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Depositional development of the Polish Upper Rotliegend Basin and evolution of its sediment source areas

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In the Polish Upper Rotliegend Basin three major depositional systems were predominant: fluvial, aeolian and playa. Sedimentary development of the basin has been controlled by two principal factors: climate and tectonics, the latter related to lithospheric extension leading to subsidence and accomodation space development. Within the framework of structural and climatic constraints, the depositional systems have been developing as a complex pattern of mutual interrelationships. Nine main depositional sequences have been described basing on results of sedimentological analysis coupled with a palaeostructural basin model focused on tracing shifts of depocentres. Definition of the sequences enabled further analysis of a sedimentary balance of the basin and an attempt to define presumable sediment source areas. The brief description of the latter areas is presented and it is shown that their changing size and shifting directions of a sediment transport considerably influenced deposition in the basin. During early stages of the basin development main source areas have been located in the west and north while later on eastern and southern provenance has become more important. An important role in a sedimentary budget of the basin has been played by periodic transfer zones linking the Central Basin (= Mid-Polish Trough) with peripheral sub-basins located on the Precambrian East European Platform.

INTRODUCTION

The investigations of sedimentary environments of the Polish Rotliegend started during late seventies due to a rapid increase of information related to numerous deep wells localized over the Polish Lowlands area including the Mid-Polish Trough. During that period also first stratigraphic sudivisions of the Rotliegend were proposed for the area of the trough (defined as the "central sedimentary basin", here labelled the Central Basin).

The present study is a first attempt to define depositional systems and sequences in the Polish part of the European Southern Rotliegend Basin. It is based on sedimentological interpretations of core material and wireline logs. Interpretation of seismic data has been used to a limited extent with a few exceptions of seismic data, analyses of acoustic impedance and some seismic sections from 3-D projects. In previous studies of the Rotliegend Basin lithofacies subdivisions have been used basing on both core and wireline log data (*Atlas litofacjalno-paleogeograficzny...*, 1978). The interpretations of lithofacies in terms of sedimentary environments has been based on scarce and partly erronous sedimentological interpretations. The current stratigraphic subdivisions are based on lithostratigraphic principles (P. H. Karnkowski, 1981, 1987) with a limited concern as to genetic and age relationships of the described lithosoms. On the other hand, allostratigraphic principles have also been applied including some elements of tectonostratigraphy (J. Pokorski, 1981) leading to correlations of different lithologies with the assumption that their approximately coeval development have been controlled by tectonic events in the basin or close to its margin. Such an approach have led to overgeneralized interpretations, mostly in terms of diastrophism.

Under such circumstances, in order to distinguish and define depositional systems, sedimentological investigations on a basin scale have been undertaken within the framework of the project "Sedimentary basin analysis of the Polish Lowlands" supplemented by the few existing sedimentological reports (P. H. Karnkowski, 1986; W. Nemec, J. Porębski, 1977; T. Jerzykiewicz *et al.*, 1976; P. Roniewicz *et al.*, 1981). This have led to a compilation of an inventory of facies types and their associations, and to definition of sedimentary envi-

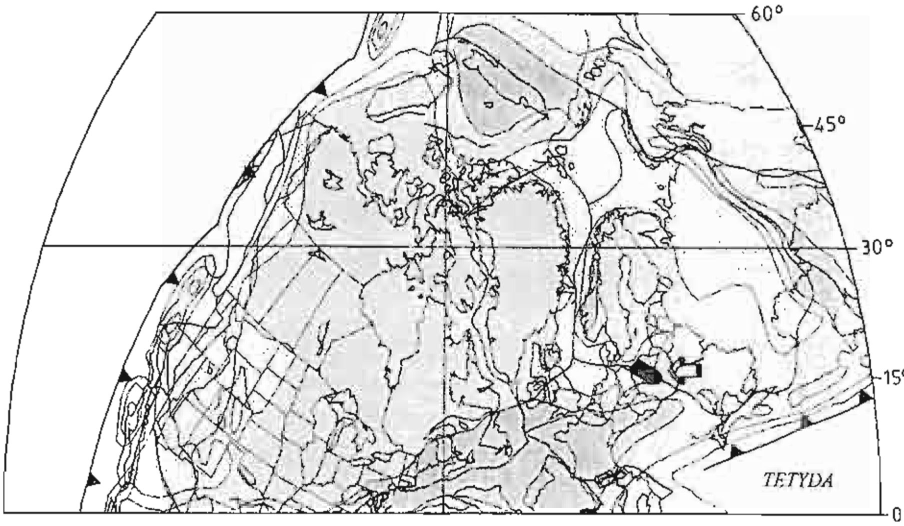

Fig. 1. Late Permian palaeogeography of Northern Pangea for the Zechstein times (after C. R. Scotese, R. P. Langford, 1995) with the location of the Polish Rotliegend Basin indicated by arrow

Darker shading — high mountain belts; lighter shading — lower land areas; dotted — shallow seas; bold lines with triangles — active plate margins

Mapa paleogeograficzna północnej Pangei dla czasu sedymentacji cechsztyńskiej (według C. R. Scotese'a, R. P. Langforda, 1995) z zaznaczonym strzałką miejscem występowania polskiego basenu czerwonego spągowca

Obszary najciemniejsze — wysokie góry; obszary jaśniejsze — lądy; obszary białe zakropkowane — płytkie morza; linie grube — aktywne krawędzie płyt

ronments. Basinwide correlation of major depositional events has been accomplished using sequence stratigraphic approach (G. Kocurek, K. G. Havholm, 1993; A. D. Miall, 1996). In addition, some aspects of cyclostratigraphy and climate-related chronostratigraphy have been applied mostly to aeolian depositional evolution. Of subordinate importance have been correlations based on ichnostratigraphy and palynostratigraphy. Standard codes for facies, subfacies and sedimentary textures have been applied in the course of the present work in order to achieve comparability of descriptions and interpretations (G. T. George, J. K. Berry, 1994; A. D. Miall, 1978).

PALAEOGEOGRAPHIC BACKGROUND

Polish Permian Basin forms the eastern, partly isolated part of the European Southern Permian Basin (SPB). Map in Fig. 1 (after C. R. Scotese, R. P. Langford, 1995) shows the location of the Polish Basin against the Late Permian palaeogeography of the Northern Pangea. The basin was located in a subtropical zone near 15°N. It was a typical continental basin (in its German portion forming partly depression with a few marine incursions) surrounded by extensive higher elevated areas. The important palaeogeographic feature was the postulated mountain barrier separating the Rotliegend basin from the nearest ocean — the Tethys. In view of Permian palaeoclimatic models including assumed ocean current directions, precipitation patterns and monsoonal seasonality (E. J. Barron, P. J. Fawcett, 1995; J. T. Parrish, 1995) the outlined palaeogeographic pattern was of crucial importance for the general style of deposition in the Rotliegend times. The basin was dominated by aeolian and fluvial sedimentation, the latter being permanently interconnected with the playa system. Such a depositional style was typical not only for the Polish Basin. Aeolian sedimentation was an important component of Late Permian sedimentary processes going on in arid subtropical climate over vast territory of the Northern Pangea from the eastern margins of the SPB to the present southwestern U.S.A. This area was dominated by desert sedimentation comprising erg complexes, playas, sebkhas and saline lakes with some proportion of fluvial deposits. In the area of present Poland forming the eastern periphery of the SPB (H. Kiersnowski *et al.*, 1995), several main palaeogeographic features have been reconstructed for the period of the Upper Rotliegend deposition: central playa-lake (with intermittent considerable input of fluvial and aeolian sediments), dune area comprising two extensive ergs, eastern and southern ones (H. Kiersnowski, 1997), and area dominated by periodic desert rivers (*wadi*).

DEPOSITIONAL SYSTEMS

During the Rotliegend time, in the foreland of the Variscan orogen, there developed a narrow elongated basin of a half-graben type filled with terrigenous, mostly siliciclastic sediments represented by sandstones, siltstones, and subordinately, conglomerates. The basin was undergoing fast, punctuated subsidence which reached the highest rate during the uppermost Upper Rotliegend time with accompanying widening of the subsiding area (*cf.* R. Dadlez *et al.*, 1995 for a discussion on the origin of the basin). As a result, the thicknesses and lateral extent of the sediments increased together with higher degree of lithofacies complexity in different parts of the basin and increased sediment input associated with a modification of source areas.

Sedimentary lithofacies reveal the onlap-type geometry pointing to a progressive lateral expansion related to levelling of an erosional edge zone and overstepping pattern of deposition. This was probably caused partly by basin extension and by the dominance of accumulation rate over subsidence, particularly in a terminal stage of the basin development (see the cross-sections in Figs. 2–4).

Present analysis is focused on the clastic lithofacies predating the deposition of marine carbonate and evaporitic lithofacies of the Zechstein. The lithofacies have been arranged with respect to their origin which enabled definition of depositional systems. Four main systems have been distinguished: (1) fluvial, (2) aeolian, (3) playa-lake, and (4) transgressive marine system of a shallow-water coastal zone. The last named system, associated with a base of the Zechstein, is not included into present eonsiderations due to its relatively small thickness and its limited importance in the basinal fill. Remaining three systems developed simultaneously, interacting with each other during different stages of the basin development.

The main factors controlling the origin and development of above systems were: (1) autogenic processes related to structural controls directly influencing relief, and (2) allogenic processes related most of all to climatic fluctuations and, probably, to eustatic changes including the Zechstein transgression. An overlapping of various factors or a dominance of only one of these created complexity of depositional systems whose pattern considerably diverges from the currently assumed simplified depositional models.

The architecture of the depositional systems reflects the ongoing changes in palaeogeomorphology of the basin and surrounding source areas, as well as evolving palaeohydrological regime. The basin was predominantly hydrologically closed with inner drainage modified by syndepositional tectonics in marginal zones and shifting depocentres controlled by segmented (block) basement structure. The exceptional feature of the basin was the characteristic "independence" of the aeolian system with respect to the classical concentric lithofacies zonation of an alluvial basin, and to geometry of the basement. This may be exemplified by the local grabens filled with aeolian sediments (Fig. 4). Aeolian sandstone facies are differently developed in central and marginal basin areas and commonly show overstepping arrangement, extending even beyond strict basin frame (Figs. 3 and 4). This influenced to a considerable degree a parallel development of fluvial and playa systems.

Presented model of depositional systems development, palaeogeography and sedimentary environments is applicable to best studied uppermost part of the Upper Rotliegend sedimentary fill. One can distinguish here: (1) in the northwestern part the area dominated by playa system, (2) in the northern part the area dominated by fluvial system of periodic rivers, (3) in the southwestern part the area dominated by aeolian system, and (4) in the southeastern part prevailing fluvial (periodic rivers) and aeolian systems. The above named systems formed a pattern of mutual interrelationships terminated during the initial Zechstein transgression.

The synthesis of the depositional architecture is presented in reconstructed cross-sections (Figs. 2–4, 9). They show i.a. the zone of a strongest and most permanent subsidence in the Resko–Czaplinek area, as well as migration of sedimentary lithofacies following sbifts in depocentres during basinal evolution. Generally, clearly seen are typical depositional attributes of half-graben basins (M. R. Leeder, R. L. Gawthorpe, 1987) including asymmetric facies pattern related to increased subsidence along fault-controlled basin margin (NE flank in our example).

FLUVIAL SYSTEM

Fluvial sediments are important component in the development of the alluvial Rotliegend basin. They frequently occur throughout the entire Rotliegend succession. The fluvial depostional system is very complex as its development has been controlled by many factors of regional and supraregional importance. Of the prime importance have been climatic fluctuations and related shifts in development and extent of drainage areas, as well as changes in erosional baselevels controlled by tectonics. Another important factor was a changing hydrological system in the basin, either confined or connected with the North German Basin. When analysing the course of the basin evolution we can observe several sequences of progradational and retrogradational type in the development of the fluvial system. There exist clear analogies between the Upper Rotliegend of the western part of the SPB (H. Kiersnowski *et al.*, 1995) and the system described by G. T. George and J. K. Berry (1994).

The sediments accumulated in generally hot and arid climatic conditions with scarce periodic rainfall. Therefore the development of the fluvial deposits is restricted and commonly closely related to local drainage zones. The fluvial sediments occur in all the studied well sections, often as periodic intercalations. In the entire basin those deposits are immature due to a short periodic transport, common shifts in sediment load and changing geometry of river-bed systems. Three main elements of the fluvial system have been distinguished and described below.

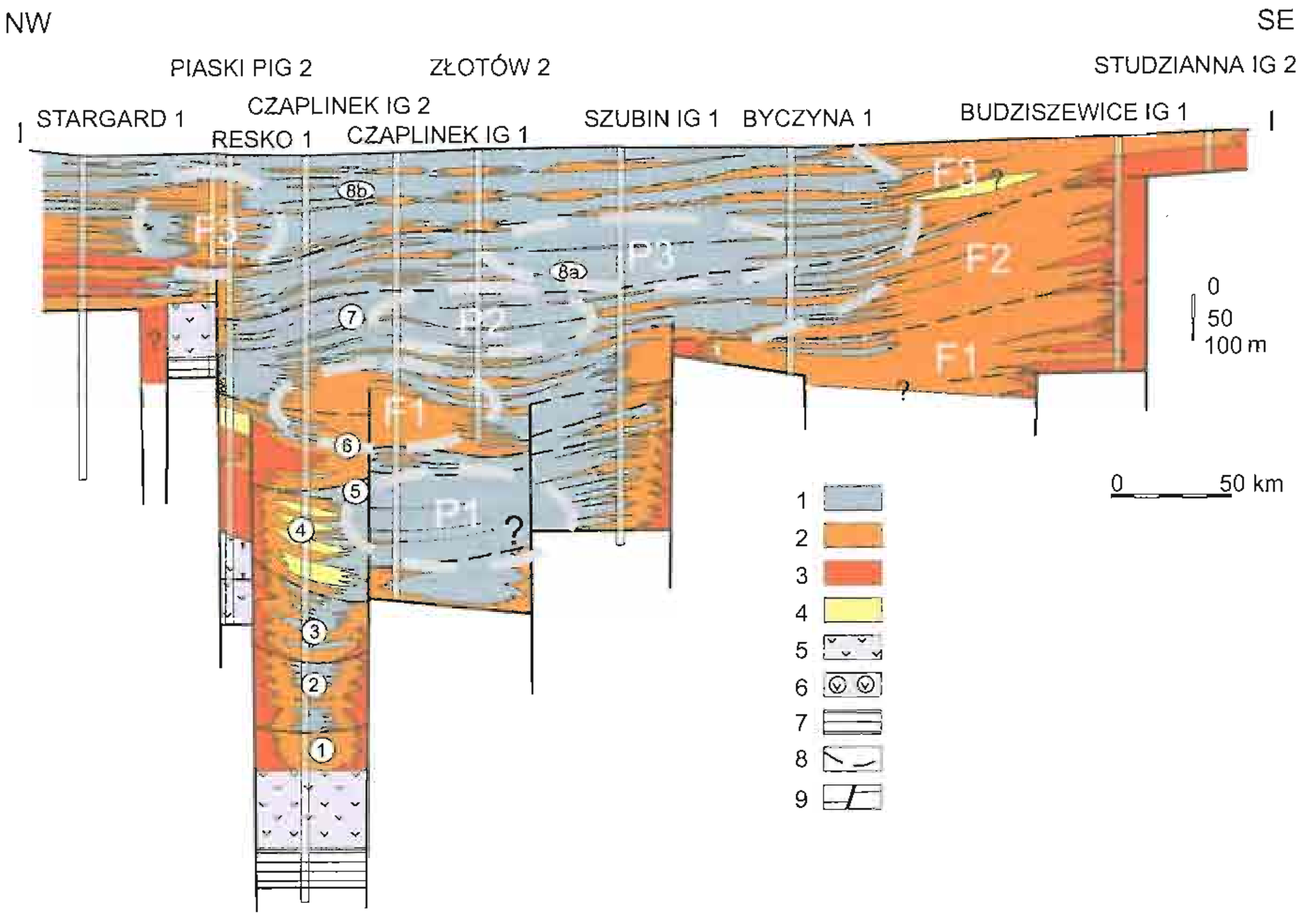

Fig. 2. Reconstructed NW–SE cross-section I–I of the Upper Rotliegend basin between wells Stargard 1 and Studzianna IG 2 (location in Fig. 7)

1 — dominance of playa siltstones and claystones; 2 — dominance of braided rivers, alluvial plain and distributary channels of marginal playa; 3 — dominance of coarse clastic deposits developed in alluvial fan and braided rivers facies; 4 — dominance of aeolian sandstones; 5 — effusive and pyroclastic rocks; 6 — conglomerates sourced from eroded volcanic rocks; 7 — sedimentary rocks of supposed Lower Rotliegend; 8 — interpreted sequence boundary; 9 — interpreted faults, partly supposed synsedimentary faults; number in circles — depositional sequences described in the text; P1–P3 — packages representing episodes of clayey sediment input; F1–F3 — fluvial depositional sequences

Przekrój paleostrukturalny I–I przez basen górnego czerwonego spągowca między otworami Stargard 1 i Studzianna IG 2 (lokalizacja na fig. 7)

1 — dominacja iłowców i mułowców plai; 2 — dominacja piaskowców w facjach równi aluwialnej, rzek roztokowych i kanałów rozprowadzających w strefach marginalnych plai; 3 — dominacja osadów gruboklastycznych w facjach stożków aluwialnych i rzek roztokowych; 4 — dominacja piaskowców eolicznych; 5 — skały wylewne i piroklastyczne; 6 — zlepieńce pochodzące z niszczenia skał wulkanicznych; 7 — skały osadowe przypuszczalnie dolnego czerwonego spągowca; 8 — interpretowane granice sekwencji; 9 — interpretowane uskoki, częściowo synsedymentacyjne; cyfry w kółkach — poszczególne sekwencje depozycyjne opisane w tekście; P1–P3 — pakiety osadów reprezentujących epizody dostawy materiału ilastego do basenu; F1–F3 — fluwialne sekwencje depozycyjne

FLUVIAL SYSTEM OF A PROXIMAL ZONE

It comprises fluvial deposits of alluvial-fan facies association embracing following facies: debris flows, sheet flows, distributary channels of the fan surface, and sediments of drainage zones sourcing fans. The example of the above sedimentary environments is found in the Wilcze IG 1 well section (Fig. 4).

During the present studies, it was possible to distinguish the deposits of alluvial fans dominated by mass flows and those dominated by stream flows. The former deposits are composed of coarse conglomerates with subordinate sandstones and siltstones. The conglomerates contain extraformational clasts, and, in the case of coarse- and fine-grained intercalations, also intraclasts. The whole spectrum of structures occurs — from close to open fabric conglomerates with a large matrix proportion. Bedding is often poorly visible and difficult to interpret in a core material. The conglomerates are either poorly sorted or unsorted. Particular depositional sequences are characterized by normal or reversed grading or lack of grading. The conglomerates are often interlayered with massive or well-bedded sandstones which may contain single large floating clasts. These sediments are interpreted as debris flows or, more commonly (T. C. Blair, J. G. McPherson, 1994) as deposited from high-energy bed-loaded braided streams (A. D. Miall, 1978) or sheet flows.

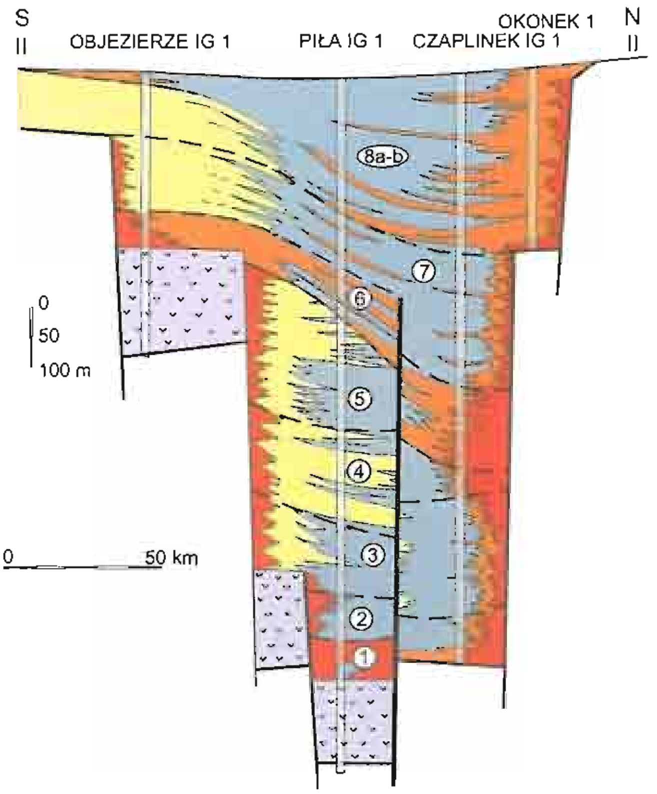

Fig. 3. Reconstructed S–N cross-section II–II of the Upper Rotliegend basin between wells Objezierze IG 1 and Okonek 1 (location in Fig. 7)
Explanations — see Fig. 2

Przekrój paleostrukturalny II–II przez basen górnego czerwonego spągowca między otworami Objezierze IG 1 i Okonek 1 (lokalizacja na fig. 7)
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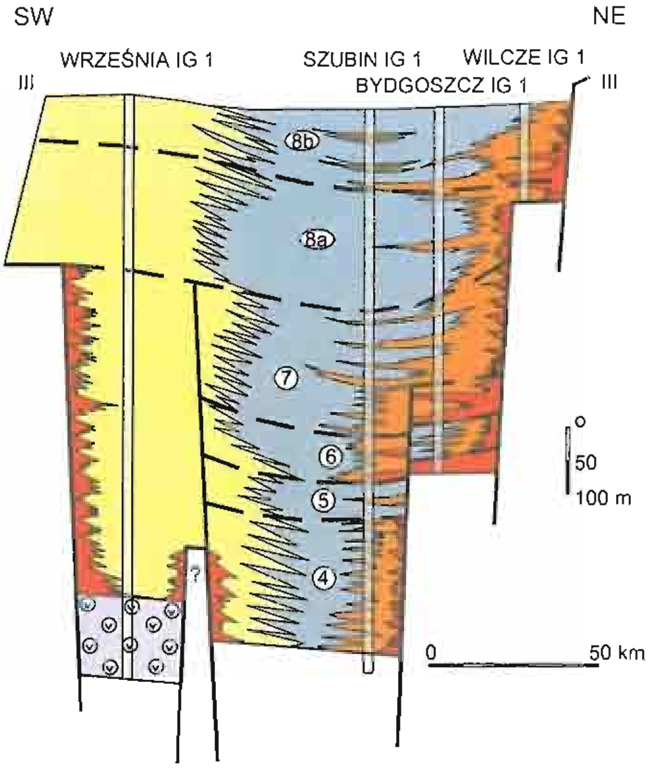


Fig. 4. Reconstructed SW–NE cross-section III–III of the Upper Rotliegend basin between wells Września IG 1 and Wilcze IG 1 (location in Fig. 7)
Explanations — see Fig. 2

Przekrój paleostrukturalny III–III przez basen górnego czerwonego spągowca między otworami Września IG 1 i Wilcze IG 1 (lokalizacja na fig. 7)
Objaśnienia jak na fig. 2

The first two sediment groups are similar. In addition to coarsely-clastic conglomerates there may occur sandstones and silty-clayey sediments. The conglomerates are often well-sorted and form normally graded sequences. There is a frequent alternation of coarse- and fine-grained sediments and one observes sedimentary structures characteristic for high-energy flow in shallow-water streams with low sinuosity. As a rule, the depositional sequences display truncated upper fine-grained members. There is a predominance of horizontal bedding, low-angle inclined bedding and, rarely, cross-lamination. The described sediments are common in marginal zones of the basin.

FLUVIAL SYSTEM OF A TRANSFER ZONE

These are deposits of distal alluvial-fan systems (alluvial plains) belonging to facies of periodic braided rivers which have developed perpendicularly to elevated areas into local depocentres or parallel to elevations as composite drainage system. The example of such depositional environments is represented by the lower part of the Byczyna 1 well-section (Fig. 2). Following depositional facies can be described here: sandy channels of braided streams in a distal alluvial-fan zone, channels of mature rivers, overbank (including crevasse), flood plain and inactive fluvial channel infillings.

FLUVIAL SYSTEM OF A DISTAL ZONE

Here belong deposits of periodic rivers, partly of high sinuosity, entering a playa area as facies of distributary-channels of highly variable range, magnitude and sediment-transportation capability. The relevant example is the Piła IG 1 well-section (Fig. 3). In some sections it is also possible to interpret fluvial deposits developed as prodelta or prograding fan-delta facies. The described system comprises the facies of channelized sheet-flood and non-channelized sheet-flood. They occur in marginal playa areas and in sandy playa sequences.

The range and relative influence of particular elements of the fluvial system are variable both in time and space. We have examples of a long-term development of the system extending far into the basin and forming fluvial sequences of considerable thickness, as in the area of Czaplinek IG 1 and IG 2 wells (Figs. 2 and 3). That system was characterized by strongly sediment-loaded sandy-gravelly braided rivers and low-sinuosity rivers.

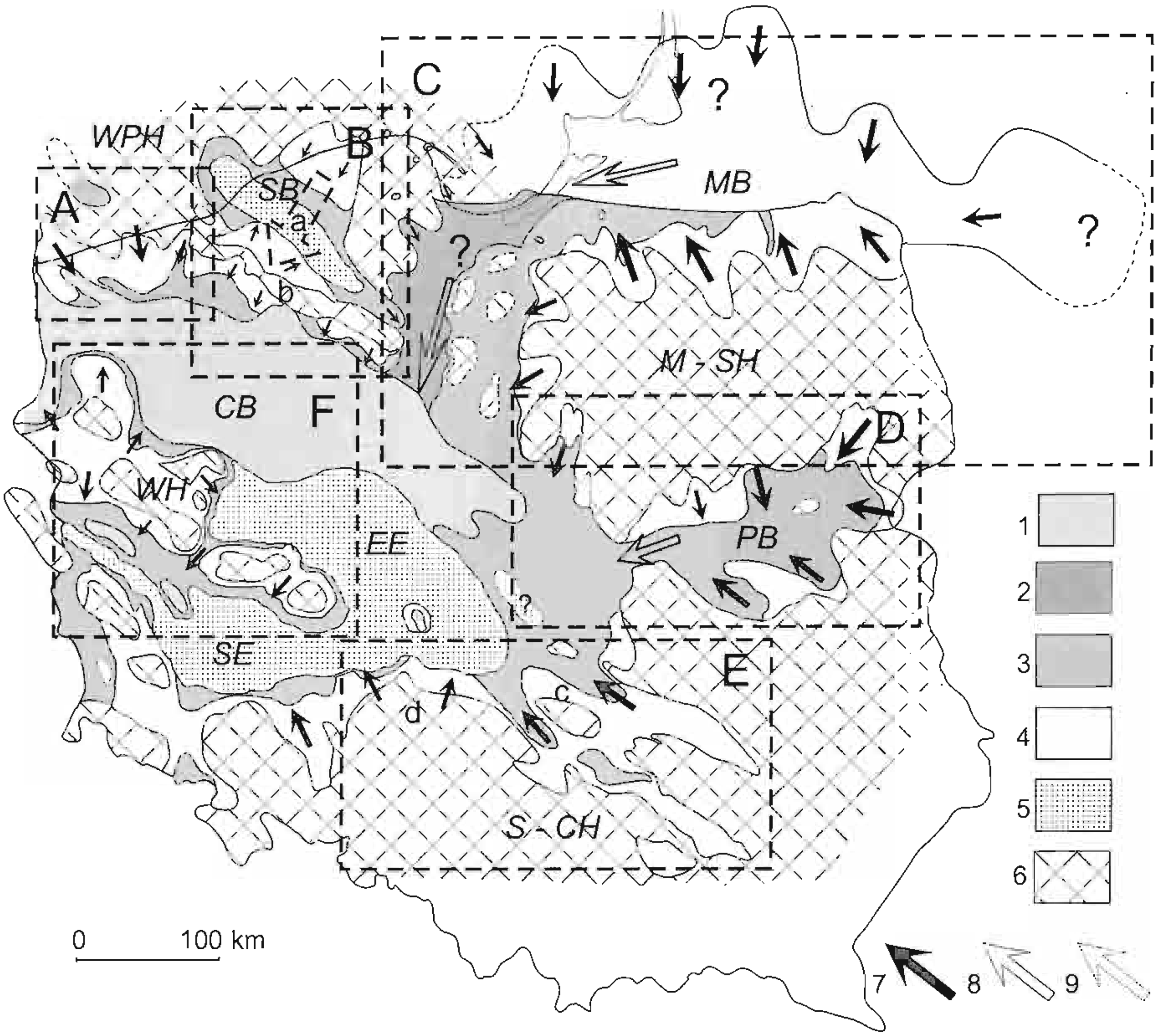


Fig. 5. General geometry of the Polish Upper Rotliegend Basin (after J. Pokorski, 1988, modified and supplemented)

1 — playa lithofacies; 2 — supposed fluvial lithofacies of transfer zone; 3 — fluvial lithofacies; 4 — alluvial lithofacies of basin margin; 5 — aeolian lithofacies; 6 — source areas; 7 — sediment transport directions (size of arrow indicates relative importance); 8 — supposed sediment transport directions; 9 — supposed early directions of sediment transport; **boxes A–F** — separate catchment areas: **A** — Western Pomerania High (drainage system controlled by tectonic blocks, sourced in the north, close to basin margin); **B** — Słupsk Basin and Koszalin–Chojnice zone (a — supposed early drainage system axis, sourced in NE, farther from basin margin, b — late local drainage system network, sourced closer to basin margin; drainage system controlled by tectonic framework of Koszalin–Chojnice uplifted zone); **C** — Mazury Basin and supposed sediment transfer zone (leaf-type drainage system with relict "islands" of older peneplain; mature, hierarchic drainage network sourced far from basin margin); **D** — Podlasie Basin and Bieżuń Bay (leaf-type drainage system with relict "islands" of older peneplain; mature, hierarchic drainage network sourced far from basin margin); **E** — Holy Cross Mts. and Silesian–Cracow Highs (c — bifurcate type drainage system with relict "islands" of older peneplain; mature, bipartite, confined drainage network, related to tectonic pattern and sourced far to the south of the basin margin, d — local poorly developed drainage system sourced close to basin margin); **F** — Wolsztyn High (western and eastern) (dispersal type, unconfined drainage system with relict "islands" of older peneplain, controlled by tectonic framework and embracing zones of selective erosion); WPH — Western Pomerania High; SB — Słupsk Basin; MB — Mazury Basin; M-SH — Mazury–Suwałki High; PB — Podlasie Basin; S–CH — Silesian–Cracow High; WH — Wolsztyn High; EE — Eastern Erg; SE — Southern Erg; CB — Central Basin (= Mid-Polish Trough)

Ogólna geometria polskiego basenu górnego czerwonego spągowca (według J. Pokorskiego, 1988, zmodyfikowane i uzupełnione)

1 — litofacje plai; 2 — przypuszczalne litofacje fluwialne strefy transferu; 3 — litofacje fluwialne; 4 — litofacje aluwialne obrzeży basenu; 5 — litofacje eoliczne; 6 — obszary alimentacyjne; 7 — kierunki transportu osadu (rozmiary strzałki wskazują na znaczenie względne); 8 — przypuszczalne kierunki transportu osadu; 9 — przypuszczalne wczesne kierunki transportu osadu; A–F — obszary zlewni: A — wyniesienie zachodniopomorskie (system drenażu uwarunkowany tektoniką blokową, zasilany od północy, blisko brzegu basenu); B — basen słupski i wyniesienia strefy Koszalina–Chojnic (a — przypuszczalna oś wczesnego systemy drenażu zasilanego od NE w oddaleniu od brzegu basenu, b — późny lokalny system sieci drenażu zasilanego bliżej brzegu basenu; system drenażu uwarunkowany strukturą tektoniczną wyniesień strefy Koszalina–Chojnic); C — basen mazurski i przypuszczalna strefa transferu osadów (liściowaty system drenażu z reliktowymi wyspami starszej peneplony; dojrzała hierarchiczna sieć drenażu zasilana w dużej odległości od brzegu basenu); **D** — basen podlaski i zatoka Bieżunia (liściowaty system drenażu z reliktowymi wyspami starszej peneplony; dojrzała hierarchiczna sieć drenażu zasilana w dużej odległości od brzegu basenu); E — wyniesienie świętokrzyskie i śląsko-krakowskie (c — widlasty system drenażu z reliktowymi wyspami starszej peneplony, dwuczęściowa sieć dojrzałego systemu drenażu, związana ze strefami tektonicznymi i zasilana daleko na południe od brzegu basenu, d — lokalny

Periodic rivers. A separate description is required in a case of fluvial deposits distinguished in sequences dominated by aeolian deposits (R. P. Langford, M. A. Chan, 1989). Their origin is two-fold. They represent either fluvial system starting to develop from basin margins (or dune fields area) and eroding through dune deposits (*wadi*), or deposits related to periodic rainfall in areas dominated by aeolian sediments. The example of both these environments is found in the Piła IG 1 well-section (Fig. 3). It comprises deposits of periodic rivers and streams prograding over dune fields during pluvial periods or sediments of ephemeral streams deposited owing to torrential rainfall. They form fluvial sequences comprising facies representative of channels, floods and sheet flows, commonly of limited extent, interlayered with aeolian sediments. Their development is attributed to a deposition in arid climate, in which episodic, often torrential, rainfall generates periodic rivers and streams of considerable erosional power and of high energy of transportation (highly loaded). In proximal areas these rivers eroded deeply incised valleys (*ueds*) supplying material deposited either in a transfer or distal zone depending on a duration of rains, loading with terrigenous material as well as on water-loss during transportation. The rivers vanished when entering flat areas, and left blankets of fine-grained alluvial sediments (sheet flows). In some cases, with higher rainfall, there may have formed periodic lakes in palaeotopographic lows, often representing interdune areas. In the proximal zone coarsely clastic sediments may dominate, carried out from areas of erosion for considerable distances and deposited within sandy aeolian sequences. Their drainage zones are restricted and sediment-sources are of local importance.

A system of periodic rivers of *wadi*-type was composed of several hierarchically arranged elements. Smaller *wadi* channels were linked with larger ones developed along axial parts of drainage zones. Central channels, probably active once during each tens of years due to catastrophic floods, were often modified by erosional slope processes and by prograding dune fields. Deposits of periodic rivers occur in aeolian sequences as single erosional channels or as larger complexes indicating longer-term climatic changes. During the present study sediments interpreted as *wadi* have been distinguished in the Witowo–Radlin area near SW basin margin (H. Kiersnowski, 1996). Such sediments are widespread in other marginal areas as well.

AEOLIAN SYSTEM

Sediments of the aeolian depositional system represent the final stage of deposition in the evolution of the Upper Rotliegend basin. Their development has modified to some degree basin palaeotopography as a result of specific depositional regime less dependent on tectonics and topography and more on climate. Sediments of the aeolian system are associated with other depositional systems, i.e. the fluvial system of periodic rivers (*wadi*) and the playa system of periodic lakes. The aeolian system comprises dune (erg) and interdune sediments. It has been described in many localities of the Piła and Pniewy area through Poznań and Września region to Kalisz area (Figs. 2–4, 8, sequence 8b).

DUNE SEDIMENTS (ERGS)

The dune system is composed of the following sedimentary associations: (1) dune, (2) interdune, and (3) extra-dune.

Dune association comprises three facies: dune top, dune core and dune base. The sediments of the dune top member are mostly not preserved due to erosion during subsequent depositional cycle. In addition, they are difficult to distinguish in core material because it is often impossible to decide whether middle or upper dune member is observed. The dune core member occurs more frequently. Both members are built of fine- to medium-grained sandstones commonly with an admixture of very fine-grained sand (dust). Lamination reflects bimodal grain-size distribution with mostly very well sorted material in particular laminae which show normal or reversed grading. Thicker sandy laminae are often intercalated with very thin laminae of fine-grained sand with clayey admixture. The sandstones commonly are weakly cemented and display considerable porosities. Laminae forming inclined sets may reach considerable thicknesses of more than 10 cm and angle of dip of more than 35° after compaction. The dips decrease downward to horizontal arrangement at the base, parallel with decreased thicknesses of laminae and their higher frequency. The lower set of laminae is described as a dune base. It is often characterized by alternation of laminae of well-sorted sandstones (sometimes medium-grained) and those with considerable clayey admixture. It also shows increased degree of cementation. In the sediments of the Eastern Erg (Fig. 5) one can distinguish sequences of barchanoidal dunes and relatively thick sequences of transversal dunes.

Interdune association comprises three facies: dry interdune, moist interdune, and wet interdune with flood sediments deposited in fluvial environment. They are composed of sandstones with flat horizontal or low-angle inclined lamination, low angle crosslamination or lenticular (adhesive ripplemarks) lamination, as well as of convoluted and homogeneous sediments. Common are scours and flat erosional surfaces. In addition to fine- to coarse-grained sandstones there occur siltstones and claystones. The dry interdune facies is represented by sediments of sand sheets. These are mostly interlayered coarse- and fine-grained sandstones with sets of

słabo rozwinięty system drenażu zasilany blisko brzegu basenu); F — wyniesienie wolsztyńskie (część zachodnia i wschodnia)(rozproszony, otwarty system drenażu z reliktowymi wyspami starszej penepleny, uwarunkowany strefami tektonicznymi i obejmujący rejony selektywnej erozji); WPH — wyniesienia zachodniopomorskie; SB — basen słupski; MB — basen mazurski; M–SH — wyniesienie mazursko-suwalskie; PB — basen podlaski; S–CH — wyniesienie śląsko-krakowskie; WH — wyniesienie wolsztyńskie; EE — Erg Wschodni; SE — Erg Południowy; CB — basen centralny (= bruzda śródpolska) horizontal or low-angle inclined lamination. Such sediments are accumulated due to a very slow accretion with frequent intermittent deflation periods. The moist interdune sediments are similar to above facies but with larger proportion of pelitic components. They contain minor clayey interbeds, adhesive ripplemarks and varts, lenticular and inclined lamination. The wet interdune deposits are distinctly finer-grained including fine-grained sandstones, siltstones and claystones which are finely parallel laminated or with a disturbed lamination (due to density loading or to a bioturbation). They represent ephemeral ponds or periodic floods. Formation of moist and wet interdune deposits is connected with periods of increased humidity and shallow occurrence of groundwater.

Extra-dune association is composed mostly of sand covers with negligible admixture of sediments forming base dune members. It has been discerned here because of its distinct features and common occurrence within the aeolian system. The sediments are analogous to dry interdune deposits, they occupied, however, vast areas in proximal windward side of ergs or in distal leeward regions behind them (I. G. Wilson, 1971). Associated with those sediments are remains of small barchanoidal or dome-shaped dunes and deflation lag deposits. They have been formed during periods of strong winds and/or limited sand input (S. G. Fryberger *et al.*, 1979; G. Kocurek, 1988). The sediments probably representing this facies occur in the Pniewy–Obrzycko region in SW part of the basin, and, possibly, in the southern area near Kutno and Łódź.

EVOLUTION OF ERGS

The aeolian complex consists of several depositional sequences interpreted as particular ergs. Ergs are composed of dune and interdune sequences separated by erosional boundaries of first-order bounding surfaces (G. Kocurek, 1988). The boundaries reflect prolonged periods of erosion and/or hampered aeolian accumulation. Dune and interdune deposits form distinct well-defined lithological units. Dune sequences are characteristic in that dune crests are commonly cut leaving only lowermost parts preserved. Erosion may have even reached down to the very base of a dune leaving only interdune deposits preserved. In such a case it is commonly difficult or hypothetical to define erg boundaries, particularly when only wireline logs are available.

Development and migration of ergs was controlled by climate and palaeotopography as exemplified by orographic barriers forming obstacles for migration of aeolian sands on a basin scale. Preliminary studies based on oriented cores and dipmeter data (H. Kiersnowski, 1996) indicate that considerable part of the Eastern Erg sediments have been deposited under prevailing northerly and north-westerly winds assuming continental reconstruction by C. R. Scotese and R. P. Langford (1995). Sediment sources were located to the south, in the area of a palaeohigh of the Variscan plateau and in the south-east in the Holy Cross Mts. palaeohigh and in its foreland, in the region of vast alluvial plain probably of recent *shatt* type. Depending on the directions of steady winds, the Wolsztyn High could have formed a barrier for erg migration towards the west. The steady winds directions, interpreted for the first time for the Polish Permian Basin, are in accordance with the atmospheric circulation patterns in the model for the Artinskian (Early Permian) by J. T. Parrish (1995) and for the Late Permian of the Northern Pangea (E. J. Barron, P. J. Fawcett, 1995). They probably reflect generally northerly winds driven by monsoonal circulation which, after dropping off their moisture load in the mountains or uplands of the Tethys margins (J. T. Parrish, F. Peterson, 1988) played the role of the main driving force of the aeolian transport in the studied basin.

When accepting generally assumed overall increase of climatic aridity during the Late Permian, one can ascribe the onset of a desert sedimentation to deposits of lower part of the Upper Rotliegend. In the initial stage of the basin development incipient dune fields have formed probably on the alluvial plains and along the margins of the incipient playa. Broadening of the basin during the deposition of the upper part of the Upper Rotliegend created suitable conditions for accumulation and preservation of considerably larger amounts of aeolian and fluvial sediments. At the same time it has been a period of a formation of tectonic grabens system undergoing fast and widespread subsidence, and in many cases filled with aeolian sandstones. In the uppermost Upper Rotliegend time playa expanded over vast areas previously dominated by an aeolian sedimentation. Playa sediments are lithologically differentiated as they reflect periodic considerable influence of fluvial and aeolian sediments prograding towards playa centre. At the same time, ergs reached their maximum lateral extent encroaching over new areas and forming overstepping pattern relative to older deposits of the Rotliegend. The aeolian sedimentation has continued up to the onset of the Zechstein sea transgression, and even coevally with it in marginal zones, as exemplified by drowned deformed or scoured crests of various types of dunes observed in the areas of Poznań and Lubin (Silesian Basin) (P. H. Karnkowski, 1986; T. Jerzykiewicz *et al.*, 1976).

Aeolian deposition has been controlled by differentiated subsidence of particular parts of the basin and, most of all, by considerable periodic climatic fluctuations influencing the source areas and mode of sediments transport. Depending on relative importance of the above depositional controls there has occurred either vertical sediment accretion within local depocentres or transfer zones have developed related to a migration and accumulation of aeolian deposits. During the deposition of a lower part of the Upper Rotliegend the dune fields periodically encroached over the playa area thus stopping its envelopment or limiting its lateral extent. On the other hand, during the latest Upper Rotliegend time the central playa has reached maximum extent by onlapping considerable area of dune fields. The playa contraction and expansion was related to climatic changes characterized by repeated humid and arid periods controlling hydrological conditions including directions and extent of drainage zones. These changes are also reflected in a clear record of cyclic deposition of aeolian sandstone covers (ergs). The development and evolution of ergs correlates with arid periods during which fine-grained material has been blown out from the source areas mostly in the south and south-east, and transported to the north and north-west. During pluvial periods the aeolian sedimentation has been slowed down or even ceased. The erg areas have been vegetated, eroded or overlain by locally accumulating fluvial deposits.

PLAYA SYSTEM

Playa deposits form a permanent element in the Rotliegend basin development. As they develop in arid and semi-arid climate they are a good indicator of climatic shifts. During its development playa has been undergoing considerable changes of its extent and position across the basin. This was controlled by shifting depocentres and periodic pushing by prograding fluvial system or replacement by dune complexes migrating across the basin. The very existence of the playa has been strictly controlled by palaeohydrological conditions in the basin and therefore the detailed sedimentological analysis of the system allows to interpret the changes of these conditions (J. T. Neal, 1975).

The playa system is composed of the following facies associations: (a) sandy playa, (b) clayey playa, (c) evaporitic playa, (d) marginal (transitional) playa zone. Playa deposits are represented predominantly by siltstones, sandy siltstones, and subordinate claystones. There may occur also fine-grained sandstones or even very fine-grained, silty and often clayey sandstones. These deposits are developed as facies of rhythmically occurring channelized and non-channelized sheet floods. They form successions of minor normally graded cycles bounded by numerous erosional surfaces. The characteristic feature is lack of dessication evidence (apart from rare traces of deep cracks related to huge contractional polygons — J. T. Neal, W. S. Motts, 1975) and a common occurrence of sulphate concretions. The dessication features occur in a transit zone in the playa margin transitional to fluvial system. Less common in the playa system are well-sorted fine- to medium-grained sandstones associated with a system of fluvial distributary channels periodically entering playa area. There may also occur sandstone interbeds representing migrating isolated dunes being precursors of the thick aeolian complexes replacing playa system (e.g. the Piła IG 1 section, Fig. 3). The coarser sand grains admixed to the finer sandy material may have also been transported by winds. The opposite scenario of playa onlapping the areas of dune fields is also shown in Figs. 3 and 4. In the available core material no evidence has been found of evaporitic (halitic) playa, which is so characteristic for the North German Rotliegend Basin. Consequently, we see no evidence of sebkha deposits surrounding the great German salt lake. Some indications of evaporitic playa are manifested by a common occurrence of early diagenetic anhydrite concretions.

The expansion and disappearance of playa take place in conditions largely similar to lacustrine environment and therefore they may be analysed using sequence stratigraphic approach. In the Upper Rotliegend succession two major depositional cycles have been distinguished (Fig. 9) of which the lower one represents the wet playa development with predominant silty-clayey lithofacies (Fig. 8, sequences 2–5) whereas the upper is associated with the dry playa of predominantly clayey-sandy development (Fig. 8, sequences 7–8b).

BASIN EVOLUTION AND THE DEVELOPMENT OF SEDIMENT SOURCE AREAS

Analysis of areas supplying sedimentary material is a key to understanding the depositional history of the Rotliegend basin. In previous palaeotectonic studies (J. Pokorski, 1988; R. Wagner *et al.*, 1980) the main emphasis has been put on erosion of the Wolsztyn High (WH) as a main source of sediment for the Central Basin (CB), and, to a large degree, for the Silesian Basin (Figs. 5 and 7). The assumed eroded thicknesses, mostly of the Lower Permian volcanics and Carboniferous clastics, have been interpreted as sufficient to explain the amount of basinal sedimentary fill (*cf.* palaeostructural cross-section in *Atlas litofacjalno-paleogeograficzny...*, 1978). Słupsk (J. Pokorski, 1976), Peri-Baltic (J. Pokorski, 1974) and Podlasie (J. Pokorski, 1971) Basins were described as separate shallow basins whose origin has been controlled by tectonic activity at the turn of Lower to Upper Rotliegend times. Because of lacking or merely minor intermittent connections with the Central Basin those areas have not sourced the CB.

In this paper I will attempt to substantiate the opposite interpretation assuming a prime importance of the above basins as source areas along with the possible existence of a widespread drainage zone in northeastern and eastern margin of the basin, being main source of sediment. The presented model stresses the importance of erosional processes, development of drainage zones and palaeorelief differentiation in source areas. On the other hand, less importance is attached to tectonic subsidence which, according to this interpretation, could have been lacking in the area of the Precambrian Platform during the Rotliegend and Zechstein sedimentation. In his papers from 1988 and 1997 J. Pokorski assumes no subsidence in this area during the Upper Rotliegend time. According to R. Wagner (1994) "...the Precambrian platform has been characterized by a weakest subsidence entirely compensated by a sedimentation during all stages of the Zechstein basin development". The cited author argues that the overstepping extent of the Zechstein relative to the Upper Rotliegend, particularly conspicuous in the Precambrian Platform area, have been possible "...owing to strong impulses of subsidence during transgression". According to this interpretation the subsidence would start precisely at the time of the Zechstein transgression. There is a highly interesting coincidence of palaeotopographic lows formed due to pre-Zechstein erosion with the areas of presumed stronger or weaker subsidence. This problem was attracting the attention of

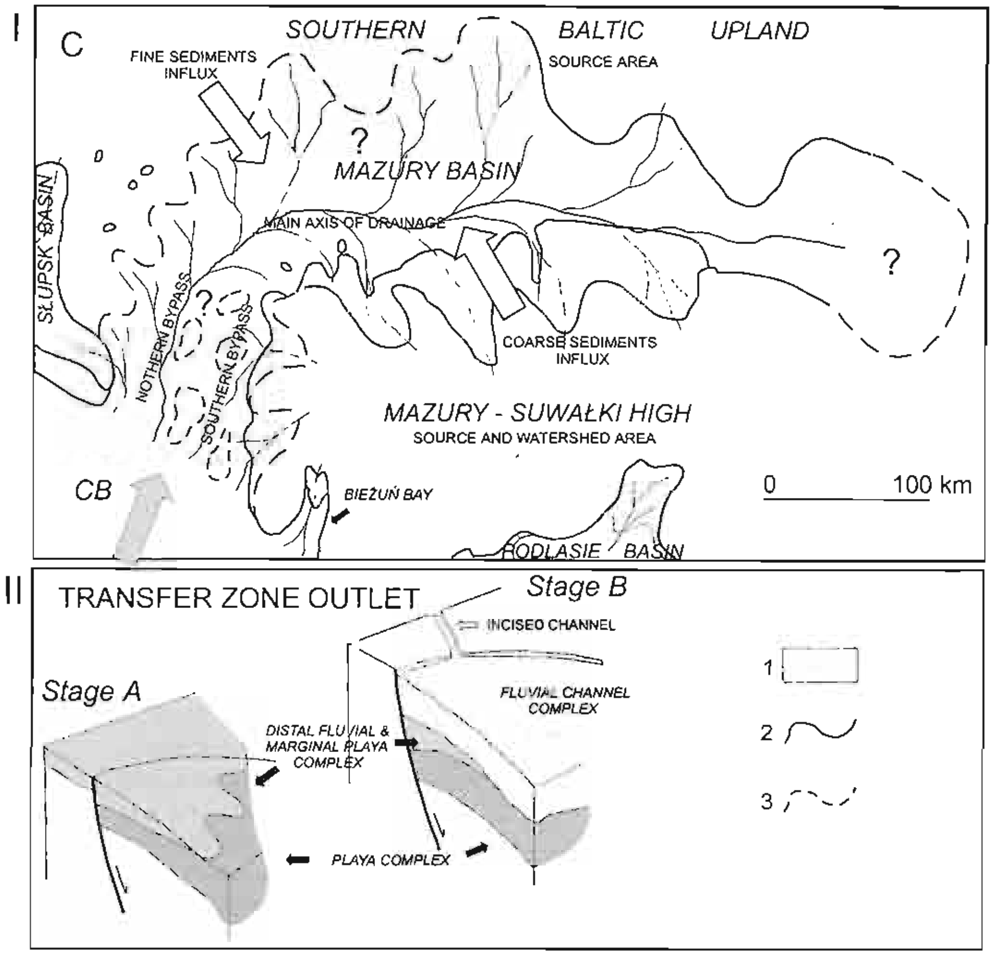


Fig. 6. Catchment zone C of the Mazury Basin (I) and conceptual model of a supposed sediment transfer zone (II) (partly based on J. Pokorski, 1974 and B. M. Edwards, 1995)

1 — coarse deposit fringe around Mazury–Suwałki High, 2 — present extend of Upper Rotliegend deposits, 3 — supposed extend of Upper Rotliegend deposits; **stage A** — topography healed by sedimentation; sediment transfer across inactive fault zone without development of topographical relief; **stage B** — topography controls sedimentation; bypassing of more coarse sediment across active fault zone to rapidly subsiding down-dip block with development of topographical relief (scarps and incised valleys); CB — Central Basin

Obszar zlewni C basenu mazurskiego (I) i model poglądowy przypuszczalnej strefy transferu (II) (częściowo na podstawie J. Pokorskiego, 1974 i B. M. Edwardsa, 1995)

1 — pas osadów grubookruchowych wokół wyniesienia mazursko-suwalskiego, 2 — dzisiejszy zasięg górnego czerwonego spągowca, 3 — przypuszczalny zasięg górnego czerwonego spągowca; **etap A** — rzeźba zamaskowana przez osady; transfer osadów przez nieczynną strefę uskokową bez powstawania rzeźby powierzchniowej; **etap B** — relief warunkuje sedymentację; tranzyt osadów grubiejklastycznych przez aktywną strefę uskokową do szybko obniżanego bloku zrzuconego przy rozwoju rzeźby powierzchniowej (skarpy i wcięte doliny); CB — basen centralny

above authors (R. Wagner *et al.*, 1980) who compiled the maps of persistenee of palaeotopographic lows during the Rotliegend and Zechstein times which stresses the trends and a frequency of occurrence of the maximum depression and uplift of particular areas. The areas of the Słupsk Basin (SB), Podlasie Basin (PB) and the southern part of the Mazury Basin (MB) and Chełmno Peneplain has been assigned to the group of areas without or with a small subsidence.

SOURCE AREAS AND SEDIMENTARY FILL OF THE CENTRAL BASIN

Prolonged period of subaerial exposure characteristic for the Rotliegend time have led to preferential erosion of the most susceptible rocks, partial exhumation of older palaeorelief in the surroundings of the CB and consequently to a considerable differentiation of the palaeotopography. Depending on climate and topographic gradients either mechanical or chemical weathering prevailed with eroded material being transported by fluvial or aeolian processes. The different lithological composition of the bedrock in eroded areas has been presented on the map by J. Pokorski and A. M. Żelichowski (*fide* J. Pokorski, 1997). In the area of the northeastern basin margin the erosion affected Proterozoic metamorphic rocks and siliciclastic and carbonate deposits of the Silurian to Carboniferous. In the south-west eroded have been mostly clastic Carboniferous and volcanic Carboniferous–Permian rocks. The lithological variability of the bedrock in source areas could have influenced directions, transportation intensity and accumulation of detrital material, and, indirectly, also type and petrological composition of depositional facies (A. Maliszewska, J. Pokorski, 1986). In many investigated sections clear local sediment sources are interpreted. Only during certain periods dominated by a fluvial sedimentation the expanding drainage areas could have transported sediments for considerable distances. Similarly, in the case of aeolian sandstones their source areas could have been removed far from the accumulation areas.

In order to analyse a balance of the Rotliegend sediments in the CB (i.e. Mid-Polish Trough) it is necessary to trace the evolution of particular source areas. The latter have been ascribed to earlier distinguished palaeogeomorphological elements (J. Pokorski, 1988) and categorized according to their presumed importance as source areas and differentiation of catchment zones (Fig. 5). Two main groups are distinguished:

I. The areas of accumulation and sediment transfer: Słupsk Basin (SB), Mazury Basin (MB), Podlasie Basin (PB).

II. The areas of erosion and sediment transfer: the highs in the northwestern basin margin (West Pomeranian), the highs of the Koszalin–Chojnice zone, Chełmno Peneplain, Mazury–Suwałki High (M–SH) (Bieżuń Bay), the highs of the southeastern basin margin (Holy Cross and Silesian–Cracow), Wolsztyn High (WH) (eastern and western element).

THE HIGHS IN THE NORTHWESTERN BASIN MARGIN (WEST POMERANIAN)

These elevated areas (Fig. 5) have been intensely eroded during the Upper Rotliegend time. In the marginal zone this area has been transsected by several active tectonic blocks (R. Dadlez, 1990) with drainage system developing along bounding faults. Consequently, numerous narrow and deep tectonic grabens have formed and accumulated coarse-grained clastics mostly derived from erosion of the volcanic rocks. This material has been transported by fluvial systems far to the south (A. Maliszewska, J. Pokorski, 1986). It is assumed that the drainage system has been well-developed, persistent and often rejuvenated due to proximity of the marginal basin zone characterized by strong lateral gradients of a subsidence rate. In the course of the basin evolution the system gradually moved to the north.

THE SŁUPSK BASIN AND HIGHS IN KOSZALIN–CHOJNICE ZONE

The palaeogeomorphological unit attributed to the accumulation of the Upper Rotliegend sediments of the SB is named the Słupsk Depression (J. Pokorski, 1988, 1997). According to the cited author the thickness of sediments is less then 80 m. They are bipartite, with the lower conglomeratic part of a fluvial origin, and the sandy upper part of fluvial and aeolian origin. In the palaeogeographic framework the SB has formed a local tectonic depression isolated from the CB by a narrow belt of the Devonian and Lower Carboniferous rocks of the Koszalin–Chojnice zone. The coarse clastic facies concentrate along this margin and in the northeastern part of the basin.

Because of a specific location of the SB in the pre-Zechstein Kaszuby elevated area it seems probable that clastic sedimentation in the basin occurred in several stages separated by periods of erosion or non-deposition, and thus dissimilar to the MB and PB. The extent and outline of the basin reflect processes of early erosion and tectonic evolution (R. Dadlez, 1976). Tectonic origin of the basin is probably related to a development of several horsts and grabens (L. Antonowicz *et al.*, 1993) clearly seen in the Koszalin–Chojnice zone and further to the north-east at the margin of the subsided platform. The basin outline reflects the main tectonic NW–SE directions. Paradoxically, although located close to the CB the described basin has not been a main source of sediment (fine-grained in particular) for the CB during the Upper Rotliegend time, i.e. time equivalent of the Noteć Formation or depositional sequences 6 to 8b (Fig. 8).

The hypothetical evolution of the SB may be subdivided into several stages. The first stage has been related to the early development of the Czaplinek Trough (Fig. 7, 8, sequences 1–5). In its eastern termination, at the boundary with the platform, a zone of a strong erosion has formed with a drainage from the South Baltic High (Fig. 6) towards the depocentre developing in the Czaplinek Trough area. The main axis of the zone may have paralleled the trough axis and the deposited sediments may have formed an incipient SB infill. In the Drawa Formation of the Upper Rotliegend basin (Czaplinek IG 2 well) predominant are the lithoclasts composed of sedimentary rocks from source area to the north-west (A. Maliszewska, J. Pokorski, 1986). The described stage has continued up to the onset of tectonic block movements (L. Antonowicz *et al.*, 1993) which probably have led to a formation of a narrow barrier built of the Devonian and Lower Carboniferous rocks along the NE Central Basin margin (Koszalin–Chojnice zone), cutting off the sediment supply from the South Baltic High to the Mid-Polish Trough (CB). Parallel to this barrier a small depocentre has been formed whose sediments probably have buried remains of the sediments deposited during the early first stage of development. Gradual erosion of this barrier and its partial disintegration induced transportation of detrital material to topographic lows on both flanks: newly formed part of the SB and NE part of the CB. In the Noteć Formation succession of the Czaplinek IG 2 well predominant are lithoclasts of volcanic rocks indicating new transport direction from the north-west. The SB has been isolated, filled with sediments and, probably, has been undergoing weak subsidence in its SW part.

During stages 2 and 3 the SB did not form important source area for the CB, having been blocked by the elevated barrier of the Koszalin–Chojnice zone. There could have probably existed local transfer zones (gorges?) particularly in a southern part of the SB (J. Pokorski, 1976, 1978) linking it to the CB. The Koszalin–Chojnice zone have been a local source zone for the Czaplinek area. During the final stage before the onset of the Zechstein transgression parts of the SB undergoing a weak subsidence have been filled with the aeolian deposits(?) of the Darłowo Formation (J. Pokorski, 1976, 1997) whereas a fragment of the previous basin within the Koszalin and Łeba Highs has been partly eroded.

MAZURY BASIN

The Mazury Basin (Figs. 5 and 6) is represented by the Rotliegend deposits filling the palaeotopographic element named Peri-Baltic or Warmia Depression. According to J. Pokorski (1974) the sedimentary fill has been composed of conglomerates and arkosic or greywacke sandstones with subordinate proportion of siltstones and claystones. This author argues, basing on numerous cited petrological studies, that clastic material deposited in a southern part of the Polish Peri-Baltic Depression has been supplied from the M–SH. It was composed of the Proterozoic and also Cambrian to Silurian sedimentary rocks. Basing on vertical variability in composition of clastics in selected Rotliegend sections it has been shown that source area has been shifting to the south in the course of the basin development, with the increasing proportion of eroded crystalline basement-rocks (M. Juskowiakowa, J. Pokorski, 1970). The sedimentological-facies studies have demonstrated that these are relatively immature sediments with short transport distances, developed mostly as alluvial fan (*op. cit.*) and braided rivers lithofacies. The entire succession ranges to 60 m in thickness, with a maximum up to 100 m in places, and is composed of at least five depositional units developed as fining-upward cycles. The small islands lacking Rotliegend deposits have been found in the study area which suggests differentiated palaeotopography of the basement, probably displaying hierarchical system of river valleys evidencing erosional origin of the basin. The further evidence are highly variable sediment thicknesses. In general, however, the more coarsely-grained deposits occur in the south, passing to the north into more and more fine-grained ones.

The outline and extent of the MB are closely related to the neighbouring palaeohighs: South Baltic one in the north and the M–SH in the south. According to the Lithuanian data (*Atlas of the lithologic-paleogeographical maps...*, 1990) the northern basin portion is similar to the southern one in the existence of a system of palaeo-valleys perpendicular to its margin; it was, however, topographically less inclined and thus formed less significant sediment source. J. Pokorski (1974) suggested a tectonic origin of the basin stating that formation of the Saxonian macrocycle in the Precambrian Platform area is related most of all to a regional downwarp at the turn of the Rotliegend and Zechstein times. In the later paper (J. Pokorski, 1997) he writes, however, that the stable Precambrian Platform area did not undergo subsidence and the Rotliegend deposits fill palaeorelief, without explaining how was the palaeorelief formed and what was the fate of its original sedimentary infill. It is to be remainded that we are dealing with the basin with a mapped E–W extent of nearly 400 km. The formation of such a vast depression must have been associated with an output of a considerable amount of, mostly fine-grained, clastic material.

The shape and lateral extent of the MB, the thickness of the depositional fill and mapped lithofacies distributions are indicative, according to the present author, of erosional rather than tectonic origin of the sub-basin and of its relationship with the CB. The basin has formed due to lowering the erosional baselevel in the Upper Rotliegend CB. Its geometry reflects the area most susceptible to erosion, built of the Silurian sediments. The late sedimentary fill pre-dating the Zechstein transgression represents frozen drainage system of an accumulation phase comparable to a highstand system tract, with elevated or stable erosional bases.

CHEŁMNO PENEPLAIN

This is a marginal CB (Mid-Polish Trough) area located between the southeastern termination of the Koszalin–Chojnice zone and a marginal portion of the M–SH in the area of the Bieżuń Bay (Fig. 6). The peneplain has been underlain by clayey Silurian rocks, susceptible to erosion and therefore probably forming one of the most important clay material sources for the playa system, particularly for its upper dry complex. The lithological homogeneity of the bedrock in the area, favoured the formation of flat lowlands during successive phases of erosion accompanying lowerings of erosional bases. During intervening periods of erosion the area could have displayed differentiated topography related to developing drainage system and, possibly, to taking over a role of a transfer zone for sediments accumulating in the MB. The area underwent multistage erosion of unclear extent. In the authors opinion, prior to the Zechstein transgression it has formed a broad topographic depression opened towards the CB.

According to pioneer analysis by J. Pokorski (*Atlas litofacjalno-paleogeograficzny...*, 1978) the MB formed isolated, hydrologically confined depocentre not forming source area for the CB. The main sediment-transport directions towards north and north-west have been interpreted basing on lithofacies mapping results, analysis of maximum grain sizes (J. Pokorski, 1974) and heavy-minerals study (M. Juskowiakowa, J. Pokorski, 1970). The evidence is suggestive of a model of further westerly transport of sedimentary material and possibility of the Rotliegend deposits extending to the south-west, to the CB margin. The area may have formed a transfer zone for the sediments carried away from the northern part of the M–SH with fine-grained sediments of the Silurian provenance being introduced during the course of transportation. In the Szubin IG 1 well the lithoclasts of the coarse clastic fraction are composed of more than 15% of magmatic and metamorphic rocks from the eroded M-SH (A. Maliszewska, J. Pokorski, 1986).

The northern MB part together with the hypothetical transfer zone (Fig. 6) may have been supplied mostly with a clayey material from the vast exposures of the Silurian in the northwest, possibly also from the SB region during the last stage. The southern zone has been dominated by a more coarsely-grained material derived directly from the erosion of the M–SH. Depending on a magnitude of erosion (changes of erosional bases), either a sediment-mixing zone may have occurred in the axial transfer zone or one of main lithological components may have predominated. Such a model of the drainage zone, reflecting the eroded bedrock lithology, implies its asymmetry, with a main drainage axis having been shifted to the north of the margin of the initially more exposed M–SH. The asymmetry of the MB and PB was stressed by J. Pokorski (1971, 1974) who, however, attributed this phenomenon to tectonic controls rather than to processes of differential erosion.

In few wells that have reached the Silurian below Zechstein there is so far no evidence in core materials for the existence of the Rotliegend clastics in the possible transfer zone. However, in the authors opinion this does not exclude such a possibility. The zones of a sediment transfer may have been limited to a network of relatively narrow palaeo-valleys with their outlets facing the areas of maximum subsidence in the CB, i.e. Mid-Polish Trough (M. B. Edwards, 1995) (Fig. 6). Width and depth of the valleys may have been controlled by a lateral range and rate of shift of erosional bases. In general, a stage of a deep incision was followed by a period of drainage zones development and peneplain formation. During periods of stable continuous subsidence in the CB a slow erosion has been occurring over extensive catchment areas. This has led to levelling of a relief (lateral erosion and long-distance transport), most of all of the Silurian clayey bedrock, and to related supply of a clay material to the basin.

One can assume the development of a main northern zone transferring sediments to the Czaplinek–Szubin area. The zone could have included gorges or a roley ramps system in the CB edge built of the Devonian rocks. The northern zone, in addition to intermittent sandstone input, may have drained considerable amount of clayey material. The second, southern transfer zone may have had its mouth facing the Łódź Depression (J. Pokorski, 1997). It may have ran parallel to the Bieżuń Bay (*Atlas litofacjalno-paleogeograficzny...*, 1978) as possibly evideneed by preserved parts of sandy braided-river sequenees in the Byczyna area. The southern zone may have drained relatively larger amounts of a coarse elastic material, both sandy and gravelly, derived from closer or more remote regions of the eroded M–SH.

In the reconstructed eross-section I–I (Fig. 2), located perpendicularly to directions of sediment transport from a northern and eastern basin margin, marked are presumed main stages of mostly fine-grained sediment supply to the basin. There are three episodes (P1 to P3) of a considerable flux of clayey material forming a main component of playa sediments. Each of the episodes was probably related to enhanced erosion of the Silurian bedrocks. Only in a case of the lower wet playa complex also the WH has been important sediment source area. Successively retreating erosional escarpments have finally reached sandstones accumulated in the inner part of the drainage area and transport of sand towards the basin has started. In such a way, significant changes in erosional baselevels have led to a formation of megasequences with reversed grading. The sediments have been transported presumably mainly in the northern erosional and transfer zone (Figs. 5 and 6). The outlet of the zone to the basin has shifted gradually to the south during the sediment deposition (sediment fluxes P1 to P3). In a terminal stage of the Rotliegend basin development indications of a reactivated sand supply appear over vast areas the basin.

During periods of a strong subsidence in CB, particularly in its marginal zones, there has been an increase of erosion rate and reactivation of transfer zones. Stronger erosion have created incised valleys and have led to a coarser sediment transportation for longer distances. The sediments have been undergoing sorting in the transfer zone (P. F. Friend, 1993). The palaeogeographic map (Fig. 5, based on: J. Pokorski, 1988) presents assumed possible geometry of the transfer zone during its last developmental stage, predating the Zechstein transgression. It has been presumably a period of rising erosional baselevels and associated minor periodic transport of a detrital material from a remote area of the MB. Within an axis of the extensive drainage system there could have existed a network of shallow broad palaeo-valleys eroded in strongly weathered Silurian clayey rocks and, perhaps, in some cases filled mostly with a redeposited Silurian material.

PODLASIE BASIN AND THE MAZURY–SUWAŁKI HIGH (BIEŻUŃ BAY)

The Podlasie Basin (PB) (Fig. 5) is represented by the Rotliegend deposits filling the palaeomorphological structure labelled the Podlasie Depression. The basin, carefully studied by J. Pokorski (1971, 1974, 1978), is mostly represented by fine elastics (mainly sandstones) with a similar composition as those in the Peri-Baltic Depression, i.e. derived from the northern M–SH, with an admixture of Devonian and Upper Carboniferous material from the Radom–Lublin area in the south. Basing on heavy-mineral assemblages in the Rotliegend, J. Pokorski (1971) determined temporal changes in main directions of a sediment supply to the PB and mapped several palaeo-valleys at the same time assuming tectonic controls for some of them (J. Pokorski, 1978). In the northern part of the PB coarse detrital fraction dominates in alluvial fan facies (J. Pokorski, 1974 distinguished 3 main alluvial fans there); overall, however, sand fraction is dominant in the basin. The Rotliegend thicknesses have been found to exceed 50 m in wells in central parts of the sub-basin where, however, also elevated erosional remnant of the substrate has been

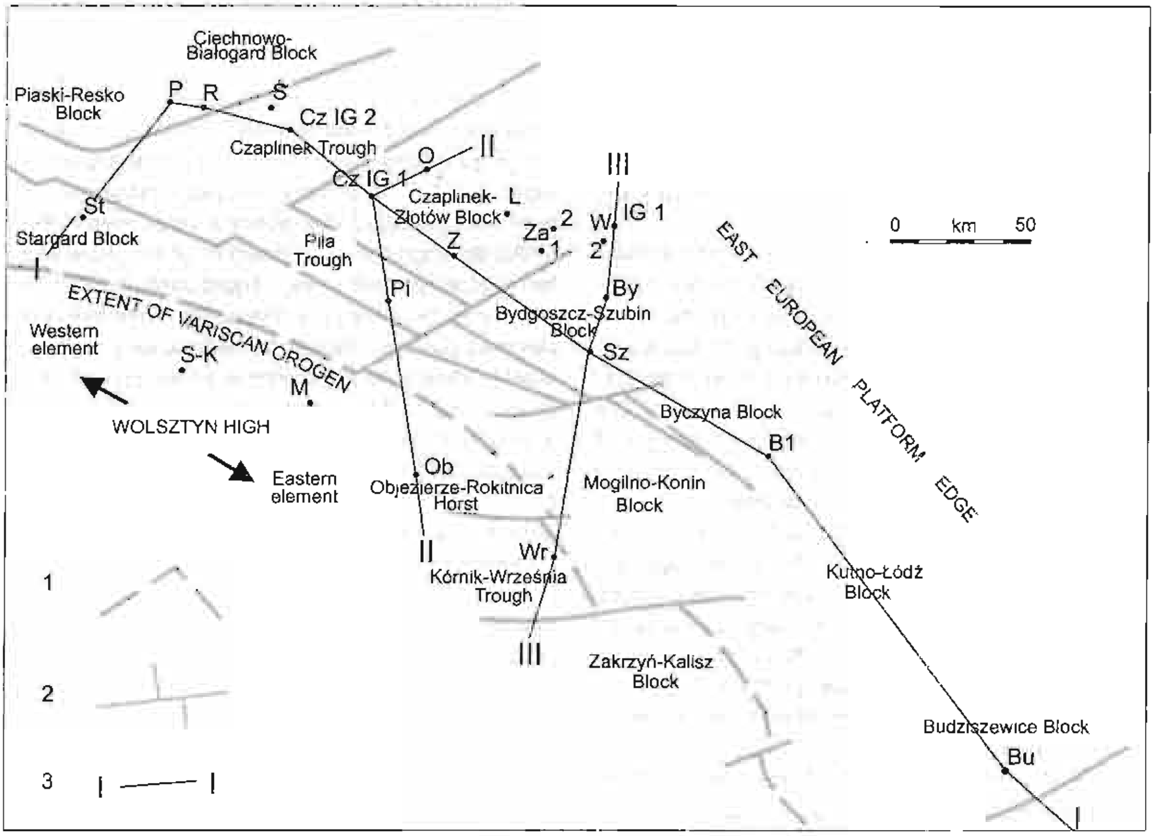


Fig. 7. Palaeotectonic sketch-map with described structural elements and wells

1 — front of Variscan deformations (after J. Pokorski, 1989), 2 — presumed main tectonic lineaments (partly after J. Pokorski, 1997), 3 — lines of cross-sections (Figs. 2–4); B1 — Byczyna 1, By — Bydgoszcz IG 1, Bu — Budziszewice IG 1, Cz IG 1 and Cz IG 2 — Czaplinek IG 1 and Czaplinek IG 2, L — Lipka 1, M — Mężyk 1, Ob — Objezierze IG 1, O — Okonek 1, P1 — Piła IG 1, P — Piaski PIG 2, R — Resko 1, S-K — Strzelce Krajeńskie IG 1, St — Stargard 1, Sz — Szubin IG 1, Ś — Świdwin 3, W IG 1 — Wilcze IG 1, W2 — Wilcze 2, Wr — Września IG 1, Z — Złotów 2, Za 1 and Za 2 — Zabartowo 1 and Zabartowo 2

Szkic paleotektoniczny z wyróżnionymi w opracowaniu elementami strukturalnymi i otworami wiertniczymi

1 — przebieg frontu deformacji waryscyjskich (według J. Pokorskiego, 1989), 2 — przypuszczalny przebieg głównych stref tektonicznych (częściowo według J. Pokorskiego, 1997), 3 — linie przekrojów paleostrukturalnych (fig. 2–4)

detected. This observation and a variable pattern of sediment thicknesses mapped by J. Pokorski (1971) is the evidence of a differentiated basin substratum being in favour of its erosional rather than tectonic origin.

Mapped geometry of the PB (*Atlas litofacjalno-paleogeograficzny*..., 1978) displays a characteristic development of a drainage zone between the M–SH (forming palaeowatershed with the MB) in the north and the Radom–Lublin High in the south. The sediments accumulating in the basin have been periodically reactivated and carried out to the CB in concert with climatic changes and shifting baselevels in a gorge zone linking both the depocentres. Existence of such a gorge is necessary to explain assumed palaeohydrological drainage and removal of sediments leading to a formation of such an extensive erosional feature. J. Pokorski (1971) mentions it as the Okunie–Dębe Wielkie Depression (suggesting the existence of many similar depressions) through which "...the excess of waters and also finer clastic material discharged....to the Kujawy–Pomorze basin". It is not clear how significant was the proportion of the material carried away from the PB in overall mass balance of the CB. It could have been important in its southern part as a possible source of material for aeolian sandstones deposited on the western flank of the CB.

The M–SH which was a principal source of sediments for the PB and MB to some degree has supplied also a clastic material directly to the CB ignoring transfer zones. This is exemplified by the Bieżuń Bay (J. Pokorski, 1978) representing probably one of several palaeo-valleys developing around the M–SH. Sediment transported in this local drainage system has been supplied directly to the CB.

HIGHS NEAR THE SOUTHEASTERN BASIN MARGIN (HOLY CROSS AND SILESIAN–CRACOW)

This area is characterized by differentiated palaeotopography and geological structure of source areas (Fig. 5). The eastern, more differentiated part is bounded to the north by the active Grójec fault zone influencing subsidence development and thus inducing frequent changes of erosional baselevels. This may be reflected in three main fluvial depositional sequences F1 to F3 developed to the north of the southern basin edge (Fig. 2). Axes of the drainage system (palaeo-valleys) have been running along tectonic zones striking NW–SE. Consequently, the drainage system has been relatively deeply incised and developed far into source areas whereas the transported material was of a very variable provenance. The differentiated palaeotopography is confirmed by the subsequent development and distribution of the Zechstein lithofacies (A. Morawska, 1992; R. Wagner, 1994). The western part of the catchment area formed a more uniform system causing a drainage system to be much weaker developed with dominance of a local sediment source in the basin marginal zone.

WOLSZTYN HIGH

During the evolution of the Rotliegend basin the Wolsztyn High (WH) (Fig. 5) has been an important elevated element undergoing erosion and during most of the time supplying terrigenous material to the Silesian Basin and, at the early stage, also to the CB (Fig. 8, sequences 1–3 and 6). J. Pokorski (1988) on his palaeotectonc map of the Upper Rotliegend distinguished several elevations within the WH, defined as degradation areas divided by depressions (tectonic grabens). Above palaeotopography has been controlled structurally in the area forming part of the Variscan externides belt (R. Wagner *et al.*, 1980).

The area, initially covered by thick volcanic rocks, has been probably faulted and subsequently strongly eroded and cut by several, mostly structurally controlled, valleys (P. H. Karnkowski, 1991). The grabens are commonly filled with thick coarse clastic deposits. The palaeogeographic-facies sketches (Fig. 8) show progressive degradation and differentiation of the eastern and western part of the WH area along with a gradual development of more mature drainage zones. It seems that the eroded material has been transported mostly towards the south, to the SB (Fig. 5). Sedimentological investigations confirmed a dominance of fluvial deposits along the southern slope of the WH. This has been caused i.a. by blocking the drainage systems development in the north, towards the CB, by dune fields of the Eastern Erg expanding to the south-west.

PALAEOGEOGRAPHY AND DEPOSITIONAL SEQUENCES

The basic depositional lithofacies are represented by texturally and compositionally variable conglomerates, sandstones and siltstones. The distribution and thicknesses of the lithofacies reflect polygenetic character of the basin. In the northwestern part fine clastic sediments up to 1400 m thick predominate whereas in the southeastern part such sediments are subordinate and the entire sequence attains a thickness of 800 m at most (J. Pokorski, 1988). At the same time, concentric distribution-pattern of the lithofacies, typical for many alluvial basins, characterizes the Rotliegend basin, particularly its NW part, with some asymmetry due to a depocentre shift towards the eastern basin margin. Lithofacies geometry indicates continuous lateral expansion related to topographic levelling in the marginal areas and overstepping depositional pattern presumably controlled partly by a crustal extension. The overstepping lithofacies arrangement presumably has been directly caused, particularly at the last stage of the basin development, by a predominance of an accumulation rate over a subsidence one.

Basing on analysed Rotliegend sections several depositional sequences have been distinguished, reflecting stages of evolution of the sedimentary basin. The sequences have been arbitrarily defined mainly on the basis of vertical lithological changes interpreted in terms of changing sedimentary environments distinguished in the course of sedimentological analysis of a core material. It has been attempted to correlate the sequence boundaries defined in studied sections across the basin assuming their isochroneity. To accomplish this, three sections have been constructed (Figs. 2–4) restoring original geometry of some parts of the basin and depositional systems architecture for the time of deposition of the uppermost Rotliegend. Such a procedure made it possible to understand and integrate the synchronous development of different depositional systems, as well as to trace main developmental trends of particular systems. In addition, the diachroneity of depositional trends related to diastrophism and climate has been emphasized.

Presented analysis refers to the part of the Rotliegend basin between the T-T Zone in the north-east (coinciding more or less with the Precambrian East European Platform edge) and assumed range of the area affected by Variscan deformations in south-west (Fig. 7). To make the description more clear several palaeotectonic elements have been distinguished, earlier defined as blocks with deep structural controls (J. Pokorski, H. Kiersnowski, 1996) or proposed in the present paper. Postulated blocks in the sub-Permian substrate (Fig. 7) are areas characterized by a mobility during basin evolution and thus determining sedimentation patterns. The area of Variscan deformations includes palaeotectonic elements composing vast region of the WH (J. Pokorski, 1989) as shown in Fig. 7. The sketches (Fig. 8) present palaeogeographic-facies models of the basin for terminal stages of particular depositional sequences. Thus, the boundaries drawn between particular sequences are thought to represent time boundaries. It is also possible to distinguish several minor lithogenetic units comparable to parasequences. Three main depositional systems, marked in Fig. 8 with different graphic patterns, display a dynamic pattern of changes during the basin evolution. This has been described in comments to particular depositional sequences. The sequences are

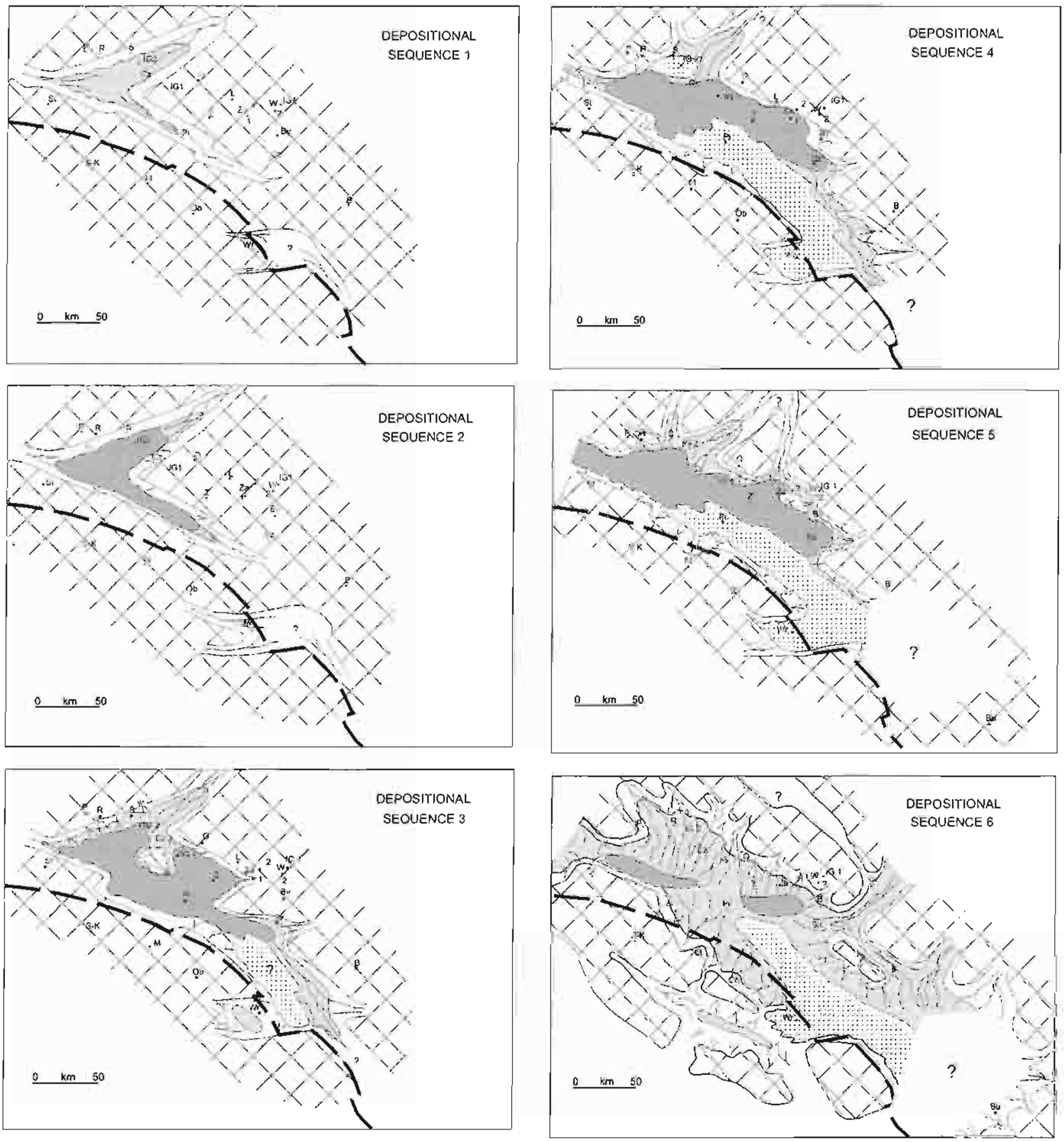
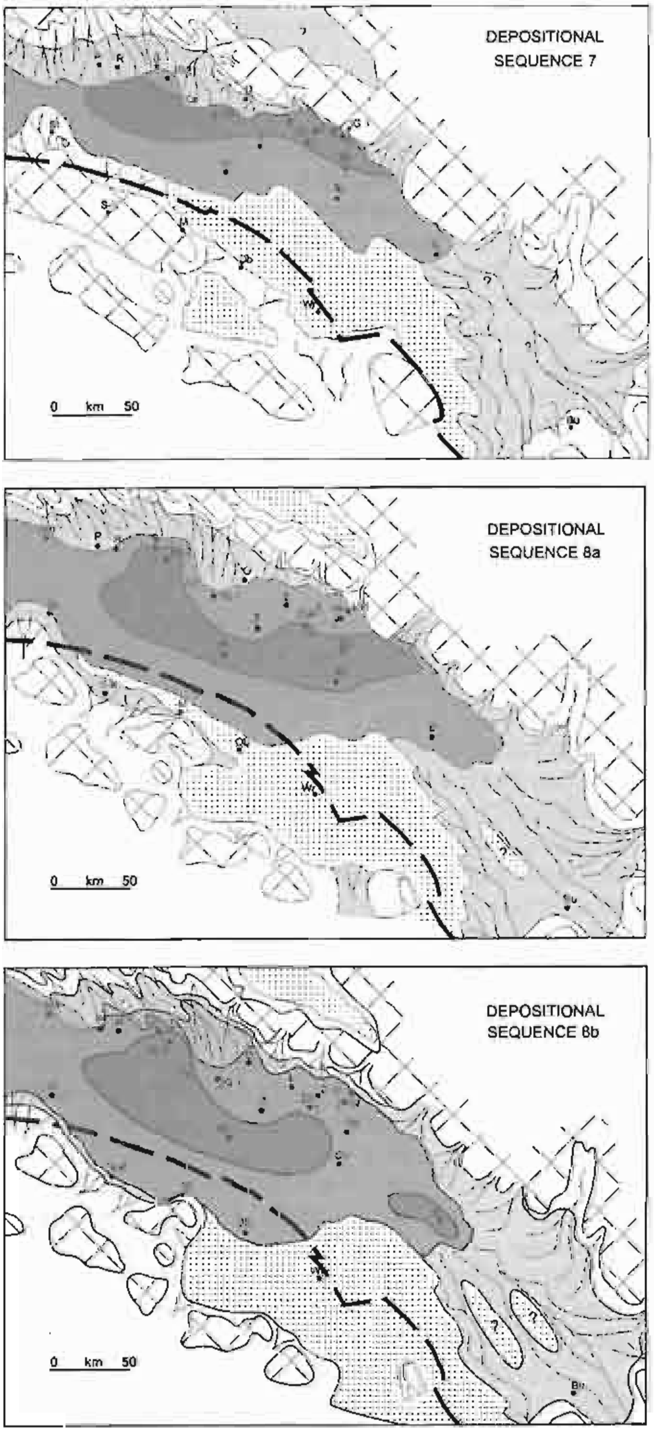


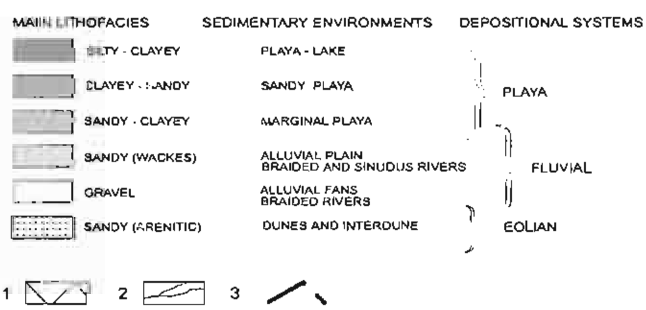
Fig. 8. Palaeogeographic-facies sketch-maps showing distribution of main lithofacies types in depositional sequences 1 to 8b
1 — source areas (eroded Silurian to Lower Permian rocks); 2 — schematic pattern of drainage system; for other explanations and abbreviations of well-names — see Fig. 7

presented against the background of main clastic lithofacies distribution. The described sequences, their boundaries and interpretation represent the authors views referring to the current state of knowledge of the Upper Rotliegend basin structure and its sedimentary fill.

DEPOSITIONAL SEQUENCE 1

The deposits of this sequence are interpreted as starting the Upper Rotliegend sedimentation in the area of future central Permian basin (Fig. 8). After a period of volcanism,





Szkice paleogeograficzno-facjalne przedstawiające rozmieszczenie głównych typów litofacjalnych sekwencji depozycyjnych 1–8b

1 — obszary alimentacyjne (erodowane utwory syluru do dolnego permu); 2 — schemat systemu drenażu; pozostałe objaśnienia i skróty nazw otworów patrz fig. 7

two tectonic grabens have been formed with incipient small depocentres: (1) Czaplinek Trough bounded to NW by the elevated Piaski–Resko Block and to SE by the Czaplinek–Złotów Block, and (2) Piła Trough bounded to NE by the Czaplinek–Złotów Block and to SW by a hypothetical edge zone of the Variscides block. The Piła Trough is probably linked with the Czaplinek Trough in the north-west, whereas to SE it gradually disappears, probably in the Byczyna Block area. During the same time also the Kórnik–Września Trough could have been initiated, and also other troughs (grabens) to E and SE of the Września region. Remaining areas have been undergoing slow erosion or a small-scale accumulation has been continuing in so far unresolved depocentres (e.g. Kutno–Łódź area). The extensive and shallow Czaplinek Trough and probably narrower Piła Trough have been filled with prograding sequences of alluvial fan deposits, and, in the central parts, probably fluvial deposits of braided rivers. Predominant were sandy-conglomeratic lithofacies.

DEPOSITIONAL SEQUENCE 2

The sediments composing this sequence reflect a period of slowed subsidence and probable expansion of the basin and thus of clastic deposition areas (Fig. 8). Gradual filling with sediments has been associated with slow subsidence in the Czaplinek and Piła Troughs. Still active have been tectonic edges of the following blocks: Piaski–Resko, Ciechnowo–Białogard, Czaplinek–Złotów and Stargard. In addition, a probable regional tilt of the Czaplinek–Złotów Block to ESE has been observed. The SE prolongation of the Piła Trough seems to be less significant. In the remaining areas erosional processes prevailed. In the Kórnik–Września Trough presumably accumulation of fluvial deposits has started. The axes of drainage zones have been located along the grabens, but the drainage embraced considerably broader areas outside the grabens. Probably in the most depressed area of grabens connection the playa lake has formed. The troughs have been filled with mainly prograding facies of alluvial fans arranged in retrogradational sequences, and probably with braided-river facies along axes of drainage zones.

DEPOSITIONAL SEQUENCE 3

The sequence 3 is characterized by a considerably wider distribution of clastic sediments, which represent several sub-basins with local depocentres (Fig. 8). The deposits record a new stage of the basin development related probably to its lateral expansion controlled by extensional tectonics (tilting and subsidence of particular blocks in a substrate) and development of new depocentres. There has been marked increase in subsidence in a zone parallelling the presumed Variscan front. The first stage of subsidence in the Czaplinek Trough has been terminated while the subsidence started in the Czaplinek–Złotów and, possibly, Bydgoszcz–Szubin Block areas. In the Czaplinek Trough the playa has been pushed out by prograding fluvial system developing in the eastern part of the Ciechnowo–Białogard Block. Minor tilting or subsidence of the above block could have been associated with the development of an initial tectonic zone in the Resko region, probably related to the Trzebiatów fault zone (J. Pokorski, 1990). Small graben developed near Resko, filled with coarse clastics, derived mainly from erosion of a local volcanic cover. At the same time the playa has been expanding upon presumably tilted SE slope of the Czaplinek–Złotów Block. The playa development towards SE in the Szubin direction has been blocked by topographic barrier developed due to activation of the Bydgoszcz–Szubin Block. Probably, also a slow subsidence of the Mogilno–Konin Block commenced, where dune fields of the Eastern Erg migrating from S and SE have blocked the playa expansion to the south. Fluvial deposits (Piła IG 1) have appeared intermittently even in more central playa areas. The predominance of the playa system in the Piła region could have been an effect of faster subsidence close to the tectonic line between Piła and Objezierze. In the remaining area erosional processes have been continuing parallel with gradually expanding drainage zones.

DEPOSITIONAL SEQUENCE 4

These deposits record further lateral expansion of a subsidence area with new aetive tectonic zones involved and a gradual structural basin rearrangement (Fig. 8). In the north, in newly developed small graben in the Resko region, alluvial fans have been prograding, which was probably associated with further tilting of the Ciechnowo–Białogard Block to SE and with further considerable subsidence near the edge of the Czaplinek Trough and the Piaski–Resko and Ciechnowo–Białogard Blocks. In the area of the Czaplinek IG 2 well-section fluvial sediments have been deposited probably with intermittent aeolian intercalations. The subsidence along the Czaplinek–Złotów line increased, which was connected with expansion of the playa to NE up to the line of wells Okonek–Lipka–Zabartowo. This line together with synsedimentary fault located between Bydgoszcz and Szubin evidence a development of new active tectonic elements (a sill or several sills forming tectonic steps) controlling increased subsidence along the margin of the T-T Zone. Possible reactivation embraced also northern flank of the Byczyna Block. In the northern part of the basin, the fluvial system, permanently developing from NE, has been burying and pushing out the playa to the south. Southern expansion of the playa has been, however, blocked by an ongoing development of dune fields of the Eastern Erg towards N and NW (Piła IG 1), whereas its SE propagation has been hampered by an alluvial system prograding from a postulated edge of the Byczyna Block. Aeolian sands bave been trapped in the Kórnik–Września Trough which has been undergoing continuous subsidence. In the remaining area erosional processes have been continuing with related gradual expansion of drainage zones.

DEPOSITIONAL SEQUENCE 5

The deposits of this sequence reflect the ongoing subsidence throughout the entire basis area, which has been compensated by a fast increase in sediment thickness mainly of the playa system (Fig. 8). The depocentre has been located probably along the Variscan front, i.e. along the flank of the Stargard Block. Other active zones comprised flanks of the Piaski–Resko and Byczyna Blocks. Fluvial system has remained active in the Czaplinek Trough area. Over the remaining area the playa has expanded by encroachment over the western part of the Piaski–Resko Block, overstepping the Lipka–Zabartowo tectonic zone and reaching the Bydgoszcz region. Towards SE the playa development has been limited by a conspicuous elevation of the Byczyna Block and probably further to the east by continuous development of dune fields of the Eastern Erg. Formation of extensive alluvial plains dominated by sandy facies around the playa enabled a development and migration of aeolian sediments across the entire basin. Thin aeolian sand covers have been deposited in the Resko Trough area and near Zabartowo where they transgressed over playa area probably after migrating from the Bydgoszcz region. At the same time the aeolian sands have been still trapped in the subsiding Kórnik–Września Trough. Over the remaining area erosional processes have been operative continuously.

The polycentric alluvial basin was a depocentre for a vast drainage system developing around it. The system has been modified by an activity of tectonic blocks controlling a development of the basin and its margins. It has been particularly well-developed in N and NE where erosion affected Lower Palaeozoic rocks of the South Baltic High. In the east eroded were the Silurian and Proterozoic rocks of the M–SH. In S and SW erosion affected volcanics of the WH, whose importance gradually decreased due to blocking the basinward drainage by dune fields developing in the north-west. The source area for the aeolian sandstones was located in the south (where it is unknown) and in the south-east, in the incipient Podlasie Basin.

DEPOSITIONAL SEQUENCE 6

The sediments of the sequence 6 record the clear turning point in the basin development (Fig. 8). It consisted in activation of new tectonic zones and associated repeated expansion of the basinal tectonic framework. Strong pulse of subsidence over entire basin have caused rapid breakdown of erosional baselevels and activation of further source areas. Sediment transfer zones have originated along with a strongly developed drainage system supplying fluvial sandstones down to the basin centre. The process has not been uniform as it was associated with slowdown or termination of subsidence in many parts of the basin, and with a partial erosion of older sediments within the accumulation area. Activity continued along tectonic edges in the Okonek–Lipka–Zabartowo–Bydgoszcz zone and in the Byczyna Block which probably has been tilting gradually to the north-east. Continuously developing fluvial system from NE has buried the Ciechnowo–Białogard Block decreasing significance of the Resko Graben and leaving isolated elevation of the Piaski Block. The Stargard Block has been still eroded. At the same time, the SW basin margin has become active in the Obrzycko–Objezierze region and the small Poznań Sub-basin has been formed at the western prolongation of the Kórnik–Września Trough. The relic playa, presumably forming a fresh-water lake, has developed probably only in the local depocentre forming prolongation of the Piła Trough along the Nowogard–Wałcz axis. It represented hydrologically closed basin presumably lacking the western linkage with the German Basin. The contraction of playa has been controlled by a rapid progradation of rimming fluvial deposits towards the basin centre. Particularly active has been still the drainage zone developing in the Czaplinek Trough area (perhaps due to a slow subsidence along the flank of the Czaplinek–Złotów Block) which was manifested in encroachment of a coarse clastic facies far into the basin. Development of dune fields of the Eastern Erg has been stopped, and a subsequent period of stagnation and erosion followed. Over the tilted(?) Byczyna Block, along its NE tectonic flank, the fluvial deposits have developed owing to a system of braided-rivers flowing probably towards the unknown depocentre located in the Kutno–Łódź Block area. In SE basin peripheries the tectonic Grójec zone has become active, bounding the basin from the south. This area is characterized by sediments of alluvial fans prograding to NW.

DEPOSITIONAL SEQUENCE 7

The deposits of the sequence 7 reflect a rapid pulse of subsidence over the entire basin (Fig. 8). It has been expressed among others as a renewed considerable expansion of the playa most of all to the north and east, which could have been related to a shift of depocentres in those directions. A western connection with the German Basin has been opened (reopened?). During the initial phase, probably owing to a new stage of crustal extension, reactivation embraced tectonic zones separating particular blocks in the substratum. Their activity is particularly well visible during the onset of deposition of the described sequence. A very strong subsidence appeared along the Piaski–Resko Block. The Czaplinek–Złotów Block has been probably tilted to SE with resultant sediment-thickness increase near the boundary with the Bydgoszcz–Szubin Block. Tectonic zones between Szubin and Byczyna, and between Szubin and Bydgoszcz have been also active. The Byczyna Block has strongly subsided and has been buried gradually, much the same as in the case of the Piaski–Resko Block. Sedimentary cover appeared upon the so far eroded Stargard Block, probably due to an onset of subsidence.

During later stage of deposition steady strong tectonic activity has been more pronounced in marginal parts of the basin whereas activity of intrabasinal faults ceased and a subsidence has slowed down. It seems that the influence of the tectonic edge Okonek–Lipka–Zabartowo–Bydgoszcz ceased whereas the edge near the Wilcze IG 1 well has been reactivated. Similar synsedimentary faults have played an important role in the area of the Okonek 1 well, to the east of Byczyna, to the south-west of the Objezierze IG 1 well, in the zone flanking the Zakrzyń–Kalisz Block and, finally, in the Budziszewice zone with the active Grójec fault zone. Dune fields of the Eastern Erg after having buried topographic depressions (grabens) encroached over marginal parts of the WH and dominated considerable parts of the Poznań Trough. Fluvial deposits dominate along northern and northeastern basin margins. Probable renewed influence of the tilted Czaplinek–Złotów Block is marked there by pushing to SE one of the main drainage systems. Sediments of fluvial channels are found in the playa area, evidencing periodic progradation of the fluvial system.

DEPOSITIONAL SEQUENCE 8a

The sequence reflects ongoing basin subsidence whose main axis has been running from Resko to Byczyna region (Fig. 8). The playa has remarkably expanded probably due to shifting of subsidence centres towards NE and SE along the T-T Zone. At the same time the playa area started to embrace NE slopes of the WH while dune fields of the Eastern Erg have been encroaching further over the high. Southeastern tectonic margin of the basin has become less important and the basin has been opened further to the south, with periodic rivers transporting clastic material into the vast alluvial plain area. In turn, the material has been deflated and deposited further to NW as aeolian sediments of the Eastern Erg. In the Czaplinek–Okonek area the regional fluvial system has continued to develop. Both Piaski and Stargard Blocks underwent strong subsidence. In the Piaski PIG 2 area a conspicuous fluvial system has developed with drainage axes related probably to the Trzebiatów tectonic zone active further to the north (J. Pokorski, 1990). It may be observed, particularly in the better studied NE part of the basin, that fluvial deposits occur within the playa system as distinct horizons which evidences their cyclic development.

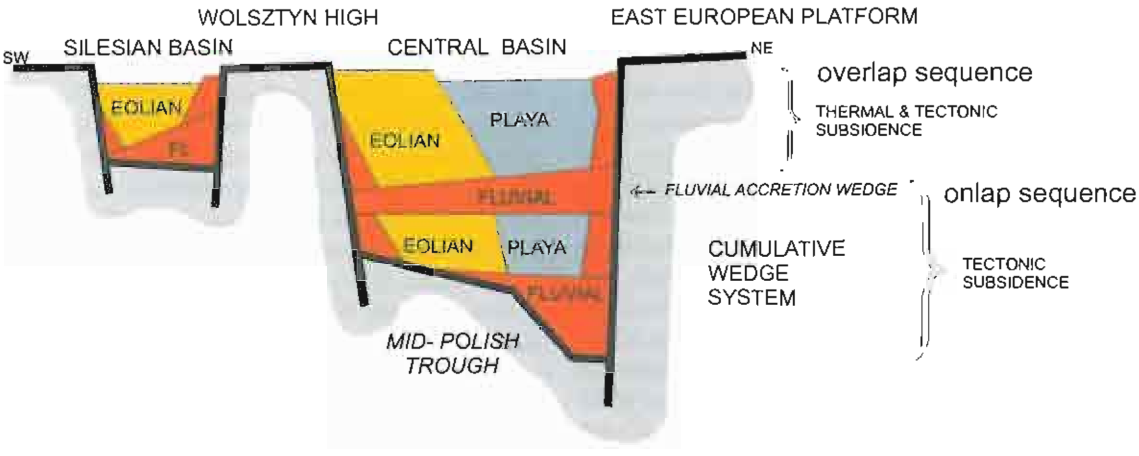


Fig. 9. Schematic cross-section of the Mid-Polish Through (Central Basin) and Silesian Basin showing their simplified depositional architecture

Schematyczny przekrój geologiczny przez bruzdę śródpolską (basen centralny) i basen śląski obrazujący w uproszczeniu architekturę depozycyjną

DEPOSITIONAL SEQUENCE 8b

The sequence represents the upper part of the depositional sequence 8 (Fig. 8, sequence 8b). It has been distinguished in order to present the stage of a maximum Rotliegend development, directly predating the Zechstein sea transgression (Fig. 8, sequence 8b). Maximum range of the Rotliegend deposits has been shown basing mostly on the map by J. Pokorski (1997). Playa has reached its maximum overstepping range over nearly entire basin area. The thicknesses of the aeolian and fluvial systems have reached their maximum values, at the same time filling the remaining topographic relief of the substrate. Towards SW the playa has extended to Strzelce Krajeńskie and Objezierze areas while in the north it onlapped the Moracz and, partly, Stargard Blocks with a broad opening to the west towards the German Basin. At the same time, during the last stage of sedimentation, a fluvial system has become active in NE which has been manifested as a periodic development of fluvial sequences within the playa deposits. Over the remaining area, similarly to the sequence 8a, predominant have been sediments of the aeolian system and periodic rivers of *wadi* type. The uppermost sediments record initial effects of developing Zechstein transgression. These are pelitic lacustrine sediments observed in the basin centre in Byczyna area, and various transgressive sediments of a shore zone related to liquefaction and redeposition of dune deposits, widespread in the marginal basin areas.

Development of a thick and extensive sedimentary eover in the basin due to accumulation of the 7, 8a and 8b sequences was associated with considerable modifications of drainage zones. Source areas located closer to depocentres have been buried and erosion shifted farther away. Subsidence pulses have induced fast changes of erosional baselevels and activation of erosion in source areas. Initially, erosion has affected closest areas undergoing strongest influences of baselevel shifts. The ongoing development of a rejuvenated drainage zone has led to outward migration of an erosional scarps with a delayed involvement of more remote areas into an active drainage zone. Sediment transport from longer distances has been associated with broad transfer zones (Figs. 5 and 6). In the authors opinion, the strongest changes in palaeotopography of the source areas have been related to a formation of erosional depressions in the areas of the later developed Zechstein Baltic and Podlasie Bays (R. Wagner, 1994). Western part of the Wolsztyn High has also undergone considerable destruction and disintegration. Strong development of aeolian system has been related to efficient sources of a detrital material in E and S, and only locally in SW.

CONCLUSIONS

1. The sedimentary development of the Polish Upper Rotliegend Basin involved three interdependent depositional systems: fluvial, aeolian and playa systems.

2. The development of particular systems have been controlled by structural evolution of the extensional (incipient rift) basin and concomittant palaeoclimatic fluctuations.

3. The above depositional systems have influenced each other via complex interrelations. Of particular importance was the influence of the aeolian system, largely independent of factors controlling sediment accumulation within the hydrologically closed alluvial basin, and thus shaping development of remaining systems.

4. The important control of basinal deposition have been the changing sediment source areas and sediment transport directions. During the early stage of the basin evolution main source areas have been located in the west and north. Later on, eastern and southern areas have became dominant. It is here assumed that the important role in sedimentary budget of the basin has been played by periodic sediment transfer zones linking Central Basin (= Mid-Polish Trough) with periferal sub-basins on the Precambrian East European Platform (EEP). The existence of extensive drainage zones implies the possibility of broad erosional depressions on the EEP existing before the Zechstein transgression.

5. Sedimentary fill is composed of two depositional cycles controlled by diastrophism. The lower megacycle has been subdivided into five depositional sequences, whereas the upper one — into four sequences.

6. The lithofacies pattern is asymmetrical (polycentric) and displays overall overstepping trend of the onlap type.

7. The central basin had a polygenetic origin, controlled by basement blocks but, at the same time, it displays general characteristics of a half-graben with the maximum subsidence along the edge of the main fault system in the north-east. The same zone and the axial one are characterized by predominance of finest-grained clastic lithofacies.

8. The persistant occurrence of the playa system (i.e. the lacustrine system of an arid climate) with asymmetrical development of aeolian sediments along the margins, allows to define the Rotliegend Mid-Polish Trough as lacustrine half-graben basin of Fundy-type (P. E. Olsen, 1990).

9. Sediments comprising the fluvial system during its maximum extent form an accretionary wedge prograding generally from north-east to south-west.

10. The aeolian system occupied areas with slower subsidence thus accentuating the basin asymmetry and delineating its less active (SW) marginal zone.

Translated by Marek Narkiewicz

REFERENCES

ANTONOWICZ L., IWANOWSKA E., JAMROZIK J., NOWICKA A. (1993) — Tilted blocks (half-grabens) of the Permian basement in NW Poland — implications for hydrocarbon exploration (in Polish with English summary). Prz. Geol., **41**, p. 71–74, no. 2.

ATLAS OF THE LITHOLOGIC-PALEOGEOGRAPHICAL MAPS OF THE SOVIET BALTIC AND ADJACENT AREAS. PERMIAN–NEOGENE (1990) — Lithuanian Research Institute of Geological Prospecting. Vilnius.

ATLAS LITOFACJALNO-PALEOGEOGRAFICZNY PERMU OBSZARÓW PLATFORMOWYCH POLSKI (1978) — Ed. S. Depowski. Inst. Geol. Warszawa.

BARRON E. J., FAWCETT P. J. (1995) — The climate of Pangaea: A review of climate model simulations of the Permian. In: The Permian of the Northern Pangea, 1 — Paleogeography, Paleoclimates, Stratigraphy (eds. P. A. Scholle, T. M. Peryt, D. S. Ulmer-Scholle), p. 37–52.

BLAIR T. C., McPHERSON J. G. (1994) — Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Jour. Sed. Resear., **A 64**, p. 450–489, no. 3.

DADLEZ R. (1976) — Tektonika. In: Permian and Mesozoic of the Pomerania Trough (ed. R. Dadlez) (in Polish with English summary). Pr. Inst. Geol., 79, p. 112–125.

DADLEZ R. (1990) — Tectonics of Southern Baltic (in Polish with English summary). Kwart. Geol., **34**, p. 1–20, no. 1.

DADLEZ R., NARKIEWICZ M., STEPHENSON R. A., VISSER M. T. M. van WEES J-D. (1995) — Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, **252**, p. 179–195.

EDWARDS M. B. (1995) — Differential subsidence and preservation potential of shallow-water Tertiary sequences, northern Gulf Coast Basin, USA. In: Sedimentary facies analysis (ed. A. Guy Plint). Spec. Publ. Int. Ass. Sed., **22**, p. 265–281.

FRIEND P. F. (1993) — Control of river morphology by the grain-size of sediment supplied. Sed. Geol., **85**, p. 171–177.

FRYBERGER S. G., AHLBRANDT T. S., ANDREWS S. (1979) — Origin, sedimentary features, and significance of low-angle eolian "sand sheet" deposits, Great Sand Dunes National Monument and vicinity, Colorado. Jour. Sed. Petrol., 49, p. 733–796, no. 3.

GEORGE G. T., BERRY J. K. (1994) — A new palaeogeographic and depositional model of the Upper Rotliegend, offshore the Netherlands. First Break, **12**, p. 147–158, no. 3.

JERZYKIEWICZ T., KIJEWSKI P., MROCZKOWSKI J., TEISSEYRE A. K. (1976) — Origin of the Weisslicgendes deposits in the Fore-Sudetic Monocline (in Polish with English summary). Geol. Sudet., **11**, p. 57–87, no. 1.

JUSKOWIAKOWA M., POKORSKI J. (1970) — Lower Permian deposits in the Peri-Baltic Syneclise (in Polish with English summary). Biul. Inst. Geol., **224**, p. 377–409.

KARNKOWSKI P. H. (1981) — The current lithostratigraphic subdivision of the Rotliegendes in Poland and proposition of its formalization (in Polish with English summary). Kwart. Geol., **25**, p. 59–66, no. 1.

KARNKOWSKI P. H. (1986) — The nature of Zechstein transgression versus origin of the Weissliegendes in the Wielkopolska area (northern Fore-Sudetic Monocline, western Poland). Geol. Sudetica, **21**, p. 101–122.

KARNKOWSKI P. H. (1987) — Lithostratigraphy of Rotliegendes in Wielkopolska (Western Poland) (in Polish with English summary). Kwart. Geol., **31**, p. 643–672, no. 4.

KARNKOWSKI P. H. (1991) — Problems of tectonic movements in the Rotliegendes (in Polish with English summary). Prz. Geol., 39, p. 352–356, no. 7–8.

KIERSNOWSKI H. (1996) — Analiza sedymentologiczno-strukturalna utworów czerwonego spągowca w wierceniach Witowo 1 i Witowo 3. Arch. BG Geonafta. Warszawa.

KIERSNOWSKI H. (1997) — Upper Permian eolian complex in Poland. Proceedings of the XIII International Congress on the Carboniferous and Permian, part. 2. Pr. Państ. Inst. Geol., **157**, p. 107–110.

KIERSNOWSKI H., PAUL J., PERYT T. M., SMITH D. B. (1995) — Facies, paleogeography, and sedimentary history of the Southern Permian Basin in Europe. In: The Permian of the Northern Pangea, 2 — Sedimentary basins and economic resources (eds. P. A. Scholle, T. M. Peryt, D. S. Ulmer-Scholle), p. 119–136.

KOCUREK G. (1988) — First-order and super bounding surfaces in eolian sequences — bounding surfaces revisited. Sed. Geol., **56**, p. 193–260, no. 1/4.

KOCUREK G., HAVHOLM K. G. (1993) — Eolian sequence stratigraphy — a conceptual framework. In: Siliciclastic sequence stratigraphy (ed. P. Weimer and H. W. Posamentier). Am. Ass. Petrol. Geol. Mem., 58, p. 393–419.

LANGFORD R. P., CHAN M. A. (1989) — Fluvial-aeolian interactions, part 2 — Ancient systems. Sedimentology, 36, p. 1037–1051.

LEEDER M. R., GAWTHORPE R. L. (1987) — Sedimentary models for extensional tilt-block/half-graben basins. In: Continental extensional tectonics (eds. M. P. Coward, J. F. Dewey, P. L Hancock). Geol. Soc. Spec. Publ., no. 28, p. 139–152.

MALISZEWSKA A., POKORSKI J. (1986) — Mapping of results of petrographic studies on the Rotliegend in western Pomerania (in Polish with English summary). Prz. Geol., 34, p. 427–436, no. 8.

MIALL A. D. (1978) — Lithofacies types and vertical profile models in braided rivers: a summary. In: Fluvial sedimentology (ed. A. D. Miall). Can. Soc. Petrol. Geol. Mem., 5, p. 597–604.

MIALL A. D. (1996) — The geology of fluvial deposits. Sedimentary facies, basin analysis and petroleum geology. Springer Verlag.

MORAWSKA A. (1992) — Permian north of the Holy Cross Mts (Central Poland) (in Polish with English summary). Prz. Geol., 40, p. 216-223, no. 4.

NEAL J. T. (1975) — Playa surface features as indicators of environment. In: Playas and dried lakes. Occurrence and development (ed. J. T. Neal). Benchmark Pap. Geol., 20, p. 363–388.

NEAL J. T., MOTTS W. S. (1975) — Recent geomorphic changes in playas of western United States. In: Playas and dried lakes. Occurrence and development (J. T. Neal). Benchmark Pap. Geol., 20, p. 363–388.

NEMEC W., PORĘBSKI J. (1977) — Weissliegendes sandstones: a transition from fluvial-eolian to shallow marine sedimentation (Lower Permian of the Fore-Sudetic Monocline). Rocz. Pol. Tow. Geol., 47, p. 387–418, no. 3.

OLSEN P. E. (1990) — Tectonic, climatic and biotic modulation of lacustrine ecosystems — examples from Newark Supergroup of eastern North America. In: Lacustrine basin exploration (ed. B. J. Katz). Am. Ass. Petrol. Geol. Mem., 50, p. 209–224.

PARRISH J. T. (1995) — Geologic evidence of Permian climate. In: The Permian of the Northern Pangea, 1 — Paleogeography, Paleoclimates, Stratigraphy (eds. P. A. Scholle, T. M. Peryt, D. S. Ulmer-Scholle), p. 53–61.

PARRISH J. T., PETERSON F. (1988) — Winds directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States — a comparison. Sed. Geol., 56, p. 261–282.

POKORSKI J. (1971) — Lower Permian in the Podlasie Depression (in Polish with English summary). Kwart. Geol., 15, p. 589–604, no. 3.

POKORSKI J. (1974) — The Rotliegendes of the Precambrian Platform — thickness and facies (in Polish with English summary). Kwart. Geol., 18, p. 80–89, no. 1.

POKORSKI J. (1976) — Czerwony spągowiec, warstwy darłowskie i miasteckie. In: Permian and Mesozoic of the Pomerania Trough (ed. R. Dadlez) (in Polish with English summary). Pr. Inst. Geol., 79, p. 10–18.

POKORSKI J. (1978) — The Rotliegendes in north-eastern part of the Podlasie Basin (in Polish with English summary). Kwart. Geol., 22, p. 537–547, no. 3.

POKORSKI J. (1981) — Formal lithostratigraphic subdivision proposed for the Rotliegendes of the Polish Lowlands (in Polish with English summary). Kwart. Geol., 25, p. 41–58, no. 1.

POKORSKI J. (1988) — Palaeotectonic maps of the Rotliegendes in Poland (in Polish with English summary). Kwart. Geol., 32, p. 15–32, no. 1.

POKORSKI J. (1989) — Evolution of the Rotliegendes basin in Poland. Bull. Pol. Acad. Sc. Earth Sc., 37, p. 49–55, no. 1/2.

POKORSKI J. (1990) — Rotliegendes in the northwesternmost Pomerania and the adjacent Baltic Basin (in Polish with English summary). Kwart. Geol., 34, p. 79–92, no. 1.

POKORSKI J. (1997) — Perm dolny (czerwony spągowiec). In: The epicontinental Permian and Mesozoic in Poland (eds. S. Marek, M. Pajchlowa) (in Polish with English summary). Pr. Państw. Inst. Geol., 153, p. 35–62.

POKORSKI J., KIERSNOWSKI H. (1996) — Litofacjalne podstawy prognoz ropo-gazonośności permu na Niżu Polskim, 1. Arch. Państw. Inst. Geol. Warszawa.

RONIEWICZ P., CZAPOWSKI G., GIŻEJEWSKI J., KARNKOWSKI P. H. (1981) — Variability in the depositional environment of the Rotliegendes of the Poznań area. Proceedings International Symposium Central European Permian, 1978, p. 262–272.

SCOTESE C. R., LANGFORD R. P. (1995) — Pangea and the paleogeography of the Permian. In: The Permian of the Northern Pangea, 1 — Paleogeography, Paleoclimates, Stratigraphy (eds. P. A. Scholle, T. M. Peryt, D. S. Ulmer-Scholle), p. 3–19.

WAGNER R. (1994) — Stratigraphy and evolution of the Zechstein basin in the Polish Lowland. Pr. Państw. Inst. Geol., 146.

WAGNER R., POKORSKI J., DADLEZ R. (1980) — Palaeotectonics of the Permian basin in the Polish Lowlands (in Polish with English summary). Kwart. Geol., 24, p. 553–569, no. 3.

WILSON I. G. (1971) — Desert sandflow basins and a model for the development of ergs. Geogr. Jour., 137, p. 180–199.

ROZWÓJ SEDYMENTACJI W POLSKIM BASENIE GÓRNEGO CZERWONEGO SPĄGOWCA I EWOLUCJA JEGO OBSZARÓW ŹRÓDŁOWYCH

S t r e s z c z e n i e

Przeprowadzono analizę sedymentologiczno-facjalną osadów górnego czerwonego spągowca na podstawie rdzeni i danych geofizycznych pochodzących z kilkudziesięciu otworów wiertniczych znajdujących się na obszarze polskiego permskiego basenu sedymentacyjnego. Wykazano, że trzy podstawowe systemy depozycyjne: fluwialny, eoliczny i plai determinowały rozwój pokrywy osadowej. Osady tych systemów depozycyjnych powstawały generalnie w warunkach klimatu podzwrotnikowego, suchego z okresowymi opadami. Z tego powodu rozwój i zasięg osadów fluwialnych był limitowany i często ściśle związany z lokalnymi strefami drenażu. Rozwój osadów eolicznych był głównie kontrolowany przez fluktuacje paleoklimatu. Zostały wydzielone obszary zdominowane przez rozległe pokrywy piaskowców wydmowych o znacznej miąższości (Erg Wschodni i Erg Południowy). Osady plai osiągają również znaczne miąższości. Plaja w trakcie swojej historii depozycji podlegała znacznym fluktuacjom, zmieniając zasięg i przemieszczając się w poprzek basenu. Działo się tak na skutek przesuwania się centrów depozycji oraz okresowego spychania plai przez progradujący system fluwialny lub zastępowania jej osadów migrującymi w poprzek basenu kompleksami wydm.

Wymienione systemy depozycyjne współistniały w trakcie ewolucji basenu oddziaływując na siebie wzajemnie. Szczególnie istotne było oddziaływanie eolicznego systemu depozycyjnego, który nie podlegając generalnym regułom akumulacji w zamkniętym hydrologicznie basenie aluwialnym modyfikował rozwój pozostałych systemów depozycyjnych. Skala rozwoju poszczególnych systemów depozycyjnych była warunkowana fluktuacjami paleoklimatu i rozwojem tektonicznym basenu (jego zakładaną ekstensją, zróżnicowaną w czasie i przestrzeni subsydencją i związaną z tym zmienną przestrzenią akomodacji). Przeprowadzono analizę paleostrukturalną, na podstawie której przedstawiono model rozwoju basenu oparty o wydzielone sekwencje depozycyjne. Granice sekwencji depozycyjnych są w założeniu izochroniczne i mają odzwierciedlać charakter zmian (o genezie tektonicznej lub paleoklimatycznej) zachodzących w całym basenie w poszczególnych stadiach jego rozwoju.

Część pracy została poświęcona analizie potencjalnego wpływu obszarów źródłowych na obserwowane zmiany w rozwoju sedymentacji w basenie. Skonstruowano model wydarzeń depozycyjnych, na podstawie którego wykazano, że istotne znaczenie dla depozycji w basenie odgrywały zmiany

wielkości obszarów źródłowych i zmienne w czasie kierunki transportu materiału osadowego. We wczesnym etapie rozwoju basenu podstawowe obszary źródłowe znajdowały się na zachodzie i północy. W późnym etapie rozwoju basenu zaczęły przeważać obszary źródłowe na wschodzie i południu. Założono istotną rolę w budżecie sedymentacyjnym basenu, okresowych stref transferu osadów, łączących centralny basen czerwonego spągowca z peryferycznymi basenami zlokalizowanymi na platformie prekambryjskiej. Istnienie rozległych stref drenażu implikuje możliwość istnienia przed transgresją cechsztyńską rozległych erozyjnych obniżeń na platformie prekambryjskiej.

Wykreowany model architektury depozycyjnej w basenie nasunął następujące konkluzje: (1) powstawanie osadów wypełniających basen związane jest z tektoniką synsedymentacyjną; (2) cały kompleks osadowy tworzą dwa megacykle depozycyjne o genezie diastroficznej: w dolnym megacyklu depozycyjnym wyróżniono pięć sekwencji depozycyjnych, a w górnym cztery; (3) rozkład i pionowe następstwo litofacji w obrębie całego basenu sedymentacyjnego wykazujc generalnie tendencję przekraczającą; (4) rozkład litofacji w basenie jest niesymetryczny (policentryczny); (5) basen pomimo swojego poligenicznego charakteru, uwarunkowanego blokową budową głębokiego podłoża, ma generalnie cechy półrowu tektonicznego, z największą subsydencją w głównej strefie krawędziowej; odzwierciedla się to w postaci dominacji litofacji najbardziej drobnoklastycznych w strefach osiowych basenu oraz wzdłuż jego północno-wschodniej krawędzi; (6) permanentne występowanie w basenie systemu depozycyjnego plai (systemu jeziornego klimatu suchego) z występującymi niesymetrycznie na jego obrzeżach osadami eolicznymi upoważnia do sklasyfikowania basenu jako jeziornego, utworzonego w półrowie tektonicznym; (7) osady fluwialnego systemu depozycyjnego w trakcie ich największej ekspansji mają formę klina akrecyjnego rozwijającego się generalnie z północnego wschodu na południowy zachód; (8) osady eolicznego systemu depozycyjnego okupują obszary o słabszej subsydencji, podkreślając w ten sposób asymetrię basenu (charakter półrowu) i wyznaczając jego mniej aktywną strefę krawędziową.