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Cenozoic tectonic evolution of the main lignite-rich grabens in Poland. Part 1. Tectonic stages

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ABSTRACT:

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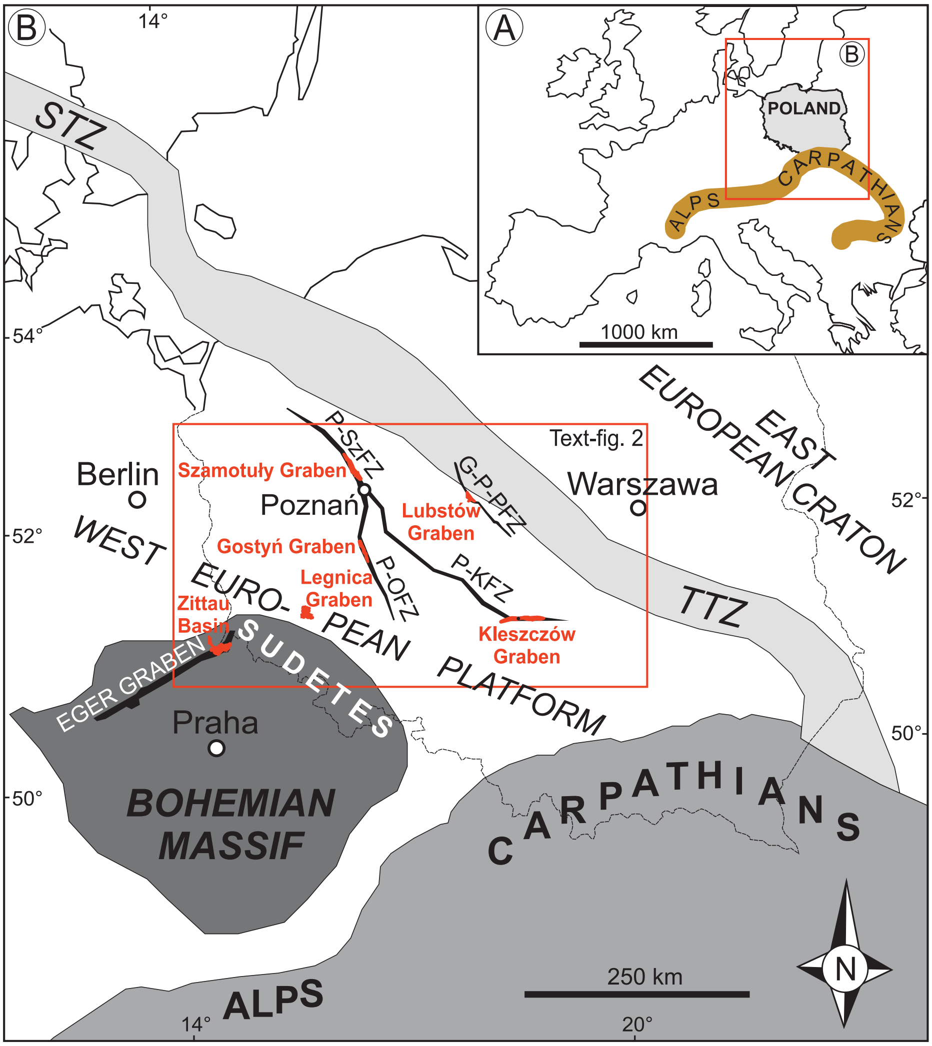
Understanding the Cenozoic tectonic evolution of grabens rich in lignite is important in the context of the accumulation of ~40–650 m of peat, as well as the exploitation of later formed lignite seams with a thickness of ~20–250 m. Six such areas were selected for a detailed palaeotectonic analysis: the Gostyń, Szamotuły, Legnica, Zittau, Lubstów, and Kleszczów grabens. During the analysis, borehole data were used, taking into account the compaction of peat at the transition to lignite, in order to reconstruct the magnitude of the total subsidence. This made it possible to distinguish between regional (covering areas also outside the grabens) and local (occurring only in the grabens) tectonic movements, and among the latter, tectonic and compactional subsidence. The hypothetical palaeosurface of the mires was reconstructed based on the lignite decompaction. As a result, it was possible to determine whether the examined peat/lignite seams underwent post-depositional uplift and/or subsidence. Between one (Gostyń Graben) and four (Zittau Basin and Kleszczów Graben) stages of tectonic subsidence were distinguished in the studied lignite-bearing areas. In the case of the Zittau Basin, as well as the Lubstów and Kleszczów grabens, post-depositional stages of tectonic uplift were also indicated. Like the boundaries of lithostratigraphic units, the successive stages of the Cenozoic tectonic development of the examined grabens are diachronic.

Key words: Peat-to-lignite compaction; Decompaction; Compactional subsidence; Tectonic subsidence; Tectonic uplift.

INTRODUCTION

The main Polish lignite-rich tectonic grabens were formed in the area of the West European Palaeozoic Platform during the Cenozoic. An exception is here the Zittau Basin, which is the easternmost part of the Eger (Ohře) Graben, belonging to the Bohemian Massif (Text-fig. 1; Malkovsky 1987; Ziegler *et al.* 1995; Kasiński 2000; Špičáková *et al.* 2000; Kasiński *et al.* 2015). This graben constitutes an integrated, easternmost segment of the European Cenozoic Rift System – ECRiS (Ziegler 1990; Ziegler and Dèzes 2007). The Legnica Graben is located in the so-called Fore-Sudetic Block, adjacent to the Sudetes. The Gostyń, Szamotuły, Lubstów, and Kleszczów grabens are located along the main Permian-Mesozoic-Cenozoic fault zones in central and south-western Poland (Text-figs 1 and 2).

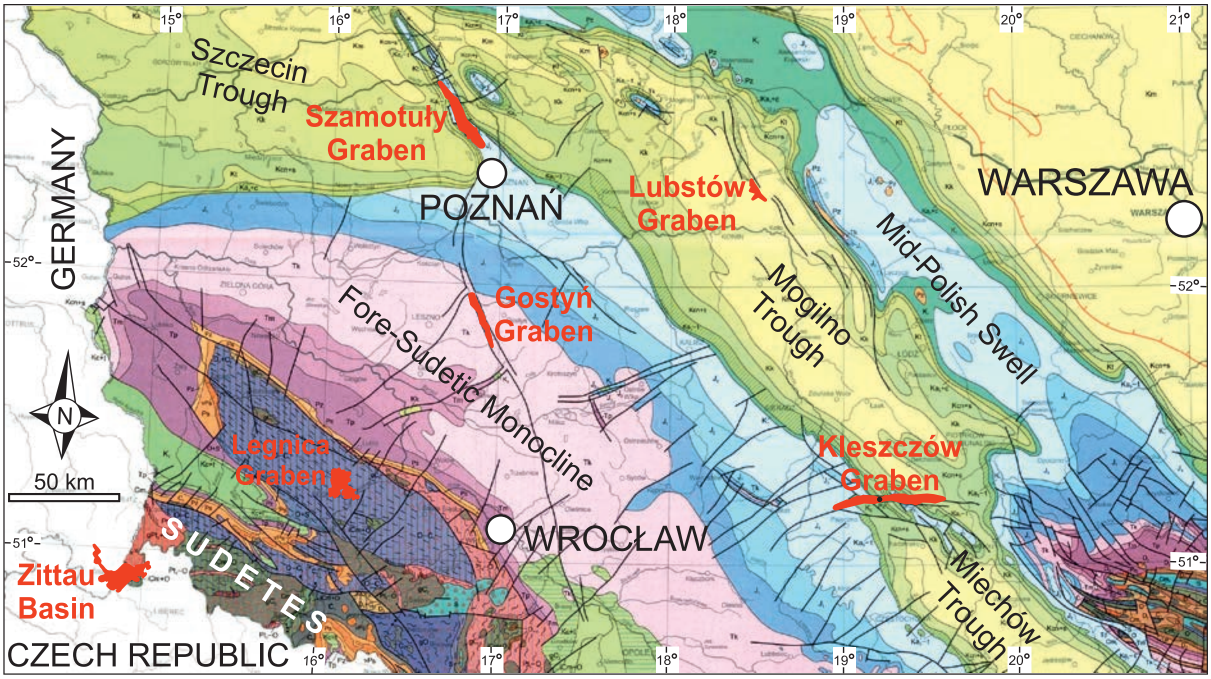
Comparative thickness analysis plays a key role in both regional (continental basins) and local (grabens) palaeotectonic studies. These studies commonly involve the back-stripping method, which takes into account the presence of stratigraphic unconformities and sediment compaction (Van Hinte 1978; ten Veen and Kleinspehn 2000). When comparing several grabens/basins, this technique enables the calculation of the following components of the total subsidence: epeirogenic (regional) subsid-



Text-fig. 1. Location map of the examined lignite-rich grabens (modified after Kasiński 1984; Dadlez and Marek 1998; Gotowała and Hałuszczak 2002; Widera 2004, 2007; Widera and Hałuszczak 2011; Kasiński *et al.* 2019). A – Poland against the outlines of Europe. B – Abbreviations of regional tectonic zones: P-KFZ, Poznań-Kalisz Fault Zone; P-SzFZ, Poznań-Szamotuły Fault Zone; P-OFZ, Poznań-Oleśnica Fault Zone; G-P-PFZ, Gopło-Ponętów-Pabianice Fault Zone; STZ, Sorgenfrei-Tornquist Zone; TTZ, Teisseyre-Tornquist Zone. Note the location of the Eger (Ohře) Graben in the Bohemian Massif (modified after Malkovsky 1987; Ziegler *et al.* 1995; Špičáková *et al.* 2000; Ziegler and Dèzes 2007).

ence, tectonic (local) subsidence, and compactional (local) subsidence. Consequently, back-stripping is also used to determine the timing of vertical movements, and even to calculate the rate of sediment accumulation and the rate of subsidence or uplift (e.g., Zijerveld *et al.* 1992; Michon *et al.* 2003; Van Balen *et al.* 2005; Widera 2007).

The accuracy of the back-stripping method depends on knowledge of the chronostratigraphy and/or biostratigraphy of an area (Van Hinte 1978; ten Veen and Kleinspehn 2000), these being more precise than lithostratigraphy – the main stratigraphic method used for the division of Cenozoic sediments in the grabens studied here. On the other hand, the knowledge about the compaction of non-organic sediments, including siliciclastics (cf. Sclater and Christie 1980; Baldwin and Butler 1985; Sheldon and Retallack 2001), is much better than in the case of the transformation of peat into lignite (cf. Ryer and Langer 1980; Hager *et al.* 1981; Kasiński 1984; Nadon 1998; Widera *et al.* 2007; Widera 2015). Therefore, most researchers over- or underestimate the magnitude of lignite compaction, and omit or determine its impact on subsidence only qualitatively. In other words, tec-



Text-fig. 2. Main Polish lignite-rich grabens analysed in this paper against the background of the geological map of Poland without Cenozoic cover (modified after Dadlez *et al.* 2000). See Text-fig. 4 for the stratigraphy of the sub-Cenozoic top.

tonic subsidence is rarely distinguished from compactional subsidence, and these two phenomena together may create a relatively large accommodation space for fresh sediments (e.g., Courel 1987; Hager 1993; Opluštil 2005; Schäfer *et al.* 2005; Rajchl *et al.* 2008, 2009; Schäfer and Utescher 2014).

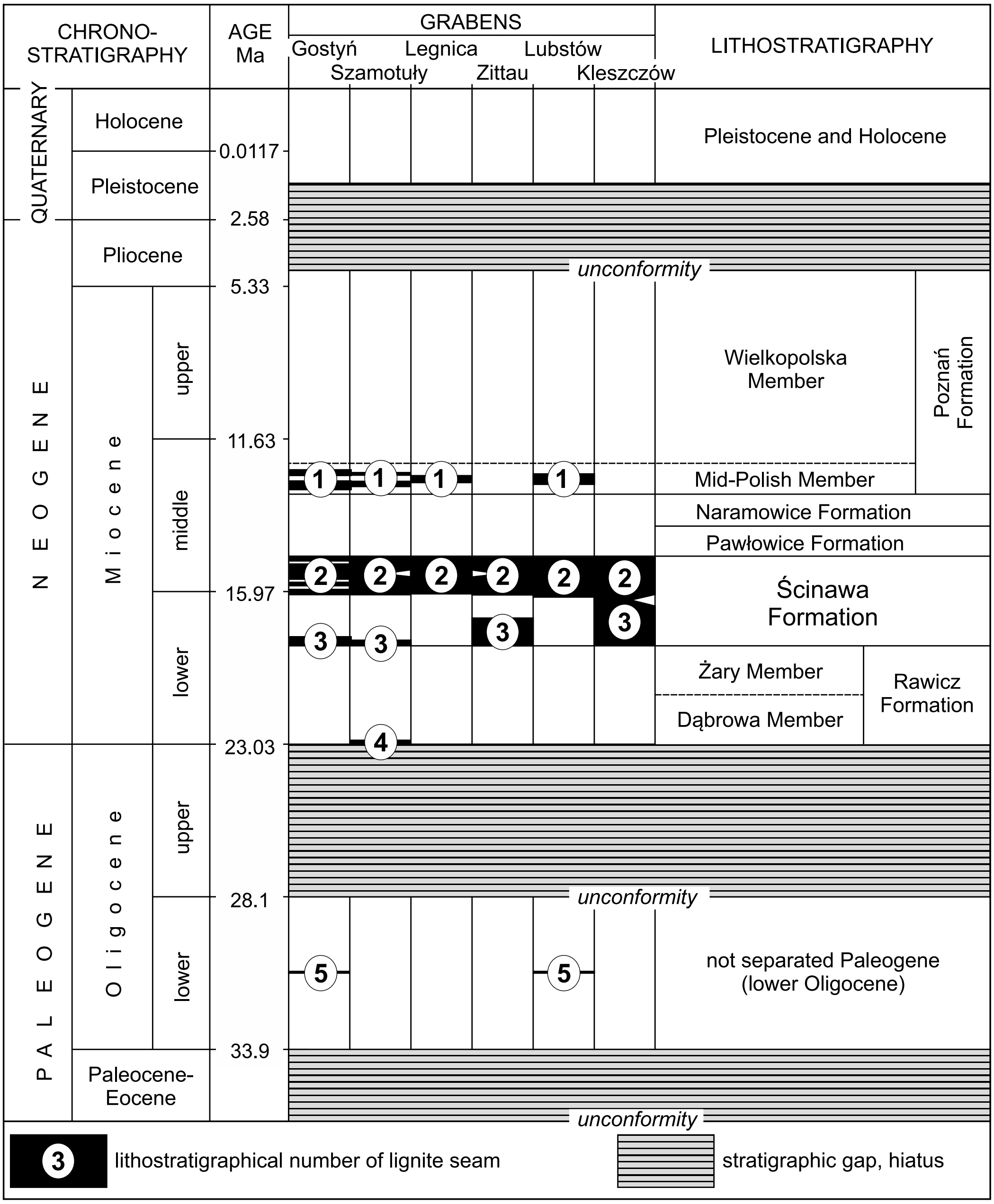
It should be noted here that no algorithms for analysing the compaction and decompaction of sediments containing relatively thick coal (lignite) seams have been proposed so far. This is due to the above-mentioned insufficient knowledge about the process of transforming peat into lignite and then into hard coal. Likewise, both total tectonic and tectonic subsidence diagrams are not constructed for Cenozoic lignite-bearing areas. In the case of Polish lignite deposits, this is due to the low precision of stratigraphies based on lithostratigraphic division with diachronic boundaries of subsequent units. And finally, there is no mention of the impact of the weight of the Scandinavian ice sheets on the compaction of Paleogene and Neogene lignites in world geological literature. Such an impact certainly occurred, but its effects are unnoticeable (i.e., indistinguishable) in the architecture of the lignite seams, excluding, of course, glaciotectonic deformations. Therefore, it will also not be taken into account in the following palaeotectonic analysis.

The main goal of this study was to identify the stages of tectonic evolution of selected Polish lignite-rich grabens. This was achieved by: (1) comparing (if possible) the average thickness of the relevant layers in the axial zone of the graben and in its surroundings to distinguish between epeirogenic and tectonic vertical movements; (2) determining the impact of the compaction of thick lignite seams on the non-tectonic deformations of younger sediments – the distinction between tectonic and compactional subsidence; (3) identifying the stages of tectonic subsidence and uplift, and estimating their magnitude in some of the grabens; and (4) discussing the influence of tectonics and compaction on the grabens' infill with clastics and lignites.

GEOLOGICAL SETTING

Regional geology

The aforementioned major fault zones, that is, Poznań-Oleśnica (P-OFZ, with the Gostyń Graben), Poznań-Szamotuły (P-SzFZ, with the Szamotuły Graben), Gopło-Ponętów-Pabianice (G-P-PFZ, with the Lubstów Graben), and Poznań-Kalisz (P-KFZ, with the Kleszczów Graben) are from several dozen to



Text-fig. 3. Unified and simplified stratigraphy for the examined sedimentary grabens with particular reference to the chronostratigraphic position of the main lignite seams. Numerical ages after Cohen *et al.* (2013; updated). Lithostratigraphy modified after Piwocki and Ziembińska-Tworzydło (1997), Widera (2007), Widera *et al.* (2008, 2019b). See Widera (2021) for local lithostratigraphy in individual grabens. Abbreviations and nomenclature of the main lignite seams: (5) – the fifth Czempiń lignite seam (CzLS-5); (4) – the fourth Dąbrowa lignite seam (DLS-4); (3) – the third Ścinawa lignite seam (ŚLS-3); (2) – the second Lusatian lignite seam (LLS-2); (1) – the first Mid-Polish lignite seam (MPLS-1).

>100 km long and 2–7 km wide (Text-figs 1 and 2). The tectonic history of these fault zones (subsidence and/or uplift) started before the Zechstein, and movements mainly occurred during the Mesozoic and Cenozoic (Deczkowski and Gajewska 1980; Karnkowski 1980; Dadlez *et al.* 1995; Ziegler *et al.* 1995; Dadlez and Marek 1998; Widera *et al.* 2008; Jarosiński *et al.* 2009; Pharaoh *et al.* 2010; Widera and Hałuszczak 2011).

The tectonic development of the Szamotuły (Rowan and Krzywiec 2014; Widera *et al.* 2019b), Lubstów (Dadlez and Marek 1998; Widera 2007), and Kleszczów (Gotowała and Hałuszczak 2002) grabens was related to the evolution of the salt diapirs over which they are located. The mechanisms and development of salt structures, as well as the grabens co-occurring with them, were similar throughout the entire Permian-Mesozoic Central European Basin System (Ziegler 1990). Numerous such salt-related structures and grabens were generated in extensional or contractional tectonic regimes in the territories of the Netherlands (e.g., ten Veen *et al*. 2012; Harding and Huuse 2015), Germany (e.g., Brandes *et al*. 2012; Warsitzka *et al*. 2019; Ahlrichs *et al*. 2021), Denmark (e.g., Clausen and Pedersen 1999; Rasmussen 2009, 2013; Clausen *et al*. 2012), and Poland (e.g., Krzywiec 2012; Krzywiec *et al*. 2019).

By contrast, the formation and structural development of the Gostyń and Legnica grabens, as well as the Zittau Basin cannot be associated with salt activity. The Gostyń and Legnica grabens are located in the marginal zone of the Polish Basin, where the thickness of the Zechstein salt formations is too small for the formation of pillows, diapirs, etc. (Dadlez and Marek 1998). The Zittau Basin, on the other hand, is an intra-mountain graben in the Western Sudetes. In this case, the Cenozoic sediments (predominantly of Neogene age) rest directly on the crystalline Precambrian bedrock (Kasiński 2000).

Cenozoic stratigraphy

The examined lignite-bearing grabens were formed in the eastern part of the great Northwest European Paleogene–Neogene Basin during the Cenozoic era (Vinken 1988). The Paleogene marine sediments occur locally, while Neogene (mainly of Miocene age) continental (fluvial) sediments are widespread and dominate in the studied areas. Therefore, the stratigraphic zonation of the individual areas is complex and rarely supported palaeontologically. On the other hand, the main lignite seams play a significant lithostratigraphic role, because they allow a relatively easy correlation between lignite deposits in the grabens located far apart from each other (Piwocki and Ziembińska-Tworzydło 1997; Widera 2007). Hence, they require a brief description as some of them will be analysed in detail later in this paper.

The Polish lignite seams comprise five lithostratigraphically important groups ranging in age from the early Oligocene to the Middle Miocene. These are, from bottom to top, the fifth group of Czempiń lignite seams (CzLS-5), the fourth group of Dąbrowa lignite seams (DLS-4), the third group of Ścinawa lignite seams (ŚLS-3), the second group of Lusatian lignite seams (LLS-2), and the first group of Mid-Polish lignite seams (MPLS-1) (Text-figs 3 and 4). Only the latter three are economically valuable and therefore are currently being exploited on an industrial scale. While lignite mining from the Lubstów Graben ended in 2009, mining activities are ongoing in the Zittau Basin and the Kleszczów Graben. In turn, lignite resources have been documented in the Legnica, Gostyń, and Szamotuły grabens, but no mining of these is planned for the coming years.

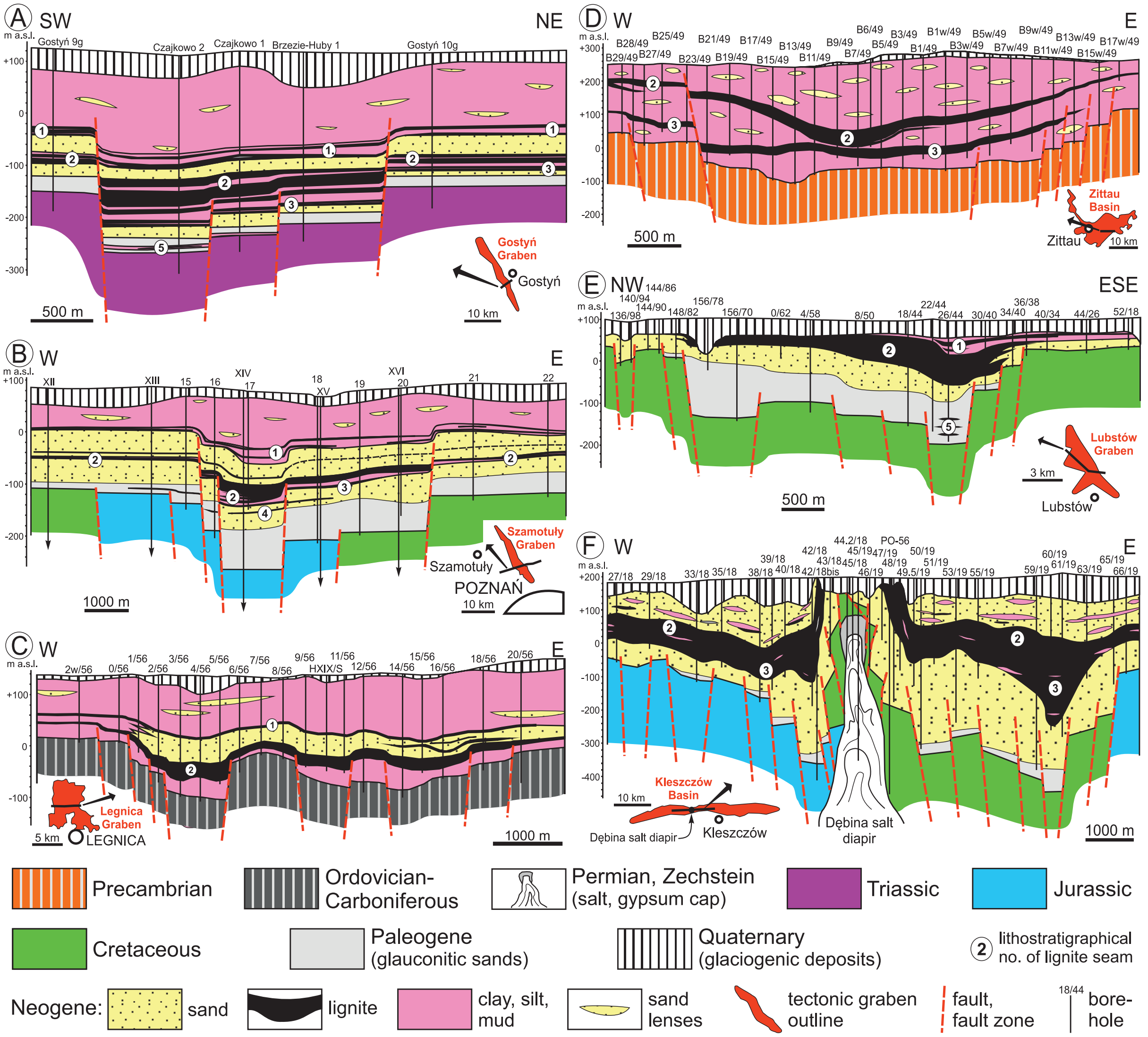
The Cenozoic succession in the investigated grabens is generally characterised by three main unconformities and associated stratigraphic gaps: Paleocene–Eocene, upper Oligocene, and lower Pliocene–middle Pleistocene (Text-fig. 3). Thus, the oldest Cenozoic deposits are marine glauconitic sands of early Oligocene age which are locally interbedded with thin lignite seams. Then, the terrestrial Neogene formation with productive lignite seams rests above the upper Oligocene stratigraphic gap. The accumulation time of these deposits covered the whole Miocene and the earliest Pliocene. As can be clearly seen in the area of all the studied grabens, the Ścinawa Formation and the Mid-Polish Member (lower part of the Poznań Formation) are the richest in lignite (Text-figs 3 and 4). It should be added that the individual grabens have their own local lithostratigraphy, which will not be discussed in detail here for the sake of simplicity (Widera 2021).

MATERIAL AND METHODS

Data sources

The results presented in this paper were mainly obtained from borehole data. It should be noted that more than 150 lignite deposits have been documented in the Polish territory, of which only a few dozens have economic value (Kasiński *et al*. 2006, 2019; Bielowicz and Kasiński 2014; Tajduś *et al*. 2014; Widera 2016a). These economic deposits include the lignite-bearing grabens that were selected for this study (see Text-fig. 1).

Numerous boreholes have been drilled for lignite, that is, from ~50 in the Gostyń and Szamotuły grabens, through 100–400 in the Legnica and Lubstów grabens, to more than 2,000 both in the Zittau Basin and in the Kleszczów Graben (Kasiński 2000; Widera and Hałuszczak 2011; Widera 2013; Widera *et al*. 2019b). However, data from only 111 boreholes were used to present the geological setting of the investigated grabens and for palaeotectonic analyses

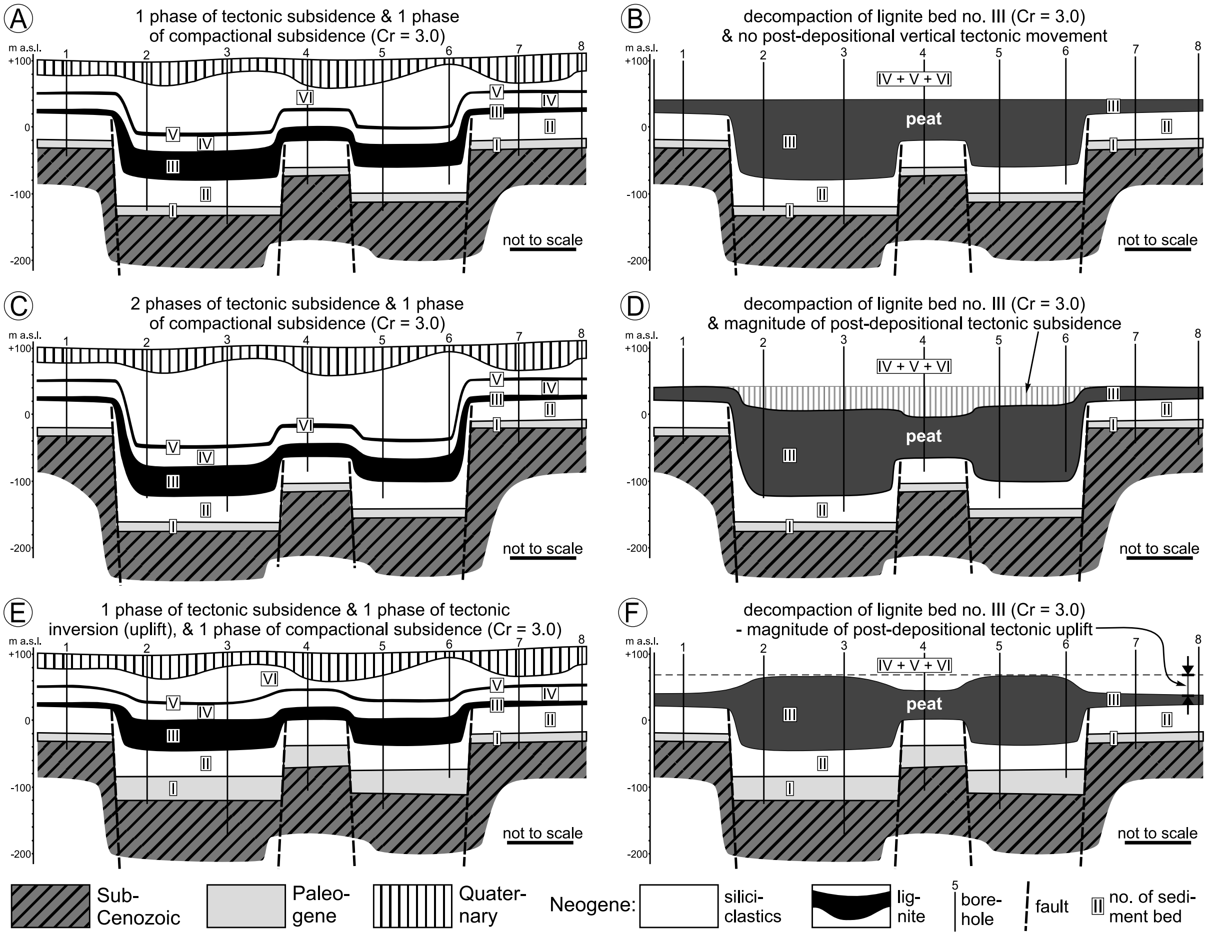


Text-fig. 4. Geological cross-sections through the lignite-rich grabens analysed in this paper. A – Gostyń Graben. B – Szamotuły Graben. C – Legnica Graben. D – Zittau Basin. E – Lubstów Graben. F – Kleszczów Graben. See the text and Text-fig. 3 for the nomenclature of lignite seams, as well as Text-figs 1 and 2 for location of the grabens.

(Text-fig. 4). These data were mainly obtained from the geological archives of currently operating lignite mines (Konin, Turów, Bełchatów), from the geological archive of the Wielkopolska Province in Poznań, as well as from the National Geological Archive and Central Geological Database of the Polish Geological Institute in Warsaw, Poland.

SEDIMENT CHARACTERISTICS

A basic sedimentological analysis was conducted on the siliciclastics (clays, silts, sands) (Allen and Allen 1990; Bridge 2003; Zieliński 2014), while a standard grain-size classification was applied to determine their granulometry (Wentworth 1922). A macro-petrographic analysis was used for the general characterisation of the lignite seams. In this case, the so-called lignite lithotypes were distinguished. The proportions of xylites (i.e., woody fragments >1 cm in size) and the fine-detrital matrix (i.e., vegetation detritus <1 cm in size) were considered here (Markič and Sachsenhofer 1997; Widera 2012). As a result, the lithotypes could be tentatively related to the original peat-forming mires in which they were created (Teichmüller 1989).



Text-fig. 5. Hypothetical examples of schematic geological cross-sections defining the research problem. A and B – One-stage tectonic (subsidence) development of the graben. C and D – Two-stage tectonic (subsidence) development of the graben. E and F – Two-stage tectonic (subsidence and uplift) development of the graben. See the text for more explanations, Text-figs 6 and 7 for results of lignite decompaction, and Text-figs 8–13 for a detailed tectono-sedimentary analysis of the lignite-rich grabens.

Vertical movements and tectonic stages

The effects of vertical movements in the studied areas could be readily identified both in the field and on geological cross-sections, as well as on thickness and structural maps (e.g., Widera 2004; Widera *et al.* 2008, 2019b). The factors governing subsidence are demonstrated here in a graphical form using three hypothetical examples (Text-fig. 5). The first example shows an area that has undergone only one tectonic stage, which took place during peat accumulation. This is confirmed by the varying thickness of the lignite seam (bed no. III) along the geological section. The remaining layers (except bed no. VI with its top deformed by Pleistocene erosion and glaciotectonism) have constant thickness in this schematic geological cross-section (Text-fig. 5A). In short, there were no local vertical movements in the area of the graben during their deposition – i.e., epeirogenic (and/or isostatic) movements – which covered both the axial zone and flanks of the graben. The decompacted lignite seam (with a compaction ratio Cr = 3.0, which determines the relationship between the initial peat thickness and the current lignite thickness) forms a horizontal surface, that is, a realistic top of the palaeomire (Text-fig. 5B). Thus, the lignite compaction was sufficient to deform layers no. IV and V, as well as the bottom of layer no. VI, without any vertical tectonic movements (Text-fig. 5A).

The next example depicts two stages of tectonic subsidence, i.e., during and after the accumulation of peat which was then transformed into lignite (bed no.

III). In this case, there are relatively large differences in the height of the main lignite seam in the axial part of the graben and on its flanks (Text-fig. 5C). Taking into account the lignite decompaction (with the same value of compaction ratio Cr = 3.0), the hypothetical surface of the palaeomire is clearly concave (Text-fig. 5D). Such a situation is actually unrealistic. Therefore, post-depositional tectonic movements are the most likely explanation for the surface being concave. The analysed example suggests the occurrence of at least two stages of local tectonic subsidence, that is, one during and the other after the peat accumulation, as well as one stage of peat compaction (compactional subsidence) between them (Text-fig. 5C, D).

The third hypothetical example is a little more complex, showing two stages of tectonic subsidence and one stage of tectonic uplift (Text-fig. 5E). The first stage of tectonic subsidence includes the accumulation of the Paleogene sediments (bed no. I) which are thicker in the axial part of the graben than on its flanks. The second stage of tectonic subsidence affects the lignite seam (bed no. III). Nevertheless, after its decompaction (by Cr = 3.0), the reconstructed surface of the palaeomire formed ‘hills’ that are several dozen metres high (Text-fig. 5F). This, of course, contradicts the knowledge about the development of modern and ancient mires (e.g., Teichmüller 1989; Markič and Sachsenhofer 1997; Diessel *et al.* 2000; Widera 2013, 2016b). This most likely implies that some parts of the graben, which were previously subjected to tectonic subsidence, have since been uplifted through a stage of tectonic uplift (Text-fig. 5B). It should be clearly stated that the examples provided here do not exhaust all possibilities regarding the palaeotectonic evolution of the lignite-bearing areas. Hence, some of their variants will be discussed below using the example of selected Polish grabens which host abundant lignite deposits. Other, more realistic interpretations will be analysed in detail in the second part of the author’s future paper.

RESULTS

Lignite seams

Description and interpretation of lignite seams

The three youngest lignite seams studied are the most important and exploited in Poland, that is, the third Ścinawa lignite seam (ŚLS-3), the second group of Lusatian lignite seams (LLS-2), and the first group of Mid-Polish lignite seams (MPLS-1). They consist of macroscopically distinguishable components defining lignite lithotypes. In general, the following lithotype associations are the most common within the lignites from the grabens studied: xylodetritic (27–34 vol.%), detroxylitic (7–35 vol.%), detritic (4–42 vol.%), and xylitic (3–10 vol.%), with massive, horizontal, folded, faulted, or fractured structures. However, a bitumen-rich lithotype association covers a significant part of the ŚLS-3 and LLS-2 (10–12 vol.%) belonging to the Zittau Basin and Kleszczów Graben. These lignites also have a largely gelified and/or nodular structure (Widera 2016c, 2021).

The lithotype associations correspond to specific environmental conditions of peat accumulation. The xylodetritic and detroxylitic lignites are typical of wet-forest and bushy swamps, respectively (Teichmüller 1989). The detritic lignites were formed in shallow lakes or ponds that existed on the mire surface, while the original depositional environment of the xylitic lignites was a dry forest swamp. In the latter case, as evidenced by the so-called stump horizons, the groundwater table was relatively low (e.g., Markič and Sachsenhofer 1997; Diessel *et al.* 2000). On the contrary, the presence of bitumen-rich lignites required phytoplankton, which accumulated at the bottom of open-water reservoirs existing in the mire area (Kasiński 2000; Widera 2016c, 2021). In the context of palaeotectonic analyses, it can be concluded that the lithotype composition did not have a major impact on the differentiation of compaction magnitudes in various parts of the lignite seams. This statement is supported by observations in opencast mines, where different lithotypes are almost evenly distributed within the lignite seams. However, the presence of mineral interbeddings, for example, in the form of crevasse-splay sandbodies or layers of lacustrine clays (e.g., Widera *et al.* 2022, 2023) in the lignite seams must be treated individually, because they may have a significant impact on the compaction process.

Compaction of lignite seams

The characterised lithotype composition of the lignites did not significantly affect the compaction of peat during its transition to lignite, as stated above. Hence, the compaction of the same stratigraphically correlated lignite seams is very similar (almost equal) along any cross-sectional line analysed. The magnitude of the compaction is most often expressed by the so-called compaction ratio (Cr), which corresponds to the relationship between the initial peat thickness and the current lignite thickness, as stated above.

The Polish lignite seams have compaction ratios of Cr = 2.9 for the ŚLS-3 (Kasiński 1984, 2000), Cr =

2.5 for the LLS-2, and Cr = 2.0 for MPLS-1 (Widera 2007, 2015; Widera *et al.* 2007). The reported average Cr values were applied in the palaeotectonic analysis. First, they were used to reconstruct the initial thickness of the peat by decompacting the lignite seams (Text-fig. 5), and then to determine the stages of tectonic development of the investigated grabens (Text-figs 6–13). However, it is worth bearing in mind that peat compaction is most intensive during the accumulation of its most recent layers and immediately after it is covered by other sediments (e.g., Courel 1987; Van Asselen 2011; Widera 2019).

Siliciclastics

Description and interpretation of the siliciclastics

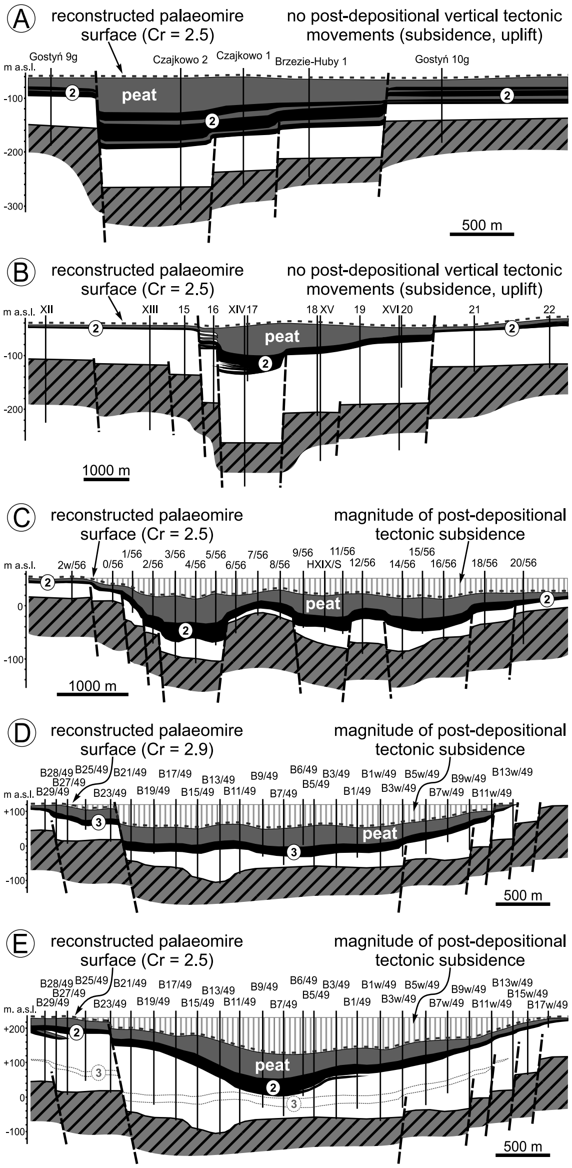
Apart from the above-characterised lignites, the investigated grabens are mainly filled with sands, and to a lesser extent with clays, silts, and muds (see Text-fig. 4). Obviously, the Paleogene glauconitic sands are of marine origin, while the Neogene siliciclastics represent mainly fluvial environments such as braided, meandering, and anastomosing river settings (Widera *et al.* 2021). Particularly, well studied fine-grained deposits overlying the youngest lignite seam (MPLS-1) include sandy-muddy channel sediments and clayey-muddy extra-channel (overbank) ones. They are interpreted as typical of upper Neogene anastomosing or anastomosing-to-meandering river systems (e.g., Widera *et al.* 2019a; Zieliński and Widera 2020; Kędzior *et al.* 2021). The exception here is the Zittau Basin, where siliciclastics were deposited mainly as intra-mountain alluvial fans (Kasiński 2000; Kasiński *et al.* 2015).

Compaction of siliciclastics

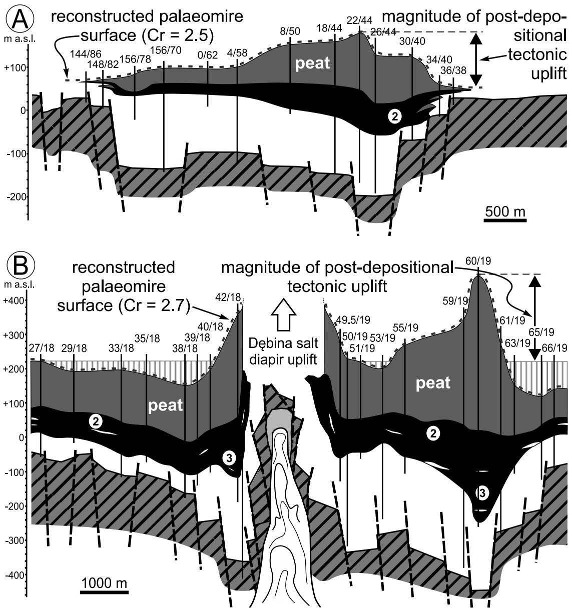
The compaction of sands accompanying the lignite seams in the Polish lignite-bearing grabens could be omitted in the palaeotectonic analysis. This is mainly due to the very low values of the compaction ratios of sands after their accumulation. According to the generalised compaction curves (e.g., Sclater and Christie 1980; Baldwin and Butler 1985; Sheldon and Retallack 2001), this ratio for sands to a burial depth of ~300 m does not exceed the value of 1.1. On the other hand, the compaction ratios of the sandy sediments filling the Cenozoic lignite-rich grabens usually range from 1.01 (Hager *et al.* 1981) to 1.05 (Widera 2007, 2011). In the latter case, the volume of a sample of intact sand (collected in the field) and the volume of the same sample of loose sand were compared. Therefore, the magnitude of compactional subsidence that the siliciclastics experienced is negligible compared to the compactional subsidence associated with the transformation of peat into lignite.

Decompaction of lignite seams

The first step in the palaeotectonic analysis of the investigated grabens was the decompaction of the lignite seams (Text-figs 6 and 7). Their thickness ranges



Text-fig. 6. Decompaction of lignite seams using the appropriate value of the peat-to-lignite compaction ratio (Cr). A – Gostyń Graben. B – Szamotuły Graben. C – Legnica Graben. D and E – Zittau Basin. Note the lack or presence of post-depositional vertical tectonic movements. See Text-fig. 5 for more explanations.

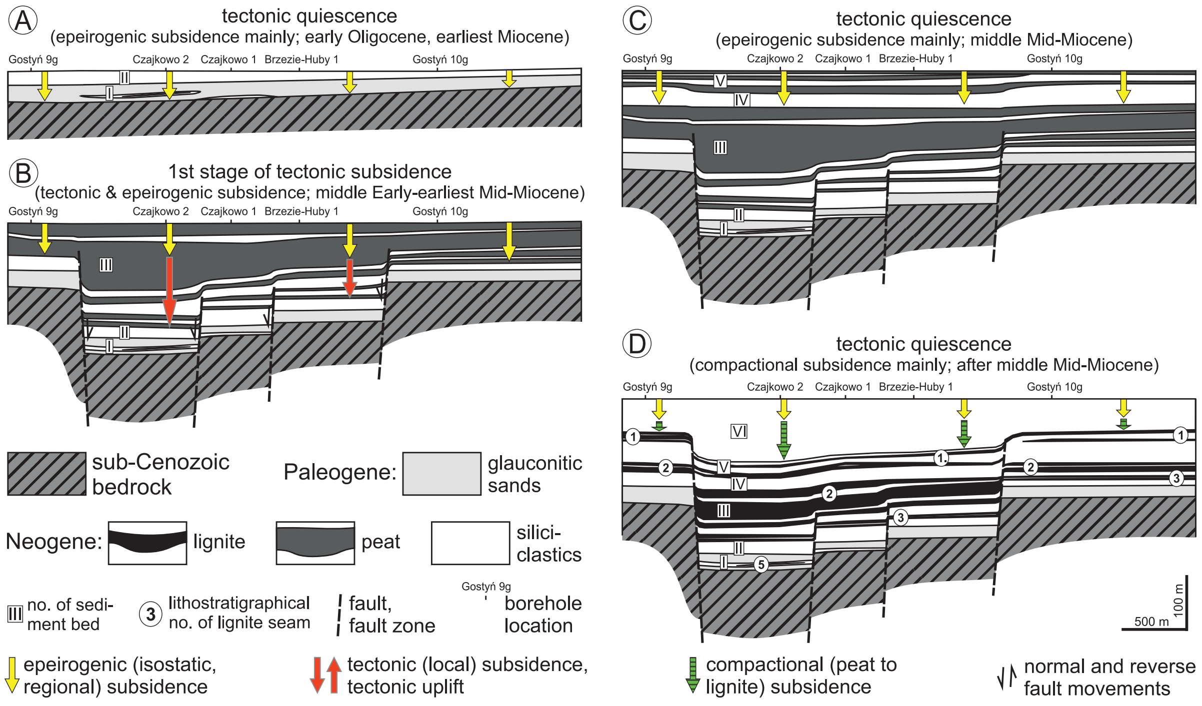


Text-fig. 7. Decompaction of lignite seams using the appropriate value of the peat-to-lignite compaction ratio (Cr). A – Lubstów Graben. B – Kleszczów Graben. Note the magnitude of post-depositional tectonic uplift and/or tectonic subsidence. See Text-fig. 5 for more explanations.

from ~20 to ~250 m, and the corresponding compaction ratios are between 2.0 and 2.9. Thus, as a result of the compaction of the mentioned lignite seams, an accommodation space from several dozen to even several hundred metres could theoretically have been created. On the other hand, the shape of the palaeomire surface (after decompaction of the lignite seam) allowed us to determine whether the study area was subjected to vertical tectonic movements, that is, post-depositional tectonics, following the peat accumulation.

In the cases of the Gostyń and Szamotuły grabens, the LLS-2 seam was decompacted, and its compaction ratio (Cr) is 2.5. The original palaeomire surface reconstructed in this way is almost horizontal (Text-fig. 6A, B). This suggests that the analysed area was not subjected to any post-depositional vertical tectonic movements (subsidence or uplift). The situation is different in the Legnica Graben and in the Zittau Basin, where the reconstructed surface of the palaeomires exhibits a concavity of ~80–120 m as a result of the decompaction of the lignite seams (LLS-2, Cr = 2.5; ŚLS-3, Cr = 2.9). In short, these values determine the approximate depth of the post-depositional subsidence of the deepest parts of both grabens in relation to their flanks (Text-fig. 6C–E).

The cases of the Lubstów and Kleszczów grabens are much more complicated. Following the decompaction of the LLS-2 seam (Cr = 2.5), some fragments of



Text-fig. 8. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Gostyń Graben. See the text for more explanations; compare with Text-figs 4A, 5A, 5B and 6A.

the reconstructed palaeomire were elevated by nearly 120 m (borehole 22/44) relative to their surroundings within the Lubstów Graben (Text-fig. 7A). Such a shape of the palaeomire surface, depending on the groundwater table, is impossible in nature. Therefore, the only explanation for this phenomenon seems to be a post-depositional tectonic uplift event (Widera 2011). Such a phenomenon is even more complex, and the magnitude of the vertical movements was larger in the Kleszczów Graben. It should be noted here that in the characterised case, an average value of Cr = 2.7 was assumed for the LLS-2 (Cr = 2.5) and ŚLS-3 (Cr = 2.9) seams. Some fragments of the graben (surrounding the Dębina salt dome and borehole 60/19) were elevated by >150–250 m, while others were lowered by as much as 80–100 m (surrounding boreholes 38/18, 85/19, and 86/19) (Text-fig. 7B). In comparison with the grabens analysed above, this situation could be explained by post-depositional uplift and subsidence, respectively.

Stages of tectonic activity

Gostyń Graben

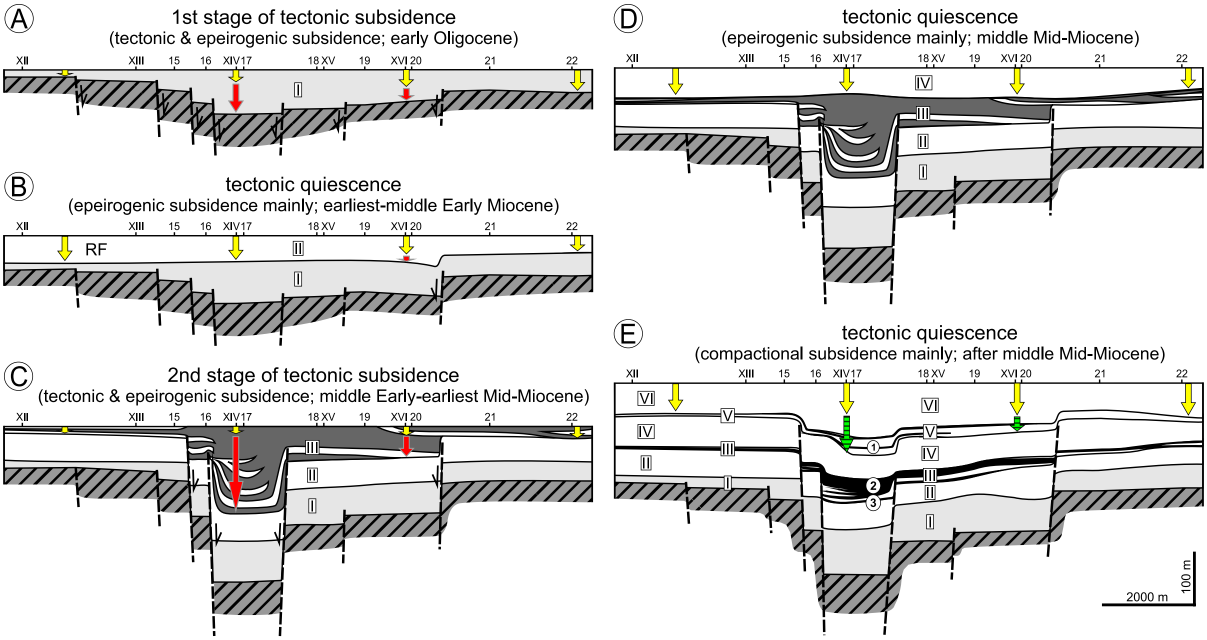
Following the Late Cretaceous–latest Eocene uplift event and erosion which occurred over most of the Polish territory, the area of the Gostyń Graben began to be subjected only to lowering epeirogenic movements. The process of uniform subsidence occurred both during the deposition of the lower Oligocene (bed no. I) and the earliest Miocene (bed no. II) siliciclastic sediments. A convincing proof of this is the fairly even thickness of both layers (beds no. I and II) along the analysed line of the simplified geological cross-section (Text-fig. 8A).

The only stage of tectonic subsidence in the case of the Gostyń Graben took place during the deposition of the most lignite-bearing lithostratigraphic unit, that is, the Ścinawa Formation (bed no. III). Between the middle Early and the earliest Mid-Miocene, nearly 140 m of peat, which later transformed into the ŚLS-3 and mainly the LLS-2 seams (with a total cumulative thickness of 55.7 m), was accumulated in the deepest part of the graben (Text-fig. 8B).

During and after the middle Mid-Miocene, beds no. IV and V were deposited first under conditions of epeirogenic lowering only, and then compactional subsidence began to play an increasingly important role. This resulted in the deformation of the abovementioned beds. Their largest vertical displacements are closely related to faults/fault zones rooted in the sub-Cenozoic bedrock (Text-fig. 8C, D). Therefore, after the middle Mid-Miocene, no vertical tectonic movements were recorded in the area of the Gostyń Graben.

Szamotuły Graben

The first stage of palaeotectonic activity in the Szamotuły Graben took place during the early



Text-fig. 9. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Szamotuły Graben. See Text-fig. 8 and the text for explanations; compare with Text-figs 4B, 5A, 5B and 6B.

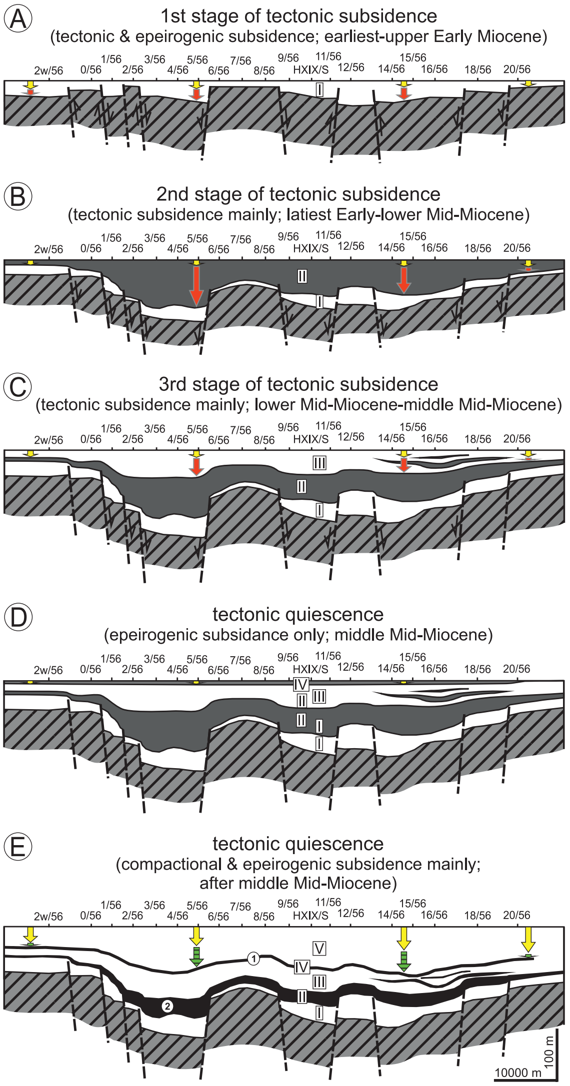
Oligocene. The Paleogene sediments (bed no. I) were deposited in the axial zone of the graben and are over two times thinner on its flanks. Thus, tectonic and epeirogenic vertical movements both occurred during the early Oligocene (Text-fig. 9A). Then, following the late Oligocene regional uplift, the overlying bed no. II (Rawicz Formation) accumulated under tectonically quiescent conditions in the area as a result of epeirogenic lowering. This is evidenced by the even thickness of the sediments (except for the vicinity of borehole XVI-20) along the entire analysed cross-sectional line (Text-fig. 9B).

The largest, second stage of the tectonic subsidence spanned from the middle part of the Early to the earliest Mid-Miocene. At that time, the thickest peat seams (up to 87.5 m, bed no. III) were deposited and then transformed into the ŚLS-3 and mainly the LLS-2 seams (with a total cumulative thickness of ~35 m). The tectonic subsidence process was accelerated in the graben area, while the epeirogenic lowering was relatively small. Then, sediments accumulated in the axial zone of the graben, with a thickness of nearly nine times that of those on its wings (Text-fig. 9C).

Following the tectonic subsidence, the process of peat compaction began in the middle Mid-Miocene. It was initially insignificant (another interpretation is also possible), as indicated by the even thickness of bed no. IV, which was mainly deposited under conditions of epeirogenic subsidence (Text-fig. 9D). Finally, the progressive compaction of the underlying lignite-rich Ścinawa Formation (bed no. III) led to the creation of the accommodation space for younger sediments (beds no. V and VI), which was followed by their deformation (Text-fig. 9E). Thus, the slightly greater thicknesses of these beds in the axial zone of the Szamotuły Graben could only be explained by the compactional subsidence.

Legnica Graben

Paleogene deposits have not previously been documented in the area of the Legnica Graben. Thus, the first relatively small-scale tectonic and epeirogenic movements likely took place in the Early Miocene when sub-lignite siliciclastics were deposited (bed no. I; Text-fig. 10A). However, the main (second) stage of tectonic subsidence took place at the turn of the Early and Mid-Miocene, when the thickest peat layers (>60 m, bed no. II) accumulated, which were later transformed into the LLS-2 seam with a thickness of up to 25 m (Text-fig. 10B).



Text-fig. 10. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Legnica Graben. See Text-fig. 8 and the text for explanations; compare with Text-figs 4C, 5C, D and 6C.

The third stage of tectonic subsidence in the deepest parts of the graben occurred immediately after the formation of the aforementioned thick peat seam – bed no. II. The magnitude of the vertical displacements may have exceeded as much as 50 m (cf. Text-figs 6C and 10C). During and after the middle Mid-Miocene, the Graben area was subjected only to downward epeirogenic movements and compactional subsidence. The process of the LLS-2 compaction is sufficient to explain the deformation of the overlying sediments (beds no. III–V), including the MPLS-1, whose thickness is highly even along the geological cross-sectional line (Text-fig. 10D, E).

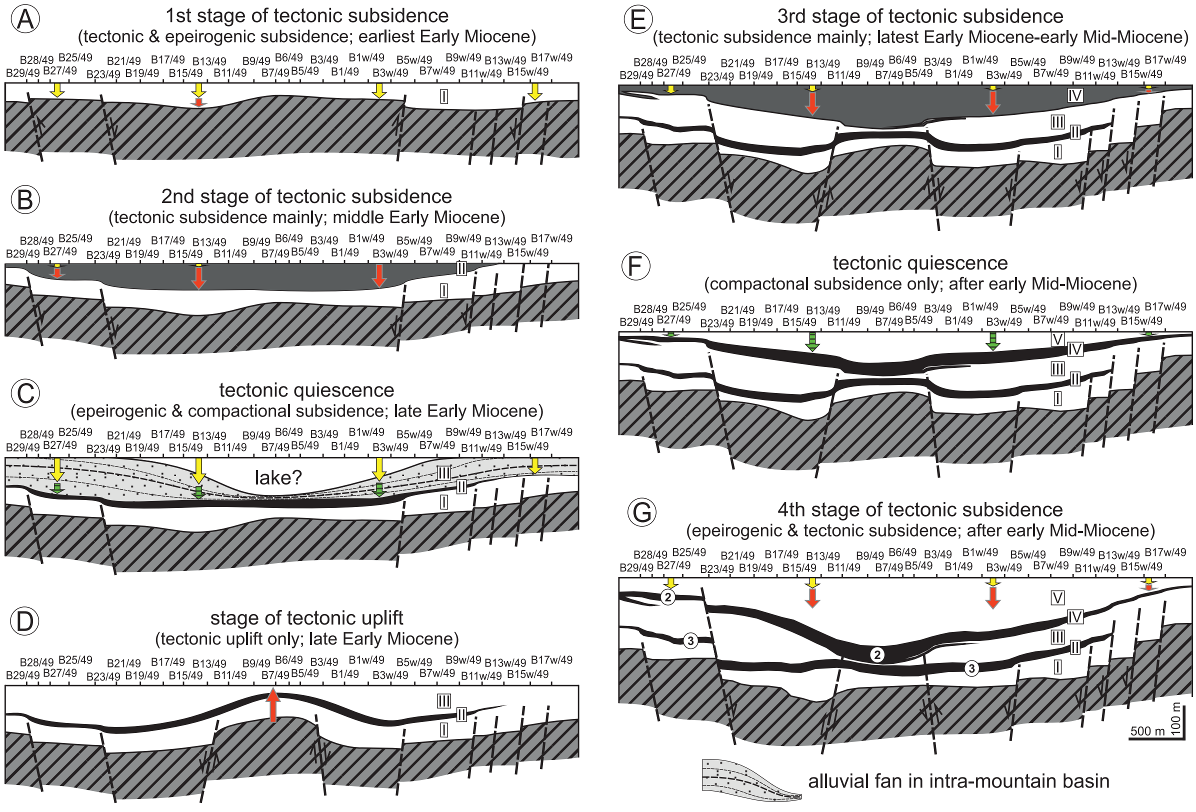
Zittau Basin

There are traces of tectonic subsidence in the Zittau Basin in the earliest Early Miocene (bed no. I), but it was not until the middle Early Miocene that this subsidence exceeded 100 m (bed no. II). At that time, peats were deposited, from which a maximum of 35.3 m of the ŚLS-3 was formed (Text-fig. 11A, B). These peats compacted under the weight of a dozen to >100 m of siliciclastic sediments, interpreted as alluvial fans typical of the intra-mountain graben (Text-fig. 11C; Kasiński 2000; Kasiński *et al.* 2015). Nevertheless, the modest thickness of the aforementioned siliciclastics (bed no. III) and the presently almost horizontal position of the LLŚ-3 in the central part of the basin (graben) allows us to distinguish the tectonic uplift of this area, that is, the stage of tectonic uplift (Text-fig. 11D).

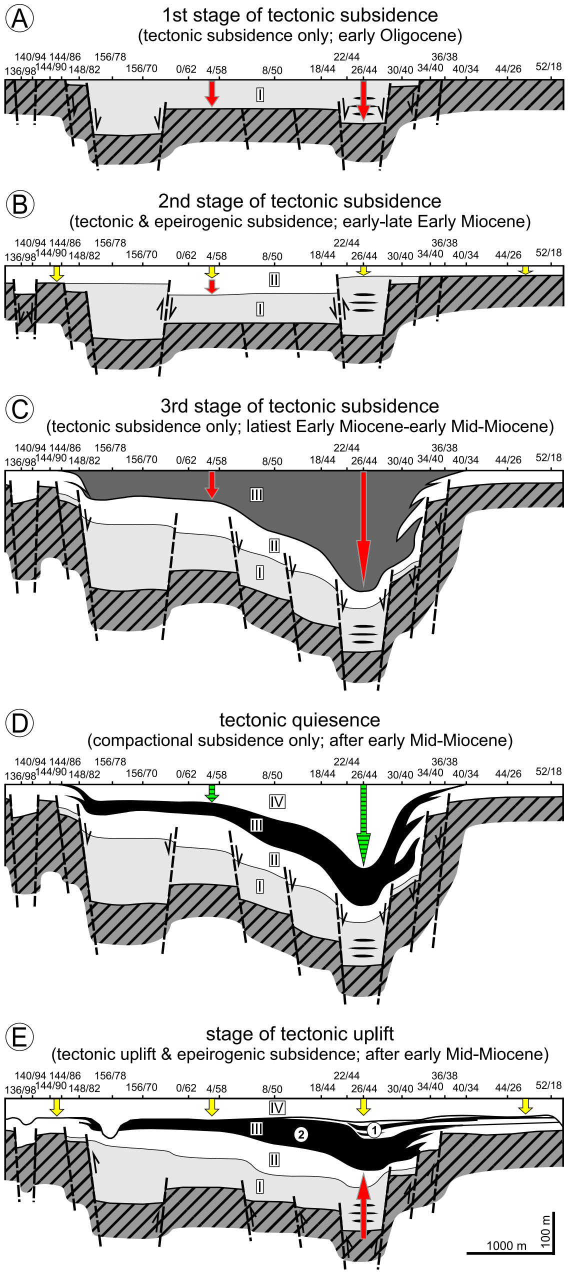
The tectonic subsidence in the area was slightly greater (>105 m) between the latest Early Miocene and early Mid-Miocene. Peats of the LLS-2 accumulated during this time interval (bed no. IV; Text-fig. 11E). Right after the early Mid-Miocene, these peats became compacted under tectonically quiescent conditions, producing a total thickness of 42.6 m of the LLS-2 (Text-fig. 11F). However, in other parts of the Zittau Basin, the LLS-2 reaches a thickness of 66.9 m (Widera 2021), suggesting that the original thickness of the peat must have exceeded 165 m. Only lowering movements, that is, weak epeirogenic and slightly stronger tectonic movements were later recorded in the axial zone of the analysed area (Text-fig. 11G).

Lubstów Graben

At least three stages of tectonic subsidence can be distinguished during the palaeotectonic development of the Lubstów Graben, including a stage of compactional subsidence and stage of tectonic uplift (Text-fig. 12). The first stage of tectonic development occurred during the lower Oligocene, when more than 135 m of glauconitic sands (bed no. I) of this age accumulated in the vicinity of boreholes 22/44 and 26/44 (Text-fig. 12B). Both epeirogenic and tectonic subsidence (the second stage) took place after the late Oligocene regional uplift (bed no. II; Text-fig. 12B). The most intense stage of tectonic subsidence in the Lubstów graben coincided with the period of peat ac-



Text-fig. 11. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Zittau Basin. See Text-fig. 8 and the text for explanations; compare with Text-figs 4D, 5C, 5D, 6D and 6E.


Ⓐ 1st stage of tectonic subsidence
(tectonic subsidence only; early Oligocene)

Ⓑ 2nd stage of tectonic subsidence
(tectonic & epeirogenic subsidence; early-late Early Miocene)

Ⓒ 3rd stage of tectonic subsidence
(tectonic subsidence only; latiest Early Miocene-early Mid-Miocene)

Ⓓ tectonic quiesence
(compactional subsidence only; after early Mid-Miocene)

Ⓔ stage of tectonic uplift
(tectonic uplift & epeirogenic subsidence; after early Mid-Miocene)

Text-fig. 12. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Lubstów Graben. See Text-fig. 8 and the text for explanations; compare with Text-figs 4E, 5E, 5F and 7A.

cumulation (>215 m), from which >86 m of the LLS-2 was formed between the latest Early Miocene to early Mid-Miocene (Text-fig. 12C).

Following the deposition of such a thick layer of peat (bed no. III), the process of its compaction began, leading to the creation of an accommodative space with a magnitude of up to 130 m (bed no. IV; cf. Text-figs 7A and 12D). Ultimately, the deepest part of the graben, where the LLS-2 seam is the thickest (bed no. III), could have been uplifted by at least 100 m (Text-fig. 12E).

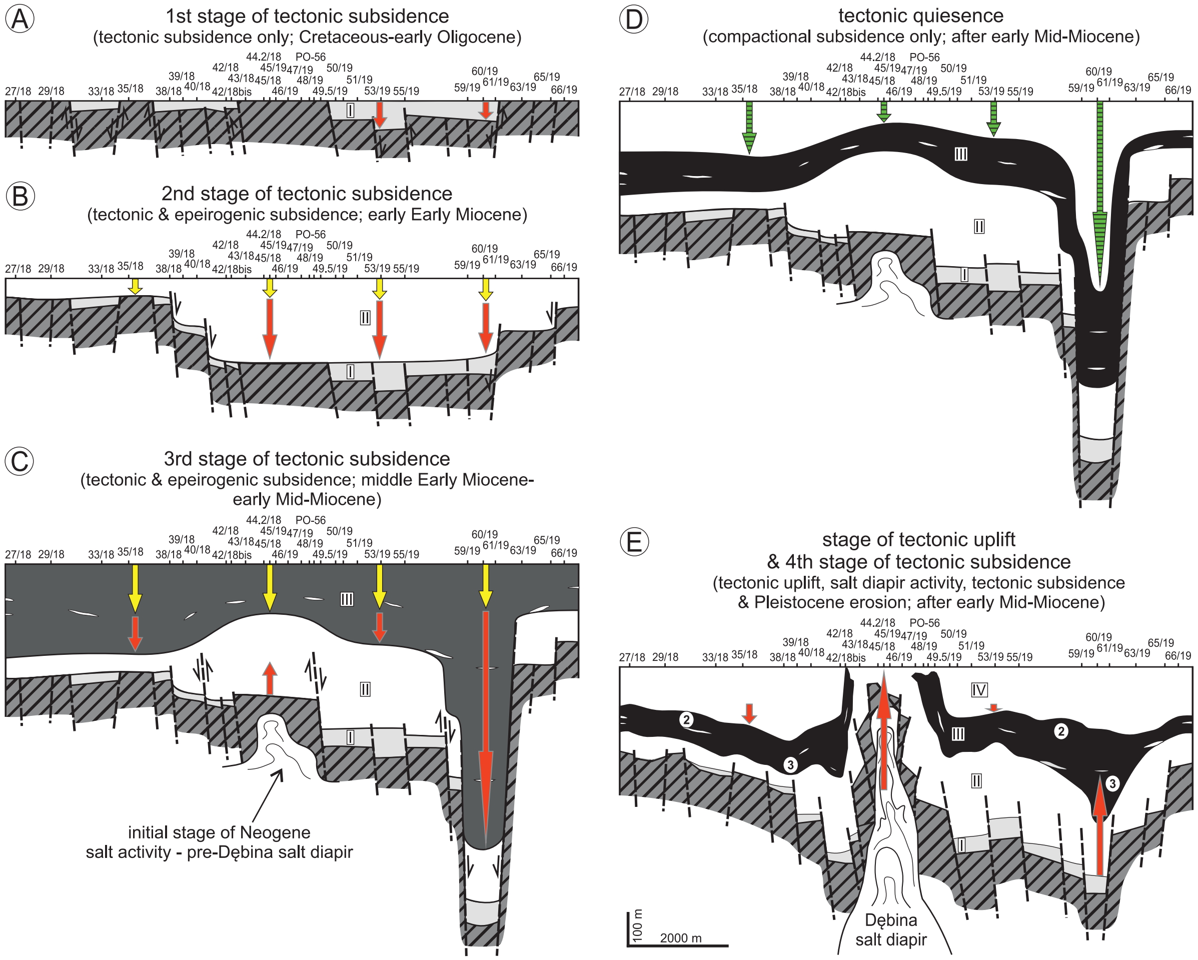
Kleszczów Graben

This area of the Kleszczów Graben is characterised by a similar palaeotectonic evolution as the Lubstów Graben, although the duration of the individual stages and the magnitude of the vertical displacements are much larger. Moreover, the uplift of the Dębina salt dome during the Neogene and Quaternary periods additionally deformed the thickest lignite seams in Poland (>250 m), some of the thickest in the world (see Text-fig. 4F). As above, the proposed conceptual model for the palaeotectonic development of the Kleszczów Graben is one of several possible interpretations, but probably not the most realistic one (Text-fig. 13).

The first stage of the tectonic subsidence covered a fairly wide time interval, that is, from the latest Cretaceous to the early Oligocene. Weathered rocks consisting of the sub-Cenozoic bedrock (Cretaceous and Jurassic) were deposited during this time (bed no. I) and were locally covered with glauconite sands of early Oligocene age (Text-fig. 13A). After the late Oligocene stratigraphic gap in the earliest Early Miocene, over 250–270 m of sub-lignite sands were deposited in the deepest parts of the Kleszczów Graben and >100 m on its flanks (bed no. II). Hence, this time interval was distinguished as the second stage of tectonic subsidence, which was also accompanied by epeirogenic lowering (Text-fig. 13B).

The third stage, with the most intense tectonic subsidence within the Kleszczów Graben, took place during the accumulation of the several hundred-metre-thick peat deposit (middle Lower Miocene–lowermost Mid-Miocene), which then turned into two lignite seams, namely, ŚLS-3 and LLS-2. Their current maximum thickness exceeds 250 m, suggesting that with an average Cr = 2.7, the original peat thickness may have theoretically reached 675 m. Of course, the provided value of the compaction ratio includes the change in peat thickness due to the mineral overburden covering it.

After the early Mid-Miocene, compactional subsidence first played a significant role in the creation of the accommodation space (even >300–400 m). Then, there was a tectonic uplift of the deepest parts of the Kleszczów Graben, which is genetically and age-related to the evolution of the Dębina salt dome. In both cases, the vertical uplift of the lignite seams (bed no. III) reached at least 300 m. However, this



Text-fig. 13. Conceptual model depicting the Cenozoic stages of tectonic evolution of the Kleszczów Graben. See Text-fig. 8 and the text for explanations; compare with Text-figs 4F, 5E, 5F and 7B.

uplift may have been much more significant around the salt dome, but extent of this uplift is impossible to accurately estimate due to the Pleistocene erosion by the Scandinavian ice sheets and their meltwaters. Finally, some fragments along the analysed cross-sectional line underwent a fourth stage of tectonic subsidence, which occurred simultaneously with the aforementioned stage of tectonic uplift (cf. Text-figs 7B and 13E).

DISCUSSION

Timing of tectonic activity

The timing of the start and end of the subsequent stages of tectonic activity of the examined grabens can only be defined quite loosely. Due to the lack of widespread chronostratigraphic horizons (e.g., tuffaceous layers), the time interval of the stages can be estimated with the same accuracy as the age of lithostratigraphic boundaries, that is, from hundreds of thousands to even over a million years. In other words, the accuracy of age estimation may be limited to only a part of the sub-epochs, for example, from the latest late Oligocene to the middle Mid-Miocene (see Text-figs 8–13). However, the stages of tectonic development involving such time intervals could not be considered isochronous, as is the case with contemporary (Holocene) tectonic movements resulting in earthquakes, volcanic eruptions, etc.

Therefore, the timing of tectonic activity of the examined grabens should be treated individually. On the other hand, considering the above inaccuracies, it was possible to identify the epochs, and even parts of them, when the tectonic activity in the area of the

Alpine-Carpathian orogen and its foreland was more intense (Jarosiński *et al.* 2009). Most of the areas filled with lignite seams commenced their Cenozoic development at the turn of the Eocene and Oligocene or shortly later. Hence, the deposits of early Oligocene age were the thickest among the Paleogene sediments in the majority of grabens of the Polish Lowlands (e.g., Deczkowski and Gajewska 1980; Karnkowski 1980; Kasiński 1984; Kasiński *et al.* 2006, 2019; Widera 2007, 2016a; Jarosiński *et al.* 2009). However, the upper Oligocene deposits were dominant in some grabens belonging to the ECRiS, which extends across France, the Netherlands, Germany, and the Czech Republic (e.g., Malkovsky 1987; Zijerveld *et al.* 1992; Hager 1993; Ziegler *et al.* 1995; Kasiński 2000, 1984; Špičáková *et al.* 2000; Michon *et al.* 2003; Schäfer *et al.* 2005; Van Balen *et al.* 2005; Rajchl *et al.* 2009).

The second period in which the tectonic activity was very pronounced in the aforementioned areas was between the middle part of the Early and the earliest Mid-Miocene. In this time span, the thickest European peat beds accumulated and were later transformed into the ŚLS-3 and LLS-2 seams and their lithostratigraphic equivalents. For example, these beds have a total thickness of ~50 m in the Most Basin (middle part of the Eger Graben), 86.2 m in the Lubstów Graben, 101.0 m in the Lower Rhine Graben, 101.6 m in the Zittau Basin, and 250.4 m in the Kleszczów Graben (cf. Widera 2021). Thus, considering the 2.5–2.9-fold peat-to-lignite compaction (average Cr = 2.7) of these seams, they may have experienced a tectonic subsidence of up to 135–675 m. Of course, the largest magnitudes of the subsidence covered those parts of the deposit where the current thickness of lignite is the greatest.

Conceptual models

This study presents conceptual models of the Cenozoic development of selected Polish lignite-rich grabens. The following is the author's interpretation, consistent with the fundamental principles of palaeotectonic analyses. It was assumed that the siliciclastics did not have a major impact on the variation in the thickness of the beds corresponding to the appropriate lithostratigraphic units, that is, formations and members (cf. Text-figs 3 and 4). On the contrary, the change in the thickness of the peat seam during its compaction (i.e., transformation of peat into lignite) created a large accommodation space for younger sediments and caused their significant deformation. Therefore, to distinguish the stages of tectonic subsidence and/or uplift, the effects of the total subsidence were separated from those of the epeirogenic and tectonic subsidence, and the latter was distinguished from the compactional subsidence (see subsection 'Vertical movements and tectonic stages').

The discussed models assumed that peat accumulation first occurred under conditions of tectonic and/or epeirogenic subsidence. Then, following the covering of the peat with a mineral overburden, intensive peat compaction could take place. The subsequent stages of tectonic development of the investigated grabens only occurred after this compaction process. As mentioned above, there are also other possible interpretations for the evolution of the grabens. One example may involve a situation where the processes of peat accumulation and tectonic uplift occurred simultaneously. However, the decompaction of the lignite seams in the Lubstów and Kleszczów grabens would not have led to the formation of such high 'hills' (see Text-fig. 7). Consequently, the vertical movements (tectonic subsidence and uplift) would have been much smaller than suggested in this paper.

CONCLUSIONS

Palaeotectonic analyses were conducted on six Polish grabens filled with abundant Cenozoic lignite deposits. The results were obtained using borehole data and by considering vertical epeirogenic and tectonic movements, and peat-to-lignite compaction. In the last case, the values of the compaction ratios (Cr = 2.0–2.9) for the main lignite seams were obtained from the geological literature. It was important to distinguish between the effects of epeirogenic subsidence and tectonic subsidence, and between those of tectonic and compactional subsidence, in the quantitative estimation of the magnitude of the subsidence and uplift.

The investigated areas could be divided into those that did not experience post-depositional (after the accumulation of peat which was later transformed into lignite seams) vertical movements (Gostyń and Szamotuły grabens), those that were mainly subjected to post-depositional lowering movements (Legnica Graben and Zittau Basin), and those that subsided and/or were uplifted post-depositionally (Lubstów and Kleszczów grabens). In most cases, the greatest total tectonic subsidence took place during the period of peat accumulation (ŚLS-3 and LLS-2), the magnitude of which could have theoretically ranged from 135 to 675 m. The later tectonic subsidence ranged from 0 m in the Gostyń, Szamotuły, and Lubstów grabens to 80–100 m in the other grabens. On the other hand, according to the adopted conceptual models, the studied areas may have been tectonically uplifted by >100 and >300–400 m in the deepest parts of the Lubstów and Kleszczów grabens, respectively.

Paleogene tectonic subsidence was recorded in the deposition of the 0–>130-m-thick sediments of early Oligocene age in the examined grabens. However, at this stage of their tectonic evolution, no productive lignite deposits were formed. Instead, the lignite deposits were formed after the late Oligocene regional epeirogenic uplift and the deposition of the oldest Neogene sub-lignite siliciclastics. Therefore, at this stage (middle Early–earliest Mid-Miocene) peats accumulated (theoretically up to 135–675 m thick), which were then transformed into some of the thickest lignite seams worldwide (ŚLS-3 and LLS-2). Their total thickness ranges from ~35 m in the Szamotuły Graben to >250 m in the Kleszczów Graben. The high position of the lignite seams in the Lubstów and Kleszczów grabens is the result of tectonic uplift. However, the timing and rate of their deposition could be interpreted in various ways, and therefore further research is desired.

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REFERENCES

Ahlrichs, N., Noack, V., Hübscher, C., Seidel, E., Warwel, A. and Kley, J. 2021. Impact of late Cretaceous inversion and Cenozoic extension on salt structure growth in the Baltic sector of the north German Basin. *Basin Research*, **34**, 220–250.

Allen, P.A. and Allen, J.R. 1990. Basin Analysis – Principles and Applications, 456 pp. Blackwell Scientific Publications; Oxford.

Baldwin, B. and Butler, C.O. 1985. Compaction curves. *American Association of Petroleum Geologist Bulletin*, **69**, 622–626.

Bielowicz, B. and Kasiński, J.R. 2014. The possibility of underground gasification of lignite from Polish deposits. *International Journal of Coal Geology*, **131**, 304–318.

Brandes, C., Pollok, L., Schmidt, C., Wilde, V. and Winsemann, J. 2012. Basin modelling of a lignite-bearing salt rim syncline: insights into rim syncline evolution and salt diapirism in NW Germany. *Basin Research*, **24**, 1–18.

Bridge, J.S. 2003. Rivers and Floodplains: Forms, Processes, and Sedimentary Record, 504 pp. Blackwell Publishing; Malden.

Clausen, O.R., Nielsen, S.B., Egholm, D.L. and Gołędowski, B. 2012. Cenozoic structures in the eastern North Sea Basin – a case for salt tectonics. *Tectonophysics*, **514–517**, 156–167.

Clausen, O.R. and Pedersen, P. 1999. Late Triassic structural evolution of the southern margin of the Ringkøbing-Fyn high, Denmark. *Marine and Petroleum Geology*, **16**, 653–665.

Cohen, K.M., Finney, S.C., Gibbard, P.L. and Fan, J.-X. (2013; updated). The ICS International Chronostratigraphic Chart. *Episodes*, **36**, 199–204.

Courel, L. 1987. Stages in the compaction of peat; examples from the Stephanian and Permian of the Massif Central, France. *Journal of the Geological Society, London*, **144**, 489–493.

Dadlez, R. and Marek, S. 1998. Major faults, salt-and non-salt anticlines. In: Dadlez, R., Marek S. and Pokorski J. (Eds), Paleogeographic atlas of epicontinental Permian and Mesozoic in Poland (1:2,500,000), 75. Polish Geological Institute; Warsaw.

Dadlez, R., Marek, S. and Pokorski, J. (Eds) 2000. Geological map of Poland without Cenozoic deposits at a scale 1:1,000,000. Polish Geological Institute; Warsaw.

Dadlez, R., Narkiewicz, M., Stephenson, R.A., Visser, M.T. and Wess, J.D. 1995. Tectonic evolution of Mid-Polish Trough. Modelling implications and significance for central European geology. *Tectonophysics*, **252**, 179–195.

Deczkowski, Z. and Gajewska, I. 1980. Mesozoic and Tertiary troughs in the Fore-Sudetic Monocline. *Przegląd Geologiczny*, **28**, 151–156. [In Polish with English summary]

Diessel, C., Boyd, R., Wadsworth, J., Leckie, D. and Chalmers, G. 2000. On balanced and unbalanced accommodation/peat accumulations ratios in the Cretaceous coals from Gates Formation, Western Canada, and their sequence-stratigraphic significance. *International Journal of Coal Geology*, **43**, 143–186.

Gotowała, R. and Hałuszczak, A. 2002. The Late Alpinie structural development of the Kleszczów Graben (Central Poland) as a result of a reactivation of the pre-existing, regional dislocation. *European Geoscience Union, Stephan Mueller Special Publication Series*, **1**, 137–150.

Hager, H. 1993. Origin of the Tertiary lignite deposits in the lower Rhine region, Germany. *International Journal of Coal Geology*, **23**, 251–262.

Hager, H., Kothen, H. and Spann, R. 1981. Zur Setzung der Rheinischen Braunkohle und ihrer klastischen Begleitschichten. *Fortschritte in der Geologie von Rheinland und Westfalen*, **29**, 319–352. [In German]

Harding, R. and Huuse, M. 2015. Salt on the move: Multi stage evolution of salt diapirs in the Netherlands North Sea. *Marine and Petroleum Geology*, **61**, 39–55.

Jarosiński, M., Poprawa, P. and Ziegler, P.A. 2009. Cenozoic dynamic evolution of the Polish Platform. *Geological Quarterly*, **53**, 3–26.

Karnkowski, P.H. 1980. The paleotectonic of platform cover in the Wielkopolska. *Przegląd Geologiczny*, **28**, 146–151. [In Polish with English summary]

Kasiński, J.R. 1984. Synsedimentary tectonics as the factor determining sedimentation of brown coal formation in tectonic depressions in western Poland. *Przegląd Geologiczny*, **32**, 260–268. [In Polish with English summary]

Kasiński, J.R. 2000. Geological atlas of the Tertiary lignite-bearing association in the Polish part of the Zittau Basin, scale 1:50,000. Polish Geological Institute; Warsaw.

Kasiński, J.R., Badura, J., Pańczyk, M., Pécskay, Z., Saternus, A., Słodkowska, B. and Urbański, P. 2015. Paleogene deposits in the Polish part of the Zittau Basin – new light on the age of the tectonic depression. *Biuletyn Państwowego Instytutu Geologicznego*, **461**, 193–250.

Kasiński, J.R., Mazurek, S. and Piwocki, M. 2006. Valorization and ranking, list of lignite deposits in Poland. *Prace Państwowego Instytutu Geologicznego*, **187**, 1–79. [In Polish with English summary]

Kasiński, J.R., Saternus, A. and Urbański P. 2019. Geological atlas of Polish selected lignite deposits in Poland. Volume 1, 240 pp. Polish Geological Institute; Warsaw. [In Polish]

Kędzior, A., Widera, M. and Zieliński, T. 2021. Ancient and modern anastomosing rivers: insights from sedimentological and geomorphological case studies of the Triassic, Neogene and Holocene of Poland. *Geological Quarterly*, **65**, 54.

Krzywiec, P. 2012. Mesozoic and Cenozoic evolution of salt structures within the Polish Basin: An overview. In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T. and Hodgkinson R. (Eds), Salt tectonics, sediments and prospectivity. *Geological Society, London, Special Publications*, **363**, 381–394.

Krzywiec, P., Kiersnowski, H. and Peryt, T. 2019. Fault-controlled Permian sedimentation in the central Polish Basin (Bydgoszcz-Szubin area) – Insights from well and seismic data. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **170**, 255–272.

Malkovsky, M. 1987. The Mesozoic and Tertiary basins of the Bohemian Massif and their evolution. *Tectonophysics*, **137**, 31–42.

Markič, M. and Sachsenhofer, R.F. 1997. Petrographic composition and depositional environments of the Pliocene Velenje lignite seam (Slovenia). *International Journal of Coal Geology*, **33**, 229–254.

Michon, L., Van Balen, R.T., Merle, O. and Pagnier, H. 2003. The Cenozoic evolution of the Roer Valley Rift System integrated at a European scale. *Tectonophysics*, **367**, 101–126.

Nadon, G.C. 1998. Magnitude and timing of peat-to-coal compaction. *Geology*, **26**, 727–730.

Opluštil, S. 2005. The effect of paleotopography, tectonics and sediment supply on quality of coal seams in continental basins of central and western Bohemia (Westphalian), Czech Republic. *International Journal of Coal Geology*, **64**, 173–203.

Pharaoh, T., Dusar, M., Geluk, M., Kockel, F., Krawczyk, C., Krzywiec, P., Scheck-Wenderoth, M., Thybo, H., Vejbæk, O.V. and van Wees, J.-D. 2010. Tectonic evolution. In: Doornenbal, H. and Stevenson, A.G. (Eds), Petroleum geological atlas of the southern Permian Basin area, 25–57. EAGE Publications; Houten.

Piwocki, M. and Ziembińska-Tworzydło, M. 1997. Neogene of the Polish Lowlands – lithostratigraphy and pollen-spore zones. *Geological Quarterly*, **41**, 21–40.

Rajchl, M., Uličný D., Grygar, R. and Mach, K. 2009. Evolution of basin architecture in an incipient continental rift: the Cenozoic Most Basin, Eger Graben (Central Europe). *Basin Research*, **21**, 269–294.

Rajchl, M., Uličný D. and Mach, K. 2008. Interplay between tectonics and compaction in a rift-margin, lacustrine delta system: Miocene of the Eger Graben, Czech Republic. *Sedimentology*, **55**, 1419–1447.

Rasmussen, E.S. 2009. Neogene inversion of the central graben and Ringkøbing-Fyn high, Denmark. *Tectonophysics*, **465**, 84–97.

Rasmussen, E.S. 2013. Cenozoic structures in the eastern North Sea Basin – A case for salt tectonics: Discussion. *Tectonophysics*, **601**, 226–233.

Rowan, M. and Krzywiec, P. 2014. The Szamotuły salt diapir and Mid-Polish Trough: Decoupling during both Triassic–Jurassic rifting and Alpine inversion. *Interpretation*, **2** (4), SM1–SM18.

Ryer, T.A. and Langer, A.W. 1980. Thickness change involved in the peat-to-coal transformation for a bituminous coal of Cretaceous age in central Utah. *Journal of Sedimentary Petrology*, **50**, 987–992.

Schäfer, A. and Utescher, T. 2014. Origin, sediment fill, and sequence stratigraphy of the Cenozoic Lower Rhine Basin (Germany) interpreted from well logs. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften*, **165**, 287–314.

Schäfer, A., Utescher, T., Klett, M. and Valdivia-Manchego, M. 2005. The Cenozoic Lower Rhine Basin – rifting, sedimentation, and cyclic stratigraphy. *International Journal of Earth Sciences*, **94**, 621–639.

Sclater, J.G. and Christie, P.A.F. 1980. Continental stretching: An explanation of post-mid-Cretaceous subsidence of the central North Sea basin. *Journal of Geophysical Research*, **85**, 3711–3939.

Sheldon, N.D. and Retallack, G.J. 2001. Equation for compaction of paleosols due to burial. *Geology*, **29**, 247–250.

Špičáková, L., Uličný, D. and Koudelková, G. 2000. Tectonosedimentary evolution of the Cheb Basin (NW Bohemia, Czech Republic) between Late Oligocene and Pliocene: a preliminary note. *Studia Geophysica et Geodaetica*, **44**, 556–580.

Tajduś, A., Kaczorowski, J., Kasztelewicz, Z., Czaja, P., Cała, M., Bryja, Z. and Żuk, S. 2014. Brown coal – an offer for Polish power industry – development possibilities for brown coal mining functioning in Poland by the year 2050, 307 pp. Mining Committee of the Polish Academy of Sciences; Kraków. [In Polish]

ten Veen, J.H., van Gessel, S.F. and den Dulk, M. 2012. Thin-and thick-skinned salt tectonics in The Netherlands; a quantitative approach. *Netherlands Journal of Geosciences – Geologie en Mijnbouw*, **91**, 447–464.

ten Veen, J.H. and Kleinspehn, K.L. 2000. Quantifying the timing and sense of fault dip slip: New application of biostratigraphy and geohistory analysis. *Geology*, **28**, 471–474.

Teichmüller, M. 1989. The genesis of coal from the viewpoint of coal petrology. *International Journal of Coal Geology*, **12**, 1–87.

Van Asselen, S. 2011. The contribution of peat compaction to total basin subsidence: implications for the provision of accommodation space in organic-rich deltas. *Basin Research*, **23**, 239–255.

Van Balen, R.T., Houtgas, R.F. and Cloetingh, S.A. 2005. Neotectonics of The Netherlands: a review. *Quaternary Science Reviews*, **24**, 439–454.

Van Hinte, J.E. 1978. Geohistory analysis – Application of micropaleontology in exploration geology. *American Association of Petroleum Geologist Bulletin*, **62**, 201–222.

Vinken, R. (compiler) 1988. The Northwest European Tertiary Basin, Results of the IGCP, Project No 124. *Geologisches Jahrbuch, A 100*, 508 pp. Bundesanstalt für Geowissenschaften und Rohstoffe; Hannover.

Warsitzka, M., Jähne-Klingberg, F., Kley, J. and Kukowski, N. 2019. The timing of salt structure growth in the Southern Permian Basin (Central Europe) and implications for basin dynamics. *Basin Research*, **31**, 337–360.

Wentworth, C.K. 1922. A Scale of Grade and Class Terms for Clastic Sediments. *The Journal of Geology*, **30**, 377–392.

Widera, M. 2004. Phases of Paleogene and Neogene tectonic evolution of selected grabens in the Wielkopolska area, central-western Poland. *Annales Societatis Geologorum Poloniae*, **74**, 295–310.

Widera, M. 2007. Lithostratigraphy and palaeotectonics of the sub-Pleistocene Cenozoic of Wielkopolska, 224 pp. Adam Mickiewicz University Science Press; Poznań. [In Polish with English summary]

Widera, M. 2011. Postsedimentary tectonic uplift in the Lubstów Graben (Central Poland). *Przegląd Geologiczny*, **59**, 681–687. [In Polish with English summary]

Widera, M. 2012. Macroscopic lithotype characterisation of the 1st Middle-Polish (1st Lusatian) Lignite Seam in the Miocene of central Poland. *Geologos*, **18**, 1–11.

Widera, M. 2013. Changes of the lignite seam architecture – a case study from Polish lignite deposits. *International Journal of Coal Geology*, **114**, 60–73.

Widera, M. 2015. Compaction of lignite: a review of methods and results. *Acta Geologica Polonica*, **65**, 367–368.

Widera, M. 2016a. Genetic classification of Polish lignite deposits: A review. *International Journal of Coal Geology*, **158**, 107–118.

Widera, M. 2016b. Depositional environments of overbank sedimentation in the lignite-bearing Grey Clays Member: New evidence from Middle Miocene deposits of central Poland. *Sedimentary Geology*, **335**, 150–165.

Widera, M. 2016c. An overview of lithotype associations forming the exploited lignite seams in Poland. *Geologos*, **22**, 213–225.

Widera, M. 2019. What can be learned about the deposition and compaction of peat from the Miocene lignite seam exposed in the Chłapowo Cliff on the Polish coast of the Baltic Sea? *Geology, Geophysics and Environment*, **45**, 111–119.

Widera, M. 2021. Geology of Polish lignite deposits, 180 pp. Bogucki Science Press; Poznań. [In Polish]

Widera, M., Chomiak, L. and Wachocki, R. 2023. Distinct types of crevasse splays formed in the area of Middle Miocene mires, central Poland: Insights from geological mapping and facies analysis. *Sedimentary Geology*, **443**, 106300.

Widera, M., Chomiak, L. and Zieliński, T. 2019a. Sedimentary facies, processes and paleochannel pattern of an anastomosing river system: an example from the Upper Neogene of Central Poland. *Journal of Sedimentary Research*, **89**, 487–507.

Widera, M., Ćwikliński, W. and Karman, R. 2008. Cenozoic tectonic evolution of the Poznań-Oleśnica Fault Zone, central-western Poland. *Acta Geologica Polonica*, **58**, 455–471.

Widera, M., Glacová, V. and Marschalko, M. 2022. Origin of clastic partings and their impact on ash yield in mined lignite: A case study from Middle Miocene of central Poland. *Journal of Cleaner Production*, **378**, 134401.

Widera, M. and Hałuszczak, A. 2011. Stages of the Cenozoic tectonics in central Poland: examples from selected grabens. Zeits*chrift der Deutschen Gesellschaft für Geowissenschaften*, **162**, 203–215.

Widera, M., Jachna-Filipczuk, G., Kozula, R. and Mazurek, S. 2007. From peat bog to lignite seam: a new method to calculate the consolidation coefficient of lignite seams, Wielkopolska region in central Poland. *International Journal of Earth Sciences*, **96**, 947–955.

Widera, M., Stawikowski, W. and Uścinowicz, G. 2019b. Paleogene–Neogene tectonic evolution of the lignite-rich Szamotuły Graben. *Acta Geologica Polonica*, **69**, 387–401.

Widera, M., Zieliński, T., Chomiak, L., Maciaszek, P., Wachocki, R., Bechtel, A., Słodkowska, B., Worobiec, E. and Worobiec, G. 2021. Tectonic-climatic interactions during changes of depositional environments in the Carpathian foreland: An example from the Neogene of central Poland. *Acta Geologica Polonica*, **71**, 519–542.

Ziegler, P.A. 1990. Geological atlas of Western and Central Europe, 2nd edition, 239 pp. Shell Internationale Petroleum

Maatschappij B.V. and Geological Society Publishing House; London.

Ziegler, P.A., Cloetingh, S.A. and van Wees, J.-D. 1995. Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples. *Tectonophysics*, **252**, 7–59.

Ziegler, P.A. and Dèzes, P. 2007. Cenozoic uplift of Variscan Massifs in the Alpine foreland: Timing and controlling mechanisms. *Global and Planetary Change*, **58**, 237–269.

Zieliński, T. 2014. Sedimentology. River and lake deposits, 594 pp. Adam Mickiewicz University Science Press; Poznań. [In Polish]

Zieliński, T. and Widera, M. 2020. Anastomosing-to-meandering transitional river in sedimentary record: A case study from the Neogene of central Poland. *Sedimentary Geology*, **404**, 105677.

Zijerveld, L., Stephenson, R., Cloetingh, S.A., Duin, E. and Van den Berg, M.W. 1992. Subsidence analysis and modelling of the Roer Valley Graben (SE Netherland). *Tectonophysics*, **208**, 159–171.

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