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Acta Geologica Polonica, Vol. 69 (2019), No. 3, pp. 387–401
DOI: 10.24425/agp.2019.126439

Paleogene–Neogene tectonic evolution of the lignite-rich Szamotuły Graben

MAREK WIDERA[1,*], WOJCIECH STAWIKOWSKI[1] and GRZEGORZ UŚCINOWICZ[2]

[1] *Institute of Geology, Adam Mickiewicz University, 12 Krygowski Street, 61-680 Poznań, Poland.*
E-mails: widera@amu.edu.pl; wojst@amu.edu.pl
[2] *Polish Geological Institute-National Research Institute, Marine Geology Branch, 5 Kościerska Street,*
80-328 Gdańsk, Poland. E-mail: gusc@pgi.gov.pl
**corresponding author*

ABSTRACT:

Widera, M., Stawikowski, W. and Uścinowicz, G. 2019. Paleogene–Neogene tectonic evolution of the lignite-rich Szamotuły Graben. *Acta Geologica Polonica*, **69** (3), 387–401. Warszawa.

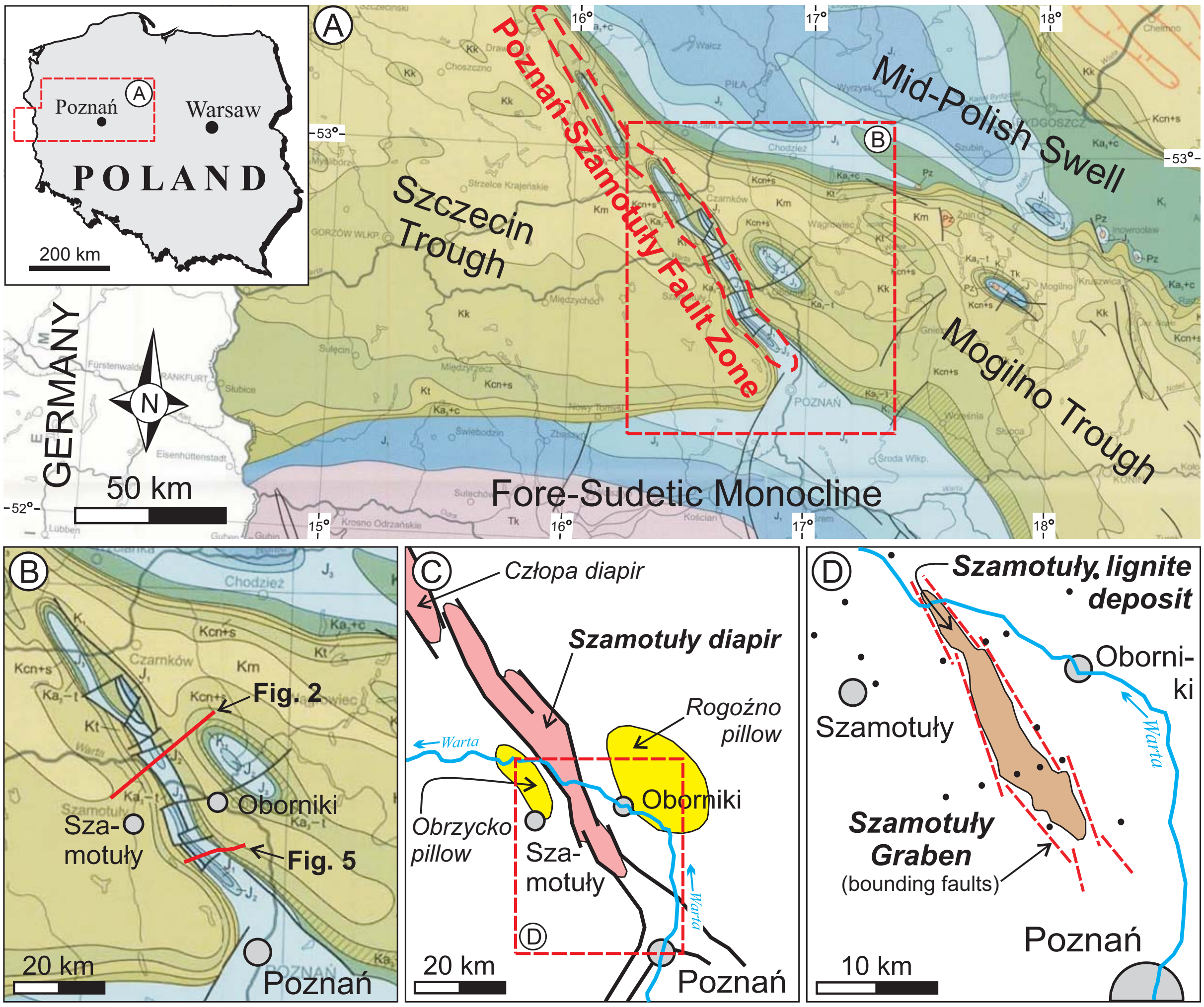
The Szamotuły Graben covers the southernmost part of the Permo-Mesozoic Poznań–Szamotuły Fault Zone. Along this regional discontinuity there are several salt structures, including the Szamotuły diapir, over which an extensional graben formed in the Paleogene and Neogene. The graben is located north of Poznań in central-western Poland, and is NW–SE-trending, ~20 km long, 3–5.5 km wide, and up to 160 m deep. It is filled with Lower Oligocene and Neogene sediments, including relatively thick lignite seams. Data from boreholes allow the assignment of the graben-fill sediments to appropriate lithostratigraphic units. Furthermore, analysis of changes in the thickness of these units provides evidence for periods of accelerated graben subsidence or uplift relative to its flanks. As a result, two distinct stages of tectonic subsidence and one inversion in the Paleogene–Neogene evolution of the Szamotuły Graben have been distinguished. Thus, relatively significant subsidence occurred in the Early Oligocene and the middle Early–earliest Mid-Miocene, while slight inversion took place in the middle part of the Mid-Miocene.

Key words: Palaeozoic Platform; Polish Basin; Salt diapirism; Syn-sedimentary tectonics; Lignite compaction.

INTRODUCTION

The Szamotuły Graben forms part of a fault-related fold zone (Text-fig. 1). This regional-size tectonic zone is referred to in a great variety of ways in the geological literature. From the point of view of pre-Cenozoic tectonics, for example, it is referred to as the Drawno–Człopa–Szamotuły Zone (Leszczyński 2002); the Drawno–Człopa–Szamotuły salt structure system (Krzywiec 2006); the Drawno–Poznań Fold-and-Fault Belt (Żelaźniewicz *et al.* 2011); and the Grzęzno–Człopa–Szamotuły Zone (Leszczyński 2012). On the other hand, taking into consideration the Cenozoic tectonic activity, it may be referred to as the Poznań–Szamotuły Dislocation Zone (Deczkowski and Gajewska 1980; Kasiński 1984, 1985; Kwolek 2000; Widera 2004; Widera *et al.* 2004; Widera and Karman 2007) or the Poznań–Szamotuły Fault Zone (Text-fig. 1; Widera *et al.* 2008; Widera and Hałuszczak 2011).

We analyse herein the area between Szamotuły and Poznań where Paleogene–Neogene vertical movements were particularly marked, and therefore, the name of Poznań–Szamotuły Fault Zone will be used throughout this paper (Text-fig. 1). In contrast, the salt diapir, the Cenozoic graben and the lignite deposit filling it have the same locality name, that is, the Szamotuły salt structure (Krzywiec 2006), Szamotuły salt diapir (Rowan and Krzywiec 2014), Szamotuły Graben (Widera 2004, 2007, 2016a), and



Text-fig. 1. Location map of the Szamotuły Graben with reference to salt structures in central-western Poland. A – Main tectonic units in the vicinity of study area on geological map of Poland without Cenozoic cover (modified from Dadlez *et al.* 2000). B – Enlarged portion of Text-fig. 1A; note location of Text-figs 2 and 5. C – Interpretative sketch of Text-fig. 1B showing location of salt structures (diapirs and pillows) in the vicinity of the study area (modified from Dadlez and Marek 1998; Krzywiec 2006). D – Enlarged portion of Text-fig. 1C with bounding faults of the Szamotuły Graben (inferred in this paper) and location of the the Szamotuły lignite deposit (modified from Central Geological Database of Polish Geological Institute); black dots show the location of the boreholes >500 m deep

Szamotuły lignite deposit (Text-fig. 1C, D; Ciuk and Piwocki 1990; Piwocki and Kasiński 1994; Widera 2004, 2007, 2016a; Kasiński *et al.* 2006, 2009; Bielowicz and Kasiński 2014), respectively.

The Late Cretaceous evolution of the Szamotuły salt diapir is relatively well known (Rowan and Krzywiec 2014; Popiela 2018). In contrast, the Paleogene–Neogene tectonic development of the overlying Szamotuły Graben has so far only been the subject of preliminary investigations (Widera 2004). Therefore, this paper focuses on the presentation of the architecture of sediments that fill the Szamotuły Graben and the quantitative and semi-quantitative evaluation of the size of the vertical displacements. The results of such research should be expected to present a closer view of the reality of the geology, including the formation of peat/lignite seams and the tectonic development of the discussed area during the Paleogene–Neogene.

This study aims to: (1) provide evidence of the relationship between the sedimentary filling of the graben and the syn-sedimentary tectonic activity; (2) discuss the major stages of the Szamotuły Graben subsidence and inversion in the Paleogene and

Neogene; and (3) propose a conceptual model taking into account the epeirogenic, tectonic and compactional vertical movements of the depositional surface in the research area.

GEOLOGICAL SETTING

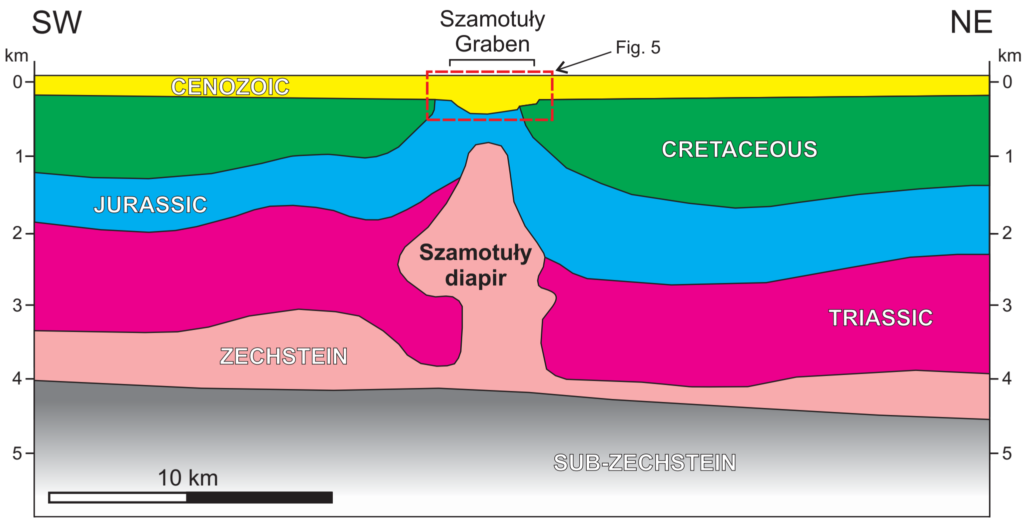
Outline of Permian and Mesozoic geology

The Szamotuły Graben is situated above the Szamotuły salt diapir (Krzywiec 2006; Rowan and Krzywiec 2014). This diapir is sourced entirely from Zechstein salt, which only partially pierces the Mesozoic overburden (Text-fig. 2). The study area covers the SW segment of the Mid-Polish Trough, belonging to the Polish Basin, which in turn is a part of the Permian–Mesozoic Central European Basin System (Ziegler 1990).

The SW segment of the Mid-Polish Trough, including the Szamotuły Graben, is located in the eastern part of the West European Palaeozoic Platform between the Bohemian Massif and the East European Craton (Pharaoh 1999; Dadlez 2006; Krzywiec 2006; Mazur et al. 2018). The Poznań–Szamotuły Fault Zone, with the Szamotuły Graben in its southernmost segment, that is, in the territory between Szamotuły, Oborniki and Poznań, extends obliquely to the Fore-Sudetic Monocline and Mid-Polish Swell. In fact, this a fault-related fold zone separates the Szczecin and Mogilno troughs (Text-fig. 1).

The Poznań–Szamotuły Fault Zone, like the entire Polish Basin, was subjected to thermal subsidence lasting at least from the Permian to the Late Cretaceous (Rowan and Krzywiec 2014). In this time interval there were several stages of accelerated subsidence in the area of the Polish Basin, the development of which ended with the Late Cretaceous–latest Eocene inversion (e.g., Deczkowski and Gajewska 1980; Dadlez *et al.* 1995; Leszczyński 2002; Stephenson *et al.* 2003; Dadlez 2006; Krzywiec 2006; Popiela 2018; and references therein). Subsequently, the Paleogene–Neogene development of the Szamotuły Graben commenced, which is the subject of this contribution.

Salt tectonic activity of the Szamotuły diapir began during the Early Triassic extension and continued intermittently until the Miocene (Rowan and Krzywiec 2014). Similarly, other salt structures with thick lignite seams above or close to them were developed in central Poland (e.g., Gotowała and Hałuszczak 2002; Widera 2007, 2016a; Kasiński *et al.* 2009). The Zechstein base (top of the Rotliegend) is located at a depth of over 4 km and is relatively flat (Text-fig. 2). In contrast, the Zechstein top lies at a depth between a few 100s m in the axial zone of the diapir and 3–4 km in its vicinity. The Mesozoic overburden is faulted and folded, creating an anticlinal architecture caused by the diapir uplifting. The salt body geometry is roughly vertical, but it is additionally characterised by some individual features that are described in detail by Rowan and Krzywiec (2014). The sub-Cenozoic surface over the Szamotuły diapir is built of strongly eroded Jurassic and Cretaceous rocks (cf. Text-figs 1 and 2).



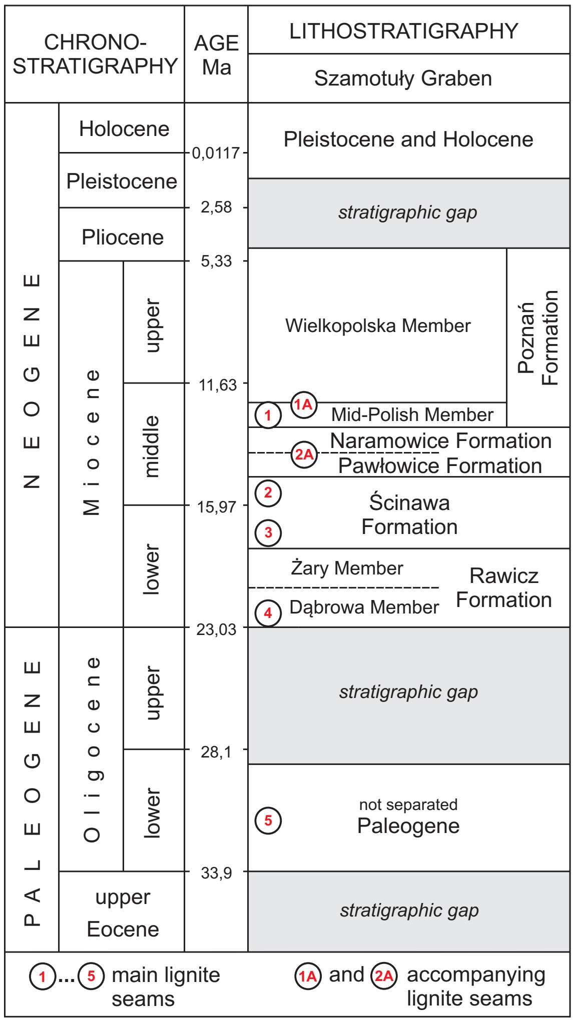
Text-fig. 2. Schematic cross-section through the Szamotuły diapir and its vicinity (based on deep boreholes and regional time-migrated seismic profiles data) showing the architecture of the Permian–Mesozoic sediments and the spatial dependence between the salt structure and the extensional graben in its Cenozoic overburden (modified from Krzywiec 2006; Rowan and Krzywiec 2014). Note, the cross-section presented in Text-fig. 5 is, in fact, located ca. 20 km to the SE from the sectional line shown in Text-fig. 2 (see Text-fig. 1B)

Outline of Paleogene and Neogene geology

During the pre-Quaternary Cenozoic, the study area covered a small portion of the eastern part of the North-West European Paleogene–Neogene Basin (Vinken 1988). In the time interval between the Late Cretaceous and the latest Eocene, the entire territory of central Poland was uplifted and eroded in conjunction with the significant inversion of the Mid-Polish Trough (Krzywiec 2006) and the uplift of basement blocks forming the Bohemian Massif of the Variscan orogeny age in the Alpine–Carpathian foreland (Lamarche *et al.* 2002; Ziegler and Dèzes 2007; Kley and Voigt 2008). In general, from the Early Oligocene to the earliest Pliocene, the discussed area (including the Szamotuły Graben) was characterised by regional, epeirogenic subsidence. An exception was the Late Oligocene, when the area of central Poland was again subjected to elevation and erosion (e.g., Deczkowski and Gajewska 1980; Karnkowski 1980; Kasiński 1984, 1985; Widera 2004, 2007; Widera *et al.* 2004, 2008; Widera and Hałuszczak 2011). This regional uplift was caused by a second minor phase of inversion, following that aforementioned dating from the Mesozoic/Cenozoic turn, which occurred in the Mid-Polish Trough area (Jarosiński *et al.* 2009).

In the Polish Lowlands territory, which constitutes the eastern part of the North-West European Paleogene–Neogene Basin, the lignite seams play a fundamental stratigraphic role mostly in the case of the Neogene (Piwocki and Ziembińska-Tworzydło 1997; Kasiński and Słodkowska 2016). Because lignite beds have a large spread in the European Lowlands they can be relatively easily correlated, for example, with those from the area of south-eastern Germany where the accompanying siliciclastic deposits are more precisely dated, among others, from microfauna and dinocysts (Standke *et al.* 1993; Grimm *et al.* 2002). Thus, for detailed correlation of the Paleogene and Neogene lithostratigraphic units between south-eastern Germany and central-western Poland, the reader is directed to the paper of Widera *et al.* (2008, p. 460).

The Cenozoic succession in the Szamotuły Graben and its vicinity begins with the Lower Oligocene glauconitic sands of marine origin (Widera and Kita 2007; Widera *et al.* 2008). These are only occasionally interbedded with terrestrial sediments including the 5th Czempiń (5th Lusatian) lignite seam; hence, they are not distinguished in this work (Text-fig. 3). Then, as mentioned above, there is a stratigraphic gap that covers the whole Upper Oligocene. The Neogene is composed of Miocene and lowermost



Text-fig. 3. Generalised stratigraphy of the Szamotuły Graben showing the approximate chronostratigraphic position of lithostratigraphic units and lignite seams. Numerical ages after Cohen *et al.* 2013. Lithostratigraphy modified from Piwocki and Ziembińska-Tworzydło 1997; Widera 2007; Widera *et al.* 2008. Main lignite seams: 5 – the 5th Czempiń, 4 – the 4th Dąbrowa, 3 – the 3rd Ścinawa, 2 – the 2nd Lusatian, 1 – the 1st Mid-Polish; accompanying lignite seams: 2A – 2And Lubin, 1A – 1Ast Oczkowice

Pliocene deposits. Due to the presence of lignite horizons, the Neogene is divided into numerous lithostratigraphic formations and members with four main and two accompanying lignite seams as shown in the generalised stratigraphic sketch (Text-fig. 3). Among them, the most important is the Ścinawa Formation (middle Lower Miocene–lower Mid-Miocene), which includes the 3rd Ścinawa (3rd Lusatian) and the 2nd Lusatian lignite seams. Their summarised thickness ranges from 20 m to almost 35 m in the axial zone of the graben, while on its flanks these lignites are usually less than 5 m thick. In the context of this research, the Mid-Polish Member of the Poznań Formation (middle portion of the Mid-Miocene) must be mentioned. This is due to the fact that the Mid-Polish Member also contains two lignite seams, that is, the 1st Mid-Polish (1st Lusatian) and the 1Ast Oczkowice, but this is significantly thinner than is in the case of those within the Ścinawa Formation (Text-fig. 3; Piwocki and Ziembińska-Tworzydło 1997; Widera 2004, 2007; Widera *et al.* 2008).

MATERIAL AND METHODS

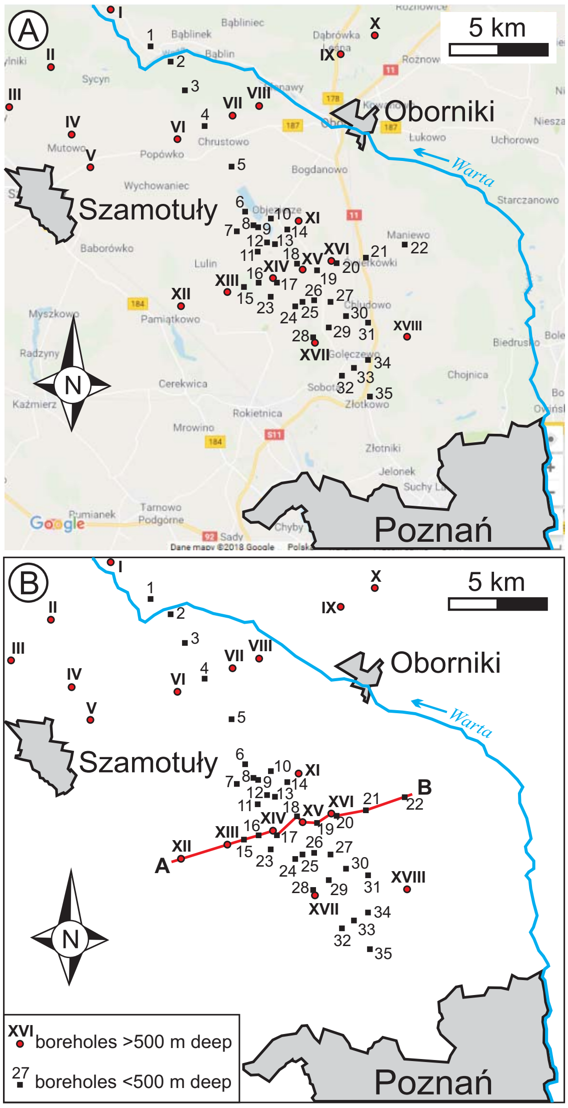
The results of the present study were obtained on the basis of the information contained in 18 deep (>500 m) and 35 shallow (<500 m) boreholes (Text-fig. 4; Table 1). The borehole data, above all the description of the rock lithology, allowed for the construction and interpretation of the geological cross-section as well as structural and isopach maps (Text-figs 5–7). All of these materials come from the National Geological Archive and Central Geological Database of the Polish Geological Institute – National Research Institute in Warsaw, Poland.

Cross-section

The cross-section through the widest and deepest part of the Szamotuły Graben shows the geology of the area under study, with sediment architecture and the location and type of brittle (i.e., faults) and ductile (i.e., folds and flexures) deformations (Text-fig. 5). This cross-section was made on the basis of data from 13 boreholes, that is, 8 with depth <500 m and 5 with depth >500 m. Furthermore, along the discussed cross-sectional line AB, calculations of the aggradation coefficient were made (Table 2). This coefficient determines the relative subsidence between the axial zone of the graben and its flanks (e.g., Kwolek 2000; Widera 2004, 2007; Widera *et al.* 2004, 2008). The calculation of the aggradation coefficient, taking into account compaction of deposits, is an important component of the main quantitative method used in palaeotectonic analysis, that is, the backstripping method (e.g., Van Hinte 1978; Michon *et al.* 2003; and references therein).

Structural and isopach maps

Two structural maps and three isopach maps are included in this contribution. In both cases, they illustrate bases and thickness variations of the most tectonically disturbed lithostratigraphic units, that is, the Paleogene (Lower Oligocene) and the Ścinawa Formation (Text-figs 6 and 7). Additionally, the thickness map of lignite within the Ścinawa Formation is attached due to the very important role that lignite compaction plays, creating the accommodation space and changing the architecture of the overlying sediments (e.g., Hager *et al.* 1981; Kasiński 1984, 1985; Diessel *et al.* 2000; Schäfer *et al.* 2005; Widera 2011,



Text-fig. 4. Location map of the boreholes and geological cross-section analysed in this paper. A – Location of the boreholes in the topographic background. B – Location of the boreholes and geological cross-section shown in Text-fig. 5 (compare with Text-fig. 1D and Table 1)

Boreholes <500 m deep					
Borehole numbering in this paper	Original numbering of the borehole	Borehole numbering in this paper	Original numbering of the borehole	Borehole numbering in this paper	Original numbering of the borehole
1	Kiszewo IA	13	Nieczajna 50	25	Zielątkowo 8/62
2	Dołęga 1	14	Kowalewko 9/62	26	Zielątkowo 52
3	Niemieczkowo 8/63	15	Żydowo 1/62	27	Zielątkowo 10/62
4	Sławienko 9/63	16	Nieczajna 21/63	28	Sobota 16
5	Chrustowo 12/63	17	Nieczajna 2/62	29	Zielątkowo 23/63
6	Ślepuchowo 16/63	18	Wargowo 13	30	Zielątkowo 17
7	Ślepuchowo 8	19	Wargowo 3/62	31	Chludowo 11/62
8	Ślepuchowo 7/62a	20	Wargowo 4/62	32	Sobota Ic
9	Ślepuchowo 7/62	21	Świerkówki 5/62	33	Golęczewo 18
10	Objezierze 9	22	Maniewo 6/62	34	Golęczewo 27/63
11	Nieczajna 49	23	Żydowo 12	35	Złotkowo 1b
12	Nieczajna 20/63	24	Sepno 51		
Boreholes >500 m deep					
I	Kiszewo Szamotuły Geo-23	VII	Uścikowo Geo-14	XIII	Przecław Szamotuły Geo-6
II	Obrzycko 2	VIII	Uścikowo Geo-9	XIV	Nieczajna Geo-5
III	Obrzycko 1	IX	Szamotuły Geo-10	XV	Szamotuły Geo-7
IV	Obrzycko 3	X	Rożnowo Geo-11	XVI	Wargowo Geo-4
V	Szamotuły Geo-15	XI	Objezierze IG-1	XVII	Golęczewo 1
VI	Niemieczkowo IG-1	XII	Przecław Szamotuły Geo-12	XVIII	Szamotuły Geo-20

Table. 1. List of boreholes with their original numeration used in this paper. Original numbering of the boreholes are derived from the National Geological Archive and Central Geological Database of the Polish Geological Institute – National Research Institute (Warsaw, Poland)

Lithostratigraphic units	Average thickness of deposits in the axial zone of the graben [m]	Average thickness of deposits on the graben flanks [m]	Aggradation coefficient [–]
	boreholes: 16, 17, 18, 19, 20, XIV, XV, XVI	boreholes: 15, 21, 22, XII, XIII	
Mid-Polish Member (Poznań Formation)	15.0	5.9	2.5
Pawłowice and Naramowice formations	24.8	23.8	~1.0
Ścinawa Formation	31.6	3.6	8.8
Rawicz Formation	38.6	41.0	~1.0
Paleogene (not separated)	61.8	29.3	2.1

Table. 2. Approximate values of the aggradation coefficient calculated along the cross-sectional line AB. Compare Text-figs 4B and 5

2013, 2015; Schäfer and Utescher 2014). These maps were made partly (due to the Cenozoic being poorly described) on the basis of information from 18 boreholes with a depth of >500 m, but mainly on the basis of data from 35 boreholes for lignite <500 m deep (Table 1).

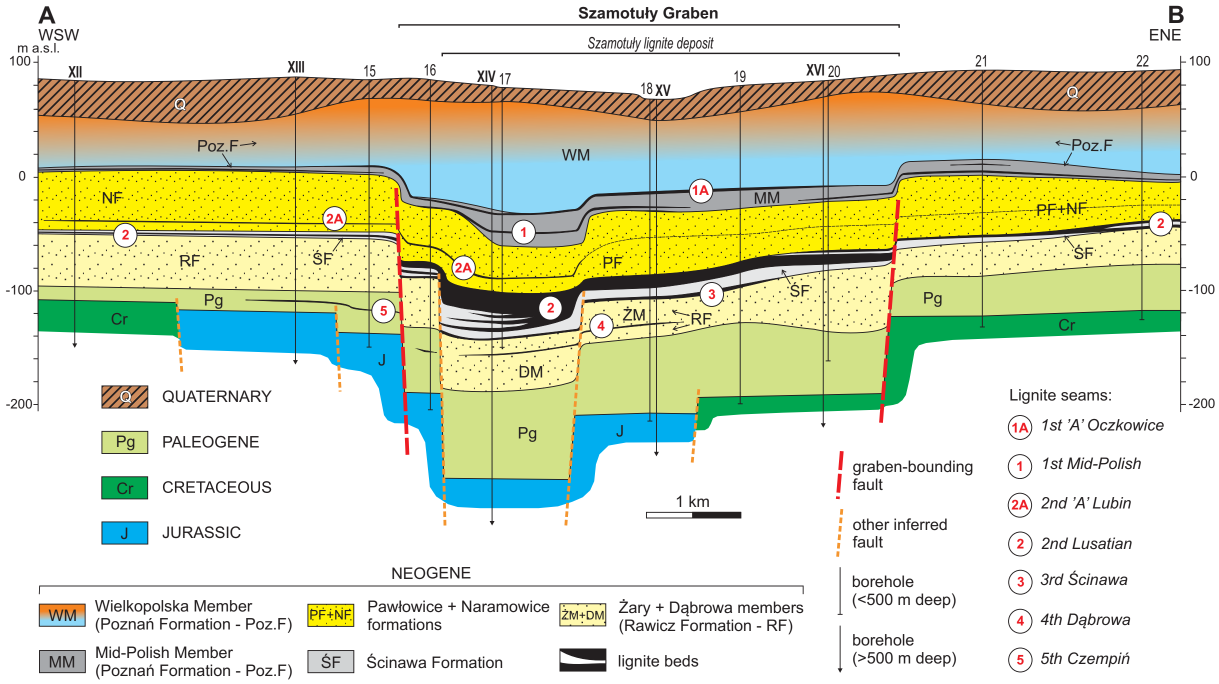
Thus, considering additional epeirogenic movements and the compaction of thick lignite seams, the stages of tectonic graben subsidence or inversion are distinguished in this paper. This is graphically illustrated in the conceptual model of the Paleogene–Neogene tectonic development of the Szamotuły Graben (Text-fig. 8).

RESULTS

Description of Paleogene and Neogene deposits

Geological cross-section

Due to the goal of the research, the described geological cross-section has been oriented in such a way that it covered both the axial parts of the Szamotuły Graben and its flanks. In fact, only the cross-sectional line AB meets the above conditions, where eight boreholes are in the graben and the remaining five boreholes are located outside of it (Text-fig. 5).



Text-fig. 5. Schematic cross-section through the Szamotuły Graben. Note, the lithostratigraphic and lignite seams nomenclature. Compare with a generalised stratigraphy shown in Text-fig. 3. For location of the cross-section line AB see Text-figs 1B and 4B

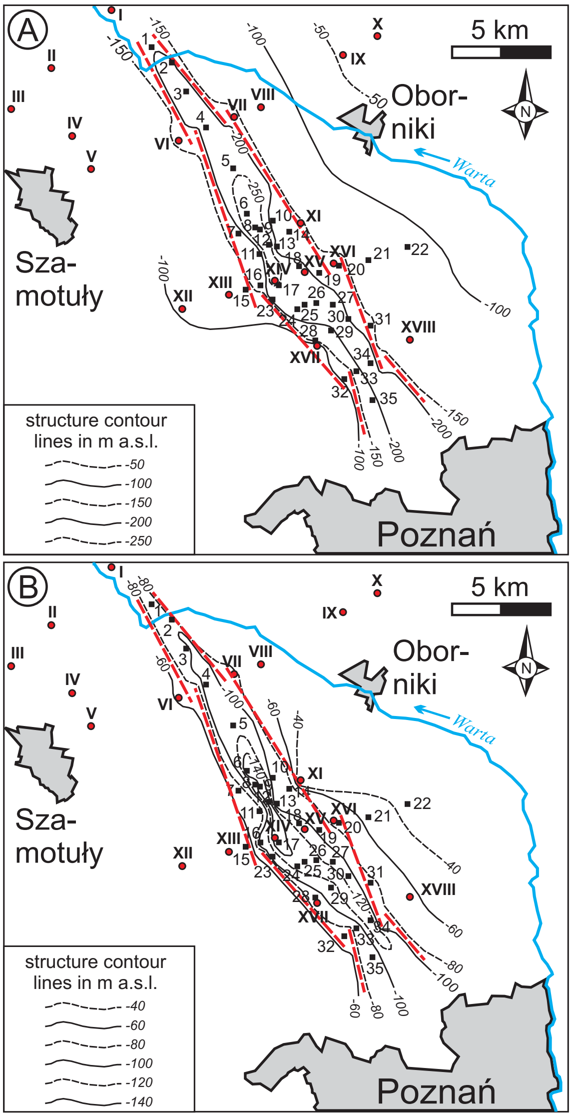
The cross-section generally shows the architecture and lithostratigraphy of the Paleogene and Neogene sediments. The Mesozoic top, both in the graben and in its surroundings, is built of strongly folded and faulted Jurassic and Cretaceous rocks. The difference in the height of their tops position, measured between the deepest parts of the extensional structure and its sides, is ~160 m, the value of which determines the maximum depth of the investigated Szamotuły Graben (cf. Text-figs 5–7).

The Lower Oligocene, described in this study as the Paleogene, is located directly on the Mesozoic bedrock. Sediments of this age are evidently thicker in the deepest zone of the graben than on its sides, especially on its western flank (Text-fig. 5). Above, rests the Neogene divided into several formations and members. Some of them are characterised by even thickness along the cross-section, that is, the Rawicz Formation as well as the Pawłowice and Naramowice formations, while others are much thicker in the deepest part of the graben, that is, the Ścinawa Formation and the Mid-Miocene Member. It is worth noting, due to the high susceptibility of the compaction process, that they are the most lignite-bearing lithostratigraphic units. In the case of the Ścinawa Formation, the maximum total thickness of lignite is ~35 m. The Neogene ends with the muddy Wielkopolska Member, which is strongly disturbed by Pleistocene erosion and glaciotectonics. Finally, there is the Quaternary cover (Text-fig. 5).

Structural maps

There are two structural contour maps for the bases of the Paleogene (= top of the Mesozoic) and Ścinawa Formation in this paper (Text-fig. 6). In contrast to the above-described cross-section, these maps show the summarised effects of all syn- and post-depositional vertical movements that affected the distinguished lithostratigraphic units (cf. Text-figs 5 and 6).

The depth of the Ścinawa Formation base lies at its deepest in borehole 12, in the central portion of the Szamotuły Graben, that is, at an altitude of less than 264 m b.s.l., while in the adjacent territory it is <100 m b.s.l. This palaeosurface, in the axial zone of the graben, decreases from <150 m b.s.l. in the most northern and southern segments to <264 m b.s.l. in the vicinity of the aforementioned borehole 12. In general, the base of the Paleogene (= top of



Text-fig. 6. Denivelations of the most tectonically deformed palaeosurfaces within the Szamotuły Graben. A – Structural map of the Paleogene base (= the top of the Mesozoic). B – Structural map of the Ścinawa Formation base (compare with Text-fig. 4 and Table 1). Inferred graben-bounding faults are marked as red dashed lines. For explanations of numbering see Table 1

the Mesozoic) is slightly inclined towards the west in the area surrounding this negative tectonic structure (Text-fig. 6A).

The base of the Ścinawa Formation has a similar shape to the Paleogene base, but the differences in the height of its position are smaller (cf. Text-fig. 6A and 6B). It lies deepest, that is, <140 m b.s.l., between boreholes 6, 12 and 17 (max. 148.5 m b.s.l. – borehole 17), which define the deepest, axial segments of the Szamotuły Graben. On the other hand, the characterised palaeosurface is located about 80–100 m higher on the graben flanks, that is, at an altitude of higher than 40–60 m b.s.l. (Text-fig. 6B).

Thickness maps

Isopach maps, in general, are the best graphic way to present the sizes of syn-depositional subsidence. However, other factors should also be carefully taken into account, for example, lignite compaction, in palaeotectonic analysis. Therefore, in addition to the thickness of the Paleogene and the Ścinawa Formation (Text-fig. 7A, B), a map of the total thickness of lignite in the most lignite-bearing lithostratigraphic unit, that is, just within the Ścinawa Formation, is presented in this research (Text-fig. 7C).

The thickness of the Paleogene in the Szamotuły Graben area is the greatest in borehole 6, where it reaches up to 92.5 m. In the adjacent territory, deposits of this age are less than 40 m thick (Text-fig. 7A). The thickness of the Ścinawa Formation ranges from <10 m on the graben flanks to more than 55 m in its axial zone. In this case, the greatest thickness of the discussed formation is in borehole 6, reaching 56 m (Text-fig. 7B). It is easy to see that the average thickness of Paleogene deposits is more than twice as high in the deepest parts of the Szamotuły Graben than outside it. In the case of the Ścinawa Formation, however, this proportion is in the range of 5–6. Furthermore, they differ significantly in various segments of the study area (Text-fig. 7A, B).

In general, the lignite thickness within the Ścinawa Formation ranges from less than 1 m on the graben sides to more than 30 m in its depocenters, marked by boreholes: 6, 8, 9, 12, XIV, 17 and 26. However, the greatest lignite thickness of 34.9 m occurs in borehole 8 in the central segment of the Szamotuły Graben (Text-fig. 7C). This means that in these boreholes, lignite (>30 m) covers 58–83% of the thickness of the entire Ścinawa Formation.

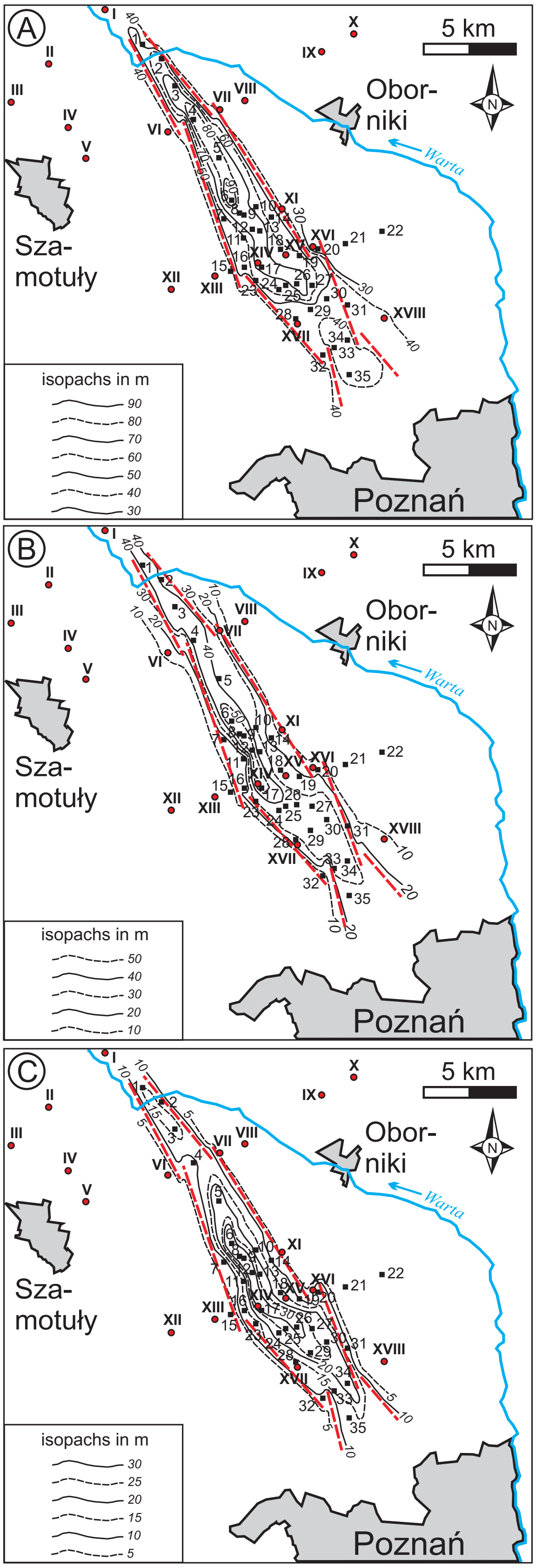
Stages of tectonic evolution

First stage of tectonic subsidence

The first stage of tectonic subsidence of the Szamotuły Graben took place between the latest Eocene and Early Oligocene. At that time, the Paleogene sediments, not separated in this paper, were deposited (cf. Text-figs 3 and 5). The initial vertical movements that lowered the axial parts of the graben in relation to its flanks commenced in the latest Eocene as evidenced by the deposits of this age at the base of Cenozoic succession (e.g., Widera 2004; Widera and Kita 2007). The accelerated subsidence continued throughout the Early Oligocene. At the end of this evolutionary stage, the graben and the entire central Poland territory were epeirogenically uplifted during the Late Oligocene (e.g., Deczkowski and Gajewska 1980; Karnkowski 1980; Widera 2007; Jarosiński *et al.* 2009; Widera and Hałuszczak 2011).

This deformational stage is perfectly marked on the geological cross-section as well as in the structural and isopach maps (Text-figs 5–7). This is confirmed by the much larger thickness of the Paleogene deposits in the axial parts of the Szamotuły Graben than on its flanks. Comparing the deepest parts of the graben (around boreholes 17 and XIV) with those on its western side (around boreholes XII and XIII) and on its eastern side (around holes 21 and 22), the thickness of the discussed sediments is from below 2 to up to 3–4 times smaller, averaging more than twice as that expressed by an aggradation coefficient of 2.1 along the cross-sectional line AB (Text-fig. 5; Table 2). During this extensional stage of subsidence, all faults (both the graben-bounded and other inferred faults) were tectonically active. However, vertical displacement of individual faults was not large, from a few to a maximum of 22 m between boreholes 16 and 17, and their total offset exceeded 30–50 m in various parts of the research area (Text-figs 5–7).

It should be noted that during the characterised first stage of subsidence, that is, in the Early Oligocene, the general outlines and orientation of the Szamotuły Graben were formed. In general, its shape as seen in map view is bounded by NNW–SSE-trending faults that were inherited from older, pre-Cenozoic discontinuities (Text-fig. 1C, D; Dadlez and Marek 1998). As shown in Text-figs 1C, D, 6, and 7 these comprise *en echelon* faults with overstepping segments, most likely forming relay ramps (*sensu* Peacock and Sanderson 1994). However, in the Neogene evolution of the extensional graben only some of these older faults, apparently originally developed in a (dextral?) strike-slip regime, were reactivated as normal or reverse faults.



Text-fig. 7. Thickness maps of the most syn-tectonically affected lithostratigraphic units and major lignite seams within the Szamotuły Graben. A – Isopach map of the Paleogene. B – Isopach map of the Ścinawa Formation with the thickest lignite seams. C – Isopach map of total lignite seams within the Ścinawa Formation (compare with Text-figs 4, 6 and Table 1). Inferred graben-bounding faults are marked as red dashed lines. For explanations of numbering see Table 1

Second stage of tectonic subsidence

Following the periods of the Late Oligocene uplift and the sedimentation of the Rawicz Formation in the tectonically quiescent conditions during the earliest Miocene, the second stage of the Szamotuły Graben development took place. This lasted from the middle part of the Early- to the earliest Mid-Miocene. In this time interval the Ścinawa Formation, with the 3rd Ścinawa and the 2nd Lusatian lignite seams, was deposited (cf. Text-figs 3 and 5). A total thickness of these seams often exceeds 20–30 m, reaching a maximum of ~35 m in borehole 8 (Text-figs 6, 7). Thus, for example, in this borehole, lignite accounts for approximately 66% of the thickness of the entire Ścinawa Formation, while the remaining 18 m are siliciclastic sediments.

In order to estimate the size of subsidence during the sedimentation of the Ścinawa Formation, lignite compaction should be taken into consideration. In other words, the original peat thickness before burial must first be reconstructed. The present thickness of the lignite seams examined should be multiplied by the compaction ratio, which for these seams and their stratigraphic equivalents is in the range of 2.5–3.0 (Hager *et al.* 1981; Kasiński 1984, 1985; Schäfer *et al.* 2005; Widera 2007, 2015; Schäfer and Utescher 2014). As a result, the estimated initial peat thickness was approximately in the range of 85.5–105.0 m; where 2.5 × 35 m = 87.5 m and 3.0 × 35 m = 105.0 m. Finally, the thickness of clastic interbeddings (~18 m) is added to the obtained values of peat thickness. Summarising, the maximum mire depth, which is equal to the size of a total (tectonic and epeirogenic) subsidence, was at this stage of the Szamotuły Graben development between 105.5 and 123.0 m. Because the thickness of the Ścinawa Formation in the graben neighbourhood is less than 10 m, with lignite layers below 5 m, the approximate sizes of epeirogenic and tectonic subsidence can be easily determined. Thus, the maximum epeirogenic lowering in the study area was <20 m, while the maximum tectonic lowering in the axial zone of the graben exceeded >85–100 m. Considering only the currently recorded thicknesses of the Ścinawa Formation along the cross-section (Text-fig. 5), even without taking into account the lignite compaction, the average values of the aggradation coefficient are as much as 8.8 (Table 2). In fact, at the end of deposition of these sediments, these values were at least twice as high as calculated above.

The comparison of structural and thickness maps for the Paleogene and Ścinawa Formation shows the parallelism of isolines (contour lines) and isopachs, respectively (Text-figs 6, 7). This is evidence that this Neogene deformational stage developed within the graben, bounded by the same faults, acting kinematically in a similar way irrespective of limited changes in the stress field orientation in which the previous Paleogene stage of subsidence took place. Therefore, the local direction of extension was in both cases close or slightly different from SSW–ENE-striking, that is, perpendicular to the graben elongation. With the end of the deposition of the lignite-rich Ścinawa Formation, the shape of the Szamotuły Graben was finally determined by the western and eastern master faults or fault zones, located between boreholes 15 and 16 as well as 20 and 21. However, the largest vertical displacements, with an offset of a few 10s m, had to be along the faults defining the deepest part of the graben, that is, in the vicinity of boreholes XIV and 17 (Text-fig. 5). Obviously, the total offset of all the faults equals the size of tectonic subsidence estimated above as 85–100 m.

Stage of tectonic inversion

In contrast to the aforementioned stages of tectonic subsidence, at the last stage of tectonic development of the Szamotuły Graben, its axial zone was elevated in relation to its flanks. This occurred in the middle part of the Mid-Miocene when the Pawłowice and Naramowice formations were deposited (cf. Text-figs 3 and 5).

Here, it must be clearly stated that the tectonic uplift cannot be quantified but only qualitatively defined. This is due to the fact that the original thickness of peat and the resulting current thickness of lignite are known, but the possible rate and the intermediate stages of peat transformation into lignite are not known. Therefore, it can only be convincingly concluded that the tectonic elevation size was approximately equal to the compaction size of the underlying sediments, mainly the thick beds of lignite within the Ścinawa Formation. This opinion is supported by the almost constant thickness of the Pawłowice and Naramowice formations along the examined cross-sectional line (Text-fig. 5; Table 2).

For a better understanding of this problem, it can be assumed, for example, that during deposition of these two formations (Pawłowice and Naramowice), the initial thickness of the underlying peat layers was reduced nearly twice. Based on the above calculations it could be up to 42.5–50 m, which would equal the tectonic uplift of the deepest parts of the Szamotuły Graben at this stage of its development. Then, the same faults were most likely active, but with an opposite direction in movement, as at the previous Neogene stage of intense subsidence. However, the question arises of what would have happened if this uplift did not take place. Obviously, the overlying sediments of the Pawłowice and Naramowice formations would have significantly greater thicknesses in the axial parts of the graben than on its flanks. Furthermore, the process of tectonic inversion justifies the high position of thick lignite seams, especially their floors, in the area of the Szamotuły Graben (Text-fig. 5).

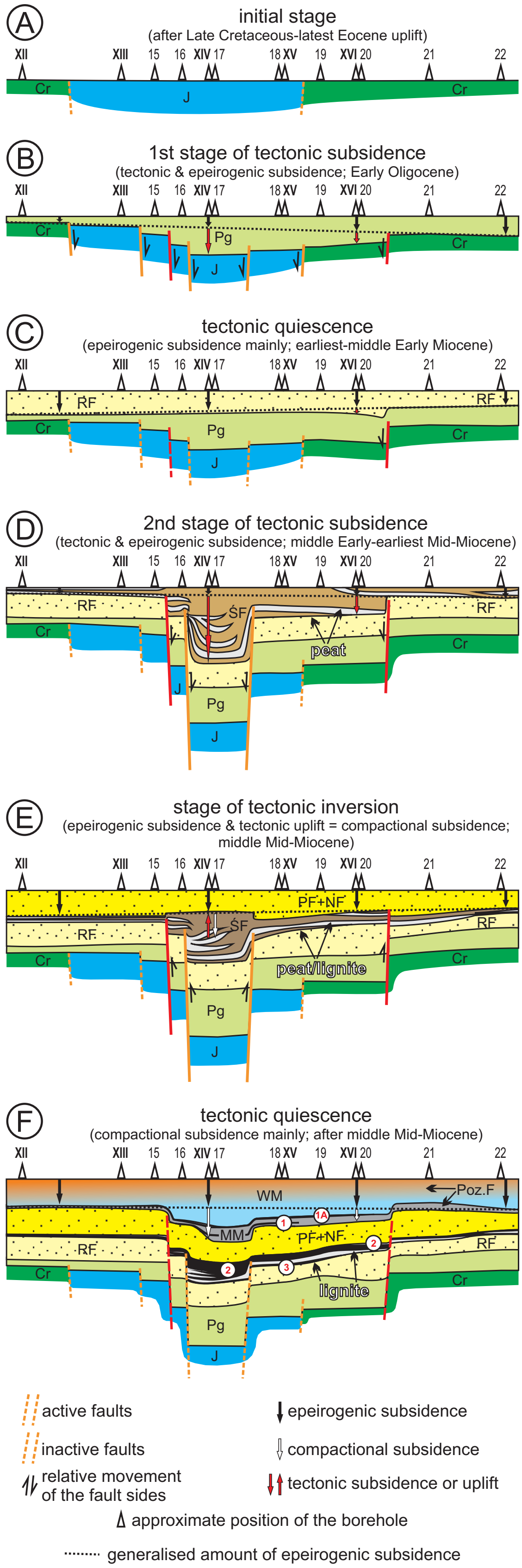
DISSCUSSION

Conceptual model of tectonic evolution

The information presented above, obtained during the implementation of this research, allows discussion of the Paleogene–Neogene tectonic evolution of the Szamotuły Graben, which is located in the overburden of the salt diapir. This extensional graben is additionally filled with rich lignite beds of Miocene age; hence, the Szamotuły lignite deposit was documented in the study area (cf. Text-figs 1C, D and 2). Thus, the conceptual model for the development of the examined tectonic structure can be proposed and discussed in this work (Text-fig. 8).

After the Late Cretaceous–latest Eocene uplift and erosion, the first stage of the Szamotuły Graben commenced. Then, the Paleogene sediments (Lower Oligocene) that are almost twice as thick were deposited in the axial zone of the graben compared to its surroundings. In this time interval both tectonic and epeirogenic vertical movements took place (cf. Text-fig. 8A, B and Table 2). The overlying Rawicz Formation was only deposited epeirogenically, that is, in the tectonic quiescent conditions. An exception may be the area between boreholes 20 and 21, where the thickness of clastic sediments on both sides of the fault is significantly different (Text-fig. 8C).

This was followed by the second stage of the largest subsidence, when the richest lignite seams were deposited. This accelerated tectonic subsidence, with a slight contribution of lowering epeirogenic movements, lasted between the middle part of the Early and the earliest Mid-Miocene. Despite the aggrada-



Text-fig. 8. Conceptual model showing the Paleogene–Neogene tectonic evolution of the Szamotuły Graben. Note, the stages of tectonic subsidence, quiescence and hardly visible inversion of the graben (compare with Text-fig. 5). The graben-bounding faults are indicated by red lines, while the other inferred faults are marked in orange tion coefficient of ~9 (Table 2), and considering the compaction of peat, the axial zone of the graben had to undergo tectonic subsidence up to several times more than on its flanks (Text-fig. 8D).

Shortly after the accelerated tectonic subsidence, the inversion of the deepest portion of the Szamotuły Graben occurred. This process of elevation was compensated by the compaction of peat. Therefore, the overlying deposits (Pawłowice and Naramowice formations combined) are characterised by an equal thickness both in the graben and in its close surroundings (cf. Text-figs 5, 8E and Table 2). Finally, the denivelations of the Mid-Polish and Wielkopolska members (Poznań Formation) may be explained by the progressive compaction of the underlying lignite-rich Ścinawa Formation. Hence, the next stage of tectonic subsidence in the research area has not been distinguished, although the compactional and epeirogenic subsidence of the depositional surface took place at that time (Text-fig. 8F).

Comparative analysis with other tectonically active areas

The same stages in the Paleogene–Neogene development of tectonic structures, as in the case of the Szamotuły Graben, are known in the Alpine-Carpathian foreland both in Poland and other countries. For example, at the turn of the latest Eocene/Early Oligocene, the Cenozoic evolution of most grabens filled with lignite in the Polish Lowlands commenced (e.g., Deczkowski and Gajewska 1980; Karnkowski 1980; Kasiński 1984, 1985; Widera 2004, 2007; Widera *et al.* 2004, 2008; Widera and Karman 2007; Widera and Hałuszczak 2011). Simultaneously, in the Polish part of the Carpathian Foredeep, the process of accelerated subsidence took place (e.g., Golonka *et al.* 2006, 2009; Jarosiński *et al.* 2009). At this stage of tectonic activity, rifting of grabens belonging to the European Cenozoic Rift System also started, extending from France across the Netherlands and Germany to the Czech Republic (e.g., Ziegler 1990; Michon *et al.* 2003; Schäfer *et al.* 2005; Ziegler and Dèzes 2007; Schäfer and Utescher 2014). In the latter case, the first negative tectonic movements marked in the territory of the Eger (Ohře) Graben in the Bohemian Massif (Rajchl *et al.* 2009; Matys Grygar *et al.* 2017), including its north-eastern segment, that is, the Polish part of the Zittau Basin (Kasiński *et al.* 2015).

In the time interval between the middle part of the Early and the earliest Mid-Miocene, pronounced development of the aforementioned areas of the European Lowlands occurred. Then, the thickest lignite deposits, representing the 3rd Ścinawa (3rd Lusatian) and the 2nd Lusatian lignite seams as well as their stratigraphic equivalents were deposited. The maximum total thickness of these lignite seams exceeds: >250 m in the Kleszczów Graben (e.g., Piwocki 1992; Widera and Hałuszczak 2011; Widera 2013); ~105 m in the Zittau Basin (e.g., Kasiński 2000; Widera 2016b), >100 m in the Lower the Rhine Graben (e.g., Hager *et al.* 1981; Michon *et al.* 2003; Schäfer *et al.* 2005; Schäfer and Utescher 2014); >85 m in the Lubstów Graben (e.g., Widera 2004, 2007, 2016b); and >50 m in the Most Basin (Eger Graben) (e.g., Rajchl *et al.* 2009; Matys Grygar *et al.* 2017). Thus, excluding the syn-sedimentary uplift and deposition of clastics, and considering a 2.5–3.0-fold compaction of peat, at this stage of development tectonic subsidence should be slightly over 100 m in the case of the Eger Graben and up to more than 700 m in the case of the Kleszczów Graben. However, the relatively low rank of lignite coalification does not indicate such a deep lowering of the basal parts of peat/lignite seams. Most likely, rising movements in the deepest parts of the grabens began at the time when the top layers of peat were still deposited (Widera 2013).

Paleogene–Neogene uplifting movements in the Alpine-Carpathian foreland, including the above-mentioned tectonic grabens, are widely known and accepted (e.g., Ziegler 1990; Michon *et al.* 2003; Ziegler and Dèzes 2007; Jarosiński *et al.* 2009; Matys Grygar *et al.* 2017). Subsequently, in the case of some grabens located in the Polish Lowlands, stages of their tectonic elevation are indicated, but only in a qualitative or semi-quantitative manner (e.g., Gotowała and Hałuszczak 2002; Widera 2004, 2007; Widera *et al.* 2004, 2007; Widera and Karman 2007; Widera and Hałuszczak 2011). The Lubstów Graben area is an exception here, where the size of the tectonic inversion has been quantified. It was estimated that the deepest portion of the graben was uplifted at least 100 m after sedimentation of the 2nd Lusatian lignite seam (Widera 2011), that is, more than twice as much as in the case of the extensional structure examined in this paper.

Finally, a lignite-rich deposit filling the Szamotuły Graben may be classified from various points of view. Taking into account the location and presence of salt diapir in deeper bedrock, it can be included within lignite deposits 'above a salt structure' (Kasiński *et al.* 2009). In the opinion of these researchers, this group belongs to the economically most important lignite deposits in Poland, subject to industrial exploitation, such as: Bełchatów, Szczerców, Lubstów, etc. On the other hand, the Szamotuły lignite deposit can also be classified genetically. Tectonic and epeirogenic processes coevally affected the study area, that is, the graben and its flanks. Therefore, this lignite deposit represents both the tectonic and epeirogenic genetic types of Polish lignite deposits (Widera 2016a).

CONCLUSIONS

The area of the Szamotuły Graben is relatively well recognised as a result of exploratory drilling for lignite. In the current paper, the Paleogene–Neogene tectonic evolution is presented not only qualitatively, but also quantitatively and/or semi-quantitatively for the first time. To reconstruct the graben evolutionary stages, the thickness of main lithostratigraphic units inside and outside the graben has been compared and calculated as an aggradation coefficient. Such research activities allowed us to distinguish at least two stages of tectonic subsidence and one inversion of the Szamotuły Graben during the Paleogene and Neogene.

The Szamotuły Graben commenced its Cenozoic development at the turn of the latest Eocene/Oligocene and lasted until the Early Oligocene. Following the period of regional elevation in the Late Oligocene and tectonic quiescent conditions during the earliest Miocene, the second stage of the largest subsidence of the Szamotuły Graben took place. Then, two of the thickest lignite seams were deposited between the middle part of the Early and the earliest Mid-Miocene. Shortly thereafter occurred an inversion process, which is confirmed by the even thickness of the overlying clastic deposits. The currently observed deformations of the youngest Neogene deposits, however, are connected to a progressive compaction of the underlying thick lignite beds. Thus, it can be convincingly stated that the area of the Szamotuły Graben was subjected to two distinct stages of tectonic subsidence and one stage of inversion.

Summarising, the present study can have both cognitive and practical significance in economic validation of lignite deposits, and also during their possible exploitation. Understanding the tectonic development of the lignite-bearing areas, including the Szamotuły Graben, can be helpful in predicting potential geological uncertainties such as interruptions in the continuation of lignite seams along faults and/or their steep inclination. This information is very important both when estimating the resources of lignite deposits and at the stage of planning their opencast mining.

Acknowledgements

We (especially MW) warmly thank Piotr Krzywiec (Polish Academy of Science) for inspiring discussions, including those numerous by e-mails, on the tectonic evolution of the Szamotuły diapir. Furthermore, the authors are greatly indebted to Marek Jarosiński (Polish Geological Institute – National Research Institute), an anonymous reviewer, and Piotr Łuczyński (University of Warsaw) for their constructive comments and editorial help, respectively. The current research was partially funded by the National Science Centre of Poland (Research Project No. 2017/27/B/ST10/00001).

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Manuscript submitted: 27th September 2018
Revised version accepted: 5th January 2019