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The geology of the deepest Cenozoic lignite-rich grabens in Poland with particular reference to their lithostratigraphy: a comparative study

Marek Widera[1], Jakub Klęsk[2], Paweł Urbański[3]

[1] *Adam Mickiewicz University, Institute of Geology, Poznań, Poland, e-mail: widera@amu.edu.pl (corresponding author), ORCID ID: 0000-0001-5092-2845*
[2] *Adam Mickiewicz University, Institute of Geology, Poznań, Poland, e-mail: jakub.klesk@amu.edu.pl, ORCID ID: 0000-0001-7437-1232*
[3] *Polish Geological Institute – National Research Institute, Warsaw, Poland, e-mail: purb@pgi.gov.pl, ORCID ID: 0000-0002-5440-6562*

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Abstract: The thickest lignite seams in Poland are located in tectonic depressions such as the Kleszczów, Złoczew, and Lubstów grabens, as well as the Zittau (Żytawa) Basin. Their depth ranges from 220 m to 550 m, while the maximum lignite thickness ranges from approximately 90 m to over 250 m. The areas selected for this study include two Miocene lignite seams that have been exploited or prepared for mining, i.e. the third Ścinawa lignite seam (ŚLS-3) and the second Lusatian lignite seam (LLS-2). Currently, more than 95% of the Polish lignite production comes from the exploitation of these seams. Both lignite seams are accompanied by siliciclastic sediments that are lithologically very diverse. The lignite-rich grabens examined in this study form isolated structures and their individual geology is complex. Hence, apart from the Lubstów Graben, local lithostratigraphy is applied for each case, an approach that makes it difficult to compare the lithological units and their stratigraphic position with the Paleogene and Neogene lithostratigraphy used for the Polish Lowlands area. Therefore, it seems appropriate to present an outline of the geology of the Polish regions bearing most of the lignite seams, including a brief overview of their lithological and palaeotectonic characteristics. However, it is first necessary to clarify and compare the lithostratigraphy of the Cenozoic sediments that fill the studied grabens.

Keywords: Paleogene–Neogene, tectonic depressions, lignite seams, lithology, lithostratigraphic units, lithostratigraphic correlation

INTRODUCTION

The geology of lignite deposit areas is relatively well known thanks to thousands of exploration and documentation boreholes (e.g., Piwocki 1992, Kasiński 2004, Piwocki et al. 2004, Widera & Kita 2007, Urbański & Widera 2016, 2020). Additional valuable geological data have also been provided by field observations in opencast mines where lignite is and was exploited (e.g., Kasiński 2000, Gotowała & Hałuszczak 2002, Widera 2007, 2013, 2016a, 2021, Widera & Hałuszczak 2011). There are >150 known lignite deposits in Poland, several dozens of which are suitable for the production

of electricity by combustion of lignite in power plants, and only a few of which are potentially suitable for underground lignite gasification (e.g., Bielowicz & Kasiński 2014, Bielowicz 2016, Urbański & Widera 2020, Widera et al. 2024). The deposits that are of the greatest geological and mining interest are those with the thickest (dozens of metres) lignite seams.

Fig. 1. *Location map of the deepest lignite-rich grabens in Poland (modified after Piwocki 1992, Piwocki et al. 2004, Widera 2021): A) examined grabens against the background of the extent of the third Ścinawa lignite seam (ŚLS-3); B) examined grabens against the background of the extent of the second Lusatian lignite seam (LLS-2)*

These exceptionally thick seams also fill one of the deepest Cenozoic tectonic depressions (grabens) in Poland. Hence, four of them (i.e. the Kleszczów, Złoczew, and Lubstów grabens, and the Zittau Basin) have been selected for study in this paper (Fig. 1).

Despite some similarities, the aforementioned grabens are characterised by significant differences in geology. Firstly, they were tectonically active at different times and were subject to tectonic subsidence and/or uplift-related movements at various rates (e.g., Kasiński 2000, Gotowała & Hałuszczak 2002, Kasiński et al. 2009, Widera & Hałuszczak 2011, Widera 2024a, 2024b). Secondly, they represent isolated tectonic structures where the sediments filling them often do not extend into the surrounding areas. Thirdly, the Paleogene and Neogene lithostratigraphy in each of them, especially the Kleszczów and Złoczew grabens, is more of a mining (local) character than geological. The division of sediments for mining purposes has, of course, practical justification. Nevertheless, for scientific investigations – for example, during comparative analyses of distant lignite-bearing areas – it is of little use to researchers who are unfamiliar with the geology and detailed lithostratigraphic issues (e.g., Piwocki et al. 2004, Widera 2021).

Taking into account the above facts, the current study had the following aims: 1) to present the geology of the deepest grabens with the thickest lignite seams in Poland; 2) to discuss the local lithostratigraphy of the Cenozoic sediments; 3) to show the most characteristic sediments representing the main lithostratigraphic units; and 4) to compare the lithostratigraphy between the examined grabens valid for the Paleogene and Neogene of the Polish Lowlands.

GEOLOGICAL SETTING

Apart from the intra-Sudetic Zittau (Żytawa) Basin, the remaining studied lignite-rich grabens constitute the eastern segment of the North-West European Paleogene and Neogene Basin (Vinken 1988). The Kleszczów and Lubstów grabens are located in the central segment of the Szczecin-Miechów Synclinorium. The Złoczew Graben belongs to the Fore-Sudetic Monocline, while the Zittau Basin forms part of the intermountain

depression of the Lusatian Massif according to the division of Poland into tectonic units (Żelaźniewicz et al. 2011). In the first three cases, the sub-Cenozoic bedrock is predominantly composed of Mesozoic (Jurassic and/or Cretaceous) carbonate rocks (Dadlez et al. 2000). The situation is different for the Zittau Basin, where Precambrian plutonic rocks occur below the Cenozoic, but locally there are also Paleogene volcanites (Kasiński 2000, Kasiński et al. 2015, Pańczyk et al. 2023).

There are numerous lignite deposits in Poland, most often filling tectonic depressions, including the Kleszczów ('Bełchatów' and 'Szczerców' deposits), Złoczew ('Złoczew' deposit) and Lubstów ('Lubstów' deposit) grabens, and the Zittau Basin ('Turów' deposit). The grabens are characterised by the thickest lignite seams in Poland (up to 35–115 m), and in the case of the 'Bełchatów' deposit (up to 250 m), one of the thickest in the world (Piwocki 1992, Kasiński 2004, Piwocki et al. 2004, Widera 2013, 2021, 2024a, 2024b). These lignite seams belong to the third Ścinawa lignite seam (ŚLS-3) and the second Lusatian lignite seam (LLS-2) (Fig. 1). Moreover, the mentioned lignite deposits represent a tectonic genetic type: in all cases, extractable lignite resources only occur in the grabens (Widera 2016b).

In addition to ŚLS-3 and LLS-2, there are three more main lignite seams (or groups of seams) occurring in the Polish Lowlands area: the fifth Czempiń lignite seam (CLS-5) from the Oligocene, the fourth Dąbrowa lignite seam (DLS-4) and the first Mid-Polish lignite seams (MPLS-1) of Miocene age (Fig. 2).

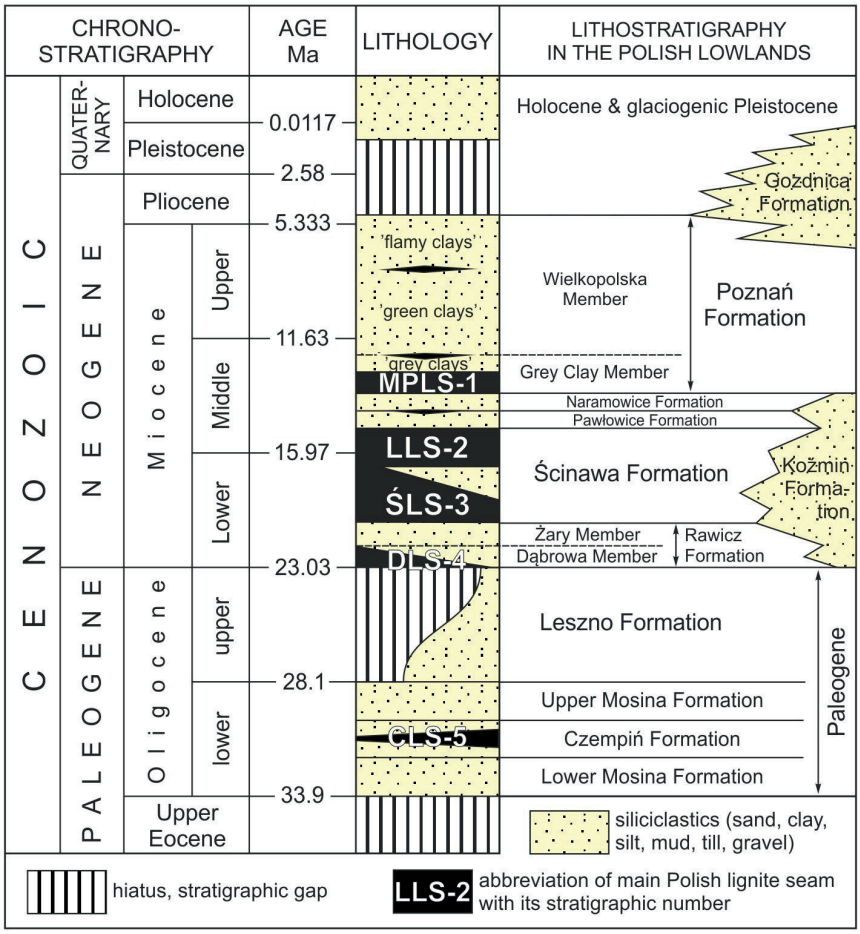

Fig. 2. *Stratigraphic position of the main lignite seams against the background of lithostratigraphy for the Polish Lowlands area (modified after Piwocki & Ziembińska-Tworzydło 1997, Widera & Kita 2007, Widera 2007, 2016b, 2021, Urbański & Widera 2016). Age of chronostratigraphic boundaries is given after Cohen et al. (2013, updated). Main lignite seams: CzLS-5 – the fifth Czempiń lignite seam; DLS-4 – the fourth Dąbrowa lignite seam; ŚLS-3 – the third Ścinawa lignite seam; LLS-2 – the second Lusatian lignite seam; MPLS-1 – the first Mid-Polish lignite seam*

At present (i.e. early 2024), ŚLS-3 and LLS-2 are mined from the 'Bełchatów' and 'Szczerców' deposits (Kleszczów Graben), and from the 'Turów' deposit (Zittau Basin). LLS-2 is also mined in small quantities (<1 Mt/year) from the 'Sieniawa 2' deposit (not examined in this paper) and was exploited from the 'Lubstów' deposit (Lubstów Graben) until 2009. In turn, MPLS-1 is only mined from the 'Tomisławice' deposit (also not examined in this paper).

The Cenozoic lithostratigraphy in the investigated grabens, similarly to other areas of the Polish Lowlands, is characterised by the occurrence of three main stratigraphic hiatuses (Fig. 2). In the Paleogene, the hiatuses cover almost the entire Paleocene and Eocene, and the upper Oligocene (i.e. Chattian). Their formation is explained by regional tectonic uplift (inversion) in the foreland of the Alpine-Carpathian orogen (e.g., Krzywiec 2006, Ziegler & Dèzes 2007, Kley & Voigt 2008, Widera et al. 2008, Jarosiński et al. 2009, Widera 2024a, 2024b). The Neogene stratigraphic gap covers almost the entire Pliocene (excluding its lowest part) and the Lower Pleistocene (Fig. 2). This is most likely the result of erosional processes caused by the Scandinavian ice-sheets and their melt waters (e.g., Piwocki et al. 2004, Widera 2007, 2013).

MATERIALS AND METHODS

Materials

The grabens examined in this paper have been intensively explored to determine the lignite deposits that fill them. For this purpose, over 7,700 boreholes have been drilled with depths ranging from less than 100 m to more than 550 m, almost half of which pierced the Cenozoic. The number of boreholes in the individual areas is over 4,000 in the Zittau Basin, over 3,000 in the Kleszczów Graben, over 370 in the Lubstów Graben, and over 330 in the Złoczew Graben. For this study, 105 boreholes from the examined grabens were selected, on the basis of which four geological cross-sections were constructed to depict the stratigraphic architecture of the sediments that fill the grabens.

All materials, including borehole profiles and mining maps, were obtained upon official permissions from the geological archives of lignite mines (Bełchatów, Turów and Konin) and from the Central Geological Database of the Polish Geological Institute in Warsaw, Poland. Field observations also played an important role in this study. Photographs of the sediments that fill the examined grabens, taken in 2004–2018, come from four lignite opencast mines (i.e. Bełchatów, Szczerców, Turów, and Lubstów).

Methods

The stratigraphy of the Paleogene terrestrial-marine sediments is only occasionally supported by microfauna or microflora in the Polish Lowlands (Piwocki & Ziembińska-Tworzydło 1997, Widera & Kita 2007). In contrast, lignite seams play a fundamental stratigraphic role in the Neogene lithostratigraphy of Poland (Kasiński & Słodkowska 2016, Słodkowska & Kasiński 2016). Their broad distribution allows for the correlation of the lignite seams as well as the accompanying siliciclastics, even in distant areas (e.g., between SW Poland and SE Germany) (Piwocki 1992, Piwocki & Ziembińska-Tworzydło 1997, Widera et al. 2008). In the last case, there is greater detail for the chronostratigraphic position of lignite seams due to the study of inter-seam marine deposits rich in microfauna and/or dinocysts (Vinken 1988, Standke et al. 1993, Grimm et al. 2002).

Moreover, occasionally Polish lignite seams bear a more precise age due to radiometric dating of tuffaceous horizons. They are commonly known from the 'Bełchatów' deposit (Kleszczów Graben), but occasionally also from the 'Lubstów' deposit (Lubstów Graben), as well as the Carpathian Foredeep (e.g., Wagner 1984, Matl & Wagner 1987). Therefore, the obtained dates allow for at least partial regional correlation between the mentioned areas, including top lignite layers in both studied grabens (Kasiński 2004, Widera 2021). Such tuffaceous horizons have not yet been detected in the Złoczew Graben and the Zittau Basin.

Unfortunately, other research methods such as magnetostratigraphy, borehole geophysics, petrography, and lignite geochemistry cannot be applied to achieve the aims of this study. The explanation for this is the fact that the listed methods were used sporadically, not in all examined grabens, and above all only for small fragments of the lignite seams. The Quaternary deposits and processes have not been analysed in this paper.

RESULTS

Kleszczów Graben

The W–E-trending Kleszczów Graben is over 80 km long and 2–3 km wide. From the geological and mining points of view, its central parts located on both sides of the Dębina salt dome are most interesting. It is the deepest tectonic depression in the Polish Lowlands, with a depth exceeding to over 550 m (Gotowała & Hałuszczak 2002). The sub-Cenozoic bedrock is composed of Jurassic and Cretaceous carbonates, as well as the Permian (Zechstein) salts and its clay-gypsum cap, probably from the Cenozoic (Fig. 3).

The Cenozoic development of the Kleszczów Graben began in the early Oligocene (Rupelian), as evidenced by weathered Mesozoic rocks and locally occurring glauconitic sands in its deepest parts. Following the late Oligocene (Chattian) regional uplift, the palaeotectonic evolution of this graben accelerated. First, Lower Miocene siliciclastics up to 270 m thick (average 60 m) were deposited, called (together with the Paleogene deposits mentioned) the sub-coal complex. It is mainly composed of sands, but also of muds, clays, and thin layers of lignite (Fig. 3, Czarnecki et al. 1992).

Overlaying the Lower Miocene siliciclastic strata a coal complex is present, currently 200–300 m thick. However, during peat accumulation (between middle Early Miocene and early Mid-Miocene) its thickness was at least 200% greater than at present due to the large magnitude of the peat-to-lignite compaction (Widera 2024a). It is predominantly composed of lignite accompanied by lenses of non-coal sediments and rocks, including sands, clays, lacustrine chalk, flints, sandstones and paratonsteins (tuffaceous horizons). In the mining (local) lithostratigraphy, this coal complex is divided into three lignite seams – D, C and B (with an average thickness in the range of 20–50 m, 2–15 m, and 1–6 m, respectively) – collectively known as the main seam (Fig. 3).

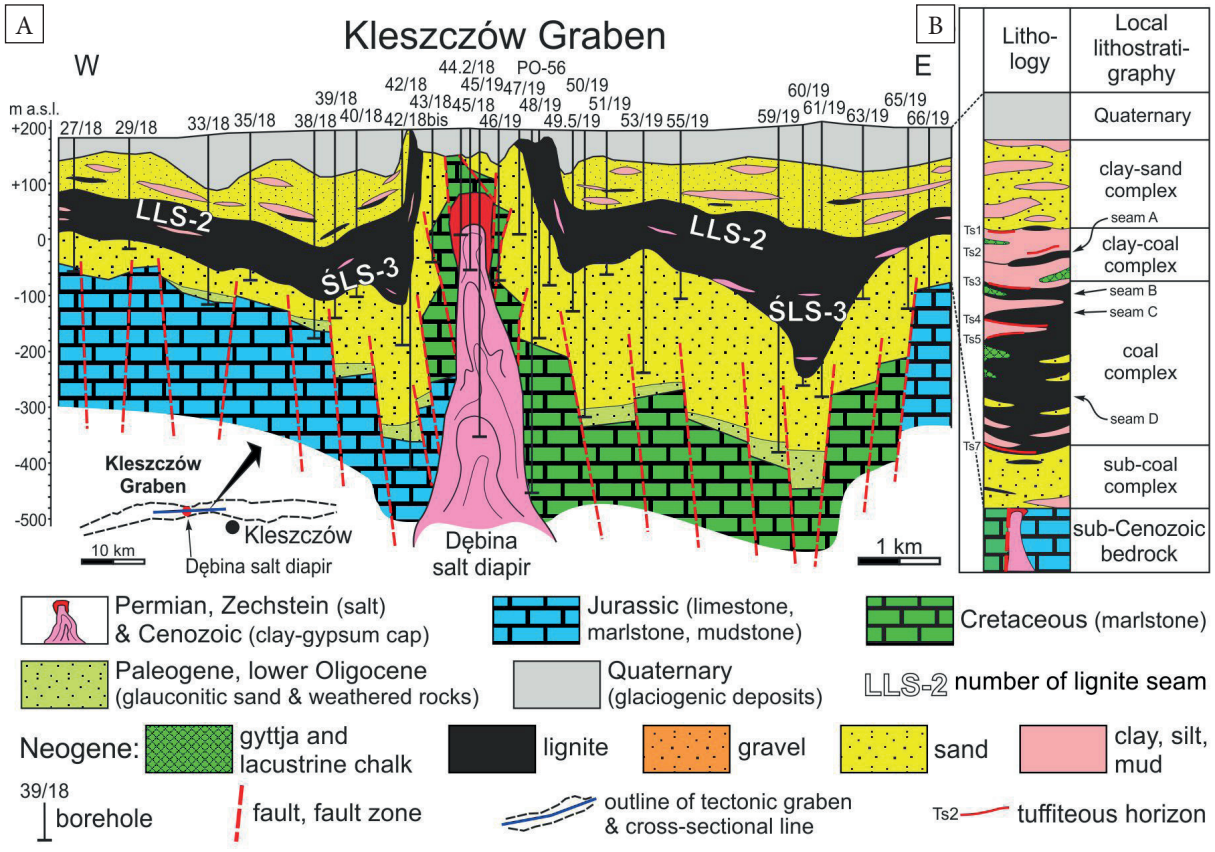

Fig. 3. *Geology and lithostratigraphic division of the Cenozoic deposits in the Kleszczów Graben: A) simplified geological cross-section (modified after Gotowała & Hałuszczak 2002, Widera & Hałuszczak 2011); B) sketch of local lithostratigraphy (modified after Czarnecki et al. 1992)*

Nevertheless, numerous palynological studies and dating of the mentioned tuffaceous horizons have allowed for the correlation of the main seam with ŚLS-3 (seam D) and LLS-2 (seams C and B) in other Polish lignite deposits (Kasiński 2004). The maximum continuous thickness of ŚLS-3 and LLS-2 in the Kleszczów Graben is 250.4 m, i.e. the largest in Europe (Piwocki 1992, Widera 2013, 2016b).

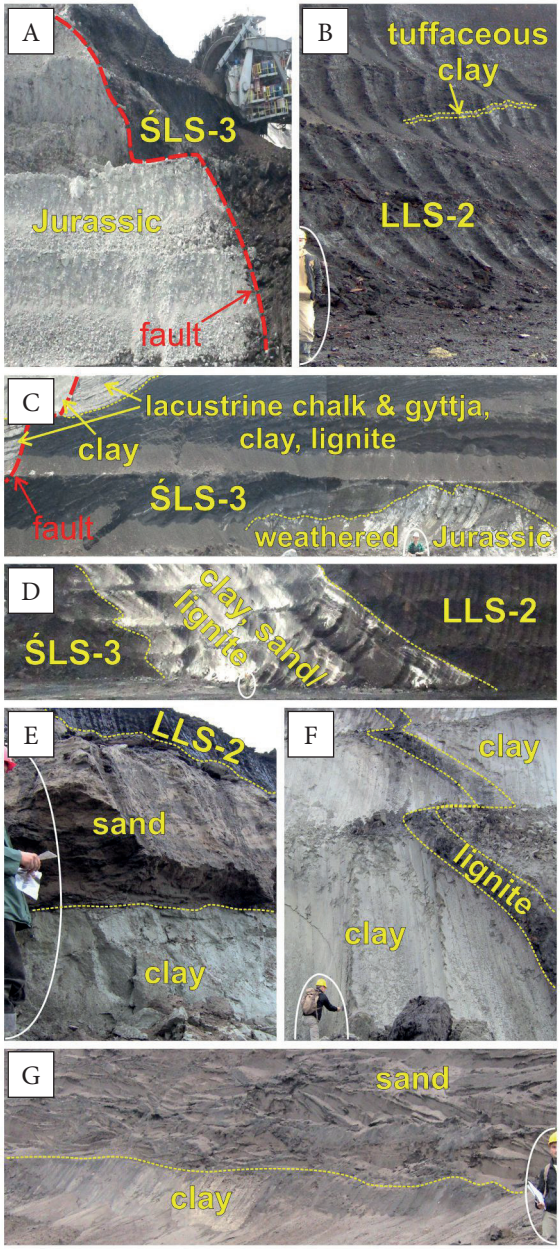

Fig. 4. *Characteristic rocks and sediments representing the main lithostratigraphic units in the Kleszczów Graben (Bełchatów and Szczerców lignite opencast mines): A), B) Mesozoic bedrock and coal complex; C)–E) sub-coal and coal complexes; F) clay-coal complex; G) clay-sand complex*

The Neogene succession in the Kleszczów Graben, overlaying the main seam – coal complex, ends with clay-coal and clay-sand complexes with a total thickness of up to 100–150 m. Their designations provide a good reflection of their lithological composition. It is worth noting the occurrence of the so-called seam A in the clay-coal complex (equivalent to the roof parts of LLS-2) and lignite lenses in the clay-sand complex (equivalent to MPLS-1) (Fig. 3B, Widera 2021).

The oldest rocks available for direct field observations in the Kleszczów Graben area are the Jurassic carbonate rocks (also from the Cretaceous) and their weathered residues. Contact between the Mesozoic bedrock and the above-characterised Cenozoic lithostratigraphic complexes along the main faults (W–E-trending with total vertical throws reaching 200–300 m) of the graben is also often visible in the field (Fig. 4A–C). Most of the studied sediments are inclined, folded, or faulted as a result of tectonic and compaction processes. This phenomenon is particularly clearly visible thanks to the colour contrast between the lignites and other rocks or sediments (Fig. 4D–G).

Złoczew Graben

The Złoczew Graben is about 15 km long and only 1–1.5 km wide. This WSW–ENE-trending tectonic depression, with a depth of up to 350 m, is the second deepest in the Polish Lowlands after the above-described Kleszczów Graben, located 50 km to the east (see Fig. 1). The Mesozoic top of the graben is predominantly composed of Jurassic carbonates, although Cretaceous carbonates have also been documented locally (Fig. 5, Urbański & Widera 2020).

It is worth noting that the two lignite seams (ŚLS-3 and LLS-2) along the presented cross-sectional line rest on each other and often directly on the Mesozoic bedrock. Their total thickness ranges from 16.1 m to 114.4 m, with an average of 46.2 m. The overburden of these seams is composed mainly of sands and clays with a thickness of up to 250 m (Fig. 5A).

Due to the great similarity between the Złoczew and Kleszczów grabens, the palaeotectonic evolution of the described area in the Cenozoic will not be repeated here.

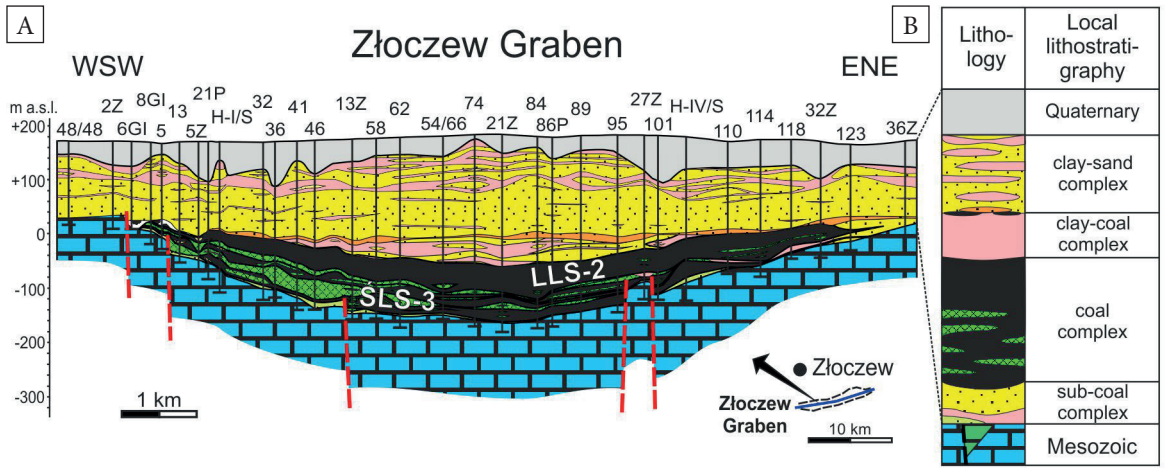

Fig. 5. *Geology and lithostratigraphic division of the Cenozoic deposits in the Złoczew Graben: A) simplified geological cross-section (modified after Urbański & Widera 2020); B) sketch of local lithostratigraphy (modified after Czarnecki et al. 1992). For explanations see Figure 3*

In turn, the close proximity between these grabens resulted in the use of the same local lithostratigraphy applied for the Kleszczów Graben when exploring and documenting the sediments filling the Złoczew Graben. Thus, the following lithostratigraphic complexes have been distinguished: sub-coal, coal, clay-coal, and clay-sand (Fig. 5B, Kasiński 2004, Urbański & Widera 2020).

The 'Złoczew' lignite deposit is not currently mined, but it has been well documented and prepared for possible exploitation at an as yet unspecified future time. To the authors' knowledge, conventional opencast lignite mining from the Złoczew Graben will not be carried out in the coming years. Therefore, the Cenozoic sediments filling this tectonic structure are not discussed in this paper.

Zittau (Żytawa) Basin

The Zittau Basin is a cross-border tectonic structure because it covers areas of Poland, the Czech Republic and Germany; however, its Polish segment is the largest and bears most of the lignite. This basin constitutes the NE part of the Eger (Ohře) Graben belonging to the Bohemian Massif (Malkovsky 1987, Kasiński 2000). On a supraregional scale, it is the easternmost branch of the European Cenozoic Rift System (ECRiS) (Ziegler & Dèzes 2007).

The Zittau Basin has an irregular shape. In general, it is W–E-trending, 20 km long, 15 km wide, and more than 200–400 m deep tectonic structure. The sub-Cenozoic bedrock is strongly faulted and composed of the Precambrian gneisses and granites (Fig. 6A, Kasiński 2000, Żelaźniewicz et al. 2011). Along these discontinuities (faults), there are local outflows of lava, from which trachytes, phonolites, and basalts have formed (Fig. 6B). Most of the radiometric dates obtained indicate their early Oligocene age (Kasiński et al. 2015, Pańczyk et al. 2023). The weathered Precambrian plutonic and Paleogene volcanic rocks locally reach a thickness of up to 80 m (Piwocki et al. 2004, Słodkowska & Kasiński 2016).

At the turn from the Oligocene to the Miocene, there was significant subsidence in the Zittau Basin. This is evidenced by the weathered Precambrian plutonic and Paleogene volcanic rocks that constitute the lower (Paleogene) part of the Turoszów Formation according to the local lithostratigraphy (Fig. 6B). Overlaying, in the Cenozoic sediment profile with a thickness of up to 300 m, several cycles can be distinguished. Each cycle begins with gravel, sand and clay sediments and ends with lignite. Three lignites constitute economic seams and were numbered, during the early stages of exploration of the Zittau Basin, from the oldest to the youngest as seams 1, 2 and 3. Thus, the lowermost seam 1 (ŚLS-3), with a maximum thickness of 35.3 m (average 20 m), is assigned to the Opolno Formation.

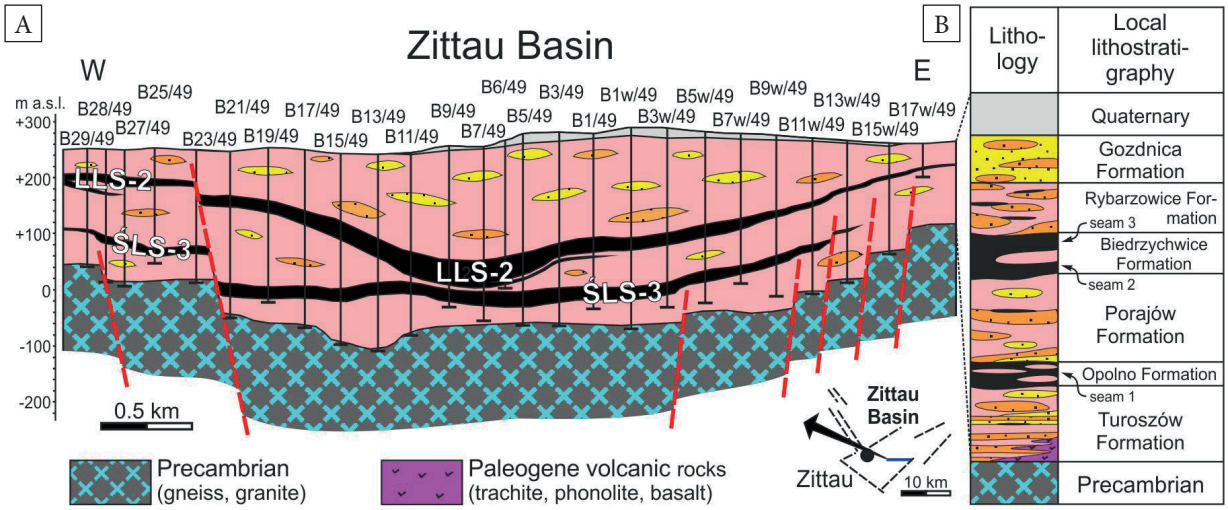

Fig. 6. *Geology and lithostratigraphic division of the Cenozoic deposits in the Zittau (Żytawa) Basin: A) simplified geological cross-section (modified after Widera 2016a, 2024); B) sketch of local lithostratigraphy (modified after Kasiński 2000, Kasiński et al. 2015, Kasiński & Słodkowska 2016). For other explanations see Figure 3*

Two younger seams 2 and 3 (LLS-2), with a total maximum thickness of 66.9 m (average 45 m), represent the Biedrzychowice Formation (Kasiński 2000, Widera 2021). The siliciclastics occurring between them are called the Porajów Formation. In turn, the Neogene lignite overburden includes the Rybarzowice and Gozdnica formations (Fig. 6B).

The lithological diversity of the Cenozoic sediments that fill the Zittau Basin is much greater in the field than the borehole data suggest. In the lowest part of the Turów opencast mine, below seam 1 (ŚLS-3), lacustrine clays with thin but laterally wide lignite layers are exposed. Characteristic is their sheet-like structure (Fig. 7A). However, the most typical yet enigmatic siliciclastics in the Zittau Basin are mixtures of clays and gravels or clays, sands and gravels in various proportions (Fig. 7B–D). While their origin has not yet been clearly identified, their formation was initially associated with sedimentary processes taking place on alluvial fans, which gradually entered the area of the intermountain tectonic depression, i.e. the Zittau Basin (Kasiński 2000). On the other hand, the Neogene top contains sediments that are different from the other grabens analysed in this study. These sediments are rusty-coloured fluvial gravels and sandy gravels of the Gozdnica Formation (Fig. 7E).

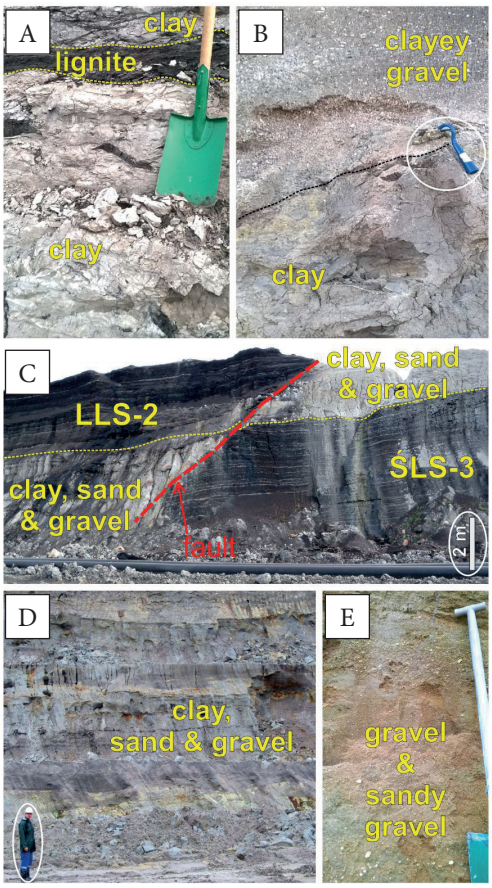

Fig. 7. *Characteristic sediments representing the main lithostratigraphic units in the Zittau (Żytawa) Basin (Turów lignite opencast mine): A) Turoszów Formation; B) Porajów Formation; C) Opolno, Porajów and Biedrzychowice formations; D) Rybarzowice Formation; E) Gozdnica Formation*

Lubstów Graben

The Lubstów Graben is the third deepest tectonic depression in the Polish Lowlands, after the Kleszczów and Złoczew grabens. In simple terms, the Lubstów Graben is up to 240 m deep (e.g., Widera 2007). It is generally NNW–SSE-trending, 6 km long, and 1–3 km wide. The sub-Cenozoic carbonates from the Cretaceous are highly faulted between adjacent boreholes (Fig. 8A). Moreover, the tectonic evolution of the Lubstów Graben is related to the activity of the so-called Gopło salt diapir located in its deep substratum (e.g., Kasiński et al. 2009, Widera 2024b).

Among the studied grabens, the Lubstów Graben stands out with the largest magnitude of the Paleogene subsidence. In the early Oligocene (Rupelian), nearly 140 m of glauconitic sands accumulated in its deepest parts. After the late Oligocene (Chattian) regional uplift (Krzywiec 2006, Jarosiński et al. 2009), the so-called Neogene sub-lignite 20–60 m thick sands were deposited. Higher in the profile there is the main lignite seam (LLS-2), with a maximum thickness of 86.2 m, average 25 m. Overlaying it, mainly in the SW segment of the graben, are clays, muds, and sands with lignite (MPLS-1) in the top layers (Fig. 8A).

Generally, the lithostratigraphic division used for the Lubstów Graben area is the same as for the majority of the territory of the Polish Lowlands. In the described case, the Paleogene is not separated. However, there are lithological grounds for its division in the deepest part of the graben, where thin lignite beds (CLS-5) occur. These are the Lower and Upper Mosina formations (glauconitic sands) separated by the Czempiń Formation (lignites and coaly muds) (cf. Figs. 2, 8B). The sub-lignite sands belong to the Rawicz Formation, while LLS-2 (locally called the Lubstów seam, Widera 2007) represents the Ścinawa Formation. In turn, the partially preserved Neogene overburden represents the Pawłowice, Naramowice, and Poznań formations. The lignite beds/lenses present in them (MPLS-1) are locally called the Konin seam (Sadowska & Giża 1991, Fig. 8B).

During the exploitation of the main lignite seam (the Lubstów seam, LLS-2) from the Lubstów Graben, only the Neogene sediments were available for observation. Among them, the most interesting are the high-angle-inclined sub-lignite sands (Fig. 9A). They dip at an angle of up to 55°, are faulted and can only be compared with the inclined layers occurring around the Dębina salt dome in the Kleszczów Graben (cf. Figs. 4D, F, 9A). On the other hand, the clayey-sandy overburden has only been preserved in places where the roof of LLS-2 is significantly concave upwards (Fig. 9B, C).

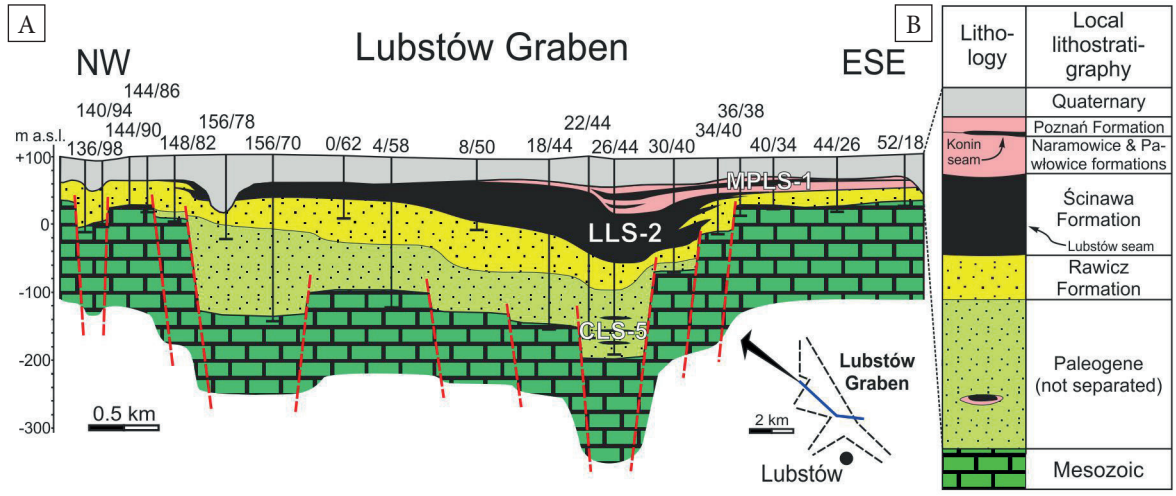

Fig. 8. *Geology and lithostratigraphic division of the Cenozoic deposits in the Lubstów Graben: A) simplified geological cross-section (modified after Widera 2007); B) sketch of local lithostratigraphy (modified after Widera 2021, 2024b). For explanations see Figure 3*

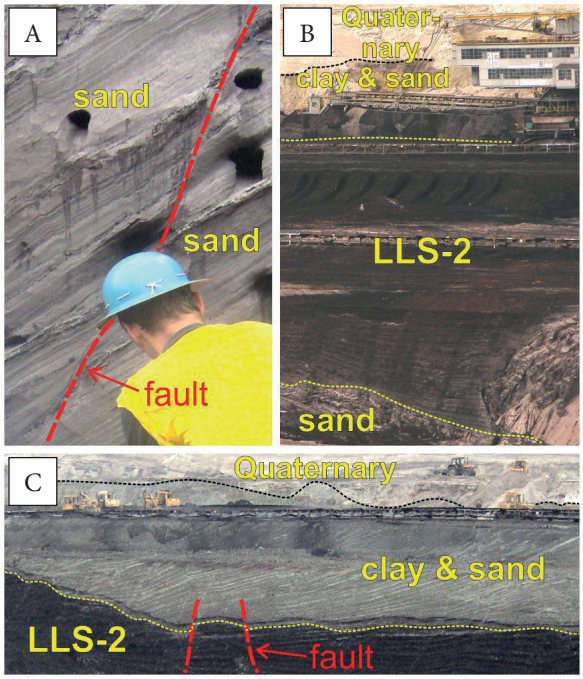

Fig. 9. *Characteristic sediments representing the main lithostratigraphic units in the Lubstów Graben (Lubstów lignite opencast mine): A) Rawicz Formation; B) Rawicz, Ścinawa, Pawłowice and Naramowice formations; C) Ścinawa, Pawłowice and Naramowice formations*

DISCUSSION

The Paleogene and Neogene lithostratigraphic terminology currently valid for the Polish Lowlands area was proposed by Piwocki and Ziembińska-Tworzydło (1997), with later minor corrections (Widera 2007). From a scientific point of view, local lithological divisions and their nomenclature are still applied for some lignite-rich areas. This approach bears historical justification, as the corresponding terminology was used by geologists and miners long before the establishment of modern regional lithostratigraphic schemes. Thus, the results obtained in this study allow for the compilation, comparison, synthesis, and discussion of the lithostratigraphy from the Kleszczów, Złoczew, Lubstów grabens, as well as the Zittau Basin (Fig. 10).

Due to the fact that the Kleszczów and Złoczew grabens are located close to each other and managed by the Bełchatów Lignite Mine, they should be treated together. Thus, the same lithological complexes are distinguished in both the grabens. So far, only Kasiński (2004) and Widera (2021) have attempted to compare these complexes with lithostratigraphic units of the Polish Lowlands. In turn, the lithostratigraphic division of the Paleogene and Neogene sediments and rocks in the Zittau Basin is more extensive (Kasiński 2000, Kasiński & Słodkowska 2016). Nevertheless, the very good palynological identification of lignite seams is supported by radiometric studies of volcanites and tuffaceous horizons. Thus, it allows for a relatively easy correlation of the main lithostratigraphic units (i.e. complexes and formations) between the Kleszczów and Złoczew grabens, and the Zittau Basin. Finally, the lithostratigraphy of the Lubstów Graben, representative of the Polish Lowlands, is comparable to the other three grabens (cf. Figs. 2, 10).

The latest dating of the mentioned volcanites from the Zittau Basin, achieved using the $^{40}Ar/^{39}Ar$ isotope method (ca. 31–29 Ma, Pańczyk et al. 2023), only means that the studied lignites (ŚLS-3, LLS-2) are younger than the middle Rupelian, i.e. middle part of the early Oligocene. In turn, tuffaceous horizon located in the roof layers of LLS-2 in the Lubstów Graben may be correlated with similar horizon resting on the roof of the seam A (LLS-2) in the Kleszczów Graben (see Fig. 3B, Matl & Wagner 1987). In the last case, using the fission-track method for detrital zircon, it has been dated to be 16.5 Ma ±1.3 Ma (Burchart et al. 1988), i.e. from middle Lower Miocene to lower part of the Mid-Miocene. This indicates the time range for the completion of the accumulation of peat from which LLS-2 was formed in all of the grabens examined (cf. Figs. 2, 10).

At this point, the following question arises: what are the benefits of the present study? Firstly, the individual lithostratigraphic units distinguished in isolated grabens can be compared. Secondly, the approximate chronostratigraphic position of the various lithostratigraphic units can be determined (see Fig. 2). Lastly, knowing the age of subsequent complexes and formations, it is possible to reconstruct the geological processes that occurred during specific time intervals of the Paleogene and Neogene in various regions of Poland.

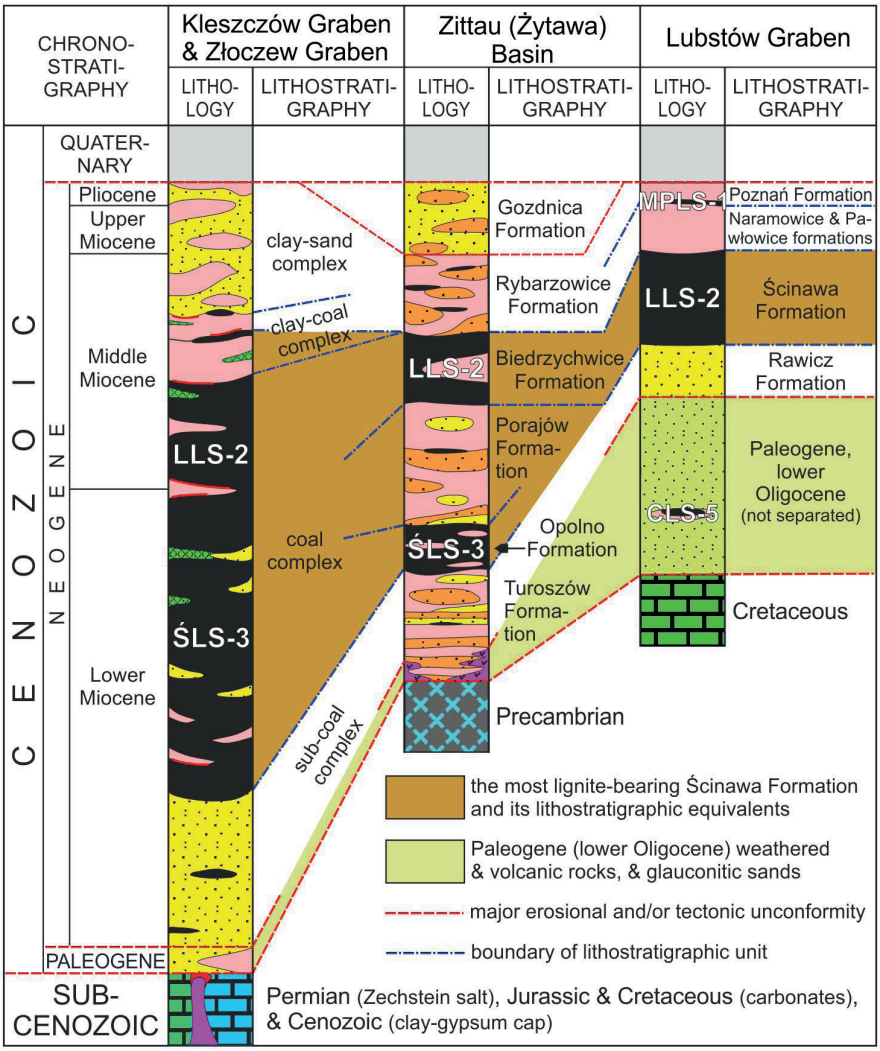

Fig. 10. *Compilation of the Cenozoic lithostratigraphy for the deepest Polish lignite-rich grabens studied. For other explanations see Figures 2, 3 and 6*

CONCLUSIONS

1. The deepest Polish tectonic depressions are also the richest in lignite resources. These are the Kleszczów, Złoczew and Lubstów grabens, and the Zittau (Żytawa) Basin. Their depth is over 240–550 m, and the total maximum thickness of productive lignite seams filling them is more than 86–250 m.
2. The geology of the analysed grabens is complex, and the lithology of the Paleogene and Neogene sediments and rocks as well as their thicknesses and their distribution vary intensely. Therefore, a different lithological division is used in each of these areas, and lithostratigraphic units have a local nomenclature.
3. The current study compiled the lithostratigraphic profiles from the examined grabens. It allowed for a relatively simple correlation of the main lithostratigraphic units (complexes and formations) between the deepest lignite-rich grabens of Cenozoic age in Poland.
4. The results presented above are not final. In the context of the diachronic nature of the boundaries of lithostratigraphic units, it is suggested to continue research on, for example, tuffaceous horizons. Their discovery is still possible in existing lignite opencasts (Kleszczów and Zittau grabens), and in the case of the Lubstów and Złoczew grabens only in preserved borehole cores.

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