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Sequence stratigraphy of Carboniferous paralic deposits in the Lublin Basin (SE Poland)

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ABSTRACT:

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Based on lithofacies analysis of clastic, clay and carbonate rocks, wireline logs and sequence stratigraphy, sixteen depositional sequences have been distinguished in the paralic Carboniferous succession of the Lublin Basin from the Viséan to the base of Westphalian B. The facies evolution and depositional architecture of the deposits belonging to three types of depositional systems tracts, i.e. lowstand (LST), transgressive (TST) and highstand (HST) have been reconstructed. The sequences are bounded by type 1 basal unconformities formed during subaerial erosion following relative sea-level fall and lowstand. This erosion, that in some cases reached down to the LST deposits of the underlying sequences, mainly affected the HST deposits. Relative sea-level rise controlling the base level of the rivers during lowstand was the basic factor influencing facies development, cyclicity and thickness of fluvial deposits, as well as the vertical and lateral transformation of rivers in the paralic Carboniferous succession. Vertical transition of high- to low-energy fluvial environments can be observed within the LST. The LST deposits typically occur in incised shelf valleys and in non-incised fluvial systems. Within the LST of sequences 2 and 4 to 10 commonly occur medium and large systems of simple incised valleys that developed in a coastal-plain system. The LST of sequences 11 to 15 comprises large systems of compound incised valleys that developed in a piedmont system. Relative sea-level rise in the late lowstand, sea-level oscillations during transgression and highstand and the volume of sediment supply were the main factors influencing facies development, cyclicity, thickness and lateral distribution of the deltaic deposits, shallow-shelf shales and limestones. Within the TST commonly occur coarsening-upward and non-gradational cyclothems that correspond to parasequences and were formed in the distal parts of the inner-shelf delta lobes. In the HST, the most common types are coarsening-upward cyclothems developed during the progradation of inner-shelf delta lobes and small lake deltas, as well as non-gradational cyclothems formed in lakes on a delta plain without influence of delta lobes. The transgression of sequence 7 probably had the widest extent of all the sequences in the paralic Carboniferous succession of the Lublin Basin. It was presumably much wider to the N, NE and NW than the presently accepted boundaries of the basin. Based on analysis of three curves of relative sea-level changes in the paralic Carboniferous succession of the Lublin Basin and the transgressive-regressive curve for the Carboniferous of Western Europe, the sequences distinguished have been correlated with the chronostratigraphic scheme for the Carboniferous System. The diachronous commencement of sedimentation has been confirmed and evaluated. The lack of deposits of sequence 5 in the eastern part of the basin suggests the presence of a stratigraphic gap encompassing the upper Brigantian. The position and range of stratigraphic gaps present elsewhere in the basin has also been indicated. In the north-westernmost and easternmost parts of the study area the gap has the widest range, encompassing the upper Arnsbergian to lower Marsdenian strata. The mid-Carboniferous boundary between the Mississippian and Pennsylvanian has been located at the base of sequence 8.

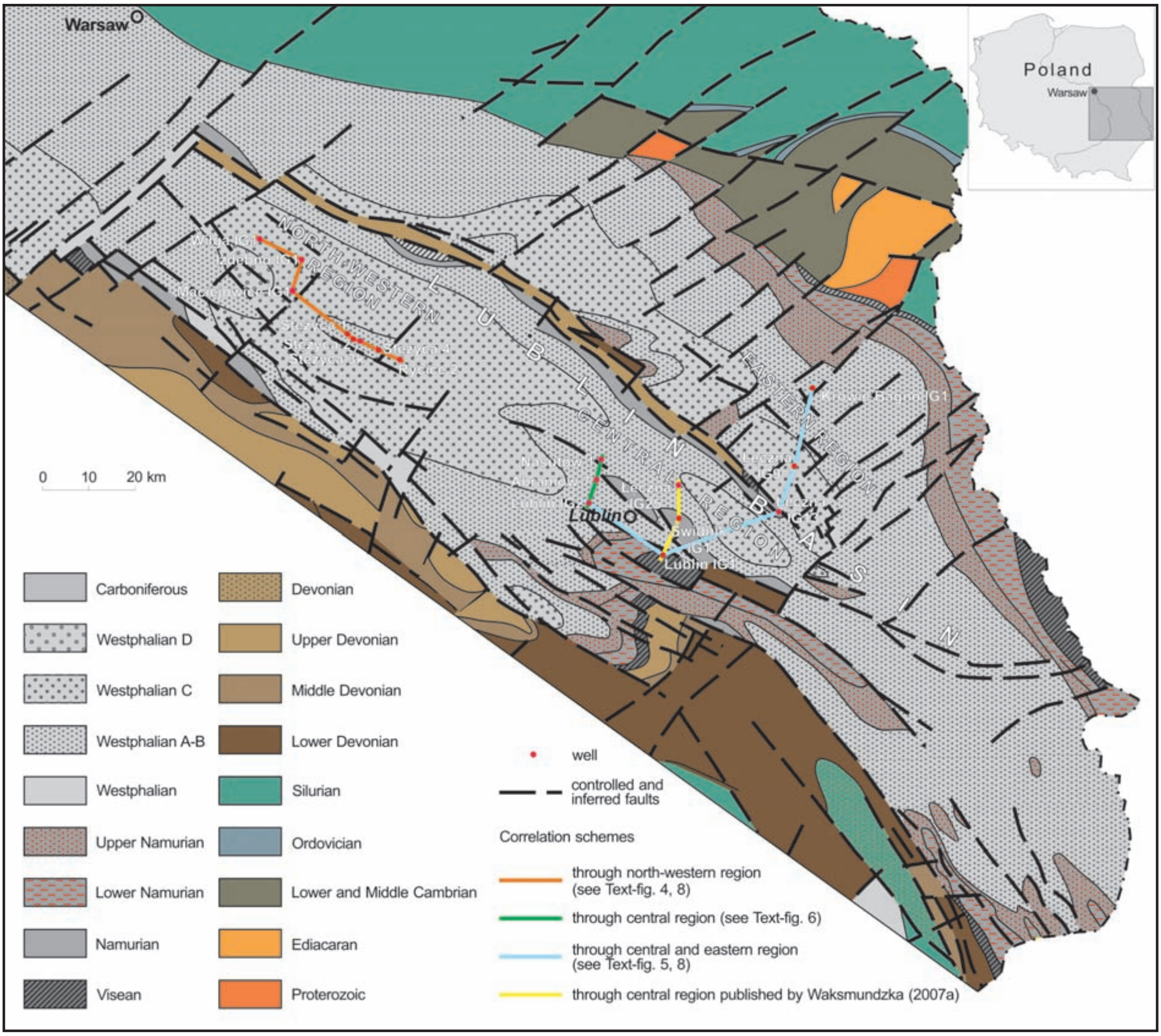
Key words: Carboniferous; Sequence stratigraphy; Lublin Basin; Depositional architecture; Stratigraphic gaps; Cyclothems.

INTRODUCTION

The Lublin Basin is an area in SE Poland with boundaries reflecting the extent of the infilling Carboniferous deposits under a Mesozoic rock complex (Text-fig. 1). It continues to the SE into the Lvov-Volhynia Coal Basin (Ukraine). Although the term suggests correspondence of the basin boundaries to the depositional area, in reality the extent of the Basin was much wider than its presently accepted boundaries, a fact that is evidenced by the results of this study.

The Lublin Basin is filled with sediments representing the ?Middle Viséan to Upper Westphalian (Text-figs 2, 10, 11; Musiał and Tabor 1979, 1988; Skompski 1996; Waksmundzka 2005, 2007a, b). Their deposition was preceded by erosion during the Tournaisian and Early Viséan (Żelichowski 1972). The largest denudation is observed in the sedimentary cover of the Precambrian platform, where erosion removed up to 3000 m of older Palaeozoic deposits. Carboniferous strata lie unconformably on Devonian, older Palaeozoic, and Ediacaran deposits, as well as on the older crystalline basement (Cebulak 1988). Permian, Mesozoic and Cenozoic strata lie unconformably on the Carboniferous succession and the base of this younger complex declines from 200 m below sea level in the east to about 1000 m in the SW of the area.

Żelichowski (1969) distinguished two main structural units in the Lublin Basin – the eastern and central units; the latter is referred to as the Lublin Trough, and its NW part is called the Mazowsze–Lublin Trough (Żelichowski 1972; Żelichowski and Kozłowski 1983). These units show a NW–SE orientation. Recently, a new concept of the tectonic style of the Variscan deposits in the Lublin



Text-fig. 1. Geological sketch-map of the Lublin Basin, without strata younger than Carboniferous (modified after Żelichowski and Porzycki 1983), with location of the studied boreholes area was presented by Antonowicz *et al*. (2003) (the so-called 'synclinal' model). This concept has been widely discussed in the literature (Antonowicz and Iwanowska 2003a, b, 2004; Dadlez 2003; Krzywiec and Narkiewicz 2003; Narkiewicz 2003; Krzywiec 2007; Narkiewicz *et al*. 2007). The most recent interpretations of seismic profiles largely verify and question both the old 'trough' concept, as well as the new 'synclinal' concept. Based on these seismic data, a number of structural features have been recognized within the Carboniferous deposits and in their basement. These include: compressional deformations, strike-slip, reverse and normal faults, thrusts and accompanying ramps, and fault-related folds (Krzywiec 2007). The presence of these deformations indicates the complex evolution of the Lublin Basin and its Late Carboniferous inversion (Narkiewicz *et al*. 2007). The basin subsidence was probably controlled by strike-slip movements along the Teisseyre–Tornquist Zone under the pull-apart regime (Żelichowski 1987; Narkiewicz *et al*. 1998).

Since the discovery of the Lublin Basin in 1938, interest in its Carboniferous deposits was not restricted to the coal deposits but focused also on their stratigraphy and petrography. Litho- and biostratigraphic aspects were presented in a number of publications (Korejwo 1958; Cebulak and Porzycki 1966; Żelichowski 1969, 1972, 1979; Kmiecik 1978, 1988; Mazak 1979; Musiał and Tabor 1979, 1988; Porzycki 1979, 1980; Skompski 1980, 1986, 1987, 1995a, 1995b, 1996, 1998; Skompski and Soboń-Podgórska 1980; Vdovenko and Poletaev 1981; Żelichowski and Kozłowski 1983; Żelichowski *et al*. 1983; Dembowski and Porzycki 1988; Skompski *et al*. 1989, 1995; Zdanowski 1991; Shulga *et al*. 1992; Zdanowski and Żakowa 1995; Grocholski and Ryka 1995; Żywiecki and Skompski 2004); there are, however, several unsolved problems with regard to sedimentological and stratigraphic interpretations. So far, the existing reports present rather generalized opinions on the sedimentary environments of the Carboniferous strata. Strangely enough, the most detailed cyclothem analysis was presented in one of the first studies devoted to the Carboniferous rocks in the Bug area (Korejwo 1958). Besides, a large disproportion exists between the knowledge of the intensely studied carbonate elements of the sedimentary succession (Skompski 1985, 1988, 1996, 1998) and that of the much less known clastic members (Żelichowski 1961, 1964; Porzycki 1979, 1988; Gurba 1984; Gurba and Pietruszka 1984a, b; Skupień and Nurkiewicz 1984; Chabiera 1997a, b; Żywiecki *et al*. 1997; Baszkiewicz and Karpoluk 2000; Żywiecki 2003). Thus, a better understanding of Carboniferous lithofacies and correlation in the Lublin Basin (Waksmundzka 1998; 2007a, b, 2008a) is an essential basis for current and future research on conventional and non-conventional hydrocarbons, coalbed methane, and carbon dioxide storage. High lateral and vertical variability of the Carboniferous deposits, intense disjunctive tectonics and different degrees of thickness reduction due to erosion hamper resolution of these issues through conventional lithostratigraphic or geophysical methods (Kaczyński 1984). Correlation is hampered by the abundance of terrestrial deposits, which limit use of precise biostratigraphic tools. Particularly complex is the correlation of unfossiliferous sandstones, which are of interest as potential oil and gas reservoirs (Waksmundzka 2008b).

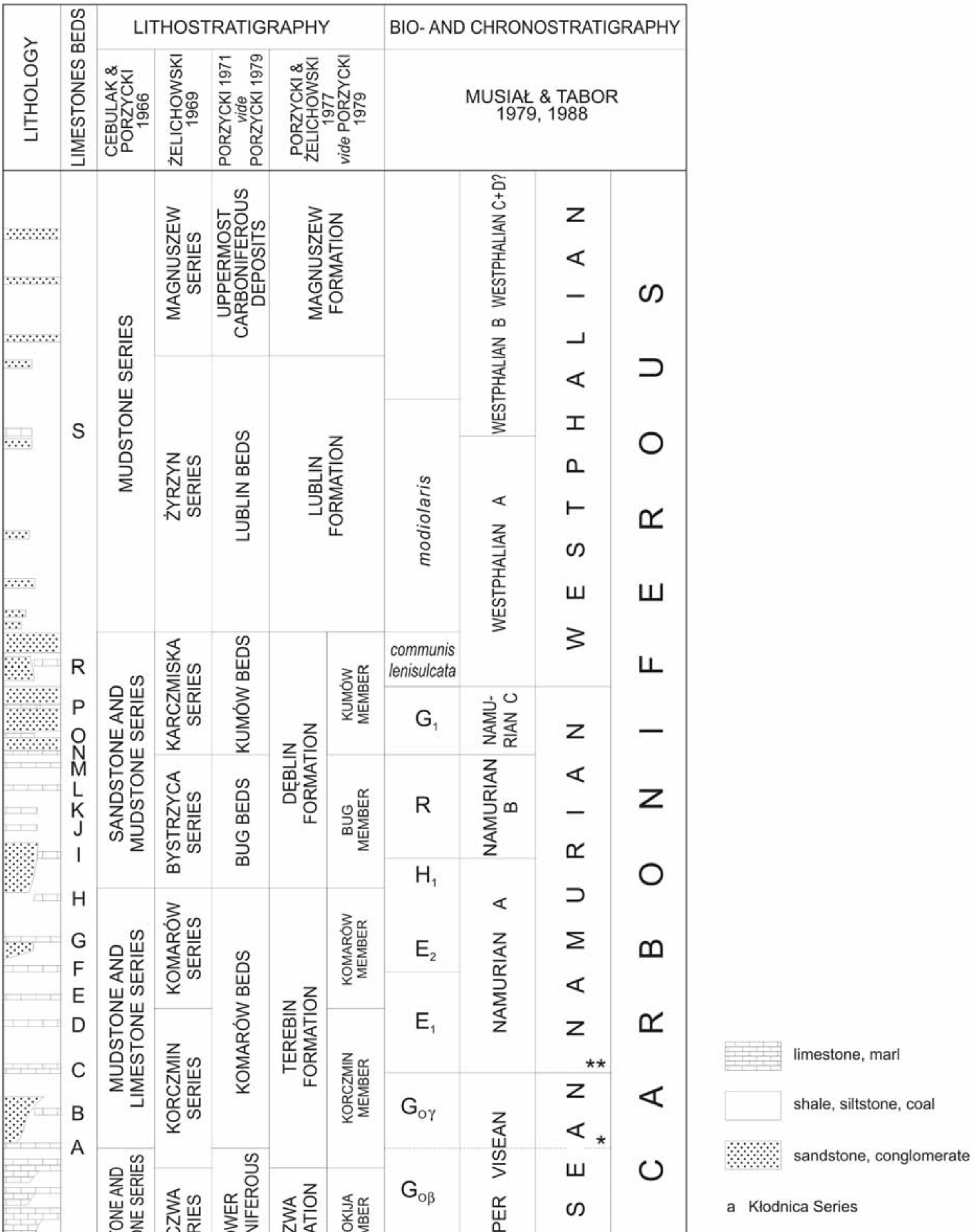
The potential existence and vertical range of the stratigraphic gaps, the position of crucial chronostratigraphic boundaries, e.g. the mid-Carboniferous boundary, and the presence and subdivision of the uppermost Namurian strata are equally important issues that were never unequivocally solved using classical biostratigraphic methods. The references cited above report various approaches to these problems.

Moreover, the relationship between the Carboniferous sedimentary events and relative sea-level supra-regional oscillations is unknown. This relationship is very important in studies of Carboniferous deposits, because most of the recent stratigraphic schemes are more or less based on the sedimentary record of the relative sea-level oscillations.

A commonly applied method developed during hydrocarbon research is sequence stratigraphy. In Poland it has been applied to deposits representing e.g. the Tertiary (Porębski 1996, 1999), Lower Jurassic (Pieńkowski 1997, 2004), Cambrian and Neoproterozoic successions (Pacześna 2001; Pacześna and Poprawa 2005), as well as to Carboniferous strata (Waksmundzka 2005, 2006, 2007a, b; 2008a). The concept of sequence stratigraphy lies in the identification in a sedimentary succession of surfaces of isochronous nature developed in the course of relative sea-level oscillations. Some of these surfaces, such as sequence boundaries, are related to fluvial erosion. The methodology is thus appropriate for application to the Carboniferous succession in the Lublin Basin, which is composed of sandstones and other fluvial deposits, intercalated with marine and deltaic sediments; these facies changes indicate the link between deposition and relative sea-level oscillations (Skompski 1996; Waksmundzka 1998).

This paper is focused on solving the problems outlined above, particularly:

- reconstruction of the variety and evolution of sedimentary environments in the Carboniferous deposits of the Lublin Basin;



Text-fig. 2. Litho-, bio- and chronostratigraphic divisions of the Carboniferous succession in the Lublin Basin (after Musiał and Tabor 1979, 1988; Porzycki 1979; Porzycki and Zdanowski 1995). Top of Visean: * after Musiał and Tabor (1979, 1988); ** after Skompski (1996)

– determination of their lateral relationships, i.e. interpretation of elements of the depositional architecture;
– identification of the boundaries between the depositional sequences, maximum regression and maximum transgression surfaces, as well as three types of depositional systems tracts;
– construction of a sequence stratigraphy scheme;
– correlation of the sequence stratigraphy scheme with the chronostratigraphic scheme for the Carboniferous System;
– reconstruction of the origin and lateral distribution of the depositional architecture elements in a chronostratigraphic frame, with particular focus on sandstones with reservoir potential.

MATERIALS AND METHODS

The results presented below are based on: lithofacies analysis of well cores, application of lithofacies and lithogenetic codes (after Miall 1977, 1978; Rust 1978 modified by Zieliński 1992, 1995), application of sediment compaction coefficients (after Baldwin and Butler 1985), cyclicity analysis, lithological-facies correlation and interpretation of wireline logs (Waksmundzka 2005, 2008b). The sequence stratigraphy scheme and regional conclusions have been based on regional lithological-facies correlations, of which three are presented herein. A fourth correlation has already been published (Waksmundzka 2007a).

The studies were focused on deposits representing the paralic Carboniferous succession, the top boundary of which was placed at the top of the highest deltaic interval with the *Dunbarella papyracea* faunal horizon. This is the last bed with a marine fauna in the Carboniferous succession of the Lublin Basin, and the Westphalian A–B boundary is located within it (Musiał and Tabor 1988; Porzycki 1988). The analyzed part of the succession corresponds to the Visean, Serpukhovian and lower Bashkirian of the global stratigraphic scheme, and this interval corresponds to the ?Middle Visean to the top of Westphalian A of Western Europe. The deposits have been assigned to the Huczwa, Terebin, and Dęblin formations, and to the lower part of the Lublin Formation according to the informal lithostratigraphic scheme of Porzycki (1979) (Text-fig. 2). The upper part of the Carboniferous, representing the upper Bashkirian and Moscovian (Westphalian B, C and D), was not included in this study.

The main study focused on shales and clastic sediments; the co-occurring coals, carbonaceous shales, limestones and marls were studied only for macroscopic lithofacies analysis to the extent needed to reconstruct the depositional environments and spatial relationships within them.

The studies were based on well cores and wireline logs from 17 wells located in the NW and central part of the Mazovian–Lublin Trough and in the eastern part of the basin (Text-fig. 1). Of the wells studied, four were fully cored (Łęczna IG 9, Łęczna IG 13, Łęczna IG 25, Lublin IG 2), and in the remaining wells 10-15% of the Carboniferous thickness was cored. Therefore the most detailed and full lithofacies analysis, characteristics of cyclothems and interpretation of river types have been based on the fully cored wells, whereas in the remaining wells the degree of detail was variable, depending on the completeness and condition of the core. A total of 4,400 m of core was analyzed, of which the fully cored wells comprise intervals from 290 to 738 m in thickness, and the wells with incomplete coring each comprise intervals from 73 to 312 m in thickness. A total of about 13,000 m of well data was analyzed. All sections of the investigated wells with lithology, cyclicity, depositional environments and stratigraphical details are shown in Text-fig. 3 and in the Appendix ‘(Appendix available only in electronic version), Figs 1–16.

The thickness of the part of the succession studied varies from about 440 m in the Wilga IG 1 well to about 1180 m in the Nasutów 1 well. The Lublin IG 2 and Łęczna IG 25 wells did not pierce the entire Carboniferous succession, thus its complete thickness is not known therein.

SEQUENCE STRATIGRAPHY

The basis for recognition of the depositional sequences

Sequence boundaries

Sixteen **depositional sequences,** defined after Michum (1977) as “generally conformable successions of genetically related strata bounded by unconformities or their correlative counterparts”, have been distinguished in the well sections studied (Text-figs 3–6; Appendix, Figs 1–16; Waksmundzka 2007a). Being bounded by **type 1 unconformities**, all the sequences distinguished belong to **type 1** successions *sensu* Vail and Todd (1981). These unconformities are formed during intense fluvial erosion and sub-aerial exposure of the shelf due to relative sea-level lowstand.

In the paralic Carboniferous succession, type 1 unconformities can be clearly identified as fifth- or sixth-order erosional surfaces, representing beds of river channels, channel belts or incised valleys. These surfaces are indicated by high-energy lithofacies, i.e. conglomerates and sandstones, containing different types of intra- and extraclasts. Such lithofacies are linked with the formation of lag deposits and erosional washouts of the river channel bed, and with the initial stage of infilling of incised shelf valleys; they are referred to 'lowstand basal conglomerates' (e.g. Plint 1988). Detailed characteristics of the fluvial deposits are shown in author's Ph. D. research (Waksmundzka 2005; and in preparation).

The base of sequence 1, which is also the base of the Carboniferous system in the study area, comprises conglomerates with a very specific, extremely variable composition, with extraclasts of granites, flint stones, porphyry, quartz, and feldspars, alternating with greywacke sandstones (Świdnik IG 1 well) or clasts of dolomitic siltstones, calcareous sandstones, and shales (Lublin IG 1 well). The basal parts of sequences 2 to 16 also contain clasts, but of a different composition. Intraclasts prevail, composed of pedogenic sideritic concretions, carbonaceous shales or siltstones, whereas the much rarer extraclasts comprise quartz and feldspar. Unconformity surfaces typically show distinct facies contrasts, because they typically overlie lithofacies that developed in a distal deltaic environment or within a shallow shelf. Sequence boundaries with these features recognized in well sections have been correlated on lithofacies schemes. In the marginal parts of the basin, typically out of the range of deltaic or marine deposition, the unconformities can be correlated with the beds of river channels, lying above thick shale-siltstone intervals with paleosols and coals, formed on river floodplains. In the central part of the basin, basal unconformities of incised valleys can usually be correlated with the base of coals, the base of the delta distributary channels, or the base of shales formed on the delta plain.

The bases of sequences 14 and 15 were relatively difficult to correlate. These sequences were distinguished in the Lublin IG 2 well, where they were not subject to intense erosion. In the remaining well sections, the deposits of sequence 14 show considerable erosional reduction and are represented by lowstand sandstones. These usually terminate in an erosion surface; this is also the base of an incised valley filled with high-energy sandstones with intra- and extraclasts, which is the basis for distinguishing the basal part of sequence 15. In the Łączna IG 25 well, this boundary runs between two lithofacies sets formed in braided river channels. These sets are separated by a third-order erosional surface that has been considered the base of sequence 15 due to the presence of characteristic quartz extraclasts, noted also in the lowermost parts of this sequence in the Łęczna IG 9 and IG 13 well sections.

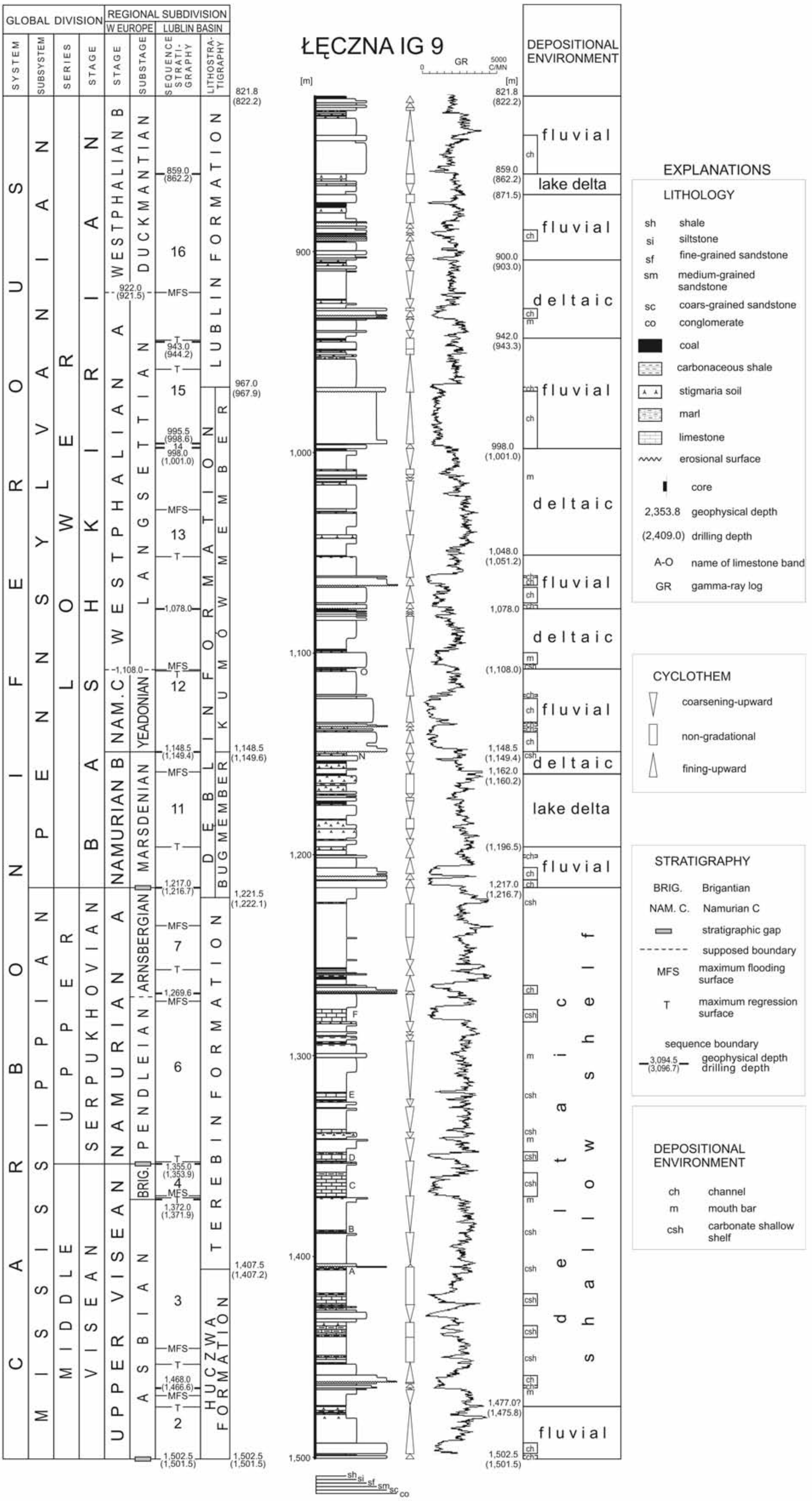
The basal unconformities of sequences 4 to 10 occur in the bases of small incised valleys, as well as between these valleys, where subaerial exposure and erosion took place. Some of these unconformities can also be linked with bypass zones, through which deposits were transferred into deeper parts of the basin. Correlation of sediments filling the particular valleys is difficult, and the position of the unconformities corresponding to areas lying between the valleys and in the transfer zones is less certain than the other sequence boundaries.

Apart from the basal and top unconformities, intrasequence unconformities have also been distinguished. They include surfaces marking the **regression maxima** that are also initial flooding surfaces *sensu* Helland-Hansen and Gjelberg (1994), located at the base of the first transgressive deposits, i.e., coals occurring at the top of fluvial deposits or deltaic deposits lying above fluvial sediments. **Maximum flooding surfaces** (MFS), separating the transgressive and regressive parts of the sequences have also been distinguished. Most MFS surfaces were identified as distinct gamma-ray maxima, linked to the deepest water lithofacies of shallow-shelf shales enriched in organic matter. Next, they were correlated with the corresponding maxima in the remaining wireline logs or with other relatively deep marine lithofacies, e.g. limestones or prodelta shales. The occurrence of gamma-ray maxima is particularly distinct within the *Posidonia corrugata* I and II faunal horizons, distinguished by Musiał and Tabor (1988) in the Carboniferous of the Lublin Basin.

Parasequences

Distinguishing the depositional sequences was preceded by determining several **parasequences**, which are their basic elements, based on the definition of Van Wagoner (1985). Classical examples of parasequences are coarsening-upward cyclothems (types Ic and IIc), as well as non-gradational cyclothems (type IIIc) formed in the submarine part of the delta. These cyclothems, and types Id and IId, were identified according to Elliot (1974, 1975, 1976a, b, 1978). Non-gradational cyclothems of types IIIc and IIId were distinguished by Waksmundzka (1998; 2005). Although Tye and Coleman (1989, see figure 21) and Fielding (1984, see figure 13) described cyclothems similar to type IIId, they did not refer them to a separate type. [see Waksmundzka 2005 for the details of particular cyclothem types].

Single parasequences were not correlated due to large distances between the particular wells and insufficient coring in most of the well sections studied. On the other hand, **parasequence sets** composed of coarsening-



Text-fig. 3. Lithological log with depositional environments, sequence stratigraphy, litho- and chronostratigraphy of Carboniferous paralic deposits in the Łęczna IG 9 well (lithostratigraphy modified after Zdanowski 1995) upward and non-gradational cyclothems have been determined in core sections and on wireline logs (Text-fig. 3, 8; Appendix, Figs 10, 14, 15). Such parasequence sets, distinguished in the paralic Carboniferous succession, represent **depositional systems tracts**, according to the definition of Posamentier *et al*. (1988).

Most of the fining-upward cyclothems, noted within fluvial deposits and related to the relative sea-level rise, correspond to parasequences. Their detailed characteristics is shown in author's Ph. D. research (Waksmundzka 2005; and in preparation). Unequivocal indication of their boundaries is difficult and has not been undertaken during this study. However, intervals of fluvial deposits or deposits linked with incised valleys can be considered as parasequence sets, i.e. depositional systems tracts which can easily be identified and correlated in core sections and wireline logs (Text-fig. 3, 8; Appendix, Figs 10, 14, 15).

Depositional systems tracts

Based on the definitions of Van Wagoner *et al.* (1987), three types of depositional systems tracts have been distinguished in the paralic Carboniferous deposits of the Lublin Basin:

(1) **lowstand systems tracts** (LST), (2) **transgressive systems tracts** (TST), and (3) **highstand systems tracts** (HST).

The abbreviations: LS for relative sea-level lowstand, TS for transgression, and HS for relative sea-level highstand are used throughout in the text.

Below are given the general characteristics of the lithofacies representing particular systems tracts, illustrated by sequence 12 (Text-fig. 8). The variety of depositional environments in the paralic Carboniferous of the Lublin area depending on the relative sea-level is presented in Text-fig. 9.

Lowstand systems tracts are bounded by basal sequence unconformities and by maximum regression surfaces. Typically, they comprise sandstones, rarely conglomerates, developed in river channels. They alternate with sandstones, siltstones, shales, *Stigmaria* soils, and coals of the floodplain environment, on which deposition took place within levees, crevasses, lakes, and marshes.

LST deposits begin with high-energy lithofacies sets developed in braided rivers and river channels where hyperconcentrated flows prevailed. Above this occur lower energy sets deposited in an anastomosed fluvial system. In some cases, a reduction in energy of the fluvial system (e.g. of meandering rivers) can be observed, but without change of the fluvial system type. Typical of the fluvial LST deposits is the abundance of massive sandstones, developed during strong aggradation of deposits in the channels. The strongest aggradation of sand deposits was linked with the hyperconcentrated flow environment, during which extremely thick intervals of these sandstones were deposited. The occurrence of massive sandstones and other high-energy lithofacies, as well as correlation, indicate that the fluvial deposits were generally formed within incised shelf valleys, eroded during the early LS with relative sea-level fall.

Applying the terminology of Zaitlin *et al.* (1994) to the incised valleys in the paralic Carboniferous of the Lublin Basin, the following systems can be distinguished: **simple systems** that developed during one cycle of relative sea-level rise and fall, filled with deposits of one sequence; **compound systems**, that contained sequence boundaries linked with several cycles of relative sea-level rise and fall; and two main physiographic types such as **piedmont** and **coastal plain incised valley systems**.

Incised valleys are formed on an exposed shelf, and fluvial erosion continues when relative sea-level, which controls the base-level of river channels, falls. When this gradient is higher, then the valleys are more incised. The thickness of the fill, which ranged from 20–65 m, allowed an evaluation of the depth of the valleys. Estimated valley depths range from c. 20 to c. 70 m, and, excluding the largest valley of the Lublin area, generally correspond to the depths of Holocene valleys observed on the passive margins of North America described by Ashley and Sheridan (1994). The following categories of incised valleys from the Lublin Basin can be distinguished, applying the classification of Ashley and Sheridan (1994): (1) **small**, with depths below 10 m and widths below 200 m; (2) **medium**, with depths in the range of 10–20 m and widths in the range of 1–2 km; and (3) **large**, with depths in the range of 20–40 m and more; widths in the range of 10–20 km and more.

The values of incision obtained reflect the scale of relative sea-level fall for particular sequences, and are quite justified at this stage of recognition of incised valleys in the Lublin area. Calculation of the actual values of relative sea-level rise requires additional well data, representative of the entire Basin, which lies beyond the scope of this study.

LST successions also contain fluvial deposits belonging to **non-incised fluvial-channel systems** that develop landward of the incised valley systems; changes in the relative sea-level do not affect the fluvial processes in these non-incised channels (see Van Wagoner *et al.* 1990). In some cases, sandstones that developed in the delta distributary channels and deposits of lake deltas, lakes, and marshes of the delta plain have also been included in the LST.

Transgressive system tracts are bounded by maximum regression and maximum flooding surfaces. Typically, regression maxima occur at the base of coals overlying fluvial deposits or delta plain sediments that represent LST deposits. The formation of marshes, in which organic matter accumulated, was linked with relative sea-level rise, connected with groundwater level rise and flooding of the seaward fluvial plains.

In some cases, the regression maxima are located at the base of sediments that, following Dalrymple *et al.* (1992), probably accumulated in estuaries. The presence of estuary sediments in the well sections studied was confirmed by the existence of systems of incised valleys that were flooded during relative sea-level rise. In the succession studied the likely presence of estuary sediments was indicated by spatial relationships on lithofacies schemes and the succession of lithofacies in section. Marine faunas, trace fossils and sedimentological structures such as symmetrical ripples or humocky cross-stratification have not been observed in the sandstone intervals filling incised valleys that contain fining-upward cyclothems. Estuarine deposits possibly occur above these cyclothems, as for example, in sequence 12 (Rycice 2 well, Text-figs 4, 8; Appendix, Fig. 8), and begin with a very thin marl bed (0.5 m) probably formed in the outer, seaward zone of the estuary, capped by coarsening-upward type Ic and IIc cyclothems. In the lower parts of the cyclothems commonly occur reworked sandy siltstones and sandstones, which are not present in such numbers in other deltaic deposits. This reworking results from bioturbation by animals burrowing in the sediment, a feature frequently observed in estuarine deposits (Kvale and Barnhill 1994). The subsequent coarsening-upward cyclothems have a proximal character that is probably linked with progradational filling of the estuary by deposits of the bay-head delta. It can be assumed that if the described coarsening-upward cyclothems were formed within a shoal-water delta and shallow-shelf, then during relative sea-level rise the trend within them should be retrogradational, a feature commonly observed in TST deposits of other well sections studied.

Unequivocal recognition of estuary deposits was not possible in the case of most of the incised valleys due to lack of complete core sections from these intervals. A crucial difficulty in the identification of these deposits is linked mainly with interpretational constraints in core and wireline log analysis. Thus, the very subtle differences that would allow the distinguishing of coarsening-upward cyclothems formed in shoal-water deltas from coarsening-upward cyclothems formed in bay-head deltas often cannot be seen in the available material.

TST deposits are dominated by shales and siltstones formed within a shallow shelf and in the distal parts of inner-shelf delta lobes, alternating with limestones and marls formed within a shallow carbonate shelf. Limestone beds are encountered only in the lower part of the Carboniferous paralic succession. Mouth bar and delta plain deposits are rare. Within TST deposits occur parasequences, which correspond to the commonly occurring coarsening-upward type IIc cyclothems and to non-gradational type IIIc cyclothems.

In the marginal parts of the Basin, the TST deposits also comprise shales, siltstones, sandstones, *Stigmaria* soils, and coals formed on the floodplains of anastomosed fluvial systems.

Maximum flooding surfaces, bounding the TST at the top, commonly occur within: (1) shallow shelf shales, which correspond to gamma-ray maxima; (2) prodelta shales; and (3) basal parts of limestone beds.

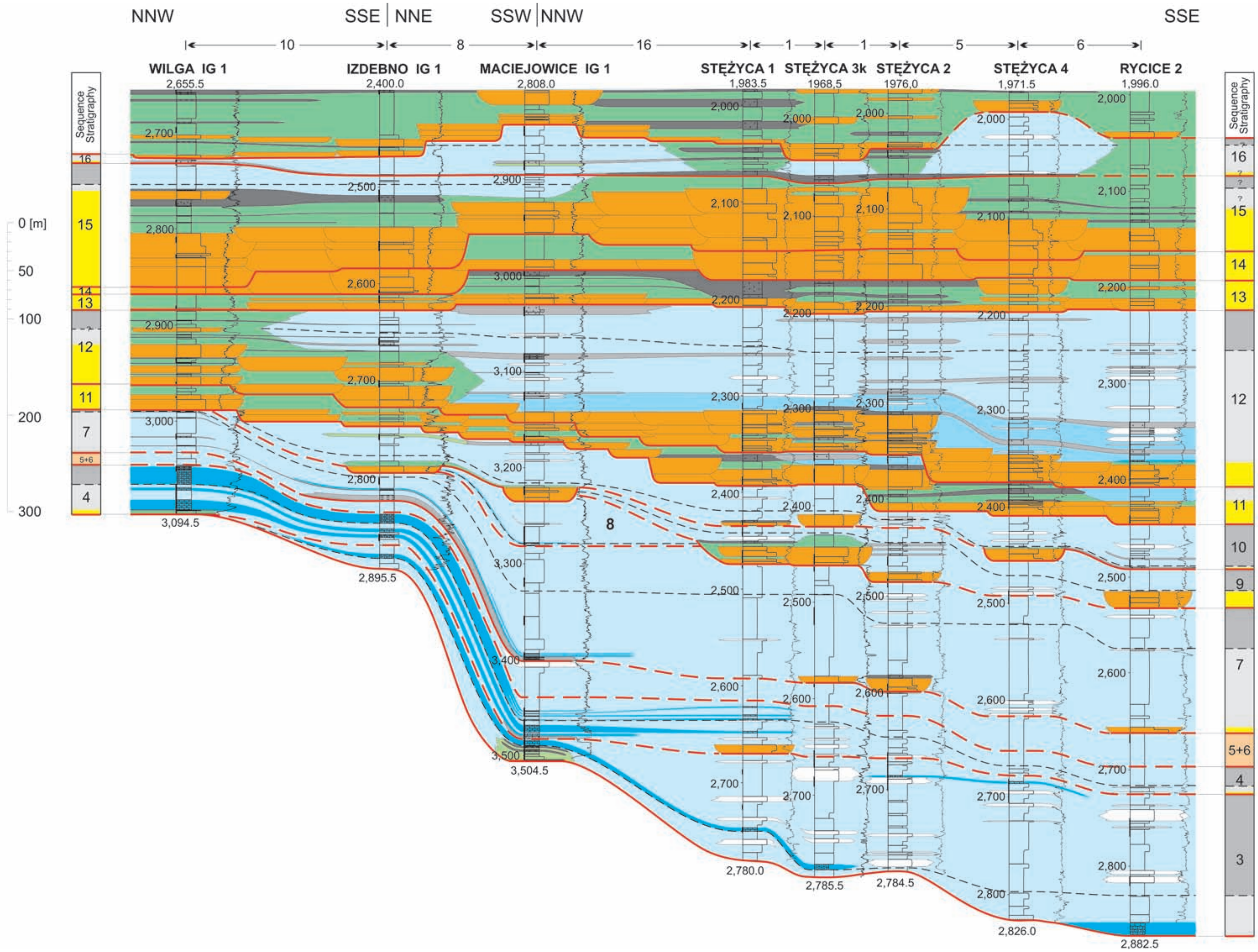
Highstand system tracts are bounded by maximum flooding surfaces and basal unconformities of the subsequent sequence. Erosion that formed the unconformities also greatly reduced or even completely removed the HST deposits. HST deposits comprise shales, siltstones, and sandstones produced in the distal and proximal parts of inner-water delta lobes. Rather common are mouth-bar sandstones, attaining thicknesses greater than those formed during TS. In rare cases, deposits of the submarine parts of delta lobes alternate with limestones and marls. Within HST deposits may occur coarsening-upward type Ic and IIc cyclothems and non-gradational type IIIc cyclothems that correspond to parasequences.

Also quite common are shales, siltstones, sandstones, *Stigmaria* soils, and coals formed on delta plains. These deposits occur within coarsening-upward type Id and IId cyclothems formed in lake deltas, and within non-gradational type IIId cyclothems, formed in lakes devoid of delta lobe influence (Text-fig. 7). Sandstones formed in delta distributary channels are also present within HST deposits.

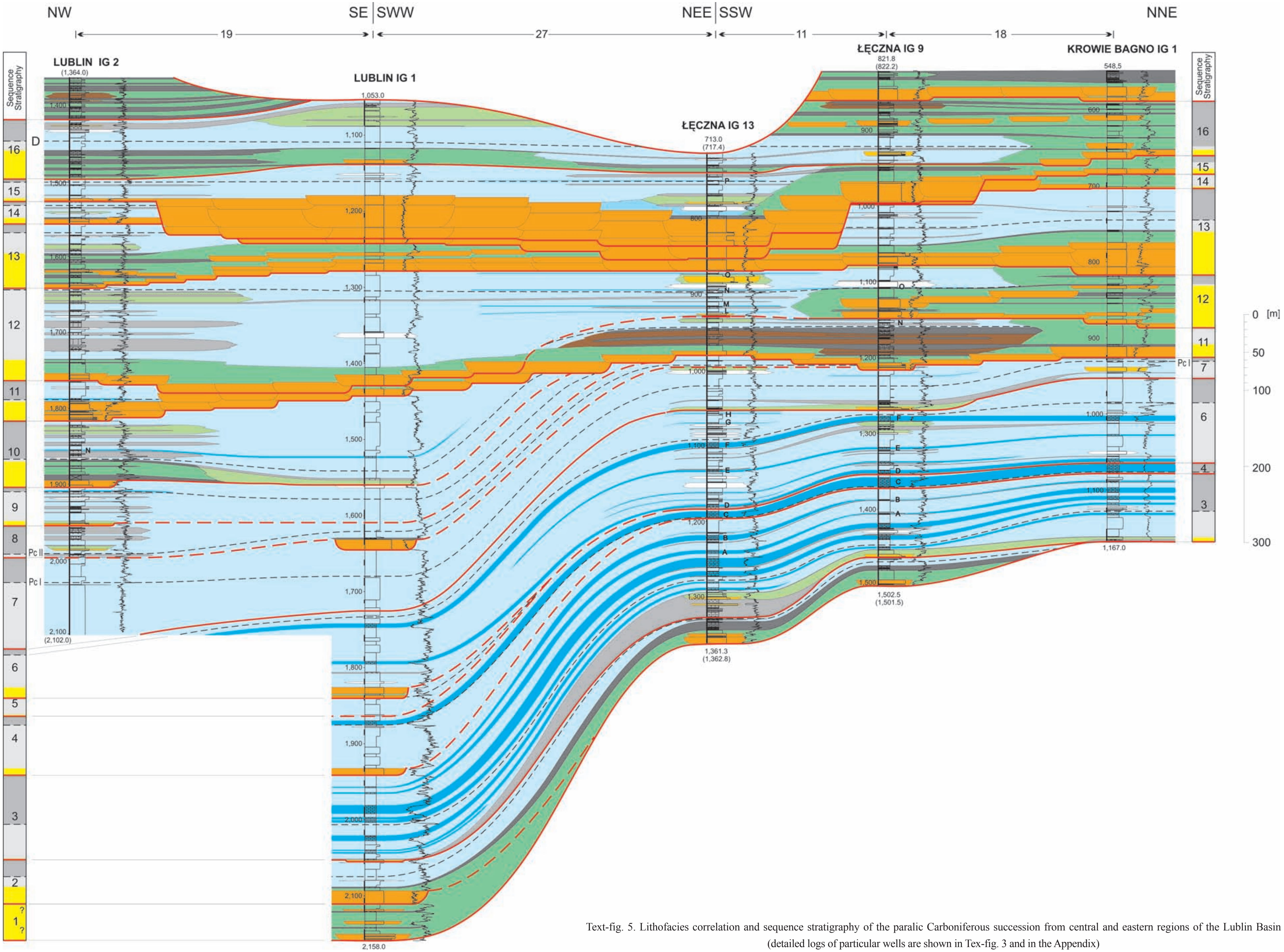
In the upper parts of HST deposits may sometimes occur shales, siltstones, sandstones, *Stigmaria* soils, and coals formed on floodplains of anastomosing fluvial systems.

SEQUENCE CHARACTERISTICS AND DEVELOPMENT OF DEPOSITIONAL ARCHITECTURE OF THE PARALIC CARBONIFEROUS OF THE LUBLIN BASIN

The depositional architecture of the sequences in the paralic Carboniferous of the Lublin Basin described below is presented in Text-figs 4–6, 8 and their summary characteristics is shown in Table 1.



Text-fig. 4. Lithofacies correlation and sequence stratigraphy of the paralic Carboniferous succession from north-western region of the Lublin Basin (detailed logs of particular wells are shown in the Appendix)



Text-fig. 5. Lithofacies correlation and sequence stratigraphy of the paralic Carboniferous succession from central and eastern regions of the Lublin Basin (detailed logs of particular wells are shown in Tex-fig. 3 and in the Appendix)

Sequence 1

Deposits of sequence 1 occur only in the central part of the Basin, near the Lublin IG 1, Świdnik IG 1, Abramów 7 and Nasutów 1 wells (Text-figs 4, 5; Appendix, Figs 9, 11–13; Waksmundzka 2007a). They are thickest (Table 1) in the Lublin IG 1 well section and decrease in thickness towards the NE. The lowest thickness was observed near the Abramów IG 1 well, a fact that is possibly linked with erosion preceding deposition of sequence 2. Sequence 1 generally thins out to the NE and NW of the Lublin IG 1 well.

LST: The base of sequence 1 in the central part of the study area corresponds to the base of the Carboniferous succession and is represented by an erosional surface, above which occur conglomerates and volcanic rocks. Żelichowski (1971) assigned these deposits to the Kłodnica Member in the lowermost part of the Huczwa Formation. Conglomerates characterized by a specific and varied composition have been observed only at the base of sequence 1 (Świdnik IG 1 well section). Their low petrographic maturity indicates proximity to the source area. They were probably deposited in proximal gravel-bed braided channels that were rapidly filled with sediments and became obliterated due to relative sea-level rise. The base of this sequence shows a different development near Nasutów and Abramów (Text-fig. 6). Arkosic sandstones (Nasutów 1) or green siltstones followed by thin arkosic sandstones (Abramów 7) have been noted there. The lowest sandstones could have been formed in distal sand-bed braided channels. This suggests that, at the beginning of Carboniferous sedimentation, the Abramów–Nasutów area was located farther from the source area than the Lublin–Świdnik region (Waksmundzka 2007a), which suggests in turn that transport of detrital material took place generally to the W or NW. Channel deposits occurring above the base of this sequence probably developed during relative sea-level LS.

Sandstones occurring above these basal deposits, reach a maximum thickness of 5 m and were also deposited in fluvial channels belonging to a low-energy anastomosed system. This is indicated by the presence of extremely thick floodplain deposits, e.g. shales, siltstones, and carbonaceous shales, surrounding the channel sandstones. At first, these deposits were formed during relative sea-level LS, whereas the transition from high-energy proximal or distal braided channels into low-energy anastomosed fluvial systems was probably linked with base level rise.

TST?, HST?: Sequence 1 is dominated by fluvial deposits; therefore, data collected from only four wells do not allow surfaces representing maximum regression and flooding to be distinguished. Most probably, these surfaces should occur in floodplain deposits above the lowermost braided channels, whereas deposits of the anastomosed system developed during flooding and the following relative sea-level HS. Confirming this implication would require recognizing the lowermost parts of the Carboniferous succession, occurring to the SW of the study area, where sequence 1 should be represented by deltaic or marine deposits.

The topmost part of sequence 1 was probably eroded during the next LS. It is thus possible that erosion removed HST deposits, and probably also part of the TST sediments.

The top of sequence 1 in the Nasutów 1 (Text-fig. 6; Appendix, Fig. 12) and Świdnik IG 1 (Appendix, Fig. 13; Waksmundzka 2007a) wells is characterized by the presence of volcanic rocks or diabases formed during a volcanic episode in late Viséan times (Porzycki 1988; Grocholski and Ryka 1995). They have not been encountered in the nearby Abramów 7 (Text-fig. 6; Appendix, Fig. 11) and Lublin IG 1 well sections (Text-fig. 5; Appendix, Fig. 9), which may be linked with their erosional removal during formation of large incised valleys in the LST of sequence 2. Assuming the isochronous character of the volcanic episode, the presence of volcanic rocks in the lowermost part of the Carboniferous can be regarded as useful in distinguishing and correlating sequence 1 deposits.

Sequence 2

Deposits of this sequence cover a larger area than those of sequence 1, which indicates the establishment of deposition to the NE of the central region. The greatest thickness of sequence 2 (Table 1) occurs in the Lublin IG 1 well section; this sequence generally thins to the NE, and in the vicinity of the Krowie Bagno IG 1 well does not occur at all. Deposits of sequence 2 are also absent in the NW part of the Basin, and their thinning out farther to the NW can be observed beyond the study area.

LST: The base of sequence 2 in the central part of the study area corresponds to the top of sequence 1, whereas near the Łęczna IG 13 and Łęczna IG 9 wells (Text-fig. 5) it corresponds to the base of the Carboniferous succession. In the lower part of the sequence in the Abramów 7 well section occur 36-m thick sandstones that were deposited in sand-bed braided channels and partly also during hyperconcentrated flows. Extremely thick massive sandstones were deposited during the

Sequence number	Thickness [m]	Extend	LST facies character	TST facies character	HST facies character
16	5.0-120.5	all study area	- anastomosed fluvial system - lake delta, peat swamp and overgrown by vegetation of floodplain	- inner-shelf delta (prodelta, delta front) - lake, peat swamp and overgrown by vegetation of floodplain - claly shallow shelf	- inner-shelf delta (prodelta, delta front, mouth bar) - deltaic distributary channels - anastomosed fluvial system - lake, lake delta, peat swamp and overgrown by vegetation of floodplain
15	21.0-129.0	all study area	- braided and meandering river; anastomosed fluvial system; hyperconcentrated flow; incised valey - overgrown by vegetation of floodplain	- inner-shelf delta (prodelta, delta front) - lake, peat swamp and overgrown by vegetation of floodplain - estuary	- inner-shelf delta (prodelta, delta front, mouth bar) - peat swamps and overgrown by vegetation of delta plain - lake and overgrown by vegetation of floodplain - carbonate shallow shelf
14	2.5-37.0	all study area	- braided and meandering river; hyperconcentrated flow; incised valey - overgrown by vegetation of floodplain	- lack of TST deposits or - inner-shelf delta (prodelta, delta front, mouth bar) - peat swamp of floodplain	- lack of HST deposits or - inner-shelf delta (prodelta) - overgrown by vegetation of delta plain
13	14.0-114.5	all study area	- braided and meandering river; anastomosed fluvial system; incised valey - lake delta, peat swamp and overgrown by vegetation of floodplain	- lack of TST deposits or - inner-shelf delta (prodelta, delta front, mouth bar) - peat swamps and overgrown by vegetation of delta plain - peat swamp of floodplain	- lack of HST deposits or - inner-shelf delta (prodelta, delta front, mouth bar) - peat swamps and overgrown by vegetation of delta plain
12	59.0-185.0	all study area	- braided and meandering river; anastomosed fluvial system; hyperconcentrated flow; incised valey - peat swamp and overgrown by vegetation of floodplain - deltaic distributary channel - delta plain	- inner-shelf delta (prodelta, delta front, mouth bar) - peat swamps and overgrown by vegetation of delta plain and floodplain - carbonate and claly shallow shelf - estuary	- inner-shelf delta (prodelta, delta front, mouth bar) - peat swamps and overgrown by vegetation of delta plain - deltaic distributary channel - carbonate shallow shelf
11	12.5-68.5	all study area	- braided river; anastomosed fluvial system; hyperconcentrated flow; incised valey - peat swamps and overgrown by vegetation of floodplain	- lack of TST deposits or - lake delta, peat swamp and overgrown by vegetation of floodplain - estuary	- lack of HST deposits or - inner-shelf delta (prodelta, delta front, mouth bar) - peat swamp and overgrown by vegetation of delta plain - carbonate shallow shelf
10	17.0-116.5	NW with the extention of Wilga IG 1 well and central regions	- river channel; incised valey - peat swamp and overgrown by vegetation of floodplain and delta plain - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta) - claly shallow shelf	- inner-shelf delta (prodelta, delta front, mouth bar) - peat swamp and overgrown by vegetation of delta plain - deltaic distributary channels - carbonate shallow shelf
9	25.0-76.0	NW with the extention of Wilga-Maciejowice and central regions	- river channel; floodplain; incised valey - deltaic distributary channel - delta plain - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta, delta front, mouth bar) - delta plain	- inner-shelf delta (prodelta, delta front) - carbonate shallow shelf
8	15.0-62.0	central region, Łęczna IG 13 and Maciejowice IG 1 wells area	- river channel; incised valey - peat swamp and overgrown by vegetation of delta plain - lack of sedimentation in transfer zones	- inner-shelf delta (prodelta) - claly shallow shelf	- peat swamp and overgrown by vegetation of delta plain - inner-shelf delta (prodelta, delta front, mouth bar)
7	28.0-153.0	all study area	- river channel; floodplain; incised valey - deltaic distributary channel - peat swamp and overgrown by vegetation of delta plain - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta, delta front) - claly and carbonate shallow shelf - delta plain - peat swamp of floodplain	- inner-shelf delta (prodelta, delta front, mouth bar) - carbonate shallow shelf
6	10.0-39.5 84.5-152.5	all study area	- river channel; incised valey - overgrown by vegetation of floodplain - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta, delta front, mouth bar) - carbonate and claly shallow shelf - peat swamp and overgrown by vegetation of delta plain	- inner-shelf delta (prodelta, delta front, mouth bar) - carbonate and claly shallow shelf - overgrown by vegetation of delta plain
5	22.0-74.5	NW and central regions	- river channel; floodplain; incised valey - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta, delta front) - carbonate shallow shelf - peat swamp of floodplain	- inner-shelf delta (prodelta, delta front)
4	13.0-82.0	all study area	- river channel; incised valey - peat swamp and overgrown by vegetation of delta plain - lack of sedimentation in transfer zone	- inner-shelf delta (prodelta, delta front, mouth bar) - carbonate and claly shallow shelf - deltaic distributary channels - peat swamp and overgrown by vegetation of delta plain	- inner-shelf delta (prodelta, delta front) - carbonate shallow shelf

3	22.5-180.0	all study area with the exception of Wilga IG 1 region	- inner-shelf delta (prodelta, delta front) - peat swamp and overgrown by vegetation of delta plain - deltaic distributary channel	- inner-shelf delta (prodelta, delta front) - carbonate and clayly shallow shelf - peat swamp and lake of delta plain	- inner-shelf delta (prodelta, delta front, mouth bar) - carbonate shallow shelf
2	12.0-55.5	central region	- channel of braided river; hyperconcentrated flow; incised valey - channel and floodplain of anastomosed river system - lake, peat swamp and overgrown by vegetation of floodplain	- inner-shelf delta (prodelta, delta front, mouth bar) - clayly shallow shelf - peat swamp of floodplain	- inner-shelf delta (prodelta, delta front, mouth bar)
1	25.0-47.5	central region	- channel and floodplain of anastomosed river system - channel of braided river - volcanic	- supposed lack or floodplain	- supposed lack or floodplain

Table 1. Characteristics of sequences of the paralic Carboniferous succession from the Lublin Basin

flows (see Martinsen 1994, fig. 12; Walker 1995, p. 71). These deposits point to sedimentation within a large incised valley that developed due to erosion during relative sea-level fall. This is a simple incised valley, filled during a single cycle of sea-level rise and fall that most probably belongs to a coastal-plain incised-valley system (Text-fig. 9A).

A similar origin can be supposed in the case of a 17.5-m thick sandstone that lies at the base of sequence 2 in the Lublin IG 1 well section. Its lesser thickness can most likely be ascribed to smaller incision of the valley in its most proximal part. The sandstone is covered by siltstones and shales, as well as *Stigmaria* soils that developed on a floodplain occasionally covered by water, or in an estuary during relative sea-level rise. If an estuary origin is assumed, then the base of these deposits would correspond to a maximum regression surface and they would represent the TST.

To the NE of the central part of the study area, the base of sequence 2 is composed of fluvial channel deposits that were not linked with incised valleys. In the Łęczna IG 9 and Łęczna IG 13 well sections sandstones occur that were formed in braided channels, which pass vertically into anastomosed channels. Near these wells occur thin sandbodies (1 to 8 m thick) that are separated by thin beds of siltstones formed on the floodplains of braided rivers. Above these rocks occurs a very thick interval composed of siltstones and shales with very thin sandstone intercalations, deposited on the floodplain of the anastomosed system. At the top of the fluvial deposits occurs a thick horizon of *Stigmaria* soils, carbonaceous shales, and coals. Their formation is linked with the filling and obliteration of fluvial channels and the evolution of a floodplain overgrown by vegetation that was covered by shallow lakes and peat swamps.

The above-described succession of the fluvial interval of sequence 2 was formed during relative sea-level LS. Its evolution from sand-bed braided channels, through sand-bed anastomosed channels, to a very thick complex of floodplain deposits should be linked with the fall of fluvial channel gradient and energy due to relative sea-level rise (see Hampson *et al.* 1997). Further sea-level rise and expansion of the accommodation space allowed long-term deposition on continuously flooded floodplains, leading to very great thickness of deposits. The LST fluvial succession is terminated by phytogenic deposits. In the Łęczna IG 9 and Łęczna IG 13 well sections the base of the uppermost coal bed in sequence 2 represents the maximum regression surface and the coals belong to the succeeding TST.

TST, HST: The fluvial interval is covered by relatively thin deltaic deposits (Text-fig. 9C, D); their thickness increases towards the centre of the Lublin Basin. This increase can also be observed in the upper part of the succession up to sequence 10, and in sequence 12. In the Łęczna IG 13 well section (Appendix, Fig. 14), two coarsening-upward cyclothems formed in an inner-shelf delta can be observed. The lower one, representing type IIc, was formed during sea-level rise, whereas the upper, type Ic, was developed almost entirely during the HS. The maximum flooding surface of sequence 2, marked also as a gamma-ray maximum, lies in its lowermost inner-shelf and prodelta part. This surface is also located in a similar position in the Lublin IG 1 well section. In the Łęczna IG 9 well section occurs one coarsening-upward type Ic cyclothem; its lowermost prodeltaic part was formed during sea-level rise, and deposits of the delta slope and mouth-bar formed during the progradation of the delta lobe in HS conditions (Text-fig. 9F).

Sequence 3

Deposits of sequence 3 are encountered throughout the study area, with the exception of the NW region (Wilga IG 1; Text-fig. 4). This indicates the distinct expansion of the depositional area towards the NE and NW.

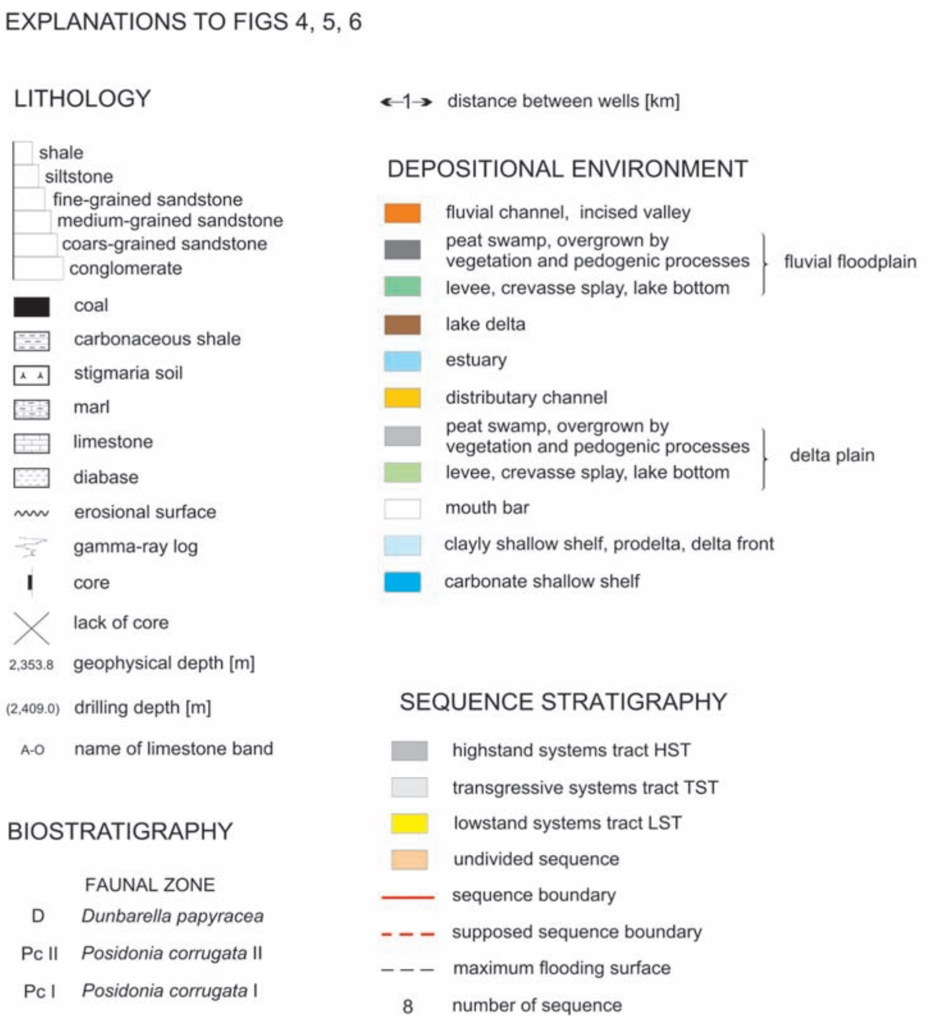
The thickness of sequence 3 (Table 1) is relatively great near the Świdnik IG 1 well (Appendix, Fig. 13; Waksmundzka 2007a), then decreases to the NE

(Krowie Bagno IG 1; Text-fig. 5; Appendix, Fig. 16) and to the NW (Abramów 7; Text-fig. 6; Appendix, Fig. 11). In the Stężyca–Rycice region it increases again. The sequence is thinnest in the NW near the Izdebno IG 1 and Maciejowice IG 1 wells.

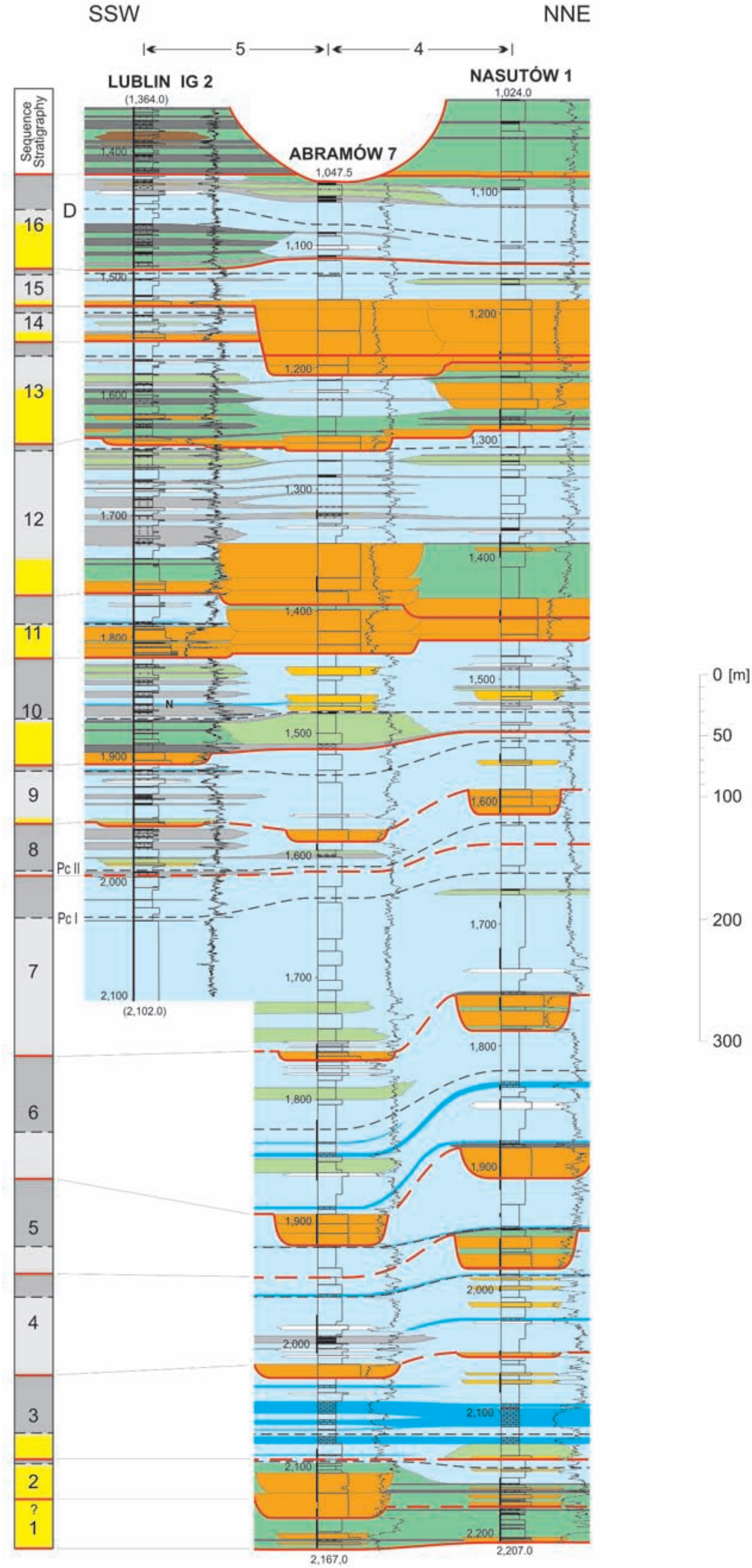
LST: The base of sequence 3 is generally the top of sequence 2, whereas near the Krowie Bagno IG 1 well and in the NE of the study area it corresponds to the base of the Carboniferous succession. Above the base delta plain deposits occur, i.e. coals, *Stigmaria* soils (Krowie Bagno IG 1, Łęczna IG 13, Maciejowice IG 1) or sandstones of distributary channels on the delta (Lublin IG 1 and Łęczna IG 9). This may indicate that the topmost parts of the underlying sequence underwent little or no erosion during the formation of small distributary channels. Deposition on the delta plain was longest in the vicinity of Łęczna (Łęczna IG 13), where these deposits attain the greatest thickness, and shortest in the vicinity of Lublin (Lublin IG 1).

In the NW part of the study area (Text-fig. 4), LST sections for sequence 3 in the Stężyca 1, Stężyca 2, Stężyca 3k, Stężyca 4, Rycice 2, and Izdebno 1 wells (Appendix, Figs 2, 4–8) did not contain fluvial or delta plain deposits at their base. The section begins there with deposits formed in the submarine part of the delta that possibly started to develop during the LS (Text-fig. 9A, B). By analogy with the nearby Maciejowice IG 1 well (Appendix, Fig. 3), where the delta plain deposits were observed in cores, it can be assumed that in the vicinity of the Izdebno IG 1 well terrestrial LS deposits are also present, but their discrimination on wireline logs was not possible.

TST: In the area of the Łęczna IG 13 well and to the NE (Text-fig. 5), the top of the delta plain deposits is marked



Text-fig. 6. Lithofacies correlation and sequence stratigraphy of the paralic Carboniferous succession from central region of the Lublin Basin (detailed logs are shown in the Appendix)


SSW
NNE
5
4
LUBLIN IG 2
ABRAMÓW 7
NASUTÓW 1
Sequence Stratigraphy
D
N
Pc II
Pc I
0 [m]
50
100
200
300

by coals (Text-fig. 9C). Their thickness increases from 0.2 to 1 m towards the Krowie Bagno IG 1 well. Their formation is linked with relative sea-level rise, gradual flooding of the delta plain and development of peat swamps. Accumulation of organic matter was longest to the east, and was much shorter in the centre of the basin, reflecting progressive transgression. Swamps were not formed at all in the region of Lublin, where thin deposits of the delta plain are covered by lake shales overlain by *Stigmaria* soils. Deposits accumulated in the coastal plain lake that was formed during relative sea-level rise, and subsequently filled with sediment and overgrown with vegetation. The formation of this lake, as well as of swamps to the NE, is related to groundwater level rise linked with relative sea-level rise. The base of the coals and the correlative lake deposits corresponds to the maximum regression surface of sequence 3, and the deposits belong to the TST.

Above the coals occur carbonaceous shales, indicating supply of clay material to the peat swamps, passing into prodelta shales that are the first marine deposits formed above the swamps. This facies contact, as well as the occurrence of carbonates above coals, is very typical of the entire paralic succession in the Lublin Basin, and is particularly frequent in sequences 3 to 10. This succession is the result of increasing transgression, as well as rapid subsidence related to compaction of plant remains accumulated in peat swamps. In consequence, rapid flooding of flat areas of the delta and fluvial plains took place, followed by drastic changes in sedimentary conditions (Riegel 1991; Skompski 1996).

The TST is composed of interfingering deltaic and shallow-shelf facies (Text-fig. 9C, D), which predominate in sequence 3. It comprises deposits of the prodelta and delta slope, occurring in coarsening-upward type IIc cyclothems that are parasequences (Łęczna IG 13 and Lublin IG 2 well sections; Appendix, Fig. 10, 14). Above them, in an interval that extends up to the maximum flooding surface, occur limestones intercalated with two types of shales. The first are represented by deposits formed on the prodelta, whereas the second were deposited laterally adjacent to the limestones or slightly deeper within the shallow-shelf. In the TST section, the second limestone bed has a wider extent than the first, which indicates expansion of transgression from the central region to the NE.

Distinguishing between the prodelta and shallow-shelf shales is very difficult or even impossible due to their macroscopic similarities. This task is much easier when they occur within coarsening-upward cyclothems with siltstones of the delta slope, demonstrating a shallowing trend. The TST can contain similar lithofacies successions that differ in origin:

– type 1: shallow-shelf limestones – prodelta shales
– shallow-shelf limestones, in which the transition of limestones into shales is linked with shallowing, and that of the shales into the overlying limestones with deepening within a shallow carbonate shelf subject to deltaic deposition;
– type 2: shallow-shelf limestones – shallow-shelf shales – shallow-shelf limestones, in which the transition of limestones into shales corresponds to deepening, and that of the shales into the overlying limestones to shallowing within a shelf without deltaic deposition.

The type 2 transition presumably represents gradual transgression, during which prodelta shales are covered by shallow-shelf limestones; limestone accumulation is terminated by further increase of water depth and development of anoxia below the thermocline identified according to Heckel (1977, 1986). In such conditions, linked with the transgression maximum, are formed black shales rich in organic matter of marine origin (maxima on gamma-ray logs), referred to as “marine bands” (Davies and McLean 1996). These deposits can be formed in the deepest central part of the sedimentary basin, and pass laterally into prodelta shales towards its shores. The succeeding shallowing during relative sea-level HS causes the disappearance of anoxia and the commencement of limestone deposition. It is probable that an analogous lithofacies succession occurs in the TST of sequence 3. The supposed origin of black shales as an anoxic facies is based solely on analogy and on the interpretations of Heckel (1977, 1986), and the determination of the bottom-water conditions obtaining during their deposition needs geochemical investigations which have not been undertaken during this study. This situation occurs in sequence 3, where the maximum flooding surface was identified as a gamma-ray maximum in the Lublin IG 1, Abramów 7 and Nasutów 1 wireline logs (Appendix, Figs 9, 11, 12). The type 2 transition in these well sections was thus formed in the deeper part of the sedimentary basin, similar to the case of the Łęczna IG 9 well section (Text-fig. 3). In contrast, the maximum flooding surface in the Łęczna IG 13 well section occurs in prodeltaic shales, located within a coarsening-upward type Ic cyclothem (Appendix, Fig. 14).

In the NW part of the Basin, the TST is composed of relatively thin deltaic deposits formed mainly within the submarine part of the delta. The maximum flooding surface in the well sections located to the NW of the Stężyca 2 well corresponds to the base of the limestones, whereas to the SE it is located within prodelta deposits (Stężyca 4, Rycice 2).

HST: The maximum flooding surface is covered by intercalated deltaic deposits and limestones (Text-fig. 9F). The greatest thickness of HST deposits is observed in the Świdnik IG 1 well (Appendix, Fig. 13; Waksmundzka 2007a) and decreases to the NE, SSE and NW. Most probably, it was partially eroded during the following LS throughout the study area. The lower part of the HST comprises thick limestone beds, intercalated with probable prodelta shales, forming the type 1 transition described above. Accretion of sediments was aggradational, whereas the complete coarsening-upward type Ic cyclothems lying above these rocks (and corresponding to parasequences, with thin limestone beds at their base), were formed during the accretion of delta lobes and progradational filling of the sedimentary basin accommodation space.

A relatively thick HST succession has been observed in the Stężyca–Rycice area. Accelerated subsidence was compensated there by deposition of prodelta, delta slope and mouth-bar deposits, formed during progradation of delta lobes. In contrast to the central and eastern area, only two thin limestone beds occur in these deltaic deposits, which indicates deposition in a shallower part of the basin, under the influence of abundant clastic and clay material supplied from the land area.

Sequence 4

Deposits representing sequence 4 have been recognized throughout the study area, thus its regional extent was wider than that of the preceding sequence. Near the Wilga IG 1 well (Text-fig. 4), sequence 4 deposits overlap those of sequence 3, which indicates that deposition expanded towards the NW, where subaerial expossure and erosion had prevailed. Deposits of sequence 4 are rather thin (Table 1), and have been erosionally reduced, particularly in the vicinity of Łęczna–Krowie Bagno (Text-fig. 5), during the LS of the overlying sequence. The greatest thickness is noted in the central area; the sequence is somewhat thinner to the NW.

LST: The basal unconformity in the central and NW area near the Stężyca 1 well (Text-fig. 4; Appendix, Fig. 4) is located below fluvial sandstones and conglomerates. On lithofacies schemes, it can be correlated to the east with the base of thin carbonaceous shales or *Stigmaria* soils, overlain by coal (Łęczna IG 9; Text-figs. 3, 5). In the NW, the unconformity occurs at the base of *Stigmaria* soils or deposits of the delta plain. Sedimentation of these deposits was preceded by intense erosion linked with relative sea-level fall. The shoreline was most likely displaced to the basin centre, which at that time was located to the SW or S of the study area. The Lublin–Abramów–Nasutów area (Text-figs 5, 6) thus became an exposed shelf, within which small incised valleys, c. 10 m deep, were eroded. During relative sea-level rise these valleys began to be filled with sandy sediments deposited in river channels. This is indicated by small- and large-scale cross-stratification, the presence of erosional surfaces with erosional lags within the sandstones and the lack of evidence of marine deposition.

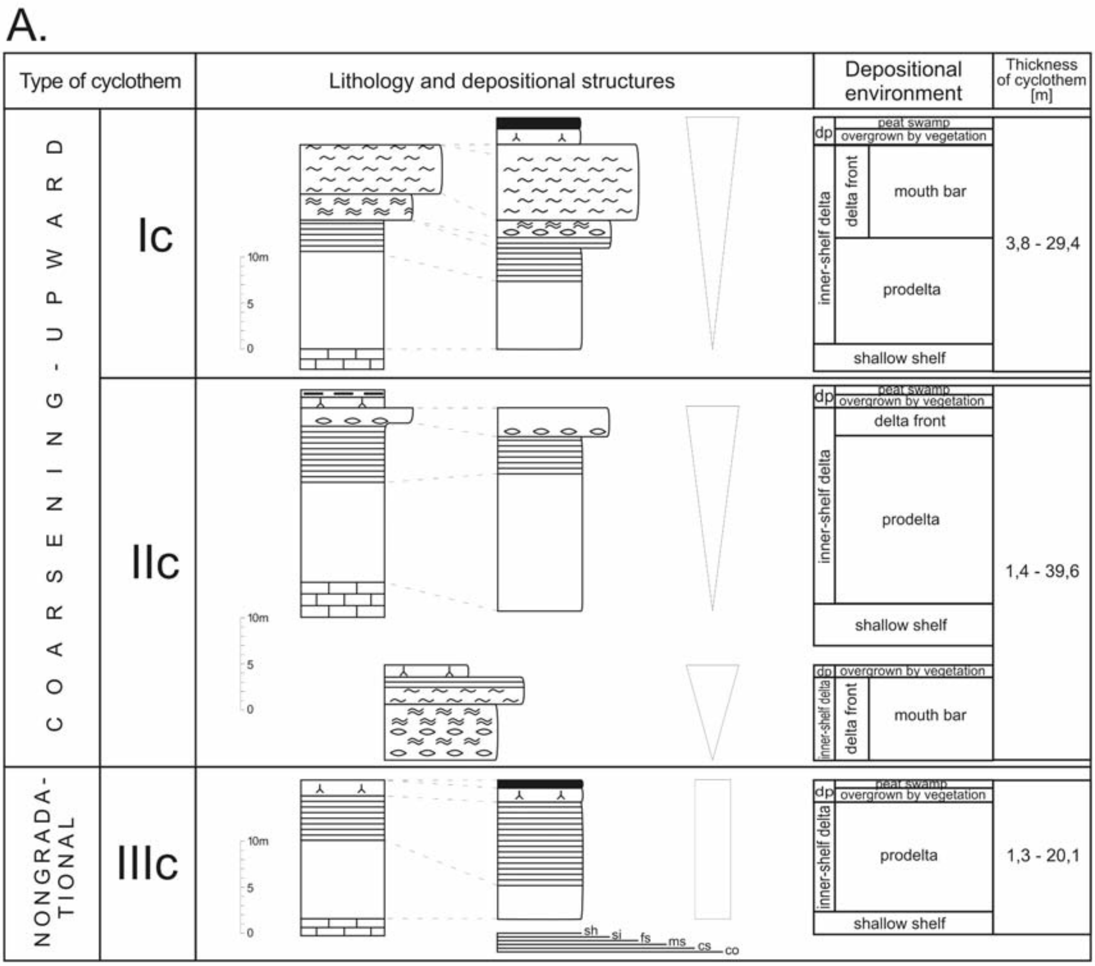
In the E and NW part of the study area (excluding the Stężyca 1 well section; Text-fig. 4), channel deposits do not occur at the base of sequence 4. During the LS, these areas were probably located between incised valleys and were subject to subaerial exposure and erosion (Text-fig. 9A). It is also possible that the base of sequence 4 in the vicinity of the Stężyca 3k, Stężyca 2, Stężyca 4, and Rycice 2 wells may be linked with a transfer zone, through which sediments were transported from incised valleys to the marine basin during relative sea-level LS (see Posamentier and Allen 1993, p. 457). Thus, erosion linked with LS, which took place both in and between the incised valleys, was responsible for the thickness reduction of sequence 3 HST deposits. In the area located between the incised valleys the existence of erosion and reduction of thickness is evidenced by the lack of channel deposits representing the LST (instead of the expected surface of fluvial erosion). This interpretation is subtly confirmed in cores, where disturbed sandstones formed in mouth-bars (HST of sequence 3) occur directly below the base of sequence 4. Irregular lamination, load structures and discontinuous deformations have been encountered therein; these structures could have originated in a non-consolidated deposit located close to the surface and subject to erosion (Łęczna IG 13 and Łęczna IG 9; Text-fig. 5).

TST, HST: *Stigmaria* soils and carbonaceous shales that lie directly above the basal unconformity are the first deposits of sequence 4 formed after LS erosion; they occur in the NW and E part of the study area. They developed on a delta plain generated by relative sea-level rise (Text-fig. 9B-F). The plain was overgrown with vegetation and covered by peat swamps that were partly subjected to an influx of clastic and clay material. Deposition in these swamps probably took place at the end of relative sea-level LS. The overlying coals (Łęczna IG 9; Text-figs 3, 5) are linked with the advancing transgression, and their base is also the maximum regression surface.

Above and directly on these sediments lies a relatively thick, uniform limestone bed. In the eastern part of the study area this bed was designated by Porzycki (1988) with the letter index C. The bed is probably isochronous, an interpretation that is confirmed by biostratigraphic data (conodont and calcareous algae analysis; Skompski 1996), as well as the detailed lithological-facies correlation presented herein. To the east, the maximum flooding surface is the base of the limestone bed; the limestone and the overlying prodelta shales or coarsening-upward type IIc cyclothem belong to the HS deposits.

In the vicinity of Abramów–Nasutów (Text-fig. 6), the transgressive deposits include a limestone bed, distal and proximal deltaic deposits, as well as coals and palaeosols formed on the delta plain. This indicates oscillations of the shoreline, probably linked with episodes of intense clastic material influx. In contrast, the vicinity of the Lublin IG 1 well (Text-fig. 5) was reached only by the distal parts of the delta lobes. In the centre of the study area, c. 100 m of TST deposits filled the relatively large accommodation space. In the Lublin IG 1 well section, the maximum flooding surface occurs just below the limestone bed that can be correlated with limestone C from the eastern part of the area, where a gamma-ray maximum was observed, pointing to the presence of shallow-shelf shales. The limestone bed attains its greatest thickness in the E and thins distinctly to the SW and W, towards the central part of the Basin.

In the Wilga–Maciejowice area (Text-fig. 4), the TS deposits are represented by intercalated limestones and prodelta and shallow-shelf shales. This suggests that when a swampy delta plain developed to the east, the transgression expanded to the NW, where a shallow carbonate shelf, influenced by a distal delta, was present. The maximum flooding surface in this area occurs at the base of the uppermost thick marl in the sequence. In the Stężyca area the marl is subdivided into four thin beds intercalated with prodelta shales. These deposits represent the HST. Throughout the study area, deltaic deposits developed during the HS are thin, and were probably reduced by erosional processes linked with the following relative sea-level LS.



Text-fig. 7AB. Different types of coarsening-upward and non-gradational cyclothems and interpretation of depositional

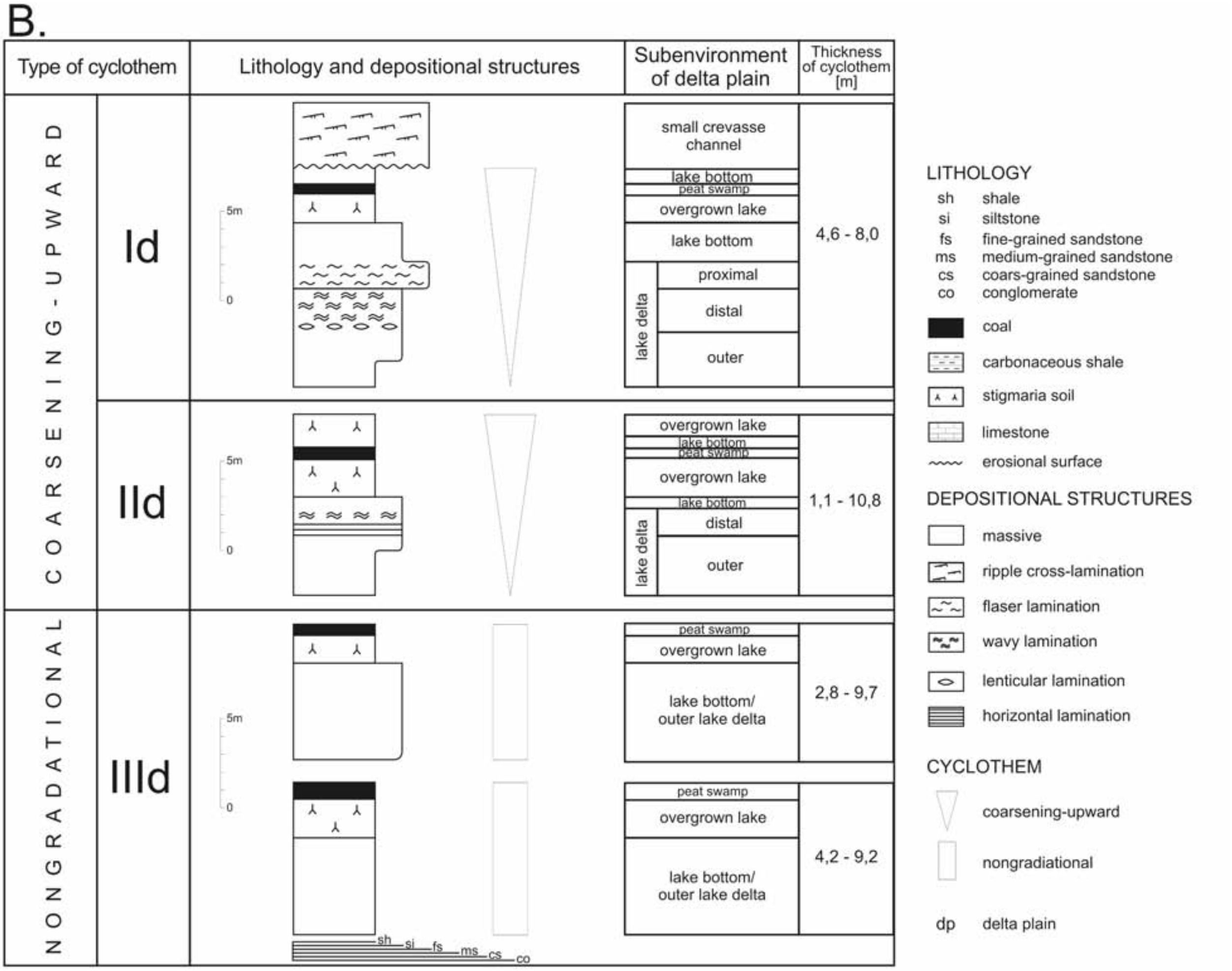
Sequence 5

This sequence is thickest (Table 1) in the central part of the study area (Nasutów 1; Text-fig. 6; Appendix, Fig. 12). It is partly or completely eroded in the east (Text-fig. 5), where deposits of this sequence do not occur at all. This is probably linked with erosion of this area during the following LS. The position of sequence 5 boundaries in the NW is unclear due to the lack of incised valleys, the bases of which are unequivocal sequence boundaries. Therefore, during correlation in this area, the position of sequences 5 and 6 in the succession was interpreted jointly, without their subdivision. A small total thickness of both sequences indicates that they could be extensively eroded.

LST: The basal unconformity of sequence 5 in the Nasutów 1 well section consists of an erosional lag, above which occur channel sandbodies up to c. 20 m thick. They were formed similarly to the LS deposits described above, during infilling of a medium-sized incised valley (Text-fig. 9A, B). In regions without incised valleys, located between the valleys or representing a transfer zone, the placement of the sequence boundary was based on correlation. It probably lies within deltaic deposits, with the lower strata belonging to the HST of sequence 4, and the upper to the TST of sequence 5.

TST, HST: In the Nasutów 1 well section, above the channel deposits occur floodplain or estuary siltstones, which could not be distinguished due to lack of core data from this interval. The siltstones are overlain by coals, representing TS deposits. Directly above the coals a thin limestone bed occurs with the maximum flooding surface at its base. Thus, the swampy area from the Nasutów region was flooded relatively late, during the maximum extent of transgression. In the vicinity of the Lublin IG 1 well (Waksmundzka 2007a), this limestone bed was probably eroded during the following LS. To the S and SW, TST deposits are represented by deltaic lithofacies.

The HST deposits are erosionally reduced and developed as shales and siltstones of the prodelta and delta slope.



environments based on the Lublin IG 2, Łęczna IG 9, and Łęczna IG 13 wells (modified after Waksmundzka 2005)

Sequence 6

This sequence occurs in the central and eastern part of the study area, where it is relatively thick. The greatest thickness is (Table 1) in the Abramów 7 well section (Appendix, Fig. 11), then decreases to the NE. On the other hand, to the NW, deposits of this sequence are very thin and erosionally reduced, and could not be distinguished from sequence 5 deposits.

LST: The lower boundary of sequence 6 is an unconformity, above which occur sandstones that are thickest (c. 26 m) in the Abramów–Nasutów area (Text-fig. 6), and are thinner (12 m) in the Lublin IG 1 well section (Text-fig. 5; Appendix, Fig. 9). The sandstones filled large- and medium-sized incised valleys that developed during the relative sea-level LS, and represent the LST. The eastern part of the study area was probably located between the incised valleys and during the LS was subject to subaerial exposure and erosion (Text-fig. 9A, B). *Stigmaria* soils of the delta plain were formed here by the end of relative sea-level LS or in the beginning of TS. Carbonaceous shales overlying *Stigmaria* soils (Łęczna IG 9; Text-fig. 3) represent transgressive deposits.

In the Abramów 7 and Nasutów 1 well sections there are oil shows within the LST sandstones of sequence 6 indicating their reservoir potential (Waksmundzka 2008b).

TST, HST: In the Lublin IG1 well section, the LST deposits are overlain by shales and siltstones of the delta slope and prodelta, intercalated with limestones and representing the TST (Text-fig. 9C, D). To the NW and NE, in addition to distal facies, proximal deltaic facies, i.e. mouth-bar sandstones and phytogenic deposits of the delta plain, are also encountered. Within the deltaic deposits occur coarsening-upward type IIc, and rarely type Ic, cyclothems, representing parasequences. Their presence points to oscillations of relative sea-level during transgression, possibly linked with episodes of more intense supply of clastic and clay material from land. Some cyclothems begin with limestones, indicating shallow-shelf conditions with no clay influx. The TST top is marked by a thick limestone bed that thins towards the SW. It has been designated by Porzycki (1988) with the letter index F and, as in the case of limestone C, is isochronous as shown by the biostratigraphic studies of Skompski (1996), as well as the detailed lithological-facies correlation presented herein. Above the limestone, within the shallow-shelf shales, occurs the maximum flooding surface, indicated by gamma-ray maxima (Lublin IG1 and Krowie Bagno IG 1 sections; Appendix, Figs 9, 16). Deposition of inner-shelf shales in the vicinity of the Krowie Bagno IG 1 well, which are not noted lower in the section, suggests that this transgression could have extended farther to the NE than the preceding sequences.

The top of the overlying HST deposits is eroded. They comprise shallow-shelf and prodelta shales, and more proximal deltaic facies in the upper part (Text-fig. 9F).

Sequence 7

Deposits of sequence 7 occur throughout the study area, and are thickest (Table 1) in the Abramów–Nasutów region (Text-fig. 6). The thickness decreases distinctly in the marginal parts of the basin, partly due to erosion of the topmost parts of the sequence.

LST: The basal unconformity of sequence 7 is indicated by various clasts, including, for the first time in the succession, quartz and feldspar extraclasts (Stężyca area, Text-fig. 4; Łęczna IG 9, Text-fig. 3, 5), indicating an expanded source area for these strata in comparison to the lower sequences.

Above the unconformity lie sandstones, often underlain by conglomerates, deposited within medium- and large-sized incised shelf valleys that developed during early LS (Text-fig. 9A). These deposits are thickest (c. 25 m) in the Nasutów 1 (Text-fig. 6; Appendix, Fig. 12) and Stężyca 2 well sections (Appendix, Fig. 5), where the incised valleys were most likely the deepest. In the Łęczna IG 9 well section (Text-fig. 3), LST deposits comprise rather thin sandstones of delta distributary channels. The basal unconformity of the sequence in the vicinity of the Lublin IG 1 and Świdnik IG 1 wells (Waksmundzka 2007a) could have been formed in the transfer zone, across which the sediments brought through incised valleys were transported to the deeper part of the sedimentary basin to the SW.

TST: The lowermost TST deposits comprise carbonaceous shales or coals located above the incised valley sandstones (Text-fig. 9C, D). In the Izdebno–Maciejowice area (Text-fig. 4), where deposits of incised valleys have not been encountered, sequence 7 begins with deposits of the delta plain that was formed at the beginning of TS. The upper part of the TST, which is thickest in the Abramów–Nasutów area (Text-fig. 6) and relatively thick in the Maciejowice–Rycice region (Text-fig. 4), is composed of siltstones and shales representing distal parts of delta lobes, as well as of shallow-shelf shales, in which goniatites are present (Nasutów 1).

The maximum flooding surface of sequence 7 occurs within shallow-shelf shales (Text-fig. 9E) and is manifested as very high maxima in gamma-ray logs (in some cases, a characteristic pair of maxima as e.g. in the Abramów–Nasutów area). Black shales as much as 2 m thick and containing abundant organic matter occur in a similar position in cores of the Łęczna IG 13 (Appendix, Fig. 14) and Łęczna IG 9 wells (Text-fig. 3, 5); these shales also contain goniatites. Shallow-shelf shales are present in the thick, lowermost members of coarsening-upward type Ic and IIc cyclothems. The deposits of the upper members of these cyclothems were formed during progradation of delta lobes during the HS.

Shallow-shelf shales formed during the maximum flooding of sequence 7 are located in the *Posidonia corrugata* I horizon, which in the Łęczna IG 13 and Łęczna IG 9 well sections is represented by the lowermost shale member of coarsening-upward type Ic and IIc cyclothems. This macrofaunal horizon is isochronous (Musiał and Tabor 1988) and is characterized by an abundant marine (rarely freshwater or brackish) fauna. The horizon is termed after the most abundant bivalve, *Posidonia corrugata*, and to its important elements, albeit not always present, belong goniatites typical of the E_{2b} Zone. Because gamma-ray maxima linked with the maximum flooding surface of sequence 7 occur in most of the wells studied, it is possible that "anoxic facies" of the shallow-shelf shales (see disscussion in description of TST sequence 3) developed at the same time in the entire study area. This facies, however, represents only a small percentage of deposits commonly included in the *Posidonia corrugata* I horizon. Therefore, it seems that only the part of this horizon made up of black shales corresponding to gamma-ray maxima that are correlated on lithological-facies schemes can be considered as isochronous. The lower as well as higher parts of the *Posidonia corrugata* I horizon containing benthic fauna indicative of oxygenation of bottom waters were formed during the end of the TS and at the beginning of the HS.

The transgression recorded in sequence 7 was probably the widest of all Carboniferous transgressions in the Lublin Basin. This is evidenced by gamma-ray maxima in almost all the wireline logs studied, interpreted as the maximum flooding surface of sequence 7. This is probably linked with the evolution of anoxic conditions in the entire study area. During the transgression maximum such conditions should occur in the central part of the sedimentary basin (see Heckel 1977). This suggests that **the N and NW extent of paralic deposition in Carboniferous times was much wider that the presently accepted boundaries of the Lublin Basin**.

HST: The transgression maximum is followed by HST deposits, developed as prodelta and delta plain shales and siltstones, as well as mouth-bar sandstones. The basal parts of the HST deposits are erosionally reduced in the basin centre, and almost entirely removed at its margins.

Sequences 8, 9, 10

Deposits of sequence 8 are thickest (Table 1) in the central area (Świdnik IG 1 well section; Appendix, Fig. 13; Waksmundzka 2007a); however, even there they are partially eroded. In the NW, the sequence is observed only near the Maciejowice IG 1 well (Text-fig. 4), where its thickness has also been reduced. Deposits representing sequence 9 can be observed in the basin centre (Text-figs 5, 6) and in the Stężyca–Rycice area (Text-fig. 4), whereas elsewhere in the study area (in the NW margin of the basin) they have been removed by erosion. Deposits representing sequence 10 occur farther to the NW, and slightly less extensively eastwards, in relation to deposits of sequence 9. Sequences 8 to 10 are thickest in the central area (Lublin IG 1 well section; Text-fig. 5), and thinner in the NW.

LST: Above the basal unconformities occur sandstones and occasionally conglomerates, up to c. 20 m thick, which fill medium-sized simple incised shelf valleys, eroded during the early LS, that were part of the coastal-plain system (Text-fig. 9A). These strata occur in sequence 8 in the Lublin IG 1 and Świdnik IG 1 well sections (Appendix, Figs 9, 13), and in sequence 9 in the Nasutów 1, Stężyca 1, Stężyca 3k, and Rycice 2 well sections (Appendix, Figs 4, 6, 8, 12). The thinnest example, just over 10 m of sandstone formed in a delta distributary channel, was observed in sequence 9 in the Lublin IG 2 well section (Text-figs 5, 6; Appendix, Fig. 10). Along with the overlying siltstones deposited on the delta plain between the distributary channels, these strata belong to the LST. The vicinity of the Lublin IG 2 well, unlike other areas where incised valleys were formed, was characterized by the smallest slope gradient and was probably located closer to the ancient shoreline.

During LS, unconformities also formed through subaerial exposure and erosion of areas located between the incised valleys. Their position in these zones was confirmed by correlating the bases of the adjacent incised valleys or delta distributary channels. This can be observed in sequence 8 in the Lublin IG 2 and Łęczna IG 13 well sections (Text-figs 5, 6; Appendix, Figs 10, 14), where the lower boundary of the sequence probably lies below coals formed in peat marshes on the delta plain. During LS, erosion most likely prevailed here, whereas the development of delta plain conditions could be linked with the onset of TS.

In the Stężyca 3k well sections there is oil (Helcel-Weil and Dzięgielowski 2003) within the LST sandstones of sequence 9, indicating their reservoir potential (Waksmundzka 2008b; Kombrink *et al.* 2010 see chapter 6.3.6).

TST: The TST of sequence 8 comprises thin prodelta and shallow-shelf shales located above phytogenic deposits (Text-fig. 9C, D). Within these shales occurs the maximum flooding surface, which in the Lublin IG 2 well section is manifested by a gamma-ray maximum, suggesting the appearance of possible anoxic conditions. This maximum corresponds to the *Posidonia corrugata* II horizon, which has been identified in the Łęczna IG 13 well section (Text-fig. 5). Similarly developed is the TST of sequence 10, with the maximum flooding surface at its top, corresponding to a gamma-ray maximum on the Lublin IG 2 log (Appendix, Fig. 10). Near Maciejowice IG 1 (Text-fig. 4; Appendix, Fig. 3), the maximum flooding surface of sequence 8 lies at the base of a thin carbonate bed, which is probably a facies equivalent of the *Posidonia corrugata* II horizon.

The TST deposits of sequence 9 are thicker and are dominated by coarsening-upward type IIc cyclothems, with thick prodelta shales and siltstones, and siltstones of the delta slope. Mouth-bar sandstones are rarely encountered. In the Lublin IG 2 well section deposits of the submarine part of the delta are intercalated with deposits of the delta plain. The maximum flooding surface lies at the base of the overlying limestones. Gamma-ray maxima have not been observed in sequence 9 shales. This suggests that the anoxic shale facies was not developed in the preserved sections, which most probably represent a coastal part of the marine basin, whereas possible anoxic shale should be expected to the W and SW in the deeper part of the basin.

HST: The HST deposits of sequences 8 and 10 are more completely preserved in comparison to the HST of sequence 9, which is strongly reduced erosionally. In the Lublin IG 2 well section occur coarsening-upward type Ic and IIc cyclothems, developed during progradation of the delta lobes, as well as coarsening-upward type IId cyclothems and non-gradational type IIId cyclothems formed during intense aggradation of the delta plain (Text-fig. 9F), that were not observed in the lower part of the paralic succession of the Basin. The presence of thick intervals of this origin suggests that the delta plain environment appeared near the Lublin IG 2 well rather frequently and lasted for a relatively long time. A single limestone bed that occurs in the HST of sequence 10 in the Lublin IG 2 well section was designated by Porzycki (1983) with the letter index N. Along with the limestone beds M and O it has been considered a good correlation horizon (Porzycki 1983). This interpretation, however, is not supported by the results of lithological-facies correlation and sequence stratigraphy. These findings suggest instead that limestone bed N is of different ages in two neighbouring wells, because it occurs in sequence 11 in the Łęczna IG 9 well section, and in sequence 12 in the Łęczna IG 13 well section.

The HST desposits of sequence 10 in the Lublin IG 1 and Świdnik IG 1 well sections (Appendix, Figs 9, 13; Waksmundzka 2007a) are dominated by prodelta and delta slope shales and siltstones, generally without intercalations of delta plain deposits, which suggests deposition in more distal deltaic environments. This contrasts with the Abramów–Nasutów region (Text-fig. 6), where phytogenic deposits of the delta plain as well as sandstones of the distributary channels are present.

Sequence 11

Deposits of this sequence, as well as those of the five overlying sequences, are preserved in the entire study area. The greatest thickness of sequence 11 (Table 1) is observed in the Łęczna IG 9 well section (Text-fig. 3), and the smallest in the basin centre (Lublin IG 1, Świdnik IG 1; Appendix, Figs 9, 13; Waksmundzka 2007a; Nasutów 1, Text-fig. 6; Appendix, Fig. 12) and to the NW (Maciejowice IG 1; Text-fig. 4; Appendix, Fig. 3). The most intense erosion linked with the following LS is observed in the topmost parts of the sequence in the central part of the study area.

LST: Formation of the basal unconformity of sequence 11 was linked with fluvial erosion that destroyed deposits of older sequences. Most probably at that time a large incised shelf valley (Text-fig. 9A) formed in the vicinity of the Lublin IG 2, Abramów 7, and Nasutów 1 wells (Text-fig. 6). Comparison of the thicknesses of sandstones infilling this and the other valleys of the sequence indicates that the incision of the channels is deepest in the vicinity of Abramów. The incision reached at least c. 40 m, which marks the probable relative sea-level fall. Taking into account the erosional reduction of the deposits of the valley analyzed, the incision could have been even deeper.

The LST deposits filling the incised valley in the Lublin IG 2 well section are represented by sandstone lithosomes reaching 8 m, 3.5 m and 12 m, deposited in three stacked braided channels. The two lower are separated by thin (less than 1 m thick) shales, shaly *Stigmaria* soils and siltstones deposited on the fluvial plain after cessation of channel flow. The basal part of the sequence is dominated by high-energy lithofacies linked with alternating processes of local erosion and deposition. Above these strata occur massive sandstones, indicating rapid aggradation of sandy deposits and filling of channels during relative sea-level rise.

A thinner interval of the fluvial channel deposits is observed in the eastern part of the basin. During the upper LS, deposition first took place in a high-energy braided channel in the vicinity of the Łęczna IG 9 well (Text-figs 3, 5); these deposits are c. 4 m thick. As base level rose and channel energy fell, the channels were transformed into an anastomosed system and filled with sandy deposits. A similar origin is interpreted for the 7 m thick sandstones in the Łęczna IG 13 well section. Within this low-energy fluvial system, the aggradation of sediments took place in channels, followed by filling and later aggradation of the flooded fluvial plain.

It can be assumed that the eastern part of the study area represented flat land with low-gradient rivers. On the other hand, to the SW, in the central part of the basin, relative sea-level fall caused exposure of the shelf here characterized by a higher gradient. This resulted in intense fluvial erosion and the formation of incised valleys.

Similar processes took place during the LS in the NW part of the Basin (Text-fig. 4). The Wilga–Izdebno–Maciejowice region, like the eastern area, represented land with a network of generally low-energy rivers. Channel sandbodies attain small thickneses, reaching a maximum of 10 m. They are accompanied by shales and siltstones deposited on floodplains.

To the SW, in the Stężyca–Rycice area, occur incised shelf valleys like those in the vicinity of Abramów. It is possible that the Stężyca 1, Stężyca 2, Stężyca 3k, Stężyca 4, and Rycice 2 well sections represent the same large valley. This valley was deepest near the Stężyca 2 well, as shown by c. 40-m thick fluvial deposits in this area. Its depth would thus correspond to the incision of the valley in the vicinity of Abramów. Assuming that during the LS only fluvial deposits developed, it can be suggested that to the NW and SE of the Stężyca 2 well the depth of the valley reached at least c. 30 m. However, because the fluvial deposits are overlain by estuary deposits that also filled the valley, most probably its depth near the remaining wells could be close to maximum.

Filling of the valley probably began near the Stężyca 2, Stężyca 4, and Rycice 2 wells. The thickness of the channel sandstones lying above the valley base, and deposited during relative sea-level rise, increases there from 9 to 24 m to the SE. The lowest channels represent high-energy environments, whereas the uppermost probably belonged to an anastomosed system (e.g. Stężyca 4). After the channels were filled, deposition took place on a flooded fluvial plain. Similar transformation of high- into low-energy channels in an incised valley has been described by Hampson *et al.* (1997).

In the vicinity of the Rycice 2 well, sandstones are overlain by deposits of the bay-head delta, representing the TST. This indicates flooding of the incised valley generally from the S or SE. Further relative sea-level rise caused translocation of the valley mouth towards the position of the Stężyca 3k and Stężyca 2 wells. Its rapid filling with sandy sediments deposited from fluvial hyperconcentrated flows resulted in the formation of thick (7 m) massive sandstones, characteristic of early phases of valley filling (see Martinsen 1994). To the SW occur deposits of high-energy fluvial channels, followed by low-energy fluvial channels, passing into floodplain deposits. The thickness of the sandbodies formed in the LS in this area reached c. 20 m, similar to the thicknesses in the vicinity of the Lublin IG 2 well.

TST: Thin transgressive sediments occurring above deposits of the LST in the Stężyca area were probably formed within an estuary (Text-fig. 9C). In the Stężyca 1 well section they consist of bioturbated sandstones, and in the Stężyca 3k and Stężyca 2 well sections, of single coarsening-upward cyclothems, probably formed in a bay-head delta. Shales deposited in the estuary basin contain disarticulated crinoid columnals, bivalves and goniatite shell remains, indicating a marine setting that can develop in the widest outer zone of the estuary, under the influence of marine processes (see Dalrymple and *al*. 1992; *vide* fig. 1; 1994, p. 5). It is also possible that the remains of marine fauna were introduced into the estuary basin during storms.

In the vicinity of the Lublin IG 1 well (Text-fig. 5), the TST deposits have been completely removed during the LS of the next sequence. In the Lublin IG 2 well section (Text-fig. 6), above the LST sandstones filling the incised valley, occur shales (c. 5-m thick) probably deposited in an estuary basin. At their base are present two thin conglomerate beds composed of intraclasts of carbonaceous shales and sideritic concretions. The conglomerates developed due to wave erosion of deposits on the floodplain and document the transgressive wave ravinement surface (according to Swift 1968). Above the shales occur sandstones and siltstones of the bay-head delta overlain by coals, pointing to the development of a marsh setting in place of the filled estuary (Text-fig. 9D).

In the Łęczna IG 13 (Appendix, Fig. 14) and Łęczna IG 9 well sections (Text-fig. 3, 5), the TST deposits are developed as a thick interval composed of coarsening-upward type IId cyclothems and non-gradational type IIId cyclothems, representing lake deltas, as well as deposits of the submarine part of the shallow-shelf delta.

In the Łęczna IG 9 well section, the maximum flooding surface is located at the base of a coarsening-upward type IIc cyclothem, within shallow-shelf shales, corresponding to a gamma-ray maximum. The maximum flooding surface corresponds to the base of a non-gradational type IIc cyclothem in the Łęczna IG 13 well section, whereas in the Lublin IG 2 well section (Text-figs 5, 6; Appendix, Fig. 10) it lies at the base of marls covering the TST estuary deposits.

HST: Deposits of the HST are generally thin and highly eroded. They comprise non-gradational type IIIc and IIId cyclothems, indicating aggradational accumulation of deposits, followed by a coarsening-upward type Ic cyclothem formed during progradation of the delta lobe (Łęczna IG 13). In the Lublin IG 2 well section occurs one very thick coarsening-upward type Ic cyclothem, indicating locally accelerating subsidence. In the upper part of the HST occurs a thin limestone bed that in the Łęczna IG 9 well section was designated by the letter index N (Porzycki 1988). This limestone, however, does not correlate with the other limestone beds marked by the same index in adjacent wells (e. g. Łęczna IG 13).

Sequence 12

Deposits of sequence 12 are thickest (Table 1) in the NW (Stężyca 4 and Rycice 2 wells; Text-fig. 4; Appendix, Figs 7, 8) and central part (Świdnik IG 1; Appendix, Fig. 13; Waksmundzka 2007a) of the study area. The thickness generally decreases towards the margins of the basin, to the NW and to the E.

LST: Throughout the study area, deposits of the LST comprise fluvial deposits filling incised shelf valleys or formed between the valleys (Text-fig. 9A), except in the Łęczna IG 13 well section (Text-fig. 5), where sandstones and siltstones of the delta plain are present. In the central and eastern part of the study area in the Krowie Bagno IG 1 well section occur thin single channel sandbodies (a few to more than 10 m thick), indicating rather low fluvial erosion, probably linked with the low gradient of the area during early LS. In the vicinity of the Lublin IG 2 well, fluvial deposits were produced in a low-energy anastomosed system.

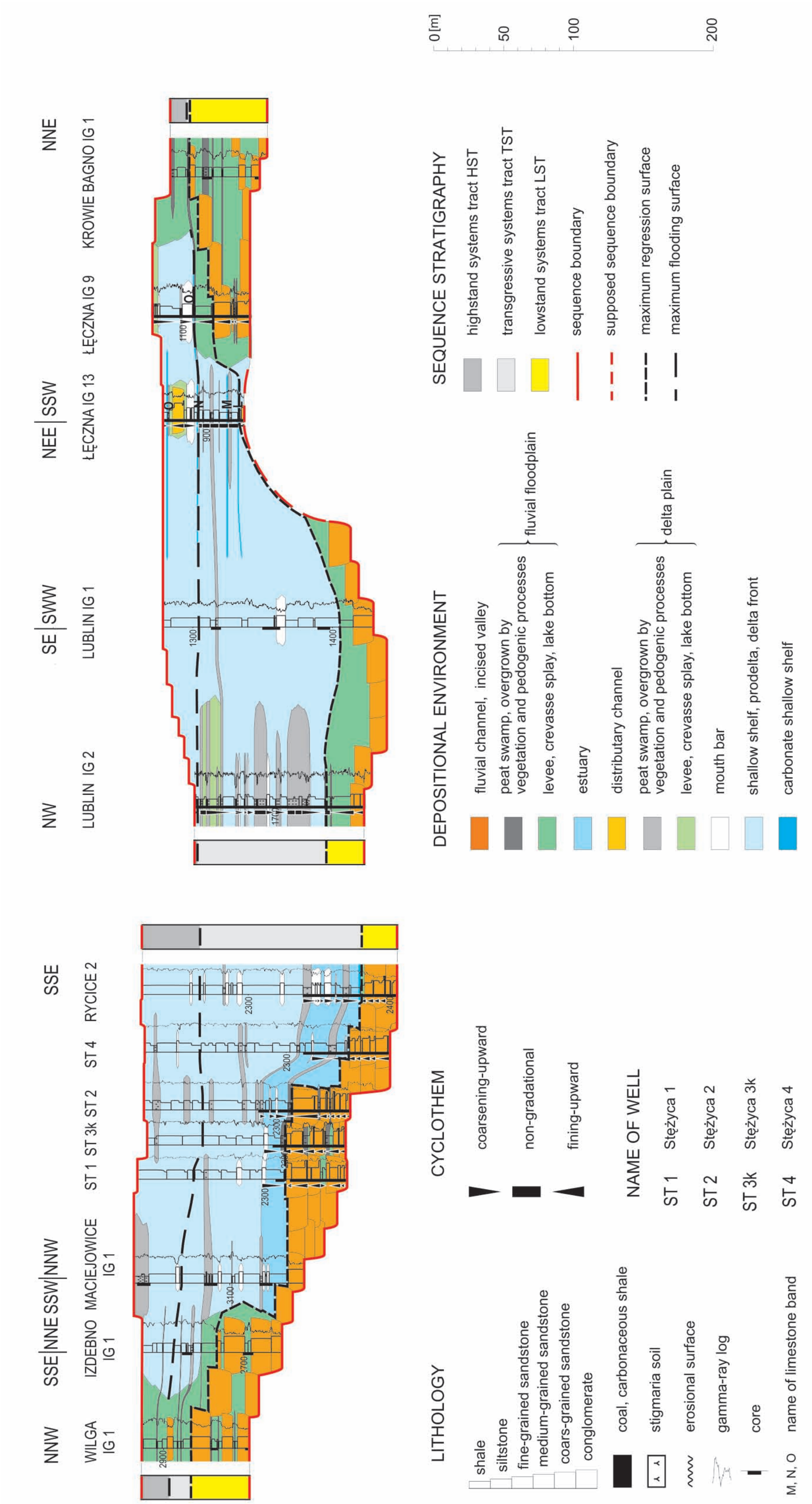
To the E, near the Łęczna IG 9 well, and to the NW, the gradient was higher, therefore fluvial erosion reached deeper, creating large incised valleys, where thick sandbodies were deposited in the late LS. Above the basal unconformity in the incised valley section from the Łęczna IG 9 well occur sandstones developed in sandbed braided channels and, above this, sandstones deposited in channels and on the floodplain of the anastomosed system. The transition from high- to low-energy fluvial environments was linked with fall of gradient and flow energy in channels, connected with relative sea-level rise. The fluvial interval is terminated by extremely thick floodplain siltstones that could have been formed during the TS. A similar interpretation may also apply to the NW of the area, in the Wilga–Izdebno region.

The Maciejowice, Stężyca and Rycice areas (Text-fig. 4) are probably located in the same incised valley. The thickness of the deposits that fill the valley (c. 40 m) corresponds approximately to the value of incision and relative sea-level fall. The smaller, 10-m thickness of sandstones in the Maciejowice IG 1 well section indicates that the incised valley was shallower there. To the SE, towards the Rycice 2 well, the thickness of the channel sandstones also decreases. The process of incised valley filling was similar to that for the valleys from sequence 11; the sequence 11 valley was partly exhumed near the position of the Stężyca 2 and Stężyca 4 wells during the LS of sequence 12. Thus, the valleys occurring in these sequences belong to compound, piedmont incised-valley systems, filled with deposits representing two sequences.

The filling probably began earlier in the area near the Stężyca 4 and Rycice 2 wells, where the total thickness of two or three stacked channel sandbodies and floodplain deposits developed during relative sea-level rise, is c. 30–40 m. The two lowermost channels were formed in high-energy braided rivers; the third, uppermost channel in the Stężyca 4 well section probably represents the anastomosed system. After the channels were filled, deposition took place on a flooded floodplain; deposits representing this stage can be found in the Rycice 2 well section. In this area they are overlain by thin marls, belonging to the TST, which indicate that the valley mouth was widest here and marine conditions prevailed (see Pritchard 1967). The sea flooded the area generally from the S or SE.

To the NW, in the vicinity of the Stężyca 1, Stężyca 3k, and Stężyca 2 wells, occur three stacked channel sandbodies. The lowest is probably contemporaneous with channels of the anastomosed system from the Stężyca 4 well section, whereas the upper ones are younger. The two lower channels were formed in a meandering river system. The uppermost sandstones from the Stężyca 3k well section were also formed in this environment. Near the Stężyca 2 well section, rapid aggradation of deposits took place, as evidenced by the presence of 11-m thick massive sandstones, developed in hyperconcentrated flows.

In the Stężyca 1 and Stężyca 3k well sections there is oil and gas (Helcel-Weil and Dzięgielowski 2003)



Text-fig. 8. Lithofacies of depositional systems tracts in sequence 12 from north-western, central and eastern regions of the Lublin Basin (detailed logs are shown in Text-fig. 3 and in the Appendix) within the LST sandstones of sequence 12 indicating their reservoir potential (Waksmundzka 2008b; Kombrink *et al.* 2010 see chapter 6.3.6).

The maximum regression surface is located at the top of the floodplain deposits, which are the topmost sediments of the LST.

TST: In the Stężyca–Rycice area, the TST comprises marls and coarsening-upward type-Ic and IIc cyclothems (Text-fig. 8), probably formed in a bay-head delta (Text-fig. 9C). At the top of the estuary sediments occur shaly *Stigmaria* soils, indicating brief emersion and growth of vegetation. The total thickness of the fluvial and estuary deposits suggests that the valley incision could have reached c. 50 m.

In the eastern part of the study area (Text-figs 5, 8), the TST deposits consist of coarsening-upward and non-gradational cyclothems (corresponding to parasequences), formed in an inner-shelf delta, interfingering with two thin limestone beds (beds L and M of Porzycki 1988). In the Łęczna IG 13 well section occur only distal non-gradational type IIIc cyclothems, which indicates that this area was farthest from the ancient shoreline. In the Lublin IG 2 well section are present mainly coarsening-upward type Ic cyclothems, with very thin mouth-bar sandstones, and type IIc cyclothems. Type IId and IIId cyclothems can also be observed, indicating rather long-lasting deposition on the delta plain. The TST deposits attain the greatest thickness in the central area, thus the supply of material from land areas must have been larger here than in the Łęczna region.

The maximum flooding surface is located within probably "anoxic" shallow-shelf shales (see discussion in the description of TST sequence 3), which correspond to a gamma-ray maximum on the Łęczna IG 13 wireline log. Elsewhere, this facies is not present, and the maximum flooding surface lies within prodelta shales and, in the east, at the base of a thin limestone bed. This bed in the Łęczna IG 9 well section was designated by Porzycki (1988) with the letter index O but with the letter index N in the Łęczna IG 13 well section.

In the eastern part of the study area, fluvial sediments were deposited during LS and TS. Most of this region was flooded by the sea during the maximum transgression. The areas of the Wilga IG 1 (Text-fig. 4) and Krowie Bagno IG 1 (Text-fig. 5) wells, at opposite ends of the sedimentary basin, were not covered by TS deposits; in these areas, sequence 12 is developed entirely as fluvial sediments.

HST: The top of the HST deposits in sequence 12 is eroded, particularly near the Abramów 7 and Lublin IG 2 wells (Text-fig. 6) where HST deposits have been entirely removed. In the east, the HST deposits are composed of coarsening-upward type Ic and IIc cyclothems developed during progradation of an inner-shelf delta. These strata contain relatively thick sandstones of mouth-bars and distributary channels. In the Łęczna IG 13 well section, the HST deposits include a thin, partly dolomitic limestone bed that was designated by Porzycki (1988) with the letter index O, documenting short-term shallow-shelf conditions.

Sequence 13

The greatest thickness of sequence 13 deposits (Table 1) occurs in the eastern part of the study area (Text-fig. 5), where it is relatively thick in parts of the central area and reduced erosionally in marginal parts.

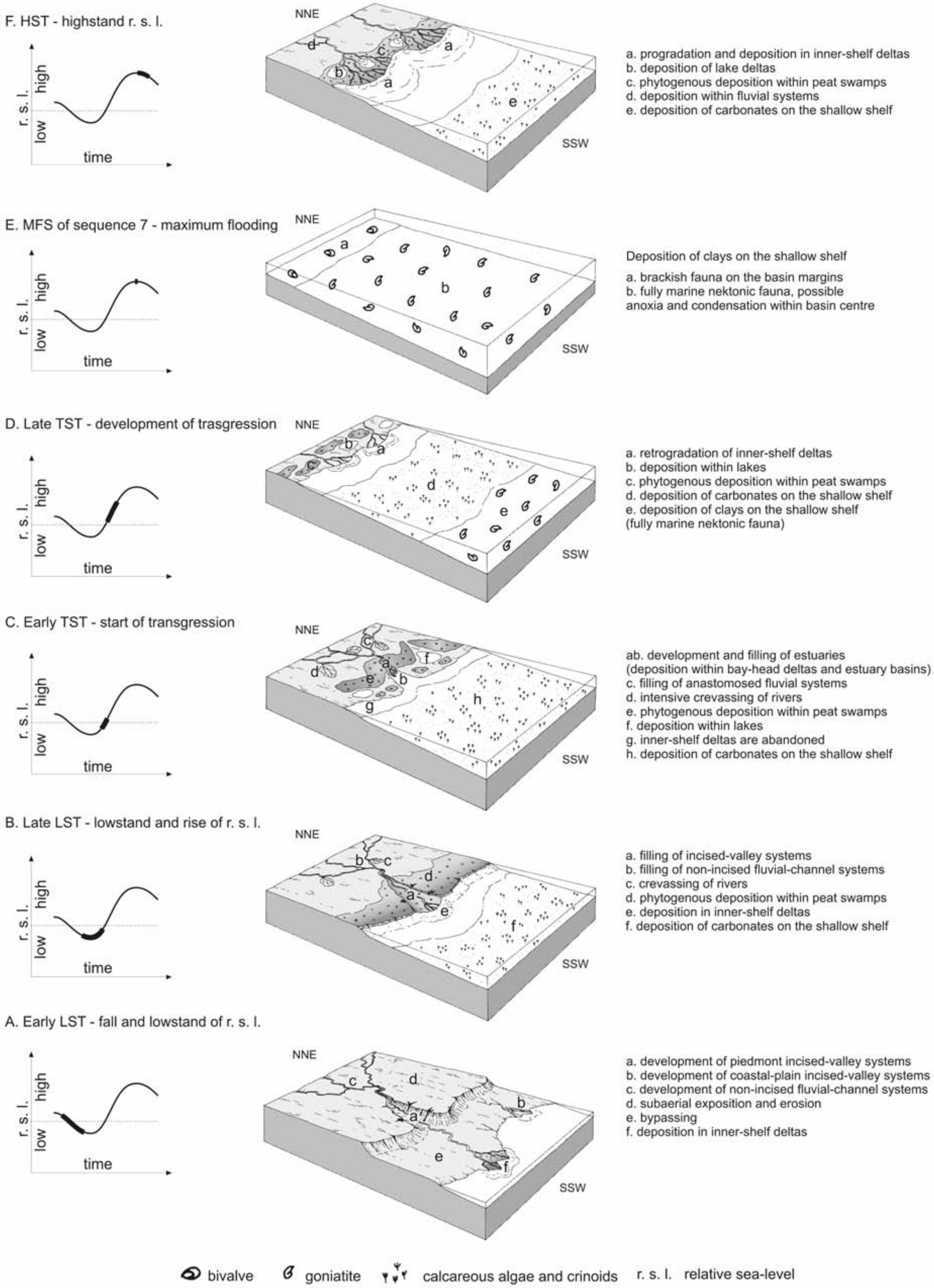
LST: Above the basal unconformity occur fluvial sandstones formed during late LS. They are thickest (*ca*. 45 m) in the easternmost part of the area, in the Krowie Bagno IG 1 well section (Appendix, Fig. 16). These sediments probably fill a large incised valley formed during early LS (Text-fig. 9A).

To the SW, the rivers eroded shallower valleys, as reflected in thinner deposits–c. 15 m near Łęczna and in the Lublin IG 1 well section, and several metres in the Lublin IG 2 and Nasutów 1 well sections (Text-fig. 6). Presumably a flat coastal-plain of the anastomosed system was located near the position of the Lublin IG 2 well.

To the SW, a lateral transition of the channel types can be observed. In the vicinity of the Łęczna IG 25 well (Waksmundzka 2007a), a high-energy braided river developed at first, followed by a low-energy braided river. Braided rivers also occurred in the vicinity of the Łęczna IG 13 and Łęczna IG 9 wells (Text-figs 3, 5), whereas meandering rivers with lower energy flow were present near the Lublin IG 2 well. Gradual rise of relative sea-level caused further decrease in gradient and the river system was transformed into an anastomosed system. Above the channel sandstones are present thick intervals of shales and siltstones representing a flooded flood-plain. Shallow lakes with small deltas were present there, which, after filling with sediments, became overgrown by vegetation. Similar processes took place during LS in the NW part of the study area.

The maximum regression surface is located at the base of coals or carbonaceous shales that overlie the fluvial deposits.

TST, HST: Above the LST occur TST deposits, developed in the Lublin IG 2 well section as coarsening-upward type Ic and IId cyclothems, as well as non-grada-



Text-fig. 9. Variation in depositional environments of the paralic Carboniferous deposits reflecting their position on the relative sea-level curve tional type IIIc cyclothems. In the Łęczna IG 9 well section only type IIc cyclothems are observed, which are thicker and more distal in character.

The maximum flooding surface is located within prodelta or shallow-shelf shales, which in the Krowie Bagno IG 1 well section contain brachiopods, crinoid columnals, bivalves, and goniatite remains.

The HST comprises coarsening-upward type Ic and IIc cyclothems, formed during progradation of delta lobes. In most of the NW part of the basin and in its centre, TST and HST deposits were completely eroded during the next LS.

Sequence 14

Deposits of sequence 14 are generally thin (Table 1), erosionally reduced and, in some cases, only several metres thick. They are slightly thicker to the NW, except in the Wilga IG 1 well area (Text-fig. 4).

LST: The LST deposits comprise massive sandstones, up to c. 18-m thick, filling an incised valley (Łęczna IG 13; Text-fig. 5; Appendix, Fig. 14). They could have been deposited during high-energy hyperconcentrated flow within a large incised valley (Text-fig. 9A, B). The valley was at least 30 m deep, allowing for erosional reduction of the topmost deposits. Most probably the same origin can be assumed for the LST deposits in the Łęczna IG 9 well section; they were, however, almost completely reduced during the following LS. Near the Łęczna IG 25 well (Waksmundzka 2007a), deposition took place in a braided channel with downstream-accreting alternate bars. It is possible that this river flowed within an incised valley in its more proximal part, where deposits of sequence 14 are largely eroded.

Incised valleys most probably did not develop in the easternmost part of the study area, in the centre near the Lublin IG 2 well (Text-fig. 5) and in the NW near the Maciejowice IG 1 well (Text-fig. 4). Near the Lublin IG 2 well, sandy deposits several metres thick were deposited during LS, filling a meandering river channel. This channel was located on a near-shore alluvial plain, passing into a delta plain. The sandstones are overlain by siltstones and *Stigmaria* soils that were formed on a floodplain. The maximum regression surface has been placed at the base of the overlying coal bed.

TST, HST: Deposits representing the TST and HST occur only near the Lublin IG 2 well (Appendix, Fig. 10). Within the TST occur two coarsening-upward cyclothems corresponding to parasequences. The lower and upper cyclothem represent types Ic and type IIc respectively, indicating transition from proximal to more distal parts of the delta lobe. Higher up occurs the most distal, non-gradational type IIIc cyclothem, within which the maximum flooding surface is located in prodelta shales. The upper part of this cyclothem, developed as prodelta shales and shaly *Stigmaria* soils, represents the HST. Its upper part is eroded.

Sequence 15

Deposits of sequence 15 attain their greatest thickness (Table 1) in the NW part of the study area in the Wilga IG 1 well section (Text-fig. 4) and decrease to the SE (Text-fig. 5).

LST: The basal unconformity of this sequence corresponds to the base of incised valleys that developed during early LS (Text-fig. 9A). These valleys most probably had a similar pattern to the incised valleys of sequence 14. Erosion resulted in the exhumation of the older generation of deposits filling the valleys; in late LS with relative sea-level rise, secondary filling of the valleys took place with sandy deposits of fluvial channels and hyperconcentrated flows. Thus, the valleys of sequences 14 and 15 belong to compound incised valleys filled with deposits representing more than one sequence, and they therefore represent a piedmont incised-valley system. Amalgamation of LST sandstones from sequences 13 to 15 near the Łęczna IG 13 (Text-fig. 5; Appendix, Fig. 14) and Łęczna IG 25 (Appendix, Fig. 15; Waksmundzka 2007a) wells, and of sequences 14 to 15 in the remaining area, resulted in formation of the thickest sandbody in the Lublin Basin, reaching 75–96 m in thickness. Studies of fully-cored sections allowed reconstruction of the vertical succession of lithofacies and depositional environments which, like those of the deposits filling the incised valleys of lower sequences, is characterized by the vertical transition of high-energy environments into low-energy sedimentary conditions. However, particular sections located in different incised valleys differ in the individual successions of environments represented. Examples are given below, based on the Łęczna IG 9, Łęczna IG 13 and Łęczna IG 25 well sections from the central and eastern parts of the basin.

To the NNE, in the vicinity of the Łęczna IG 9 well (Text-fig. 5), was located a relatively shallow valley (compared to those located to the SW). It is filled with c. 30 m of sandstones, which formed at first in high-energy hyperconcentrated flow conditions. A specific lithofacies of 22-m thick massive sandstone was formed at this stage. Due to relative sea-level rise, valley gradient and flow energy decreased. Hyperconcentrated flow disappeared, and the upper part of the sandstones was formed in a sand-bed braided channel, followed by a sand-bed channel of the anastomosed system. The maximum regression surface probably lies at the top of these sandstones.

The sandstones filling the valley in the vicinity of the Łęczna IG 13 well are thicker (40 m) than those in the Łęczna IG 9 well section. Initial deposition took place in a sand-gravel-bed braided channel, followed by a sand-bed braided channel. Next, deposition from high-energy hyperconcentrated flow prevailed; this flow was probably briefer than that which produced the Łęczna IG 9 well section, as suggested by thinner (6 m) deposits at Łęczna IG 13. Hyperconcentrated flow terminated with a decrease in flow energy and sediment concentration. Subsequent deposition took place in a high-energy sand-bed braided channel that evolved later into a low-energy declining channel and floodplain of a low-energy sand-bed braided river. At the top of the fluvial interval there are sandy *Stigmaria* soils, indicating cessation of flow and the evolution of vegetation cover in the area. The soils are overlain by coals, at the base of which the maximum regression surface is located; the coals belong to the TST.

The deposits filling the incised valley in the vicinity of the Łęczna IG 25 well section are thickest (65 m). At first, the sediments were deposited in a sand-bed braided channel with alternate bars, and next in a sand-bed braided river. The channels are characterized by intense aggradation of deposits. Decrease in valley gradient and flow energy influenced deposition of the following interval, which developed in the channel and on the floodplain of a meandering river and consists mainly of fine-grained deposits. Higher in the succession, deposits representing a braided river appear, and again pass into sediments of a sand-bed meandering river. Thick floodplain deposits above these strata were formed after the channels were completely filled and the area was flooded during relative sea-level rise. The floodplain deposits are overlain by coals and carbonaceous shales formed during transgression.

In the vicinity of the Lublin IG 2 well, as in sequence 14 (Text-figs 5, 6), incised valleys do not occur at all, and the LST is represented by meandering river deposits. Several-metre-thick sandstones developed in a channel on a coastal plain passing into a delta plain. Above the sandstones occurs a coarsening-upward type-IId cyclothem formed on a flooded floodplain. At its top lie coals assigned to the TST.

TST, HST: Typically, the TST deposits begin with coal beds, above which, as e.g. in the Łęczna IG 13 well section, occur estuary deposits that fill the incised valley (Text-fig. 9C, D). These deposits include a coarsening-upward type Ic cyclothem that could have formed within a bay-head delta. Above this lie cyclothems deposited within the delta plain: a coarsening-upward type IId cyclothem, then a fining-upward cyclothem composed of distributary channel sandstones and thick fine-grained deposits, and a non-gradational type IIId cyclothem. These cyclothems were formed during the final stage of the filling of the incised valley. The total thickness of fluvial deposits representing the LST and the estuary deposits of the TST filling the incised valley indicate that erosion during the LS of sequence 15 cut into at least 60 m of older deposits.

In the upper part of the TST deposits in the Łęczna IG 13 well section occur two subsequent cyclothems: a coarsening-upward type IIc cyclothem and a non-gradational type IIIc cyclothem with thick prodelta members, formed within a distal inner-shelf delta. A similar origin has also been inferred for the thin TST deposits in the Łęczna IG 25 and Lublin IG 2 well sections.

The maximum flooding surface is located at the base of the thin limestone bed designated by Porzycki (1988) with the letter index P (Łęczna IG 13) or within prodelta shales representing the lower part of a coarsening-upward type IIc cyclothem (e.g. Lublin IG 2). This surface was not recognized in the Łęczna IG 9 well section and in the Stężyca–Rycice region, because the TST and HST deposits are developed there in terrestrial facies. They comprise extremely thick floodplain deposits of the anastomosed system. Presumably a flooded land occurred in this area, on which lakes were formed during relative sea-level rise and filled later with shales and siltstones and overgrown with vegetation. In the flooded zones, without supply of clastic material, marshes developed. Coals overlying the fluvial deposits belong to the succeeding sequence.

Deposits of the HST are typically thin and have been eroded. Deltaic cyclothems have been recognized within them: a non-gradational type IIIc, coarsening-upward type IIc and a non-gradational type IIId with a progressively proximal character (Łęczna IG 13), or a single coarsening-upward type IIc cyclothem (Łęczna IG 25).

Sequence 16

The deposits of sequence 16 are thickest (Table 1) in the vicinity of the Świdnik IG 1 and Łęczna IG 25 wells, and relatively thick in the eastern and central part of the study area.

LST: The lowermost deposits of this sequence are represented by channel sandstones deposited initially in high-energy conditions that later passed into a low-energy anastomosed system (Łęczna IG 25; Appendix, Fig. 15; Waksmundzka 2007a). Above them occurs an extremely thick interval of shales, siltstones, *Stigmaria* soils and coals formed on a flooded alluvial plain (Text-fig. 9A, B). Coarsening-upward type IId cyclothems that were deposited in lake deltas are present within them. In the remaining area, above the base of the sequence alluvial plain deposits occur, i.e. coals and *Stigmaria* soils, which are thickest in the Lublin IG 2 well section (Text-fig. 5; Appendix, Fig. 10), and thinnest in the Abramów–Nasutów area (Text-fig. 6; Appendix, Fig 11, 12) and to the NW.

TST: In the Lublin IG 2 well section, the maximum regression surface lies below coals overlying floodplain deposits (Text-fig. 9C, D). The coals, along with the overlying deltaic type IIc cyclothem, belong to the TST. The maximum flooding surface lies within the prodelta shales of the higher type IIc cyclothem and is located within the *Dunbarella papyracea* horizon (Musiał and Tabor 1988), recognized in the fully cored Łęczna IG 9, Łęczna IG 13 (Text-figs 5), Łęczna IG 25 (Waksmundzka 2007a), and Lublin IG 2 wells (Text-figs 5, 6). This is the highest faunally documented marine horizon and indicates the top of the paralic succession in the basin. In the Łęczna IG 25 well section, shallow-shelf shales reflected by gamma-ray maxima occur within this horizon, suggesting that the maximum flooding surface is linked with this horizon. Analogous gamma-ray maxima have also been observed in the Nasutów IG 1 wireline log. In the remaining wells the maximum flooding surface is placed in distal deltaic lithofacies corresponding to gamma-ray maxima. The *Dunbarella papyracea* horizon is treated herein as isochronous (following Musiał and Tabor 1988), and corresponds to the boundary between Westphalian A and Westphalian B.

In the NW part of the study area, gamma-ray maxima have not been observed within the deltaic and shallow-shelf deposits of sequence 16, indicating that this area was located in the marginal zone of the sedimentary basin, where anoxic conditions did not develop.The absence of gamma-ray maxima there could also be attributed to erosion of anoxic shales during the next LS.

HST: In central and eastern areas, HST sediments of sequence 16 were deposited in an inner-shelf delta environment (Text-fig. 9F) and consist of coarsening-upward type IIc and Ic cyclothems that are progressively more proximal in character. Sandstones of mouth-bars and delta distributary channels occur within them, pointing to intense clastic material supply and filling of accommodation space. In the upper part of sequence 16 near the Łęczna IG 9 well a thick fluvial interval occurs above the deltaic deposits. It comprises channel sandstones of the anastomosed system, as well as shales, siltstones, *Stigmaria* soils, and coals deposited on the floodplain of this system. Coarsening-upward cyclothems developed in lake deltas are also present.

Deposits of the inner-shelf delta from the HST thin out to the east, and in the Krowie Bagno IG1 well section (Text-fig. 5) the entire sequence is composed of fluvial deposits. Therefore, the maximum extent of the transgression was to the east of the position of the Łęczna IG 9 well. In the NW part of the study area, the transgression reached farther to the NW, beyond the Wilga IG 1 well area (Text-fig. 4).

In the E and NW parts of the study area, the top of sequence 16 is erosional and linked with the LS of the following sequence 17, which was not a subject of this study. The greatest thickness reduction is present in the NW part of the area in the Wilga IG 1 well section, where erosion removed the entire HST and a large part of the TST. More complete sequence 16 successions are represented in the Maciejowice IG 1 and Stężyca 4 well sections, in which deltaic deposits of the TST, the maximum flooding surface and the lower part of the HST are all present.

In the central part of the study area, the top of sequence 16 corresponds to the top of the Carboniferous and is linked with the erosion that prevailed in the Lublin Basin area from Stephanian to Early Jurassic time. Erosion was deepest in the Łęczna IG 13 well section, where it removed the HST and the upper part of the TST of sequence 16. In the Lublin IG 2 well section (Text-figs 5, 6), the upper boundary of sequence 16 corresponds to the top of the sediments deposited in the submarine part of the delta, above which fluvial deposits occur that are assigned to the following sequence.

SUMMARY OF DEPOSITIONAL CHARACTERISTICS

The sequence stratigraphy of the paralic Carboniferous succession shows a distinctly bi-partite character. In its lower part, comprising sequences 2 to 10, the thickest deposits represent the TST and HST and include thick limestone beds and shallow-shelf shales. Deposits of incised valleys of the LST are thin or lacking. This part of the succession formed in a generally marine or distal-deltaic sedimentary regime.

With regard to lithofacies development and origin, similar sequences have been described from the Pennsylvanian of Kansas, USA by Maynard and Leeder (1992) and Archer *et al*. (1994), as well as from the Carboniferous of Ireland by Davies and Elliot (1996) and England by Davies and McLean (1996), Davies and *al*. (1999) and Tucker (2003). The lithofacies of sequences 2 to 10 from the Lublin Basin greatly resemble those described by Smith Jr. and Read (1999, 2001) from the Upper Mississippian of the Illinois Basin, USA. The latter differ, however, in having thicker limestone beds and including other microfacies, e.g. ooid, not noted in the limestones from the Lublin Basin.

The upper part of the paralic succession, encompassing sequences 11 to 16, is characterized by generally thick deposits filling incised valleys and thin TST and HST complexes. Within the latter, thin limestone beds and shallow-shelf shales occur only occasionally. This part of the succession was generally formed in a deltaic and fluvial sedimentary regime.

Similar sequences with regard to the lithofacies composition and thickness relations between the particular depositional systems tracts have been described from the Pennsylvanian of the Ruhr Basin in Germany (Hampson *et al*. 1999; Süss *et al.* 2001), England (Church and Gawthorpe 1994; Martinsen *et al.* 1995), North Sea (O'Mara *et al.* 1998), Ireland (Hampson *et al.* 1997), Wales (Hampson 1998; George 2001; Jerrett and Hampson 2007), the limnic Lorraine Basin, France (Izart *et al.* 2005), the Moscow Platform, Russia (Briand *et al.* 1998) and the Donets Basin, Russia/Ukraine (Izart *et al.* 1996, 2002, 2003a and b) and the U.S. (Aitken and Flint 1994).

Detailed analysis of coarsening-upward and non-gradational cyclothems allowed the paralic Carboniferous of the Lublin Basin (except for sequence 1 which is composed only of fining-upward cyclothems) to be subdivided into three intervals differing in their depositional regime.

Within sequences 2 to 7, coarsening-upward type IIc cyclothems representing the submarine part of the delta prevail. Non-gradational type IIIc cyclothems are quite frequent and the least frequent are coarsening-upward type Ic cyclothems. These cyclothems consist of the thickest beds of shallow-shelf limestones, marls and shales; prodelta shales and siltstones, as well as siltstones of the delta front. Prodelta shales and siltstones attain maximum thicknesses (c. 35 m) within these cyclothems. The large number of coarsening-upward type-IIc cyclothems typically formed in transgressive conditions is linked with the great thickness of TST deposits. The dominance of shallow-shelf and prodelta lithofacies indicates generally marine and distal-delta sedimentary regimes and aggradation of sediments. In turn, the maximum thickness of cyclothems reaching c. 30–40 m is connected with maximum depth of the marine basin and subsequent filling of the maximum accommodation space. The rarity of complete type Ic cyclothems, which generally develop during the progradation of delta lobes during HS, reflects erosion and locally complete removal of HST deposits. This factor could also explain the rarity or absence of type IId cyclothems that developed in lakes and small deltas on the delta plain.

In sequences 8 to 10, coarsening-upward type IId cyclothems representing the delta plain and formed in the small lake deltas prevail. Their great thickness (up to c. 10 m) indicates rather long periods of deposition in an environment of a rapidly aggrading delta plain during relative sea-level HS. Also numerous are coarsening-upward type IIc cyclothems, formed in the submarine part of the delta during both the TS and HS. Less numerous are type Ic cyclothems, developed during progradation of delta lobes under HS conditions. Their thickness, reaching a maximum of c. 14 m, probably reflects the maximum depth of the marine basin during deposition of sequences 8 to 10; this maximum was, however, less than that during the deposition of sequences 2 to 7.

Sediments deposited during sequences 8 to 10 accumulated in a deltaic sedimentary regime. Within coarsening-upward cyclothems, individual members are rather thin (thickness up to several metres). This indicates regular migration of delta sub-environments from prodelta, through delta slope, to a fully developed delta plain, indicated by the presence of sandstones of delta channels and coarsening-upward cyclothems of small lake deltas.

Coarsening-upward cyclothems in the uppermost part of the paralic succession in the Lublin Basin, encompassing sequences 11 to 16, were characterized on the basis of fully cored sections of the Lublin IG 2, Łęczna IG 9, and Łęczna IG 13 wells. They are dominated by coarsening-upward and non-gradational cyclothems of the submarine part of the delta.

In the Lublin IG 2 well section, coarsening-upward type Ic and IIc cyclothems predominate, reaching c. 17 m and c. 23 m in maximum thickness respectively, and reflect the rather deep sea in that part of the basin. In these cyclothems, distal facies, i.e., shallow-shelf and prodelta shales as well as siltstones of the delta slope, attain a maximum of c. 13 m in thickness, whereas the proximal facies, i.e., mouth-bar sandstones as well as shales and phytogenic deposits of the delta plain, are typically several metres thick. In type Ic cyclothems formed during transgression, mouth-bar deposits are very thin, whereas in the more common cyclothems formed during HS, mouth-bar sandstones are much thicker.

In the Łęczna IG 13 well section, non-gradational type IIIc cyclothems and coarsening-upward type Ic cyclothems are commonest, reaching a maximum of c.

12 m and c. 16 m respectively, and reflect a shallower marine basin than that seen in the Lublin IG 2 well section. Non-gradational type IIIc cyclothems aggraded during maximum transgression and at the beginning of the HS, when the sea was deepest and the distance to land was greatest.

In the Łęczna IG 9 well section, coarsening-upward type IIc cyclothems, up to c. 20 m thick, occur. Those that developed during TS comprise thick prodelta and inner-shelf shales and sometimes lack deposits of the delta plain, whereas those formed during HS have a thinner prodelta and a well-developed phytogenic delta plain member.

In sections of the analyzed wells coarsening-upward cyclothems and non-gradational cyclothems of the delta plain attaining c. 7 to 11 m in thickness also occur. Their development was linked with intense aggradation of delta plain deposits in response to increasing relative sea-level during TS, as well as abundant supply of detrital material, filling of accommodation space and evolution of the delta plain during HS.

The paralic Carboniferous sediments representing sequences 11 to 16 were deposited under a deltaic sedimentary regime dominated by prograding submarine delta deposits during HS, which is shown by relatively thick delta slope and mouth-bar deposits. The maximum thicknesses of coarsening-upward cyclothems of the submarine part of the delta reflect relatively great water depths, which were greater than those from sequences 8 to 10, but smaller than those from sequences 2 to 7. Rather thick coarsening-upward type IId and Id cyclothems indicate long-term deposition on a fully developed delta plain with distributary channels and small lake deltas.

CORRELATION OF SEQUENCE STRATIGRAPHY WITH THE CHRONOSTRATIGRAPHIC SCHEME FOR THE CARBONIFEROUS SYSTEM

A principal assumption in sequence stratigraphy is the prime significance of relative sea-level oscillations in the formation of depositional sequences. In the case of the Carboniferous System, this opinion is justified by a relatively simple link between sea-level changes and the rhythm of successive glacial episodes. Glaciation began in the southern hemisphere in latest Viséan time and lasted, with only short breaks, until about Early Permian time (Veevers and Powell 1987). Thus, in the entire succession of the paralic Carboniferous of the Lublin Basin, glacial episodes could represent a major factor influencing the course of sedimentary processes. This concept was confirmed in numerous reports on the rhythm of shelf sedimentation developed on the margins of the Laurussia palaeocontinent (Ramsbottom 1973, 1977, 1979, 1981).

On the other hand, the Carboniferous Period was a time of numerous diastrophic events that resulted in unconformities or stratigraphic gaps. Determining the presence of unconformities is relatively easy, whereas resolving whether a stratigraphic gap is of tectonic or eustatic origin is much more difficult. A specific case is the mid-Carboniferous boundary between the Mississippian and Pennsylvanian. This boundary is linked with one of the larger Phanerozoic extinction events (Nemirovskaya *et al*. 1993); moreover, it is accompanied by stratigraphic gaps (Ramsbottom 1973, 1977, 1979, 1981; Saunders *et al.* 1979; Vdovenko and Poletaev 1981; Saunders and Ramsbottom 1986; Alekseev *et al* 2004).

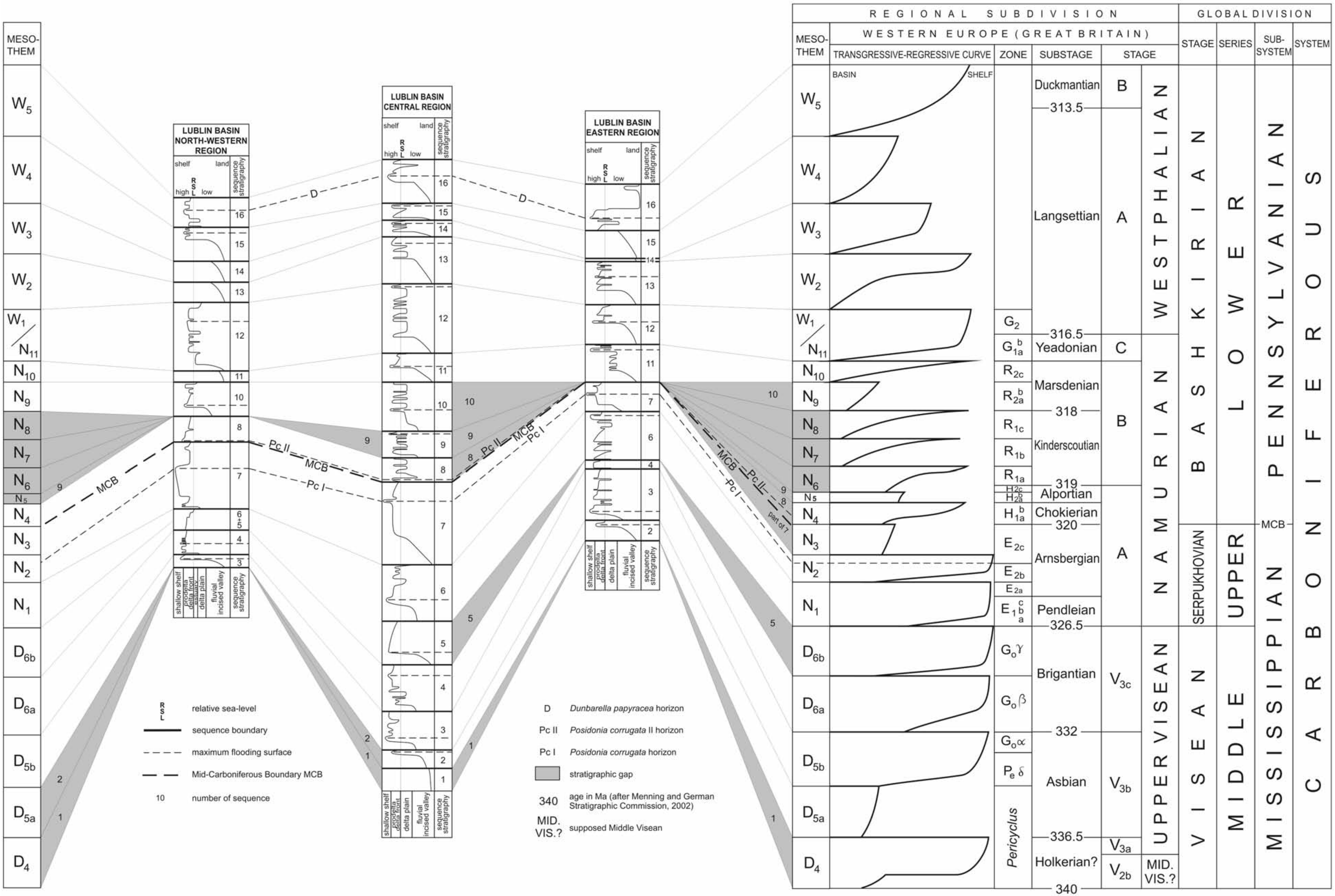
The sequence stratigraphy scheme presented herein, supplemented by biostratigraphic data (summarised in Musiał and Tabor 1988 and Skompski 1998), allows very precise determination of the number and duration of stratigraphic gaps in the paralic succession of the Carboniferous in the Lublin Basin.

Based on lithofacies schemes and analysis of depositional sequences, three relative sea-level curves have been constructed for the paralic Carboniferous for the NW, central and E parts of the Basin (Text-fig. 10). They illustrate the fluctuations of terrestrial, deltaic and shallow shelf environments within each of the 16 depositional sequences distinguished. Three of the 16 maximum flooding surfaces identified, precisely dated by goniatites and conodonts, have been used in chronostratigraphic correlation of the relative sea-level curves:

- the maximum flooding surface of sequence 7, corresponding to the gamma-ray maximum within the *Posidonia corrugata* I horizon, is equivalent to the E_{2b} goniatite Zone;
- the maximum flooding surface of sequence 8, corresponding to the gamma-ray maximum within the *Posidonia corrugata* II horizon, is equivalent to the H_{1ab} goniatite Zone;
- the maximum flooding surface of sequence 16, corresponding to the gamma-ray maximum within the *Dunbarella papyracea* horizon, is considered to mark the boundary between Westphalian A and Westphalian B (Musiał and Tabor 1988; Skompski 1996).

The age of the deposits composing sequence 10 is also well constrained based on the presence of the goniatite *Reticuloceras bilingue*, an index taxon of the R_{2b} goniatite Zone, in the Lublin IG 2 well section (Musiał and Tabor 1983).

Transgressive-regressive intervals composed of smaller cyclothems are a well-known feature of the



Text-fig. 10. Correlation of sequence stratigraphy and relative sea-level oscillations of the paralic Carboniferous in the Lublin Basin with the stratigraphic scheme (Gradstein and Ogg 2004) and the transgressive-regressive curve for the Western European Carboniferous (Ross and Ross 1985)

Carboniferous succession. In the UK, these intervals have been called mesothems, and defined "as stratigraphical units of middle rank bounded by unconformities on cratonic (block or shelf) areas, but with their limits defined in conformable successions" (Ramsbottom 1977, 1979, 1981). The presence of abundant goniatites in the Carboniferous sections in the UK has enabled precise correlation of the mesothems with goniatite zones, and thus with local stages. The resulting chronostratigraphic scheme is commonly applied in many European Carboniferous basins, despite the existence of a new global chronostratigraphic standard (Gradstein and Ogg 2004).

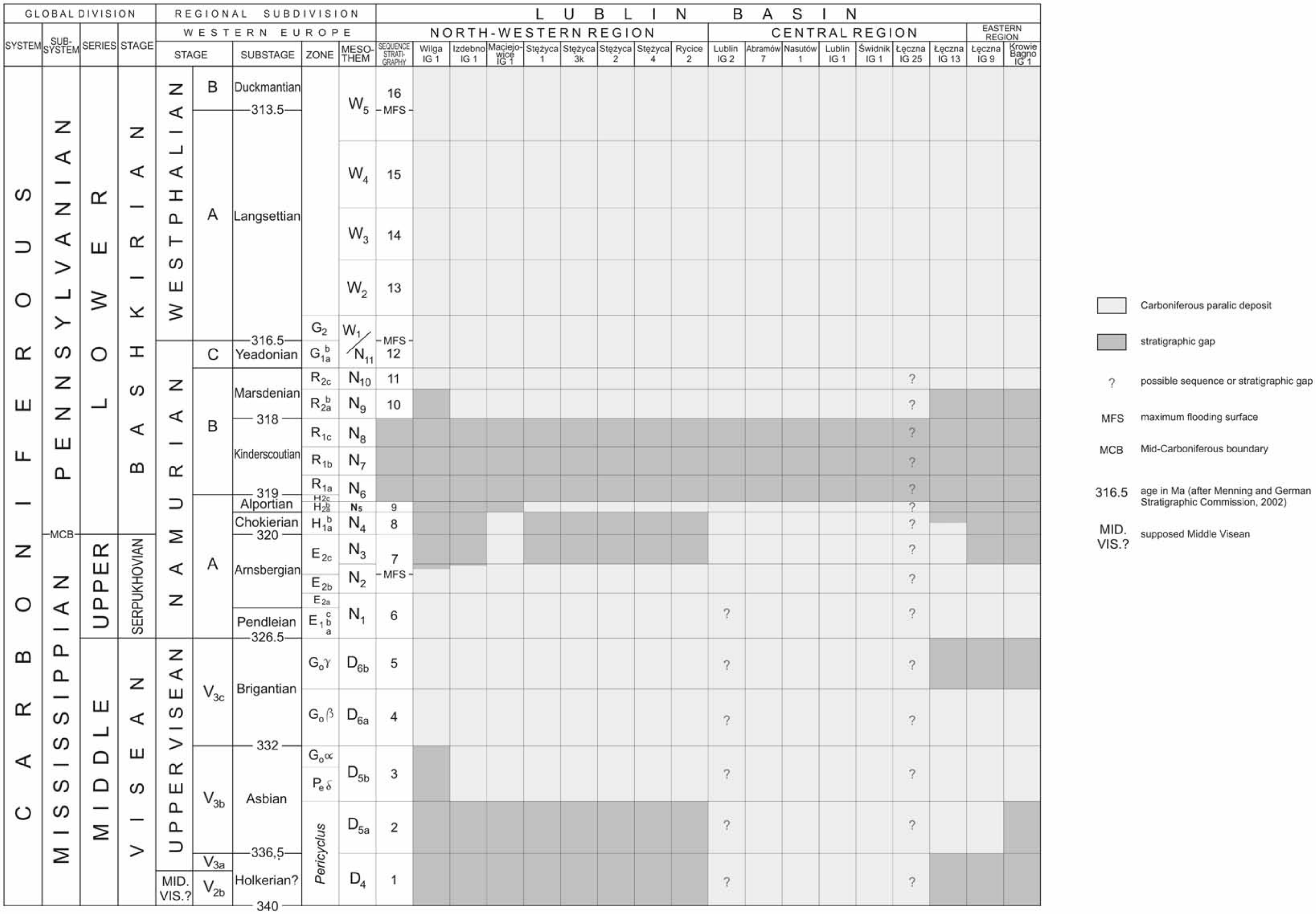
The eustatic origin of mesothems, assumed by Ramsbottom (1973, 1977, 1979, 1981), allows their correlation with other Carboniferous sections, including those from Western Europe (Ramsbottom 1977, 1978), North America (Saunders *et al.* 1979; Ross and Ross 1985, 1988; Maynard and Leeder 1992), as well as Eastern Europe (Russian Platform) (Ross and Ross 1985, 1988; Izart *et al.* 2003b; Alekseev *et al.* 2004). The sequence stratigraphy scheme and curves of relative sea-level oscillations of the paralic Carboniferous in the Lublin Basin have been correlated with the stratigraphic scheme and transgressive-regressive curve for the English Carboniferous (Ross and Ross 1985), as has been done by other authors (e.g. Alekseev *et al.* 1996; Smith and Read 2001) (Text-fig. 9). The correlation was based on the genetic similarity between the English mesothems and the depositional sequences from the Lublin Basin, as well as on biostratigraphic data for the faunal horizons. This resulted in detailed correlation of all the well sections studied with the English stages and substages; such correlation would have been imprecise or even impossible using solely biostratigraphic methods. In the chronostratigraphic subdivisions presented in the text-figures, the global scheme accepted by the Carboniferous Stratigraphy Subcommission (Gradstein and Ogg 2004) has also been applied.

The closest and most applicable reference section for the Carboniferous of the Lublin Basin is the succession from the Moscow Basin in Russia, for which Alekseev *et al.* (2004) presented a curve of relative sea-level changes. However, correlation with this section is hampered by the presence of a large stratigraphic gap encompassing an interval from the uppermost Arnsbergian to the lowermost Duckmantian in the Moscow Basin section. For this reason, it is better to compare with the sequence stratigraphy of the Donets Basin in Ukraine (Izart *et al*. 2003b).

The known age of several correlation horizons, i.e. the maximum flooding surfaces of sequences 7, 8 and 16, as well as sequence 10, allows attribution to the corresponding mesothems. Thus, the maximum flooding surface of sequence 7 has been correlated with the upper boundary of the E_{2b} goniatite Zone, which lies in the upper part of mesothem N_2. This mesothem is characterized by the largest transgression of all English mesothems (Ramsbottom 1977) and correlates well with the lower part of sequence 7, which formed during the maximum transgression of the entire paralic Carboniferous succession of the Lublin Basin. Due to the great thickness of sequence 7, and thus the likely longer duration of sedimentation compared with other sequences, its upper part has been attributed to the next mesothem, N_3, which in the UK is distinctly regressive and has a smaller geographic extent (Ramsbottom 1977). The remaining Lublin Basin sequences correspond to single mesothems.

Comparison of the lower part of the succession encompassing sequences 1 to 6 with mesothems D_4 to N_1 allowed the likely age of sequence 1 deposits to be determined (Text-fig. 11). Previously, estimation of the age of these deposits was relatively difficult (see discussion in Porzycki 1988 and Skompski 1998). Deposits of this sequence correspond to the Variegated Series, described from the Carboniferous succession in the Lublin Basin by Cebulak and Porzycki (1966); this unit is devoid of fossils and lies above biostratigraphically documented Upper Fammenian deposits and below Upper Viséan strata. Porzycki (1988) suggested that the age of the Variegated Series may correspond to the Middle Viséan. Based on the correlation presented herein, it is assumed that deposition of sequence 1, which begins the Carboniferous succession in the Lublin Basin, starts in the base of the Holkerian or slightly later within this substage (which corresponds to mesothem D_4). In sequence 1 only alluvial deposits occur, and the data from only four wells do not allow surfaces related to the succeeding stages of the transgressive-regressive cycle to be distinguished. If deposits of these late stages are indeed present, it would suggest that sequence 1 is fully developed and corresponds entirely to mesothem D_4 and thus to the Holkerian. However, the occurrence of deposits representing this substage has not been confirmed by biostratigraphic data in the Lublin Basin. Verification of this idea would require additional studies that lie beyond the scope of this paper.

The transgressions of the succeeding sequences are of greater extent, and the pattern of sequences indicates overlapping. In the vicinity of the Łęczna IG 13 and Łęczna IG 9 wells, deposition of Carboniferous deposits began later than in the central part of the basin, at the beginning of the early Asbian (sequence 2) corresponding to mesothem D_{5a}. In the E and NW part of the



Text-fig. 11. Correlation of the sequence stratigraphy of the paralic Carboniferous in the Lublin Basin with the Western Europe Carboniferous stratigraphic scheme (Ross and Ross 1985) and the global standard (Gradstein and Ogg 2004)

Lublin Basin deposition began even later – in the later Asbian (sequence 3). Sedimentation in the NW part of the basin near the Wilga IG 1 well began last, at the beginning of the Brigantian.

The sequence stratigraphy scheme presented here supports the diachronous commencement of deposition of the Carboniferous succession in the Lublin Basin that was suggested by Porzycki (1988) and Skompski (1998). A time gap of about 2.5 Ma in the E part of the basin seems likely, with a gap of about 2.5–4.5 Ma in the NW part. This time range is based on the geochronological scale of Menning and The German Stratigraphic Commission (2002), and does not take into account the duration of the Holkerian Substage (3.5 Ma), deposits of which are only possibly present in the Lublin Basin. Both the range of the diachroneity, as well as the absolute extent of the stratigraphic gaps, are estimated values with a large error (which for the intervals analyzed ranges from ±2.2 to ±8 Ma according to Menning *et al.* 2000). These errors reflect the precision of the absolute dating, on the basis of which Menning and The German Stratigraphic Commission (2002) constructed their geochronological scale.

The lack of deposits of sequence 5 in the Łęczna IG 13, Łęczna IG 9 and Krowie Bagno IG 1 well sections, in the E part of the basin, suggests the presence of a stratigraphic gap encompassing mesothem D_{6b} (upper Brigantian). The presence of a gap in this part of the Carboniferous succession in the Lublin Basin has not been suggested previously. Its presence is probably linked with erosion and non-deposition during the relative sea-level LS of sequence 5. Elsewhere there is no evidence of this gap, albeit its recognition is hampered by the lack of core data from this interval. The presence of this gap is highly probable in the NW part of the basin. The paralic Carboniferous succession there resembles that in the E part of the basin, which suggests location in an analogous palaeogeographic position. In the Wilga IG 1 and Izdebno IG 1 well sections, the separation of sequence 5 from sequence 6 was not possible due to low total thickness, which indirectly supports the interpretation of a stratigraphic gap.

Correlation of the upper part of the succession is constrained by biostratigraphic data of sequences 8, 10 and 16. Correlation of sequence 8 with mesothem N_4, and of sequence 10 with mesothem N_9, suggests the absence of an interval corresponding to mesothems N_6 to N_8 (equivalents of the H_{2c} and R_{1abc} goniatite zones) in the paralic Carboniferous succession in the Lublin Basin. This stratigraphic gap occurs throughout the study area, and its duration varies within the basin. In the north-westernmost and easternmost areas the gap is largest, encompassing the upper part of sequence 7, as well as sequences 8 to 10 (which were probably present throughout the study area prior to erosion). Thus, the greatest extent of the stratigraphic gap encompasses an interval from the upper Arnsbergian to the lower Marsdenian, corresponding to the goniatite zones from E_{2c} to R_{2ab}, and represents about 4.5 Ma. The gap could have developed as a result of many stages of erosion and non-deposition, linked with the successive LS of sequence 9 to sequence 11.

In a similar stratigraphic position occur two gaps separated by sequence 9 deposits in the Stężyca–Rycice area. The lower gap encompasses the upper part of sequence 7 and sequence 8 (upper Arnsbergian and Chokierian), and probably developed during erosion linked with the sequence 9 relative sea-level LS. The upper gap, corresponding to mesothems N_6 to N_8 (upper Alportian and Kinderscoutian), also occurs in the central part of the Basin where the paralic succession is most complete, this gap located between sequences 9 and 10.

The possible existence of stratigraphic gaps in this part of the Carboniferous in the Lublin Basin is supported by biostratigraphic data. No evidence has been found for the H_2 goniatite Zone (Musiał *et al.* 1995; see table 1, fig. 7) and the R_1 and R_2 goniatite zones are very poorly documented (Musiał and Tabor 1979). Palynologic data indicated the probable absence of the upper part of the E_2 goniatite Zone and the lower part of the H goniatite Zone (Kmiecik 1988).

These suggestions were confirmed by my earlier report (Waksmundzka 1998). Four transgressive-regressive intervals distinguished within the Bug Member in the SE part of the Lublin Basin were considered equivalents of mesothems discriminated by Ramsbottom (1977) and correlated with the continuous section of Namurian strata in the Craven Basin in England. Comparison of the number of mesothems and transgressive-regressive intervals indicated the presence of a stratigraphic gap encompassing at least the entire H_2 goniatite Zone and part of the R_{1ab} goniatite Zone. As expected, the gap has the greatest extent in the marginal, Ukrainian part of the basin. From Carboniferous strata in the Lvov-Volhynia Coal Basin, Vdovenko and Poletaev (1981) described a gap encompassing the upper part of the E_2 goniatite Zone to goniatite zones H and R.

Correlation of the sequence stratigraphy of the paralic Carboniferous in the Lublin Basin with the Carboniferous succession of Western Europe indicates that some deposits belonging to the biostratigraphically undocumented H_{2ab} goniatite Zone, and corresponding to sequence 9, occur in the NW in the Stężyca–Rycice area and in the central part of the basin, whereas they are absent to the east and in the Wilga–Maciejowice area.

The present study found no evidence for deposits of the poorly documented R_{1abc} goniatite Zone and, in the marginal parts of the basin, deposits of the R_{2ab} goniatite Zone are also absent; thus, a stratigraphic gap encompassing these intervals is postulated. This study has also shown that the upper part of the E_2 goniatite Zone and the lower part of the H goniatite Zone are absent in the E and NW part of the basin.

The age of sequences 11 to 16 was determined as late Marsdenian–earliest Duckmantian.

The presence of stratigraphic gaps of various extent is common in the Namurian of Western European (Ramsbottom 1973, 1977, 1979, 1981), Eastern European (Russian Platform) (Alekseev *et al.* 2004), and North American successions (Saunders *et al.* 1979). Such gaps are typical of extremely shallow sedimentary environments, e.g. on the Ozark shelf in North America (Saunders *et al.* 1979; Saunders and Ramsbottom 1986). The formation of stratigraphic gaps was linked by Saunders and Ramsbottom (1986) with the mid-Carboniferous eustatic event, during which distinct relative sea-level fall took place, followed by deep erosion of the exposed shelves. Veevers and Powell (1987) described three glacial episodes on Gondwana that took place in the Fammenian, Early Viséan and from the Namurian to the Sakmarian (Early Permian). These authors suggested that the fluctuation of the Gondwana ice-sheet volume greatly influenced eustatic sea-level oscillations, as well as contributing to the formation of transgressive-regressive sequences in Euramerica, e.g. the English mesothems. Most probably, these same factors greatly influenced the formation of depositional sequences and stratigraphic gaps in the paralic succession of the Carboniferous in the Lublin Basin (Skompski 2003).

However, it seems that the influence of eustatic oscillations was modified by local factors, e.g. supply of detrital material and rate of subsidence. Intense subsidence, evidenced by great thickness of the paralic Carboniferous strata, was enhanced by sediment compaction. The compaction of shale-siltstone (Baldwin and Butler 1985) and phytogenic deposits (Ryer and Langer 1980) was relatively great in a short time interval. This interpretation is supported by the studies of Tiadens and Haites (1944), who showed that a 2-m thick peat layer under a 1-m overburden of sand reduced in thickness by 50% during the first three years from its creation. Thus the numerous coal beds, 0.05 to 1.0 m thick, occurring in the paralic succession of the Lublin Basin were formed through compaction of peat layers with an initial thickness of 1–20 m each (after Waksmundzka 2005).

A notable feature of the paralic Carboniferous succession in the Lublin Basin is the presence of numerous rather thick and evenly distributed carbonate beds in sequences 1 to 6. Their formation during transgression indicates deposition of carbonates in the foreland of the retrograding delta lobes in a shallow shelf area. The sedimentation of deeper, shallow-shelf shales is linked with further transgression, and with the appearance of anoxic conditions at its maximum. During relative sea-level HS, sedimentation in the prograding delta lobes was again preceded by the formation of carbonate beds, pointing to relative sea-level fall.

The upper part of the succession (sequences 7 to 16) is characterized by the infrequent occurrence of thin carbonate beds. Shallow-shelf anoxic shales, which developed during maximum flooding, are directly overlain by deposits of the prograding delta. It seems that in this case the progradation was not caused by relative sea-level fall (during which a shale-carbonate succession would be expected), but by the increased supply of detrital material transported by rivers into the basin. The suggestions presented herein that the maximum lateral extent of sequence 7 was probably wider than the area of the present-day basin, indirectly indicate a larger source area supplying increased amounts of sediment to the basin. The influx of large amounts of detrital material was probably caused by diastrophic events, typical of the Mississippian/Pennsylvanian boundary both in Europe and North America.

In the central part of the study area, where the succession of sequences 1 to 10 is most complete, the mid-Carboniferous boundary between the Mississippian and Pennsylvanian is located in the base of sequence 8, corresponding to the boundary between the E_{2c} and H_{1a} goniatite zones. This boundary is eroded in the NW part of the basin, except for the Maciejowice IG 1 well section, and to the east.

SUMMARY

1. Based on lithofacies analysis of clastic, clay and carbonate rocks, wireline log analysis, as well as sequence stratigraphy, sixteen depositional sequences have been distinguished in the Carboniferous paralic succession of the Lublin Basin. Type 1 basal unconformities bounding the sequences were formed during subaerial erosion, relative sea-level fall and LS. The greatest erosion, which in some cases reached down to the LS deposits of the underlying sequences, was observed within HS deposits.

2. Carboniferous sedimentation commenced in the central part of the study area, and later covered the E and

NW areas. The thickness of sequences 1 to 10 and 12 increases towards the basin centre, whereas the thickness of the remaining sequences does not show this pattern.

3. Three types of depositional systems tracts have been distinguished: (1) lowstand systems tracts, (2) transgressive systems tracts, and (3) highstand systems tracts.

4. Relative sea-level rise that affected the base level of the rivers was the basic factor influencing facies development, cyclicity and the thickness of fluvial deposits, as well as the vertical and lateral transition of the river types during LS in the Carboniferous paralic succession.

5. Within LS deposits, a vertical transition of high- to low-energy environments can be observed. LS deposits typically occur in incised-valley systems and in non-incised fluvial-channel systems. Within the LS deposits of sequences 2 and 4 to 10 several medium and large systems of simple coastal-plain incised valleys can be identified. The incision of these valleys most probably reached 20–40 m, which corresponded to the value of relative sea-level fall. Within the LS deposits of sequences 11 to 15 can be identified large systems of compound incised valleys that developed in a piedmont system. The incision of these valleys most probably reached 40–70 m, which corresponded to the value of relative sea-level fall. The areas between incised valleys or in sediment bypass zones are characterized by a lack of LS deposits.

6. In TST commonly occur coarsening-upward type IIc cyclothems and non-gradational type IIIc cyclothems that correspond to parasequences and were formed in the distal parts of inner-shelf deltas, whereas in HST prevail coarsening-upward type Ic cyclothems that developed during the progradation of inner-shelf deltas. In HST also quite common are coarsening-upward type Id and IId cyclothems formed in lake deltas, as well as non-gradational type IIId cyclothems, formed in lakes without the influence of delta lobes.

7. Rise of relative sea level during the late LS and its oscillations during transgression and HS, as well as changes in sediment supply, were the main factors influencing facies evolution, cyclicity, thickness, and lateral distribution of delta deposits as well as inner-shelf shales and limestones.

8. The TST and HS deposits of sequences:
   – 1 were possibly eroded;
   – 2 to 7 developed in a generally marine and distal-deltaic sedimentary regime when depths of the sea basin were greatest;
   – 8 to 10 were deposited in a deltaic sedimentary regime with a fully developed delta plain, when depth of the sea basin was smallest;
   – 11 to 16 developed in a deltaic sedimentary regime and were deposited mainly in the prograding submarine part of the delta during the HS, in a relatively deep sea basin that was larger than that during deposition of sequences 8 to 10 and smaller than that during sedimentation of sequences 2 to 7, as well as in a fully developed delta plain, with distributary channels and small lake deltas.

9. The transgression of sequence 7 probably had the widest lateral extent of all the Carboniferous sequences of the Lublin Basin. It was much wider to the N, NE and NW than the presently accepted boundaries of the basin.

10. At its maximum, the last transgression in the Lublin Basin (sequence 16) extended far to the east near the Łęczna IG 9 well and to the NW beyond the Wilga IG 1 well area.

11. Based on analysis of relative sea-level curves in the paralic Carboniferous succession of the NW, central and E parts of the Lublin Basin, as well as the Carboniferous transgressive-regressive curve for western Europe, the sequences distinguished in the Lublin Basin may be correlated with the Carboniferous chronostratigraphic scheme.

12. The diachroneity of Carboniferous deposition is confirmed; deposition began about 2.5 Ma later in the eastern part of the Lublin Basin than at the centre and about 2.5 to 4.5 Ma later to the NW.

13. The absence of sequence 5 in the eastern part of the basin suggests the presence of a stratigraphic gap encompassing mesothem D_{6b} (upper Brigantian).

14. The major stratigraphic gap present throughout the basin varies in extent. To the NW and E the gap is largest and encompasses the uppermost part of sequence 7, sequences 8 to 10 and mesothems N_6 to N_8 (uppermost Arnsbergian–lower Marsdenian). The time range of this gap was estimated at about 4.5 Ma. In the Stężyca–Rycice area, in a similar stratigraphic position, two gaps occur separated by

deposits of sequence 9. The lower gap comprises the uppermost part of sequence 7 and sequence 8 (upper Arnsbergian–Chokierian). The higher gap is located between sequences 9 and 10 and corresponds to mesothems N_6 to N_8 (upper Alportian–Kinderscoutian); this gap is also present in the central part of the Lublin Basin where the Carboniferous paralic succession is most complete.

15. The mid-Carboniferous boundary between the Mississippian and Pennsylvanian most probably occurs at the base of sequence 8, i.e., between the E_{2c} and H_{1a} goniatite zones.

16. Based on lithofacies correlation and sequence analysis, the facies evolution and depositional architecture of the paralic Carboniferous deposits has been reconstructed, with particular attention to potential sandstone reservoir bodies of the LST sequences 6, 9 and 12; the origin and distribution of which is linked with subaerial erosion, followed by deposition during relative sea-level fall and LS.

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