

Sedimentary record of the late Neogene avulsion process at the Tomisławice lignite opencast mine in central Poland – a new hypothesis

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ABSTRACT:

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Around the town of Konin in central Poland, lignite deposits are exploited in opencast mines. Surface mining has enabled the discovery of many sediments and structures, both tectonic and sedimentary. However, the greatest research challenge appeared in the Tomisławice lignite opencast mine in 2022, when a so-called lignite-free zone was found during mining activity. Initially, due to limited data, its genesis was associated with syn- or post-depositional tectonics and peat-to-lignite compaction. In 2024, two deeper boreholes were drilled in which no lignite and tectonic denivelations of the Mesozoic bedrock were detected in the mentioned zone, meaning that the above hypotheses were disproved. Therefore, in this paper a new hypothesis was proposed for the creation of the aforementioned lignite-free zone crossing the Tomisławice lignite deposit – palaeochannel I – and as well as marking its NE border – palaeochannel II. The inclusion of data from a larger number of boreholes and the reinterpretation of the depositional architecture of the fills of the lignite-free zones indicate the palaeochannel avulsion of the late Neogene fluvial system. The palaeochannels are filled with fine-grained and multi-coloured Poznań Clays. Unfortunately, they are mainly massive, and the poorly visible sedimentary structures are masked by post-depositional weathering processes. The palaeochannels were incised into the underlying lignite seam and sub-lignite sands during the initial stages of major floods and then filled by the accretion of heterolithics, mainly from suspension, during subsequent flood episodes. Rather than a tectonic/compactional origin, data are consistent with palaeochannel avulsion. Finally, the current paper is the first in Poland devoted exclusively to the effects of avulsion in the rock record.

Key words: Overbank erosion; Overbank sedimentation; Abandoned palaeochannel fill; Fluvial system; Poznań Clays.

INTRODUCTION

Lignite opencast mines that have a large area and are several dozen to several hundred metres deep are a valuable source of various geological data, including primarily sedimentological information. In the case

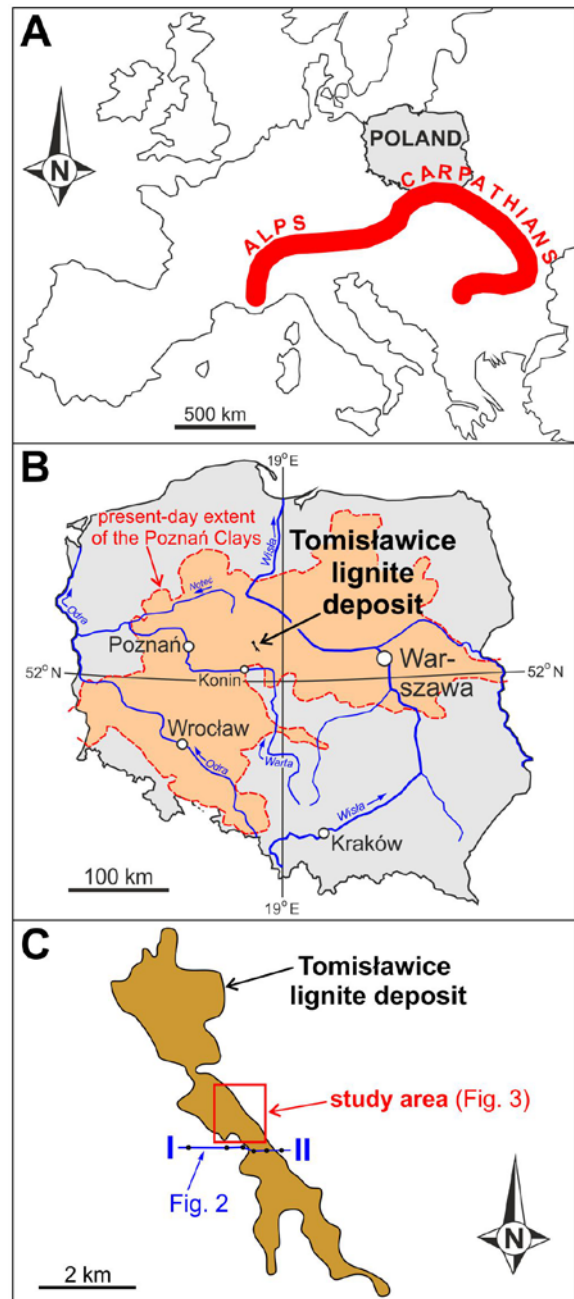
of Poland, the largest number of sediments and sedimentary structures, often unique on a global scale, have been described from lignite opencast mines in the Konin Basin (Wachocki *et al.* 2025). The most important of them are the following: 1) single crevasse splays and their complexes within the exploited



lignite seam (e.g., Widera 2016, 2017, 2020; Chomiak 2020; Widera *et al.* 2022, 2023, 2024a; Działara *et al.* 2023; Chomiak *et al.* 2024); 2) numerous fluvial palaeochannels from sandy, through sandy-muddy, to muddy within the mud-dominated Poznań Clays, resting on the roof of the mined lignite seam (e.g., Widera 2013a; Maciaszek *et al.* 2019; Widera *et al.* 2019, 2021b; Zieliński and Widera 2020; Kędzior *et al.* 2021); and 3) overbank (extra-channel), multi-coloured sediments of the Poznań Clays, containing thin layers of lignite and palaeosol horizons (e.g., Maciaszek *et al.* 2020; Widera *et al.* 2021b; Klęsk *et al.* 2023; Wachocki *et al.* 2025).

After more than 80 years, lignite mining in the Konin region (central Poland) will end in 2026 or 2027 (Frydrychowicz *et al.* 2024; Kasztelewicz *et al.* 2025). Currently (September 2025), lignite is exploited only in the Tomisławice opencast mine (Text-fig. 1). In terms of the above-mentioned geological peculiarities, when it seemed that nothing worthy of study would be discovered, the so-called lignite-free zone appeared in 2022. It should be added here that this zone was not detected during the exploration of the Tomisławice lignite deposit – the distance between the boreholes being too large (Kozula 1999, 2001). Taking into consideration previous field observations and additional shallow boreholes that did not pierce the fill of the lignite-free zone (Wachocki *et al.* 2024), two hypotheses concerning its genesis were proposed. The first one considered syn-depositional tectonic subsidence and the subsequent uneven compaction of peat/lignite, while the second one took into account only post-depositional tectonic subsidence. In both of these hypotheses, it was assumed that lignite occurs in the lignite-free zone, but at a lower (by at least several metres) hypsometric position (Widera *et al.* 2024b).

New data from boreholes drilled in 2024 and located in the area of the lignite-free zone have disproved the above hypotheses. Therefore, the authors of this study have attempted to explain the formation of this zone mainly as a result of Neogene river avulsion, which is what all the available data indicated. This process led to bifurcation, or the abandonment of the parent channel and the formation of a new river channel, which is particularly common in the unconfined environments of meandering and anastomosing (anabranching) rivers (e.g., Allen 1978; Stanistreet *et al.* 1993; Morozova and Smith 2000; Tooth 2000; Farrell 2001; Makaske 2001; Makaske *et al.* 2002; Bridge 2003; Gradziński *et al.* 2003; Miall 2006; North *et al.* 2007; Page *et al.* 2009; Boggs 2012; Ghinassi *et al.* 2014; Zieliński 2014; Kemp and Pietsch 2024).



Text-fig. 1. Location map. A – Poland against the map of Europe. B – Tomisławice lignite deposit in central Poland against the present-day extent of the Poznań Clays (modified after Widera and Klęsk 2025). C – study area with a cross-section I-II shown in Text-fig. 2.

The necessary conditions (i.e. autogenic and allogenic processes) for river avulsion have been presented in many publications (e.g., Smith *et al.* 1989; Slingerland and Smith 1998, 2004; Stouthamer and Berendsen 2000, 2007; Aslan *et al.* 2005; Rajchl and

Uličný 2005; Gouw 2007; Davies-Vollum and Smith 2008; van Asselen *et al.* 2009; North and Davidson 2012; Kleinhans *et al.* 2013; Hajek and Edmonds 2014; Chadwick *et al.* 2022; Donselaar *et al.* 2022; Karamitopoulos *et al.* 2022; Valenza *et al.* 2022; McEwan *et al.* 2023; Li *et al.* 2024). Most of the above studies focus on modern fluvial environments, while examples of avulsion in the rock record are relatively few (e.g., Kraus and Wells 1999; Mohrig *et al.* 2000; Kraus and Davies-Vollum 2004; Jones and Hajek 2007; Speed *et al.* 2024), including coal/lignite-bearing deposits (e.g., Flores and Hanley 1984; Michaelsen *et al.* 2000; Rajchl and Uličný 2005; van Tooreneburg *et al.* 2018; Novotný and Mach 2024). In addition, van Tooreneburg *et al.* (2016) provided reasons why avulsion deposits in ancient fluvial sequences are only sporadically investigated.

The major goal of the current paper is to explain the origin of the lignite-free zones (i.e. palaeochannels) in the Tomisławice lignite deposit. This will be achieved by 1) characterising the lithology of the studied sediments and their depositional architecture; 2) explaining the deformation of the roof parts of the exploited lignite seam containing siliciclastic beds; 3) proposing a conceptual model showing the development of the palaeochannels; 4) discussing the avulsion process in terms of the climatic and tectonic conditions of the accumulation of the upper Neogene Poznań Clays in central Poland; and 5) depicting global analogues of the studied mud-filled palaeochannels.

GEOLOGICAL SETTING

The geology in the Konin Basin is particularly well known thanks to opencast lignite mining (Text-fig. 1). During the Paleogene and Neogene, the research territory covered the eastern part of the Northwest European Basin, extending from the present-day Netherlands to Belarus (Vinken 1988). In turn, according to the tectonic division of northern Europe, the study area belongs to the eastern part of the European Palaeozoic Platform (e.g., Karnkowski 1980; Ziegler and Dèzes, 2007). The most significant climatic and sudden changes in sedimentary environments in central Poland, as well as in the entire European Lowlands, took place in the Neogene, and mostly in the Miocene. They were a consequence of tectonic and climatic changes in the area of the Alpine–Carpathian orogen and its foreland (e.g., Kasiński and Słodkowska 2016; Kováč *et al.* 2017; Widera *et al.* 2021a, b). At that time, depositional and erosional processes took place, which are analysed in

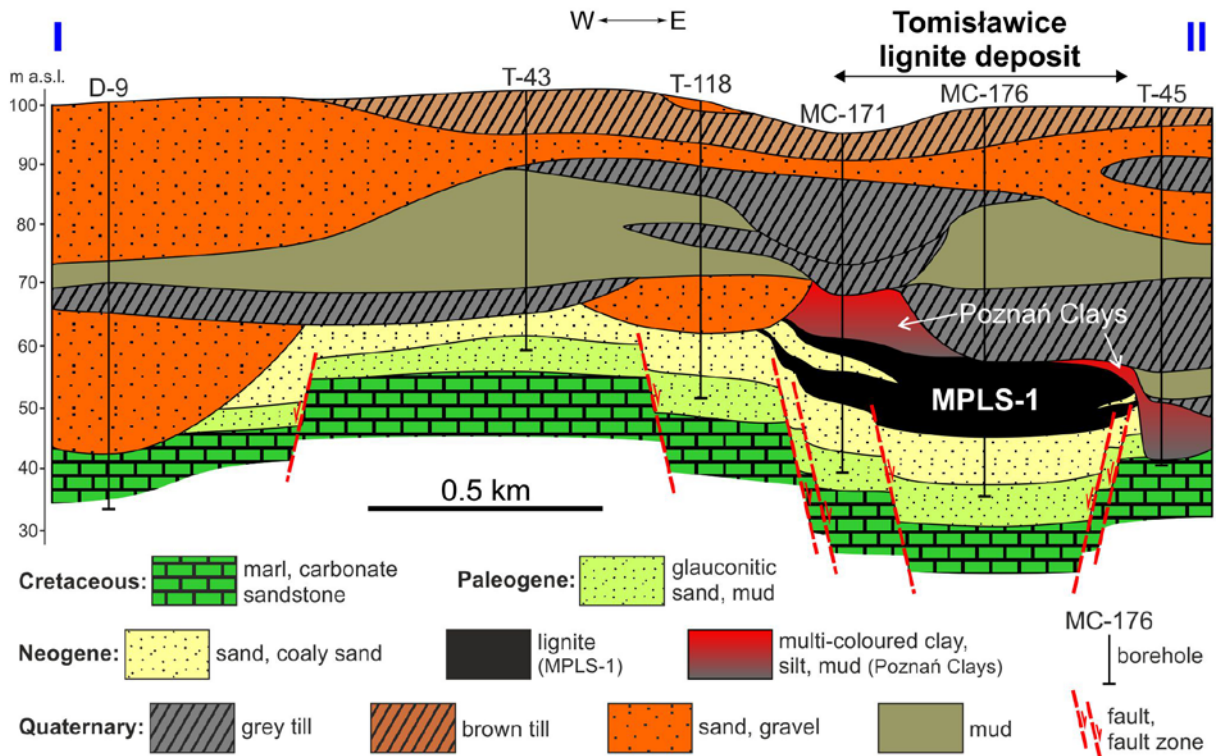
detail in this study from the area of the Tomisławice lignite deposit.

The Tomisławice lignite opencast mine is geologically representative of the surroundings of the town of Konin in central Poland. This mine operates on a lignite deposit of the same name. The Tomisławice lignite deposit fills a relatively shallow tectonic graben which has a depth of up to 10–20 m and a NNW–SSE orientation (Text-fig. 1). Tectonically, this graben covers the most NE part of the Konin Elevation (Widera 2022), which includes the central segment of the Szczecin–Miechów Synclinorium (Żelaźniewicz *et al.* 2011).

The uppermost Mesozoic is composed mainly of Late Cretaceous marls and carbonate sandstones (Dadlez *et al.* 2000). In the study area, these rocks are densely fractured and faulted, although the vertical throw of the individual faults/fault zones does not exceed 10 m between boreholes (Text-fig. 2). The Cenozoic succession is not complete because it contains long-term stratigraphic gaps. The two older ones (Paleogene age) are the result of regional tectonic uplift, and the third (late Neogene–Early Pleistocene age) was created by the erosion of the Scandinavian ice sheets. Thus, the Rupelian (early Oligocene age) marine glauconitic sands and muds are the only Paleogene sediments in the study area (Text-fig. 2; Chomiak 2020; Wachocki *et al.* 2024).

The Neogene sediments are the most important in this paper because they contain the first Mid-Polish lignite seam (MPLS-1), also called the Konin lignite seam (Sadowska and Giża 1991; Kasiński and Słodkowska 2024). Lithostratigraphically, they include two formations in the area of the Tomisławice lignite deposit. The lower one, i.e. the Koźmin Formation (Lower–Middle Miocene), is composed of fluvial sands and coaly sands with thin (up to 1 m thick) lignite interbeddings. On the contrary, the upper one, i.e. the Poznań Formation, is traditionally divided into the Grey Clay and Wielkopolska members (Piwocki and Ziemińska-Tworzydło 1997; Widera 2007, 2021; Widera and Klęsk 2025).

The Grey Clay Member consists predominantly of the above-mentioned lignite seam (MPLS-1); it also contains siliciclastic interbeddings (Text-fig. 2). In the Tomisławice lignite deposit, MPLS-1 is up to 11.8 m thick (6.9 m on average), while the interlignite sand lenses are up to 5.3 m thick (Chomiak 2020; Dziemara *et al.* 2023, Widera *et al.* 2022, 2023, 2024a; Chomiak *et al.* 2024); additionally, a vast clay layer is only up to 0.8 m thick (Chomiak *et al.* 2020). On the contrary, the Wielkopolska Member comprises multi-coloured clays, silts and muds (Klęsk *et al.* 2022, 2023), which are roughly called the Poznań Clays (Piwocki



Text-fig. 2. Geological cross-section. A–B through the Tomislawice lignite deposit depicting the stratigraphy and lithology of the Cenozoic sediments (based on borehole data obtained from the Konin Lignite Mine; modified after Widera *et al.* 2024a). Note the low hypsometric position of the multi-coloured, fine-grained Neogene sediments (Poznań Clays) in the borehole T-45; for location of the cross-section I–II see Text-fig. 1C; MPLS-1 – the first Mid-Polish lignite seam.

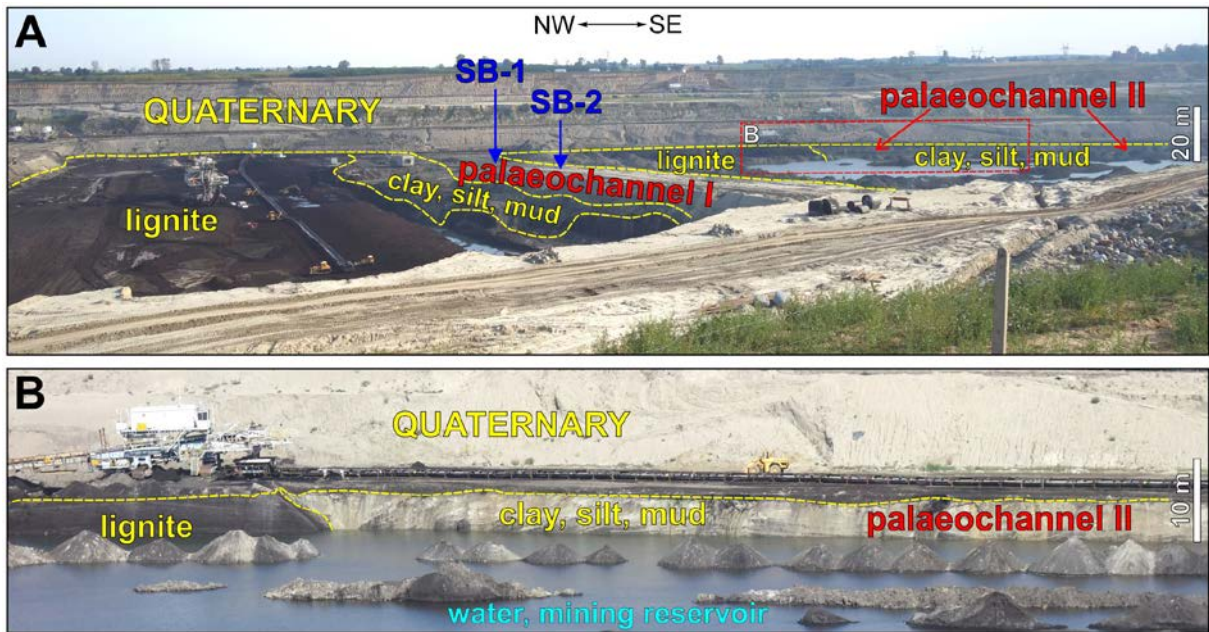
and Ziemińska-Tworzydło 1997; Widera and Klęsk 2025). These fine-grained sediments are preserved residually and are often glaciotectonically and compactionally deformed, as well as partially removed by post-depositional erosion (Text-fig. 2).

The Neogene is overlain by the Quaternary succession, which is 35–60 m thick in the study area. This thickness variation is caused primarily by the erosion of Pleistocene ice sheets and their meltwaters. The sediments of this age are glaciogenic tills, sands and gravels, and muds (Text-fig. 2). In contrast to the Pleistocene, the Holocene is characterised by a thickness of <1–1.5 m and includes a layer of soil and only locally peat and gyttja or sand and mud of periodic surface streams (Kozula 2001; Widera 2017, 2020; Wachocki *et al.* 2024).

MATERIAL AND METHODS

This study comprised field observations and borehole data obtained from the archives of the Konin Lignite Mine. Fieldwork was carried out in 2022–2025

during several campaigns at the Tomislawice lignite opencast mine. In general, the observations of the examined Neogene sediments were conducted in the area covering the central part of the Tomislawice lignite deposit (see Text-fig. 1C). The archival materials include both mine maps and descriptions of borehole profiles, containing lithology, thickness and elevation data (in m a.s.l.) of subsequent lithostratigraphic units. Some of the deepest boreholes (up to 80 m) reach the Cretaceous bedrock, while others (50–70 m deep) end in the Neogene or Quaternary but always pierce MPLS-1 if it is present (cf. Text-figs 2 and 3). This information comes from geological documentation which was created about a quarter of a century ago in order to estimate the resources of the Tomislawice lignite deposit (Kozula 1999, 2001). On the contrary, the majority of the shallow boreholes (up to 20 m deep) were drilled from the overburden levels between December 2022 and March 2023 to determine the extent of the so-called lignite-free zone. However, two shallow boreholes, SB-1 and SB-2 (both 18.0 m deep), drilled in July 2024 (cf. Text-figs 3–5), were of key importance for the current research. It should



Text-fig. 4. Broad view of the examined palaeochannels in the Tomislawice lignite opencast mine. A – eastward view from the ground surface. B – the palaeochannel II sediments exposed in the lowest part of the eastern wall of the Tomislawice opencast mine; for location where the photos were taken see Text-fig. 3.

deep. Simply, they all end in Cretaceous bedrock or Paleogene marine sediments. These features of cross-section I–II allow the presentation of the stratigraphic architecture of the successive lithological units (Text-fig. 2). On the other hand, the numerous above-mentioned boreholes, both deep and shallow, were used to construct four simplified geological cross-sections. They were routed to show the low hypsometric position of the Poznań Clays in the lignite-free zone – palaeochannel I – and along the NE margin of the Tomislawice lignite deposit – palaeochannel II (cf. Text-figs 3–5). Finally, Figure 3 marks the places from which the photographs (Text-figs 4, 6–8) included in this paper were taken.

The Poznań Clays examined in detail in this study

Code	Granulometry (texture)
S ¹	sand
T ²	silt
Y ³	clay
M ³	mud
Code	Sedimentary structure
m ¹	massive
h ¹	horizontal lamination

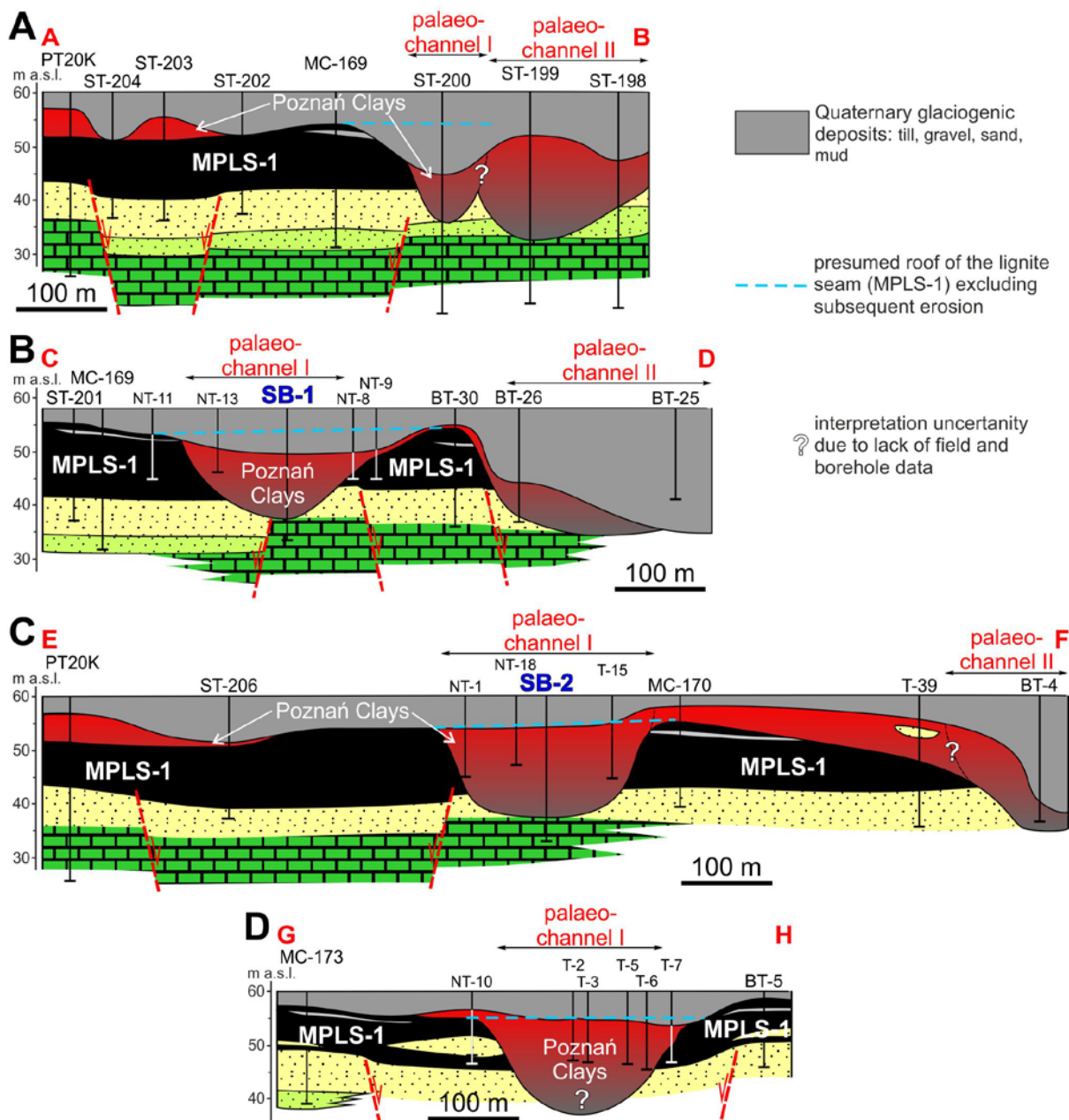
Table 1. Facies codification used in this paper (codes modified after Miall 1977¹, Ghibaudo 1992², Widera *et al.* 2019³). Etymology of the facies code is in bold.

are fine-grained and poor in sedimentary structures, i.e. massive and multi-coloured. The standard classification of fine-grained siliciclastics (clay, silt, sand) after Wentworth (1922) is applied below. In the case a mixture of clay-silt-sand fractions, the term mud is used as defined by Shepard (1954). On simplified sedimentary logs, the facies codification after Miall (1977) is applied, with later additions by Ghibaudo (1992) and Widera *et al.* (2019) (Table 1). It should be added here that the scarcity of cross-stratification at various scales in the examined sediments did not allow measurements of the palaeoflow directions.

RESULTS

General characteristics of the lignite-free zones

Palaeochannel I. The first to be identified and mapped was the lignite-free zone, referred to in this study as palaeochannel I, which crossed the Tomislawice deposit from south to north. It was over 500 m long and 150–200 m wide (Text-figs 3, 4). The lack of lignite (ca. 0.9 million tonnes) in this zone, not confirmed in previous geological documentation, was a surprise and a problem for the Konin Lignite Mine. Hence, there was great interest in this area (palaeochannel I) from both miners – additional shallow



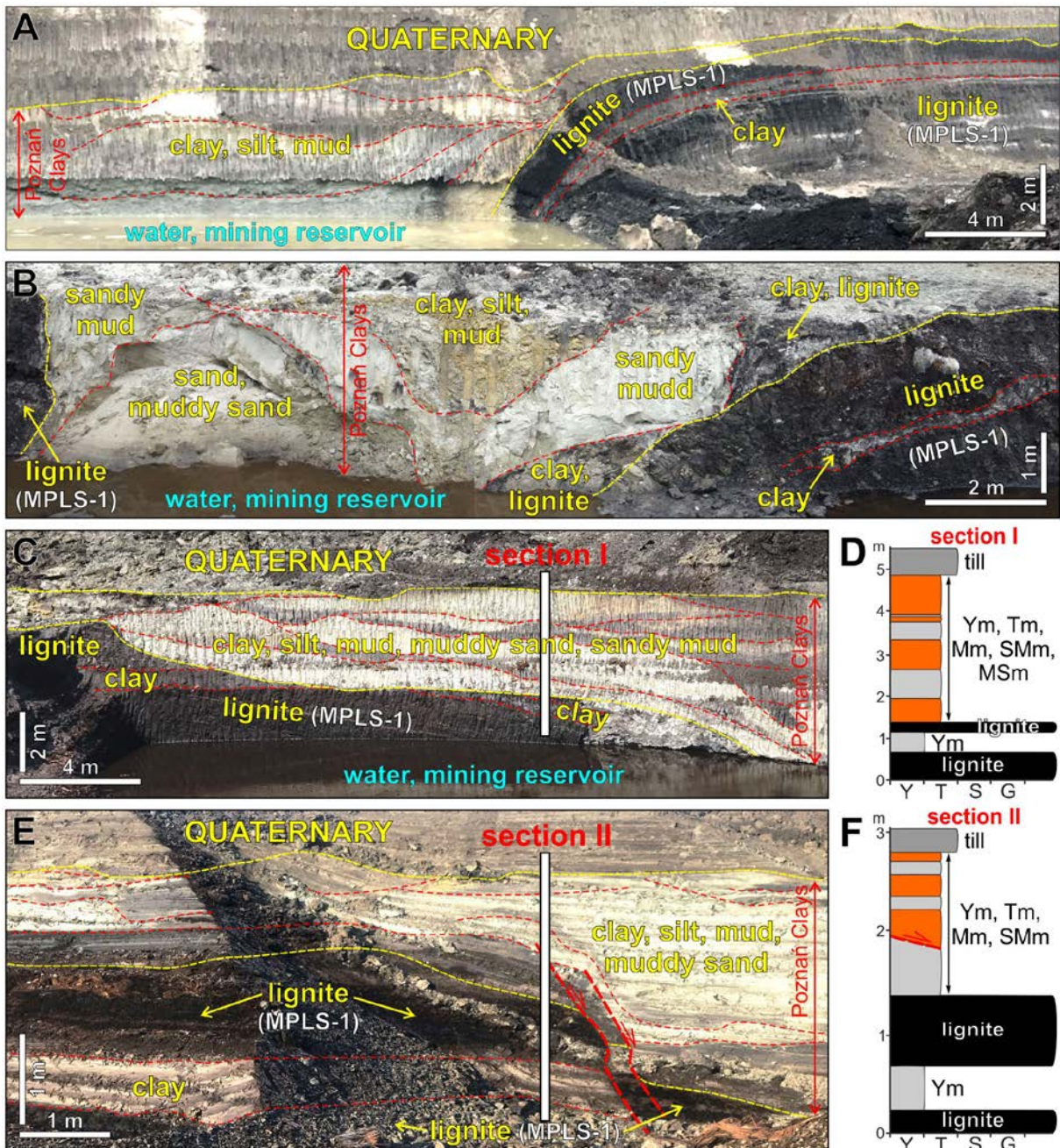
Text-fig. 5. Simplified cross-sections through the examined palaeochannels. Note the lignite-free zones (palaeochannels) and the depth of their filling with Neogene and/or Quaternary sediments; for location of the cross-sections see Text-fig. 3; for other explanations see Text-fig. 2 and the text.

boreholes (Text-figs 3, 5) – and scientists – research hypotheses (Widera *et al.* 2024b).

Comparing the data from the newly drilled boreholes BS-1 and BS-2, it can be stated that the bottom of palaeochannel I is inclined towards the north. This is proven by the fact that in the borehole BS-1, it reaches the Mesozoic top at an altitude of 37.4 m a.s.l., while in the borehole BS-2, this occurs at an

altitude 38.1 m a.s.l. (Text-fig. 5B, C). Assuming that the average height of the MPLS-1 roof (= the base of the Poznań Clays) is about 55 m a.s.l., the depth of this palaeochannel can be estimated at >17–18 m.

Palaeochannel II. The length of palaeochannel II is >1 km, while its width is unknown – there are too few boreholes. However, based on the available



Text-fig. 6. Palaeochannel I. A–C, E – sediments and their depositional architecture seen in the field. D, F – generalised sedimentary logs for selected sections I and II. Note the alternating filling of fine-grained sediments of different colours (Poznań Clays) and the tilting/faulting of the lignite beds with a clay layer towards the axial zone of the palaeochannel I; for explanation of facies codes see Table 1 and for location where the photos were taken see Text-fig. 3.

data, it can be estimated that it is slightly wider than palaeochannel I (i.e. >200 m) and oriented NW–SE (Text-figs 3–5). It should be clearly emphasised that the interest of miners and geologists in palaeochannel II, located obliquely to palaeochannel I as character-

ised above, was negligible in 2022 and 2023. This was due to the fact that this area was situated outside the Tomislawice deposit (lignite thickness <3 m) intended for exploitation (Kozula 1999, 2001). Moreover, previous documentation omitted the low position of the

Poznań Clays, focusing on deep subglacial channels filled with glaciogenic sediments (Text-figs 2, 5).

So far, there has been no mention in the geological documentation and literature of the pre-Pleistocene deep erosion of Polish lignite deposits. On the contrary, the flanks and roof parts of lignite seams are often partially removed by the erosion of the Scandinavian ice sheets and/or their meltwaters (e.g., Widera 2021). However, the data from the boreholes ST-215, BT-4 and ST-199, where the Poznań Clays filling palaeochannel II were drilled the deepest (36.7, 36.5 and 32.7 m a.s.l., respectively), do not determine in which direction its bottom is inclined. This ambiguity is caused by the fact that the boreholes ST-215 and BT-4 are most likely not located in the axial zone of this palaeochannel. Moreover, the fill (i.e. Poznań Clays) of the borehole BT-4 has not been pierced (cf. Text-figs 3 and 5C). The bottom of palaeochannel II is at least 4–5 m lower than the bottom of palaeochannel I; thus, its depth can be estimated at >21–23 m.

Field characteristics of sedimentary architecture and facies

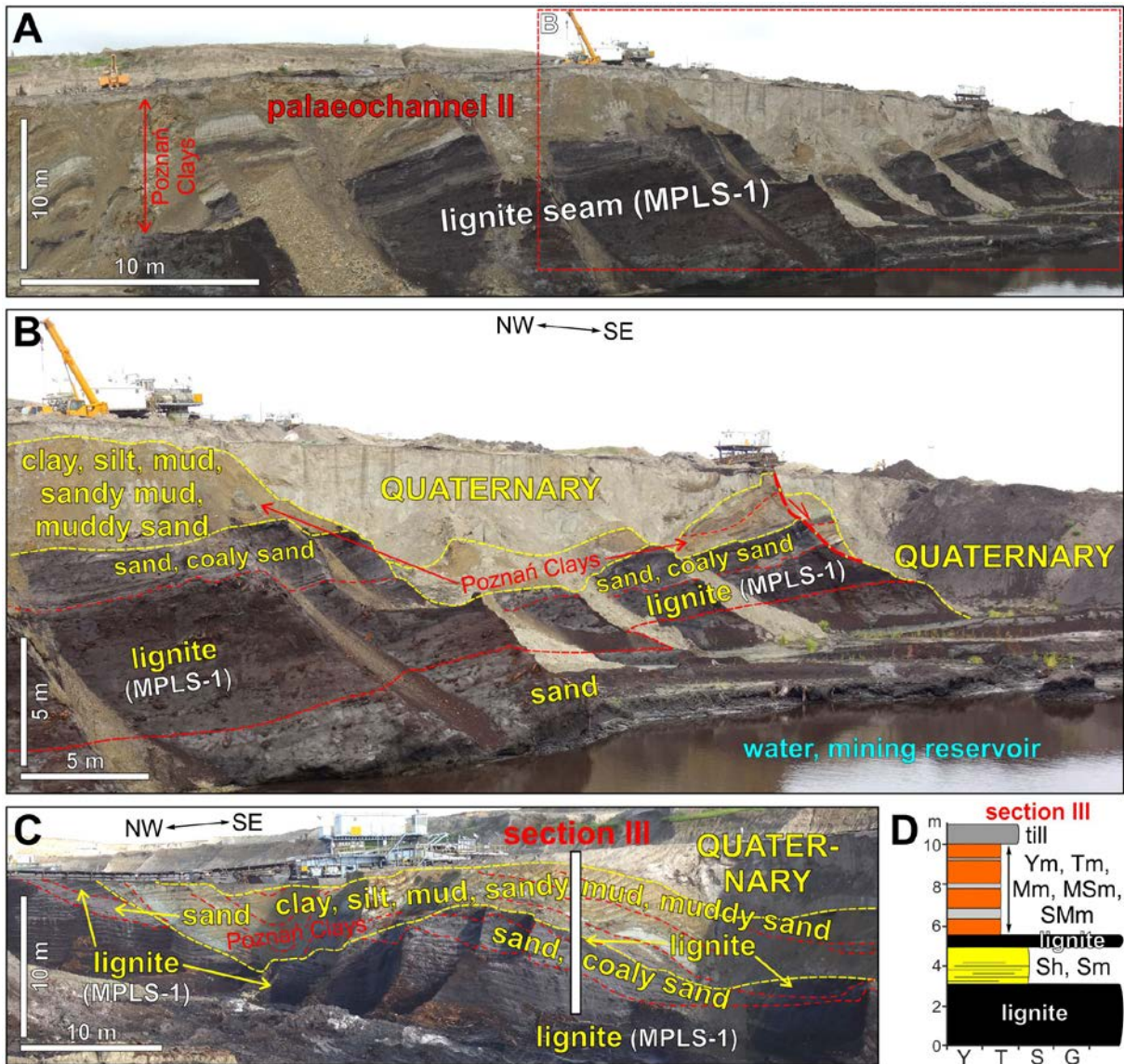
Description. During fieldwork, the fill of palaeochannel I was available for direct observations at a distance of up to 20–30 m. The height of the walls with the examined sediments was 3–6 m (cf. Text-figs 3 and 6). In the case of palaeochannel II, residually preserved Poznań Clays at the top of lignite layers, <3 m thick on average, were exposed in the NE wall of the Tomisławice opencast mine over a distance of 300 m (cf. Text-figs 3 and 6–8). Sediments in the analysed palaeochannels are most often limited in the lower parts by the water level in the mining reservoirs (cf. Text-figs 4 and 6–8). In all cases, the Poznań Clays are present both on the roof of the lignite seam (MPLS-1) and in the described palaeochannels. The contact between MPLS-1 and the fine-grained siliciclastics is clearly erosional. It is worth noting that the roof layers of MPLS-1, with its clay interbedding, are inclined towards the axial zone of the palaeochannels. However, occasionally faults with vertical throws <1 m have been documented in the field (Text-fig. 6E). Moreover, the siliciclastics of Neogene age (i.e. Poznań Clays) resting stratigraphically higher are strongly inclined (Text-fig. 6–8).

Interest in the sediments filling palaeochannel II appeared only after the disproval of earlier hypotheses concerning the genesis of the lignite-free zone characterised above, i.e. palaeochannel I (see Widera *et al.* 2024b). First, attention was drawn to the fact that both lignites with accompanying siliciclastics

(sands, coaly sands) and the overlying Poznań Clays are generally inclined towards the NE (Text-fig. 7). Then, taking into account the borehole data, it was found that along the NW border of the Tomisławice deposit, there is an erosional structure, which is called palaeochannel II in this study (cf. Text-figs 3 and 4). Finally, the facies filling both erosional structures (i.e. palaeochannels I and II) and their sedimentary architecture were analysed (Text-figs 7C, D, 8).

The fill of palaeochannels I and II is characterised by the alternating occurrence of fine-grained sediments of cold and warm colours. These are mainly clays, silts and fine sands in various proportions, with a massive structure. Therefore, the following facies were distinguished: massive clay – Ym, massive silt – Tm, massive mud – Mm, massive muddy sand – SMm and massive sandy mud – MSm (Text-figs 6D, F, 7D and Table 1). In one case, a sand body cross-stratified at a large scale was also found (Text-fig. 6B). Unfortunately, due to the field inconveniences (e.g., steep walls and mass movements), the type of this stratification (planar or trough) was not specified in the case of palaeochannel I. On the contrary, observations of vertical walls with a height of ca. 5 m and a length of >200 m (cf. Text-figs 4 and 8), composed of multi-coloured fine-grained sediments of palaeochannel II, in the lowest part of the Tomisławice opencast mine (i.e. above the water level in the mining reservoir), gave good results. Erosional, secondary structures were clearly visible within this primary palaeochannel. These secondary palaeochannels are up to 2–4 m deep, while their apparent width is >20–70 m. Their filling is muddy-sandy or muddy, characterised by inclined heterolithic stratification – IHS (Thomas *et al.* 1987). These sets of layers have a thickness of 1–3 m and an apparent width of 20–50 m. Moreover, it is worth noting that these heterolithic layers are almost parallel to the basal surfaces of the secondary palaeochannels (Text-fig. 8). Finally, it should be added that the upper parts of the studied sections of palaeochannels I and II pass into younger layers of the Poznań Clays, which were erosionally truncated in the Pleistocene (Text-figs 6–8).

Interpretation. The results of field studies obtained for the two palaeochannels described above (I and II) are partly similar and partly complementary. Moreover, all the geological facts indicate that both palaeochannels constitute a genetically integral part of the late Neogene river system in central Poland. They are characterised by similar morphometric features, i.e. a width of 150–200 m and a depth/thickness of 17–23 m. This means that their width/thickness ratio (w/t ratio) is in the range of 6.5–11.8; hence, they

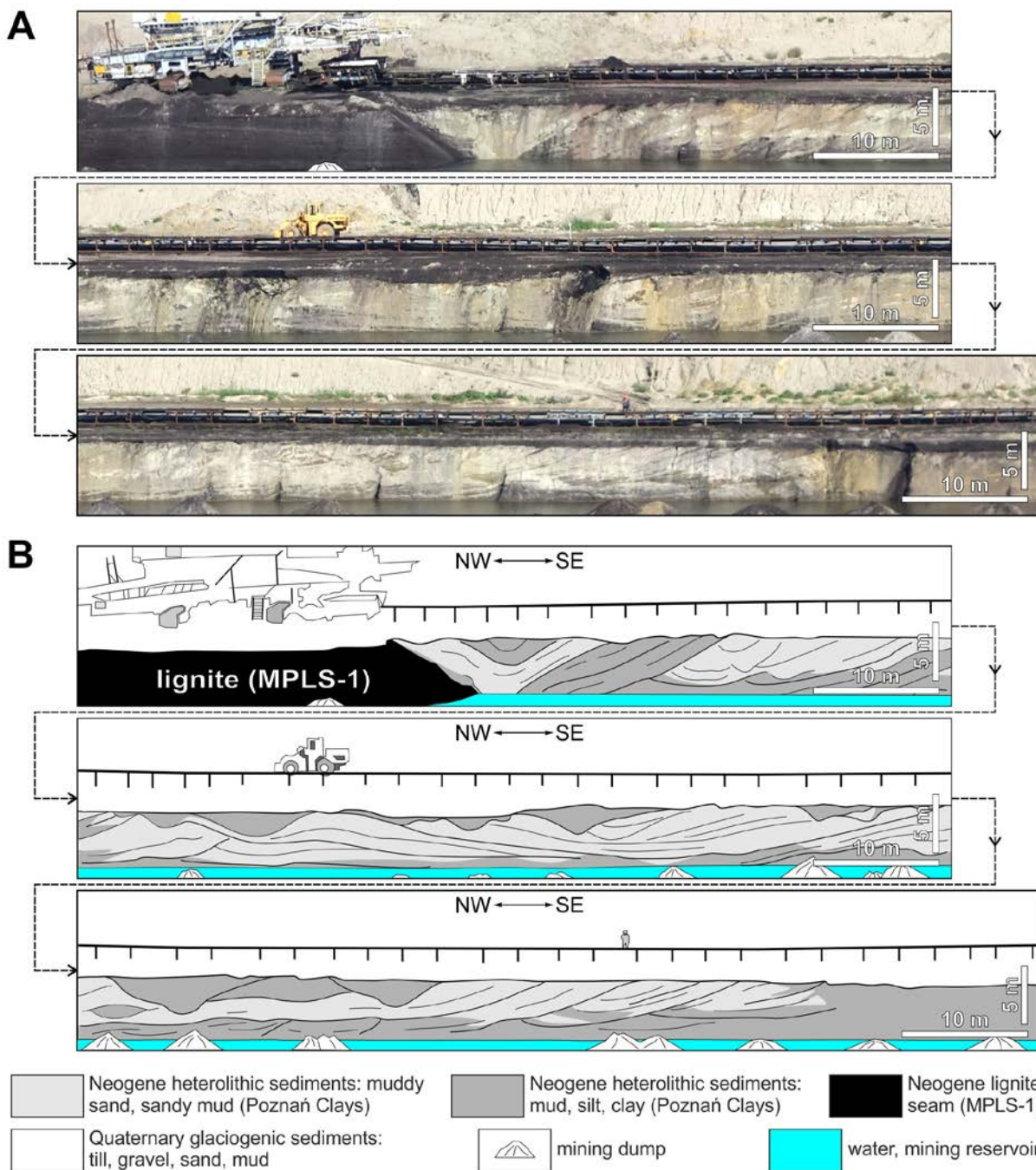


Text-fig. 7. Palaeochannel II. A–C – sediments and their depositional architecture seen in the field. D – generalised sedimentary log for selected section III. Note the alternating filling of fine-grained sediments of different colours (Poznań Clays) and the tilting of the lignite, sand and coaly sand layers towards the NE, i.e. towards the axial zone of the palaeochannel II; for explanation of facies codes see Table 1 and for location where the photos were taken see Text-fig. 3.

can be called ribbons (Gibling, 2006). The w/t ratio has not been determined for the secondary palaeochannels. This is caused by the lack of measurements of the palaeoflow directions (scarcity of cross-stratification) and the apparent widths of the palaeochannels observed in the field (see Text-figs 6–8).

In this paper, the facies analysis is very limited due to the widespread massiveness of the sediments. In most cases, layers with various grain sizes occur alternately, but their stratification is poorly visible (see Text-figs 6, 7). However, the depositional architecture

is more legible in palaeochannel II, where low-angle inclined, muddy/muddy-sandy and sandy-muddy beds are visible (see Text-fig. 8). These sediments, facies Ym and Tm, should be interpreted as originating mainly from suspension, while facies Mm, MSm and SMm indicate a rapid dumping of high-density turbulent suspension – hyperconcentrated flows (e.g., Beverage and Culbertson 1964; Lowe 1988; Nemeč 2009). On the contrary, the presence of layers/lenses of cross-stratified sands at a large scale (see Text-fig. 6) convincingly proves tractional deposition. In



Text-fig. 8. Detailed depositional architecture of the palaeochannel II. A – broad view of the analysed sediments (Poznań Clays). B – the corresponding line-drawings shown in Text-fig. 8A. Note the presence of the secondary palaeochannels, heterolithic filling and the stratification almost parallel to the basal surfaces.

the middle and upper parts of the lower flow regime, 2D and 3D dunes were formed, respectively (e.g., Miall 2006; Bridge 2003; Boggs 2012; Zieliński 2014).

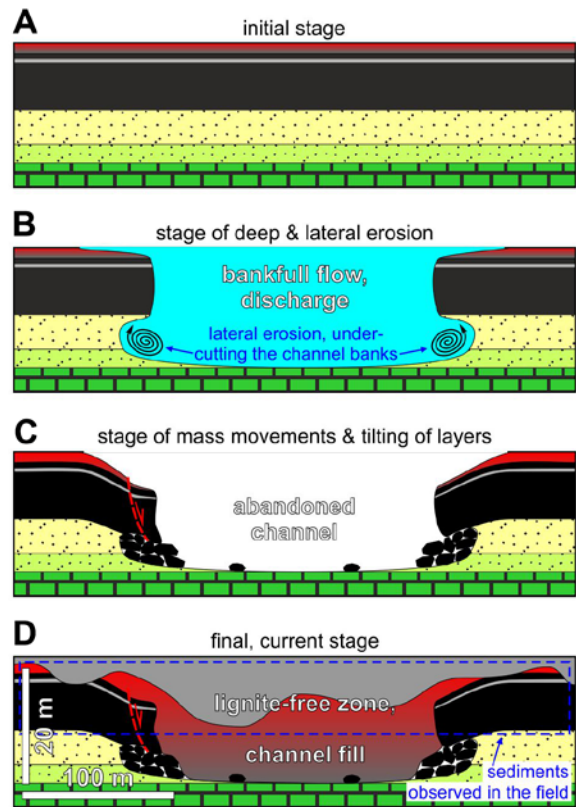
During the genetic interpretation of the sediments filling the examined palaeochannels from the

Tomisławice opencast mine, the results of sedimentological studies from the neighbouring lignite mines in the Konin region must also be taken into account. Several dozen (>30) mud- to sand-filled palaeochannels within the Poznań Clays have been docu-

mented in the Kazimierz N and Józwin IIB opencast mines located approximately 20–25 km SW of the study area (e.g., Widera 2013a; Widera *et al.* 2017; Maciaszek *et al.* 2019, 2020; Zieliński and Widera 2020; Kędzior *et al.* 2021; Wachocki *et al.* 2025). The largest of them (Józwin IIB opencast mine) were characterised by a width of up to 140–150 m, a filling thickness of 9–12 m and a w/t ratio in the range 9.2–15.5. Numerous sedimentary structures were found there, both at a large scale (e.g., planar, trough, horizontal) and at a small scale (e.g., ripple), including heterolithic bedding, i.e. flaser, wavy and lenticular (Maciaszek *et al.* 2019; Widera *et al.* 2019). It can therefore be assumed that structures of this type also may (although not necessarily) occur in the studied sediments, but they have not been identified so far. On the other hand, IHS (i.e. inclined heterolithic stratification) is the most common and is associated with point-bar deposition in meandering streams/rivers (Thomas *et al.* 1987). Based on the thickness of the IHS sets, the average depth of bankfull flow in secondary channels can be calculated (Donselaar and Overeem 2008). In the cases observed in the Tomisławice lignite opencast mine, this depth could even reach over 3 m (cf. Text-fig. 8).

Finally, an attempt should be made to interpret the tilting and local faulting of the MPLS-1 layers, together with the clay and/or sand interbeddings. They are evidently inclined towards the axial zones of the examined palaeochannels I and II (see Text-figs 6, 7). These features were previously incorrectly interpreted as the result of edogenic processes, i.e. bedrock tectonics and peat compaction during its transition to MPLS-1 (Wachocki *et al.* 2024; Widera *et al.* 2024b). Now, in the light of the avulsion hypothesis, the mentioned deformations can be associated either with the erosion of the sub-lignite sands (Text-fig. 9) or with the peat/lignite compaction caused by the uneven loading of the overlying Poznań Clays (Text-fig. 10).

The first process could have occurred at a time when the palaeochannels were active and the erosion of their banks was very intensive. This could result in undercutting, the collapse of the lower layers and the tilting of the upper layers of MPLS-1, and locally it could also result in triggering mass movements (landslides) and the formation of faults (cf. Text-figs 6E and 9C, D; e.g., Makaske *et al.* 2002; Brooks 2003; Gradziński *et al.* 2003). On the contrary, the peat-to-lignite compaction process could play a decisive role in the deformation of the underlying MPLS-1 at the final stage of filling both palaeochannels. The uneven loading of the partially compacted peat/lignite seam by siliciclastics (i.e. by the Poznań Clays in the inter-

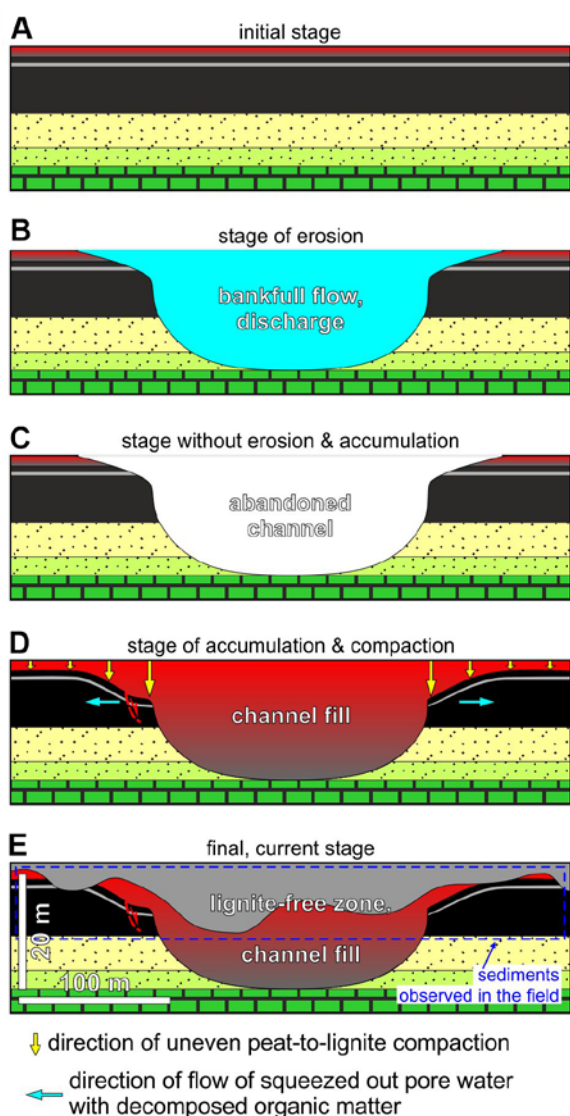


Text-fig. 9. Interpretation cartoon showing the tilting/faulting of the lignite beds with a clay layer due to erosion. Note the lateral erosion of sub-lignite sands resulting in undercutting of the peat/lignite seam.

preted case) leads to the squeezing out of a significant amount of water but also a certain amount of biochemically decomposed organic matter (cf. Text-figs 6, 7 and 10D, E; e.g., Nadon 1997; Rajchl and Uličný 2005; Gouw 2007; Widera *et al.* 2007; Törnqvist *et al.* 2008; van Asselen *et al.* 2009; Widera 2015, 2019). The effects of this process are best documented in Czech lignite opencast mines (Novotný and Mach 2024; their figs 3–7 and 9), but their traces are also known from the Tomisławice mine (Widera 2020; his fig. 4). However, similar deformations may also be the result of the diversity of lignite lithotypes, as well as the presence of siliciclastic lenses within lignite, which are less susceptible to compaction than peat/lignite (Widera 2013b; his fig. 13).

DISCUSSION

The new erosional hypothesis presented above, regarding the creation of lignite-free zones (palaeochannels I and II) as a result of avulsion in the



Text-fig. 10. Interpretation cartoon showing the tilting/faulting of the lignite beds with a clay layer due to peat-to-lignite compaction. Note the uneven loading of the peat/lignite seam by mineral (Poznań Clays) overburden.

Tomisławice opencast mine in central Poland, requires in-depth discussion. First, the impact of the Mid-Miocene tectonic-climatic changes on sedimentary environments is considered. Second, the studied sediments are related to the appropriate fluvial environment. Third, a conceptual model for the formation of the lignite-free zones (palaeochannels I and II) is proposed and discussed. Finally, examples of analogues of the studied mud-filled palaeochannels, including both those in the geological record and modern ones, will be indicated.

Tectonic and climatic changes versus depositional environments

During the last peak of the Middle Miocene Climatic Optimum (MMCO; ca. 15 ± 0.1 Ma), low-lying mires began to develop intensively in central Poland. Up to 40 m of peat accumulated in local tectonic grabens, and it was subsequently transformed into MPLS-1, with a maximum thickness of ca. 20 m in the vicinity of Konin (e.g., Widera 2021). Starting during the MMCO, the process of the gradual cooling and drying of the climate began in, among other places, the study area (e.g., Sadowska and Giża 1991; Kasiński and Słodkowska 2016, 2024; Słodkowska and Widera 2022; Worobiec *et al.* 2022). However, a sudden change in the depositional environment occurred around 13.8 Ma, resulting in an abrupt change in the accumulated sediments, i.e. the Poznań Clays, filling the examined lignite-free zones (palaeochannels I and II). This is directly related to tectonic movements in the Alpine-Carpathian orogen and its surroundings. They resulted in the interruption of sea connections, a drop in temperature of ca. 7°C and the beginning of the Badenian Salinity Crisis in the Carpathian Foredeep (e.g., Peryt 2006; de Leeuw *et al.* 2010; Kováč *et al.* 2017; Sant *et al.* 2019).

During the accumulation of MPLS-1 and the above-lying Poznań Clays, the study area was located in the vicinity of river palaeochannels. In the first case, channel-fill sediments have never been exposed and investigated in lignite opencast mines in central Poland. However, the presence of numerous crevasse-splay bodies within MPLS-1 (e.g., in the boreholes: BT-5, NT-10, T-42, BT-29, etc.) indirectly proves the presence of such palaeochannels on the SW and NE flanks of the Tomisławice lignite deposit (cf. Text-figs 3, 5D and 7B, C). Hence, the morphological type of this river is generally considered to be meandering or anastomosing (e.g., Chomiak 2020; Widera *et al.* 2021a, b; Dziamara *et al.* 2023; Chomiak *et al.* 2024). The situation is different in the case of the palaeochannels within the Poznań Clays, which are examined in the current paper. More than thirty of them have been examined so far, with two additional palaeochannels (I and II) being the subject of this study. Their morphological type is discussed below.

Facies, depositional architecture and river type

The dominant part of the Poznań Clays, which also fill the examined palaeochannels I and II, consists of very fine-grained massive clays, silts, muds, sandy muds and muddy sands (cf. Text-figs 6 and 7

and Table 1). This common massiveness of the sediments indicates accumulation in a waning flow or standing water from suspension (facies Ym and Tm). In the case of poorly sorted sediments (facies Mm, MSm and SMm), the deposition process occurred suddenly and also from suspension, where the clay, silt and fine sand fractions were in turbulence (e.g., Beverage and Culbertson 1964; Lowe 1988; Nemeč 2009). Occasionally occurring cross-stratified sands (see Text-fig. 6B) are evidence for a relatively long-term flow, during which the bedforms (i.e., 2D or 3D dunes) were created as a result of the accumulation of well-sorted sands in the traction process (e.g., Miall 2006; Bridge 2003; Boggs 2012; Zieliński 2014).

The main palaeochannels I and II are characterised by an average w/t ratio <15 – they are ribbons (Gibling 2006). This is due to the high cohesion of the Poznań Clays and the partially compacted MPLS-1, which strongly limits lateral migration. The secondary palaeochannels, as documented for palaeochannel II, are slightly asymmetric, and in addition, their filling stratification is heterolithic and clearly inclined – IHS (Thomas *et al.* 1987; see Text-fig. 8B). This indicates the lateral migration of these palaeochannels by the accretion of the finest particles (clay, silt) on their banks and/or on their bottoms. In the latter case, this causes the palaeochannels to become shallower and, consequently, increases the w/t ratio to >15 (e.g., Makaske *et al.* 2002; Ghosh *et al.* 2006; Donselaar and Overeem 2008). Taking into account the information provided, it can be stated that the main palaeochannels (w/t <15) are anastomosing, and the secondary palaeochannels (w/t >15) are meandering. Therefore, it is currently believed, as confirmed by the results presented above, that the Poznań Clays were formed in a transitional anastomosing-to-meandering late Neogene fluvial system (Zieliński and Widera 2020).

Conceptual model of the formation of the lignite-free zones proposed

The research results presented above justify the formulation of a new hypothesis on the creation of the lignite-free zones in the Tomisławice lignite deposit. Thus, it is proposed here that the main process responsible for lignite removal was avulsion (Text-fig. 11). It took place in the initial phase of deposition of the Poznań Clays, resting on the roof of MPLS-1. They are of fluvial origin, so one of the palaeochannels (e.g., palaeochannel II) could have been located on the NE side of the present Tomisławice lignite deposit – pre-avulsion stage (Text-fig. 11A). During the first stage of avulsion, the active palaeochannel

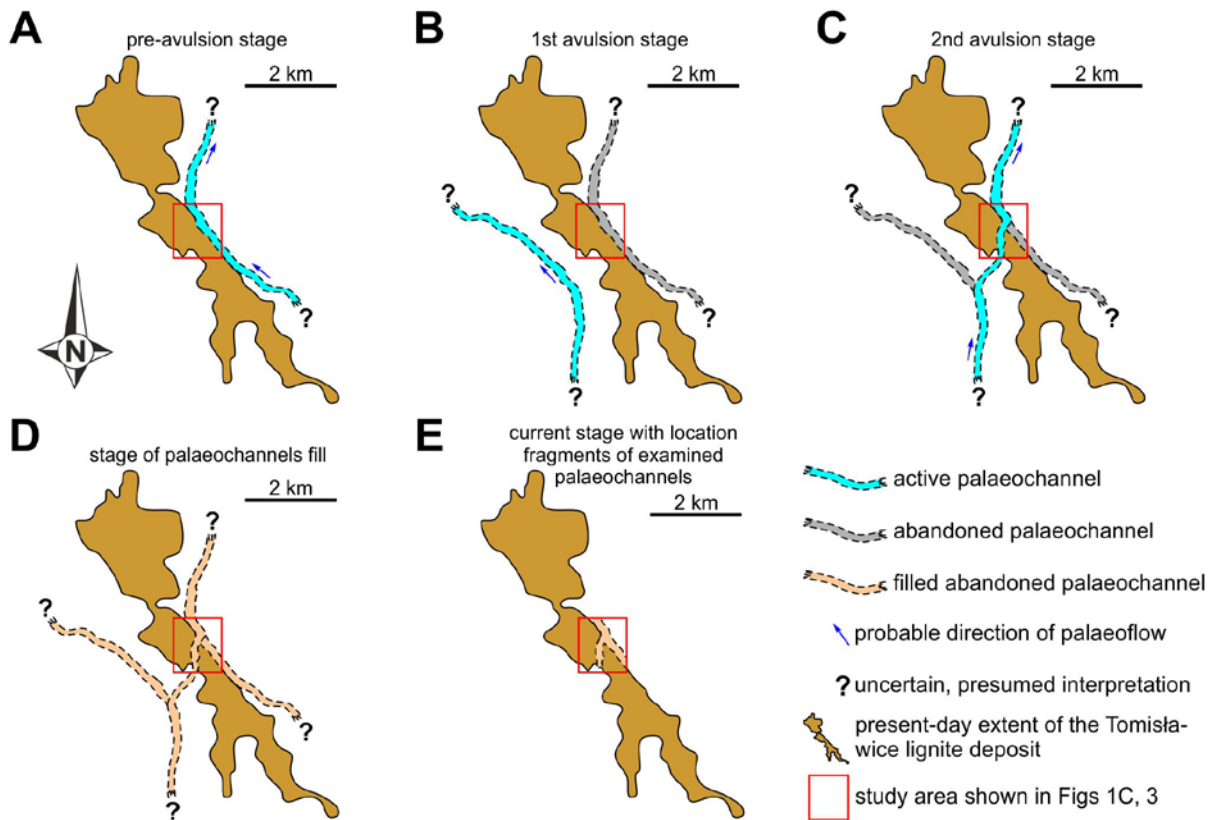
was moved to the SW side of the deposit (Text-fig. 11B). Then, during the second stage of avulsion, there was a partial reoccupation of the former, abandoned palaeochannel II. This took place across the lignite deposit through its erosion and the creation of palaeochannel I (Text-fig. 11C). Later, all the above-mentioned palaeochannels, including palaeochannels I and II, were filled with fine-grained siliciclastics (i.e., Poznań Clays) originating from subsequent floods (Text-fig. 11D, E).

The proposed model is probable, although it is partly speculative; thus, alternative models are possible. This is due to the fact that, based on borehole data, it is impossible to distinguish the sediments of a mud-filled channel from the very similar mud-dominated overbank (extra-channel) sediments of the Poznań Clays. Hence, the course of the studied palaeochannels I and II outside the Tomisławice lignite deposit is only assumed (Text-fig. 11). These palaeochannels were gradually abandoned and partially filled many times. This mechanism is typical for progradational avulsions on low-gradient floodplains of anastomosing (anabranching) rivers (e.g., Makaske 2001). It has been particularly well studied in modern river systems in a semi-arid environment in South America, e.g., from the Río Colorado in Bolivia. In this case the channels are active for a longer period of time than their inter-avulsion period (e.g., van Tooreneburg *et al.* 2018; Donselaar *et al.* 2022).

The cyclical nature of the cut-and-fill process is further supported by the occurrence of many secondary palaeochannels within the main palaeochannels and the alternating colour changes of the sediments filling them (cf. Text-figs 6–8). In the latter case, the warm colours of the sediments indicate their relatively long-term location above the groundwater table and oxidation, mainly of iron-bearing minerals – palaeosol processes (e.g., Kraus and Davies-Vollum 2004; Hajek and Wolinsky 2012; Kłęsk *et al.* 2022, 2023; Widera and Kłęsk 2025). It is worth noting that the discussed model does not take into account the bifurcation of the palaeochannels, which often accompanies the avulsion process (e.g., Slingerland and Smith 1998; Stouthamer 2001; Aslan *et al.* 2005; Gouw 2007; Hajek and Wolinsky 2012; Toonen *et al.* 2012; Kleinhans *et al.* 2013; Karamitopoulos *et al.* 2022), so as not to complicate the presented line of reasoning.

Comparison of mud-filled ancient and modern (palaeo)channels

Mud-filled palaeochannels in the sedimentary record are relatively rarely described in the geolog-



Text-fig. 11. Conceptual model for the formation of the lignite-free zones in the area of the Tomisławice lignite deposit as a result of the avulsion process of the palaeochannels of the late Neogene fluvial system. Note that one of many possibilities is presented, and the number of palaeochannels, their location and course outside the study area are entirely speculative.

ical literature. In Poland, they are known only from Triassic (e.g., Gruszka and Zieliński 2008; Jewuła *et al.* 2019) and Neogene sequences, i.e. from the Poznań Clays (e.g., Widera 2013a; Zieliński and Widera 2020; Kędzior *et al.* 2021). In turn, throughout the world, mud-dominated channels have been described mainly from Triassic (e.g., Ghosh *et al.* 2006), Paleogene (e.g., Kraus and Wells 1999; Kraus and Davies-Vollum 2004) and Late Weichselian fluvial systems (e.g., Berendsen and Stouthamer 2000). All of these channels are filled mainly with mud, but they are also characterised by being relatively deep in relation to their width – the ribbons of Gibling (2006). This indicates near-stagnation conditions in partially abandoned channels with very limited lateral migration caused by highly cohesive extra-channel sediments. Finally, the coexistence of channel-filling bodies of low width/thickness ratio, fine-grained lithology and characteristic depositional architecture occurring in various stratigraphic intervals suggests the existence of an anabranching (anastomosing) river system (e.g., Kraus and Wells 1999;

Berendsen and Stouthamer 2000; Kraus and Davies-Vollum 2004; Ghosh *et al.* 2006).

In contrast, there are many more examples of modern mud-filled channels in different parts of the world. In the Rhine-Meuse Delta (the Netherlands), Stouthamer (2001) describes a great number of channels and inter-channel areas characterised by a clear predominance of clay and silt over sand. Texturally similar are the mud-dominated stream fills of the Red River (Manitoba, Canada) or those from the American Midwest (Jackson 1981). In these cases, as with the sediments (i.e. Poznań Clays) of the studied palaeochannels from the Tomisławice lignite open-cast mine, the sedimentary structures are poorly defined (Brooks 2003). However, the best analogues of late Neogene rivers in central Poland seem to be the suspended-load and laterally stable rivers from SE Australia. In the Murray-Darling Basin, these are, for example, the Baron River (Woodyer *et al.* 1979), the Lachlan River (Kemp 2010) and other rivers from the Riverine Plain (Page *et al.* 2009; Kemp and Pietsch 2024). On the other hand, the most intensively de-

scribed analogue from the Lake Eyre Basin is Cooper Creek, which transports mainly mud, but in the form of sand-sized aggregates (e.g., Rust and Nanson 1989; Fagan and Nanson 2004; North *et al.* 2007).

Most of the above examples represent inland anastomosing (anabranching) river systems from semi-arid climatic environments. Both their channel and extra-channel sediments are mostly massive, low-energy and fine-grained, i.e. clay, silt and mud. In addition, the channels are relatively narrow and deep ($w/t < 15$) due to the high cohesiveness of the above-mentioned (over)bank sediments, sometimes with palaeosol horizons. All these features are consistent with those identified in the studied palaeochannels from the Konin Basin. Therefore, taking into account the specificity of each of the above-listed global mud-dominated fluvial systems, the filling process of the palaeochannels investigated in this study must have been similar.

CONCLUSIONS

In the Tomisławice lignite opencast mine in central Poland, unexpectedly, lignite-free zone(s) were found. Explaining their genesis has turned out to be a scientific challenge in recent years in the area of all Polish lignite deposits. Due to the limited amount of data from deep boreholes, two hypotheses were previously formulated. They linked the formation of the lignite-free zones with syn-depositional tectonics and peat/lignite compaction or only with post-depositional tectonics. However, both these hypotheses have been disproved by data from newly drilled boreholes reaching the Mesozoic bedrock.

An attempt to solve this research problem is made in the current paper. A new hypothesis is put forward in which the creation of the lignite-free zones is attributed to the process of palaeochannel avulsion in an anastomosing-to-meandering transitional late Neogene fluvial system. The depositional architecture of the palaeochannels indicates the occurrence of secondary palaeochannels within the main palaeochannels I and II. Unfortunately, the fine-grained (mud-dominated Poznań Clays) and massive nature of the sediments filling the palaeochannels did not allow a detailed facies analysis.

The main palaeochannels were formed during the initial stages of catastrophic floods following the avulsion process. During subsequent floods, these abandoned palaeochannels ($w/t < 15$) were filled by the secondary palaeochannels ($w/t > 15$), creating cut-and-fill structures. Non-stratified, massive muddy

sand, sandy mud and mud (i.e. Poznań Clays) were accumulated by a turbulent, high-density flow during its rising and falling water stages. During the falling stage, it was heavily charged with mud by the draining of mud-laden overbank floodwater back into the channel. Finally, first silt and then clay particles were deposited from the suspension in a waning flow or stagnant water.

Mud-filled (palaeo)channels within mud-dominated sequences are known from both ancient and modern fluvial environments. The identification of such palaeochannels is often impossible without their field exposures. Fortunately, such an opportunity arose in the Tomisławice lignite opencast mine, where the effects of late Neogene avulsion were most likely documented for the first time in Poland.

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