have nothing in common with TST or HST (*cf.* G. Pieńkowski, 1989, 1991).

In the German Basin this entire interval has been correctly classified into LST and only its uppermost part (cyclothem Z7 and its terrigenous equivalents) are regarded as TST. Cyclothem Z7 (Mölln) most probably corresponds to subcyclothem PZ4d in the Polish Basin which has been deposited in an intracontinental salt lake in LST. In view of such controversies it may be assumed that correlation of terrigenous sediments in the peripheries with evaporites in the basin centre is incorrect in the German Basin or the correlation of the uppermost Zechstein in the Polish and German Basins is erroneous.

In the Polish Basin LST/TST sediments have been identified in the lowermost part of the Baltic Formation (G. Pieńkowski, 1989, 1991) on the basis of wave-generated heteroliths in fine-grained sediments. Similar heteroliths occur probably in the German Basin in the Upper Bröckelschiefer (U. Bruning, 1988). Therefore the lower boundary of the Baltic Formation can be correlated with the lower boundary of the Upper Bröckelschiefer.

CONCLUSIONS

Applying the Exxon method for sequence distinction, four depositional sequences can be distinguished in the Polish Zechstein, out of which the first commenced during the deposition of the upper portion of the Rotliegend and the fourth continued up to the lower portion of the Buntsandstein. The first depositional sequence is the continuation of the sedimentation of the uppermost Rotliegend; Basal Limestone Kupferschiefer, and Zechstein Limestone deposits (except of the uppermost part) are TST and HST deposits. The second and third Zechstein sequences contain evaporite deposits (LST) and carbonate and sulphate deposits (TST and HST); evaporites, although encountered in different systems tracts, mostly represent LST sediments. Our proposal of subdivision of the Polish Zechstein into sedimentary sequences refers to some extent to the principles introduced by M. E. Tucker (1991) and C. Strohmenger *et al.* (1996*a*, *b*) although our approach differs in details. It should be stressed, however, that in our opinion the Exxon approach is not the significant step in understanding the principles controlling the Zechstein basin evolution during the deposition of carbonate and evaporite-dominated, lower and middle parts of the Zechstein.

The fourth depositional sequence commences with evaporite deposits of LST, but afterwards a general change of sedimentary regime occurred and the upper part of the Zechstein is dominated by terrigenous-evaporite lithofacies. It is not possible to distinguish typical depositional sequences within this lithofacies. It may be related to that all depositional systems of the Upper Zechstein represent LST; the only TST that is supported by sedimentological studies occurs at the Zechstein–Buntsandstein boundary. In the Polish Basin this boundary coincides with the boundary between deposits included into the Rewal Formation and the Top Terrigenous Series on the one hand and the Baltic Formation on the other hand. Because it is not possible to distinguish typical depositional sequences in the Zechstein terrigenous-evaporite lithofacies, it was decided to distinguish climatic sequences what, however, is a major deviation from principles of distinction of eustatic depositional sequences. Despite of fundamental differences between the origin of climatic and eustatic sequences, they have an important common feature; their boundaries are isochronous. There are possible two solutions for the Upper Zechstein: to distinguish a typical climatic sequences or to apply the practical cyclothem subdivision.

Translated by Grażyna Niemczynow-Burchart

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O MOŻLIWOŚCI PODZIAŁU POLSKIEGO CECHSZTYNU NA SEKWENCJE STRATYGRAFICZNE

Streszczenie

W klasycznym ujęciu litostratygraficznym osady cechsztynu charakteryzują się budową cykliczną. W dolnej i środkowej części profilu występują trzy cyklotemy węglanowo-ewaporatowe PZ1, PZ2 i PZ3 utworzone w cyklach transgresywno-regresywnych interkontynentalnego basenu morskiego, w klimacie suchym i gorącym. W górnym cechsztynie (cyklotem PZ4) utworzyły się zupełnie odmienne genetycznie subcyklotemy terygeniczno-ewaporatowe, powstałe w warunkach oscylacyjnych zmian klimatu od wilgotnego do suchego.

Stosując Exxonowską metodę wyróżniania sekwencji wydzielono w cechsztyńskim basenie polskim cztery eustatyczne sekwencje depozycyjne. Trzy starsze sekwencje: PZS1, PZS2 i PZS3 powstały, zdaniem autorów, w wyniku największych eustatycznych zmian poziomu morza III rzędu (1–10 Ma). Dla tego samego odcinka czasu wyróżniono w basenie angielskim cztery sekwencje. Większa liczba sekwencji niż w basenie polskim wynika, zdaniem autorów, z innej interpretacji rangi zmian poziomu morza. Wydaje się, że niektóre z nich mogą reprezentować cykle wzrostu poziomu morza IV rzędu (0,1–0,2 Ma).

Najmłodsza sekwencja w basenie polskim PZS4, obejmująca osady od górnej części anhydrytu głównego (A3) aż do spągu dolnego pstrego piaskowca (Tp_1), reprezentuje wyłącznie system LST. W obrębie tej sekwencji eustatycznej zaproponowano wyróżnienie trzech sekwencji klimatycznych: PZS4-C1, PZS4-C2 i PZS4-C3. Podstawą ich wyróżnienia były cykliczne i izochroniczne wahania klimatu od wilgotnego do suchego. W okresach wilgotnych tworzyły się w zewnętrznych częściach basenu głównie osady terygeniczne — iły solne, a w depocentrum — zubry. W okresach suchych osadzały się ewaporaty, głównie sole kamienne. W najmłodszej sekwencji klimatycznej wyróżniono trzy parasekwencje: PZS4-C3.1, PZS4-C3.2 i PZS4-C3.3, odpowiadające wahaniom klimatu niższego rzędu, wskazujące na postępujący wzrost jego wilgotności.

W tym samym przedziale czasowym wyróżniono w basenach niemieckim i angielskim po trzy sekwencje eustatyczne o różniących się granicach, wynikających z odmiennych interpretacji środowisk depozycyjnych.

Zdaniem autorów wyróżnienie odmiennych genetycznie sekwencji klimatycznych pozwala na uniknięcie niejednoznacznych interpretacji systemów depozycyjnych oraz stworzenia szansy chronostratygraficznego podziału najwyższego cechsztynu.

Podział osadów cechsztynu na sekwencje depozycyjne jest trudny przez niejednoznaczną identyfikację wielkości i czasu zmian poziomu morza. Z tego powodu podział ten nie stanowi znaczącego kroku w poznaniu prawidłowości sedymentacji osadów cechsztynu. Niemniej jednak jest to interesujący eksperyment rzucający nowe światło na izochroniczność sedymentacji w skomplikowanym układzie węglany — ewaporaty i osady terygeniczne — ewaporaty.

Stratygrafia sekwencyjna nie zastępuje cyklotemowej, ale ją wzbogaca i uzupełnia.