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Cenozoic tectonic evolution of the main lignite-rich grabens in Poland. Part 2. Tectonics *versus* autocompaction and compaction

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ABSTRACT:

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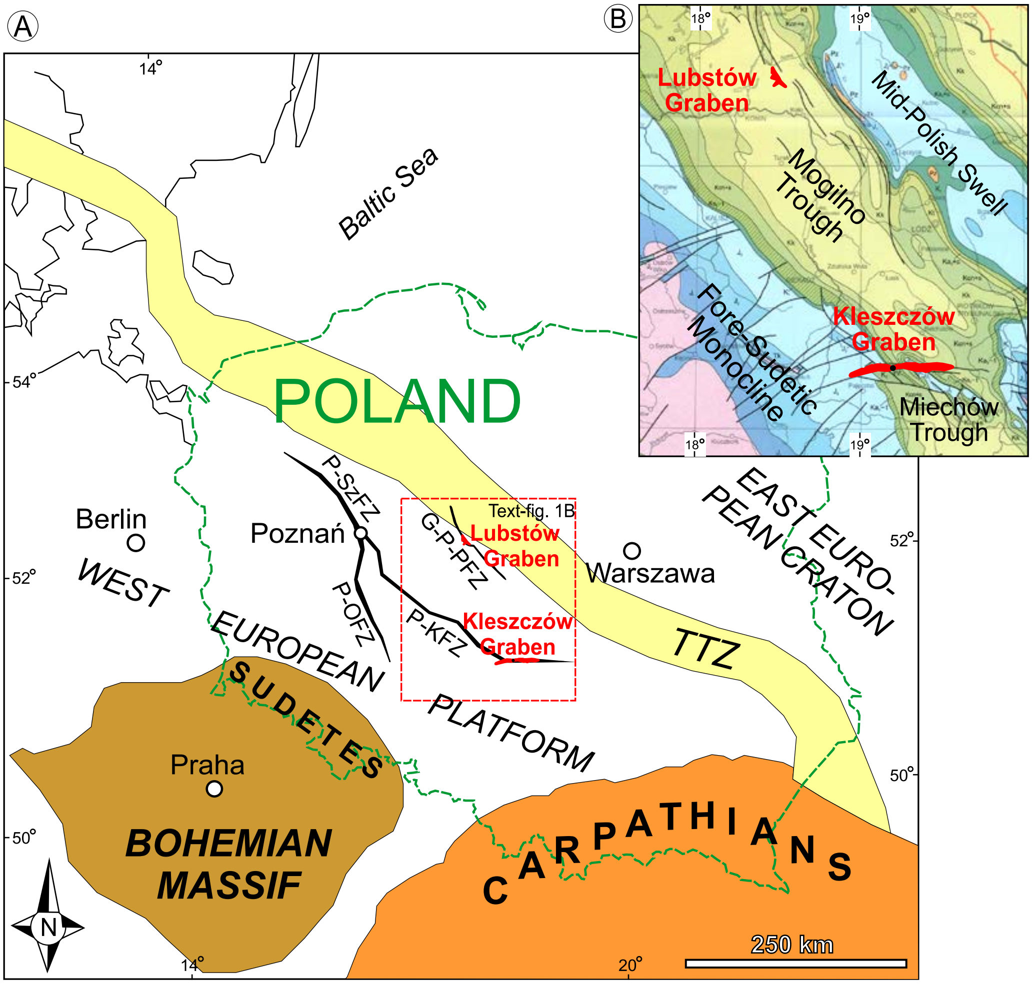
This paper is a continuation of the previous one (*Widera, 2024. Acta Geologica Polonica, 74 (1), e2*). A new, alternative interpretation of the tectonic development of two lignite-rich deposits in the Lubstów and Kleszczów grabens in central Poland is presented. The maximum thickness of lignite mined from both deposits is >86 and >250 m, respectively. These grabens were selected for detailed tectonic analysis because syn-depositional or post-depositional tectonic uplift is undeniably evident. The current study focuses on the distinction between tectonic subsidence/uplift and autocompactional subsidence, and on the timing of their occurrence. Such a research approach allows for the presentation of new conceptual models of Cenozoic tectonic evolution during the formation of the third, very thick, Ścinawa lignite seam (ŚLS-3) and the second Lusatian lignite seam (LLS-2). As a result, it is shown here that the magnitude of both the downward and upward tectonic movements are significantly smaller than previously thought. This new interpretation is also confirmed by the low rank of lignite coalification and the net calorific value of the ŚLS-3 and LLS-2.

Key words: Peat-to-lignite autocompaction; Peat-to-lignite compaction; Lignite deposit; Tectonic subsidence; Tectonic uplift.

INTRODUCTION

In the area of the Polish Lowlands there are several dozen Cenozoic tectonic grabens filled with productive lignite deposits. However, the richest in lignite are the Lubstów and Kleszczów grabens located in central Poland (Text-fig. 1). During the Cenozoic, these grabens were subject to both tectonic subsidence and/or tectonic uplift (e.g., Gotowała and Hałuszczak 2002; Widera 2004, 2011; Widera and Hałuszczak 2011). The consequence of this was the formation of very thick Cenozoic peat deposits, which were then transformed into the thickest lignite deposits in Poland by, among other things, autocompaction and compaction processes. The deposits are among the thickest in the world. The interplay between tectonic vertical movements and peat-to-lignite autocompaction played a fundamental role in the development of the recent geology and subsequent mining (e.g., thickness, depth of the floor and roof, etc.), as well as the chemical-technological parameters of the lignite seams (e.g., ash yield, caloric value, etc.).

The main aim of this paper is to provide a new, alternative interpretation of the tectonic development of the Lubstów and Kleszczów grabens during the formation of extremely thick lignite seams. As a result, other conceptual models of their tectonic evolution in the Cenozoic are suggested, where the processes of tectonic uplift and autocompactional subsidence occur simultaneously. The spatio-tem-



Text-fig. 1. Location map of the Lubstów and Kleszczów grabens (modified after Kasiński 1984; Dadlez and Marek 1998; Gotowała and Hałuszczak 2002; Widera 2004, 2007, 2024; Kasiński *et al.* 2009; Widera and Hałuszczak 2011). A – Examined grabens against the outlines of Poland and main tectonic units. Abbreviations: 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; TTZ, Teisseyre-Tornquist Zone. B – Examined grabens against the background of the geological map of Poland without Cenozoic cover (modified after Dadlez *et al.* 2000).

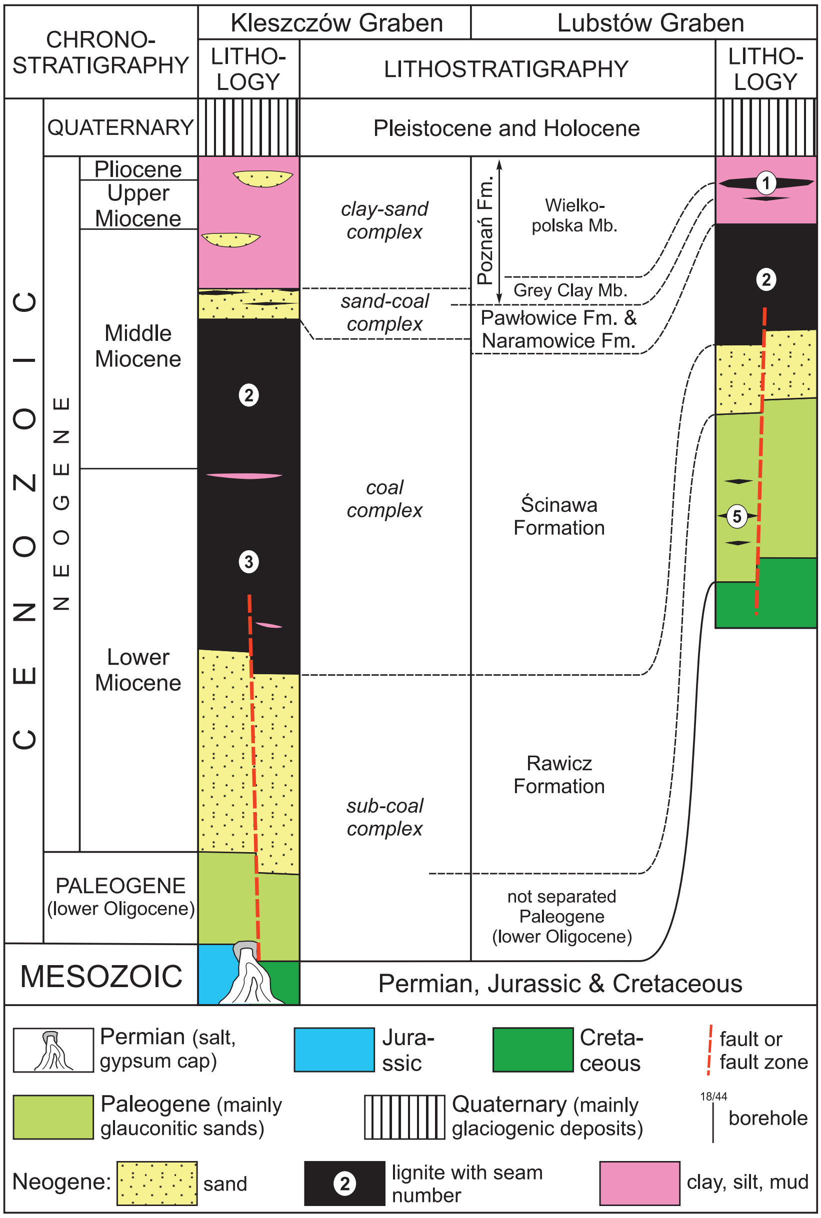
poral relationships between these processes and the accumulation of fresh peat layers are also discussed. Finally, petrographic (i.e., the reflectance of huminite) and chemical-technological evidence (i.e., net calorific value) is provided to support the interpretation presented in this paper.

GEOLOGY OF THE STUDY AREAS

Tectonic setting

In the Cenozoic, the Lubstów and Kleszczów grabens developed in the eastern part of the West European Palaeozoic Platform. They are located between the Bohemian Massif, the East European Platform and the Carpathians. The Lubstów Graben overlies the Gopło-Ponętów-Pabianice Fault Zone (G-P-PFZ), while the Kleszczów Graben belongs to the Poznań-Kalisz Fault Zone (P-KFZ) (see Text-fig. 1A). The tectonic evolution of these fault zones commenced before deposition of the salt-bearing Zechstein and continued periodically until the Cenozoic. Over such a long period of time, the study areas were subject to both tectonic subsidence and/or tectonic uplift, as in the other major fault zones occurring in the Polish Lowlands territory (Deczkowski and Gajewska 1980; Karnkowski 1980; Dadlez *et al.* 1995; Widera *et al.* 2008, 2019).

These vertical movements resulted from changes



Text-fig. 2. Compilation of simplified Cenozoic stratigraphy for the Kleszczów and Lubstów grabens (modified after Piwocki and Ziembińska-Tworzydło 1997; Widera 2007, 2021; Urbański and Widera 2020). Chronostratigraphic boundaries after Cohen *et al.* (2013; updated). Abbreviations and nomenclature of lignite seams mentioned in this paper: 5 – the fifth Czempiń lignite seam (CzLS-5); 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).

in the palaeostress field (extensional or compressional) occurring in the foreland of the Alpine-Carpathian orogen in the Cenozoic (e.g., Ziegler *et al.* 1995; Golonka 2004; Ziegler and Dèzes 2007; Jarosiński *et al.* 2009; Pharaoh *et al.* 2010; Widera *et al.* 2021). Additionally, the evolution of the Lubstów and Kleszczów grabens is closely related to the activity of salt structures located in their substratum, i.e., the Gopło and Dębina salt diapirs, respectively (e.g., Dadlez and Marek 1998; Widera 1998; Gotowała and Hałuszczak 2002; Kasiński *et al.* 2009; Widera and Hałuszczak 2011; Krzywiec 2012).

According to the tectonic division of Poland, both grabens belong to the Szczecin-Miechów Synclinorium. More precisely, the Lubstów Graben is located in the central part of the Mogilno Trough, called the Konin Elevation (Widera 1998), while the Kleszczów Graben is located between the Mogilno and Miechów troughs (Text-fig. 1B; Żelaźniewicz *et al.* 2011) on a structure called the Radomsko Elevation (Pożaryski 1971) or the Radomsko High (Karnkowski 2008). In the Lubstów Graben, the youngest Mesozoic is made up of Cretaceous carbonate rocks. However, in the Kleszczów Graben, the youngest Mesozoic rocks are Cretaceous or Jurassic carbonates (Text-figs 1A and 2; Dadlez *et al.* 2000).

Stratigraphic setting

Lithostratigraphy is the most significant stratigraphic method in study areas where terrestrial sediments predominate. Only occasionally are fauna or tuffitic horizons found in these sediments, as is the case also in the examined grabens. Hence, the palynological documentation of lignite seams is of fundamental importance (Piwocki and Ziembińska-Tworzydło 1997; Widera 2007, 2021) because it enables the correlation of lignite beds (seams) between the Lubstów and Kleszczów grabens, which are ~150 km apart (see Text-fig. 1). From an economic point of view, but also in the context of the tectonic analysis applied in this paper, the two thickest lignite seams are important. In the Kleszczów Graben these are the third Ścinawa lignite seam (ŚLS-3) and the second Lusatian lignite seam (LLS-2). Their maximum total thickness is 250.4 m (borehole 60/19, the 'Bełchatów' deposit). In the Lubstów Graben it is the LLS-2 seam, with a maximum thickness of 86.2 m (boreholes 22/44 and 24/49, the 'Lubstów' deposit) (cf. Text-figs 2 and 3; Widera 1998, 2013, 2021). On the other hand, according to the genetic classification of Polish lignite deposits, those from the study areas represent the tectonic type and graben subtype (Widera 2016a). This means that the mentioned lignite seams are restricted to the grabens and do not occur in the surrounding area.

The lithostratigraphic profiles of the Cenozoic succession in both studied grabens are incomplete. This is related to the presence of at least three relatively long-lasting stratigraphic gaps, which are the result of regional tectonic inversion and Pleistocene erosion (Krzywiec 2006; Kley and Voigt 2008; Jarosiński *et al.* 2009; Widera and Hałuszczak 2011). Therefore, no sediments of Paleocene–Eocene, late Oligocene, or Early Pliocene–Middle Pleistocene age were found in the Lubstów and Kleszczów grabens (cf. Text-figs 2 and 3). In both cases, the lowermost parts of their fill are glauconitic marine sands of early Oligocene age, which are classified as unsubdivided (not separated) Paleogene or the lower part of the sub-coal complex (see Text-fig. 2).

Overlying the lower Oligocene is the Neogene, which begins with siliciclastic deposits (mainly sands with thin lignite intercalations) called the Rawicz Formation in the Lubstów Graben. In the Kleszczów Graben, the upper part of the sub-coal complex is early Early Miocene in age. The sub-coal complex is overlain by the aforementioned, extremely thick lignite seams ŚLS-3 and/or LLS-2. They are middle to late Early Miocene and late Early Miocene to middle Mid-Miocene in age, respectively.

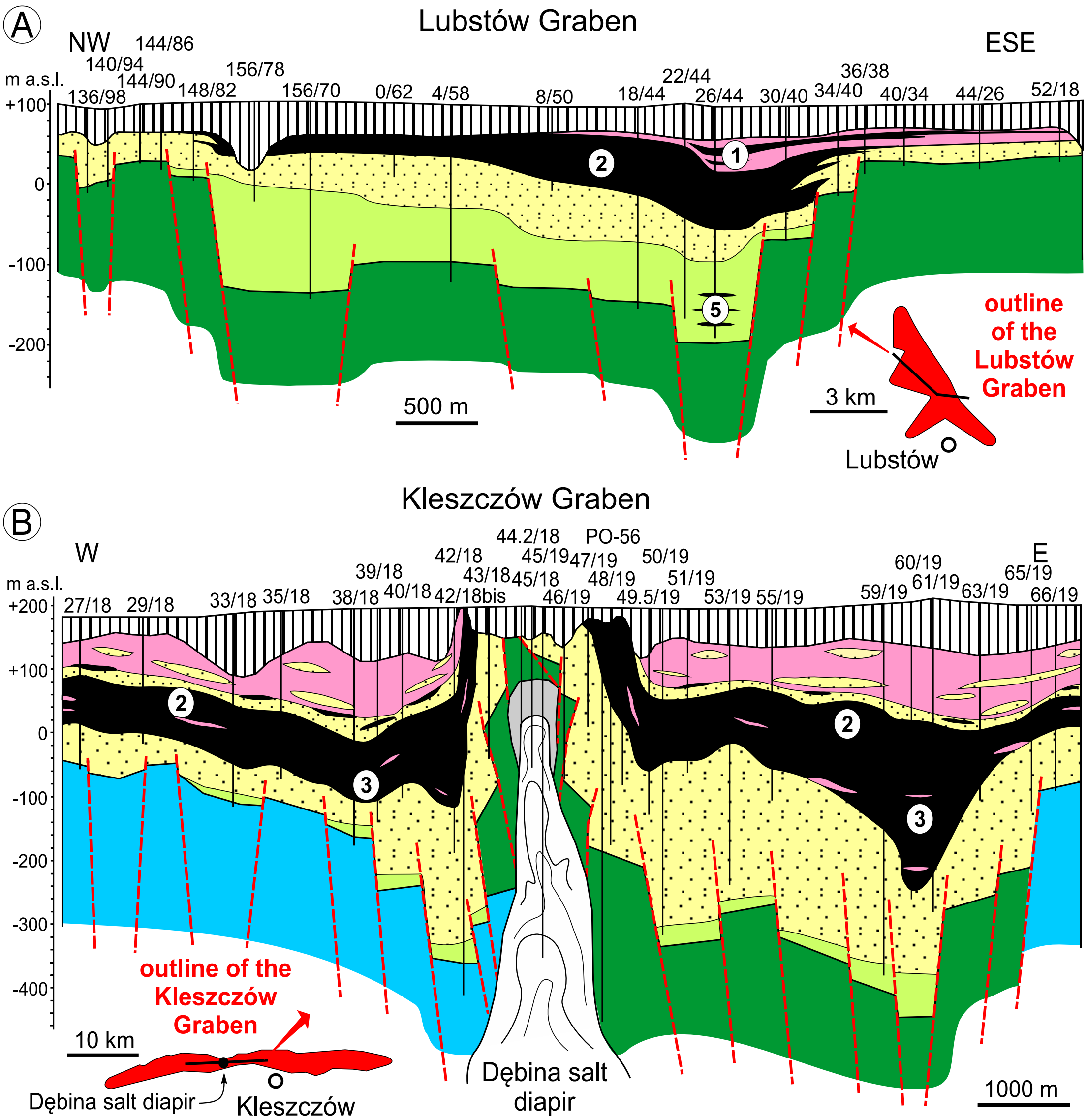
In turn, the lignite seams (ŚLS-3 and/or LLS-2) are covered by sandy-clayey sediments (locally with lignite lenses), which are assigned to various lithostratigraphic units, formations, members or complexes. They accumulated between the late Mid-Miocene and the earliest Early Pliocene (Text-fig. 2; Piwocki and Ziembińska-Tworzydło 1997). In the tectonic analysis presented below, these sediments are treated together, as the Neogene overburden. In the same way, the overlying glaciogenic sediments (tills, sands and gravels, and muds, etc.), which constitute the Quaternary overburden of the lignite seams, are treated as one unit.

MATERIAL AND METHODS

Data sources

The main sources of information used in this paper were borehole profiles made for the purpose of documenting the 'Lubstów' (Lubstów Graben), 'Bełchatów' and 'Szczerców' (Kleszczów Graben) lignite deposits. In total, data from 47 boreholes were used, 19 from the Lubstów Graben and 28 from the Kleszczów Graben area, to construct geological cross-sections along which tectonic analysis was carried out (see Text-fig. 3). All of the necessary information was obtained from the geological archives of the Konin and Bełchatów lignite mines.

Fieldwork was carried out in three opencast mines, to study the tectonic deformations of the examined lignite seams (ŚLS-2, LLS-2). In the Lubstów opencast (Lubstów Graben) managed by the Konin Lignite Mine, where lignite was exploited in the years 1982–2009, the photographs shown in this paper were taken in 1995 (see Text-fig. 4). In the currently operating Bełchatów (since 1980) and Szczerców opencasts (since 2009) managed by the Bełchatów Lignite Mine, located in the Kleszczów Graben, the effects of tectonic deformations were documented in 2009, 2017, and 2018 (see Text-fig. 5).

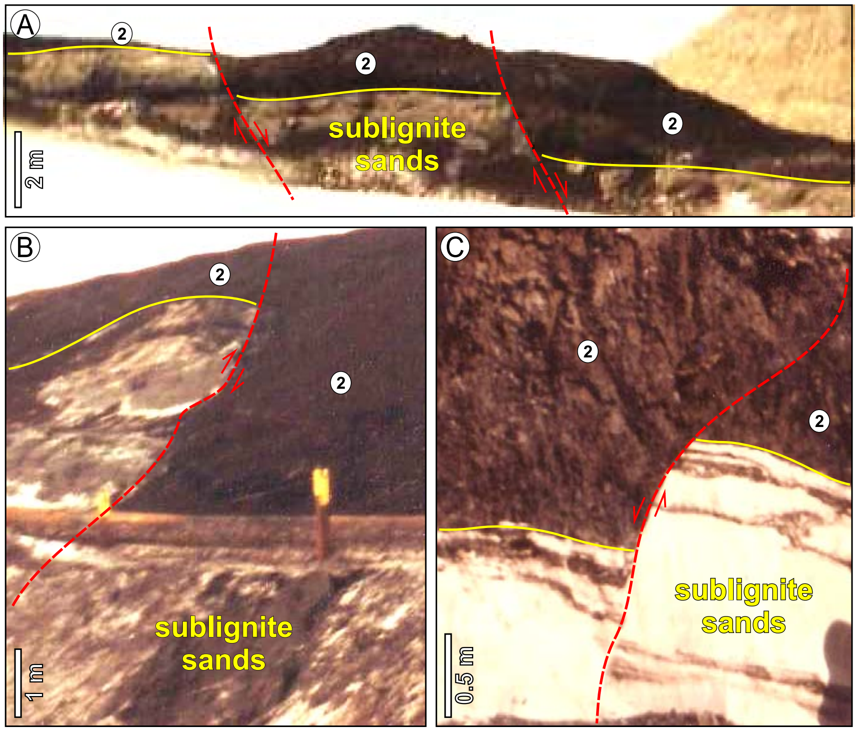


Text-fig. 3. Simplified geological cross-sections through the grabens analysed in this paper. A – Lubstów Graben. B – Kleszczów Graben. See the text and Text-fig. 2 for the nomenclature of extremely thick lignite seams, and Text-fig. 1 for location of the examined grabens.

Compaction of siliciclastic sediment and lignite

The siliciclastic sediments that underlie the thick lignite seams (i.e., ŚLS-3 and LLS-2) in both grabens are predominantly sands. Their compaction ratio to a depth of 300 m is <1.1 (Sclater and Christie 1980; Baldwin and Butler 1985; Sheldon and Retallack 2001). Laboratory tests show that the compaction ratio (the volume of the loose sample to the volume of the field, compacted sample) is in the range 1.01–1.05 (Hager *et al.* 1981; Widera 2007, 2011). This means that 100 m of sand was created from 101–105 m of originally accumulated sediments. Such an insignificant magnitude of sand compaction, compared to the peat-to-lignite compaction characterised below, can be omitted from tectonic considerations.

Compared to the above-described physical compaction of siliciclastics (mainly sands), the compaction of organic sediments is much more complex. For example, the peat-to-lignite compaction includes both physical (i.e., dewatering and compression), biochemical, and geochemical processes (e.g., Ryer and Langer 1980; Hager 1993; Nadon 1998; Widera 2013, 2021). Its magnitude is calculated by divid-



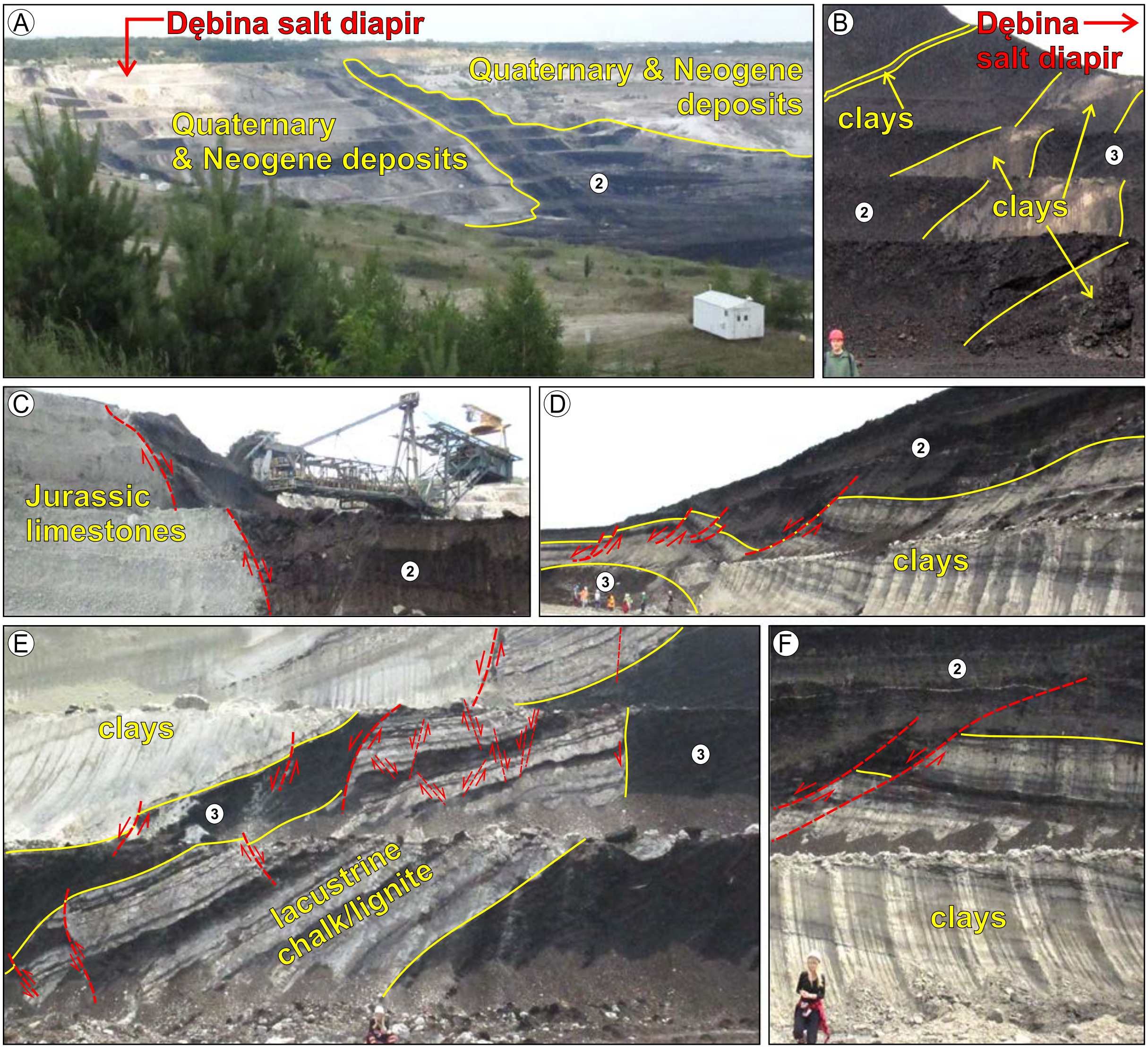
Text-fig. 4. Examples of tectonic deformations from the Konin Lignite Mine (reproduced from the author's analogue photographs). A, C – normal faults (Lubstów opencast in 1995). B – reverse fault (Lubstów opencast in 1995). See Text-fig. 2 for the nomenclature of lignite seam.

ing the original peat thickness before burial and the present-day thickness of the lignite seam. The reconstruction of the original height of the mire surface (indirectly, the thickness of mire/peat), after meeting several fundamental assumptions, was described in detail in the author's earlier papers (e.g., Widera *et al.* 2007; Widera 2015). The result obtained in this way is referred to as the compaction ratio – Cr. The average values for ŚLS-3 and LLS-2 were 2.9 and 2.5, respectively (Kasiński 1984, 2000; Widera 2015, 2024). This means that, to create 100 m of these lignite seams, 250–290 m of peat was needed, when it was covered by clastic overburden. Due to the diverse macropetrographic composition (i.e., lignite lithotypes) and content of non-organic matter (when burned measured as ash yield), as well as interlayering of siliciclastics (sands, clays, etc.) in these seams, individual values of the compaction ratio obviously differ from the given average values. For example, for LLS-2 from the Lubstów Graben, the obtained values of Cr are in the range of 2.34–2.56 (Widera *et al.* 2007).

At this point, it is necessary to distinguish between the compaction of entire lignite seams, as described above, and the compaction of the surface layers of fresh peat. In the latter case, the values of the compaction ratio may be several times higher (e.g., Van Asselen 2011; Widera 2019). This compaction process, prior to covering the peat surface with non-organic overburden, is called autocompaction or self-compaction (e.g., Courel 1987; Gayer and Pešek 1992; Widera 2015). It is the process of the autocompaction of peat-to-lignite that will be particularly important in the tectonic considerations presented below.

Tectonic and compactional subsidence

In order for sediments to accumulate, accommodation space is needed, which is created as a result of lowering the depositional surface (subsidence). This process can occur in at least two basic ways: as a result of downward tectonic movements and/or of compaction. In lignite-bearing areas, the latter process mainly occurs by peat-to-lignite transformation during autocompaction and compaction. Tectonic subsidence can be regional (epeirogenic) and involve areas outside the grabens or local, restricted to the grabens. The compactional subsidence of lignite is expected to be local in the examined cases due to the tectonic type and graben subtype of both lignite deposits (Widera 2016a).



Text-fig. 5. Examples of tectonic deformations from the Bełchatów Lignite Mine. A, B – steeply tilted strata in the vicinity of the Dębina salt diapir (Bełchatów opencast in 2018 and 2009, respectively). C – tectonic contact between the Jurassic limestones and the Neogene lignites of the LLS-2 (Szczerców opencast in 2017). D–F – folded and faulted lignite seams (ŚLS-3, LLS-2) together with interlignite deposits, i.e., clays and lacustrine chalk (Szczerców opencast in 2018). Note the coexistence of both normal and reverse faults in Text-fig. 5E, and see Text-fig. 2 for the nomenclature of lignite seams.

In this paper, as in the previous one (Widera 2024), the fundamental principles of the back-stripping method were also used (Van Hinte 1978; ten Veen and Kleinspehn 2000). However, since the Cenozoic stratigraphy in the Lubstów and Kleszczów grabens is based on the lithostratigraphic division, where the boundaries of the units are diachronic, the construction of tectonic subsidence diagrams would be burdened with a large error which is difficult to estimate. In contrast to the siliciclastic sediments, algorithms for coal compaction/decompaction, including lignite, have not been proposed in the geological literature. The timing of vertical movements, the rate of sediment accumulation, and the rate of tectonic subsidence/uplift cannot be consistently calculated with such a high accuracy as in other areas (e.g., Michon *et al.* 2003; Van Balen *et al.* 2005).

The above-listed methodological limitations have forced an original, individual approach to the tectonic analysis of lignite-bearing Polish areas. This was presented graphically in the author's previous study (Widera 2024, his text-figs 5–7), although the most important thing in the mentioned hypothesis was that no upward movement was assumed during the accumulation of peat. However, a different scenario for the development of the Lubstów and Kleszczów grabens, during the formation of ŚLS-3 and LLS-2, will be shown. In other words, other temporal relationships between tectonics, autocompaction and compaction will be proposed in this paper.

RESULTS

Field observations of tectonic structures

Hundreds of deformation features were found in opencasts (Lubstów, Bełchatów, Szczerców) operating in the studied areas, where lignite was/is mined, resulting from both peat-to-lignite autocompaction and compaction, and vertical tectonic movements. Photographs of a few of these are presented in Text-figs 4 and 5. The effects of the compaction process are mainly manifested in the form of bending (folding) or minor faulting in the roof layers of the lignite seams. Unfortunately, in such cases, compactional and tectonic deformations are difficult to distinguish because they overlap. This problem does not exist in the case of the floor parts of these seams, that is, at the contact with the underlying sands (Text-figs 4 and 5).

Nearly 30 years ago, tectonic faults were documented in the form of analogue photographs in the deepest part of the Lubstów opencast (the Lubstów Graben). Normal faults with vertical throws of 0.5–2.0 m predominated (Text-fig. 4A, C). However, normal and reverse faults, with throws >5 m, were also observed (Text-fig. 4B; Widera 1998, 2007). It is also worth noting that the sub-lignite sands in the Lubstów opencast were sometimes tectonically inclined at a high angle, reaching up to 55° (Widera 2016b).

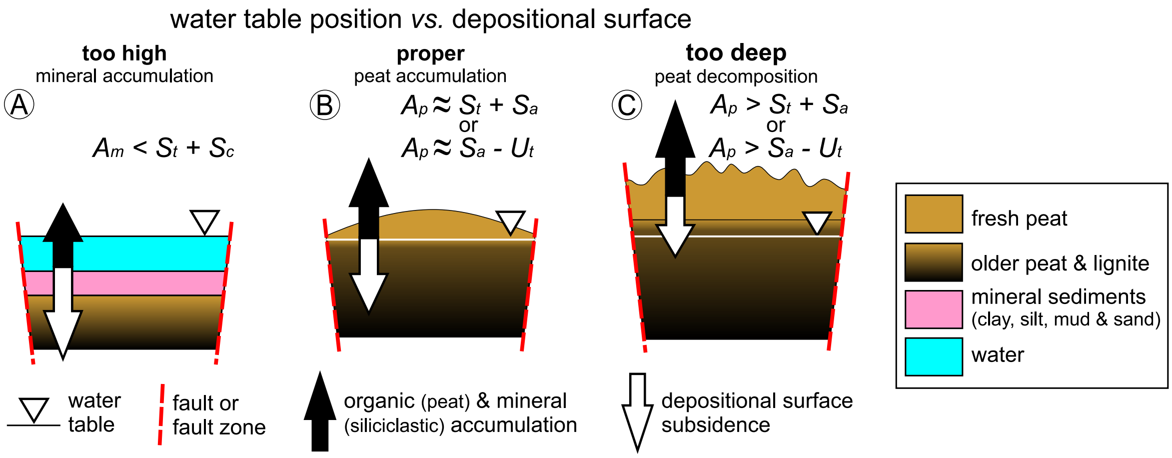
On the other hand, the Bełchatów and Szczerców opencasts (Kleszczów Graben) belong to the areas in Poland where Cenozoic tectonic activity has been best documented (Gotowała and Hałuszczak 2002; Widera and Hałuszczak 2011; Widera 2016b, 2021). Various deformation features were observed in the field, with magnitudes ranging from decimetres to >200–300 m (Text-fig. 5). The largest of them (up to 150 m), in the form of steeply tilted lignite and siliciclastic layers, occurred in the vicinity of the Dębina salt diapir (Text-fig. 5A, B). Normal and reverse faults, with a total throw of >200–300 m (Widera and Hałuszczak 2011), were observed at the contact of the Neogene and Mesozoic rocks (Text-fig. 5C). However, due to the colour contrast, the most visible in the field are the normal faults, sometimes reverse faults, which occur at the contact of black lignite and interbedded grey-white lacustrine chalk and clay (Text-fig. 5D–F).

Formation of lignite seams

Just like peat accumulating today, lignite and hard coal appear in the stratigraphic record in various sedimentary environments, such as deltaic, fluvial, lacustrine, etc. (Horne *et al.* 1978). A necessary factor controlling the development of any peatlands (mires) is a permanently high position of the water table, close to the depositional surface, as summarised by Teichmüller (1989) and Dai *et al.* (2020). On the other hand, peat-forming environments, geodynamic conditions and overburden thickness strongly influence the economic value of the resulting coals, including lignites (e.g., Nurkowski 1984; McCabe 1987; Diessel *et al.* 2000; Markič and Sachsenhofer 1997, 2010; Moore and Shearer 2003; Opluštil 2005; Flores 2014).

In the case of very thick lignite deposits, such as those filling the Lubstów and Kleszczów grabens, the environmental conditions are more complex. The main factors controlling the formation of lignite seams with a thickness ranging from several dozen to over a hundred metres, were characterised and discussed by Kasiński (2000), as well as Kasiński and Słodkowska (2016). They can be divided into climatic and geodynamic factors. The production of fresh peat is, of course, highest in warm and humid climates. However, without favourable geodynamic conditions, no extremely thick peat beds will be created and then transformed into these very thick lignite deposits. For this to happen, the deposition surface of the mire had to be subject to long-lasting and relatively steady subsidence (Hager *et al.* 1981; Schäfer *et al.* 1995, 2005; Markič and Sachsenhofer 1997; Diessel *et al.* 2000; Holdgate *et al.* 2002; Holdgate 2005; Rajchl *et al.* 2008, 2009; and references therein) (from hundreds of thousands of years to as much as 6–9 million years; Zagwijn and Hager 1987; Hager 1993). It should be added, however, that the period in which thick layers of peat accumulated in the Lubstów and Kleszczów grabens has not yet been established.

The main factors controlling subsidence, excluding external ones, are as follows: peat-to-lignite (local) autocompaction and compaction, tectonic (local) subsidence, epeirogenic (regional) subsidence and salt



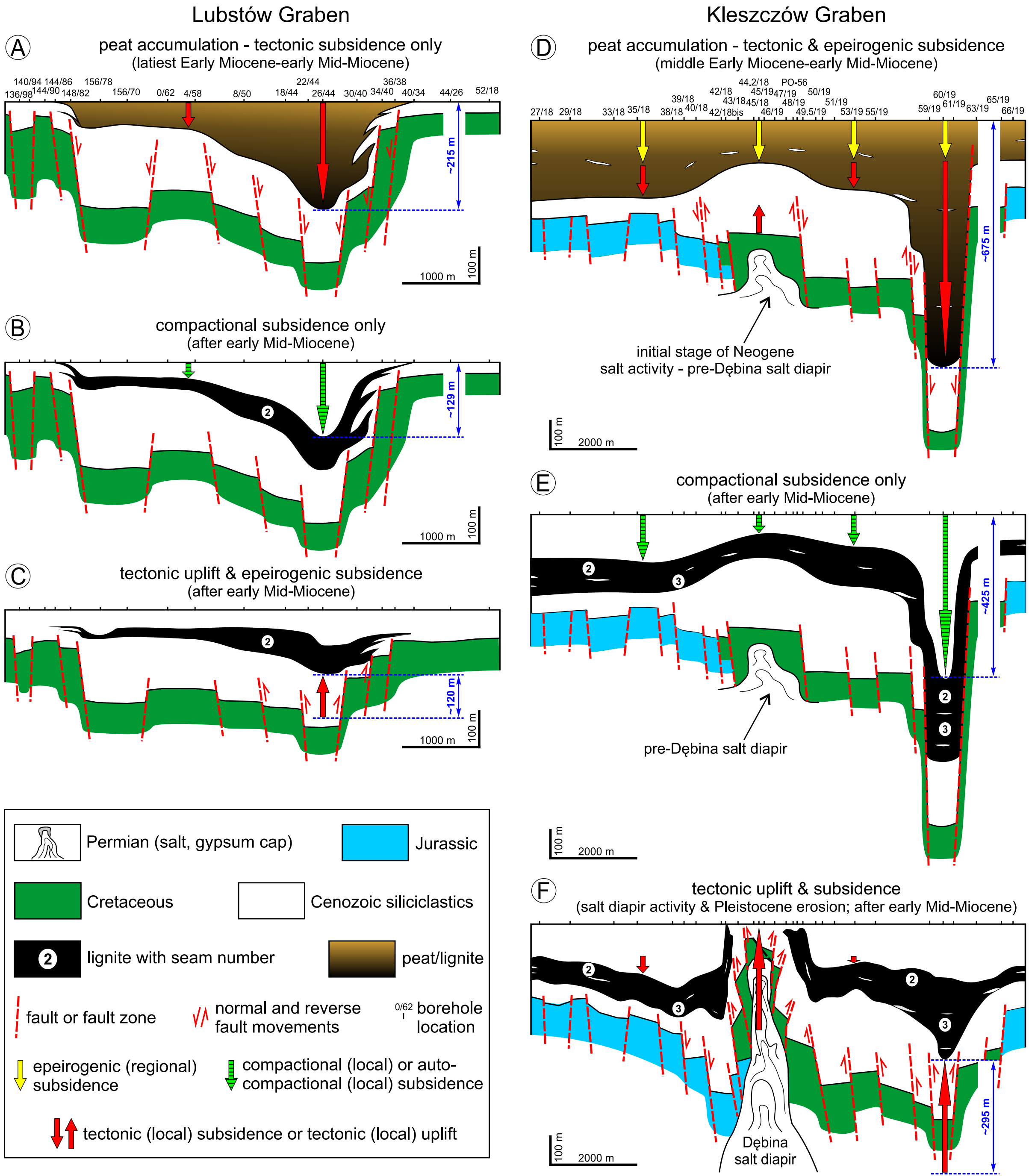
Text-fig. 6. Relationship between the location of the depositional surface and the height of the water table in the mire area (modified after Kasiński 2000; Kasiński and Słodkowska 2016). Abbreviations: A_m – mineral (siliciclastic) accumulation; A_p – peat accumulation; S_t – tectonic subsidence; S_c – compactional subsidence of peat; S_a – autocompactional subsidence of peat; U_t – tectonic uplift. See the text for other explanations.

(local outflow, dissolution) (Kasiński 2000; Kasiński and Słodkowska 2016). The relationships between them determine the position of the water table, relative to the depositional surface (Text-fig. 6). If the lowering of the depositional surface is greater than the growth of fresh peat (tectonic subsidence + compactional subsidence > mineral/siliciclastic and organic accumulation), lakes or ponds will be formed on the surface of the mire, in which (>2 m water depth) mineral (siliciclastic) accumulation will dominate (Text-fig. 6A; Diessel *et al.* 2000). Otherwise (tectonic subsidence + peat autocompaction < peat accumulation or peat autocompaction – tectonic uplift < peat accumulation) the top layers of peat would decompose (mainly biochemically), which would not result in the formation of peat/lignite (Text-fig. 6C). Thus, the most favourable conditions for peat accumulation occur when the growth of peat-forming vegetation is intense and peat accumulation almost equal to the total effect of the tectonic and autocompactional subsidence or to the difference between autocompactional subsidence and tectonic uplift (Text-fig. 6B).

Previous hypothesis

Continuous lignite seams, with maximum thicknesses exceeding 86 and 250 m in the studied areas, prove that the balance between the lowering of the depositional surface and the production of fresh peat layers described above persisted for a very long time (Text-fig. 6). However, this does not explain the mutual relations between tectonic and compactional subsidence, that is, between their magnitude and timing. In the case of the Lubstów and Kleszczów grabens, it was assumed that, during the formation of lignite seams (ŚLS-3, LLS-2), tectonic subsidence and peat accumulation occurred first and then, after being covered with non-organic overburden, peat-to-lignite compaction occurred. In turn, the process of post-depositional tectonics was assumed to take place after the covering of the peat with the aforementioned siliciclastic sediments (e.g., Gotowała and Hałuszczak 2002; Widera and Hałuszczak 2011; Widera 2011, 2024).

From the current thickness of lignite seams (~86 and ~250 m) and the values of compaction ratios given above (Cr = 2.5 for the LLS and average Cr = 2.7 for the ŚLS-3 and LLS-2, respectively, where (2.9 + 2.5)/2 = 2.7), the maximum tectonic subsidence was calculated and taken to be equal to the maximum thickness of peat before it was covered with overburden sediments (Text-fig. 7A, D). Thus, it was estimated that the peat thickness could, theoretically, reach as much as 215 m (86 m × 2.5) and 675 m (250 m × 2.7) in the Lubstów and Kleszczów grabens, respectively. In this simplified model, it was also the stage of most intense tectonic subsidence in both grabens. Then the main peat-to-lignite compaction process took place, which is estimated by calculating the compaction ratio of the entire lignite seam (e.g., Hager *et al.* 1981; Kasiński 1984; Widera *et al.* 2007). It is worth remembering, however, that the autocompaction process (under the weight of younger peat layers) took place syn-depositionally, prior to the



Text-fig. 7. Previous conceptual model depicting first the accumulation of peat, then its compaction and finally the post-depositional tectonic uplift of some parts of the lignite seams (modified after Widera 2024, his text-figs 12, 13). A–C – Lubstów Graben. D–F – Kleszczów Graben. Note the large magnitude of tectonic subsidence, compactional subsidence, and tectonic uplift. See Text-fig. 2 for the nomenclature of lignite seams, and see the text for more explanations.

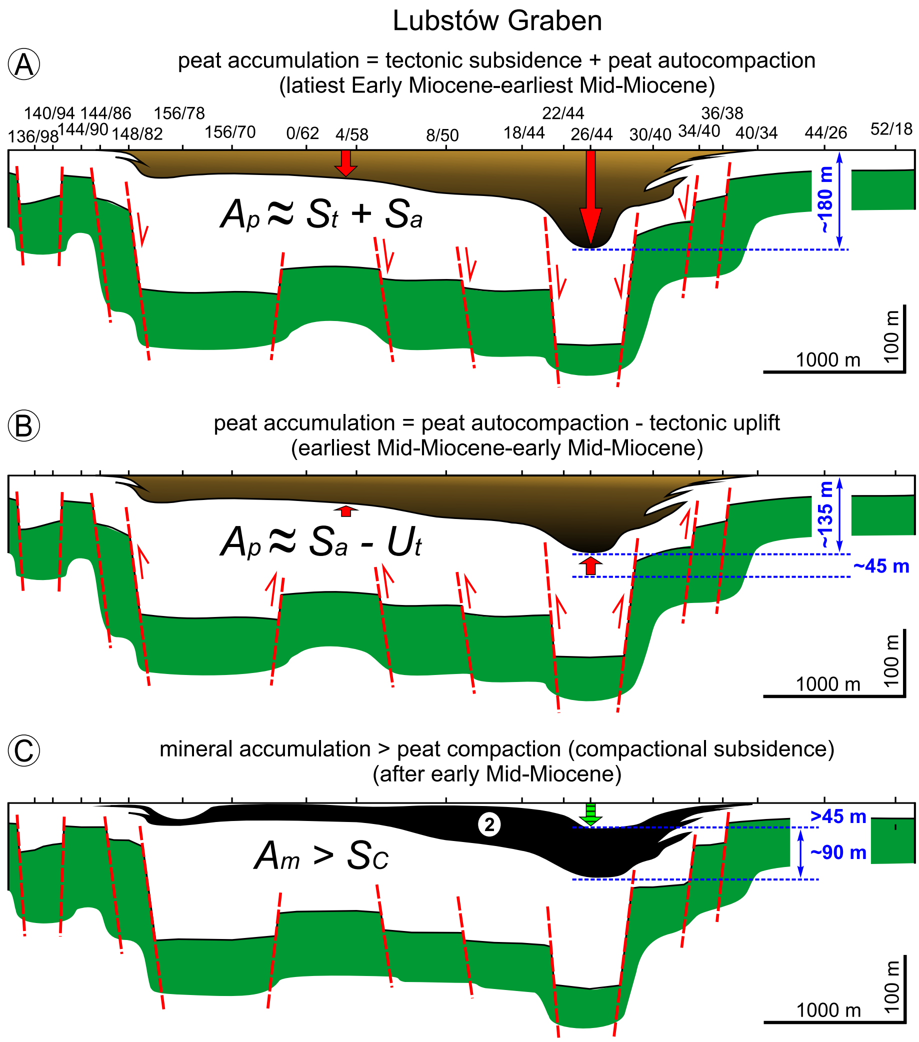
peat being covered with siliciclastic overburden (e.g., Courel 1987; Gayer and Pešek 1992).

According to the previously proposed conceptual model, when the peat surface was covered by the first siliciclastic layers, the tectonic subsidence stage ended and the compaction process began. As a result, the roof of the lignite seams (ŚLS-3, LLS-2) subsided through compaction by a maximum of 129 m

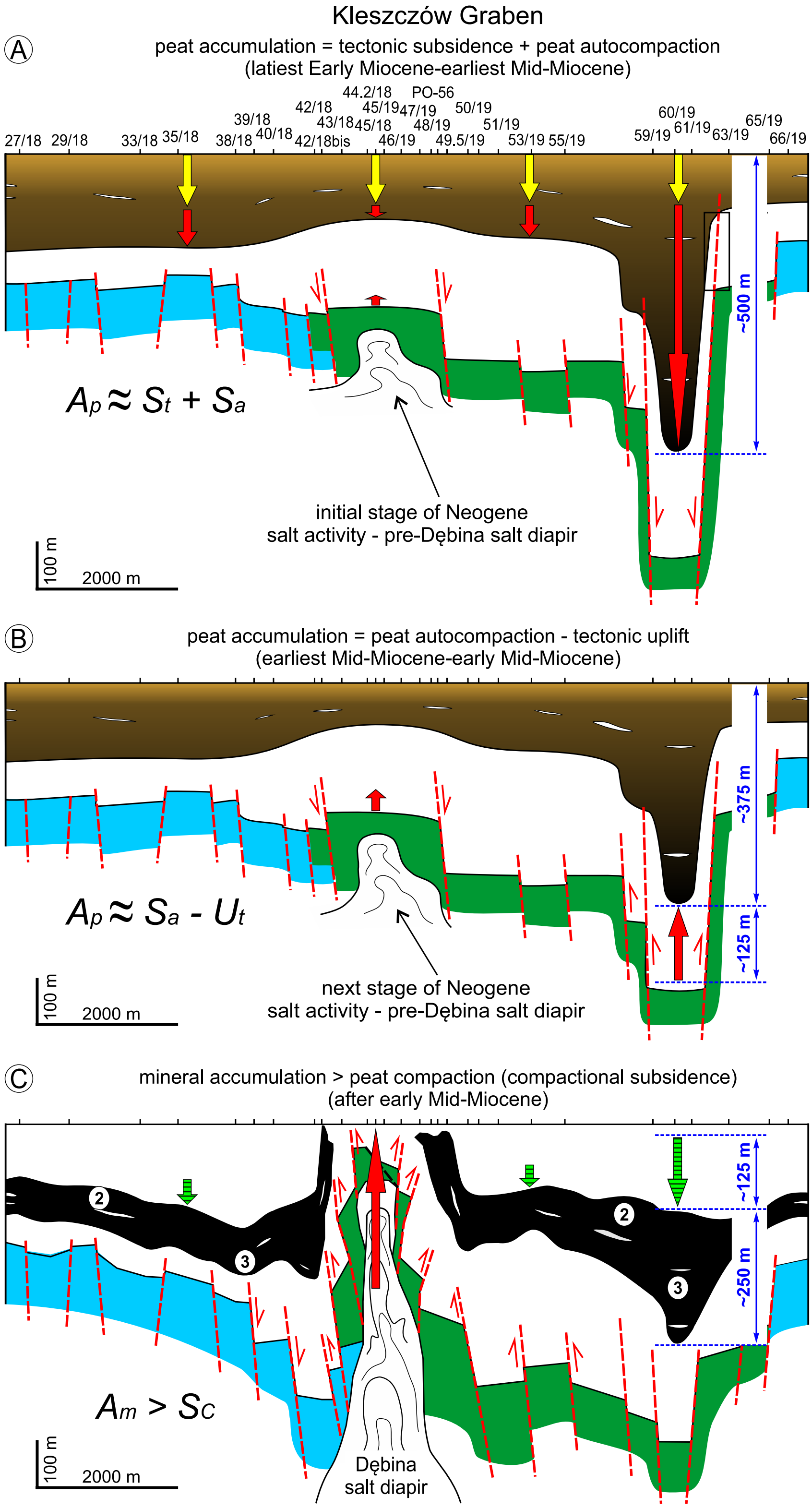
(215 minus 86 m) in the Lubstów Graben and 425 m (675 m minus 250 m) in the Kleszczów Graben (Text-fig. 7B, E). Finally, after peat-to-lignite compaction was mostly completed (in fact, it continues to this day but to a negligible extent), the deepest parts of these two grabens were tectonically uplifted. The magnitude of the tectonic uplift was ~120 m in the Lubstów Graben and ~295 m in the Kleszczów Graben, probably reaching >300 m above the Dębina salt diapir (Text-fig. 7C, F).

Alternative hypothesis

Another possible scenario for the tectonic evolution of both grabens analysed during the formation of the thickest lignite seams in Poland (ŚLS-3, LLS-2) assumes that the magnitudes of tectonic subsidence and, consequently, the resultant of autocompaction subsidence, compactional subsidence, and post-depositional uplift, were smaller. Most likely, they (i.e., magnitudes of tectonic uplift and subsidence, respectively) did not exceed 120–215 m in the Lubstów Graben and 295–675 m in the Kleszczów Graben (Text-fig. 7) but were in the hypothetical range of ~45–180 m in the first case and ~125–500 m in the second case (Text-figs 8 and 9). For example, the deepest parts of the Lubstów Graben may have first subsided by only ~180 m (Text-fig. 8A) and then slowly uplifted by ~45 m as the upper layers of peat accumulated (Text-fig. 8B). In the case of the Kleszczów



Text-fig. 8. New conceptual model depicting the Miocene tectonic evolution of the Lubstów Graben during the formation of the second Lusatian lignite seam (LLS-2). Abbreviations: A_m – mineral (siliciclastic) accumulation; A_p – peat accumulation; S_t – tectonic subsidence; S_c – compactional subsidence of peat; S_a – autocompactional subsidence of peat; U_t – tectonic uplift. See the text and Text-figs 2, 6 and 7 for other explanations.



Text-fig. 9. New conceptual model depicting the Miocene tectonic evolution of the Kleszczów Graben during the formation of the third Ścinawa lignite seam (ŚLS-3) and the second Lusatian lignite seam (LLS-2). Abbreviations: A_m – mineral (siliciclastic) accumulation; A_p – peat accumulation; S_t – tectonic subsidence; S_c – compactional subsidence of peat; S_a – autocompactional subsidence of peat; U_t – tectonic uplift. See the text and Text-figs 2, 6 and 7 for other explanations.

Graben, this hypothetical range is of course much larger (Text-fig. 9A, B), because the current maximum lignite thickness in the Kleszczów Graben is many times greater than in the Lubstów Graben (cf. Text-figs 3, 8C and 9C). Unfortunately, the magnitudes of vertical movements (tectonic subsidence and uplift or autocompaction and compactional subsidence) can only be determined qualitatively according to this hypothesis. This is due to the lack of data on changes in the peat-to-lignite compaction ratio with depth. Therefore, the given numerical values (in metres) should be taken as educated guesses that are helpful in explaining this alternative hypothesis. It was assumed that the magnitude of tectonic uplift approximately equalled post-depositional compactional subsidence (Text-figs 8 and 9).

In both of the examined grabens, the same stages of tectonic development were distinguished, when thick lignite seams were created. The presented hypothesis has the same limitations characterised above, in both the Lubstów Graben and the Kleszczów Graben, but it differs significantly, in terms of the magnitude of vertical movements.

The first stage of the formation of the analysed lignite seams (ŚLS-3, LLS-2) was certainly related to tectonic subsidence, which was balanced by the growth of peat slowed by autocompaction. The magnitude of the lowering tectonic movements must have been much greater than the present-day total thickness of the lignite seams, that is, in the range ~86–215 m in the Lubstów Graben and 250–675 m in the Kleszczów Graben. Due to lack of accurate data, it was assumed in this study that it was approximately twice the thickness of the lignite, ~180 and ~500 m, respectively (Text-figs 8A and 9A).

In the second stage, the direction of tectonic vertical movement was reversed. In this case, the rate of tectonic uplift had to be almost equal to the accumulation and autocompactional subsidence of peat (cf. Text-figs 6, 8B and 9B). As explained above, it was assumed that the magnitude of the tectonic uplift was similar to the magnitude of the post-depositional peat-to-lignite compaction. This was ~45 m, in the case of the Lubstów Graben, and ~125 m, in the case of Kleszczów Graben. Then, after the uplifting movement ended and the lignite was covered by the siliciclastic overburden, the peat-to-lignite compaction process began. According to the accepted line of reasoning, where the average values of compaction ratio are 2.5 for LLS-2 and 2.9 for ŚLS-3 (e.g., Kasiński 1984; Widera 2015), the lowering of the peat surface in the deepest part of both grabens was only ~45 and ~125 m (Text-figs 8C and 9C).

DISCUSSION

Magnitude of peat-to-lignite autocompaction

In this study, the value of the autocompaction ratios were assumed to be 2.0 and 1.5 at the stage of tectonic subsidence and inversion, respectively. They were calculated as follows: 180/90 m = 2.0 and 135/90 m = 1.5 (LLS-2 in the Lubstów Graben), and 500/250 = 2.0 and 375/250 m = 1.5 (ŚLS-3 and LLS-2 in the Kleszczów Graben) (Text-figs 8 and 9). These values are smaller than the average values of the compaction ratios estimated using various methods for global lignites, including Polish ones, which are in the range of 2–4 (for a review, see Widera 2015). However, in the context of the discussed issue, the values of the autocompaction are more important. For example, Gayer and Pešek (1992) found that the autocompaction ratio, calculated for coal clasts (upper Westphalian of the South Wales), ranged from 1.3 to 5.7. The adopted values of 2.0 and 1.5 are within the given range, therefore it is justified to include them in tectonic considerations.

Timing of tectonic and compactional processes

In the current study, when creating a new, alternative to the previous model (Widera 2024), the timing of tectonic and compactional processes was changed. Too low maturity of the examined lignites, characterised in detail below, allows the assumption that peat accumulation took place both at the stage of tectonic subsidence and tectonic uplift (see Text-figs 8A, 8B, 9A and 9B). During this time, there was also a continuous and progressive process of peat-to-lignite autocompaction. The magnitudes of vertical movements had to be close to the total effects of peat accumulation and autocompaction (see Text-fig. 6; Diessel *et al.* 2000; Kasiński 2000; Kasiński and Słodkowska 2016; and references therein).

The above-mentioned local balance between vertical tectonic movements and peat/lignite autocompaction was subsequently disturbed, most likely by changes of regional tectonics and climate (Kasiński and Słodkowska 2016; Widera et al. 2021). In unfavourable environmental conditions, the growth of fresh peat layers ended and the accumulation of siliciclastics started on the top of the peat/lignite seam. From that moment the process of peat-to-lignite compaction under the weight of the overburden began (see Text-figs 8C and 9C). According to the proposed new conceptual models, the maximum magnitude of this compaction is much smaller (45 and 125 m) than previously assumed, that is, ~130 m in the Lubstów Graben and ~425 m in the Kleszczów Graben (Widera 2024).

Finally, it must be clearly stated that the tectonic development model of the Lubstów and Kleszczów grabens presented in this study does not exhaust all possibilities. In other words, it shows in a simplified way geological processes such as tectonic subsidence, compaction subsidence, including autocompaction, and tectonic uplift. In the case of coal(lignite)-bearing areas, precise determination of the time, magnitude and rate of each of the above processes is very difficult. This is due to the fact that, in addition to physical processes (e.g., water outflow, compression of plant fragments, etc.), peat-to-lignite auto- and compaction are also influenced by bio- and geochemical processes (Diessel *et al.* 2000; Widera *et al.* 2007; Dai *et al.* 2020). Nevertheless, both in the previous model (Widera 2024) and in the one proposed above, without the stage of tectonic uplift of the deepest parts of the examined Lubstów and Kleszczów grabens, it is impossible to explain the formation of lignite seams 90 and 250 m thick, respectively.

Petrographic and chemical-technological evidence

The rank of lignite is determined on the basis of the reflectance of huminite (eu-ulminite B) – the main petrographic component (maceral) of lignite. The measured results are called the mean reflectance (Rm), which is used to classify lignite (e.g., Stach *et al.* 1982; Kwiecińska and Wagner 1997; Markič and Sachsenhofer 2010; Bielowicz 2012; Havelcová *et al.* 2012; Ratajczak *et al.* 2022). The reflectance (Rm) value for LLS-2 from the Lubstów Graben is 0.26%. In the case of the Kleszczów Graben, however, there is a noticeable difference in the Rm value between both lignite seams, that is, 0.26% for the younger LLS-2 and 0.28% for the older ŚLS-3 (Kwiecińska and Wagner 1997; Bielowicz 2012). It should be noted that a significant anomaly occurs in the vicinity of the Dębina salt diapir, where the average Rm values are 0.32% (Ratajczak *et al.* 2022). The latter can be explained by analogy with the Büsum salt diapir in Germany: the thermal conductivity of salt is higher than that of the surrounding sedimentary rocks (Magri *et al.* 2008).

On average, the ŚLS-3 lies 100 m deeper than the LLS-2 in both study areas (see Text-fig. 3). This means that the reflectance value (Rm), outside the vicinity of the Dębina salt dome, increases by 0.02%/100 m. It should be recalled that, according to the previously proposed models, the magnitude of tectonic subsidence during peat accumulation was ~100 m greater in the Lubstów Graben and ~200 m greater in the Kleszczów Graben (Widera 2024, his text-figs 12C, D and 13C, D). Thus, the Rm value in the first case should be higher by 0.02% for the LLS-2 and, in the second case, by 0.04% for the LLS-2 and ŚLS-3. As a result, the LLS-2 in the Lubstów Graben should be characterised by the values of Rm = 0.28% while, in the Kleszczów Graben, Rm = 0.30% for the LLS-2 and Rm = 0.32% for the ŚLS-3. The reflectance values (Rm) are closer to those typical of low-rank C coals (ortho-lignites), as for instance, from the Polish part of the Eger Graben (Zittau Basin – Rm = 0.30%; Kwiecińska and Wagner 1997; Havelcová *et al.* 2012), but lower than those of low-rank B coals (meta-lignites) from the Slovenian Velenje Graben (Velenje Basin – Rm = 0.37%; Markič *et al.* 2007; Markič and Sachsenhofer 2010). These similar-aged, Miocene (Zittau Basin) and younger, Pliocene (Velenje Basin) lignites underwent the coalification process in areas where the geothermal degree is much higher than in the Polish Lowlands.

Consequently, lignites from the examined Lubstów and Kleszczów grabens should also have higher net calorific values (NCV or Q_i^r). The average NCV is in the range of 8.4–10.1 MJ/kg for the Miocene ortho-lignites discussed (Widera 2021), which is lower than for the Velenje Pliocene meta-lignites, where NCV = 10.5 MJ/kg (Markič *et al.* 2007). It should be noted that the average caloric values (NCV = 9.1–9.7 MJ/kg) for lignites from the Zittau Basin are similar to those from the Kleszczów Graben (Widera 2021). Summarising this, it can be said that the low values of both selected petrographic and chemical-technological parameters (Rm, NCV) clearly prove that during the formation of the ŚLS-3 and LLS-2, the deepest segments of the Lubstów and Kleszczów grabens never underwent such large syn-depositional tectonic subsidence as previously suggested (cf. Widera 2024).

CONCLUSIONS

This study refers to the author's previous paper on the tectonic analysis of the richest lignite areas in Poland, which were significantly active in the Cenozoic (Widera, 2024). Therefore, both studies should be treated together; however, the conclusions arising from the current study are as follows:

1. The Lubstów and Kleszczów grabens are characterised by some of the thickest lignite seams not only in Poland but worldwide. The formation of >86 and >250 m of lignite, respectively, required the accumulation of significantly greater peat thicknesses

under conditions of long-lasting and slow subsidence, both tectonic and autocompactional.

2. A steady position of the depositional surface could also be caused by slow tectonic uplift, balanced by the process of almost equal peat autocompaction. Such an interpretation is proposed in this study. New conceptual models show that the magnitude of syn-depositional tectonic subsidence was smaller by ~35 m in the Lubstów Graben and ~275 m in the Kleszczów Graben, than was previously assumed.

3. The obtained results are consistent with what appear to be 'too low' values of reflectance of huminite (reflectivity; Rm) and net calorific values (NCV) of the lignites from both grabens. If these lignites had been originally much deeper, then the values of both the parameters would have to be much higher and, therefore, the quality of the lignite would also be better, by ~7–14%.

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