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A MIOCENE ANASTOMOSING RIVER SYSTEM IN THE AREA OF KONIN LIGNITE MINE, CENTRAL POLAND

Marek WIDERA[1], **Emilia KOWALSKA**[2] & **Mateusz FORTUNA**[3]

[1] *Institute of Geology, Adam Mickiewicz University, 12 Bogumił Krygowski Str., 61-680 Poznań, Poland;*
e-mail: widera@amu.edu.pl
[2] *8 Bernardynka Str., 62-510 Konin, Poland; e-mail: emmilia.k92@gmail.com*
[3] *40/10 Adam Mickiewicz Str., 64-915 Jastrowie, Poland; e-mail: fortun991@gmail.com*

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Abstract: This sedimentological study of the Wielkopolska Member of the Miocene Poznań Formation in the Jóźwin IIB opencast lignite-mining field, central Poland, reveals a late mid-Miocene anastomosing fluvial system with ribbon-shaped channels filled mainly by sandy and muddy deposits. The fluvial system, extending across the eastern flank of the post-Mesozoic Kleczew Graben, was tributive in its eastern upper reaches, but was increasingly distributive and northwards deflected in its lower reaches near the graben axis. Lithofacies analysis of a representative palaeochannel indicates that the river discharge significantly fluctuated and that the channels were filled with mud-bearing stratified fine-grained sand by low-density tractional turbulent flow during the high and low water stages and with a massive mud or sandy mud by a high-density flow during the rising and falling stages. The spatial pattern of fluvial channels and deformation channel-fill sandbodies were controlled by the graben topography and the differential compaction of peat substrate, with possible influence of bedrock faults. The fluvial system is thought to have drained to an endorheic 'terminal' basin to the north, rather than into the hypothetical Baltic River and further westwards to the distant North Sea basin, as postulated by some previous authors. The present case study contributes to the known spectrum of anastomosing river systems as a sand- to mud-dominated end-member.

Key words: sedimentology, fluvial deposits, palaeochannel pattern, anastomosing river, sand-filled channels.

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INTRODUCTION

In the original classification of fluvial systems by Leopold and Wolman (1957), river channel patterns were divided into straight, meandering and braided types. Subsequent studies found this classification to be not fully representative of the wide variety of river channels (e.g., Schumm, 1968; Rust, 1978; Bridge, 1993; Knighton and Nanson, 1993; Makaske, 2001). On the basis of the braiding index and sinuosity, Rust (1978) proposed a classification of river channels into four types: straight – with single channel and sinuosity <1.5; meandering – with single channel and sinuosity >1.5; braided – with multiple channels and sinuosity <1.5; and anastomosing – with multiple channels and sinuosity >1.5. Some researchers consider a sinuosity index of 1.3 to be the boundary value between straight and meandering channels (Makaske, 2001). However, not every high-sinuosity channel must necessarily be meandering (i.e., laterally migrating and forming point-bars) and likewise not every multi-channel river must necessarily be braiding (i.e., laterally active and forming migratory braid-bars). Schumm (1985) put more focus to the channel lateral stability and categorized both braided and meandering rivers as laterally unstable and bedload-dominated. It was also pointed out earlier by Schumm (1968) that the use of the terms 'braided or braiding' and 'anastomosed or anastomosing' as synonyms is incorrect, because these channel patterns represent different types of river behaviour. Smith and Smith (1980) defined an anastomosing river as 'an interconnected network of low-gradient, relatively deep and narrow, straight to sinuous channels with stable banks of fine-grained sediment and vegetation'. Nanson and Knighton (1996) had similarly classified anastomosing rivers as a specific variety of a broader category of anabranching rivers, characterized by laterally stable multiple channels irrespective of their sinuosity. It is now also widely recognized that an anastomosing river system requires cohesive and/or densely vegetated, relatively stable channel banks (e.g., Rust, 1981; McCarthy *et al.*, 1991; Gibling *et al.*, 1998; Gradziński *et al.*, 2000; Gruszka and Zieliński, 2008; Gross *et al.*, 2011).

However, relatively few ancient cases of anastomosing river systems have thus far been documented, in contrast to

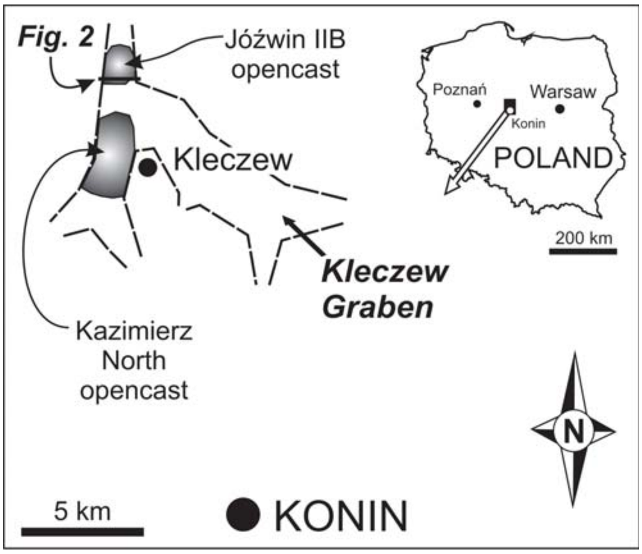

Fig. 1. Location of the Jóźwin IIB and Kazimierz North opencast lignite-mining fields in the Kleczew Graben, central Poland.

the innumerable examples of braided and meandering systems (cf. Miall, 1996; Bridge, 2003). The present case study from the Miocene in the Konin Lignite Mine, central Poland, contributes to the existing knowledge on varieties of anastomosing river palaeochannels. This field study builds upon an earlier research in the Kazimierz North lignite opencast mine and the adjacent Jóźwin IIB lignite opencast ~2 km to the north (Fig. 1), where 25 alluvial palaeochannels have been recognized (Widera, 2012, 2013a). The alluvial deposits represent the Wielkopolska Member of the mid-Miocene Poznań Formation and comprise both channel-fill and overbank lithofacies. The palaeochannels are ribbon-shaped, as mapped, and their striking feature is the fine grain size and massive structure of the channel-fill deposits, with only sparse evidence of tractional sediment stratifications. The aim of this article is to describe the palaeochannel system and to discuss the depositional style of its channel infilling processes, including soft-sediment deformation structures.

GEOLOGICAL SETTING

Tectonics and peat deposition

The study area is located in the northernmost segment of the Kleczew Graben, about 10–20 km north of Konin (Fig. 1). The graben is a fault-bounded shallow tectonic depression, up to a few tens of metres deep and formed in Mesozoic bedrock, with the late Cretaceous calcareous sandstones as pre-Cenozoic substrate (Fig. 2; Widera, 1998, 2014). The area was subject to tectonic uplift throughout the Palaeogene. Subsidence in the axial part of the Kleczew Graben commenced in the early Miocene (Widera, 2007; Fortuna, 2016) and the first Mid-Polish lignite seam (MPLS-1) was deposited in the middle Miocene, during the last phase of the Mid-Miocene Climatic Optimum (MMCO) ~15 Ma ago (Zachos *et al.*, 2001; Bruch *et al.*, 2007; Kasiński and Słodkowska, 2016; Słodkowska and Kasiński, 2016). The MPLS-1 is estimated to represent an accumulated peat thickness of about 40 m, reduced to a maximum thickness of 19.8 m by compaction (Piwocki, 1992). The present study focuses on the alluvium that directly overlies this lignite seam (Fig. 2).

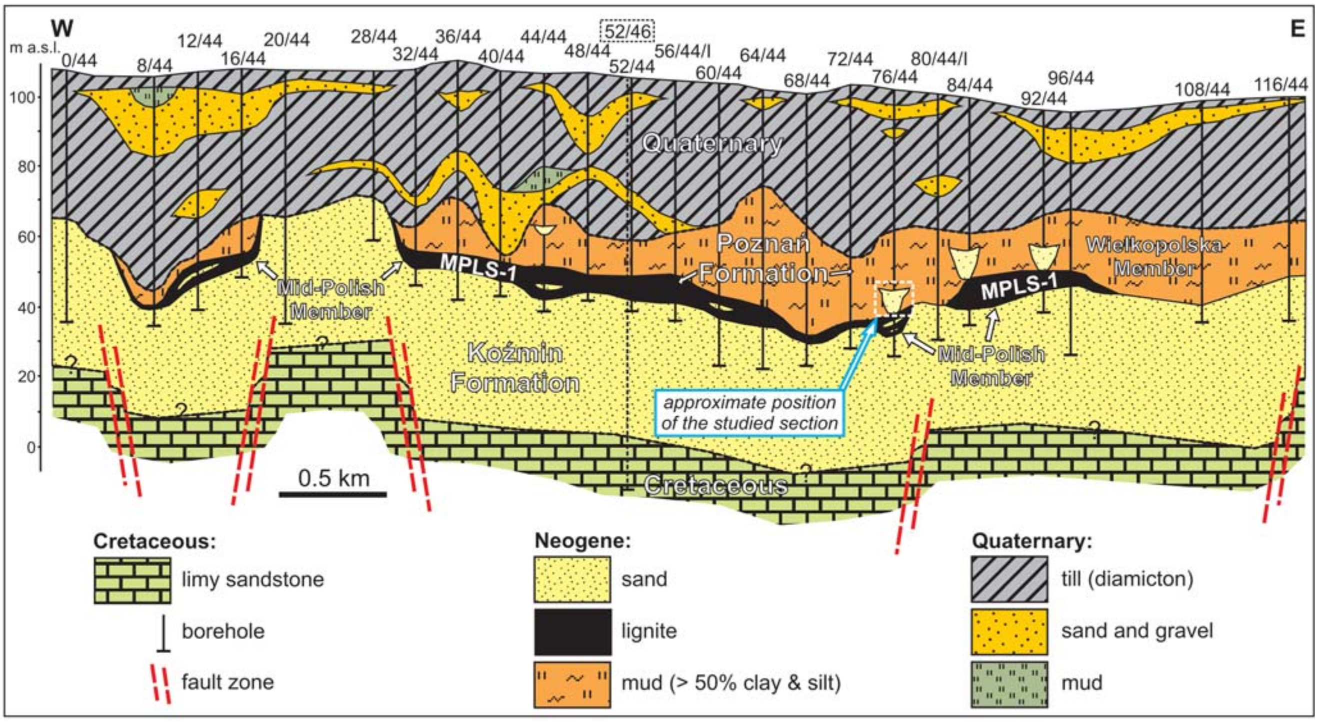

Fig. 2. Geological cross-section through the southern part of the Jóźwin IIB lignite-mine field (slightly modified from Widera, 2014). Note the stratigraphic position of the studied fluvial palaeosystem within the Wielkopolska Member of the Miocene Poznań Formation.

Lithostratigraphy

The Neogene sedimentation in the studied part of the Kleczew Graben commenced with deposition of the earliest to middle Miocene Koźmin Formation (Fig. 2), composed of fluvio-lacustrine sand and silt deposits with lignite intercalations (Widera, 2007). It is overlain by the mid-Miocene to early Pliocene Poznań Formation (Fig. 2), the youngest Neogene lithostratigraphic unit in central Poland (Piwocki and Ziembińska-Tworzydło, 1997). The Poznań Formation is traditionally divided into the lignite-rich lower Grey Clays Member (or Middle-Polish Member, Fig. 2) and the muddy upper Wielkopolska Member (Piwocki and Ziembińska-Tworzydło, 1997; Widera, 2013a). The Middle-Polish Member contains the MPLS-1 lignite seam, mined in the Kazimierz North and Jóźwin IIB opencasts of the Konin Lignite Mine (Fig. 1). The accumulation of peat occurred in low-lying mires in the overbank zone of mid-Miocene fluvial system (Widera, 2016a; Widera *et al.*, 2017). The overlying fine-grained siliciclastic deposits of the Wielkopolska Member (Fig. 2), attributed to an anastomosing river system, are the subject of the present study. Previous studies of this unit included its mineral and geochemical composition (e.g., Wyrwicki, 1975; Wyrwicki and Wiewióra, 1981; Duczmal-Czernikiewicz, 2010, 2013), palaeogeography (e.g., Badura and Przybylski, 2004; Piwocki, 2004) and sedimentology (e.g., Widera, 2012, 2013a; Kowalska, 2016), but with only a limited focus of the fluvial channel-fill deposits.

The Neogene succession is capped by a thick Quaternary cover (Fig. 2). It is composed mainly of glaciogenic deposits, including glacial tills, fluvioglacial sand and gravel and glaciolacustrine mud.

METHODS AND DATA BASE

Observations on fluvial palaeochannels in the Kazimierz North opencast mine, where 25 fluvial palaeochannels have been exposed by mining activity (Widera, 2012, 2013a), are herein supplemented with new observations made in 2013–2015 from the nearby Jóźwin IIB opencast (Fig. 1). Fieldwork was carried out during this period and included mapping of palaeochannels, observations on depositional and deformational sedimentary structures, detailed logging and sediment sampling. The main outcrop section studied (Fig. 3) was up to 6 m high and more than 80 m long in the S–N direction (Fig. 4). A total of 5 sedimentological logs were measured (Fig. 5) and were subsequently improved with details from laboratory grain-size analyses (37 samples of channel-fill and 12 samples of overbank sediments). Conventional sieving technique was used for sediment coarser than 0.1 mm, whereas the grain-size distribution of fine-grained sediment was determined by the areometric method.

The standard Wentworth (1922) grain-size scale, modified from Udden (1914), is used for sediment fractions (Fig. 5), with mud defined as a sediment containing >50 vol.% of clay and silt (Lundegard and Samuels, 1980). The sediment sorting parameter (σ_I) and scale are according to Folk and Ward (1957), based on the phi grain-size scale. Lithofacies are defined according to Harms *et al.* (1975). The letter code for lithofacies (Table 1) is after Miall (1977) and Ghibaudo (1992), and the terminology for sedimentary structures is according to Collinson and Thompson (1982).

Table 1

Letter code for sedimentary lithofacies used in the present article (code for sands is after Miall, 1977; code for finer-grained deposits after Ghibaudo, 1992)

Main code	Lithology
S	sand
T	silt, siltstone
M	clay, claystone
Suffix	**Sedimentary structure**
m	massive
p	planar cross-stratification
t	trough cross-stratification
r	ripple cross-lamination
h	plane-parallel stratification
d	soft-sediment deformation

Palaeochannels were delineated and 31 palaeocurrent measurements collected in the vertical outcrop section (see example in Fig. 5), and the spatial distribution of palaeochannels was tentatively outlined on the basis of a 200×200 m grid of more than 700 boreholes (Fig. 3). The closest 52 boreholes around the main outcrop section were used to map the palaeochannel plan-view pattern in more detail. The width/thickness (W/T) ratio of the palaeochannel bodies was used to classify them according to the terminology of Friend *et al*. (1979) and Friend (1983).

RESULTS

Channel-fill deposits

The example representative palaeochannel studied in detail (Figs 4, 5) is lenticular in cross-section, approximately 80 m wide and 6 m thick, with a W/T ratio of 13.3. Its base is erosional, incised in muddy floodplain deposits, concave upwards and strongly deformed in the southern part, whereas the top is depositional and relatively flat (Fig. 4). In its thickest and most deformed part, the palaeochannel overlies directly the lignite seam MPLS-1 (Fig. 4).

Despite their apparent macroscopic similarity, the channel-fill deposits differ significantly from overbank floodplain deposits. The mean grain size of channel-fill sediment ranges from 0.0007 to 0.30 mm (37 samples), averaging 0.135 mm and indicating fine sand. The sediment is moderately well sorted (σ_I = 0.51 phi) to extremely poorly sorted (σ_I = 9.54 phi). The overbank sediment, in contrast, is much finer-grained, with a mean grain size from 0.0002 to 0.012 mm (12 samples), averaging 0.003 mm and thus indicating mud. The overbank mud is very poorly to extremely poorly sorted, with σ_I in the range of 3.05–8.89 phi (Kowalska, 2016).

Table 2

Channel-fill lithofacies and their associations in the Wielkopolska Member of the Miocene Poznań Formation in the study area (lithofacies code as explained in Table 1)

Lithofacies association	Code	Lithofacies	Description	Occurrence	Interpretation
Lithofacies association 1	Sm	Major lithofacies: massive fine-grained sand	Up to 2.3 m thick; massive structure; slight upward fining; poor to very poor sorting; low content of mud; white to grey in colour; sharp flat base.	All parts of channel-fill.	Hyperconcentrated flow; non-tractional deposition by rapid dumping of sediment from dense turbulent suspension.
	STm	Minor lithofacies: massive silty sand	Rich in mud admixture; mottled structure; brownish-red in colour; gradational base; weakly cemented.	Upper part of channel-fill.	Redistribution of clay and silt particles from the overlying muds due to mining dewatering; en masse deposition of fluid sandy mud by overbank floodwater drained back to channel.
Lithofacies association 2	St	Major lithofacies: trough cross-stratified fine sand	Up to 1.5 m thick, with erosional base; contains mud balls; transport direction to the W or NW.	Deepest/axial part of palaeochannel.	Tractional deposition as 3-D dunes in upper part of lower flow regime; mud balls derived from bank erosion.
	Sd	Minor lithofacies:soft-deformed St	Folds up to 3 m high; small faults with amplitude up to 10 cm.	Lower part of palaeochannel.	Soft-sediment deformation due to compaction of underlying mud and lignite.
Lithofacies association 3	Sp	Major lithofacies: planar cross-stratified fine sand	Up to 0.2 m thick, with flat erosional base; transport direction to the W.	Various parts of channel-fill, but mainly lower part.	Tractional deposition as 2-D dunes in middle part of lower flow regime.
Lithofacies association 4	Sr	Major lithofacies:ripple cross-laminated fine sand	Up to 4 cm thick, with slightly wavy erosional base; often overlying lithofacies Sh and capped by lithofacies Sm.	Various parts of channel-fill, but mainly middle to upper part.	Tractional deposition as small current ripples in the lower part of lower flow regime.
Lithofacies association 5	Sh	Major lithofacies: planar parallel-stratified fine sand	Up to 0.6 m thick, with flat erosional base.	Various parts of channel-fill, but mainly middle to upper part.	Tractional deposition by plane-bed transport (upper flow regime enforced by flow too strong for ripples and too shallow for dunes).
	Sd	Minor lithofacies: soft-deformed Sh	Stratified sediment tilted to >30° by folding (loading convolution); small faults.	Thickest part of channel-fill.	Soft-sediment deformation due to compaction of mud and lignite substrate.

Seven lithofacies have been distinguished in channel-fill deposits and grouped tentatively into five lithofacies associations (Table 2). These are described and interpreted in the ensuing text.

Lithofacies association 1

Description. This lithofacies assemblage consists of massive sand (facies Sm) accompanied by massive silty sand (facies STm) and volumetrically dominates (50 vol.%) in the channel-fill (see logs I–III & V in Fig. 5). Lithofacies Sm shows signs of normal grading and is most common in the lower part of the channel-fill, whereas lithofacies STm dominates in its upper part (see Fig. 5, log I & Fig. 6).

Interpretation. Lithofacies Sm represents non-tractional deposition of mud-bearing fine sand by a rapid dumping of high-density turbulent suspension (Lowe, 1988), which indicates hyperconcentrated flows (Beverage and Culbertson, 1964; Nemec, 2009). Lithofacies STm is considerably richer in mud and represents sand-bearing mudflows, probably in the form of fluidal mud (Baas *et al.*, 2009) derived from floodplain by the drainage of subsiding flood waters back to the channel (Allen and Williams, 1979; Bridge, 2003). The rusty mottling (Figs 6, 7A, 8I) and partial lithification of silty sands are attributed to the oxidization of clay iron compounds and their redistribution by infiltrating water coming from the overlying floodplain muds during dewatering of the underlying lignite seam (MPLS-1) due to mining activity (see the vertical colour banding in Fig. 6). It cannot be precluded that this dewatering process contributed also to the massive structure of these lithofacies and their diffuse bed boundaries.

Lithofacies association 2

Description. This lithofacies association comprises trough cross-stratified fine-grained sand, non-deformed (facies St) or hydroplastically deformed (facies Sd). These lithofacies dominate in the basal part of the channel-fill. Facies St is the most common among non-massive lithofacies (Figs 7, 8). The maximum thicknesses of its individual cross-strata sets exceed 10 cm, with co-set thicknesses reaching 1.5 m. Scattered mud balls are common, ranging in diameter from 0.5 to 5 cm (Fig. 8I, J). The measurements of palaeocurrent direction are between the SW and NW, but mainly towards the WNW (Fig. 5). Lithofacies Sd shows small- to large-scale deformations of the lithofacies St. The first type of synsedimentary deformation are small faults with a displacement amplitude of 0.5–10 cm, and the second type is a bulk tilting of cross-stratified deposit at an angle of >30 towards the east (see Figs 5, 9E, F).

Interpretation. Lithofacies St indicates unidirectional

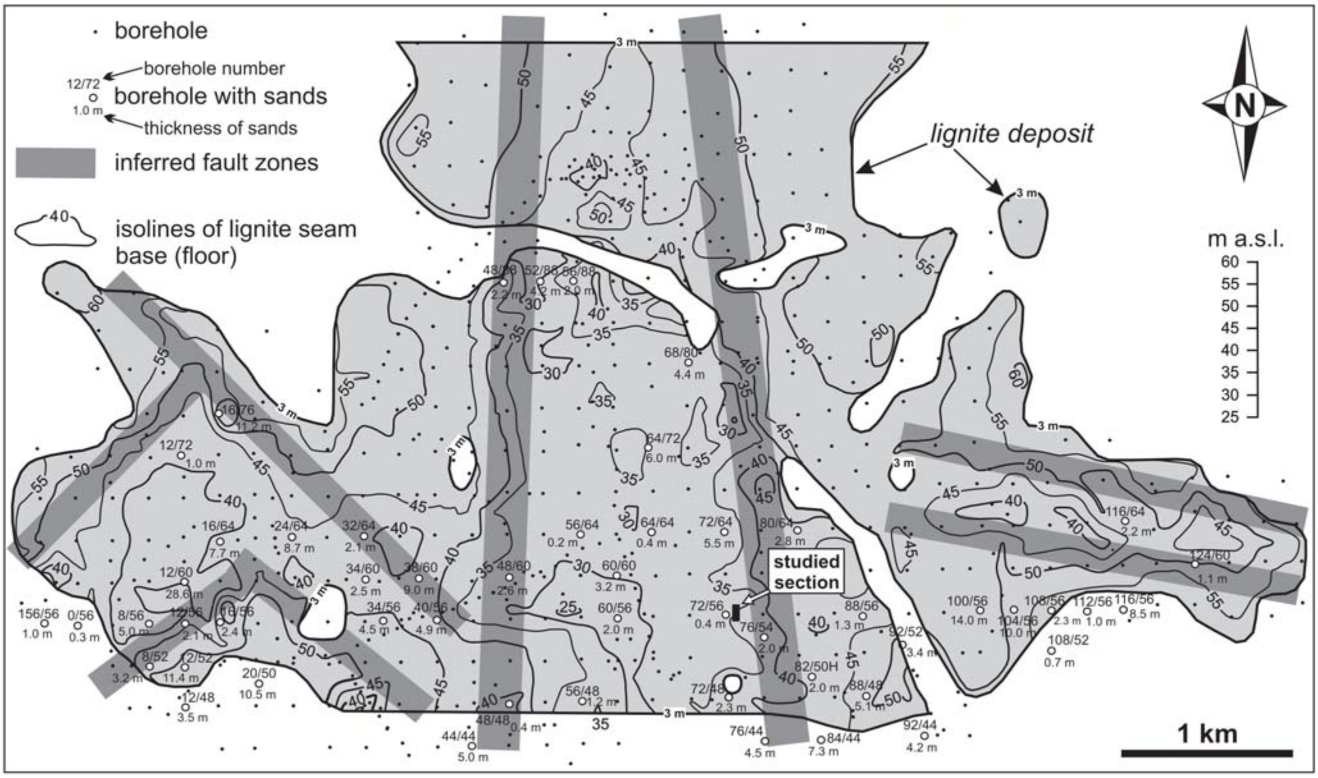

Fig. 3. Map of the base (floor) of the first Mid-Polish lignite seam (MPLS-1) in the study area (compiled from Widera, 1998; Fortuna, 2016; and Kowalska, 2016). Note the inferred fault zones in the lignite-seam substrate, the location of boreholes and the location of the studied outcrop section of a representative palaeochannel.

tractional transport of fine-grained sand in the form of small migrating 3D dunes, linguoid or crescentic, in the upper part of the lower flow regime (Allen, 1965; Harms *et al.*, 1975; Collinson and Thompson, 1982; Bridge, 2003). In comparison to the previous lithofacies association, this lithofacies assemblage indicates a more turbulent and lower-density flow conditions, apparently representing flood-stage peaks. The origin of post-depositional synsedimentary deformation (lithofacies Sd) is discussed separately in a subsequent section of the text.

Lithofacies association 3

Description. This is a mono-facies association composed of the fine-grained, planar cross-stratified sands of lithofacies Sp. Its occurrences within the channel-fill are sporadic and local, typically accompanying lithofacies St or Sh (Fig. 8E, F). The planar cross-strata sets are 6–20 cm thick, flat-based and either isolated or forming co-sets up to 60 cm thick. They range from tabular to wedge-shaped. Cross-strata are tangential, but are nearly angular in the thickest sets.

Interpretation. Lithofacies Sp indicates tractional transport of fine-grained sand in the form of small, long-crested 2D dunes by unidirectional current in the middle part of the lower flow regime (Harms *et al.*, 1975; Collinson and Thompson, 1982; Bridge, 2003). The sparse and strictly local occurrences of lithofacies Sp and its direct spatial association with lithofacies St/Sh suggest deposition at the sites of the flood-flow weakening by its flowline deviation

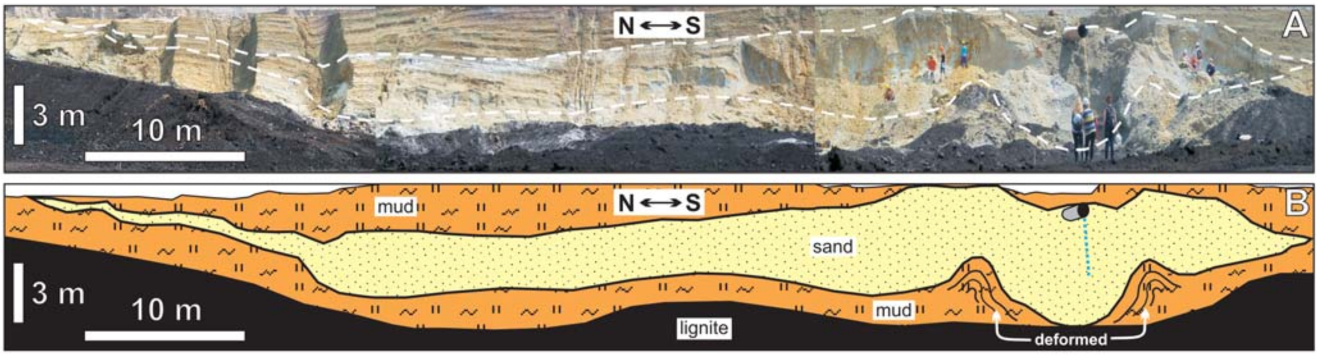

Fig. 4. The representative palaeochannel studied in detail in the Jóźwin IIB lignite opencast. **A.** Broad eastward view of the outcrop section. **B.** The corresponding line-drawing of the palaeochannel, showing its geometry and synsedimentary deformation.

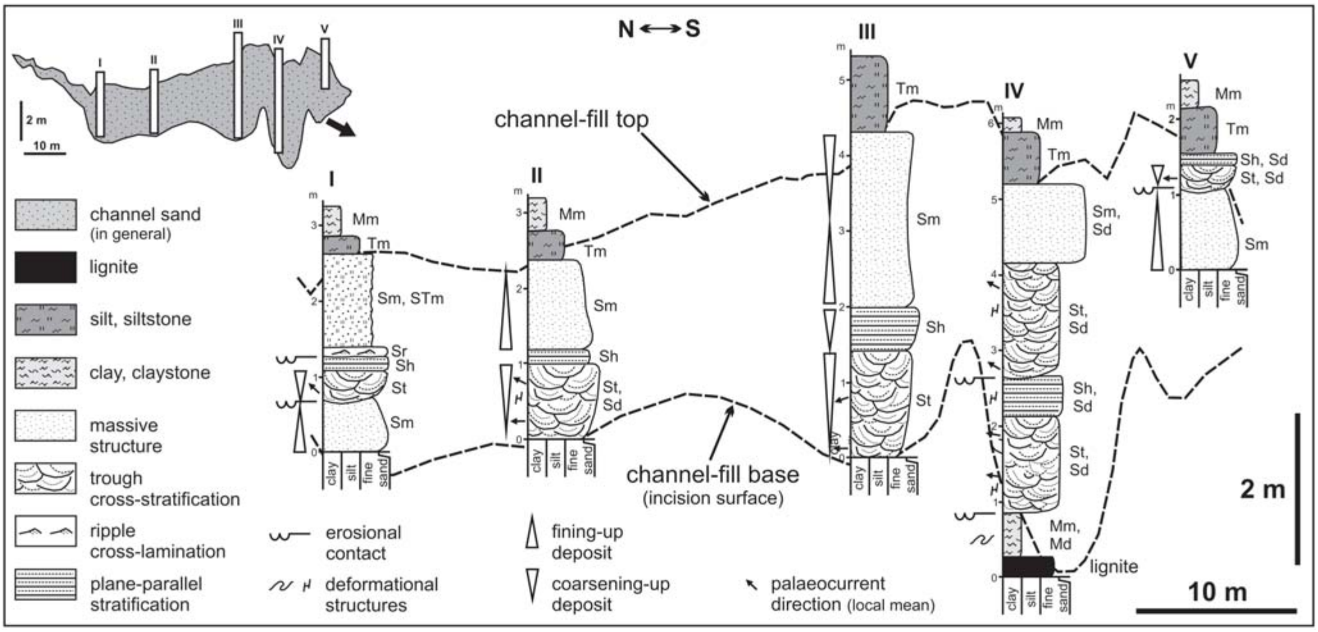

Fig. 5. Detailed sedimentological logs (I–V) of the palaeochannel shown in Fig. 4.

Fig. 6. Close-up view of the sandy channel-fill deposits (Figs 4, 5), showing a dewatering pattern of vertical colour bands (the lighter colour is sand).

due to the channel local widenings or uneven floor morphology. Mud balls were probably derived by erosion of the cohesive channel banks by flood flow (Kowalska, 2016).

Lithofacies association 4

Description. This is another mono-facies association, relatively rare within the channel-fill and composed of the faintly ripple cross-laminated sand of lithofacies Sr (Figs 5, 8G, H). Ripple forms, where recognizable, are 3–4 cm high and up to 10 cm long in longitudinal cross-sections. The inclination of ripple cross-laminae is generally towards the west and their co-sets are little more than 10 cm thick, draped with silt. Lithofacies Sr typically overlies lithofacies Sh (Fig. 8G, H).

Interpretation. Lithofacies Sr indicates tractional transport of fine-grained sand in the form of current ripples by unidirectional current in the lowest part of the lower flow regime (Harms *et al.*, 1975; Collinson and Thompson, 1982; Bridge, 2003). The water-flow velocity was probably lower than 1 m/s (Miall, 1996; Zieliński, 2014). The sparsity of this lithofacies and its vertical association with lithofacies Sh (see next section) suggest a transient deposition on local intra-channel shoals at the river low stages.

Lithofacies association 5

Description. This association comprises the planar parallel-stratified fine-grained sands of lithofacies Sh and the subordinate deformed similar sands of lithofacies Sd. Lithofacies Sh occurs as local units, 20–50 cm thick, scattered in the entire palaeochannel cross-section (Fig. 5). The bases of these units are typically erosional, whereas their tops have most often a depositional contact with the overlying lithofacies Sm, Sr or Tm (Figs 5, 7–9). Lithofacies Sd occurs only in the southern part of the palaeochannel (see logs IV & V in Fig. 5) and shows strongly tilted parallel stratification (Fig. 9E, F).

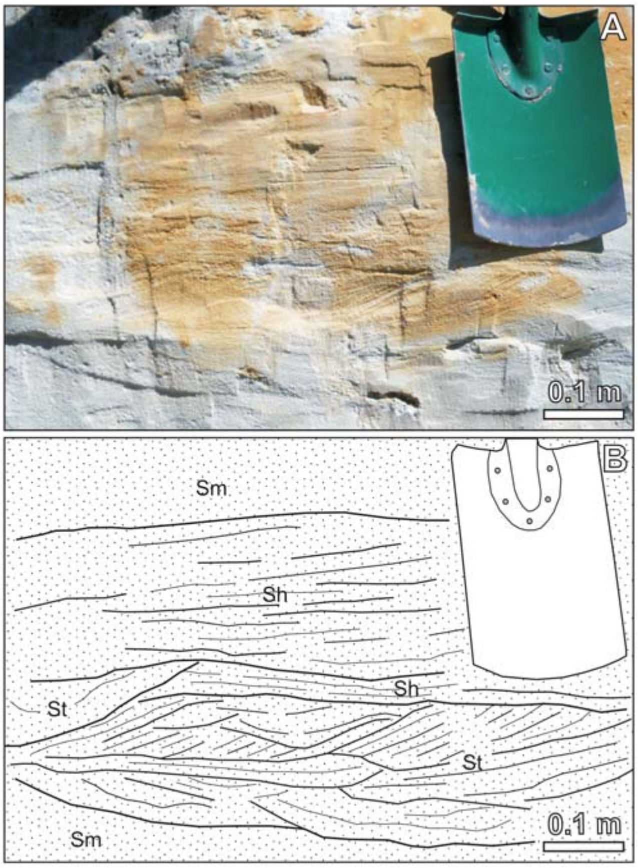

Fig. 7. Photographic details of sedimentological structures from the upper part of the studied palaeochannel. **A.** Relatively well-defined stratification. **B.** The corresponding line-drawings of the structures shown in Fig. 7A.

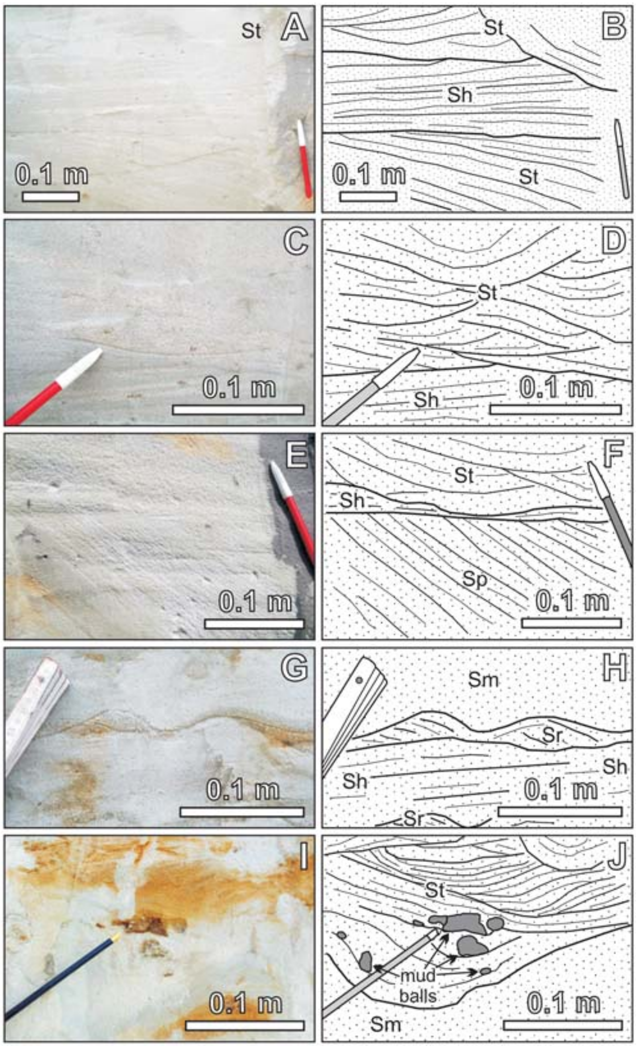

Fig. 8. Photographic details of the channel-fill lithofacies. **A, C, E, G, I.** Various types of stratification. **B, D, F, H, J.** The corresponding line-drawings of the structures shown in Figs 8A, C, G, I. The lithofacies code is as in Table 2 and in the text.

Interpretation. Lithofacies Sh represents tractional plane-bed transport of fine sand in the upper flow regime (Harms *et al.*, 1975; Bridge, 1978; Bridge and Best, 1988). The scattered occurrences of this lithofacies and its vertical association with lithofacies St, Sp and Sr (Figs 5, 7–9) indicates depositions on intra-channel shoals where the low-stage river flow was too powerful to form ripples, but too shallow to produce dunes. This interpretation would mean a flow in the middle to upper part of the lower flow regime, no deeper than ~20 cm (cf. Harms *et al.*, 1975). A weaker tractional flow would form lithofacies Sr, whereas a deeper flow would form lithofacies St or Sp. The flow depth and power in the channel must have then considerably fluctuated. The origin of soft-sediment deformation (lithofacies Sd) is interpreted in the next section.

Soft-sediment deformation

Description. The palaeochannel deposits are locally deformed (Figs 4, 5, 9; Table 2), with two types of deformation recognized: small-scale faulting and larger-scale folding. The faults have a displacement amplitude of less than 1 cm to several centimetres (Fig. 9A, B), but sporadically up to 50 cm at the top of the palaeochannel body (Fig. 9C, D). Fold features occur in the basal part of the palaeochannel, in the southern segment of the outcrop section (Figs 4, 5), where they are clearly related to the loading substrate deformation. The channel-fill deposits involved are the primary lithofacies St and Sh, turned by deformation into lithofacies Sd, and their greatest tilting (30–50°) is towards the east (Fig. 9E, F).

Interpretation. The deformation of channel-fill deposits is attributed to the differential compaction of their mud and peat substrate under the spatially-uneven load of the palaeochannel body. While folding was limited to the palaeochannel basal part and directly associated with the peat substrate. The vertical displacements by faulting had reached their cumulative expression at the top of the palaeochannel body in the form of local higher-amplitude faults. The compaction of primary peat is known to have caused deformation of the overlying deposits in virtually all European lignite-bearing areas (Widera, 2016b), and its impact on clastic deposits has been well-recognized in the Jóźwin IIB opencast area (Widera, 2013b, 2014; Fortuna, 2016; Kowalska, 2016).

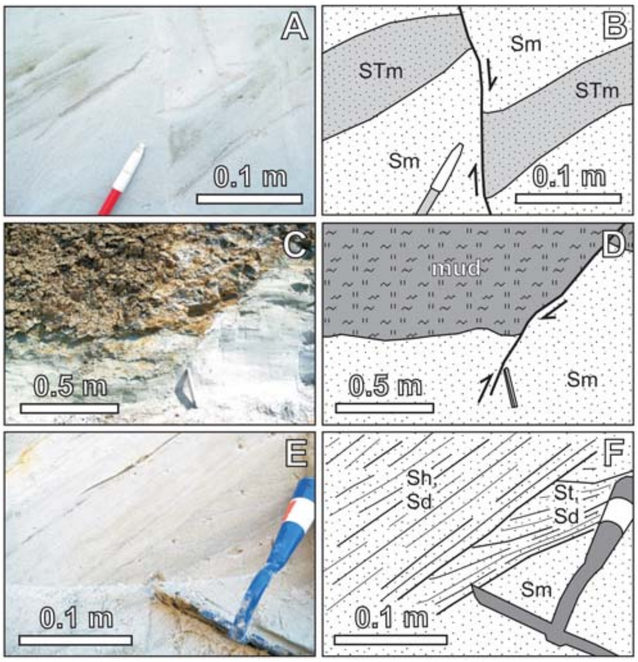

Fig. 9. Photographic details of deformational structures within the palaeochannel deposits. **A, B.** Normal fault with throw of 10 cm in the middle part of the channel. **C, D.** Normal fault with throw of 50 cm at the top of the channel. **E, F.** A steep tilting of originally horizontal strata. The lithofacies code is as in Table 2 and in the text.

Palaeochannel pattern

The plan-view pattern of palaeochannels in the lowest part of the Wielkopolska Member of Poznań Formation has been mapped in the southern to central area of the Pątnów lignite field (Fig. 3), where the Jóźwin IIB opencast operates and where 52 of more than 700 boreholes revealed sandbodies. The whole area of palaeochannel reconstruction is ~7.3 km long (E–W) and ~3 km wide (N–S). The reconstruction (Fig. 10) shows a multi-channel river system with short tributaries and anabranching longer main channels – one of which has been analysed in detail as a representative example by the present sedimentological study of channel-fill deposits (Fig. 5). The study indicates stable channels a few metres deep and a few tens of metres wide, with a W/T ratio around 13 and with little or no evidence of lateral migration. The main palaeochannels show apparently an infilling by vertical accretion and are separated by large islands in the form of cut-off floodplain areas, as is generally characteristic of anastomosing river systems (Smith and Smith, 1980; Nanson and Knighton, 1996). The west-directed river drainage system was distinctly tributive in its eastern upper reaches and turning into distributive towards the west, with short local tributaries and the main channels directed mainly to the north (Fig. 10; terminology after Weissmann *et al.*, 2010).

The river system in the Jóźwin IIB opencast area in northernmost Kleczew Graben (Fig. 1) was thus apparently draining the eastern flank of the graben and was broadly

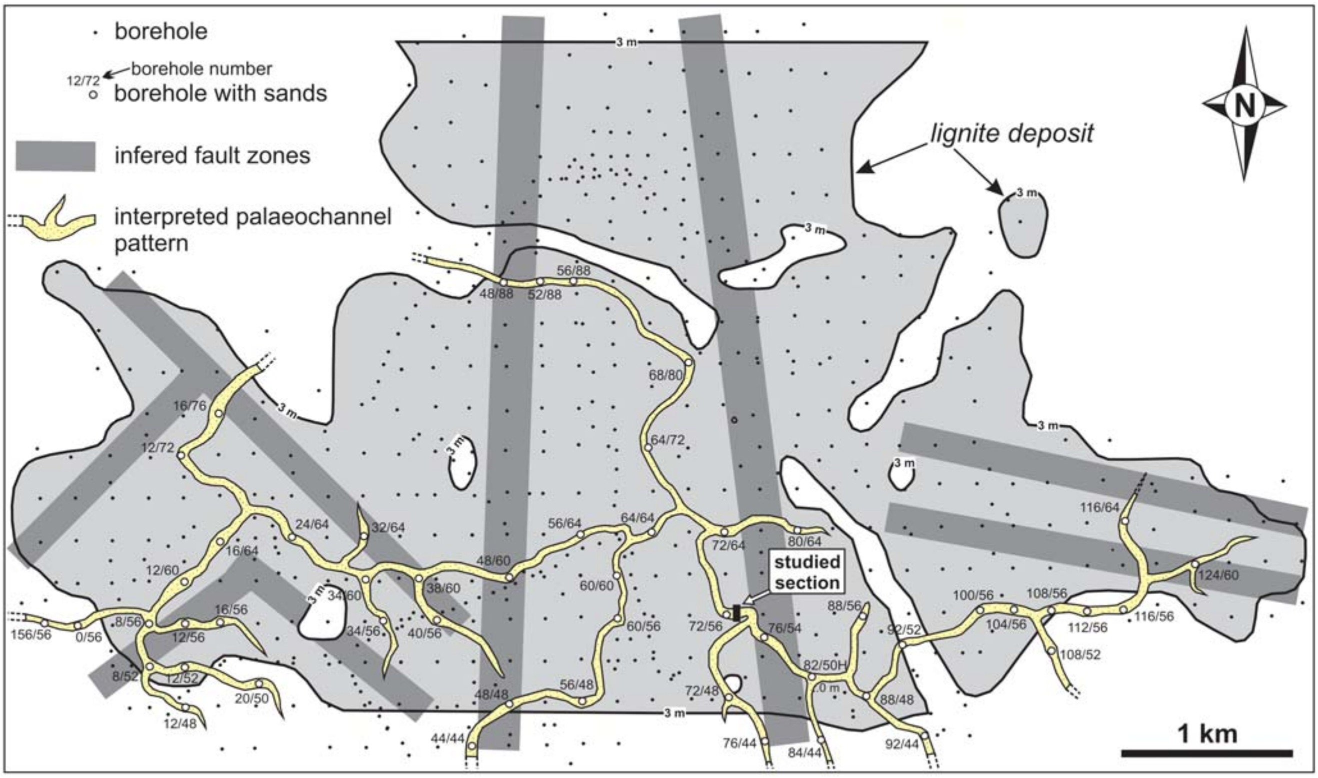

Fig. 10. Plan-view reconstruction of the fluvial palaeochannel pattern in the Wielkopolska Member of the Miocene Poznań Formation (compiled from Widera, 1998; Fortuna, 2016; and Kowalska, 2016). Note the location of the representative palaeochannel outcrop section analysed in detail in the present study.

Fig. 11. Examples of modern anastomosing rivers with cohesive vegetated banks, carrying muddy suspended and a mixed sand-mud load at high water stages. The aerial photographs (from Google Earth). **A.** The Marmaris River in SW Turkey. **B.** The Mississippi River near Keithburg in Illinois, USA. **C.** The Six Mile Creek in Alaska, USA.

transverse to the graben margin, but with the main distributaries directed parallel the graben axis, mainly northwards. Some of the river palaeochannels, or at least their major segments, appear to be parallel to the inferred bedrock faults (Fig. 10). This evidence suggests that some of the bedrock faults, or rather their active segments, had an impact on the direction of the channel network (Fig. 10).

This reconstruction of river palaeosystem is hypothetical and should be considered with caution, as it bears many uncertainties. For example, the flow direction of the main channel in the south-central part of the study area (Fig. 10) is uncertain, as it could be to the south or to the north. Although the grid of more than 700 exploration wells is relatively dense, it might have not necessarily revealed all the coeval palaeochannels. Some of the wells revealed more than one sandbodies, apparently indicating local channel avulsions, but the reconstruction at this level of detail has not been attempted and is simplified.

DISCUSSION

The present study, with a sedimentological focus on channel-fill deposits, is a significant contribution to the previous preliminary studies of the same fluvial palaeosystem in the area of the Konin Lignite Mine in central Poland (Widera, 2012, 2013a). The palaeochannel W/T ratio <15 indicates ribbon-shaped river conduits (Friend *et al.*, 1979; Friend, 1983; Gibling, 2006), and the study postulates an anastomosing system of simple cut-and-fill river channels dominated by vertical accretion, with many local avulsions, but with little or no lateral migration. Cohesive channel banks, stabilized additionally by vegetation, are considered to have been a crucial factor for the development of this anastomosing river system (cf. McCarthy *et al.*, 1991; Gibling *et al.*, 1998; Gradziński *et al.*, 2000; Gross *et al.*, 2011; Widera, 2016a; Widera *et al.*, 2017).

The existing facies models for anastomosing rivers, in their graphical portrayal, have inadvertently implied that the channel-fill of such rivers – in contrast to the surrounding muddy floodplain deposits – is distinctively coarser-grained, sandy (Miall, 1997, 2006) or perhaps even gravelly (Smith and Smith, 1980). The channel-fill in the present case is fine sandy and macroscopically differs from the adjacent floodplain deposits; their textural difference is revealed clearly also by laboratory grain-size analysis. Lithofacies analysis indicates that the river discharge in the present apparently fluctuated. The river channel was filled with stratified, mud-bearing fine-grained sand by tractional turbulent low-density flow during the highest and lowest water stages and with a massive (non-stratified) sand or muddy sand by a high-density flow during the rising and falling stages. The river flow at its rising stage was heavily charged with mud by bank erosion, in an attempt to widen the channel, and was similarly recharged with mud at the falling stage by the draining of mud-laden overbank floodwater back to the channel. The present case is not an exception, as there are many modern anastomosing river systems that carry daily a by-passing muddy suspension load and a mixed sand-mud load at their high water stages (Fig. 11).

Another issue worth further comment is the relationship of the palaeochannel system to the inferred faults, as only some of their segments appear to be paralleled by channels (Figs. 10). These bedrock faults were active mainly during the deposition of the thick underlying peat, which resulted in its lateral thickness variation and subsequent differential compaction (Widera, 1998, 2013b; Fortuna, 2016). It was probably this latter factor and the bulk gentle topographic gradient of the graben flank, rather than fault activity as such, that controlled the direction of river channels (cf. Schumm *et al.*, 2000). Substrate compaction caused also deformation of the palaeochannel sandbodies (Figs 4, 9), although some local syn- and post-depositional fault activity cannot be precluded (Widera, 2013b, 2016b).

The fluvial system of the Wielkopolska Member of the Poznań Formation developed after the accumulation of MPLS-1 at the last peak of the Mid-Miocene Climatic Optimum (MMCO) ~15 Ma ago (Kasiński and Słodkowska, 2016; Słodkowska and Kasiński, 2016). The end of the MMCO in strict terms refers to the glaciations of eastern Antarctica, after which the global climate became cooler and drier (e.g., Zachos *et al.*, 2001; Bruch *et al.*, 2007). However, this climatic change in central Europe occurred only between 14.0 and 13.5 Ma (Böhme, 2003), which would mean that the onset of mid-Miocene alluvial sedimentation in the study area was probably not earlier than around 13.5 Ma. Palaeofloristic investigations in Germany and Poland have indeed indicated that the seasonality of climate increased gradually in the late mid-Miocene to Pliocene (e.g., Utescher *et al.*, 2000; Kasiński and Słodkowska, 2016; Słodkowska and Kasiński, 2016).

A more controversial and still unresolved issue is the paleogeography of the Neogene fluvial drainage in central Poland. Even the actual direction of the river drainage was unknown and remained to be disputed. It was been hypothesized by some researchers that the rivers flowed northwards to the so-called Baltic River, or Eridanos, and further westwards to the North Sea (Badura and Przybylski 2004; Piwocki *et al.*, 2004). However, it has been pointed out by Widera (2012) that there is no evidence of a tributary drainage to the hypothetical Baltic palaeoriver in the upper Neogene of Poland. An alternative hypothesis, pursued in the present study, is that the rivers in central Poland flowed to one or more endorheic 'terminal floodplain' basins with peat-forming mires and a centripetal drainage pattern (Czapowski and Kasiński, 2002; Widera, 2013a). The development of an endorheic basin, or basins, in central Poland was likely facilitated by the Neogene regional tectonic subsidence and formation of extensional grabens. Modern analogues may include the anastomosing river system of the Okavango Delta, Botswana, which drains its waters to a vast dry plateau with extensive mires and shallow ephemeral lakes (e.g., McCarthy *et al.*, 1991); or the river systems of the Channel Country in outback Australia, where the waters are drained to a relatively small lake (e.g., Rust, 1981; Gibling *et al.*, 1998). Endorheic fluvial drainages are common in nature (Nichols, 2012), and there is no compelling evidence to postulate a hypothetical drainage route for the late Miocene Polish rivers to the distant North Sea basin.

CONCLUSIONS

1. The late mid-Miocene fluvial drainage system in the Jóźwin IIB lignite opencast area of the Kleczew Graben, central Poland, has been reconstructed and interpreted as a network of anastomosing, ribbon-shaped suspended-load river channels with a width/depth ratio around 13.
2. The river drainage system, extending across the eastern flank of the graben, was tributive in its eastern upper reaches, but was increasingly distributive and northwards directed in its lower reaches near the graben axis.
3. Lithofacies analysis of a representative palaeochannel indicates that the river discharge had fluctuated and that the river channels were filled with mud-bearing stratified fine-grained sand by low-density tractional turbulent flow during the high and low water stages and with a massive sand or muddy sa nd by a high-density flow during the rising and falling stages.
4. The river flow at its rising stages was probably charged with mud by bank erosion, in an attempt of channel widening, and was similarly recharged with mud at the falling stages by the re-draining of mud-laden overbank floodwaters back to the channel.
5. The spatial directions of fluvial channels and the deformation channel-fill sandbodies were controlled by the graben topography and differential soft-substrate compaction, with possible local influence of bedrock extensional faults.
6. The fluvial system is thought to have drained to a nearby endorheic 'terminal' basin to the north, rather than into the hypothetical Baltic River and further westwards to the distant North Sea basin, as postulated by some other authors.
7. The present case study contributes to the known spectrum of anastomosing river systems as a sand- to mud-dominated end-member characterized hydraulically by a daily bypass of mud suspension and the main deposition limited to the highest and lowest water stages.

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