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Tectonic-climatic interactions during changes of depositional environments in the Carpathian foreland: An example from the Neogene of central Poland

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ABSTRACT:

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Many geological problems have not been convincingly explained so far and are debatable, for instance the origin and changes of the Neogene depositional environments in central Poland. Therefore, these changes have been reconstructed in terms of global to local tectonic and climatic fluctuations. The examined Neogene deposits are divided into a sub-lignite unit (Koźmin Formation), a lignite-bearing unit (Grey Clays Member), and a supra-lignite unit (Wielkopolska Member). The two lithostratigraphic members constitute the Poznań Formation. The results of facies analysis show that the Koźmin Formation was deposited by relatively high-gradient and well-drained braided rivers. Most likely, they encompassed widespread alluvial plains. In the case of the Grey Clays Member, the type of river in close proximity to which the mid-Miocene low-lying mires existed and then were transformed into the first Mid-Miocene Lignite Seam (MPLS-1), has not been resolved. The obtained results confirm the formation of the Wielkopolska Member by low-gradient, but mostly well-drained anastomosing or anastomosing-to-meandering rivers. The depositional evolution of the examined successions depended on tectonic and climatic changes that may be closely related to the mid-Miocene great tectonic remodelling of the Alpine-Carpathian orogen. This resulted in palaeogeographic changes in its foreland in the form of limiting the flow of wet air and water masses from the south and vertical tectonic movements.

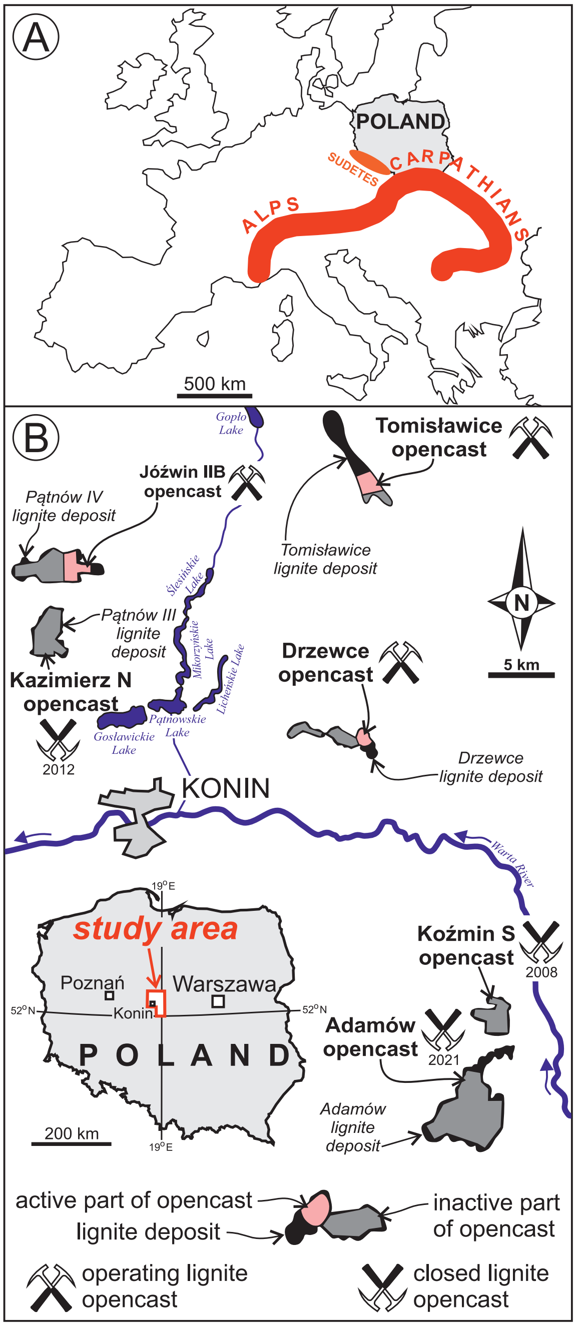
Key words: River type; Lignite seam; Sedimentology; Tectonics; Climate; Miocene.

INTRODUCTION

The Neogene, mostly the middle portion of the Miocene epoch (i.e., Langhian 15.97–13.82 Ma), covers a time interval of great tectonic and climatic changes on a global and regional scale. The overall progressive and long-term global cooling was interrupted, among others, by the last peak (~15 Ma) of the Mid-Miocene Climatic Optimum (MMCO) (Zachos *et al.* 2001, 2008; Mosbrugger *et al.* 2005; Böhme 2003). An important role in the climatic fluctuations was played by tectonic movements, which shifted mountain chains on many continents, as well as being crucial in opening and closing the ocean gateways (Sijp *et al.* 2014).

In Europe, the mid-Miocene elevation of the Alpine-Carpathian orogenic belt and its influence on the foreland territories is well known (Ziegler and Dèzes 2007; Schmid *et al.* 2008; Gusterhuber *et al.* 2012). During this time interval, the tectonic activity of the Carpathians was also marked by the climax of vertical and lateral displacements, as well as the development of sedimentary basins in the foreland and back-arc areas, alongside volcanic phenomena (Plašienka *et al.* 1997; Fodor *et al.* 1999; Krzywiec 2001; Golonka 2004; Peryt and Piwocki 2004; Schäfer *et al.* 2005; Oszczypko 2006; Andreucci *et al.* 2013; Wysocka *et al.* 2016; Kováč *et al.* 2007, 2017a, b; Widera *et al.* 2008, 2019a; Jarosiński *et al.* 2009; Mach *et al.* 2013; Jankowski and Margielewski 2015; Jankowski and Wysocka 2019; Šujan *et al.* 2020, 2021). On the other hand, climatic changes further enhanced by tectonics have been documented in both fauna (Böhme 2003; Hernández-Ballarín and Peláez-Campomanes 2017; Holcová *et al.* 2018) and flora (Schneider 1992; Planderová *et al.* 1993; Utescher *et al.* 2009, 2021; Doláková *et al.* 2021).

The Neogene sedimentary successions in central Poland are well exposed thanks to mining activities in the Konin area (Text-fig. 1). Long-term exploitation of the first Mid-Miocene Lignite Seam (MPLS-1) in numerous opencasts allowed for the study of both this seam and the siliciclastics contained within, as well as the under- and overlying sediments. In general, the examined successions represent various fluvial palaeoenvironments that usually changed suddenly on a geologic timescale (Peryt and Piwocki 2004; Widera 2007).



Text-fig. 1. Location map of the study area. A – Position of Poland in Europe in relation to the Alpine-Carpathian orogenic belt. B – location of the lignite opencasts (Konin Basin, central Poland) from which the data presented in this study were derived.

In the study area, the major changes in depositional systems (braided, meandering, or anastomosing rivers) were caused by regional subsidence, as a consequence of Miocene tectonic phenomena in the Alps and Carpathians (Golonka 2004; Ziegler and Dèzes 2007; Jarosiński *et al.* 2009; Kováč *et al.* 2017a, b). However, particularly during the mid-Miocene, there were also significant global and regional climate fluctuations (Zachos *et al.* 2001; Böhme 2003; Bruch *et al.* 2007). Such climatic changes additionally influenced the sedimentary facies (Bridge

2003; Colombera *et al.* 2017). Changes in total subsidence (i.e., tectonic and compactional) are known to influence depositional processes, including the change of sub-environments within the fluvial systems (Kasiński 1989; McCabe and Parrish 1992; Gawthorpe and Leeder 2000; Michaelsen *et al.* 2000; Michon *et al.* 2003; Schäfer *et al.* 2005; Widera 2007, 2015, 2019; Widera *et al.* 2007; Rajchl *et al.* 2008, 2009; van Asselen 2011; Schäfer and Utescher 2014; Novák *et al.* 2017; Wang *et al.* 2020).

So far, research on the Neogene successions in central Poland has been limited to one lithostratigraphic unit, preventing the reconstruction of changes of depositional environments. Therefore, we intend to explain these changes for all Neogene sedimentary successions from the Konin Basin. This main goal of the current study will be achieved through the implementation of the following research tasks: (1) description and interpretation of facies representing different environments; (2) discussion of sudden changes in depositional environments in the context of tectonic and climatic fluctuations; and (3) proposal of new conceptual models for the investigated and discussed depositional environments corresponding to the relevant Neogene lithostratigraphic units in central Poland.

GEOLOGICAL SETTING

The Konin Basin in central Poland is rich in lignite deposits. Therefore, over 7,000 boreholes were drilled to document lignite reserves (Widera 2007) and 17 opencast mines were put into operation between 1942 and 2021 (Widera *et al.* 2021). This allowed for a good understanding of the geology of the research area.

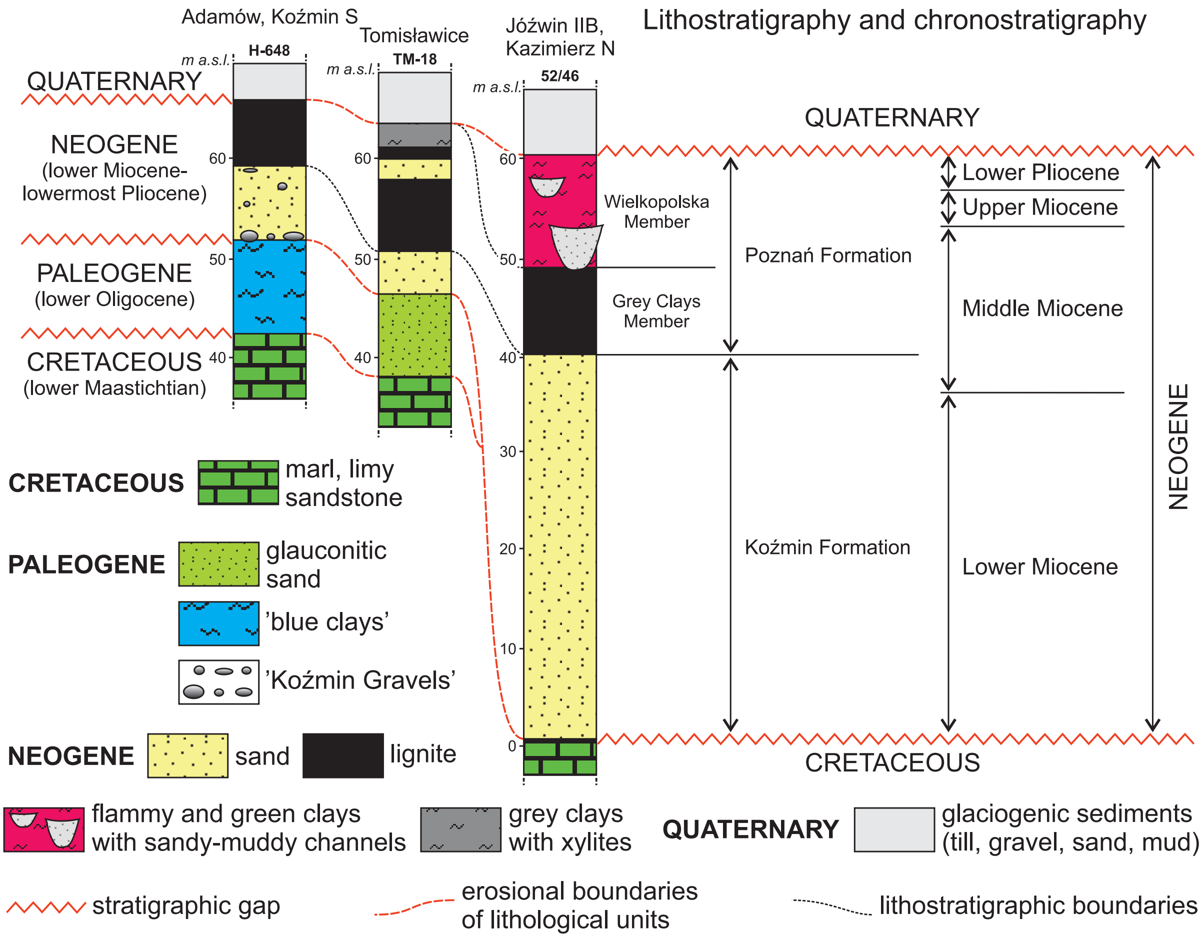
Lithostratigraphy

The Neogene sediments in the study area are almost entirely terrestrial in origin. Therefore, their lithostratigraphy is only sporadically supported by marine microfauna or microflora. Under such circumstances, lignite seams play a fundamental role in the lithostratigraphic division of the Neogene in the Polish Lowlands (Piwocki and Ziembińska-Tworzydło 1997; Widera 2007). Due to the extensive palynological documentation, it is relatively easy to correlate the lignite seams from central through western Poland with those from southeastern Germany (Widera *et al.* 2008, their fig. 4). In the latter case, the lignite-rich deposits are interbedded with marine siliciclastics, which additionally favours their more precise dating, based on the zonation of microfauna and/or dinocysts (Standke *et al.* 1993; Grimm *et al.* 2002; Janssen *et al.* 2018).

The base of the Cenozoic, namely the top of the Mesozoic bedrock, is made up of marls and limy sandstones of Late Cretaceous age (Dadlez *et al.* 2000). Locally, lower Oligocene sediments occur in the deepest parts of the shallow tectonic depressions (i.e., grabens), filled with lignite seams. They occur in the form of marine glauconitic sands (Tomisławice area) or as lacustrine 'blue clays' and beach 'Koźmin Gravels' that were redeposited into the Neogene (Koźmin and Adamów area) (cf. Text-figs 1 and 2; Widera and Kita 2007; Widera 2010). On the contrary, the Paleogene deposits have not been documented in the area of the Józwin IIB and Kazimierz N lignite opencasts.

The Neogene in the Konin Basin is divided into two lithostratigraphic formations: the Koźmin Formation succeeded by the Poznań Formation. The first one includes sub-lignite siliciclastics, mainly fluvial sands with sandstones and coaly intercalations. The Koźmin Formation was deposited in the early- to mid-Miocene time interval – ~23–15 Ma (Piwocki and Ziembińska-Tworzydło 1997). On the other hand, the Poznań Formation encompasses the following two lithostratigraphic members: the Grey Clays Member and the Wielkopolska Member. In general, they accumulated from the mid-Miocene to the early Pliocene – ~15–5 Ma (Text-fig. 2; Piwocki and Ziembińska-Tworzydło 1997; Widera 2007).

The first of these members is the most lignite-bearing in central Poland. Thus, the Grey Clays Member contains the currently exploited lignite seam (i.e., the first Mid-Polish Lignite Seam, MPLS-1) from the Konin Basin. This MPLS-1 is characterised by a maximum thickness of ~20 m, on average 6.3–8.1 m (Bechtel *et al.* 2019, 2020; Widera *et al.* 2021). Most likely, its deposition started during the last peak of the Mid-Miocene Climatic Optimum (MMCO) and continued when the climate started to cool (Kasiński and Słodkowska 2016; Słodkowska and Kasiński 2016; Słodkowska and Widera 2021). This is supported by tuff dating and calculations of the maximum peat accumulation time. The tuff horizon, occurring in the MPLS-1 roof or slightly higher (Widera *et al.* 2021, their fig. 3), was first correlated with tuffs from other sedimentary basins, including the Carpathian Foredeep (Wagner 1984), where it was dated using the ^{40}Ar/^{39}Ar method (Bukowski *et al.* 2018). The age obtained ~14.3 Ma indicates the end of peat accumulation, while its beginning took place ~0.8 My earlier



Text-fig. 2. Simplified sketch of the Cenozoic lithostratigraphy and chronostratigraphy from the Konin Basin based on borehole data (modified from Chomiak *et al*. 2019; Maciaszek *et al*. 2019; Chomiak 2020a; Worobiec *et al*. 2021).

(Chomiak 2020a), that is ~15 Ma, as estimated from original calculations of Zagwijn and Hager (1987). On the other hand, the MPLS-1 accumulated in the overbank zone of a mid-Miocene fluvial system as low-lying mires (Widera 2016a; Chomiak *et al*. 2019, 2020). Locally, relatively thin lenses of the so-called 'grey clays', with discontinuous and thin organic-rich layers (sometimes lignites) in their upper parts, rest on the MPLS-1 roof. Most likely, this period of transitional organic-mineral accumulation ended at ~13.8 Ma. Due to their genetic similarity, the MPLS-1 and the 'grey clays' belong together to the Grey Clays Member (Piwocki and Ziembińska-Tworzydło 1997; Widera 2007).

The Wielkopolska Member is the most clay-rich and the youngest lithostratigraphic unit in the study area. It is predominantly composed of mud and a mixture of sands and muds with a total thickness of up to 30 m in the study area (Text-fig. 2). It is currently interpreted as representing the overbank and channel sediments which were accumulated by the anastomosing (Widera 2013a; Widera *et al*. 2017a, 2019b; Maciaszek *et al*. 2020) or anastomosing-to-meandering river (Zieliński and Widera 2020). Most likely, their deposition commenced ~13.8–13.5 Ma, when the Mid-Miocene Climatic Optimum in a broad sense finished (Böhme 2003). At that time the climate become cooler and drier compared to the climatic optimum, with clearly marked seasonality (Kasiński and Słodkowska 2016; Słodkowska and Kasiński 2016). Finally, the Neogene succession is capped by the glaciogenic Quaternary. Its thickness varies considerably and is on average in the range of 20–80 m in the study area (Text-fig. 2).

Palaeotectonics and palaeogeography

During the Cenozoic, the Konin Basin area covered a small, eastern part of the Northwest European Paleogene–Neogene Basin that extended from the present-day territory of Belarus in the east to the Netherlands in the west (Vinken 1988; Gibbard and Lewin 2016). Tectonically, it was also located in the eastern part of the European Palaeozoic Platform, that is, between the Bohemian Massif (with the Sudetes; Text-fig. 1A) and the East European Craton (Karnkowski 1980; Pharaoh 1999; Ziegler and Dèzes 2007). In turn, according to the current division of Poland into tectonic units, the research area covers the central part of the so-called Mogilno Trough (Żelaźniewicz *et al*. 2011), which was created as a result of the Cenozoic remodelling of the Mid-Polish Trough in the Alpine-Carpathian foreland (Krzywiec 2006; Kley and Voigt 2008; Jarosiński *et al*. 2009).

During the Late Cretaceous–latest Eocene time interval, the entire area of central Poland, including the Konin Basin, was uplifted and eroded. Thus, the oldest Paleogene deposits are of latest Eocene–early Oligocene age (Text-fig. 2), when the direction of vertical movement changed to subsiding. The next stage of tectonic inversion took place in the late Oligocene. Then, the above-mentioned Mid-Polish Trough became significantly elevated, and the Mogilno Trough was formed on its SW slope (Karnkowski 1980; Krzywiec 2006; Jarosiński *et al*. 2009). The deposition occurred almost continuously, with short-lived interruptions (local relative inversion movements), from the earliest Miocene to the earliest Pliocene in a generally subsiding sedimentary basin in central Poland (Widera 2007; Widera *et al*. 2008, 2019a). Simply put, almost all observations presented herein come from tectonic grabens, hence no evidence of significant stratigraphic gaps in the study area have been documented. At that time (earliest Miocene–earliest Pliocene) large climatic and tectonic changes occurred due to the activity of the Alpine–Carpathian orogen and rifting of the Pannonian Basin System (e.g., Golonka 2004; Kováč *et al*. 2017a; Šujan *et al*. 2021). Of course, this resulted in a change in the Neogene depositional environments in its forelands, for example, in central Poland. During the Quaternary, the research area was repeatedly covered by Pleistocene ice sheets. They and their meltwaters removed and disturbed a significant part of the Neogene sediments (Widera 2013b, 2018), and also deposited a relatively thick layer of glaciogenic deposits (Text-fig. 2).

MATERIAL AND METHODS

Lignite from the Konin Basin was exploited at the Adamów Lignite Mine (closed in February 2021) and is still being exploited at the Konin Lignite Mine. Therefore, some data comes from closed opencasts, and others from those where lignite is still being mined. Most of the results presented in this study were obtained in the last decade, although some important field observations were collected over the last twenty years from both closed (Adamów, Koźmin S, Kazimierz N) and operating lignite opencasts (Jóźwin IIB, Tomisławice) (cf. Text-fig. 1). Additionally, the necessary cartographic information (mining maps, borehole data, etc.) was obtained from the geological archives of the aforementioned Konin and Adamów lignite mines. On the other hand, the research methods applied can be grouped as follows: sedimentology, macropetrography, palynology, and organic geochemistry.

Sedimentology

Facies analysis was a fundamental study method in the current contribution. The siliciclastics within the MPLS-1 also provided valuable information on the depositional environment of this lignite seam. Of course, the MPLS-1 was additionally investigated more comprehensively using methods typical for the study of organic sediments, which are only briefly mentioned below.

In the lignite opencasts, individual facies were distinguished first, which were characterised by the specific textural and structural features of the sediments. Then, they were sampled for laboratory testing, where sieve and areometric grain-size analyses were used for loose and cohesive deposits, respectively. Thus, several hundred samples of siliciclastics (260 samples from the Koźmin Formation; 205 samples from the Grey Clays Member, i.e., 170 of the crevasse-splay deposits, 35 of the lacustrine deposits, and 227 samples from the Wielkopolska Member, i.e., 116 of the channel-fill deposits, 111 of the overbank deposits), excluding lignite ash (266 samples), were previously analysed to determine their grain size (Widera 2007; Chomiak *et al*. 2019, 2020; Widera *et al*. 2019b; Chomiak 2020a, b). For deposits examined granulometrically, the standard division of siliciclastic rocks was applied: gravel, sand, silt, and clay (Shepard 1954).

An exception was a mixture of sand, silt, and clay fractions in an amount of more than 20 wt.% each. Such sediment was referred to as mud and abbrevi-

Facies texture	G	gravel
	S	sand
	M	mud
	T	silt
	Y	clay
	C	coal (lignite), carbonaceous
Sedimentary structure	m	massive
	h	horizontal (plane-parallel) lamination
	p	planar cross-stratification
	t	trough cross-stratification
	l	low-angle cross-stratification
	r	ripple cross-lamination
	rc	climbing-ripple cross-lamination
	e	erosional scours
	f	flaser lamination
	n	nodular (lenticular) lamination
	w	wavy lamination
	d	deformed

Table 1. Textural and structural codification of sedimentary facies used in this paper (modified from Miall 1977; Ghibaudo 1992; Widera *et al*. 2019b, 2021).

ated as a capital letter 'M' in the facies code (Widera *et al*. 2019b, 2021). For other deposits, the original facies codification of Miall (1977) with supplements of Ghibaudo (1992) for silt (denoted as 'T') was used in this paper (Table 1).

Macropetrography

Lignite beds that can be distinguished macroscopically in the field (i.e., lithotypes) are characterised, like siliciclastic facies, by their texture and structure. In general, the textural name of a lignite lithotype association depends on the ratio between the woody fragments bigger than 1 cm (i.e., xylites) and fine-detrital matrix (Kwiecińska and Wagner 1997; Kolcon and Sachsenhofer 1999). Texturally, the examined lignites may be as follows: xylitic, detritic, xylodetritic, detroxylitic, fusitic, and weathered. Besides, they may be distinguished by the following structure: massive, horizontal, gelified, nodular, and disturbed, that is, fractured, folded, and faulted (Widera 2012, 2016b).

Each lignite lithotype association can be pre-assigned to a specific depositional sub-environment, in this case to the type of mire. Teichmüller (1958) was the first to recognise this dependence. Then, other researchers also began initially reconstructing the original peat-forming sub-environments based on the lithotypes distinguished in the mined European lignite seams (e.g., Teichmüller 1989; Markič and Sachsenhofer 1997; Ticleanu *et al*. 1999; Markič *et al*. 2001; Widera 2012, 2016b).

Palynology and organic geochemistry

In this paper, the latest results of the palynological and geochemical analysis of 2–3 sections of the MPLS-1 from the Adamów, Jóźwin IIB and Tomisławice opencasts are only mentioned here. A total of 53 lignite samples were subjected to palynological and 55 samples (27 of detritic lignite and 28 of xylites) to organic geochemical studies. The entire research procedure, all data and obtained results were recently published, among others, by the authors of this paper. Therefore, the interested reader is directed to the original, the following publications: Bechtel *et al*. (2019, 2020), Słodkowska and Widera (2021), and Worobiec *et al*. (2021).

RESULTS

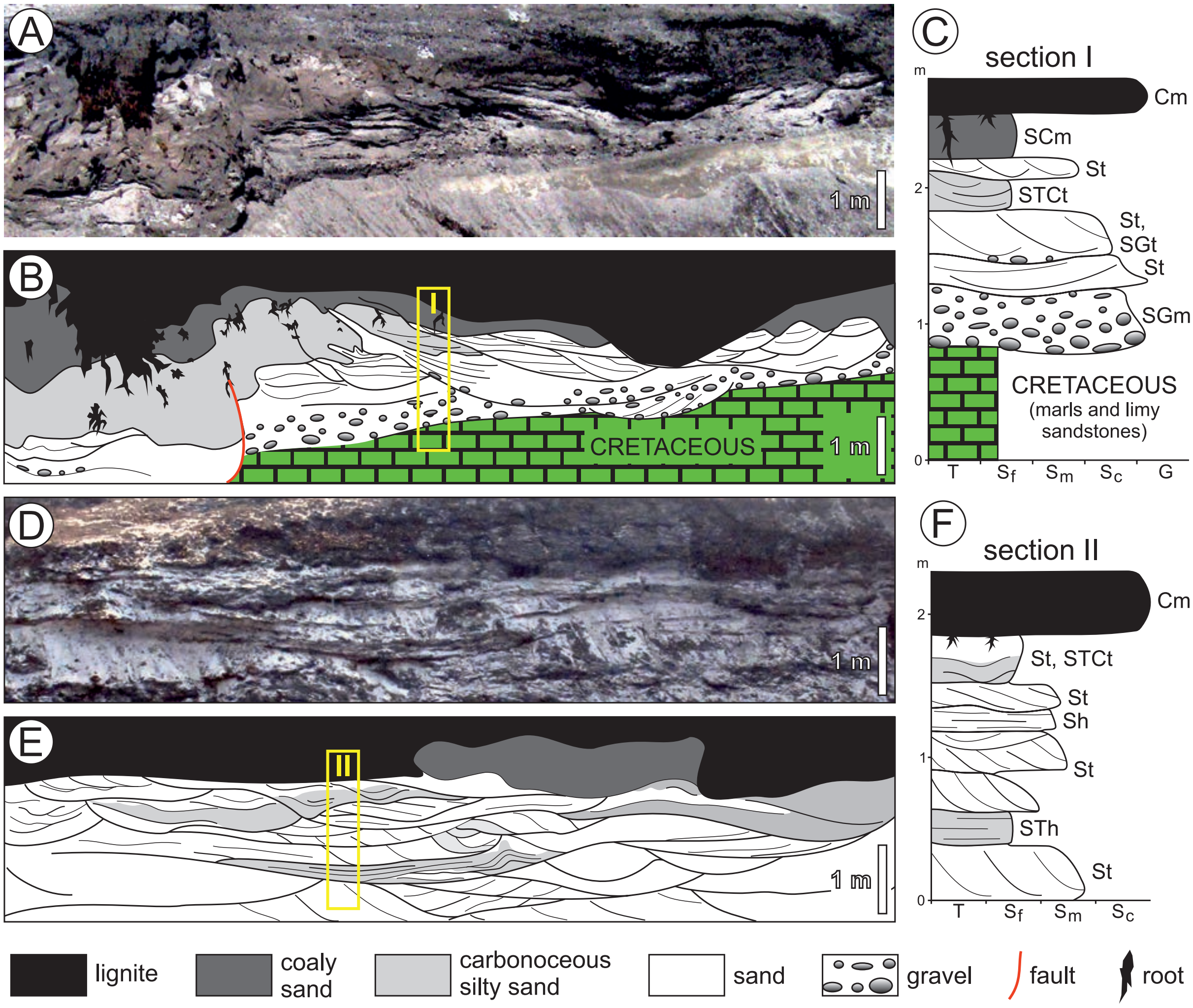
Koźmin Formation

General characteristics

The Neogene sediments lying directly on the Cretaceous bedrock, locally only on the Paleogene deposits and below the MPLS-1, represent the Koźmin Formation (Text-fig. 2). Outside the areas of lignite deposits, the glaciogenic Pleistocene sediments often rest erosively on their top. The thickness of the characterised deposits varies greatly, but its average value is in the range of 20–30 m. Sand dominates (~83 vol.%) in the Koźmin Formation, while the remaining part is composed of silt, clay, sandstone, and lignite lenses, as well as the redeposited 'Koźmin Gravels' (cf. Text-figs 2 and 3; Widera 2007). Facies analysis of these sediments will be presented on the examples of selected sections from the Koźmin S and Jóźwin IIB opencasts (Text-figs 3 and 4).

Facies description

The lowest parts of the Koźmin Formation could only be observed in the opencasts belonging to the Adamów Lignite Mine. Some of the best exposures were those from the Koźmin S opencast, that is, where the rocks of the Mesozoic top were also outcropping (Text-fig. 3A, B). In this case, the lowermost sedimentary facies is represented by a massive gravelly sand – SGm (Widera and Kita 2007). In the higher portion of the section, large-scale trough cross-stratification predominates, such as: St, SGt and STCt. An exception is the uppermost facies of coaly (carbonaceous) sand, directly underlying the MPLS-1,

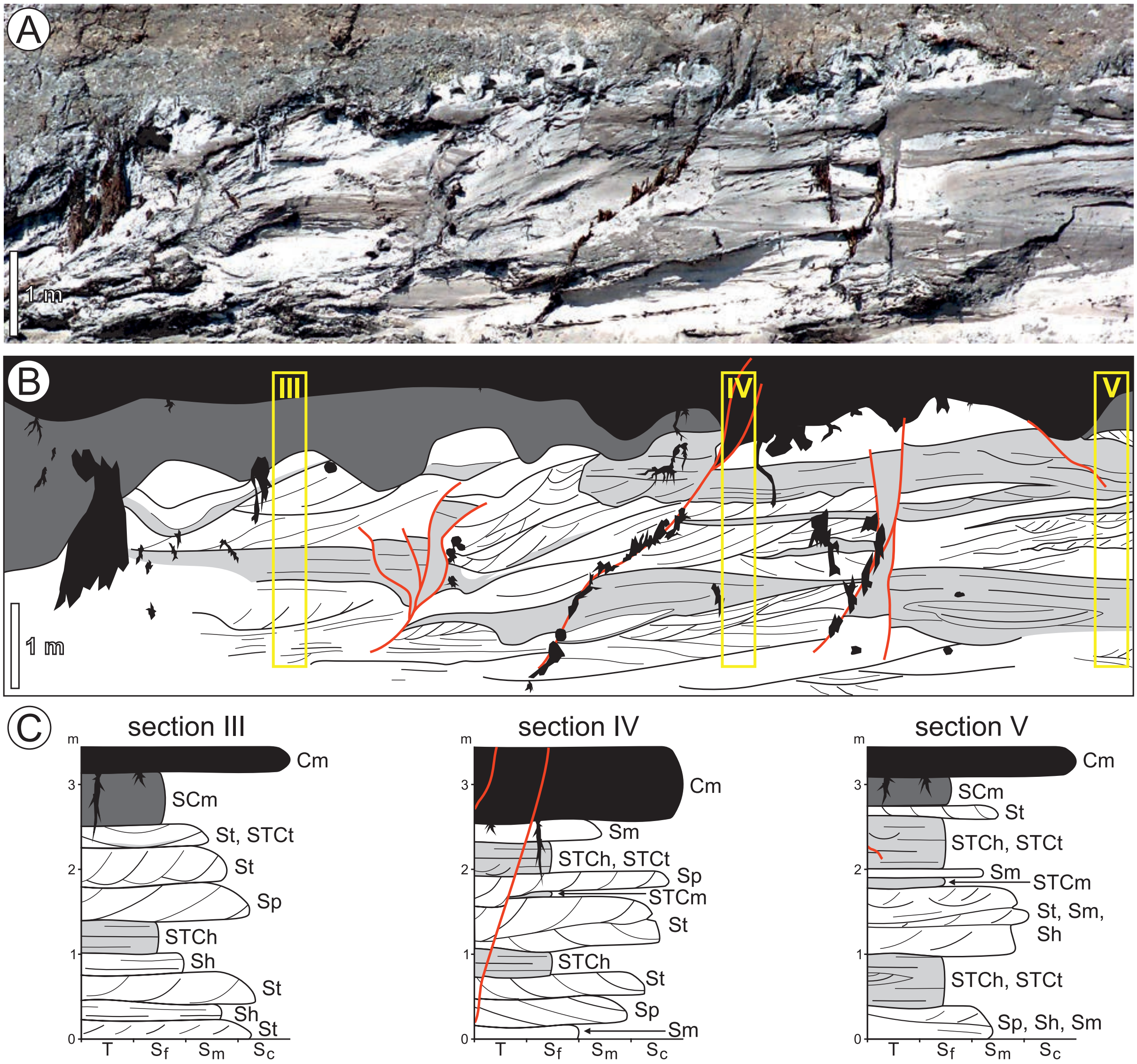


Text-fig. 3. Representative siliciclastic facies within the Koźmin Formation. A, B, C – Examples from the Koźmin S lignite opencast; note the erosional contact between the Cretaceous and the Neogene, and the presence of the redeposited Paleogene 'Koźmin Gravels' in the Neogene sediments. D, E, F – Examples from the Józwin IIB lignite opencast. A, D – Broad views of the studied deposits. B, E – Corresponding line-drawings for Text-fig. 3A, D. C, F – Sedimentary logs of the sections I and II analysed in detail; for their location see Text-fig. 3B, E, respectively. For explanation of facies codes see Table 1.

which is characterised by a massive structure – facies SCm (Text-fig. 3C; Table 1). The remaining sections described come from the upper parts of the Koźmin Formation (Text-figs 3D–F and 4). As in the case described above, large-scale trough cross-stratification of sand prevails. In addition, the thickness of all the cross-beds analysed is in the range of 15–45 cm, averaging 25 cm. Planar cross-stratification at a large scale was also documented (sections III and IV in Text-fig. 4C) – facies Sp. However, there is no gravel in these beds and horizontal layers appear upwards, often enriched with silt and organic matter – sedimentary facies Sh, STh, and STCh. A characteristic feature of the Koźmin Formation is the presence of relatively numerous, small faults with a vertical throw of up to 0.5 m (Text-fig. 4). They were formed post-depositionally, most likely during the accumulation of peat, which then transformed into the overlying MPLS-1 (Widera 2007; Wachocki *et al*. 2020).

Facies interpretation

Poorly sorted and massive deposits, containing pebble-sized gravels (facies SGm), were probably



Text-fig. 4. Examples of tectonically deformed siliciclastic facies within the Koźmin Formation in the Jóźwin IIB lignite opencast. A – Broad view of the studied deposits. B – Corresponding line-drawing for Text-fig. 4A. C – Sedimentary logs of the sections III–V analysed in detail; for their location see Text-fig. 4B. For explanation of facies codes see Table 1, and for other explanations see Text-fig. 3.

deposited abruptly as a debris flow (Widera 2010). Most likely, these gravel-rich beds accumulated during accelerated tectonic subsidence at the turn of the Paleogene/Neogene. However, their deposition in the thalweg of the river channels cannot be rejected. This interpretation is presented for the first time and requires field verification. Regardless of which of the mentioned processes dominated, the Paleogene gravels were redeposited into the lowermost beds of the Koźmin Formation (Text-fig. 3A–C). Facies characterised by trough and planar cross-stratification (St, SGt, STCt, and Sp) are typical of channel bedforms such as 3-D and 2-D dunes, respectively (Allen 1965; Bridge 1993, 2003; Šujan *et al.* 2017). Some of them may also represent the mid-channel bars (longitudinal, transverse, composite), especially when lamination is slightly convex upwards (Allen 1983; Bristow and Best 1993). Instead, plane-parallel (horizontally) laminated facies (Sh, STh, and STCh) were produced during the weakening of the water flow over the entire deposition surface as sheetfloods (Miall 1996; Shukla 2009; Zieliński 2014) or during floods under upper flow regime (Fielding 2006; Šujan *et al.* 2020). On the contrary, the massive structure of some facies may be the result of the sudden deposition (Sm, STCm) or destruction of the original stratification by soil processes – the uppermost sedimentary facies SCm and Sm. This is evidenced by the presence of rootlets and roots that come from the peat-forming vegetation from which the overlying MPLS-1 was formed (Text-figs 3 and 4).

The architecture and sedimentary facies of the Koźmin Formation are typical of a braided river (Miall 1977, 1996; Allen 1983; Bristow and Best 1993; Bridge 2003; Zieliński 2014). They are characterised by the dominance of the sandy channel facies with high width/thickness ratios (w/t >20) along mine exposures up to 10–100s m in length. The fillings of individual channels are up to 5–10 m wide, and up to 0.3–0.5 m thick (Text-figs 3 and 4). Taking into account the results of the experimental and field studies conducted by Leclaire and Bridge (2001), it can be calculated that the average height of dunes was 72.5 cm (25 cm × 2.9), and a maximum of >1.3 m (0.45 × 2.9). The factor of 2.9 is also used by Iepli and Ghinassi (2015) to estimate the mean height of the dunes based on the cross-set thickness. On the other hand, the factor between 6–10 is used to determine the formative flow depth (Leclaire and Bridge 2001), averaging 8 (Šujan *et al.* 2020). Thus, the mean flow depth for the cross-beds analysed was in the range of 1.5–2.5 m.

The overbank facies, including fills of abandoned channels, occur sporadically in the form of thin lenses of lignite or clay, and they are known only from boreholes (Widera 2007). In addition, neither the stratification characteristic of point bars (typical of meandering river) nor deep channels (w/t <15) incising into overbank sediments (anastomosing river) were documented. Considering the above results of the facies analysis and the palaeogeography of the research area in the early Neogene, it can be concluded that the sand-dominated braided rivers flowed over vast alluvial plains, generally towards the west (Piwocki *et al.* 2004; Gibbard and Lewin 2016). An additional argument for the environment of a braided river system is the impoverishment of the clay fraction and the white colour of most sediments (Text-figs 3 and 4). This means that the Koźmin Formation accumulated on a relatively steeply sloped and well-drained depositional surface. Under relatively long-lasting oxidative conditions, the organic matter originally dispersed in the sediment was not preserved (Kraus and Hasiotis 2006). In contrast, when the groundwater level was close to the depositional surface, organic matter could form palaeosol horizons, even in the form of lignite layers at their top (Davies-Vollum and Kraus 2001).

Grey Clays Member (lower Poznań Formation)

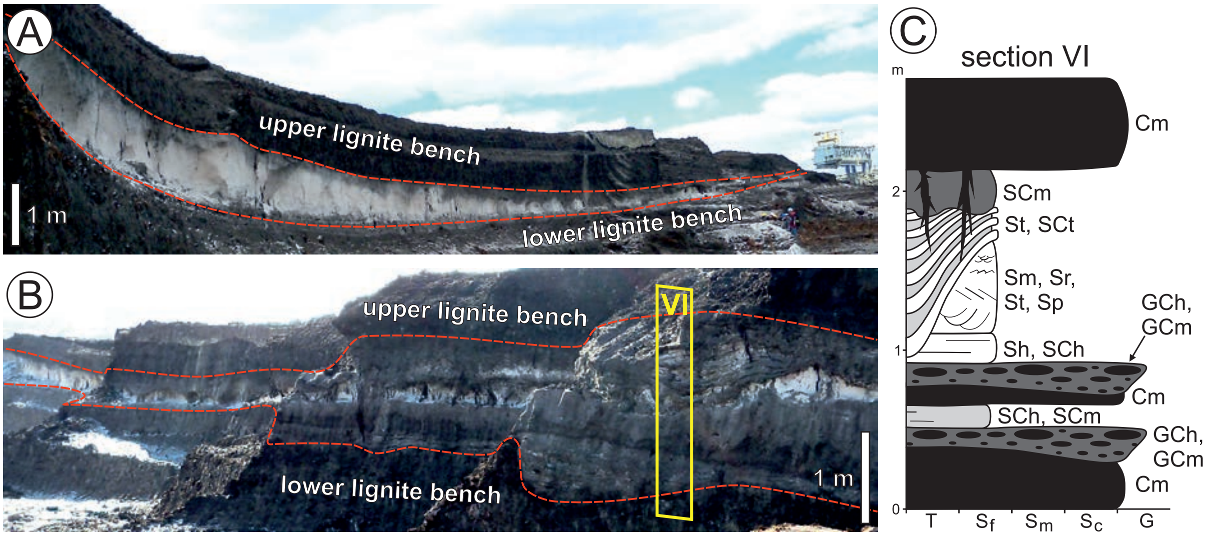
General characteristics

The Grey Clays Member, constituting a lower part of the Poznań Formation (see Text-fig. 2), mainly consists of the MPLS-1, as well as siliciclastics that split or cover it locally (Text-figs 5 and 6). The maximum thickness of this seam is nearly 20 m in the areas where lignite deposits occur and less than 3 m outside of them, while the siliciclastics are up to 2–5 m thick. The MPLS-1 will be characterised briefly first macropetrographically, palynologically, and geochemically. Subsequently, the sandy interbeddings will be examined in sedimentological detail. The so-called 'grey clays', which are occasionally present at the roof of the MPLS-1, will also be discussed.

Macropetrographical characteristics of the MPLS-1

The MPLS-1 from the Konin Basin is characterised by the predominance of the following lithotype associations: xylodetritic, detroxylitic, and detritic (Widera 2012, 2016b). All the portions of the MPLS-1 presented herein in a graphical form (photographs and sedimentary logs; Text-figs 3–6) consist solely of them. However, xylitic, weathered and fusitic lithotype associations occur occasionally in most of the studied lignite opencasts. For example, in the case of the same section from which samples for palynological and geochemical analyses were taken, the share of individual lithotype associations was as follows: xylodetritic – 58, detritic – 22, detroxylitic – 16 and weathered – 3 vol.% (Widera *et al.* 2021). Among them, it was easy to distinguish individual lithotypes which are characterised by a specific texture and structure. Thus, the most common lithotype consisted of xylodetritic lignite with a massive and fractured structure. Other lignite lithotypes occurred much more irregularly within the MPLS-1 from the Konin Basin (Kasiński *et al.* 2010; Widera 2012).

The xylodetritic lithotype association is attributed to the Myricaceae–Cyrillaceae swamp (Teichmüller 1958, 1989; Diessel 1992; Markič and Sachsenhofer 1997; Kolcon and Sachsenhofer 1999). Under the conditions of relatively high groundwater table, the detritic association was created in a treeless reed marsh, fen, or open water (Teichmüller 1958, 1989). In other words, the detritic lignite was predominantly formed



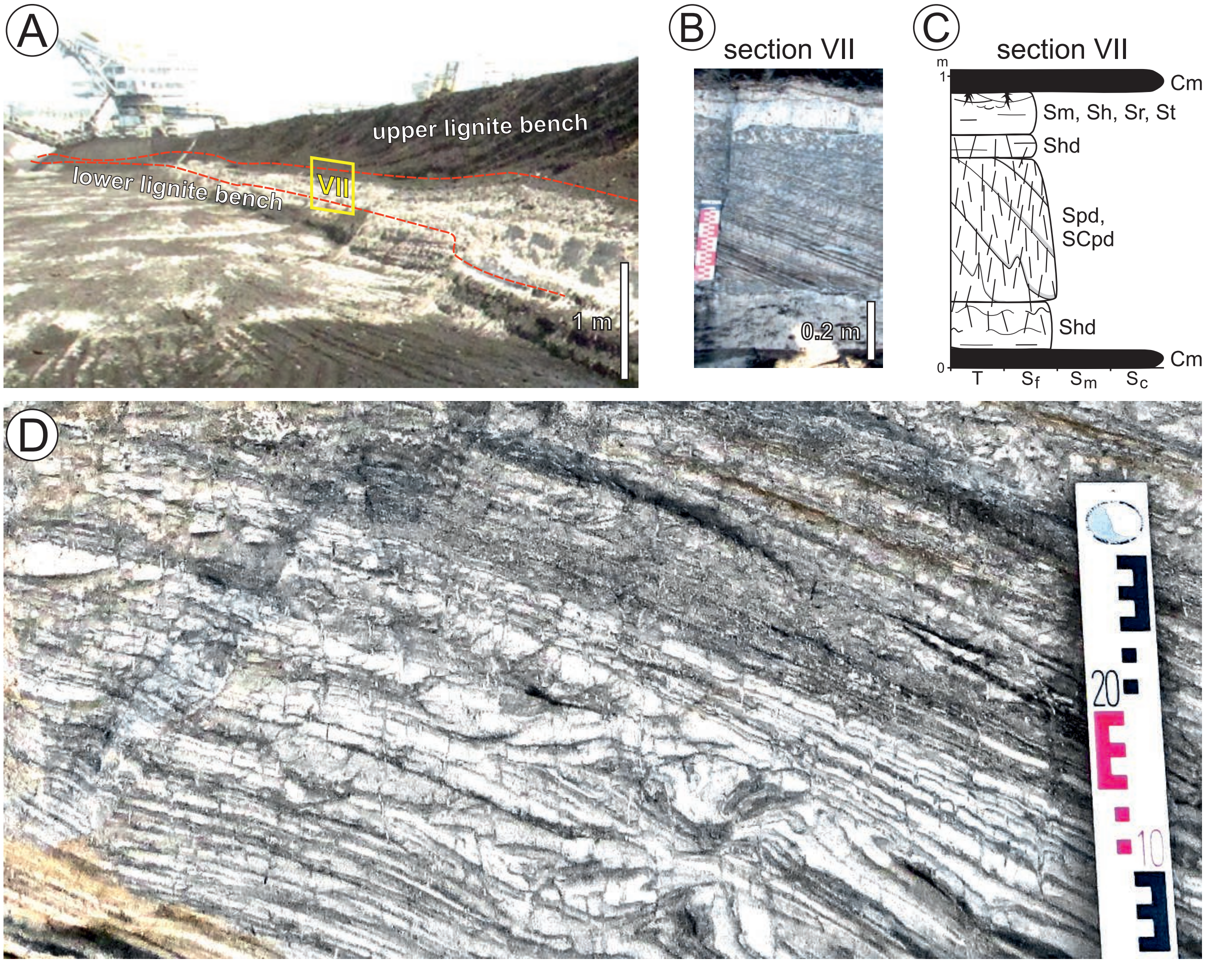
Text-fig. 5. Siliciclastics interbedding the lignite seam (MPLS-1) mined in the Tomisławice lignite opencast. A, B – Broad view of the examined sediments. C – Sedimentary log of the section VI analysed in detail (modified from Chomiak 2020a); note trough cross-stratification in the middle part of the section that is a record of filling the crevasse-splay distributary channel (not the dunes) parallel to the flow direction; for its location see Text-fig. 5B. For explanation of facies codes see Table 1, and for other explanations see Text-fig. 3.

from reed-like vegetation, sedges, and aquatic plants (Ticleanu *et al.* 1999; Markič *et al.* 2001). In a drier environment, but with a high groundwater table, conditions allowed the mire to be overgrown by hydrophilic woody vegetation. Such a type of mire is called a swamp forest or *Taxodium–Nyssa* swamp, which provides the parental material for the creation of a detroxylitic lithotype association (Teichmüller 1958, 1989; Markič and Sachsenhofer 1997; Kolcon and Sachsenhofer 1999; Ticleanu *et al.* 1999; Markič *et al.* 2001; Widera 2012, 2016b). On the other hand, the presence of the weathered lignite within the MPLS-1 proves that there was a water deficit in its upper beds during the mid-Miocene mire development. Thus, the uppermost layers of fresh peat, lying above the groundwater table, were subjected to oxidation processes, hence resulting in their pale colour (Widera 2016b; Kus and Misz-Kennan 2017; Widera *et al.* 2021).

Palynological characteristics of the MPLS-1

The section from the Adamów opencast is characterised by the presence of 84 fossil species of angiosperm pollen, 26 gymnosperm pollen species, 12 species of plant spores, and 13 species of non-pollen palynomorphs that belong to algae. In general, the listed palynological spectrum represents wetlands (shrub bogs with Ericaceae as well as swamp and riparian forests) and mesophytic forests (Worobiec *et al.* 2021). In the case of the section from the Jóźwin IIB, 74 angiosperm taxa, 21 gymnosperm taxa, and 10 spore taxa were identified. *Nyssa*, *Taxodium/Glyptostrobus,* and Ericaceae were most clearly marked in peat-forming vegetation. Moreover, siliciclastic interbedding and palynological cyclicity were documented in the section described (Słodkowska and Widera 2021). It is worth noting that there was a marked reduction in the number of thermophilous taxa upwards in both described sections (Worobiec *et al.* 2021; Słodkowska and Widera 2021).

A modern analogue of the mid-Miocene mires from the Adamów opencast may be the pocosins in the southeastern USA, extending from Florida to Virginia (Worobiec *et al.* 2021). Most likely, the mires were located further from the river channels and at a higher morphological position. Therefore, these areas were flooded occasionally. On the contrary, the territory of the Jóźwin IIB opencast was situated in close proximity to the mid-Miocene active river channels as evidenced by the siliciclastic interbeddings typical of crevasse splays that are characterised below. The estimated mean annual temperature (MAT) for the sections interpreted were in the ranges of 15.7–18.0°C and 15.7–20.5°C, respectively (Worobiec *et al.* 2021; Słodkowska and Widera 2021). The MAT values obtained for the MPLS-1 are consistent with those for its stratigraphic equivalents from other areas of Poland (Kasiński *et al.* 2010; Worobiec *et al.*



Text-fig. 6. Siliciclastics interbedding the lignite seam (MPLS-1) mined in the Jóźwin IIB lignite opencast. A – Broad view of the examined sediments. B – Close-up view of the siliciclastics (section VII) typical of the crevasse-splay microdelta; note plane cross-stratification in the middle part of the section and deformation of the deposits. C – Sedimentary log of the section VII analysed in detail. D – More detailed view of deformations (brittle and ductile) in the foreset of the crevasse-splay microdelta; for its location and close-up view see Text-fig. 6A, B, respectively. For explanation of facies codes see Table 1, and for other explanations see Text-fig. 3.

2008; Kasiński and Słodkowska 2016) and Germany (Utescher *et al*. 2009). At that time, the mean annual precipitation was in the range of 800–1300 mm (Ivanov and Worobiec 2017). Thus, a climate similar to the mid-Miocene climate in central Poland currently prevails in the southern and southeastern USA (Barnes 1991), as well as in coastal areas of eastern China and in southern China (Utescher *et al.* 2009). Taking into account all palynological data, it may be assumed that the MPLS-1 was formed during and shortly after the last peak of the MMCO, that is, its accumulation continued at a time when the global and regional tendency towards cooling and seasonality was clearly marked (Widera *et al*. 2021).

Geochemical characteristics of the MPLS-1

The basic bulk geochemical data obtained for detritic lignite and xylites from the MPLS-1 are slightly to very different. The average total carbon (TC) contents were between 45.9 wt.% for detritic lignite and 46.2 wt.% for xylites. In the case of the total sulfur (TS) contents, the average values were 1.0 and 1.2 wt.%, respectively. The average total organic carbon (TOC) contents were 45.5 wt.% for detritic lignite and 43.8 wt.% for xylites, while the average total inorganic carbon (TIC) contents were 0.4 and 2.4 wt.%, respectively. The average ash yields, obtained from geochemical analyses (55 samples), were 20.0 wt.%

for detritic lignite and 5.3 wt.% for xylites (Bechtel *et al.* 2019, 2020). However, the ash yield for the entire MPLS-1 the Konin Basin (based on 266 samples) was in the range of 9.7–17.6 wt.% on average (Chomiak 2020b). These ashes contained on average ~50 wt.% of SiO_2 and over 30 wt.% of CaO (Chomiak and Widera 2020). On the other hand, the average $\delta^{13}C$ of TOC values were -25.6 ‰ and -25.0 ‰ for xylites. In general, the obtained $\delta^{13}C$ values slightly decreased upwards in the MPLS-1 (Bechtel *et al.* 2019, 2020).

The results of geochemical studies allowed the classification of the MPLS-1 as an ortho-lignite (ECE-UN 1998) and a humic low-rank lignite B (ASTM D 388:2005). This was additionally supported by the low mean values of the reflectance coefficient (less than 0.3%) determined on euulminite B (Kwiecińska and Wagner 2001). On the other hand, the investigated lignites were classified as medium-ash (10–20 wt.%), while the ashes produced from the burning of the MPLS-1 represented the calcium-rich type (>10 wt.% of CaO) (Vassilev *et al.* 1997; Wagner *et al.* 2019; Chomiak and Widera 2020). A slight general tendency towards lower $\delta^{13}C$ of TOC values from the floor to the seam roof may be additional evidence of peat accumulation during the climate cooling (Lücke *et al.* 1999). This relationship was also true for the MPLS-1 and was consistent with the results of palynological studies presented above.

Facies description of siliciclastics related to the MPLS-1

For facies analysis, two sandy bodies that occurred in the MPLS-1 were selected for this paper. The first one was derived from the Tomisławice opencast (Text-fig. 5), and the second from the Józwin IIB opencast (Text-fig. 6). In these two examples, the siliciclastic lithosomes were lens-shaped, up to 1.4–2 m thick, and up to 400–550 m long along the exploitation walls (Text-figs 5A, B and 6A). Nevertheless, their facies were very diverse. In the first case, the sediments were usually characterised by massive structure, although in some parts of the sandy body various sedimentary structures had been identified. The best example is where the siliciclastics were separated by a 20 cm thick layer of lignite (Text-fig. 5C). Both large-scale and small-scale stratifications (facies GCh, Sh, SCh, St, SCt, Sp, and Sr) were found there. Moreover, some small-scale facies typical of 2-D and 3-D dunes (Sp an St, respectively) were up to 14 cm thick, averaging 11 cm. None of these facies were disturbed. On the contrary, the second example covered the sandy body which contained a great number of plastic and brittle deformations (Text-fig. 6B–D). The lowermost and upper parts of section VII were made up of deformed, horizontally laminated sands – facies Shd, while its uppermost facies were undeformed – facies Sm, Sh, St, and Sr. However, the most diagnostic part was its middle portion where the strongly deformed lamination of sands and carbonaceous sands (facies Spd and SCpd) dipped steeply at an angle in the range of 15–25° (Text-fig. 6C, D). Locally, the 'grey clays' rest on top of the MPLS-1 (see Text-fig. 2, borehole TM-18).

Facies interpretation of siliciclastics related to the MPLS-1

The occurrence of the siliciclastics within the coal seam, in the interpreted case within the MPLS-1, was usually associated with floods in the mire areas. In addition, the lens-like geometry of the entire sand bodies and facies associations pointed to crevasse splays that may have been accumulated in various depositional sub-environments (e.g., Horne *et al.* 1978; Guion 1984; McCabe 1984; Flores 1986; Farrell 2001; Zieliński 2014; Widera 2020). Thus, the deposits of the first crevasse splay described above (Text-fig. 5) were deposited on the surface of the mire with a relatively low groundwater table (Widera 2016a; Widera *et al.* 2017b; Chomiak 2020a). Using the factor of 2.9 (Leclaire and Bridge 2001; Iepli and Ghinassi 2015), the average height of the small-scale dunes was calculated at ~32 cm (11 cm × 2.9) and a maximum of >40 cm (14 cm × 2.9). On the other hand, the mean formative flow depth (for the factor 6–10; Leclaire and Bridge 2001) was within the range of 66–110 cm. This interpretation was confirmed by the similarity of these facies to those of other crevasse-splay sediments also deposited on the floodplains, but outside the mires (Gębica and Sokołowski 2001; Burns *et al.* 2017).

The formation of the sediments shown in Text-fig. 6 should be explained in a different way. The majority of these deposits accumulated in a lake as evidenced by steeply dipping (up to 25°) foresets of the so-called 'prograding splay deposits'. Simply put, the interpreted sediments are typical of a crevasse-splay microdelta (e.g., Teisseyre 1985; Bristow *et al.* 1999; Michaelsen *et al.* 2000; Rajchl *et al.* 2008; Zieliński 2014). On the other hand, the plastic and brittle deformations were generated post-depositionally due to mid-Miocene tectonic movements in the study area (Text-fig. 6B–D; Chomiak *et al.* 2019; Wachocki *et al.* 2020).

Finally, the presence of the crevasse-splay deposits within the MPLS-1 proves that this mid-Miocene mire was developed in the close proximity of active river channels. Such forms of overbank accumulation (crevasse splays) are known almost exclusively from the depositional environments of meandering and anastomosing rivers (e.g., Allen 1965; Bridge 2003; Zieliński 2014). Nevertheless, it should be noted that several examples of crevasse splays have also been described from braided rivers as summarised by Bristow *et al.* (1999). In any case, the determination of the river type (most likely, meandering or anastomosing) remains an unsolved research problem (Widera 2016a; Widera *et al.* 2017b, 2021; Chomiak 2020a). This is due to the simple fact that the channel sediments had not been exposed so far.

In contrast, the aforementioned ‘grey clays’ should be interpreted as having formed during the final stage of the development of the mid-Miocene mires, when organic accumulation (peat) was replaced by mineral deposition (clays with xylites). Hence, the MPLS-1 and the overlying ‘grey clays’ were joined together into the Grey Clays Member (Piwocki and Ziembińska-Tworzydło 1997).

Wielkopolska Member (upper Poznań Formation)

General characteristics

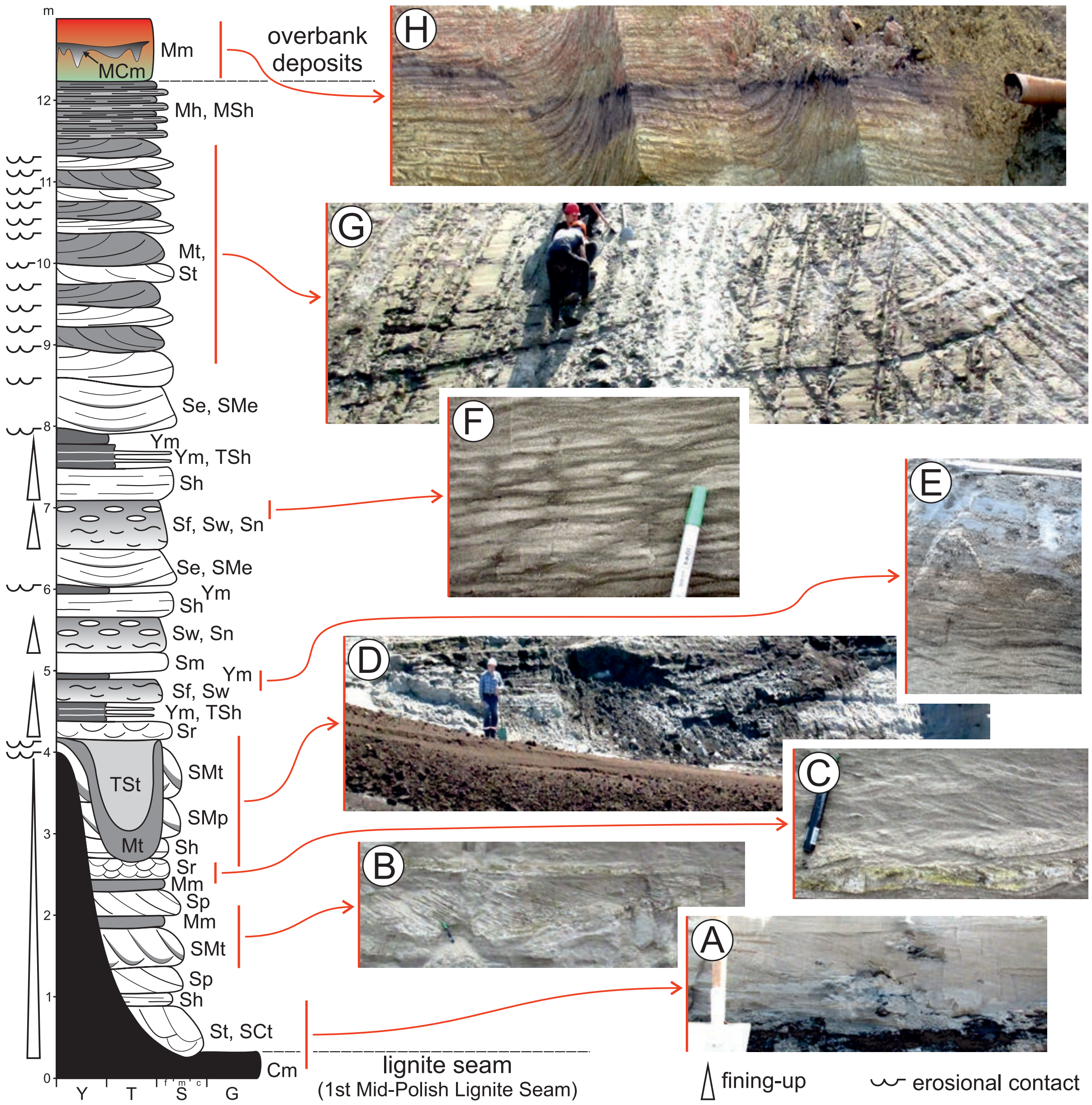
The upper portion of the Poznań Formation, namely the Wielkopolska Member, is the youngest Neogene lithostratigraphical unit in central Poland. Due to Pleistocene erosion and glaciotectonics, its thickness ranges from 0 to over 50 m, with an average of 20 m. Hence, sediments of this member were not drilled in all boreholes in the study area (cf. Text-fig. 2). It is the most lignite-poor and mud-rich (>95 vol.%) Neogene sedimentary succession in central Poland (Widera 2013a; Widera *et al.* 2017a). These generally fine-grained deposits can be divided into overbank muds and sandy-muddy channel fillings. Therefore, both channel and overbank sediments will be described and interpreted below in order to reconstruct the environment of their deposition. All characterised facies come from the Jóźwin IIB opencast (Text-fig. 7).

Facies description

The description of the channel facies presented herein is based on the data from the largest palaeochannels identified so far within the Wielkopolska Member. These primary palaeochannels are wide, in the range of 46–150 m, and their fillings are 5–12 m thick. They are cut into the muds and occasionally also into the underlying MPLS-1 to a depth of ~4 m (Text-fig. 7). At the base of the primary channels cross-stratified sandy facies dominate at large scale – facies St, Sp, Sh, and SCt. In the case of St and Sp facies, they are 15–40 cm thick, averaging ~30 cm. Generally, the content of mud, silt or clay increases from the base to the top of the channel fillings – sandy-muddy facies SMt, Mm, SMp, Ym, TSh, Mt, Mh, and MSh (Text-fig. 7A–C, G). This is also true for the heterolithic bedding, which is flaser (Sf), wavy (Sw), and lenticular/nodular (Sn), and where the mud content increases towards the top (Text-fig. 7E, F). The secondary channels (up to 30 m wide and up to 3 m thick), cut into the primary ones in their middle and upper parts (Text-fig. 7), and consist of sandwiched muddy – Mt, sandy – St, Se, and sandy-muddy facies – TSt, SMe (Text-fig. 7D, G). On the other hand, the muddy sediments that surround and cover the palaeochannel fillings described above are predominantly massive and sedimentary structures (e.g., horizontal lamination, erosive cuts, etc.) occur sporadically. The most characteristic feature is their colour variation from blue to red. Moreover, thin gray to black layers can sometimes be observed among them (Text-fig. 7H).

Facies interpretation

The channel facies are typical of high and low water stages. This is evidenced by the presence of stratification at large and small scales. The calculated flow power is between 2.5 to 21 W m^{-2} (Zieliński and Widera 2020). Using the above-mentioned formulas by Leclaire and Bridge (2001), the average height of the dunes was calculated at ~0.9 m, with a maximum of ~1,2 m. The palaeodepth was estimated at ~1.8–3 m; however, Zieliński and Widera (2020) give values up to 4 m using other formulas. The facies sequence allowed us to conclude that the majority of the palaeochannel deposits were formed under low-energy and relatively long-lasting flow conditions, when the flow was weakening, or the water was almost stagnating. Then, deposition from suspension prevailed over bedload accumulation leading to the formation of clay, mud, and muddy-sandy facies, as well as the heterolithic bedding (Reineck and Singh 1980; Martin 2000; Maciaszek *et al.* 2019). On the contrary, the facies cross-stratified at a large scale were created during short-term flood events. This was evidenced by the enrichment of sands with mud (Text-fig. 7B, C), often in the form of mud balls



Text-fig. 7. Synthetic sedimentary log and sandy-muddy facies representing primary channel and overbank sediments within the Wielkopolska Member (upper Poznań Formation) from the Józwin IIB opencast. A – Erosional contact between the MPLS-1 and the channel-fill deposits; note trough cross-stratification and channel lag at the base. B – Sandy-muddy trough cross-stratification overlain by muddy layer. C – Ripple cross-stratification. D – Secondary channels filled with mud and sandy silt. E – Heterolithic bedding (flaser and wavy) covered by clayey layer. F – Heterolithic bedding (lenticular, nodular). G – Sandwiched filling of secondary muddy and sandy channels. H – Multi-coloured overbank muds with a palaeosol horizon.

(Widera *et al.* 2017a, 2019b). The cross-sectional geometry of the primary and secondary palaeochannels (the aspect ratio width/thickness in the range of 5–15 and 15–30, respectively) indicated their lack of or limited lateral migration (Zieliński and Widera 2020).

In the case of the primary palaeochannels, their banks were stabilised by strongly cohesive muds that have been interpreted as overbank sediments. This opinion was supported by the occurrence of organic-rich palaeosol horizons (Text-fig. 7C), including lignite beds within the mud-dominated succession (Piwocki *et al*. 2004; Widera 2007; Urbański and Widera 2016; Maciaszek *et al*. 2020). Moreover, the varied colours of these muds pointed to repeated changes in the oxidation and reduction conditions, caused by fluctuations in the groundwater table (Davies-Vollum and Kraus 2001). Additionally, taking into account the reconstructed multichannel pattern in the Jóźwin IIB opencast area (cf. Widera *et al*. 2019b, 2021; Maciaszek *et al*. 2020), the river type should be classified as anastomosing (Smith and Smith 1980; Nadon 1994; Makaske 2001; Gibling 2006; North *et al*. 2007; Zieliński 2014). Finally, it can be said that the Wielkopolska Member predominantly accumulated in low-gradient and well-drained sedimentary basins. The overbank areas were covered with water during the occasional but huge floods. Then, the majority of mud-laden floodwaters drained back into the river channels during the falling stage (cf. Widera *et al*. 2019b). Thus, in long-term periods between the floods, the sediments were above the groundwater table and exposed to intense weathering. This is supported by the presence of multi-coloured muds as interpreted above. Of course, not always and not every part of the overbank zone was well drained. In such a situation, organic-rich palaeosols developed (cf. Text-fig. 7H).

DISCUSSION

Evolution of palaeoriver systems

The results of the sedimentological analysis presented above, supported by other data in the case of the MPLS-1, imply terrestrial, mainly fluvial palaeoenvironments for all the studied siliciclastics. Therefore, taking into account the views on the palaeogeography of the Alpine-Carpathian foreland (and the Sudetes) in the Neogene, new models for the development of fluvial systems in central Poland can be proposed. According to the lithostratigraphic division of the Neogene in the study area, three palaeoenvironmental models were created, which are characterised and discussed in this contribution. They include the following sedimentary successions: sub-lignite, lignite-bearing (i.e., the MPLS-1 with accompanying siliciclastics), and over-lignite (Text-fig. 8).

The first model corresponds to the depositional environment of the sub-lignite sediments classified as the Koźmin Formation (cf. Text-figs 2 and 8A). The topography of the sedimentary basin, covering extensive territories of the European Lowlands (Vinken 1988; Gibbard and Lewin 2016), was relatively steep and well-drained. As proven by field observations (Figs 3, 4), sediments characteristic of the environment of a braided river developed before ~15 Ma (Text-fig. 8A).

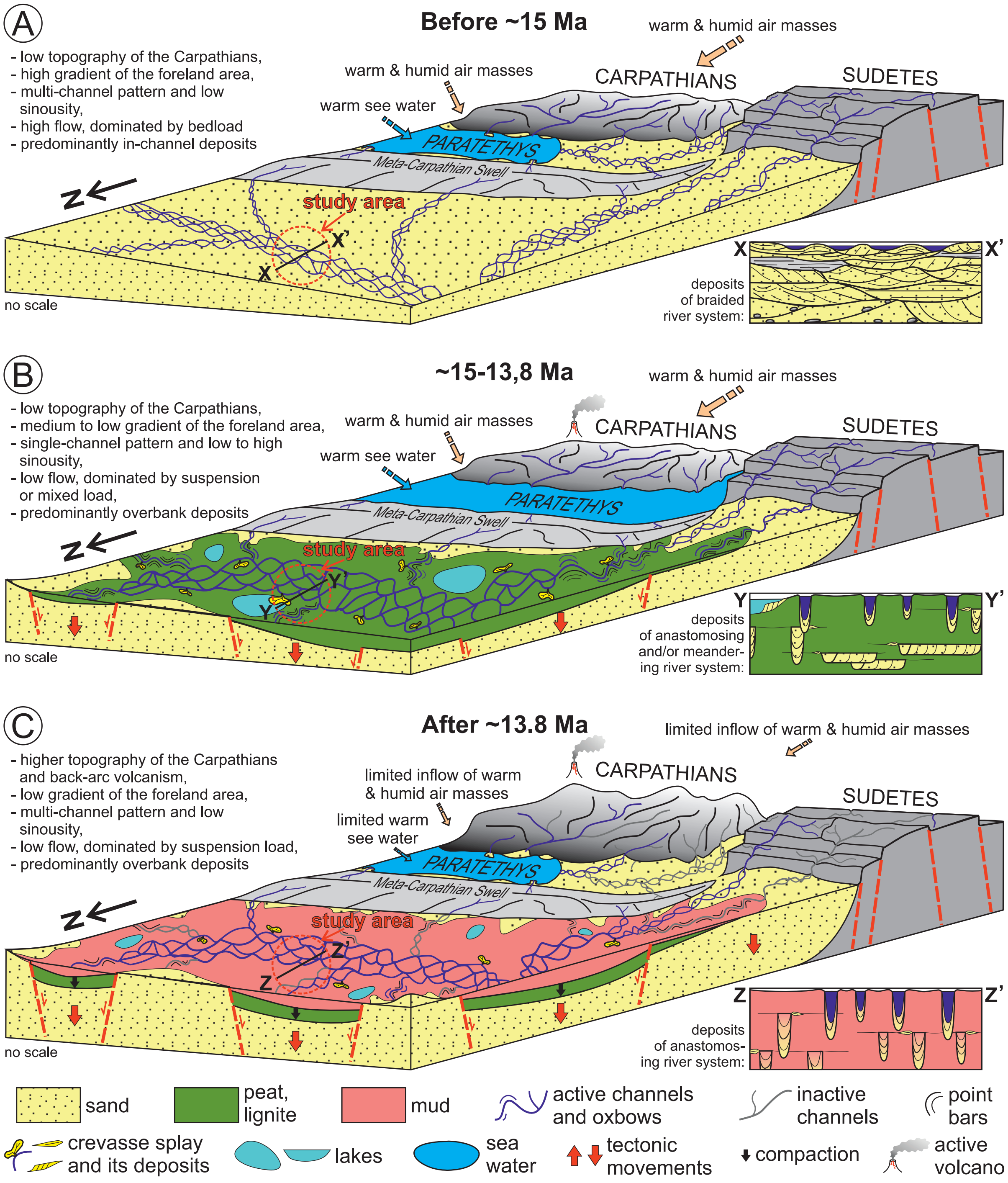
Then, the lignite-rich Grey Clays Member (lower part of the Poznań Formation) accumulated (cf. Text-figs 2 and 8B). Around the last peak of the MMCO (~15 Ma) siliciclastic deposition gave way to organic deposition, that is, peat (Text-figs 5 and 6). The low-lying mires from which the MPLS-1 was formed, most likely developed in the area with a more sloping topography in the vicinity of a meandering river (Horne *et al*. 1978), and in the flatter areas in the vicinity of an anastomosing river (Flores and Hanley 1984). However, the coexistence of these two fluvial styles (meandering and anastomosing) may also have been possible (Text-fig. 8B; Flores 1986; Widera *et al*. 2021).

Finally, after ~13.8 Ma, the mud-dominated Wielkopolska Member (upper part of the Poznań Formation) began to accumulate (cf. Text-figs 2 and 8C). In the areas with lignite deposits from the Konin Basin, the channel sandy-muddy sediments, and the overbank muddy ones (Text-fig. 7), as well as the channel pattern (Maciaszek *et al*. 2020, their fig. 8), are typical of anastomosing or anastomosing-to-meandering rivers as interpreted above. In this case, it can be assumed that outside the areas of lignite deposit (located in local tectonic depressions – grabens) and in the marginal parts of the sedimentary basin, the river system could have been meandering (Text-fig. 8C).

Tectonic and climatic changes

The boundaries between the three main lithostratigraphical units from the study area are mostly sedimentary, but sharp. This means that the above-discussed corresponding depositional palaeoenvironments changed suddenly from a geological point of view. Therefore, the question of whether the main cause of these changes was tectonic or climate-driven arises.

After the late Oligocene uplift (Krzywiec 2006; Jarosiński *et al*. 2009), the entire area of central Poland began to subside at the turn of the Oligocene/Miocene. In general, the depositional surface was well-drained, and the rivers flowed westward to the North Sea Basin (Standke *et al*. 1993; Piwocki *et al*. 2004; Gibbard and Lewin 2016). At that time, i.e., during the early and lower parts of middle Miocene, an overall trend of increasing temperature was observed persisting into the MMCO. The mean annual precipitation (MAP) was high then, exceeding 1000



Text-fig. 8. New conceptual models for the main Neogene fluvial systems from the Konin Basin in central Poland. A – Braided river system. B – Meandering and/or anastomosing river system. C – Anastomosing or anastomosing-to-meandering river system.

mm (Mosbrugger *et al*. 2005). This resulted in the fact that the river flow in the relatively high-slope area of central Poland was even and intense. Under such tectono-climatic conditions, the braided style of the fluvial system dominated in most of the Polish Lowlands (Text-fig. 8A).

Strong tectonic and palaeogeographic events took place in the Western Carpathians, as well as both in their foreland and back-arc territories around 15 Ma (Plašienka *et al.* 1997; Fodor *et al.* 1999; Krzywiec 2001; Kováč *et al.* 2007; Andreucci *et al.* 2013; Śmigielski *et al.* 2016; Šujan et al. 2021). The pronounced transgression (early Badenian) occurred then, for example, in the Carpathian Foredeep and the Pannonian Basin Systems (Oszczypko 2006; Kováč *et al.* 2017a, b; Sant *et al.* 2019). The warm oceanic waters in the northernmost branch of the Central Paratethys (i.e., in the Carpathian Foredeep) additionally increased the temperature and humidity in the foreland of the Polish Carpathians (Text-fig. 8B). This latest MMCO peak is reflected by slight increases in temperature (MAT) and precipitation (MAP) records both globally (Zachos *et al.* 2001), as well as in other European basins (Schneider 1992; Planderová *et al.* 1993; Böhme 2003; Mosbrugger *et al.* 2005; Hernández-Ballarín and Peláez-Campomanes 2017; Holcová *et al.* 2018; Utescher *et al.* 2009, 2021) and the Konin Basin studied here (Słodkowska and Widera 2021; Worobiec *et al.* 2021). In the latter case, the accumulation of the MPLS-1 started at the time of this climatic optimum (~15 Ma) and continued (max. 0.8 Ma) when the temperature began to decline (Widera *et al.* 2021). The outline of the sedimentary basin of the Poznań Formation was also formed at that time. In general, the accommodation space and sediment supply ratio were very limited. Due to greater tectonic subsidence of the central part of this basin, including the lignite-rich grabens, than that of its marginal parts, it became poorly-drained (cf. Gawthorpe and Leeder 2000). Therefore, with relatively high MAP (up to 1300–1500 mm) and MAT (up to 15.7–20.5°C) in the study area (Widera *et al.* 2021), as well as a low slope of the depositional surface, low-lying mires developed intensively, and were subsequently transformed into the MPLS-1. The exception was the territories of tectonic grabens, where the accommodation rate in relation to the sediment supply ratio was ~1.0, but both were several times greater than in the surrounding areas. Most likely, the mentioned mires existed in the overbank zone of the anastomosing and/or meandering river systems that also flowed westward to the North Sea Basin (Text-fig. 8B; Piwocki *et al.* 2004; Gibbard and Lewin 2016).

The Mi3b global cooling event terminated the MMCO sensu Böhme (2003). This corresponded closely to the glaciation of eastern Antarctica (Zachos *et al.* 2001; Bruch *et al.* 2007), as well as to the abrupt deceleration in cooling of the Tatry Mountains (Śmigielski *et al.* 2016). In the Carpathian Foredeep, the Badenian Salinity Crisis commenced at that time (~13.8 Ma) as dated radiometrically (Bukowski *et al.* 2010; de Leeuw *et al.* 2010). The event was caused by the tectonic movements of the Carpathians (Oszczypko 2006), which closed the gateway connection with the Mediterranean Sea Basin (Kováč *et al.* 2007, 2017b; Sant *et al.* 2019), and the MAT was able to drop by even over 7°C (Böhme 2003; Peryt 2006). The Langhian/Serravalian (early/late Badenian) boundary also correlated well with the intensification of volcanic phenomena (stratovolcanoes) and the beginning of the accelerated subsidence of some basins (grabens or half-grabens) in the Carpathian back-arc area (Kováč *et al.* 2007). Nevertheless, the rapid elevation of the Alpine-Carpathian mountain chains caused a climatic gradient between their foreland and back-arc basins. This has been well documented palynologically and paleontologically (Planderová *et al.* 1993; Böhme 2003; Holcová *et al.* 2018; Doláková *et al.* 2021). Thus, under conditions of both global and regional cooling, the reduction of air humidity and the increased seasonality of the climate in the foreland of the Alpine-Carpathian orogenic belt, including the Konin Basin area, increased over time (Piwocki and Ziembińska-Tworzydło 1997; Mosbrugger *et al.* 2005; Słodkowska and Kasiński 2016; Utescher *et al.* 2021). At that time (after ~13.8 Ma), the slow tectonic subsidence of the sedimentary basin continued in central Poland, and the rivers flowed to one or more endorheic 'terminal floodplain' basins with a centripetal drainage pattern (Czapowski and Kasiński 2002; Widera 2013a; Widera *et al.* 2017a, 2019b). The sandy-muddy channel deposits with a low aspect ratio (w/t <15) and the dominant muddy overbank sediments (with palaeosol horizons and thin layers of lignite) were characteristic of an anastomosing river system existing in a drier climate than when the MPLS-1 was accumulating (cf. Text-figs 7 and 8C).

Summing up, it should be stated that the research results obtained in this contribution have allowed us to clearly answer the question posed at the beginning of this section. In the foreland of the Polish Carpathians, the morphological type of the river was primarily controlled by tectonics. For example, ~15 Ma the climatic conditions changed slightly, but the fluvial style and deposits changed dramatically in the Konin Basin, that is, from a braided to anastomosing and/or meandering style (cf. Text-fig. 8A and 8B). In contrast to the Alpine-Carpathian area, slow lowering movements continued in its foreland ~13.8 Ma. Therefore, the anastomosing (and/or meandering) fluvial style also continued at that time. However, the lithology of the sediments changed rapidly then, especially in the overbank river zone (from lignite to mud), which can be convincingly explained by abrupt climatic fluctuations (cf. Text-fig. 8B and 8C).

CONCLUSIONS

The Neogene of central Poland (Konin Basin) is divided into three lithostratigraphical units that encompass three depositional palaeoenvironments. They have been evaluated in the foreland of the Polish Carpathians, which form the north-western part of the Alpine-Carpathian orogenic belt. The activity of the latter, resulting from global and regional plate tectonics, also influenced the development of sedimentary basins in the foreland areas.

At the same time, there were also significant climatic fluctuations especially in the middle Miocene (around the MMCO). These regional climatic changes, were further enhanced by the tectonics of the Alpine-Carpathian orogen, superimposed on global climatic fluctuations. Nevertheless, this study sheds new light on the role of tectonics and climate in the Neogene deposition in the lignite-rich Konin Basin.

The first depositional palaeoenvironment includes sediments that underlie the MPLS-1 (i.e., Koźmin Formation) and were formed before ~15 Ma. These predominantly sandy (>83 vol.%) deposits exemplify a braided type river system. Then, as the accommodation rate increased due to the tectonic lowering of the Polish part of the Carpathian foreland and with favourable climatic conditions, mires (later transformed into the MPLS-1) began to develop intensively in central Poland.

This boundary (~15 Ma) correlated well, among others, with the transgression of the Central Paratethys to the area of the Carpathian Foredeep and the last peak of the MMCO. Based on the presence of crevasse-splay sediments within the MPLS-1, supported by the results of macropetrographic, palynological, and geochemical studies, it was found that the Grey Clay Member (lower Poznań Formation) accumulated in an anastomosing and/or meandering river environment. However, the determination of which fluvial style dominated during the MPLS-1 deposition requires further research.

Finally, the Wielkopolska Member (upper Poznań Formation) was formed under similar tectonic conditions, but in a significantly different climate. The beginning of its accumulation (~13.8 Ma) corresponded closely to the uplift of the Alpine-Carpathian mountain chains and the start of the Badenian Salinity Crisis in the Carpathian Foredeep, of course, caused by the tectonic interruption of the connection with the warm waters of the Mediterranean Sea Basin. Hence, under the conditions of progressive cooling and seasonality of the climate, mainly muds (>95 vol.%) were accumulated in the environment of an anastomosing or anastomosing-to-meandering river system.

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