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# Geological and palaeogeographical peculiarities of the Adamów Graben area, central Poland

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**Abstract**

From a geological and palaeogeographical point of view, the area of the Adamów Graben in the vicinity of Turek ranks amongst the best known in central Poland, with several opencast mines located here where lignite was exploited for 57 years. These large-surface exposures provide a good opportunity for detailed geological studies of strata of Late Cretaceous to Holocene age. However, the present research focuses mainly on those deposits, forms and structures that have been most thoroughly examined and are best exposed. These are Cretaceous marls and gaizes, Paleogene 'blue clays' and the 'Koźmin Gravels', Neogene sandstones, as well as the Quaternary glacial 'Lake Koźmin', involutions and 'Koźmin Las'. Some of these, e.g., the 'Koźmin Gravels' and 'Koźmin Las', are not known from other Polish territories. Furthermore, results obtained by the authors over a period of nearly 30 years also include data on palaeogeographical changes across some Cenozoic intervals, especially during the early Oligocene and late Weichselian.

**Key words:** marine rocks, Oligocene clays, Oligocene pebbles, Miocene sandstones, glacial lake, periglacial involutions, fossil forest

## 1. Introduction

The name Adamów Graben, situated close to the town of Turek in central Poland (Fig. 1), was coined by the senior author of the present paper (Widera, 1998). This tectonic palaeodepression belongs to a large group of grabens that are filled with productive lignite seams. In the study area, there are four main lignite deposits, namely 'Adamów', 'Krwony', 'Koźmin S' and 'Koźmin N' (Fig. 1B). Originally, these formed a single deposit during the Miocene, which was divided into smaller occurrences by relatively deep subglacial channels during the Pleistocene (Czarnik, 1972; Trzmiel, 1996; Widera, 1998). Some portions of these lignite deposits occur beyond the outline of the Adamów Graben (Fig. 1B) and are thus classified genetically as tectonic and epeirogenic types, as well as graben and sheet subtypes (Widera, 2016a).

Lignite extraction in the vicinity of Turek, with an average annual volume of 4.5–5 Mt, was managed by the Adamów Lignite Mine. Mining activity began in 1964 in the Adamów opencast ('Adamów' deposit) and came to a halt at the same opencast in 2021 (Widera, 2021). The remaining opencasts hosted lignite mining activities in the following years: 1977–1991 (Bogdałów opencast, 'Krwony' deposit); 1991–2009 (Koźmin S opencast, 'Koźmin S' deposit) and 2009–2016 (Koźmin N opencast; 'Koźmin N' deposit) (Fig. 1B). As such, results of our studies are derived from the Adamów, Koźmin S and Koźmin N lignite opencasts and their immediate surroundings.

The lignite-fired Adamów power plant was closed at the beginning of 2018. Since then, the demand for lignite from the sole Adamów opencast has dropped sharply to less than 1 Mt per year.


**Fig. 1.** Location map of the study area. **A** – The Adamów Graben on the contour map of Poland; **B** – Outline of the Adamów Graben with the location of lignite deposits.

From 2018, until the closure of Adamów Lignite Mine operations in 2021, the extracted lignite was used in the Pątnów power plant, several dozen kilometres away from the Adamów opencast. Therefore, the closing of the last of the operating lignite opencasts in the vicinity of Turek provides a good opportunity to summarise our research results obtained over the past quarter of a century. The major goal of the present study is to describe and interpret the most interesting geological and palaeogeographical peculiarities of the Adamów Graben area.

## 2. Geological setting

Geologically, according to the division of the territory of Poland into tectonic units, the graben is situated in the Szczecin-Miechów Synclinorium and, more precisely, in the central part of the Mogilno-Łódź Segment (Żelaźniewicz et al., 2011) and in the southeastern part of the Konin Elevation (Widera, 1998). The width and length of this SSW-NNE-trending, fault-bounded palaeodepression is from between <1 km (N segment) and >3 km (S segment), and >10 km, respectively (Fig. 1). The maximum depth of this negative tectonic structure is 40–55 m, with an average of only ~30 m, calculated between the height of the Mesozoic bedrock in the axial zone of the graben and its flanks (Fig. 2). The top of the Mesozoic bedrock in the territory of the Adamów Graben and its surroundings consists

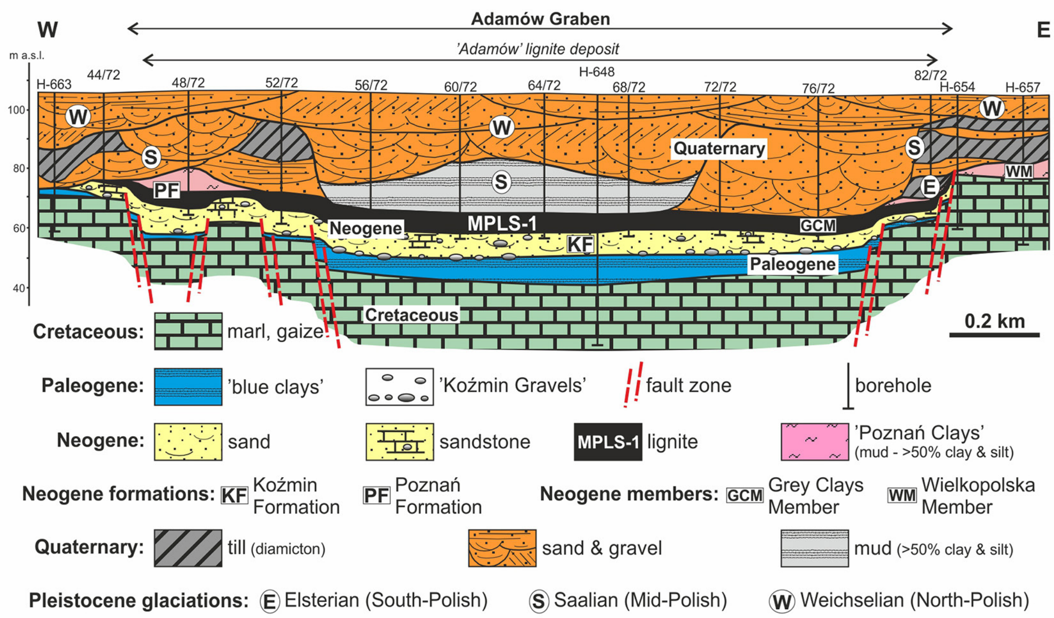


**Fig. 2.** Representative geological cross-section through the central part of the Adamów Graben. For location of the cross-sectional line see Figure 1B.`

mainly of marls and gaizes of Late Cretaceous age (Widera, 1998; Dadlez et al., 2000).

The Cenozoic succession in the study area is incomplete and contains several stratigraphical hiatuses (compare Figs. 2, 3). Due to long-term uplift and erosion, no Paleocene and Eocene sedimentary rocks have been found to date in the vicinity of Turek. Therefore, the oldest Paleogene deposits are of early Oligocene age and include two main lithological groups: the 'blue clays' and the 'Koźmin Gravels' (Widera, 2007, 2010; Widera & Kita, 2007). As far as the gravels are concerned, these have been in part redeposited into younger sediments of Miocene age (Fig. 3).

The next stratigraphical gap covers the late Oligocene, because there are no documented deposits of this age around the Adamów Graben. At the time, almost the entire region of what is now central Poland was subjected to regional tectonic uplift (Krzywiec, 2006; Jarosiński et al., 2009; Widera & Hałuszczak, 2011). Hence, sedimentation of the Neogene succession started at the beginning of the Miocene, when the trend of vertical movements changed into one of subsidence. Two main lithostratigraphical units were formed, i.e., the lower Koźmin Formation and the upper Poznań Formation (Fig. 3).

The stratotype area of the Koźmin Formation is located in the northern part of the Adamów Graben (Widera, 2001, 2004, 2007). This formation consists of sub-lignite fluvial sands and sandstones with coaly intercalations and is of early to mid-Miocene age. As noted above, the redeposited Paleogene 'Koźmin Gravels' are commonly present within this lithostratigraphical unit, especially at its base (Figs. 2, 3). The sub-lignite siliciclastics are overlain by the late middle Miocene to earliest Pliocene Poznań Formation, which comprises two second-order units, namely the lower Grey Clays Member and the upper Wielkopolska Member (Piwocki & Ziembińska-Tworzydło, 1997; Widera, 2007, 2021).

The Grey Clays Member is the most lignite-rich unit in the vast territory of central Poland. Simply put, it contains the first mid-Polish lignite seam (MPLS-1), which was exploited in the Adamów Lignite Mine. In the study area, the maximum thickness of the MPLS-1 reaches in excess of 10 m; however, its average thickness is in the range of 5–8 m in the individual lignite deposits of the Adamów Graben (see Fig. 2). This seam was deposited during and shortly after the last peak of the Mid-Miocene Climatic Optimum (Zachos et al., 2001; Bechtel et al., 2019, 2020) in the middle part of the middle Miocene (~15–14.3 Ma) (Piwocki & Ziembińska-Tworzydło, 1997; Kasiński & Słodkowska, 2016; Słodkowska & Kasiński, 2016; Widera et al., 2021a, 2021b). Most likely, the peat deposits which were

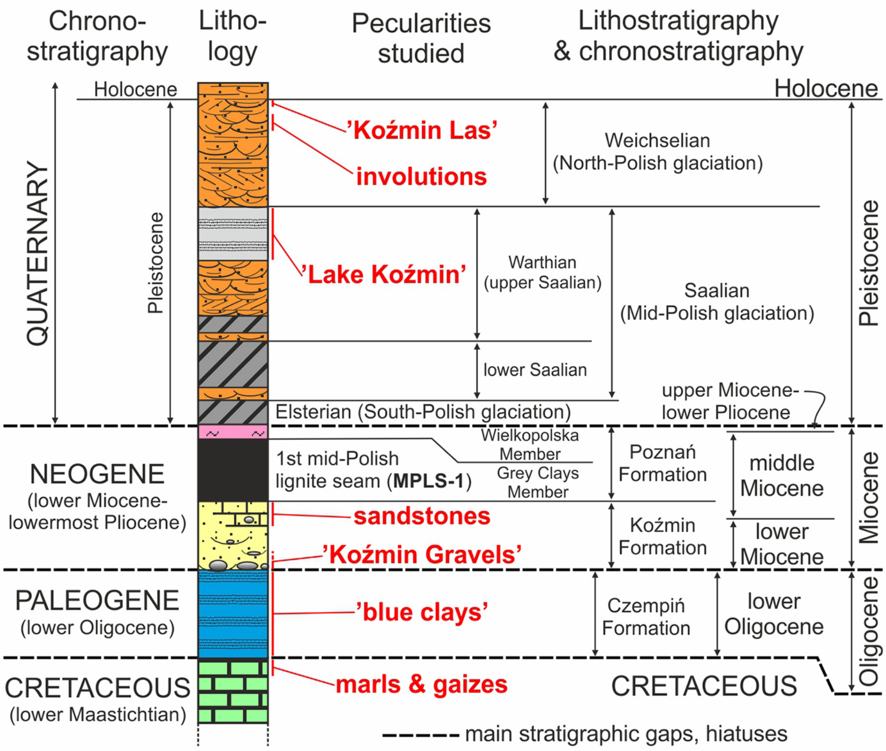


**Fig. 3.** Approximate stratigraphical position of the peculiarities examined against the chrono- and lithostratigraphy of the Adamów Graben area. Compare with Figure 2 and the text; for lithological explanations see Figure 2.

then transformed into the MPLS-1, were predominantly formed as low-lying mires in the overbank zone of middle Miocene rivers (Widera, 2016b; Widera et al., 2021a). The latest results of palynological analyses indicate, however, that the mire communities were similar in their composition to modern pocosins (southeastern USA), when the climate was warm temperate and humid, with mean annual temperatures in the range of 15.7–18.0 °C (Worobiec et al., 2021).

The deposition of the Wielkopolska Member (upper part of the Poznań Formation) covers the time period from the late middle Miocene to the earliest Pliocene (Piwocki & Ziembińska-Tworzydło, 1997). In the area of the Adamów Graben, this member is preserved residually as a result of post-depositional Pleistocene erosion and glaciotectonics. Hence, the strata assigned to this lithostratigraphical unit form isolated bodies which are sometimes strongly folded, with a maximum thickness of up to several metres (see Fig. 2). On the other hand, they consist of multi-coloured muds known as 'green clays' and 'flammy clays', with channel-fill, sandy-muddy lenses and palaeosol horizons. Therefore, the accumulation environment of the Wielkopolska Member is currently linked with anastomosing (Widera, 2013; Widera et al., 2017, 2019; Maciaszek et al., 2020) or anastomosing-to-meandering transitional late Neogene river systems (Zieliński & Widera, 2020; Kędzior et al., 2021).

The Quaternary rests erosively on top of the Neogene succession. The glaciogenic sediments of this age, such as tills, gravels, sands and muds, form a continuous bed varying in thickness from ~20 to over 40 m (Trzmiel, 1996; Czubla et al., 2013). However, in subglacial channels, which separate and determine the extent of lignite deposits, the Quaternary thickness may exceed 50–70 m (Czarnik, 1972; Widera, 1998, 2007). These deposits represent the following three groups of Pleistocene glaciations: Elsterian (south-Polish), Saalian (mid-Polish) and Weichselian (north-Polish) (Figs. 2, 3; Trzmiel, 1996; Czubla et al., 2010, 2013).

The Elsterian glaciogenic deposits (tills) are preserved sporadically in the above-mentioned subglacial channels or at the marginal faults/fault zones of the Adamów Graben. In contrast, Saalian and Weichselian strata are widespread, as well as more divers, both lithologically and genetically. The deposits of the Saalian glaciation(s) include glacial tills, fluvioglacial sands and gravels, as well as glaciolacustrine muds (glacial 'Lake Koźmin'). In contrast, the younger Quaternary is represented predominantly by fluvial sands and gravels (Figs. 2, 3). This is due to the fact that the Weichselian ice sheet extended to a maximum of ~15–30 km to the northwest and north of the study area (Marks, 2002; Petera & Forysiak, 2003; Marks et al., 2006; Widera, 2011).

Some levels contain fossilised peat and remains of forests in the uppermost strata of the Weichselian deposits (Petera-Zganiacz & Dzieduszyńska, 2007; Dzieduszyńska & Petera-Zganiacz, 2012; Dzieduszyńska et al., 2012, 2014a, b; Petera-Zganiacz et al., 2015). Furthermore, numerous periglacial deformation structures, including involutions, have been observed within deposits of late Weichselian age (Fig. 3; Klatkowa, 1996; Petera-Zganiacz, 2011, 2016; Petera-Zganiacz & Dzieduszyńska, 2017; Dzieduszyńska & Petera-Zganiacz, 2018; Dzieduszyńska et al., 2020).

## 3. Material and methods

All field data presented here derive from three former lignite opencasts and their immediate surroundings of the Adamów Graben (Fig. 1). Over the last 30 years, fieldwork was carried out by the authors and their collaborators at the Adamów, Koźmin S and Koźmin N opencasts. It should be added here that studies of Quaternary deposits were initiated by the team of Professor H. Klatkowa in the early/mid-1990s (e.g., Klatkowa et al., 1993, 1996). Our activity included a wide range of geological and palaeogeographical studies involving stratigraphical, tectonic, structural, sedimentological and palaeontological research. At the time, both the relatively high walls of mine opencasts and shallow exposures (located in the vicinity of the opencasts) were mapped, as well as photographically documented. Hundreds of samples were also collected mainly for sedimentological, petrographical, pollen, plant macrofossils, Cladocera and Chironomidae, dendrochronological, radiocarbon and luminescence dating analyses. All mining maps and borehole data were obtained from the geological archive of the Adamów Lignite Mine. For example, information obtained from 14 boreholes was used to prepare a geological cross-section through the Adamów Graben (Fig. 2).

The methodology of our studies has been described in detail in the papers cited here (see References). Petrographic analyses of the Paleogene 'Koźmin Gravels' were carried out by T. Dobosz (Dobosz & Widera 2008; Widera, 2010), while the petrography of the Quaternary gravels was determined by P. Czubla (Czubla, 2001; Czubla & Forysiak, 2004; Czubla et al., 2010, 2013; Petera-Zganiacz et al., 2010). B. Gruszka and H. Gallas carried out detailed sedimentological research of the glacial 'Koźmin Lake' deposits, including studies of deformation structures (Pawłowski et al., 2013). The analysis of textural features of Quaternary non-organic, mineral deposits was performed by J. Forysiak (Klatkowa et al., 1996; Forysiak et al., 1999; Petera, 2002; Petera & Forysiak, 2003; Czubla et al., 2013). Geological and geomorphological studies, as part of the 'Koźmin Las' project, were conducted by D. Dzieduszyńska, J. Petera-Zganiacz, P. Kittel and J. Twardy (Dzieduszyńska & Petera-Zganiacz, 2012; Kittel et al., 2012; Dzieduszyńska et al., 2014b; Dzieduszyńska & Twardy, 2014; Petera-Zganiacz et al., 2015). The latest palynological studies of the Neogene lignite exploited from the Adamów opencast were carried out by E. Worobiec (Worobiec et al., 2021). In addition, the Quaternary organic and mineral-organic interbeds were examined palaeobotanically by G. Miotk-Szpiganowicz, K. Korzeń, R. Stachowicz-Rybka, D. Pawłowski and M. Płóciennik, amongst others (Forysiak et al., 1999; Turkowska et al., 2000; Petera-Zganiacz at al., 2010; Dzieduszyńska et al., 2014b).

It is also worth mentioning that analyses of Cladocera, Chironomidae, diatoms and dendrochronology were carried out by D. Pawłowski, M. Płóciennik, M. Lutyńska-Rzodkiewicz and M. Krąpiec, respectively (Pawłowski et al., 2013; Dzieduszyńska et al., 2014b; Petera-Zganiacz et al., 2015). The age determination of the late Weichselian mineral sediments was performed using optically stimulated luminescence (OSL) at the Gliwice Luminescence Laboratory (Dzieduszyńska et al., 2014a). Radiocarbon dates for organic sediments were obtained from several laboratories, such as the Laboratory of Absolute Dating in Skała (near Kraków), the Laboratory of Absolute Dating (Łódź) and the Poznań Radiocarbon Laboratory (Dzieduszyńska et al., 2011, 2014b; Petera-Zganiacz et al., 2015).

## 4. Results

### 4.1. Cretaceous: marls and gaizes

**Description.** Until the mid-1990s, the sub-Cenozoic basement in the direct vicinity of town of Turek was known only from exploratory boreholes drilled in order to document lignite occurrences. The rocks of the Mesozoic top were defined as marls in geological documentation, although their structural features were very poorly recognised at the time (Czarnik, 1972; Trzmiel, 1996). A lot changed in 1997–1998, when the sub-Cenozoic bedrock was exposed first in the Adamów opencast and later in the Koźmin S opencast (Widera, 1998). This allowed direct observations to be made of the Mesozoic rocks


**Fig. 4.** Upper Cretaceous marls and gaizes in the axial part of the Adamów Graben. **A** – The Koźmin S lignite opencast, 2004; **B** – The Adamów lignite opencast, 2020.

in the field and sampling for laboratory analyses (Widera, 1999). In the following years, however, new outcrops of these rocks of considerable extent (up to 100–300 m in length and 6–10 m in height) became successively available for fieldwork in lignite opencasts: Koźmin S (2004–2009), Koźmin N (2011–2016) and Adamów (2019–2022) (Fig. 4).

In general, the above-mentioned outcrops of Cretaceous rocks are located in various zones of the Adamów Graben and form horst-like elevations (Załoba & Czubla, 1995; Widera, 1998, 2007, 2021). These rocks are particularly well exposed in places where dewatering channels and conveyor belts run at the bottom of the lignite opencasts (Fig. 4). Cretaceous rocks are white to white-grey in colour with visible rust (iron oxides) and greenish (glauconite) spots. Furthermore, they are strongly tectonically broken up in the form of two fracture systems with the high-angle dips, as well as NW–SE- and NE–SW-trending strikes (Widera, 2007).

**Interpretation.** Based on mineralogical studies, including X-ray analyses, these rocks were included into a group of carbonate-siliceous (siliceous limestones) rocks, that is, gaizes (Widera, 1999). This supports the fact that low-Mg calcite (68.3 wt%) and detritic quartz (21.7 wt%) predominate their mineral compositions as determined by the high average contents of CaO (~37.5 wt%) and $SiO_2$ (~25.4 wt%) (Table 1). In addition, Fe from $Fe_2O_3$ (avg. 0.75 wt%) and Al from $Al_2O_3$ (avg. 1.38 wt%) enter the crystal structure of illite and glauconite, and Fe also forms separate oxides. In view of the fact that the clay mineral contents oscillate around 5 vol.% and due to the presence of a large number of detritic quartz grains, these carbonate-siliceous rocks may represent both marls (>5 vol.% of clay minerals) and gaizes (<5 vol.% of clay minerals) (Ryka & Maliszewska, 1982). Moreover, these rocks may be interbedded with other types of marine sedimentary rocks, for example, limestones (Pożaryski, 1952).

The stratigraphy of the Mesozoic rocks in this part of Poland was examined in surface outcrops located several dozen kilometres east of the Adamów Graben. Their age was determined as early Maastrichtian (the youngest stage of the Upper Cretaceous) on the basis of studies of marine macrofauna (Fig. 3; Pożaryski, 1952). The results obtained by the latter author up to date, as can be clearly seen on geological maps of Poland (e.g., Dadlez et al., 2000; Żelaźniewicz et al., 2011).

**Table 1.** Average chemical and mineralogical compositions of Mesozoic rocks in lignite opencasts of the Adamów Graben area (slightly modified from Widera, 1999).

| Chemical composition | |
|---|---|
| parameter | average content in wt% (from–to) |
| $SiO_2$ | 24.47 (24.20–24.73) |
| $Al_2O_3$ | 1.38 (1.34–1.42) |
| $Fe_2O_3$ | 0.75 (0.74–0.75) |
| CaO | 37.56 (37.24–37.88) |
| MgO | 0.57 (0.57–0.57) |
| $Na_2O$ | 0.09 (0.08–0.09) |
| $K_2O$ | 0.46 (0.45–0.46) |
| ignition loss | 31.07 (30.86–31.28) |
| **Mineralogical composition** | |
| low-Mg calcite | 68.3 (67.7–68.8) |
| detritic quartz | 21.7 (21.4–22.0) |
| illite | 5.5 (5.4–5.7) |
| other (glauconite, feldspar, etc). | 4.5 (4.1–4.9) |

## 4.2. Paleogene: 'blue clays'

**Description.** The 'blue clays' were originally named 'blue clays' or 'green clays' and regarded as middle Miocene in age (Czarnik, 1972). The 'blue clays' were exposed only in the Koźmin S and Koźmin N opencasts in 2004–2009 and 2011–2016, respectively. These fine-grained strata were found

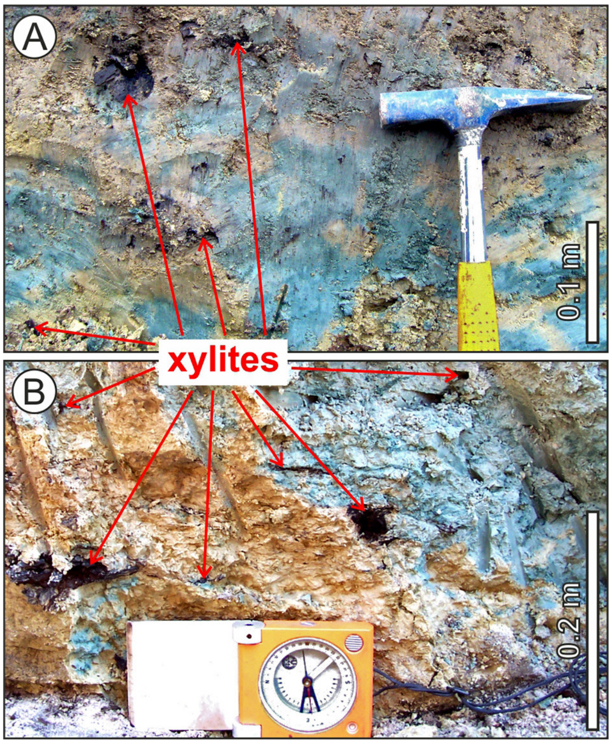


**Fig. 5.** Lower Oligocene 'blue clays' exposed in the Koźmin S lignite opencast in 2007. **A** – Position of the 'blue clays' below the Neogene sands and lignite seam; **B** – Close-up view of the weathered and fresh 'blue clays' with fossilised wood remains (xylites).

in depressions in the Mesozoic top. Their most characteristic feature is the presence of xylites, i.e., fossilised wood fragments of >1 cm in size (Widera, 2007). The 'blue clays' are indeed blue or grey-blue on freshly exposed surfaces, while on weathered surfaces they are brown or brown-green (Fig. 5). In fact, they represent silts or sandy silts rather than clays, because their average granular composition is as follows: silt – 65 wt%, sand – 31 wt%, and clay – only 4 wt% (Widera, 2012). These xylites within the 'blue clays' are relatively small; up to 15 cm in length and 5 cm in diameter. However, their distribution varies from one to several pieces of fossilised wood in an area of 1 $m^2$. These xylites are strongly coalified, manifested in the poorly visible internal structure of wood and its black colour (Fig. 5).

**Interpretation.** In contrast to the above-mentioned opinion of Czarnik (1972), the age of the 'blue clays' was specified as Paleogene (Widera, 2007; Widera & Kita, 2007), based on direct field observations and a verification of borehole data. In brief, these clays are sporadically covered by Oligocene glauconitic sands, which means that they are of Paleogene age. More precisely, they represent the Czempiń Formation, which is early Oligocene (Rupelian) in age (see Figs. 2, 3; Widera & Kita, 2007). Moreover, the 'blue clays' were probably deposited in relatively deep water under reducing conditions. This notion is supported by the blue colour of the sediments. Due to the bulk density of fossilised wood, which is markedly higher than water, its transport could not have occurred over long distances (Widera, 2012).

### 4.3. Paleogene: 'Koźmin Gravels'

**Description.** Czarnik (1972) was the first to mention gravel-sized particles (up to 3 cm in size) in Neogene sediments of the Adamów Graben during lignite exploration. Over the following >30 years, knowledge of these remained limited. This changed in 2004, when gravels were exposed within the Neogene deposits that underlie the mined lignite seam (MPLS-1) in the Koźmin S opencast (Widera & Kita, 2007). They were characterised by a large diversity in their petrography, as well as in size and shape. Similar coarse-grained sediments had not been identified within the generally fine-grained Paleogene and Neogene deposits in the area of the Polish Lowlands at the time (Piwocki, 2004). Due to their uniqueness and the place of their discovery, they were named the 'Koźmin

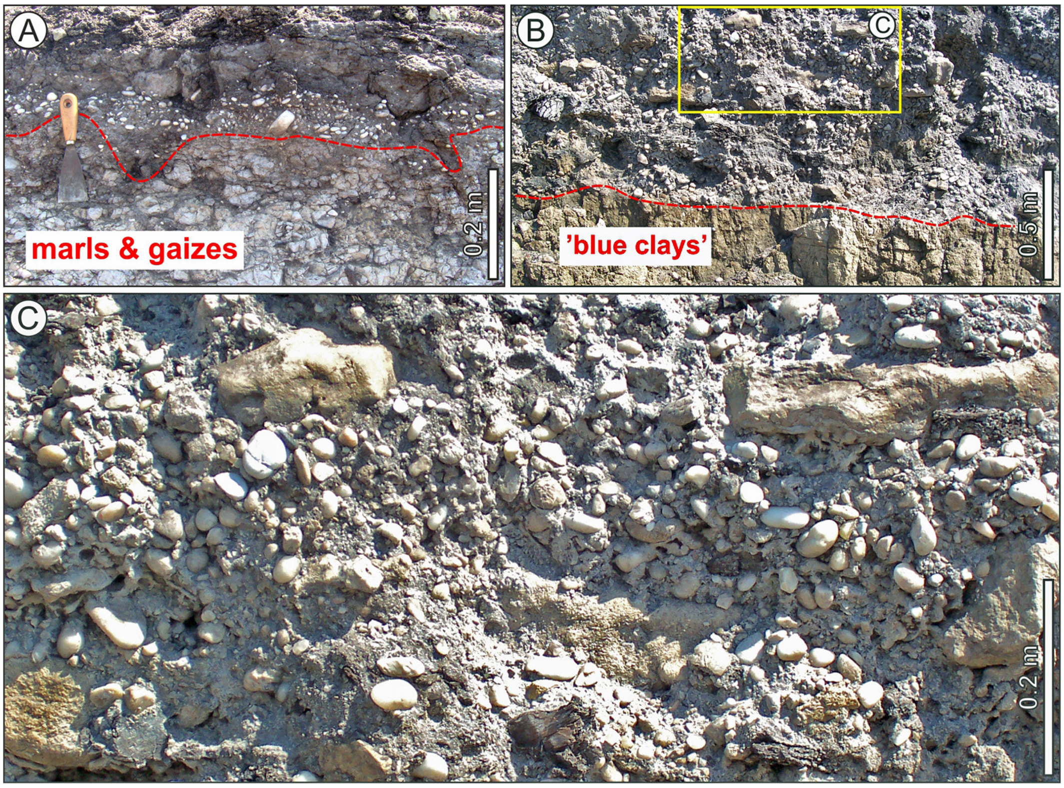


**Fig. 6.** Lower Oligocene 'Koźmin Gravels' exposed in the Koźmin S lignite opencast in 2004. **A** – Location of the gravels between the Mesozoic top and the base of the Neogene; **B** – Location of the gravels at the top of the 'blue clays'; **C** – Close-up view of the gravels shown in Figure 6B; note the massive structure and the gravel size variation.

**Table 2.** Petrographical compositions of the 'Koźmin Gravels' from the Koźmin S lignite opencast, the Adamów Graben area (slightly modified from Dobosz & Widera, 2008; Widera, 2010). *Rock types that are indicative of the origin of the gravels.

| Petrographical composition | | |
|---|---|---|
| rock type | | % of 686 gravels |
| quartz | milky-white | 46.8 |
| | greyish-blue* | 15.5* |
| | pink | 10.0 |
| | honey-yellow | 9.0 |
| | grey | 3.9 |
| | white | 1.3 |
| flints | | 2.8 |
| lydites* | | 2.1* |
| sandstones | | 0.4 |
| marls, gaizes | | 0.1 |

Gravels' (Widera & Kita, 2007; Dobosz & Widera, 2008). They also appeared in large numbers in the Koźmin N opencast, while there are currently a few at the bottom of the Adamów opencast, which is in its closing phase.

In general, the 'Koźmin Gravels' are stratigraphically situated at the base of the Koźmin Formation. In some cases, they rest directly on the Mesozoic top or overlie the above-mentioned 'blue clays' (compare Figs. 2, 3, 6A, B). These gravels are poorly sorted and matrix supported, and have a massive structure. Hence, no stratification or grading was observed amongst the layers comprising most of the gravels (Fig. 6C). The gravel-rich strata are lens shaped, up to 0.5 m thick, and up to several tens of metres long. Sediments containing the gravels may be referred to as gravelly sands because they contain: ~75 wt% of sand, ~25 wt% of gravel, and <5 wt% of fines, that is, silt and clay (Widera, 2007, 2010; Widera & Kita, 2007).

Qualitatively, the 'Koźmin Gravels' are very diverse petrographically, although quantitatively quartz predominates (>94.5%) (Fig. 7A). Other types of rock, such as flints, lydites, sandstones, marls and gaizes, account for <5.5% of the analysed gravels (Table 2). Some of them are characterised by a variety of colours, and above all by a 'fat' shine with a perfectly polished surface (Fig. 7B). The majority of these quartzes and lydites are disc- to blade-shaped (Widera, 2010).

**Interpretation.** The most important amongst the 'Koźmin Gravels' are definitely lydites and greyish-blue quartzes, because only they together can point to the area of the present Sudetes Mountains (northeastern slope of the Bohemian Massif) as a possible source area for these gravels (Dobosz & Widera, 2008; Widera, 2010). The transport and deposition processes of the 'Koźmin Gravels' can also be determined on the basis of their stratigraphical position, morphology and possible source area.

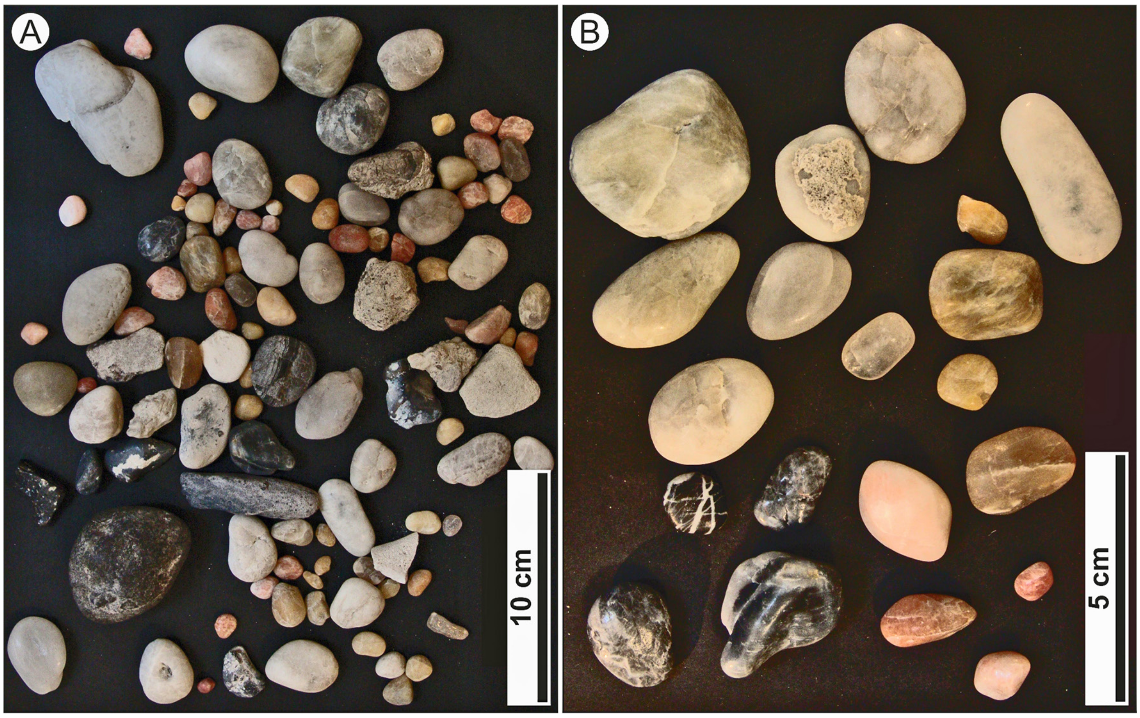


**Fig. 7.** Petrography of the 'Koźmin Gravels'. **A** – Diverse petrographical composition of the gravels; **B** – Various pebbles with perfectly polished surface.

The current discoidal shapes and polished surfaces of the 'Koźmin Gravels' were most likely formed in a littoral/beach environment of the early Oligocene sea. Moreover, enriching the sea water with a clay fraction, derived from the stratigraphically older 'blue clays', could have contributed to such a perfect polishing of the surface of some of these gravels (see Fig. 7B). From the transition of the Oligocene to the Miocene, when the Adamów Graben subsided intensively, they were redeposited within the sub-lignite (MPLS-1) sediments of the Miocene Koźmin Formation by debris flows (Widera, 2007, 2010) or as a filling of channel thalweg of a river flowing through the area subject to tectonic lowering (Widera et al., 2021b). The first mechanism is supported by the massive structure of the gravel-bearing beds (Fig. 6; Doktor, 1983), although the second mechanism is also possible, but this requires further research. Finally, it must be noted here that there is no other palaeontological or sedimentological evidence that would back up these hypotheses on the age and depositional environment of the 'Koźmin Gravels'.

### 4.4. Neogene: sandstones

**Description.** Lower to middle Miocene quartzite sandstones were available for direct observations in all lignite opencasts located in the Adamów Graben area (Fig. 8; Widera, 2001, 2007, 2021). Their sizes varied greatly from decimetres to tens of metres. The largest fragment of such a sandstone, exposed in the Adamów opencast in 2019–2022, had a volume exceeding 100 m$^3$ (Fig. 8C). However, their most characteristic feature is the presence of well-preserved roots (or their prints) of woody vegetation (Fig. 8A).

**Interpretation.** The genesis of these freshwater sandstones remained quite mysterious for many years. The origin of the silica, which binds the grains of sand, was associated with the dissolution of diatom shells or of siliceous components (e.g., gaizes, marls) commonly found in the Mesozoic bedrock (see Section 4.1.). Scanning electron microscope (SEM) observations have provided evidence of their formation in a soil environment. Therefore, it is now believed that the sub-lignite sands were bonded by silica *in situ* as a result of post-depositional soil processes (Górniak et al., 1996).

This hypothesis is confirmed by the fact that the SEM images show the presence of organo-quartz aggregates and regenerative rims in the form of crystalline silica – $SiO_2$. Organic matter, coming from roots (see Fig. 8A), played an important role in the process of activating silica. During the initial phase of decomposition of organics, the slightly alkalised pore water led to the local (in one part of a sand grain) dissolution of silica. It is likely that the silica-enriched water solution then moved to different parts of the sand grains with relatively increased acidity, which resulted in the precipitation of $SiO_2$, that is, in the form of the mentioned regenerative rims (Górniak et al., 1996).

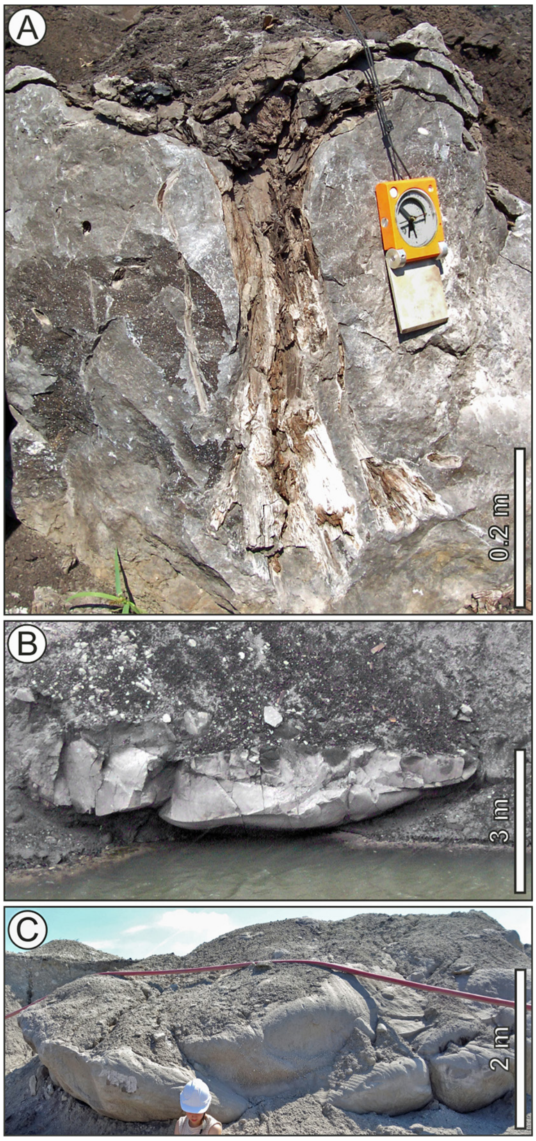


**Fig. 8.** Neogene sandstones outcropping in the Koźmin S and Adamów lignite opencasts. **A** – Sandstone with fossilised root at the base of the middle Miocene lignite seam (MPLS-1) in the Koźmin S opencast, 2004; **B** – Large body of sandstone at the top of the lower–middle Miocene Koźmin Formation in the Koźmin S opencast, 2005; **C** – Large body of sandstone located between the Upper Cretaceous top and the bottom of the MPLS-1 in the Adamów opencast, 2019.

## 4.5. Quaternary: glacial 'Lake Koźmin'

**Description.** The first information on the thick and widespread glaciolacustrine deposits of the glacial 'Lake Koźmin' was supplied by Czarnik (1972). Long-lasting research in mine exposures and an analysis of boreholes documenting the lignite deposit showed that the area of the basin exceeded 30 km$^2$. Its bottom is located at a depth of ~65 m a.s.l., the top at an altitude of ~87 m a.s.l. The contact of glaciolacustrine strata with under- and overlying strata is clearly erosive (Fig. 9A; Czubla et al., 2010).

Deposits of the 'Lake Koźmin' are represented mostly by clay, silt and sand. The clay and silt facies commonly form rhythmites that predominate in sections studied in mine outcrops, while fine sand creates thin laminae beneath the clay facies (Fig. 9B; Pawłowski et al., 2013). These clay strata are massive and usually not thicker than 5 cm. In contrast, the silt facies are massive or horizontally laminated and form layers of up to 40 cm in thickness. Sand and sandy silt are present mostly as climbing-ripple, cross-stratified or wavy laminated cosets. The distinguishing features of these sediments is the occurrence of widespread deformations observed in four horizons. The commonest type of these deformations are load casts, but there are also ball-and-pillow and flame structures. The deformed strata have a relatively even thickness and rest between non-deformed sediments (Fig. 9; Pawłowski et al., 2013). Additionally, deposits of the glacial 'Lake Koźmin' were analysed for the presence of subfossil Cladocera. Their remains were rather rare, and were not found at all in some horizons. Moreover,

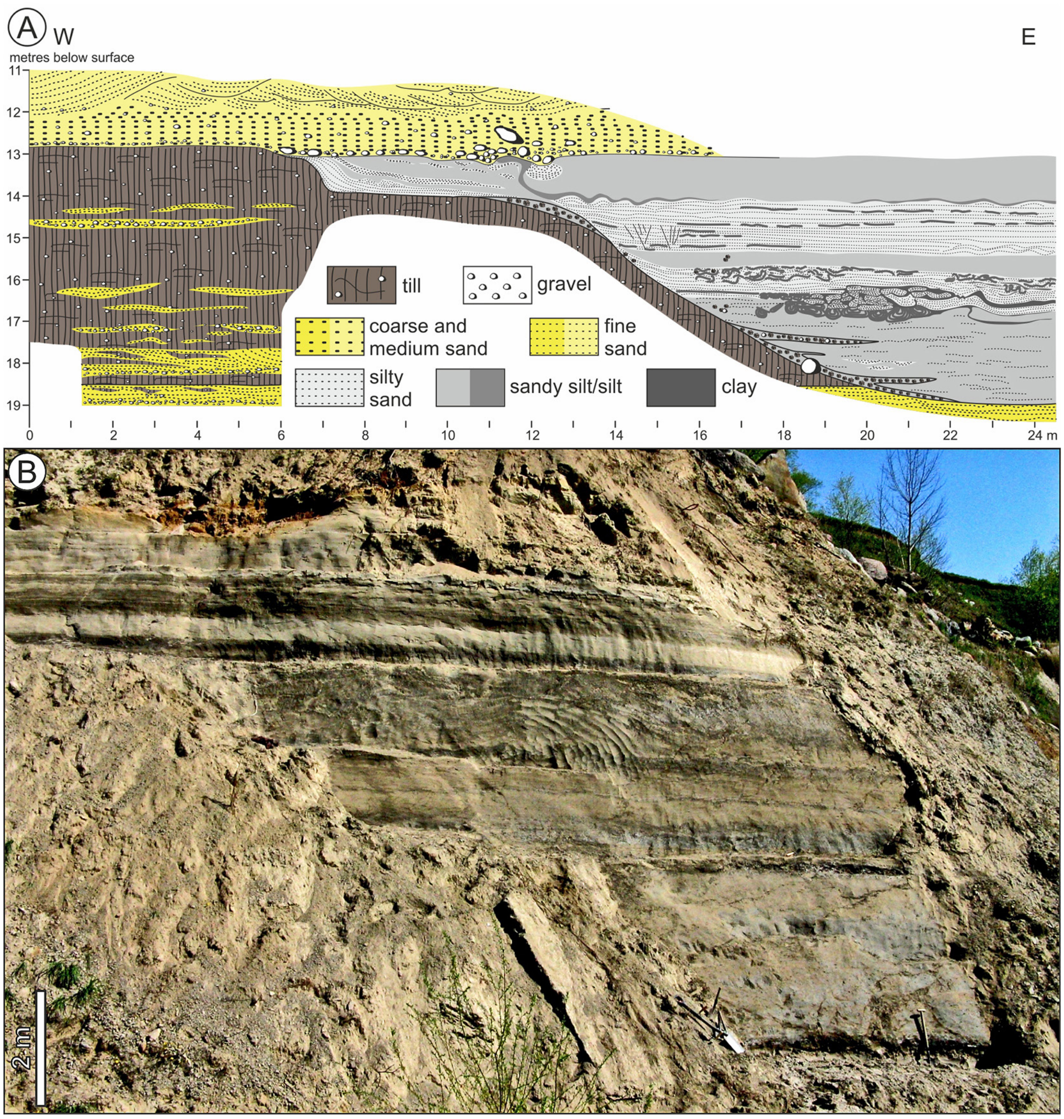


**Fig. 9.** 'Lake Koźmin' deposits in the Koźmin S lignite opencast in 2008. **A** – Sketch of marginal zone of the 'Lake Koźmin'; note the deformed strata interpreted as seismites; **B** – Field section of the glaciolacustrine deposits.

the Cladocera were represented mainly by species that live under oligotrophic conditions (Pawłowski et al., 2013).

**Interpretation.** The 'Lake Koźmin' covers an erosive form, probably a subglacial channel, with an uneven bottom and a general north-south elongation. This palaeobasin is inserted in older tills, as well as in underlying sands and gravels. The stratigraphical position of these tills, defined as Warthian (late Saalian, mid-Polish glaciation; see Fig. 3), was determined on the basis of petrographical analysis and long-axis azimuth of clast measurements. The analysis of the stratigraphical position of deposits under- and overlying the glaciolacustrine sediments of the 'Lake Koźmin' suggests that they were deposited at the end (i.e., during the regression stage) of the Warthian (Czubla et al., 2010, 2013). These results verify both the statement of Czarnik (1972) that the glacial lake developed during the Warthian ice sheet transgression and the opinion of Trzmiel (1996), who determined the accumulation of fine-grained deposits of the 'Lake Koźmin' to have occurred during the early Weichselian.

The sedimentary conditions changed as the 'Lake Koźmin' evolved. There were periods of increased inflow to the lake that delivered sandy material that caused bottom-current activity. These periods were separated by relatively long-lasting time intervals of almost stagnant water, when suspension settling predominated as indicated by the presence of rhythmites. The deformed beds were interpreted as seismites, which documents seismic activity in the Adamów Graben at the end of the Warthian (Pawłowski et al., 2013). Most likely, tectonic activity was responsible for the lack of the above-mentioned Cladocera remains in the horizons lying directly on the seismites. Thus, not only did earthquakes deform the lake-bottom sediments, they also changed habitat characteristics. It is also worth emphasising here that the documented Cladocera species represent one of the oldest records of its kind in Europe (Pawłowski et al., 2013).

### 4.6. Quaternary: involutions

**Description.** In all opencasts covering the area of the Adamów Graben, the uppermost part of the sedimentary succession consists, on average, of fluvial deposits accumulated during the Weichselian and of several metres in thickness (compare Figs. 3, 10A). The Koźmin S opencast provided an opportunity to study the deposits of the distal part of the Warta River valley, where sandy alluvia are separated by a few thin, but widespread organic-mineral series (Fig. 10A; Klatkowa et al., 1996; Forysiak et al., 1999; Petera, 2002). Radiocarbon dating allowed the age of the lower organic-mineral series to be estimated at ~30 to ~18.5 ka BP. In light of detailed studies, the age of the uppermost mineral-organic level, characterised by a significant extent and continuity, was determined as the decline of the Allerød and early part of the Younger Dryas (Dzieduszyńska et al., 2014b).

Numerous deformation structures, such as ice-wedge casts (Klatkowa, 1996; Petera, 2002) and involutions (Petera, 2002), occur in the Weichselian deposits (Fig. 10). The uppermost parts of the sandy series and organic-mineral sediments were involved in the involutions. In the lower horizons, they reached relatively high dimensions exceeding 50 cm and most often formed load casts or flame-like structures. The uppermost horizon of these involutions abounded in small-scale, although morphologically diverse, deformations such as: drop-like and flat-bottomed structures, diapirs, flame-like and fold structures, as well as irregular involutions (Fig. 10B–E). They reached a maximum height of 50 cm, but generally were in the range of 20–30 cm (Petera-Zganiacz & Dzieduszyńska, 2017).

**Interpretation.** The development of the above-mentioned involutions was connected largely with ground oversaturation with water under periglacial conditions. In the case of the presented structures and sediments (Fig. 10), originally with significant water contents, ice could thaw seasonally in the active layer. The mechanisms responsible for the deformation process of the involutions were linked to a reversed density gradient resulting from the load (Anketell et al., 1970) and cryohydrostatic pressure, which built up between impermeable layers, that is, between the permafrost table and the freezing front descending from the surface (Vandenberghe, 1992). Such favourable conditions arose in a periglacial environment. The occurrence of permafrost during the formation of lower horizons, dated to the end of the middle Pleniweichselian and the late Pleniweichselian, was confirmed by the presence of ice-wedge casts. Of course, the morphological type of the deformation structures depends on the direction of the material movement (e.g., Petera-Zganiacz & Dzieduszyńska, 2017).

Detailed analysis of some involutions in the Adamów Graben area allow several conclusions to be drawn. First, the flat-bottomed and drop-like structures formed due to the uneven load. Secondly, diapiric and flame-like structures developed through

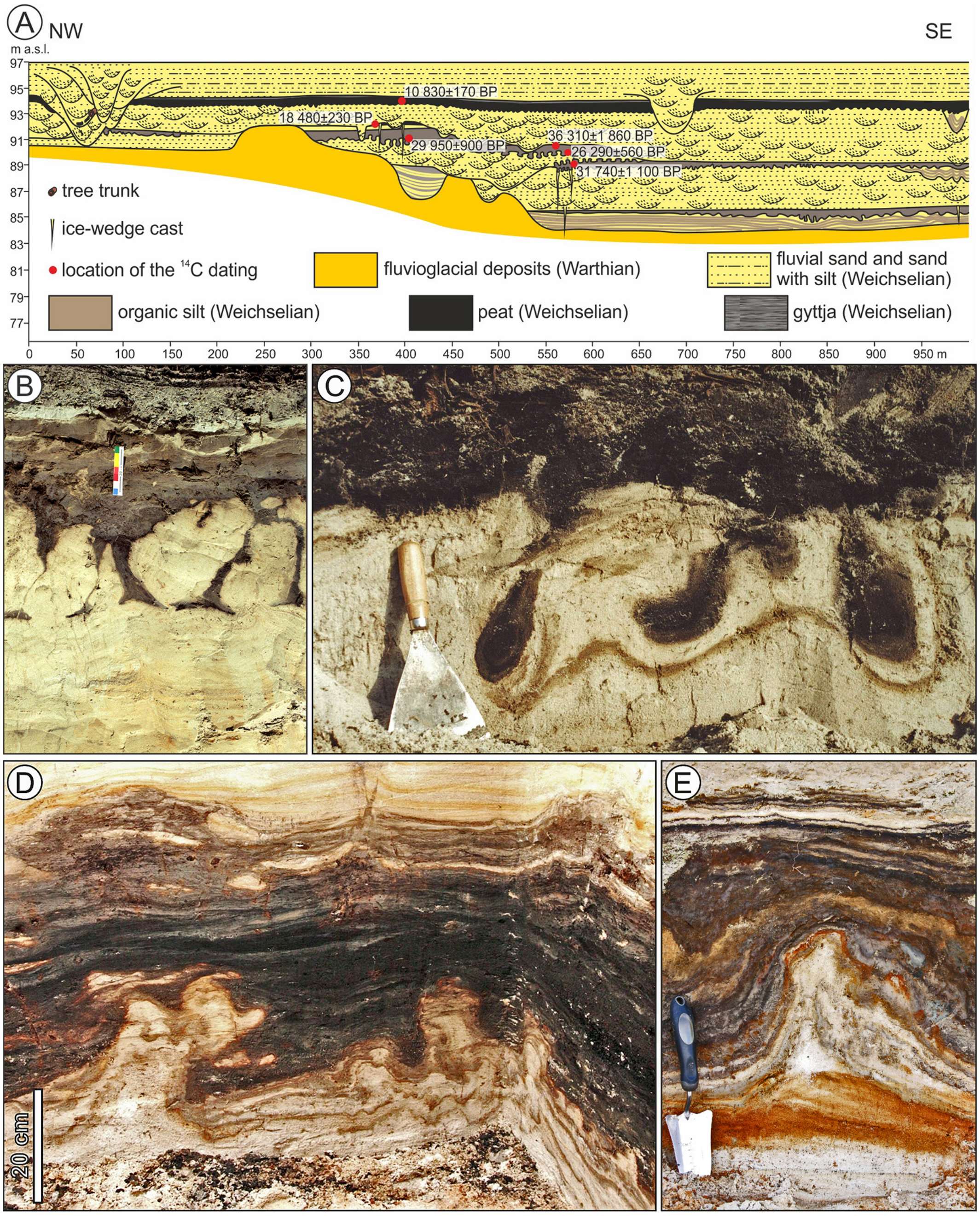


**Fig. 10**. Involutions in the Koźmin S lignite opencast. **A** – Sketch of the mine wall with involution horizons in Weichselian deposits; **B** – Flat-bottomed structures (photograph by H. Klatkowa, 1996); **C** – Drop-like structures, 2006; **D** – Flame-like structures, 2012; **E** – Diapiric structure, 2015.

upward injection as a result of cryohydrostatic pressure and, thirdly, the mechanism of deformation in the case of folded and irregular structures is still difficult to explain. Nevertheless, the age of the interpreted involutions is well defined as coinciding with the Younger Dryas event, confirming the presence of permafrost in central Europe at that time (Petera-Zganiacz & Dzieduszyńska, 2017; Dzieduszyńska & Petera-Zganiacz, 2018).

### 4.7. Quaternary: 'Koźmin Las'

**Description.** Remains of fossil forests occur within the organic-mineral horizon at ~2 m below the present-day surface. These are over 300 objects in an area of ~100 m$^2$, such as collapsed trunks measuring up to 6 m in length and more than 0.2 m in diameter, *in situ* tree stumps (Fig. 11A), individual branches and roots (Fig. 11B, C; Anderwald & Pe-


**Fig. 11.** Remains of the Younger Dryas forest 'Koźmin Las'. **A** – Tree stump *in situ* in the Koźmin S lignite opencast, 2008; **B, C** – Remains of trees in a test pit, 2011; note that the test pit area in Figure 11C is ~50 m$^2$.

tera-Zganiacz, 2012; Kittel et al., 2012; Dzieduszyńska et al., 2014b).

The stumps are characterised by well-preserved lateral root systems, while most trunks retain bark. Mostly these are pieces of *Pinus sylvestris* and singular *Betula*. Results of the radiocarbon dating of wood pieces range from 11,850±80 to 10,000±90 BP (Dzieduszyńska & Twardy, 2014). In 2010–2011, detailed field studies were carried out in an open test pit located near the eastern wall of the Koźmin S opencast ('Koźmin S' deposit), that is, in the northernmost part of the Adamów Graben (see Fig. 1B).

**Interpretation.** The 'Koźmin Las' proves the existence of a forest at the bottom of the Warta River valley during the late Weichselian decline. A wide range of research (geological, palaeobiological, geochronological, etc.) has allowed the reconstruction of a sequence of palaeoenvironmental events (Dzieduszyńska et al., 2014a, b). The following events have been identified:

1) Rapid transformation of conditions from terrestrial to aquatic, including: forest, peatland, development of hydrogenic soil horizons, shallow-water pools with episodes of overflow, and an increase of flooding and overbank deposition which is reflected in the lithological diversity of organic-rich series and in palaeoecological changes;
2) The appearance of a riparian pine forest under unfavourable habitat conditions during the Younger Dryas. Such conditions are also reflected in the morphological properties of subfossil tree trunks, such as narrow tree rings, reactionary wood resulting from the mechanical stress of trees loosing stability, and the orientation of the collapsed trees along the wind directions prevailing at the time. However, exactly why the forest ('Koźmin Las') was destroyed has not been clearly determined to date. A number of phenomena which affected the deterioration of environmental conditions has been identified,

such as temperature drops, strong winds, rising groundwater levels possibly due to permafrost re-aggradation, and water-logging of the site.

Rapid sedimentation buried the forest remains, which bogged down in the organic-mineral horizon and were therefore preserved *in situ*. Local events, including those that affected the forest ecosystem, occurred in the Warta River floodplain at the turn of the Allerød and Younger Dryas. This reflects environmental instability and dynamics at the Weichselian-Holocene transition. The environment of the Warta River valley was a refuge for the forest that covered the present-day area around Turek from the warm Allerød through the longer part of the Younger Dryas cooling period. During that time interval, the forests retreated from central Poland and were replaced by tundra and steppe communities. Thus, it can be concluded that the 'Koźmin Las' provides a significant contribution to our understanding of the mechanisms governing the transformation of geosystems under the influence of rapid climatic changes (Dzieduszyńska et al., 2014a, b).

## 5. Discussion

Like any geological and palaeogeographical peculiarities, those outlined above are also debatable. Nevertheless, in view of the overview nature of the present paper, this will not be discussed in detail here. Thus, the interested reader is invited to refer to the original articles devoted to the successively described and interpreted peculiarities (see References).

## 6. Conclusions

The Adamów Graben and its immediate surroundings rank amongst the geologically and palaeogeographically best-documented areas in central Poland. This is due mainly to the opencast lignite mining that was undertaken in the area between 1964 and 2021. During this time span, many rocks, sediments and structures were exposed and studied over almost 30 years. Indeed, they would not have been discovered (directly or indirectly) without the large-scale mining activities at the Adamów Lignite Mine.

Some of these rocks, sediments and structures may be considered to be peculiarities. Amongst them we have selected only a few of the most interesting, which are marls and gaizes (Cretaceous), 'blue clays' and the 'Koźmin Gravels' (Paleogene), quartzite sandstones (Neogene), as well as the glacial 'Lake Koźmin', involutions and 'Koźmin Las' (Quaternary). These are geologically interesting because they can be directly accessed in the field and are very rare throughout the Polish Lowlands. It is worth adding that the 'Koźmin Gravels' and the 'Koźmin Las' are unique even at the scale of the European Lowlands. Moreover, their accurate diagnosis has provided a better understanding of the palaeogeographical evolution of the Adamów Graben area over various time periods from the Late Cretaceous to the late Pleistocene.

## Dedication

The current paper is dedicated to all employees of the Adamów Lignite Mine, and in particular to members of its Geological Department, who helped us logistically and accompanied us during the field research in the mine opencasts. In alphabetical order they are: J. Bartoszek, M. Dziamara, R. Grzeszczyk, G. Jachna-Filipczuk, S. Kaczkowski and B. Owczarek.

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