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Braided-river and hyperconcentrated-flow deposits from the Carboniferous of the Lublin Basin (SE Poland) – a sedimentological study of core data

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Abstract

Fining-upwards cyclothems found in five boreholes in the Carboniferous (Lower Bashkirian) of the Lublin Basin were analysed sedimentologically. It was established that the cyclothems represent fluvial deposits, and the lithofacies were grouped into lithofacies associations. Most lithofacies associations represent three types of sand-bed braided rivers: (1) high-energy, (2) deep and (3) distal sheetflood-affected. Other associations represent hyperconcentrated flows. Both coarse-grained (type I) and fine-grained (types IIa and IIb) occur among the fining-upward cyclothems. The formation of most thick cyclothems was related mainly to allocyclic factors, i.e. a decrease in the river's gradient. The thickest fining-upward cyclothems are characteristic of hyperconcentrated flows and braided-river channels. The aggradation ratios were commonly high.

During the early Namurian C and early Westphalian A (Early Bashkirian), the eastern part of the Lublin Basin was located close to the source area. The sedimentary succession developed due to a transition from high-energy braided-rivers and hyperconcentrated flows to lower-energy braided rivers, controlled by a rise of the regional base level.

Keywords: braided rivers, hyperconcentrated flows, fining-upward cyclothems, Lublin Basin, Carboniferous

1. Introduction

The Lublin Basin is located in south-eastern Poland. Its boundaries are defined by sub-Mesozoic outcrops of Carboniferous deposits, bounded to the north and south-west by fault zones (Fig. 1). The south-eastern continuation of the basin is the Lvov-Volhynia Coal Basin in Ukraine. The Lublin Basin is filled with clayey, clastic, carbonate and coaly deposits accumulated from the Visean through the early Bashkirian (Musiał & Tabor, 1979, 1988; Skompski, 1996; Waksmundzka, 2008a, 2010a).

Studies of the Carboniferous of the Lublin Basin were focused for a long time on stratigraphic, tectonic and petrographic issues. The most important results were presented by Rühle (1966), Żelichowski (1972, 1983a,b), Skompski (1986, 1996, 1998), Dembowski & Porzycki (1988), Zdanowski & Żakowa (1995), Narkiewicz (2003), Kozłowska (2004, 2009), Żywiecki & Skompski (2004), Krzywiec (2007) and Narkiewicz et al. (2007).

Detailed sedimentological studies were also carried out, but focused mainly on marine and deltaic deposits, as well as on coarsening-upward cyclothems in these successions (Korejwo, 1958; Skompski, 1986, 1996, 1998). So far, no results of comprehensive sedimentological studies of fluvial deposits and fining-upward cyclothems, which are common, have been published; fluvial deposits have been mentioned only shortly. Żelichowski (1961) mentioned an upwards increase of terrestrial deposits, such as fluvial sandstones. Porzycki (1979) presented a subdivision of the Carboniferous into marine-paralic, paralic and limnic-fluvial deposits. Żelichowski (1983b) constructed several 'lithofacies' maps produced for individual lithostratigraphic units, based on their sand content.

Marine, fluvial and deltaic deposits from some wells were subject to a detailed study, including analysis of cyclicity, in the M.Sc. and Ph.D. theses of Mazak (1979), Porzycki (1980), Szwemin (1992), Wiśniewska (now Waksmundzka) (1993), Deuszkiewicz (2001), Żywiecki (2003), Waksmundzka (2005) and Hajdenrajch (2010), of which only some have been published. Part of the general theses on the cyclicity and sedimentary environments presented in Porzycki (1980) was published by Dembowski & Porzycki (1988). The results of sedimentological studies, e.g. of fluvial deposits from the southern part of the basin, were given by the present author (Wiśniewska,1983; Waksmundzka, 1998), who identified three types of fining-upward cyclothems that represent various sub-environments of a meandering river. Some sedimentological and sequence-stratigraphic data, e.g. of Carboniferous fluvial deposits from the north-western, central and eastern parts of the Lublin Basin, were presented by Waksmundzka (2008a,b, 2010a), who also presented lithofacies-palaeothickness maps with river channels and incised valleys, as well as river floodplains (Waksmundzka, 2010b).

The above overview of the literature shows that more detailed sequence-stratigraphic stud-

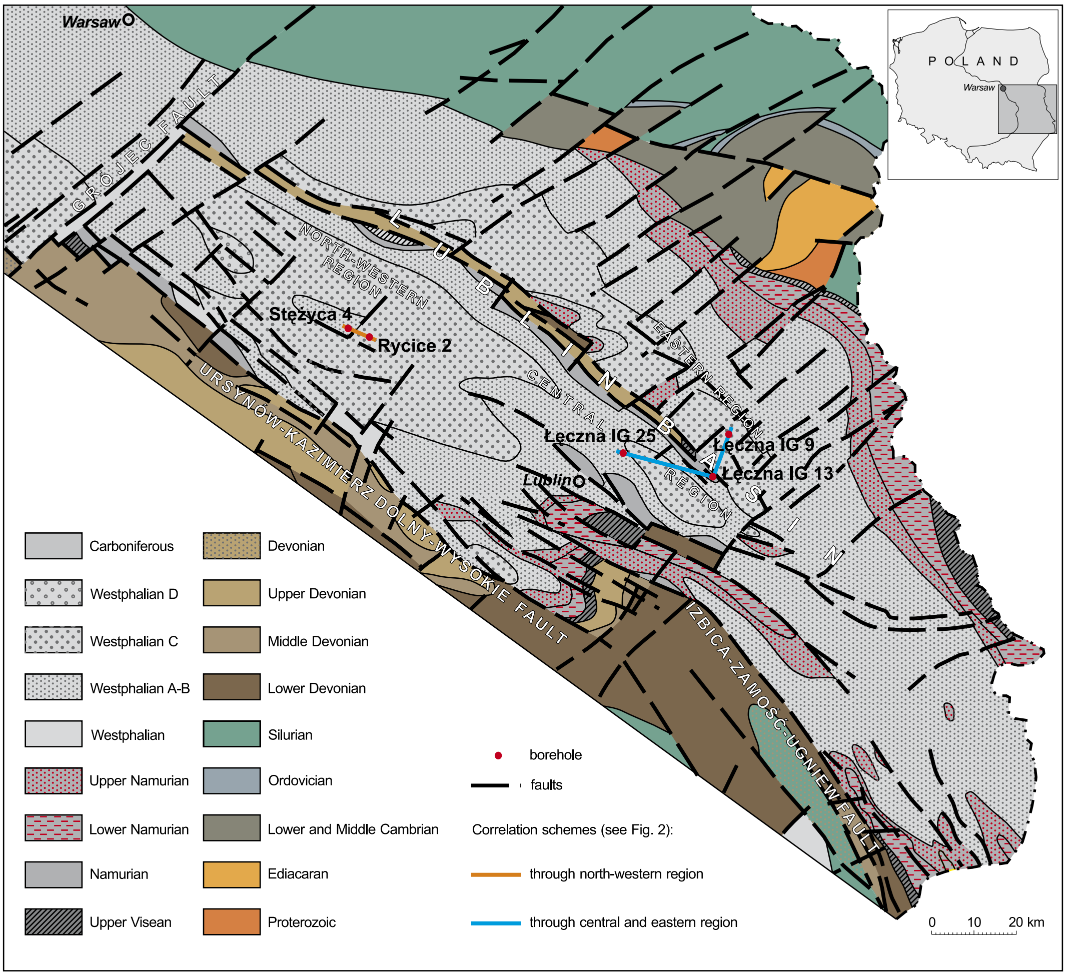


Fig. 1. Location map (fragment of the structural-geological map of the Lublin Basin without postCarboniferous strata) (modified after Żelichowski & Porzycki, 1983).

ies are needed, particularly for the fluvial and hyperconcentrated–flow deposits (Waksmundzka, 2005, 2008c, 2010a). These deposits form the thickest (70–80 m) sandstone bodies in the Carboniferous of the Lublin Basin, and are considered potential reservoir rocks.

The objective of the present study is the detailed analysis of the braided-river and, hyperconcentrated-flow deposits and of the fining-upward cyclothems in these deposits, based on fully cored sections (Fig. 1). The basis of the present contribution is my Ph.D. thesis prepared in the Polish Geological Institute in Warsaw. The core sections were studied from 1994 to 2001 in the Repositories of Drilling Cores and Geological Samples of the Central Geological Archives in Iwiczna and Hołowno and in the Storehouses of the Polish Oil and Gas Company in Wołomin and Chmielnik.

2. Materials and methods

The sedimentological investigations some sections of the Carboniferous that represent fluvial environments (Waksmundzka, 1998, 2005, 2008b, 2010a). The sections were selected on the basis of the availability of representative, well-preserved and continuous cores. Due to considerable variation within the environments represented by these cores, the present contribution focuses on the various types of braided-river deposits, as well as on the fining-upward cyclothems and their origin. The age and spatial relationships between the studied intervals and deposits representing other sedimentary environments are illustrated in Figure 2. They are, however, not the subject of this work.

As mentioned above, the study was aimed primarily at the sandstones and, to a lesser extent, the accompanying conglomerates, siltstones, mudstones, claystones and coals encountered in five fully cored wells located in the north-western, central and eastern parts of the Lublin Basin (Fig. 1). Some 210 m of core material was studied. The intervals correspond to the lower Bashkirian of the Carboniferous System (Namurian B, Namurian C and Westphalian A in the original chronostratigraphy of Western Europe) (Fig. 2).

The basis for the sedimentological study was an analysis of the individual lithofacies and their relationships. All lithofacies types are coded (Table 1) following the system introduced by Miall (1977, 1978) and Rust (1978), and modified by Zieliński (1992a, 1995). The present author introduces the symbol *n* for lenticular lamination. The symbol *R* is used for root-worked layers (following Gradziński et al., 1995).

A question mark is placed at the lithofacies symbol (e.g. Sp?) when the stratification type is uncertain, due to a low core quality or a too large size of cross-stratified sets. When it turned out impossible to distinguish between trough cross-stratification (St) and planar cross-stratification (Sp) while large-scale cross-stratified sets were visible, the sets were coded x (lithofacies Sx). The proportion of lithofacies Sx in the lithofacies associations is small, and does consequently not affect the interpretation of the environments. The origin of these associations, probably containing very large planar cross-stratification (Sp?), is more questionable than that of the other associations, because of the difference in size between core and the cross-stratified sets of 1–2 m thick. They were nevertheless included in the interpretation, because they are an important diagnostic feature to identify a river type.

The lithofacies were combined into associations that were coded following Zieliński (1993, 1995). The thickest lithofacies in each association are referred to as 'index lithofacies'. The code consists of symbols of one or two dominant lithofacies, and secondary ones are written between brackets, e.g. St (Sr, Sh).

Due to the considerable burial depth of the Carboniferous, the thickness of the individual lithofacies had to be corrected for compaction in order to reconstruct the original thicknesses. For coarse clastics and clayey deposits, the compaction correction was calculated following Baldwin & Butler (1985), determining the so-called thickness reduction ratio. For coal, this parameter was estimated based on Ryer & Langer (1980) (Table 2).

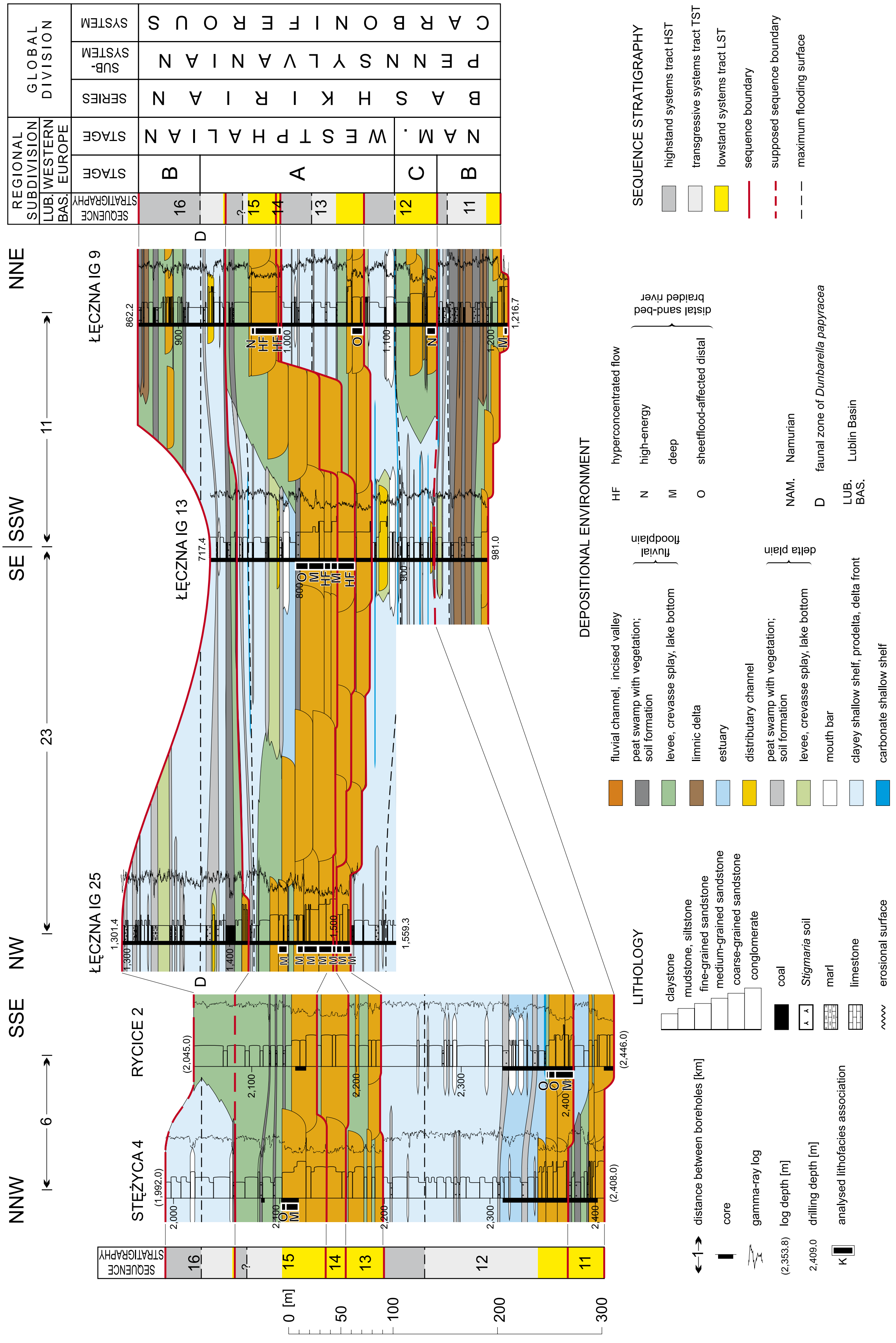


Fig. 2. Lithology, sequence stratigraphy and chronostratigraphy of the Bashkirian succession in the NW, central and E parts of the Lublin Basin.

Table 1. Lithofacies code symbols (modified after Miall, 1977; Gradziński et al., 1995; Zieliński, 1995, 1997).

Code	Textural feature
G	conglomerate
GS	sandy conglomerate
S	sandstone
SG	gravelly sandstone
SF	silty sandstone
FS	sandy siltstone
F	mudstone/claystone
R	*Stigmaria* claystone/sandstone (*Stigmaria* soil)
C	coal
Code	**Structural feature**
m	massive structure
h	horizontal lamination (stratification)
f	flaser lamination
w	wavy lamination
n	lenticular lamination
r	ripple cross-lamination
l	low-angle cross-stratification
p	planar cross-stratification (tabular and wedge-shaped)
t	trough cross-stratification
x	large-scale cross-stratification
e	erosional scours – poorly sorted massive sandstone/conglomerate with clasts on an erosional surface; thickness to 0.3 m
s	scour-fill – poorly sorted, massive or cross-stratified sandstone/conglomerate with clasts on an erosional surface; thickness over 0.3 m

The study included characterization of fining-upward cyclothems. The individual cyclothems are marked in the text and on figures by the symbol Δ. The lower boundary of each cyclothem is defined by the base of the coarsest-grained lithofacies, whereas the upper boundary is defined by the top of the finest-grained lithofacies, which coincides with the base of the overlying cyclothem. For some cyclothems, the percentage of coarse-grained lithofacies (sandstone and conglomerate lithofacies), fine-grained and organic lithofacies (mudstone, claystone and coaly lithofacies) and their mutual proportions were calculated, taking into account compaction.

Table 2. Thickness-reduction ratio due to compaction.

Lithology	Thickness reduction ratio by compaction
conglomerate/sandstone	1.2–1.5
claystone/mudstone/ siltstone	4.3–5.0
coal	20

The origin of individual lithofacies and their associations then was reconstructed, thus establishing sedimentary environments and subenvironments, which were coded following Miall (1978), Zieliński (1992a,b, 1995), slightly extended by the present author (Table 3). Environmental interpretations were refined using empirical formulas to calculate the height of palaeobedforms, i.e. transverse bars (after Williams, 1971; Saunderson & Jopling, 1980) and megaripples (after Simons & Richardson, 1962; Cant, 1978), as well as the depth of palaeochannels (after Simons & Richardson, 1962; Harms & Fahnestock, 1965; Friend & Moody-Stuart, 1972; Klimek, 1972; Eynon & Walker, 1974). The compaction of the deposits was taken into account.

In terms of thickness, the cross-stratified sets are divided into four categories: small-scale (up to 6 cm), medium-scale (6–30 cm), large-scale (30–100 cm) and very large-scale (> 100 cm).

Table 3. Genetic code symbols (modified after Miall 1978; Zieliński 1995, 1997).

Code	Genesis/environment	Representative lithofacies
CF	channel fill	Sr, Sp, St, Sx, Sl, Sh, Sm, SGm, Gp, Gt
CP	channel pools	very large-scale St
SU	sandy upper plane-bed	Sh, Sm
HF	hyperconcentrated flow	Sm, Ss
FM	foreset macroform (transverse bar)	Sp, Gp
DMF	diminished megaripple and/or transverse bar	Sl
SB	sandy bedform (ripple, megaripple)	Sr, Sp, Sl, St, Sx, Gt
SB/FM	megaripple and/or transverse bar	Sx
SS/SB	suspension settling and sandy bedform	Fn, FSw
SS	suspension settling	Fm, Fh
PS	pedogenically affected sediment	R
BS	biochemical sediment	C

3. Results

Based on macroscopic analysis of the cores, 21 lithofacies types were distinguished (Table 4). They were grouped in lithofacies associations. The most characteristic lithofacies are illustrated in Figures 3, 4 and 5.

3.1. Description of the lithofacies

3.1.1. Associations dominated by Sm lithofacies

3.1.1.1. Lithofacies association Sm (Ss)

This lithofacies, which is present at a depth of 977.0–998.9 m in borehole Łęczna IG 9 (Fig. 6), is dominated by a massive fine-grained sandstone unit (Fig. 3B) of 18 m thick. It shows a fining-upward trend from coarse-grained to fine-grained sandstones. It sporadically contains bounding surfaces spaced at intervals of several cm or more. Irregularly dispersed claystone clasts with visible sizes of 7 by 1 cm are found in the lower part of the association. This lower part is represented by massive coarse-grained sandstones, intercalated by scour-filled coarse-grained sandstones with clasts (Fig. 3A).

This lithofacies overlies an erosional surface accentuated by claystone clasts. The association Sm (Ss) forms, together with the overlying one Sl (Sx, St), an exceptionally thick (28.5 m) fining-upward cyclothem ΔSs,Sm→Sx,St,Sl,Sh (Fig. 6).

3.1.1.2. Lithofacies association Sm

This lithofacies, which is present at a depth of 838.4–855.4 m in the Łęczna IG 13 well (Fig. 7), and which has an erosional base, is dominated by massive fine-grained sandstones,

Table 4. Characteristics of the lithofacies and interpretation their depositional environments. River types according to Miall (1986): N = high-energy sand-bed braided river; M = deep sand-bed braided river; O = distal sheetflood-affected sand-bed braided river.

Lithofacies	Thickness (m)	Colour	Structure	Thickness (cm)		Flora	Depositional process	Hyperconcen-Trated flow	Type of River		
				Lamina	Lamina-Set				N	M	O
C coal	0.2	black	massive	–	–	very common, unrecognized	deposition of plant remains, coalification				■
R Stigmaria claystone/sandstone (Stigmaria soil)	0.2–1	light grey, grey	nodular			Stigmaria, plant detritus	quiet water – deposition of clayey or sandy suspension, settling of plant remains, pedogenic processes		■		■
Fm massive clayston and mudstone	0.1–0.9	dark grey, grey	massive			plant detritus	standing water – deposition of clayey and silty suspension			■	■
Fh claystone and mudstone with horizontal lamination	0.2–0.5	dark grey	horizontal lamination	0.3–3	–					■	■
Fn siltstone with lenticular lamination	0.2–0.3		lenticular lamination	0.1–0.2	0.3–2		rhythmic change of deposition: bedload transport in ripples (lower part of lower flow regime) alternatively with standing water – deposition from clayey and silty suspension			■	■
FSw wavy laminated sandy siltstone	0.3–0.5		wavy lamination	0.1–0.2	0.3–3					■	■
Sh horizontally stratified sandstone	0.06–2.4	light grey	horizontal stratification	0.5–6	–		deposition in the upper plane bed (upper flow regime)	■	■	■	■
Sr ripple cross–laminated sandstone	0.06–4.1	light grey, grey	ripple cross–lamination	0.1–0.3	0.5–5		hythmic bedload transport in ripples (lower part of lower flow regime)	■		■	■
Sx large–scale cross–stratified sandstone	0.1–4.9	light gray	cross–stratification	0.5–12	10–100	plant detritus, carbonaceous matter	bedload transport in transverse bars or megaripples (lower or upper part of lower flow regime)	■	■	■	■
Sp planar cross–stratified sandstone	0.1–1		planar cross–stratification (tabular and wedge–shaped)	1–10	10–100	carbonaceous matter	bedload transport in transverse bars (lower part of lower flow regime)			■	
	1.4–4.4				>100–220		bedload transport in alternate bars (lower part of lower flow regime)			■	
Gp planar cross–stratified conglomerate	0.4									■	
St trough cross–stratified sandstone	0.07–4.6	light grey, grey–brown	trough cross–stratification	0.5–3	7–90	plant detritus	rhythmic bed load transport in megaripples (upper part of lower flow regime)	■	■	■	■
Gt trough cross–stratified conglomerate	0.2–0.5	light grey				carbonaceous matter, large plant fragments				■	
Sl low–angle cross–stratified sandstone	0.2–1		low–angle cross–stratification	1–12	10–100	absent	bedload transport in diminished megaripples and transverse bars (transition from lower to upper flow regime)	■	■	■	
Sm massive sandstone	5.75–18		massive	–	–	plant detritus	hyperconcentrated flow	■			
	0.15–1.2						deposition in the upper plane bed (upper flow regime)		■	■	■
SGm massive gravelly sandstone	0.8					absent				■	
Gm massive conglomerate	0.1									■	
Se sandstone in erosional scours	0.2	light grey–red	massive with clasts			large plant fragments	erosion and concentration of cobbles, then sand deposition in the upper plane bed (upper flow regime)				■
Ge conglomerate in erosional scours	0.15									■	
Ss sandstone with scour–and–fill structures	0.4–1.7						erosion of large scours, their filling in upper flow regime conditions	■	■	■	
Gs conglomerate with scour–and–fill structures	1.6							■		■	

Fig. 3. Examples of lithofacies (units on scale bar are 1 cm).
A: Lithofacies Ss: poorly sorted massive coarse-grained sandstone with black carbonaceous clasts; Łęczna IG 9 borehole, depth 998.33–998.4 m.
B: Lithofacies Sm: light grey fine-grained massive sandstones with dark grey clayey clasts; Łęczna IG 9 borehole, depth 993.1–993.3 m.
C: Lithofacies St: light grey fine-grained trough cross-stratified sandstone with dark grey clayey clasts and an erosional surface accentuated by white quartz clasts; at the bottom light grey coarse-grained massive sandstones; quasi-horizontally rills after drill bit; Łęczna IG 25 borehole, depth 1,512.5–1,512.9 m.
D: Lithofacies St: light grey fine-grained trough cross-stratified sandstone with stratification accentuated by rich, fine detritus of organic matter; Stężyca 4 borehole, depth 2,109.0–2,109.2 m.
E: Lithofacies Gp: light grey planar cross-stratified conglomerate; Łęczna IG 25 borehole, depth 1,494.5–1,494.7 m.

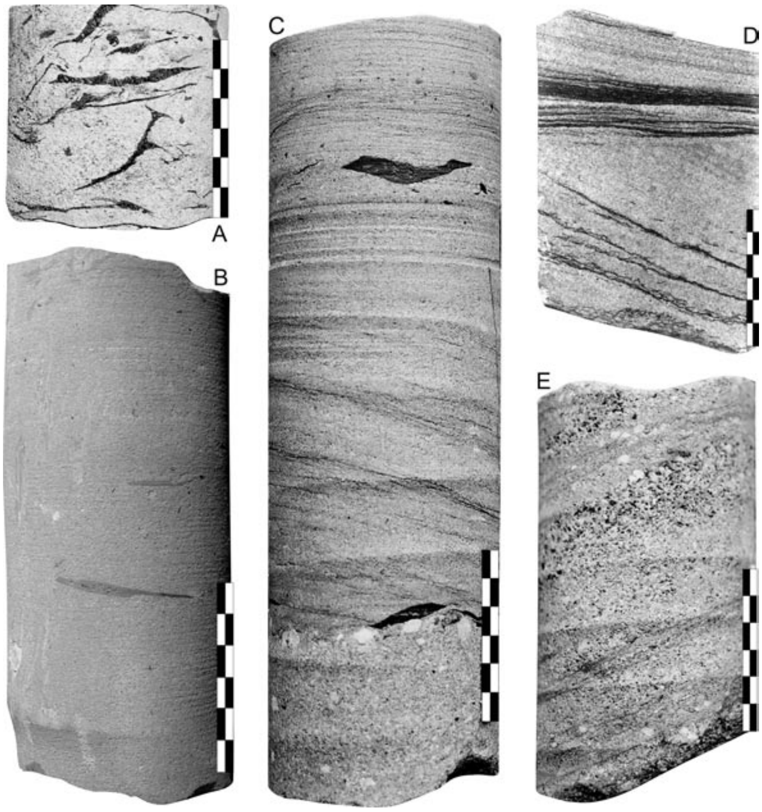
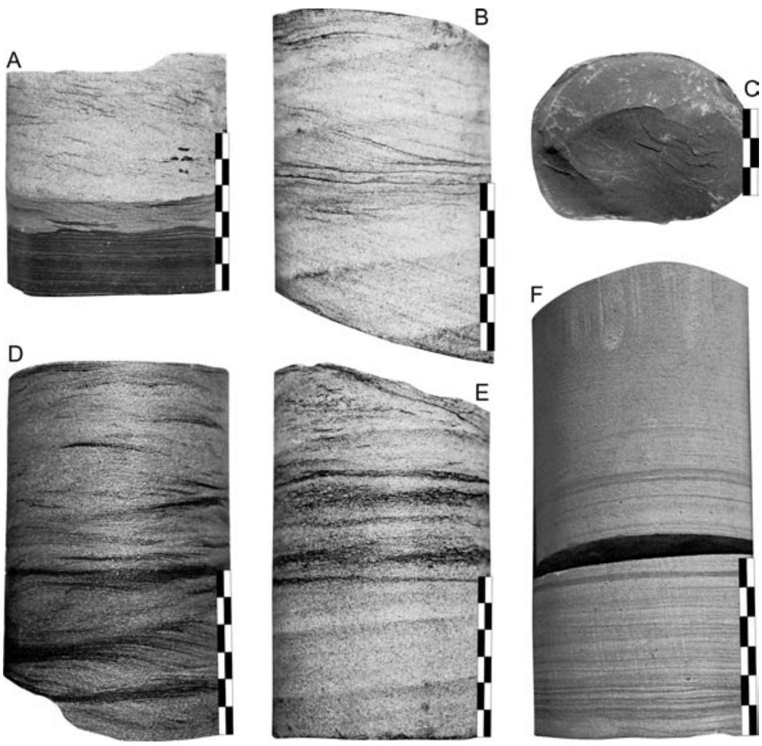


Fig. 4. Examples of lithofacies (units on scale bar are 1 cm).
A: Lithofacies Fh: dark grey horizontally laminated mudstone grading into light grey fine-grained cross-stratified sandstone; Łęczna IG 25 borehole, depth 1,452.3–1,452.4 m.
B: Lithofacies Sr: light grey fine-grained ripple cross-laminated sandstones; quasi-horizontally rills after drill bit; Łęczna IG 25 borehole, depth 1,507.6–1,507.75 m.
C: Lithofacies Fm: dark grey massive mudstone; Stężyca 4 borehole, depth 2,107.54 m.
D: Lithofacies Sr: grey fine-grained ripple cross-laminated sandstones; Łęczna IG 25 borehole, depth 1,475.5–1,475.7 m.
E: Lithofacies Sh: light grey fine-grained horizontally stratified sandstone; thick bed (a few centimetres) in the lower part; higher up thinner beds with fine organic-rich detritus quasi-horizontally rills after drill bit; Łęczna IG 25 borehole, depth 1,509.5–1,509.7 m.
F: Lithofacies Sh: light grey fine-grained horizontally stratified sandstone, higher up grading into light grey fine-grained massive sandstone; Łęczna IG 9 borehole, depth 1,000.3–1,000.5 m.



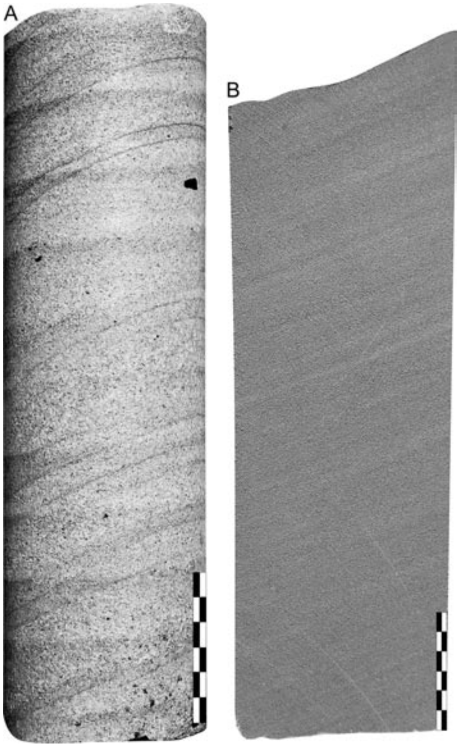


Fig. 5. Examples of lithofacies (units on scale bar are 1 cm).
A: Lithofacies Sp?: light grey coarse-grained planar cross-stratified sandstone; part of very large-scale set; quasi-horizontally rills after drill bit; Łęczna IG 25 borehole, depth 1,498.5–1,498.9 m.
B: Lithofacies Sp?: light brown fine-grained planar cross-stratified sandstone; part of large-scale set; Stężyca 4 borehole, depth 2,108.0–2,108.3 m.

with the total thickness of 14 m. Scour-filling fine-grained sandstones, containing numerous irregularly dispersed siderites, claystone and carbonaceous clasts, are much less common. The visible sizes of the clasts are up to 5 by 0.5 cm. The association also contains large-scale cross-stratified medium-grained sandstone and trough cross-stratified sandstone forming thin (0.25–0.4 m) interbeds.

Four fining-upward cyclothems (ΔSs,Sm; ΔSm; ΔSt→Sm; ΔSx→Sm) of 0.2–9 m thick are distinguished within this association.

3.1.2. Associations dominated by Sl, Sh lithofacies

3.1.2.1. Association Sl (Sx, St)

The main component of this association, which is present at a depth of 970.4–977.0 m in borehole Łęczna IG 9, (Fig. 6) is low-angle cross-stratified fine-grained sandstone of 0.5–0.76 m thick. Large-scale cross-stratified fine-grained sandstone forms another significant lithofacies. Lithofacies St, Sh and Sm contribute less. Trough cross-stratified beds are 0.1–0.22 m thick.

No fining-upward trend is present, but together with the underlying association, it forms a 19-m thick fining-upward cyclothem ΔSs,Sm→Sx,St,Sl,Sh.

3.1.2.2. Association Sh (Ss, Sx)

This association, which is present at a depth of 1,139.4–1,149.4 m in borehole Łęczna IG 9 (Fig. 8), is composed mainly of horizontally stratified fine- and medium-grained sandstone. The association also contains lithofacies Ss, Sx, Sl, Sm and R.

The association forms a fining-upward cyclothem ΔSs→Sh,Sl,Sx,St→R.

3.1.3. Associations dominated by St, Sx, Sp lithofacies

3.1.3.1. Lithofacies association St (Sx, Sm)

This association, which is present at a depth of 808.5–825.0 m in the Łęczna IG 13 well (Fig. 9), consists predominantly of fine- and medium-grained trough cross-stratified sandstones which locally contain carbonaceous clasts. They tend to have erosional surfaces accentuated by quartz clasts. The upper part of the association, composed of fine- and medium-grained sandstone, contains very large-scale cross-stratified sets of about 1.1 m thick, large-scale sets of about 0.4 m thick and, rarely, medium-scale sets of about 0.2 m thick. Massive sandstones,

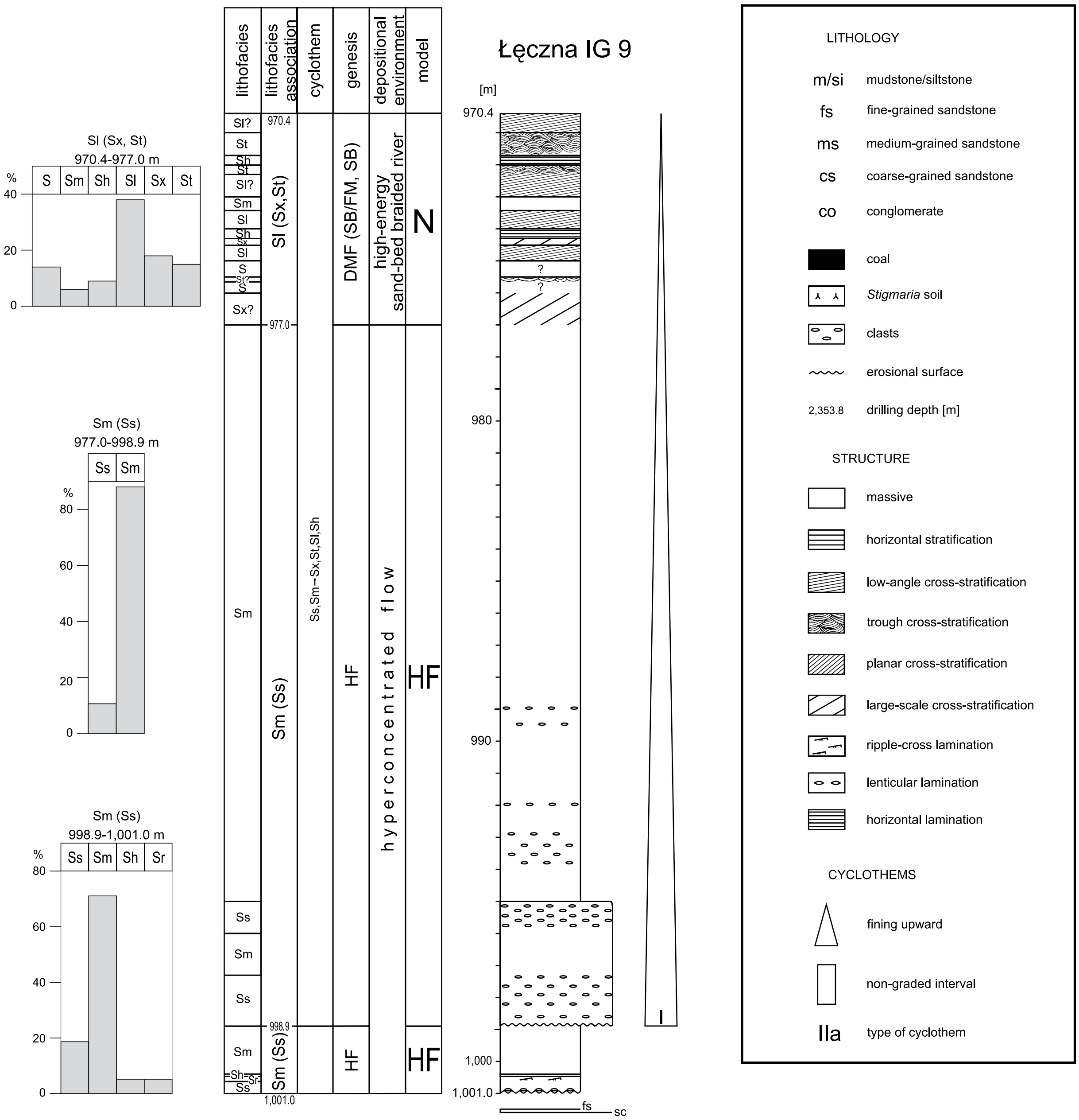


Fig. 6. Lithofacies associations and fining-upward cyclothems deposited from hyperconcentrated flows and in high-energy sand-bed braided-river environments. Łęczna IG 9 borehole.

locally with quartz and carbonaceous clasts, are common in the lower, coarse-grained part. Massive gravelly sandstone with quartz clasts is rare. There is a considerable proportion of large-scale cross-stratified sandstone in this association. An erosional surface, accentuated by claystone clasts, is present at the base of one cross-stratified set. At the top of the association claystone laminae of several millimetres thick are present.

The association contains four fining-upward cyclothems: ΔSt; ΔSt; ΔSm,SGm,Sx and ΔSx,St,Sm,Sr→Fm, of which the upper part adheres to the higher lithofacies association Sr (C, Sx).

3.1.3.2. Other lithofacies

Three lithofacies associations Sp? from borehole Łęczna IG 25 (Figs 10, 11; Table 5) are composed mainly of large and very-large (0.4–2.2 m) cross-stratified sets of sandstones

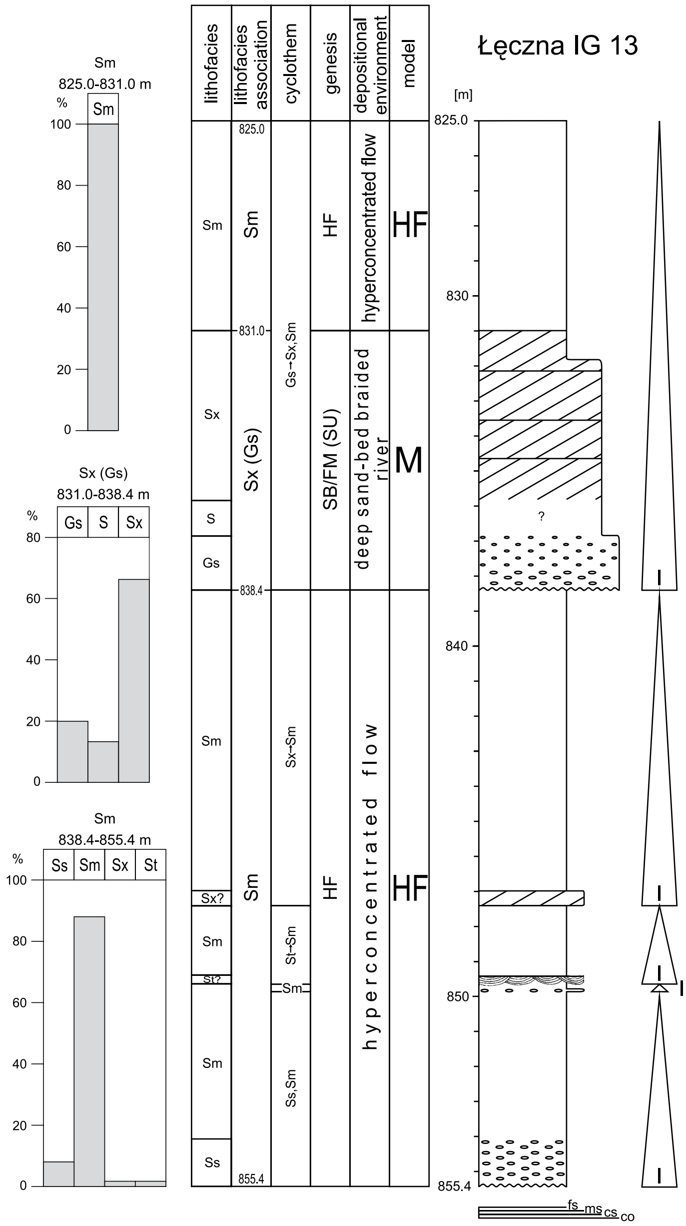


Fig. 7. Lithofacies associations deposited from hyperconcentrated flows and in deep sand-bed braided-river environments. Łęczna IG 13 borehole. For ornaments see Fig. 6.

and conglomerates (Figs 3E, 5A). At the base, occasional medium-scale cross-stratified sets of lithofacies Gt? occur, whereas lithofacies St is present at the top. Lithofacies Sm occurs sporadically.

The associations contain fining-upward cyclothems, e.g. ΔGt?,Gp?→Sp?, ΔGp?→Sp?,St, ΔSp?,Sm and ΔGt→Sm,Sh,Sp?,St,Sr.

3.1.3. Associations dominated by Sr lithofacies

This concerns (Table 5) the lithofacies associations Sr (Sx) present at a depth of 1,066.5–1,078.1 m in borehole Łęczna IG 9 (Fig. 8), Sr (C, Sx) present at a depth of 798.2–808.5 m in borehole Łęczna IG 13 (Fig. 9), Sr (Fm) present at a depth of 2,102.0–2,107.4 m in borehole Stężyca 4 (Fig. 11), and Sr and FSw, Fm (Fh) present at, respectively, 2,387.7–2,394.0 m and 2,384.6–2,387.7 m in borehole Rycice 2 (Fig. 8). All these associations are composed mainly of fine-grained sandstones (lithofacies Sr) and mudstone/siltstone and claystones (lithofacies FSw, Fn, Fh and Fm). Occasionally, lithofacies Se is present at the base of the associations, whereas medium-scale lithofacies St and Sx occur intercalated.

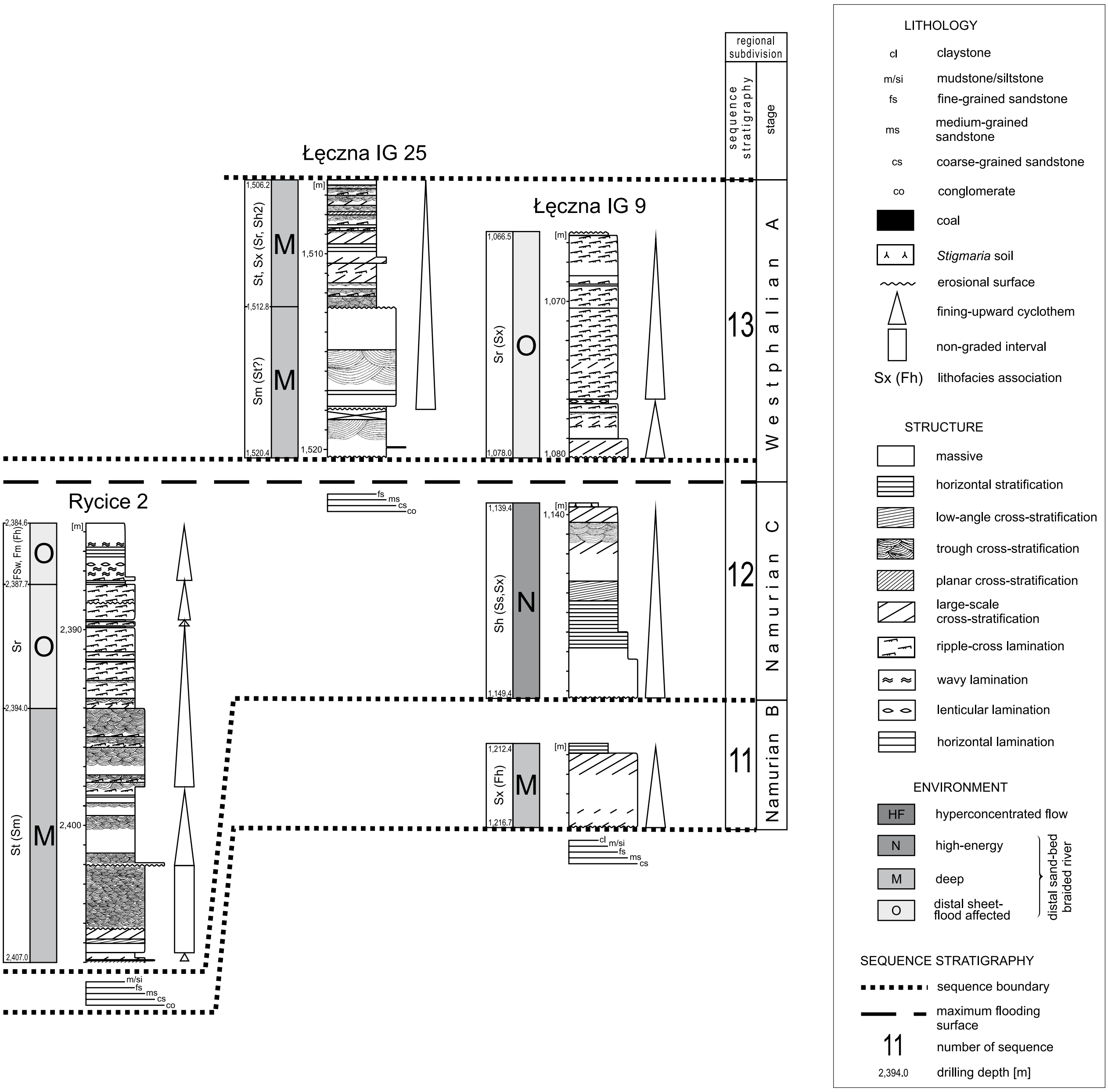


Fig. 8. Correlation of lithofacies associations from the Namurian B and C, and the lower part of the Westphalian A with the lower part of the Bashkirian (sequences 11, 12, 13).

Fining-upward cyclothems are present, e.g. ΔSe→Sx,Sm,Sr,St→Fn; ΔSr→Fm; ΔSr→FSw,Fn,Fh,Fm.

3.2. Interpretation

A common feature of most of the lithofacies associations is, also outside lithofacies Sm, the relatively high frequency of a high-energy lithofacies Sm. This is related to the rapid aggradation of sediments in the upper-plane bed regime.

3.2.1. Associations dominated by Sm lithofacies

These deposits are interpreted as hyperconcentrated–flow deposits accumulated in a valley.

3.2.1.1. Association Sm (Ss)

Deposition of this association was preceded by strong erosion that resulted in the forma-

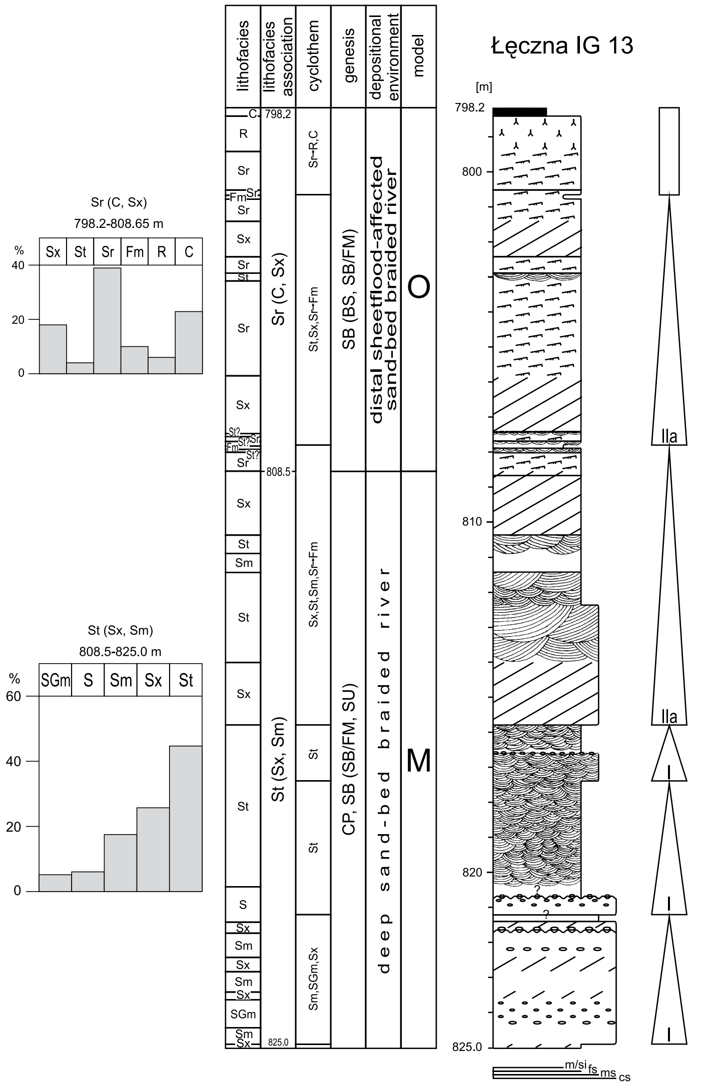


Fig. 9. Lithofacies associations and fining-upward cyclothems formed in deep and sheetflood-affected, distal sand-bed braided-river environments. Łęczna IG 13 borehole. For ornaments see Fig. 6.

tion of the erosional base (Fig. 6). The overlying scour-filled sandstones with clasts and the massive sandstone characterized by poor sorting were deposited under high-energy conditions and rapid aggradation.

The association contains no cross-stratified deposits transported as bedload in 'normal' channels (i.e. with a moderate sediment concentration). Only a massive structure is present (cf. Svendsen et al., 2003). The origin of the association must therefore be ascribed to a hyperconcentrated flow (Fig. 12). Their strong sediment overloading made normal rhythmic bedload transport impossible (cf. Pierson & Costa, 1987). The hyperconcentrated flow presumably moved along the entire width of the river valley, undercutting the slopes that thus collapsed and supplied large amounts of sandy sediment (cf. Martinsen, 1994). Deposition occurred in several stages, as indicated by bounding surfaces within lithofacies Sm.

Thick massive sandstones can be formed at early stages of filling valleys (Martinsen, 1994), and the conglomerates or sandstones with numerous clasts, present at the base, are called 'lowstand basal conglomerates' (e.g. Plint, 1988). This interpretation seems the most appropriate for this association. The valley developed probably during the relative sea-level lowstand and was filled during the early stage of sea-level rise (Fig. 13). The presence of river valleys, filled with channel and sheetflood deposits in the Carboniferous paralic series is also suggested by the results of sequence-stratigraphic studies (Waksmundzka, 2010a). The sandstones of lithofacies Ss document

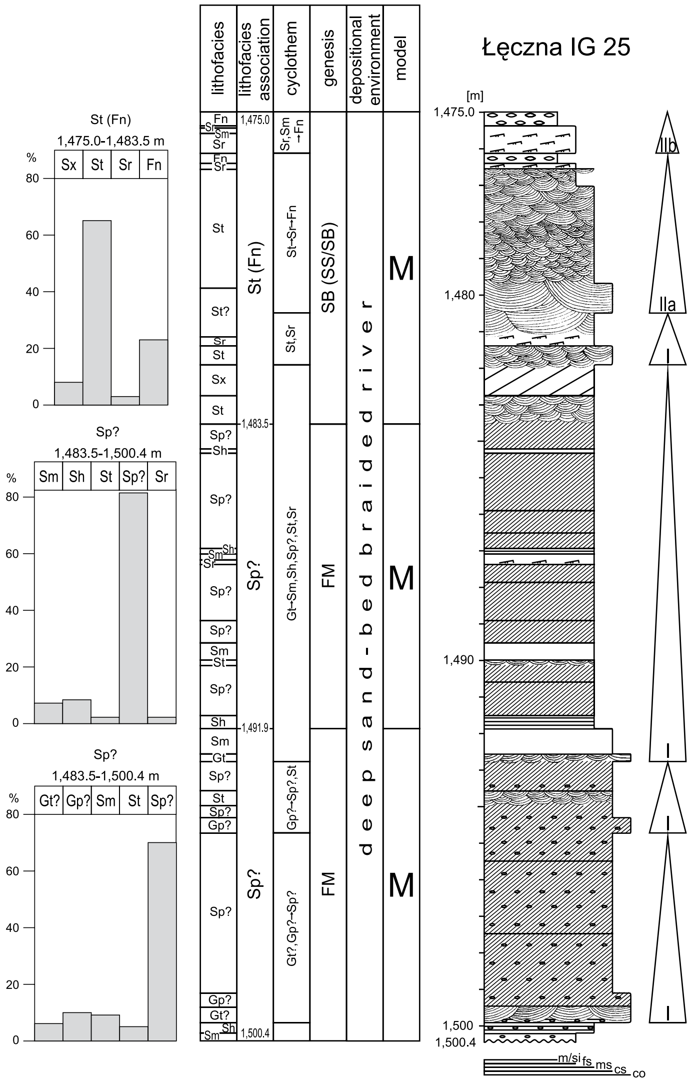


Fig. 10. Lithofacies associations and fining-upward cyclothems formed in low-sinuosity and deep sand-bed braided-river environments from the Łęczna IG 25 borehole. For ornaments see Fig. 6.

the highest energy of the environment; they are overlain by an extremely thick interval of sandstones of lithofacies Sm, deposited under similar conditions but in a slightly lower-energy environment. The fining-upward trend of deposits filling valleys has been described by Hampson et al. (1997).

Deposits of this lithofacies association gradually pass upwards into fine-grained sandstones of association Sl (Sx, St) which occurs at a depth of 970.0–977.0 m (Fig. 6) and which were deposited in a high-energy sand-bed braided river described below. This association reflects rhythmic bedload transport in the form of megaripples and/or transverse bars, as well transport during a gradual decrease of both the current energy and the sediment concentration.

The deposition of association Sm (at a depth of 838.4–855.4 m) was preceded by strong erosion, as indicated by the presence of an erosional base (Fig. 7). The overlying lithofacies Ss and Sm were deposited under similar conditions as the underlying association, except that the thin intercalations of St and Sx lithofacies indicate short-lived phases of rhythmic bedload transport (e.g. by megaripples), controlled by a decrease in current energy and sediment concentration. Thus, deposition under high-energy conditions occurred during at least three stages, separated by lower-energy episodes (lithofacies St and Sx).

The other associations listed in Table 5 were formed under conditions of hyperconcentrated flows.

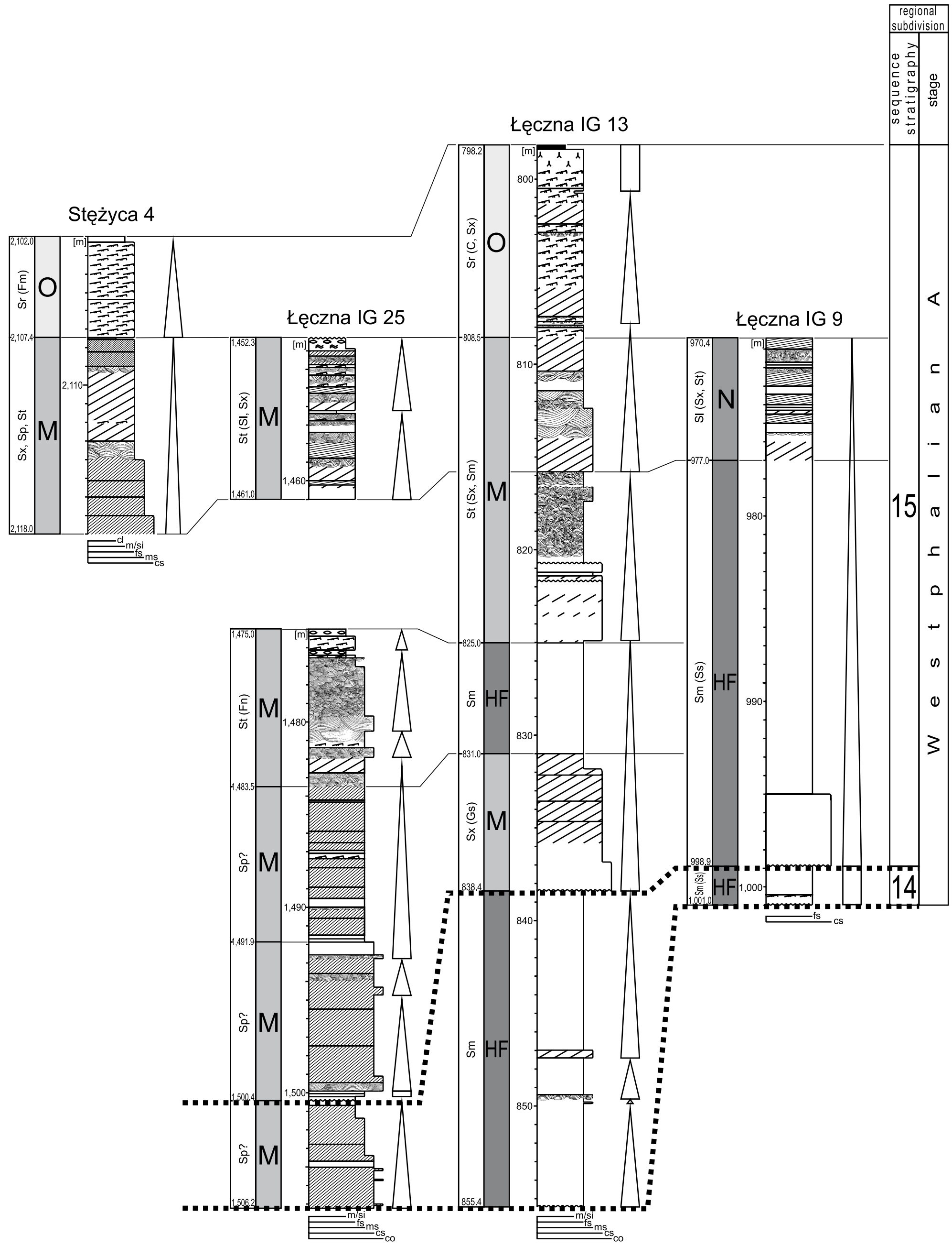


Fig. 11. Correlation of lithofacies associations from the upper part of the Westphalian A with the middle part of Bashkirian (sequences 14, 15). For ornaments and symbols see Fig. 8.

3.2.2. Associations dominated by Sl, Sh lithofacies

These deposits reflect a high-energy sand-bed braided river.

3.2.2.1. Association Sl (Sx, St)

This association, present at a depth of 970.0–977.0 m (Fig. 6), was formed at the transition from the lower to the upper flow regime. Then, megaripples and transverse bars developed under conditions of decreasing channel depth, which led to erosional truncation and a diminishing size of these sand bodies. Lithofacies Sx and St, not very common, are related to megaripples and/or transverse bars which developed in a slightly deeper channel. The thick lithofacies Sh and Sm were formed at a small channel depth during the supercritical flow.

The dominance of lithofacies Sl, associated with diminished megaripples and transverse bars, as well as the relatively high proportion of

Table 5. Characteristics of lithofacies associations developed in high-energy and distal sheetflood-affected sand-bed braided rivers, as well as hyperconcentrated flows. Δ = fining-upward cyclothem; □ = non-graded interval.

Borehole	Lithofacies association	Genesis	Cyclothems
Hyperconcentrated flow			
Łęczna IG 9	Sm (Ss) 977.0–998.9 m	HF	lower part of cyclothem: ΔSs,Sm→Sx,St,Sl,Sh
Łęczna IG 9	Sm (Ss) 998.9–1,001.0 m	HF	□Sm,Sr,Sh
Łęczna IG 13	Sm 825.0–831.0 m	HF	upper part of cyclothem: ΔGs→Sx,Sm
Łęczna IG 13	Sm 838.4–855.4 m	HF	ΔSx→Sm; ΔSt→Sm; ΔSm; ΔSs,Sm
high-energy sand-bed braided river (model N)			
Łęczna IG 9	Sl (Sx, St) 970.4–977.0 m	DMF (SB/FM, SB)	upper part of cyclothem: ΔSs,Sm→Sx,St,Sl,Sh
Łęczna IG 9	Sh (Ss, Sx) 1,139.4–1,149.4 m	SU (SU, SB/FM)	ΔSs→Sh,Sl,Sm,Sx,St→R
distal sheetflood-affected sand-bed braided river (model O)			
Łęczna IG 9	Sr (Sx) 1,066.5–1,078.0 m	SB (SB/FM)	□Sr,Sx→Fm; ΔSe→Sx,Sm,Sr,St→Fn
Łęczna IG 13	Sr (C, Sx) 798.2–808.5 m	SB (BS, SB/FM)	ΔSr→R,C; ΔSt,Sx,Sr→Fm; upper part of cyclothem: ΔSx,St,Sm,Sr→Fm
Stężyca 4	Sr (Fm) 2,102.0–2,107.4 m	SB (SS)	ΔSr→Fm
Rycice 2	FSw, Fm (Fh) 2,384.6–2,387.7 m	SS/SB, SS (SS)	ΔSr→FSw,Fn,Fh,Fm
Rycice 2	Sr 2,387.7–2,394.0 m	SB	lower part of cyclothem: ΔSr→Fh; ΔSr→Fm; upper part of cyclothem: ΔSt,Sr,Sx,Sh→Sr→Fm

the high-energy lithofacies Sh and Sm, suggest that the association was deposited in a high-energy but distal sand-bed braided river (Fig. 12) (cf. Model N by Miall, 1996).

The deposits indicate aggradation in a channel due to a rising base level. They grade into massive fine-grained sandstones deposited by hyperconcentrated flows.

3.2.2.2. Association Sh (Ss, Sx)

This association, at a depth of 1,139.4–1,149.4 m (Fig. 8), was deposited under similar hydrodynamic conditions as association Sl (Sx, St), although its deposition was, in contrast, preceded by erosion that resulted in an erosional base. The association was initially formed under high-energy current conditions in the upper plane-bed regime. Then megaripples and transverse bars developed. Subsequently, the currents weakened to the lower flow regime and deposition of megaripples and/or transverse bars started. A further decrease of the current intensity was due to filling of the channel, which became overgrown by vegetation. The decrease of the current energy is recorded in the fining-upward cyclothem ΔSs→Sh,Sl,Sx,St→R.

3.2.3. Associations dominated by St, Sx, Sp lithofacies

These deposits represent a deep sand-bed braided river.

3.2.3.1. Association St (Sx, Sm)

This association, at a depth of 808.5–825.0 m (Fig. 9), is clearly divided into three parts by erosional surfaces documenting flood stages. The lower part represents a channel facies and reflects frequent transitions of the current from the lower to the upper (and vice versa) flow regime. Erosional phases were followed by rapid aggradation. The lower flow regime structures, megaripples and transverse bars dominate.

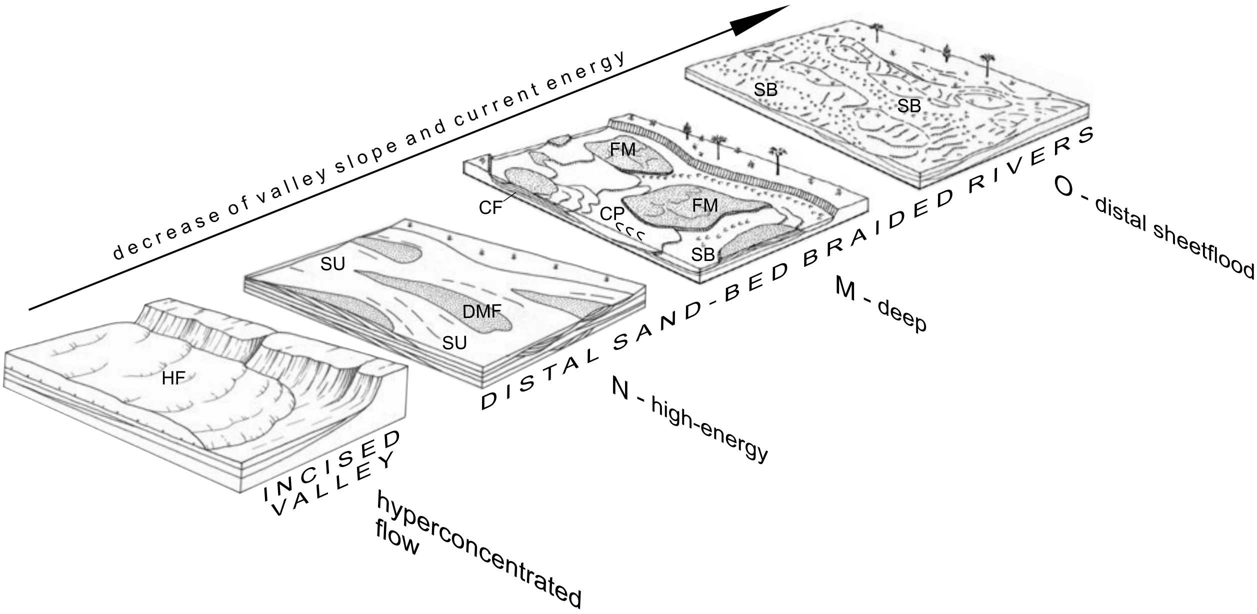


Fig. 12. Models of distal sand-bed braided-river environments within the Carboniferous of the Lublin Basin (modified after Miall).

The middle part of the association is composed of fine- and medium-grained sandstones, St, deposited in the upper part of the lower flow regime. Megaripples of 0.4–0.5 m high developed in a river channel of about 0.7–1 m deep. The presence of a intervals of lithofacies St of several metres thick suggests relatively long-lasting migration of the megaripples, which is characteristic of major, deep braided-river channels (Cant & Walker, 1978) with a relatively low concentration of bedload transport (Zieliński, 1993).

The upper part of this association was deposited under similar energy conditions reflected by similar bedforms, but is characterised by the presence of very large sets of very large megaripples (1.8–2.4 m high), in a channel of 3.6–4.8 m deep. The claystone laminae prove a temporary decreased current related to a drop of the water level, resulting in settling of clay from suspension.

This association was initially deposited in relatively shallow, and subsequently in a deep sand-bed braided river (cf. model M of Miall, 1996). Its reconstruction is shown in Figure 12. It corresponds to fluvial model 10 of Miall (1985) and to the model of the South Saskatchewan River (Cant & Walker, 1976, 1978). Deposition occurred in deep river-channel zones, but also in shallower zones where downstream accretion of transverse bars took place, as well as on shoals, were sediments accumulated under upper-plane bed conditions.

3.2.3.2. Other lithofacies associations

The characteristics of the other associations from this genetic group are presented in Table 6. The three units of association Sp? (Figs 10, 11) are supposed to have formed in the same environment, but in a shallower zone of the channel (0.95–2.6 m deep), where transverse bars occurred. Lithofacies associations St (Fn) and Sm (St?), present in borehole Łęczna IG 25, were formed in deep sand-bed braided–river environment. These associations are characterised by a high proportion of medium- and large-scale sets of lithofacies St.

3.2.4. Associations dominated by lithofacies Sr

These deposits represent distal sheetfloods in a sand-bed braided–river environment.

3.2.4.1. Lithofacies Sr

The dominant lithofacies Sr, formed consisting of ripples formed under conditions of the lower part of the lower flow regime, in combination with the mudstone/siltstone and claystone lithofacies FSw, Fn, Fh and Fm which settled partly or entirely from suspension in the absence of current activity, indicates extremely shallow, waning currents of low energy. These conditions were sometimes preceded by strong

Table 6. Characteristics of lithofacies associations developed in deep sand-bed braided rivers; Δ = fining-upward cyclothem; □ = non-graded interval; M = megariple; FM = transverse bar.

Deep sand–bed braided river (model m)					
Borehole	**Lithofacies association**	**Genesis**	**Parent macroform height (m)**	**Palaeochannel depth (m)**	**Cyclothems**
Łęczna IG 9	Sx (Fh) 1,212.4–1,216.7 m	SB/FM (SS)	–	–	ΔSx,Sm→Fh
Łęczna IG 13	St (Sx, Sm) 808.5–825.0 m	CP, SB (SB/FM, SU)	M 0.36–0.48; M 1.8–2.4	0.72–0.96 3.6–4.8	lower part of cyclothem: ΔSx,St,Sm,Sr→Fm; ΔSt; ΔSt; ΔSm,SGm,Sx
Łęczna IG 13	Sx (Gs) 831.0–838.4 m	SB/FM (SU)	–	–	lower part of cyclothem: ΔGs→Sx,Sm
Łęczna IG 25	St (Sl, Sx) 1,452.3–1,461.0 m	SB (SB/FM)	M 0.54–0.73	1.1–1.46	ΔSx,St,Sl,Sr,Sp→FSW,Fn; ΔSm,Sx,Sl,St,Sr→Fm
Łęczna IG 25	St (Fn) 1,475.0–1,483.5 m	SB (SS/SB)	M 0.59–0.78 M 2.28	1.18–1.56 4.55	ΔSr,Sm→Fn; ΔSt→Sr→Fn; ΔSt,Sr; upper part of cyclothem: ΔGt→Sm,Sh,Sp?,St,Sr
Łęczna IG 25	Sp? 1,483.5–1,491.9 m	FM	FM 0.95–1.17	0.95–1.17	middle part of cyclothem: ΔGt→Sm,Sh,Sp?,St,Sr
Łęczna IG 25	Sp? 1,491.9–1,500.4 m	FM	FM 2.0–2.6	2.0–2.6	lower part of cyclothem: ΔGt→Sm,Sh,Sp?,St,Sr; ΔGp?→Sp?,St; ΔGt?,Gp?→Sp?
Łęczna IG 25	Sp? 1,500.4–1,506.2 m	FM	FM 1.0–2.6	1.0–2.6	ΔSp?,Sm
Łęczna IG 25	St, Sx (Sr, Sh) 1,506.2–1,512.8 m	SB/FM (SB, SU)	M 0.25–0.34	0.5–0.68	upper part of cyclothem: ΔSm,Sh,St,Sr,Sx; ΔSx,Sm,Sh,Sr,Sp
Łęczna IG 25	Sm (St?) 1,512.8–1,520.4 m	SU (SB?)	M 2.1	4.2	lower part of cyclothem: ΔSm,Sh,St,Sr,Sx
Stężyca 4	Sx, Sp, St 2,107.4–2,118.0 m	SB/FM	FM 1.12–1.4 M 1.47	1.12–1.4 2.94	ΔSp?,St?,Sx,Sr→Fm
Rycice 2	St (Sm) 2,394.0–2,407.0 m	SB (SU)	M 0.53–0.7	1.06–1.4	upper part of cyclothem: ΔSt,Sr,Sx,Sh→Sr→Fm; ΔGe→St,Sm,Sh→Sr; □Sm→Sl,Sx,St; ΔSp,Sx,Sm

erosion that resulted in erosional surface with clasts, representing lithofacies Se and documenting maximum flood stages. Sometimes, in deeper parts of the channels, megaripples and/or transverse bars developed.

The associations represent the lowest-energy type of braided river interpreted in this study. Similar associations have described by, among others, Williams (1971) and Kelly & Olsen (1993). Episodes of waning currents left thin claystone and mudstone/siltstone beds. The upper part of association Sr (C, Sx) contains a succession Sr→R,C, which was formed due to a weak flow that lost all its energy on the vegetation-covered braidplain, resulting in the formation of a sandy *Stigmaria* soil, R. The overlying coal, C, documents a rise in the groundwater level and the development of peat swamps. The deposition may also have taken place in ephemeral floodbasins.

The origin of the associations is clearly connected with the aggradational conditions, which can be related to a rising base level, decreasing slope and, finally, a decrease of the current activity.

The dominance of the lithofacies formed by low-energy currents and in stagnant water indicates a sedimentary environment of a distal sand-bed braided-river affected by sheetfloods, similar to model O (Fig. 12) of Miall (1996), corresponding to model 11 of Miall (1985).

4. Fining-upward cyclothems and their origin

An important feature of the deposits is the presence of fining-upward cyclothems. This feature has been described also from similar deposits by, among others, Cant & Walker (1976, 1978), Miall (1978), Rust (1978), Rust & Gibling (1990) and Zieliński (1997).

The cyclothems was analysed on the basis of the entirety of the lithofacies associations. Two main types of fining-upward cyclothems have been distinguished: type I, being coarse-grained cyclothems, composed of conglomerates and sandstones or exclusively sandstones, and type II, being fine-grained cyclothems, composed of sandstones, mudstones/siltstones, claystones, occasionally *Stigmaria* soils and coals. The fine-grained cyclothems were subdivided into two sub-types (IIa and IIb), based on lithological differences of the lower parts of the cyclothems; the lower part of sub-type IIa is composed of lithofacies deposited under conditions of the upper and lower flow regime, whereas the lower part of sub-type IIb is characterised by a predominance of the lowermost-energy lithofacies, i.e. Sr. The characteristics of the cyclothems are presented in Table 7.

Type I cyclothems have thickness ranging from 0.2 to 28.5 m. They are built up mainly of high-energy lithofacies, i.e. Ge, SGm, Sm, Ss and Sh. The cyclothem ΔSs,Sm→Sx,St,Sl,Sh, (depth 970.4–998.9 m, borehole Łęczna IG 9; Fig. 6) is interpreted to represent a hyperconcentrated flow that reached the shallow braided channel and resulted in rhythmic bedload transport. The cyclothem ΔSs,Sm (849.9–855.4 m in Fig. 7) reflects a decrease in energy and capacity of a hyperconcentrated flow. The two next cyclothems of the succession, ΔSt→Sm and ΔSx→Sm (Fig. 7), were formed under different conditions: initial deposition from an equilibrium channelized current was followed by a hyperconcentrated flow.

Table 7. Types and genesis of fining-upward cyclothems in braided river deposits and hyperconcentrated–flow deposits.

Fining-upwards cyclothems derived from braided rivers and hyperconcentrated flow							
Cyclothem Type		Lithofacies succession		Thickness (m.)			Genesis
		Lower part	Upper part	Lower part	Upper part	Total	
type I (coarse-grained)		Ss,Sm→Sx,St,Sl,Sh Ss,Sm St→Sm	absent	0.2–28.5	absent	0.2–28.5	decreasing of energy and capacity (excluding St→Sm cyclothem) of hyperconcentrated flow, filling of channels and incised valleys as a result of base level rise
type I (coarse-grained)		Ge→St,Sm,Sh→Sr Gt→Sm,Sh,Sp?,St→Sr Gt?,Gp?→Sp?	absent	1.4–11.7	absent	1.4–11.7	decreasing of velocity and capacity of the flow in the sand-bed braided fluvial systems, filling of channels as a result of base level rise
type II (fine-grained)	a	Ss→Sh,Sl,Sx,St→ St,Sr→	R Fm	2.5–14.1	0.1–2.5	3–15.6	
type II (fine-grained)	b	Sr→	FSw, Fn, Fh, Fm	0.2–8.4	0.1–2.7	0.3–8.6	waning flood in the inter-channel zone as a result of base level rise

An example is the cyclothem ΔGe→St, Sm,Sh→Sr (depth 2,398.0–2,402.0 in borehole Rycice 2; Fig. 8), starting with an erosional surface with clasts, Ge, documenting a maximum flooding stage. This is followed by an interval with fine-grained sandstones, Sm, deposited under supercritical flow conditions, intercalating with sandstones, St, forming megaripples deposited under lower flow regime conditions. This succession was formed during alternating episodes of local erosion and strong aggradation of the river bed. In the upper part of the cyclothem, shallow-water lithofacies Sh, also deposited from supercritical flow, and lithofacies Sr, deposited under the uppermost low-energy conditions, occur. Gradziński et al. (1995; see Fig. 5) illustrated fining-upward intervals of up to about 7 m thick, which seem identical to the type I cyclothems. These intervals are interpreted as deposits of braided channel belts.

Another example of a type I cyclothem is the succession ΔGt→Sm,Sh,Sp?,St→Sr (depth 1,482.0–1,492.8 m in borehole Łęczna IG 25; Figs 10, 11), in which the lower-energy lithofacies predominate. A similar lithofacies succession of ΔSt→Sp→Sr was described by Van Huissteden & Vandenberghe (1988), who interpreted this as a result of a decrease of the current energy in braided channels.

Cyclothem ΔGt?,Gp?→Sp? (depth 1,492.8–1,494.7 m in borehole Łęczna IG 25; Figs 10, 11) is represented mainly by very-large-scale sets of lithofacies Gp? and Sp?. It was deposited under similar hydrodynamic conditions (lower flow regime), but the shallow-water lithofacies are absent in the upper part of the succession. A fining-upward cyclothem of ΔSt→Sp, with similar characteristics as that described above, was presented by Zieliński & Lewandowski (1990). This cyclothem was developed in braided channels during a decrease of the current energy.

Only a small percentage of fining-upward cyclothems of type I show a thickness of less than 2 m (Fig. 14), starting from a non-erosional base. They show a simple succession of two or three lithofacies. It seems that these cyclothems reflect variations in the velocity and capacity of waning currents. However, the most common are thick cyclothems, in which a transition

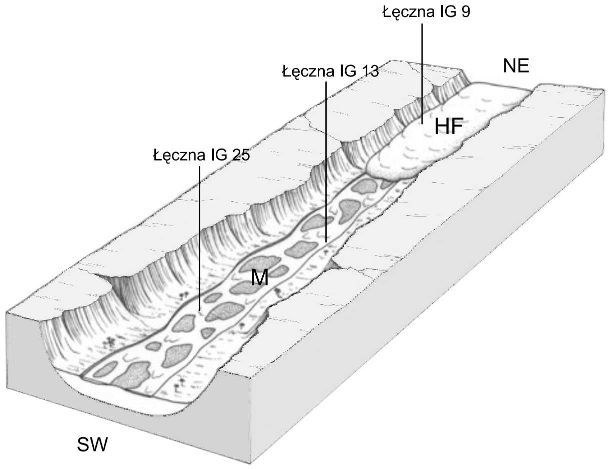


Fig. 13. Reconstruction of the depositional environments of a braided river and hyperconcentrated flows within valley formed during early relative sea-level lowstand of sequence 15 (middle part of the Bashkirian). M = deep sand-bed braided river; HF = hyperconcentrated flow.

from high-energy to low-energy conditions is recorded in successions of numerous lithofacies. These features are mostly related to the evolution from sand-bed braided channels to hyperconcentrated flows, controlled by a base-level rise.

The type IIa cyclothems has thicknesses of 3–15.6 m (Fig. 14). They are composed in their lower parts of sandstones of 2.5–14.1 m thick, and in their upper parts of fine-grained, *Stigmaria*-containing soils and coal deposits of 0.1–2.5m thick . The lower sandstone parts are commonly similar to those observed in the type I cyclothems. They are mainly composed of high-energy lithofacies, for example ΔSs→Sh,Sl,Sx,St→R (depth 1,139.4–1,149.4 m in borehole Łęczna IG 9; Fig. 8). There are also cyclothems with predominant lower-energy lithofacies, especially Sr, in the coarse-grained part, such as in the succession ΔSt,Sr→Fm (depth 2,389.8–2,398.0 m in borehole Rycice 2; Fig. 8).

The sandstone parts of IIa cyclothems pass into fine-grained parts composed of lithofacies FSw and Fn, formed by weak, waning currents with episodes of fine-grained suspension settling, and of lithofacies Fh and/or Fm, settled from suspension in stagnant water. Occasional *Stigmaria* soils, R, indicate a sedimentary hiatus and the development of vegetation and pedogenic processes. The fine-grained and plant-con-

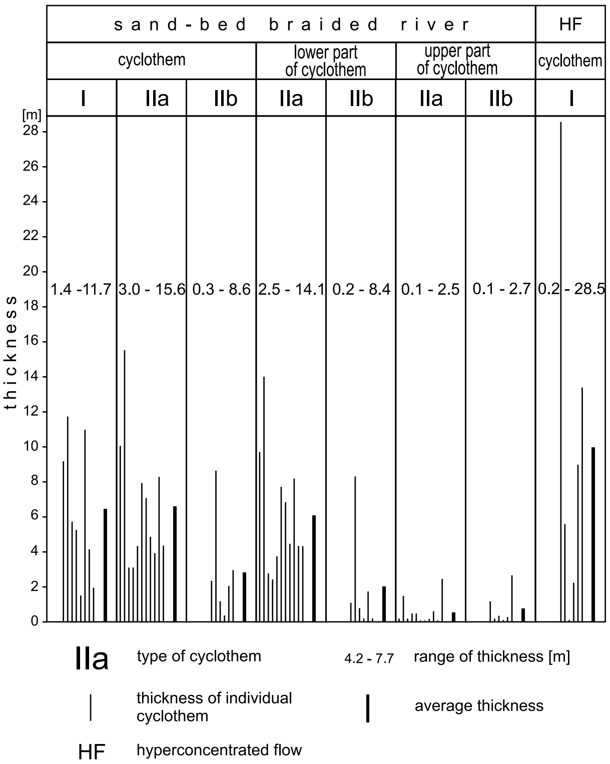


Fig. 14. Thickness distribution of the cyclothems.

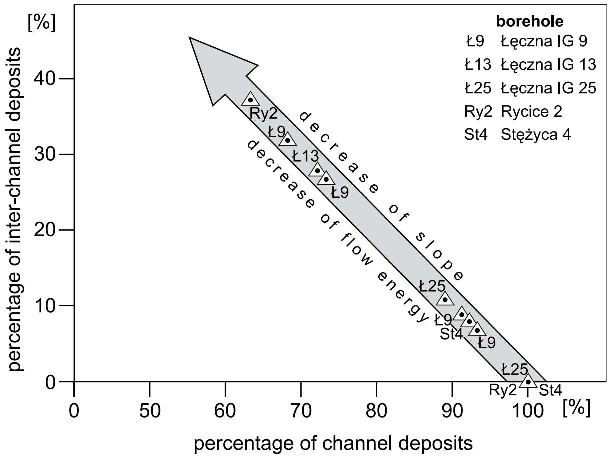


Fig. 15. Frequency diagram of the channel and inter-channel deposits.

taining lithofacies represent the inter-channel subenvironment of the braidplain.

Similar fining-upward cyclothems ΔSt→Sr→Fr,Sr,C, up to 8 m thick and also deposited in braided rivers, have been described by Rust & Gibling (1990) from the Carboniferous of Canada. Cant & Walker (1976) also characterized a thick (9 m) cyclothem ΔSt→Sp,Sr→Sh→Fh, Sr from the Canadian Devonian. Moreover, the large thickness (about 15 m), comparable to that of cyclothems of sub-type IIa, is characteristic of the cyclothem ΔSm→Sl→Sr→R→C described by Gradziński et al. (1995) from the Carboniferous of Upper Silesia (S Poland).

The large thicknesses (usually 3–16 m) are characteristic of IIa sub-type cyclothems. In addition to the fining-upward trend, they are also characterised by the transition from higher- to lower-energy lithofacies, and then to lithofacies that result partly or entirely from settling in stagnant water. The cyclothems start from a fifth-order erosional surface corresponding to a stratigraphic sequence boundary and usually include one or two lithofacies associations. They usually show a complex lithofacies succession and are characterised by the presence (7–37%) of lithofacies formed in the inter-channel subenvironment of a braidplain (Fig. 15). Commonly the proportion of these lithofacies in braided rivers, is smaller even below 5% (Blakey & Gubitosa, 1984) or 10–15% (Rust, 1978).

The formation of cyclothems IIa is ascribed to a decrease in velocity and capacity of the current, controlled by base-level rise. Their similarity to type I cyclothems is commonly related to allocyclic factors. The influence of allocyclic factors in the study area is considered responsible for the extremely large proportion of inter-channel deposits (27–37%) in the cyclothems, which resulted from the creation of accommodation space that was subsequently filled with lacustrine (lithofacies Fm and Fh) and plant-containing (R, C) deposits.

Among the type IIb cyclothems, which attain thicknesses of 0.3–8.6 m but which are commonly less than 3 m thick (Fig. 14), is a cyclothem ΔSr→FSw,Fn,Fh,Fm (depth 2,384.6–2,387.5 m in borehole Rycice 2; Fig. 8). The lower part is composed mainly of fine-grained sandstones of low-energy lithofacies Sr. The upper parts contain lithofacies FSw and Fn, formed under conditions of weak and waning currents, and lithofacies Fh and Fm, deposited from suspension settling in standing water.

Such a lithofacies succession probably formed during waning current activity on the inter-channel subenvironment of a braidplain. However, the presence of a relatively thick (2.7

Table 8. Chronostratigraphical order of the lithofacies associations in the boreholes.

Lithofacies association	Genesis	River type	Sequence stratigraphy	Chronostratigraphy	
Łęczna IG 9					
Sl (Sx, St) 970.4–977.0 m	DMF (SB/FM, SB)	N	15	Westphalian A	Bashkirian
Sm (Ss) 977.0–998.9 m	HF	–			
Sm (Ss) 998.9–1,001.0 m	HF	–	14		
Sr (Sx) 1,066.5–1,078.0 m	SB (SB/FM)	O	13		
Sh (Ss, Sx) 1,139.4–1,149.4 m	SU (SU, SB/FM)	N	12	Namurian C	
Sx (Fh) 1,212.4–1,216.7 m	SB/FM (SS)	M	11	Namurian B	
Łęczna IG 13					
Sr (C, Sx) 798.2–808.5 m	SB (BS, SB/FM)	O	15	Westphalian A	Bashkirian
St (Sx, Sm) 808.5–825.0 m	CP, SB (SB/FM, SU)	M			
Sm 825.0–831.0 m	HF	–			
Sx (Gs) 831.0–838.4 m	SB/FM (SU)	M			
Sm 838.4–855.4 m	HF	–	14		
Łęczna IG 25					
St (Sl, Sx) 1,452.3–1,461.0 m	SB (SB/FM)	M	15	Westphalian A	Bashkirian
St (Fn) 1,475.0–1,483.5 m	SB (SS/SB)	M			
Sp? 1,483.5–1,491.9 m	FM	M			
Sp? 1,491.9–1,500.4 m	FM	M			
Sp? 1,500.4–1,506.2 m	FM	M	14		
St, Sx (Sr, Sh) 1,506.2–1,512.8 m	SB/FM (SB, SU)	M	13		
Sm (St?) 1,512.8–1,520.4 m	SU (SB)	M			
Rycice 2					
FSw, Fm (Fh) 2,384.6–2,387.7 m	SS/SB, SS (SS)	O	12	Namurian C	Bashkirian
Sr 2,387.7–2,394.0 m	SB	O			
St (Sm) 2,394.0–2,407.0 m	SB (SU)	M			
Stężyca 4					
Sr (Fm) 2,102.0–2,107.4 m	SB/SS	O	15	Westphalian A	Bashkirian
Sx, Sp, St 2,107.4–2,118.0 m	SB/FM	M			

m) fine-grained part (FSw,Fn,Fh,Fm) might be related to a relative base-level rise, braidplain flooding and the development of lakes.

Lithofacies successions that are generally similar to type IIb cyclothems, except for the presence of plant-containing lithofacies, have been described by Tunbridge (1983) and Sneh (1983) from recent fining-upward cyclothems. These authors interpret them as controlled by falling flood stages of braided rivers. The principal feature distinguishing the cyclothems under study from those described by the above-cited authors, is their significantly larger thickness. This indicates that increasing accommodation space was the main factor controlling the origin of the cyclothems under study. Good analogues of cyclothems IIb are the fining-upward intervals described by Gradziński et al. (1995) mentioned above, which reach approx. 8 m, and are composed of sandstone, fine-grained and plant-containing lithofacies formed in the inter-channel subenvironment of a braided river system.

5. Spatial and age relationships

Spatial and age relationships between the various lithofacies associations have been determined using a sequence-stratigraphic model and its chronostratigraphy division (Waksmundzka, 2010a). They are shown in Figure 2 and Table 8.

The associations belonging to the lowest Namurian B and lowest Namurian C (sequences 11, 12) were deposited in two types of sand-bed braided rivers: deep (boreholes Łęczna IG 9 and Rycice 2) or high-energy (borehole Łęczna IG 9)(Fig. 8). These associations are overlain by deposits accumulated in a different type of river characterized by a lower current energy: a distal sheetflood-affected sand-bed braided or anabranching river, which is not the scope of the present contribution. In the lower fluvial parts of the Namurian B and C, a vertical transition of the river occurred from a high- to a low-energy environment. This was probably due to a rise of the regional base level.

The associations in the eastern region (borehole Łęczna IG 9l) that belong to the lower part of the Westphalian A (sequence 13), were deposited in a lower-energy distal sheetflood-affected sand-bed braided river (Fig. 11). They are overlain by deposits accumulated in an anastomosing river characterised by an even lower energy of the current, but this is beyond the scope of the present contribution. In the central region (borehole Łęczna IG 25), two associations are present that were deposited in a similar, high-energy river type, i.e. in a deep sand-bed braided river, but both the lithofacies composition of the upper association and the finer-grained material indicate that they were deposited in a current with a slightly lower energy.

The upper Westphalian A associations are included in the lowstand systems tract (LST) of sequences 14 and 15. The older associations (sequence 14) from boreholes Łęczna IG 9 and Łęczna 13 were deposited by a high-energy hyperconcentrated flow. Their deposition was preceded by erosion that took place at a regional scale. The age equivalent of these associations is the association formed in a deep sand-bed braided river in the region of borehole Łęczna IG 25. They have strong aggradation of sands in common, as indicated by the significant thickness (17 m) of the association from borehole Łęczna IG 13. The degree of aggradation of the association from borehole Łęczna IG 9 does not allow a thorough assessment due to the truncation of its top part.

The sandstones in sequence 15, at the base of which another erosional surface occurs, developed in several phases. In the region of borehole Łęczna IG 9 (situated farthest to the East), they are 28.5 m thick and consist of two associations. The older one was deposited by a high-energy hyperconcentrated flow, whereas the younger one was deposited when the energy and sediment load of the hyperconcentrated flow decreased and a high-energy sand-bed braided river developed.

The sandstones found in the Łęczna IG 13 cores are thicker (approx. 40 m) and consist of four associations. The initial deposition took place in a deep sand-bed braided river, and then from a high-energy hyperconcentrated flow that formed when the concentration of sand particles and transport energy increased.

It lasted probably for a shorter time than in the region of the Łęczna IG 9 borehole, as suggested by its thinner (6 m) development. When the sediment concentration decreased, a deep sand-bed braided river developed again. With decreasing current energy, the river subsequently evolved into a distal, sheetflood-affected sand-bed braided river, where weak, waning flows ran over the braidplain. At the top of the youngest association, the sandy *Stigmaria* soil is present, indicating a decline of the current activity and development of vegetation. The coal bed above the *Stigmaria* soil formed as a result of coalification of organic matter in a peat swamp. It developed on the site of the former alluvial plain due to a rising groundwater table.

The Łęczna IG 25 cores contain the thickest sandstones (65 m). The four associations accumulated in a deep sand-bed braided river. The youngest association was also formed in this type of river, but with a slightly lower energy. Between the two lower associations and above the youngest one an interval of sediments accumulated in a meandering river characterised by a lower current energy is present. These sediments are, however, beyond the scope of the present contribution.

It is likely that the deposition of the LST sandstones of sequence 15 in the eastern and central regions of the Lublin Basin took place within the same valley (Fig. 13). It seems that the deposits from the Łęczna IG 9 borehole accumulated in a shallower part of the valley located the farthest from its end. The deposits in Łęczna IG 13 represent probably a slightly deeper part, whereas the deposits in the Łęczna IG 25 section represent the deepest part, located close to the end of the valley. The bottom of the valley must have had an overall slope towards the south-west, and the sediment transport must consequently have occurred toward that direction. However, the reconstruction of the real shape of the valley requires additional studies and analyses of more cores.

Reconstruction of the river types of LST deposits from sequence 12 suggests that the braided rivers in the eastern region had a higher energy during the early Namurian C than those in the north-western region. Presumably this was due to a higher slope of the valleys and to a location more close to the source area. Similar palaeogeographical conditions occurred during deposition of the Westphalian A deposits present in the LST sequences 14 and 15. The proximity of the source area may consequently have caused a larger supply of sandy sediments and the development of both high-energy braided rivers and hyperconcentrated flows.

In the Westphalian A sections, a vertical transition from high-energy to lower-energy lithofacies associations occurs, like in the Namurian B and C deposits. This is probably related with a rise of the regional base level.

6. Conclusions

Lithofacies associations characteristic of braided rivers occur in the Namurian B, C and Westphalian A (Lower Bashkirian) of the Lublin Basin in SE Poland. Of the various lithofacies associations that have been distinguished, 19 were formed in distal sand-bed braided rivers, which are represented by three environments. The first type is the high-energy sand-bed braided river, the deposits of which are dominated by low-angle cross-stratification or horizontal stratification, indicating a small depth of the channels. The second type is the deep sand-bed braided river, the deposits of which are characterised by megaripples and transverse bars, indicating a channel depth of up to 4.8 m. The third type is the distal sheetflood-affected sand-bed braided river, the deposits of which are characterised by ripples formed in very shallow channels with a weak, waning current.

Four of the lithofacies associations were likely deposited by hyperconcentrated flows that were characterised by a considerable concentration of sand particles, and that took place during early stages of the filling of valleys.

Among the fining-upward cyclothems present in successions representing a braided-river environment, coarse-grained (type I) and fine-grained (sub-types IIa and IIb) can be distinguished. Cyclothems formed by hyperconcentrated flows are represented by type I only.

The characteristic feature of the fining-upward cyclothems that formed in the braided-river environment is the lack (or low percentage) of braidplain (inter-channel) deposits.

The formation of most fining-upward cyclothems was caused by an allocyclic factor (a decreasing channel slope), which resulted in the filling and abandonment of channels. Type I cyclothems deposited from hyperconcentrated flows show the largest thickness, suggesting that the strongest aggradation was related to this medium. Type I cyclothems and the sandstone parts of type IIa cyclothems were formed in braided-river channels characterised by a considerable thickness (about 4–14 m). This indicates a strong aggradation of channel deposits, controlled by allogenic factors. During the early Namurian C and early Westphalian A, the eastern Lublin Basin was located close to the source area. The north-western part of the studied basin was the distal region.

The succession of the lithofacies associations representing the Namurian B, C and Westphalian A (Lower Bashkirian) developed as a result of the transition from a high-energy environment with hyperconcentrated flows and braided rivers into lower-energy fluvial environments. This tendency was controlled by a rise of the regional base level.

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