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Factors controlling Cenozoic anthracogenesis in the Polish Lowlands

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The accumulation of large amounts of phytogenic matter, leading to the formation of lignite deposits of economic importance, has been determined by two groups of external factors: (a) climatic factors determining the indispensable production of organic matter and (b) geological factors allowing preservation of this matter in the sediment and its diagenetic transformation in the process of coalification. The overriding item among climatic factors was obviously the production of suitable amounts of phytogenic matter. It could be accumulated only under favourable vegetation conditions and therefore a warm and humid climate was a condition sine qua non for the intensive production of phytogenic matter. Problems of lignite origin do not generally relate to the lack of production of phytogenic material, but to preventing preservation in the sediment due to rapid oxidation of this material in very warm conditions. Therefore, the coal-forming process was constrained by two critical temperature values, which had to be neither too low nor too high, wherein sufficiently high humidity persisted throughout the process. Therefore, the range of mean annual temperature, which ensured favourable conditions for the growth and preservation of phytogenic matter, was from approx. 15.5 to 24°C. In the Cenozoic, such conditions commenced in the Early Oligocene and persisted up to the later Miocene – this was the interval of the most intense anthracogenesis in the Polish Lowlands. In the widespread lowland areas, lush swamp forests and peat fens developed, and thick lignite seams reflect the accumulation of phytogenic matter. This interval began with the cooling at the Eocene/Oligocene boundary and terminated at the beginning of the next cooling and drying phase known as that of the "C4 grassland" in the Late Miocene. Both the critical points are related to the surpassing of temperature limits: too high for the preservation of phytogenic deposits, and too low for the extensive development of lignite-forming vegetation. An important condition for the emergence of a large thickness of phytogenic sediments is primarily an existence of the accomodation space, where a considerable amount of plant matter might accumulate. This occurred only in conditions of dynamic equilibrium between the growth of plant matter and the lowering of the depositional surface, which ensured stabilization of the groundwater level. The rate of subsidence of the depositional surface must be balanced by the rate of vegetation growth. Therefore, no single lignite seam corresponding in age to the whole period of potential accumulation was formed at that time. Rather, a few lignite seams, separated by thick successions of mineral deposits, then formed. The vegetation of the wetlands which created the individual lignite seams was similar, this being mostly a facies element. Differences in the composition of vegetation are found mainly in plant communities outside peat-fens and it is the plants outside of the wetlands which allowed for subsequent dating of the lignite seams. The thermophilous vegetation was replaced by plants of lower thermal requirements during the progressive climate cooling towards the end of the Miocene. The ultimate cooling and completion of peat/lignite production was generated by the Middle Miocene uplift of the Carpathians arc in the Alpine orogeny. This natural barrier considerably limited the circulation of warm and humid air masses from the south to the Polish Lowlands area.

Key words: lignite, origin conditions, Paleogene/Neogene, Polish Lowlands.

INTRODUCTION

During the Paleogene and Neogene, the accumulation of large amounts of phytogenic matter took place in the extensive lowland areas of northern Europe from the Netherlands to Belarus and Ukraine. As a result, thick lignite seams developed, which are now commonly used as energy resources. The inflow of warm and humid air masses from the south, i.e. from the Paratethys area, provided a long interval of stable climate, over ca. 22 Myr, with fairly high temperature and significant humidity, contributing to the expansion of peat-forming vegetation. During the Paleogene and Neogene widespread peatlands developed, similar to peatlands recently known from the Gulf of Mexico and southeastern China. Their critical elements included lush mixed swamp forests, swamp shrubs and riparian deciduous forests (Fig. 1). Bulrush and sedge-moss peat-fens, and also subaqueous vegetation, played a secondary role in these ancient peatlands.

CHARACTERISTICS OF THE PALEOGENE/NEOGENE PEAT-FORMING PHYTOCOENOSIS

The reconstruction of vegetation that grew within the Paleogene and Neogene peat-forming basin and its surroundings is based on research into micro- and macrofloral remains, such as

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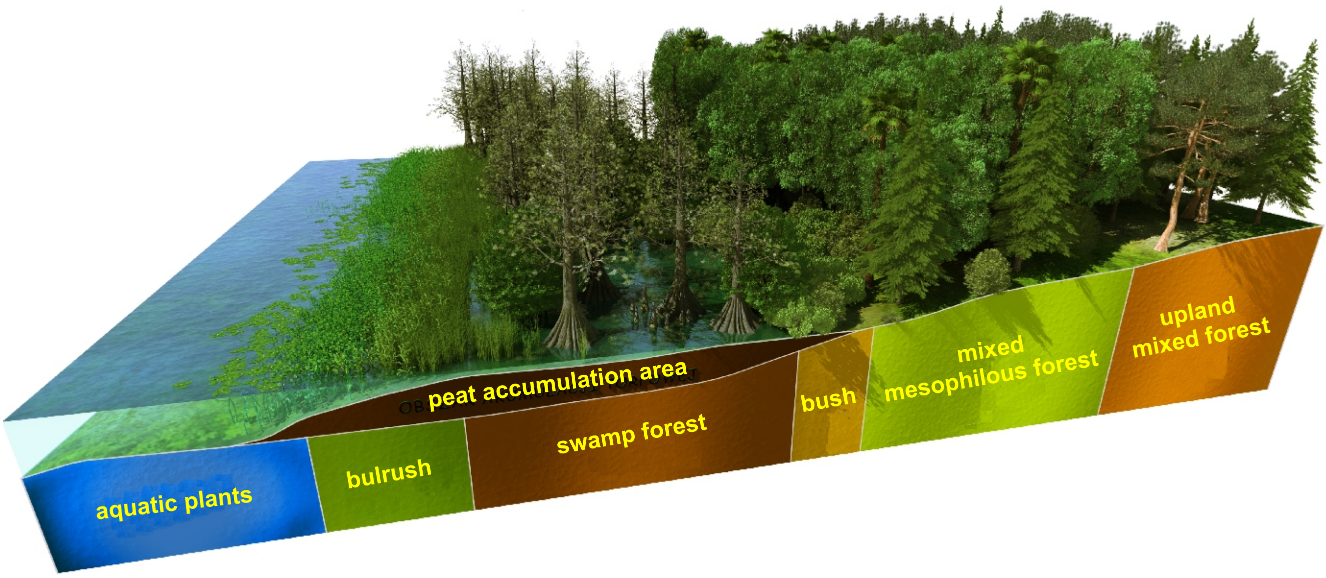


Fig. 1. Zonal variability of peat-forming vegetation in the Paleogene/Neogene peatlands

leaves, fruits, seeds, wood, or pollen grains and spores. The macrofloral remains are usually elements of the local vegetation that may be related directly to a peat-bog area. By contrast, the microfloral remains (pollen and spores) largely originated beyond the peat-bog and were transported there in two ways: lifted by wind and air currents or transported by rivers and streams. Pollen drops to the bottom of a lake or peat-bog and, to be able to be preserved in a fossil state, it must be covered by water. Fluctuations of the water table, especially periodical lowering, cause drying and oxidation of the accumulated pollen and prevent its preservation in the fossil record. For the reconstruction of the depositional environment, proper determination of pollen grains contained in the sediment and of their relationship to contemporary botanical vegetation are particularly important (Stuchlik et al., 2001, 2002, 2009, 2014). For the reconstruction of the depositional environment, the most significant factor is pollen derived from local vegetation growing in the direct vicinity of the peat-fen lake, and composing the main peat-forming biomass: swamp shrubs, bulrush and swamp forests (Fig. 1). Pollen deposited in water may also be derived from vegetation growing in areas located more distantly from the peat-fen margin, mainly from riparian forests and mixed mesophilous forests (Kasiński et al., 2010).

Swamp forests were a common element of the Paleogene and Early Neogene landscape of the Polish Lowlands. Marshes were mainly dominated by conifers such as *Glyptostrobus* (now occurring only in east Asia) and *Taxodium* (currently noted only in North America), accompanied by deciduous trees such as *Nyssa* and *Alnus*. In the undergrowth of the forest there was *Sphagnum* peat moss, Polypodiaceae and *Osmunda* ferns. *Betula, Cornus, Myrica, Fraxinus, Salix* and *Populus* also occurred. Warm-temperate elements included: *Ilex, Ficus, Liquidambar,* and representatives of the Tiliaceae and Lauraceae families. Another element of the peat-forming plant community was bulrush, which included: *Sparganium, Typha, Carex, Nymphea, Potamogeton, Butomus, Phragmites, Nuphar, Trapa*, grasses (Poaceae) and water ferns such as *Salvinia* and *Azolla*. An important element of the peat-fen was swamp shrubs including the Clethraceae, Cyrillaceae, Myricaceae, Ericaceae, and Salicaceae. Apart from wetlands, very diverse evergreen and deciduous mixed forests grew. They were dominated by plants with high temperature requirements, such as: *Mastixia, Aralia, Magnolia, Carya, Liriodendron, Liquidambar, Phellodendron, Sequoia, Sciadopitys, Cryptomeria, Ginkgo, Ficus*, lianas and ferns. These plants were similar to those growing today in warm-temperate and humid subtropical climates. The composition and mutual proportions of the plants of these forests record climate changes, mainly temperature and humidity oscillations.

The configuration of the wetland vegetation composing individual lignite seams is similar, because the fundamental taxonomic variability of the dominant part of the pollen spectrum, known as the facies element (Dyjor and Sadowska, 1977), is related to the plant environmental requirements. Thus, the contribution of individual taxa, although very variable in particular samples, and allowing for the assignment of lignite to different peat-fen zones, is statistically similar within all the lignite seams examined.

POSITION OF CENOZOIC LIGNITE IN THE STRATIGRAPHIC COLUMN

The most intense Cenozoic lignite production in Europe took place during the later part of the Early Oligocene and in the Miocene – in an interval demonstrating a fairly consistent character of the "new" flora. Changes in vegetation, in which the ancestors of recent flora began to dominate, took place earlier than the beginning of the Neogene, in fact already in the Oligocene, in an interval that corresponds to the "icehouse" climatic period that began in the Early Oligocene (Słodkowska and Kasiński, 2016).

As a result of rapid accumulation of phytogenic matter, a single thick lignite seam (with the exception of a few local appearances) that would encompass the period of intense anthracogenesis did not persist continuously throughout the entire Oligocene and Miocene. Rather, several thinner lignite seams, separated by less or more thick series of siliciclastic deposits, were formed. Thus, five main lignite seams occur in the succession of the Oligocene-Miocene sediments, covering the time interval from the Early Oligocene to the Middle Miocene (Fig. 2; Piwocki and Ziembińska-Tworzydło, 1997). These lignite seams are as follows:

– 5th Czempiń seam,

– 4th Dąbrowa seam,
– 3rd Ścinawa seam,
– 2nd Lusatian seam,
– 1st Mid-Polish seam.

However, the total thickness of lignite seams is significantly smaller than the thickness of the interbedded mineral deposits separating them within the Oligocene/Miocene succession. This is because lakes, swamps, marshes, and bogs are ephemeral bodies, relatively short-lived in geological time. Also a much higher compaction ratio of the phytogenic sediments in relation to mineral deposits (Hager et al., 1981; Hager, 1986) resulted in a post-depositional reduction of the lignite seams' thickness. The occurrence of alternating packets of lignite and mineral deposits records the dynamics of environmental change in a continental and brackish regime in relatively stable climatic conditions, continuously promoting the accumulation of lignite-forming matter.

Due to similar sedentary conditions of peat deposition in the distal part of the North Sea Basin, to which the Polish Lowland area belongs, the Neogene peat-forming communities consisted generally of similar plants. Differences in the pollen composition of subsequent lignite seams reflect the changing contribution of species from plant communities beyond the peatlands, mainly from mixed mesophilous forests and are also due to fluctuations of the groundwater level (von der Brelie and Wolf, 1981; Mosbrugger et al., 1994; Huhn et al., 1997). Species diversity of plant entomophilous pollen, particularly highly thermophilous species, is of diagnostic significance for the determination of climate conditions during subsequent lignite-forming cycles. The contribution of representatives of thermophilous flora gradually decreases in the younger seams in favour of plants of a temperate and drier climate, dominating in the latest Neogene. However, temperature and humidity were sufficient for the development of a rich peat-forming vegetation during the entire period of lignite sedimentation. Sporomorphs identified within individual lignite seams have been classified after Ziembińska-Tworzydło et al. (1994a, b) as palaeotropical, palaeofloristic elements (P1 – tropical and P2 – subtropical), and Arcto-Tertiary palaeofloristic elements (A1 – warm-temperate and A2 – temperate). The mutual proportions of these elements provide reliable palaeoclimatic information. On this basis, climatic conditions during the sedimentation of the lignite-forming peatlands have been determined (Table 1).

CHARACTERISTICS OF THE ECONOMICALLY SIGNIFICANT MAIN LIGNITE SEAMS

Differences in the vegetation composition occur mainly within the plant communities beyond the wetlands that comprise plants from the communities known as climate elements (Dyjor and Sadowska, 1977). They allow the stratigraphic position of the individual lignite seams to be distinguished (Słodkowska, 1998). In subsequent seams, thermophilic vegetation is systematically replaced by vegetation with lower thermal requirements (e.g., *Nyssa* → *Alnus* in the swamp forest community), resulting from gradual climate cooling towards the end of the Miocene.

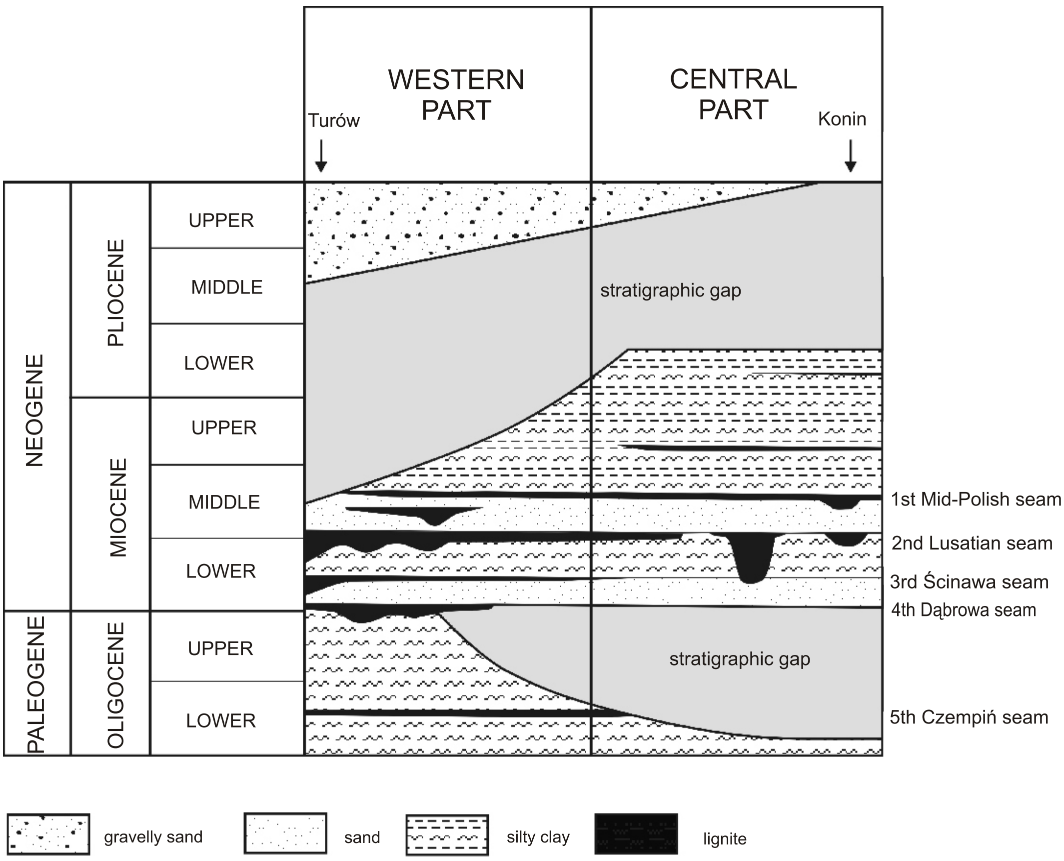


Fig. 2. Stratigraphic position of the Paleogene/Neogene lignite-forming cycles in the lignite-bearing basin of the Polish Lowlands (after Kasiński et al., 2010)

Table 1

Sporomorph taxonomic diversity in the lignite seams

Taxon	Botanical affinity	Palaeofloristic element	Lignite seams				
			1st	2nd	3rd	4th	5th
Spores							
Camarozonosporites heskemensis	Lycopodiaceae: *Lycopodiella*	*P*					+
Cicatricosisporites dorogensis	Schizaeaceae	*P1*					+
Concavisporites sp.	Gleicheniaceae?	*P*				+	
Leiotriletes sp.	Lygodiaceae	*P*		+		+	
Neogenisporis neogenicus	Gleicheniaceae, Cyatheaceae	*P2*		+	+		
Polypodiaceoisporites corrutoratus	Pteridaceae: *Pteris*	*P/A1*			+		
Stereisporites stereoides	Sphagnaceae: *Sphagnum*	*A1*	+				
Gymnosperms							
Cathayapollis sp.	Pinaceae: *Cathaya*	*A1*		+	+	+	
Cedripites sp.	Pinaceae: *Cedrus*	*A1*		+			
Cunninghamiaepollenites janinae	Taxodiaceae: *Cunninghamia*	*A1*		+		+	
Cunninghamiaepollenites lignitus	Taxodiaceae: *Cunninghamia*	*A1*		+			+
Distachyapites sp.	Ephedraceae: *Ephedra*	*A*	+				
Inaperturopollenites concedipites	Cupressaceae: *Taxodium*, *Glyptostrobus*	*P2/A1*				+	+
Inaperturopollenites dubius	Taxodiaceae	*A1*	+		+		+
Pinuspollenites sp.	Pinaceae: *Pinus sylvestris* type	*A*	+	+	+	+	+
Sciadopityspollenites sp.	Sciadopityaceae: *Sciadopitys*	*A1*		+	+	+	+
Sequoiapollenites sp.	Cupressaceae: *Sequoia*, *Sequoiadendron*, *Metasequoia*	*A1*	+	+	+	+	+
Zonalapollenites sp.	Pinaceae: *Tsuga*	*A*	+	+			
Angiosperms							
Araliaceoipollenites euphorii	Araliaceae: *Aralia cordata* type	*P/A1*		+			
Araliaceoipollenites reticuloides	Araliaceae: *Hedera helix* type	*A1*	+				
Arecipites parareolatus	Arecaceae	*P/A1*			+		
Arecipites pseudoconvexus	Arecaceae	*P2/A1*				+	
Boehlensipollis hohli	Elaeagnaceae, Lythraceae	*P2/A1*					+
Caprifolipites viburnoides	Adoxaceae: *Viburnum*	*P/A1*		+			
Celtipollenites bobrowskae	Ulmaceae: *Celtis sinensis* type	*A1*	+	+			
Cercidiphyllites minimireticulatus	Cercidiphyllaceae: *Ceridiphyllum*	*A1*		+	+		
Cornaceaepollis major	Cornaceae: *Cornus sanguinea* type	*P/A*		+			
Cornaceaepollis satzveyensis	Mastixiaceae	*P*				+	
Cupanieidites eucalyptoides	Myrtaceae?, Sapindaceae?	*P/A1*					+
Cupuliferoipollenites oviformis	Fagaceae: *Castanea*, *Castanopsis*, *Lithocarpus*	*P2/A1*			+	+	
Cupuliferoipollenites pusillus	Fagaceae: *Castanea*, *Castanopsis*, *Lithocarpus*	*P2/A1*		+	+	+	+
Cyrillaceaepollenites bruhlensis	Cyrillaceae, Clethraceae	*P*		+	+		+
Cyrillaceaepollenites megaexactus	Cyrillaceae, Clethraceae	*P*	+	+	+	+	+
Dicolpopollis kockeli	Arecaceae; Calamoideae: *Calamus, Metroxylon*	*P*			+	+	+
Dicolporopollenites middendorfii	unknown	*?*				+	+
Edmundipollis edmundii	Mastixiaceae, Cornaceae, Araliaceae	*P1*	+	+	+		
Ericipites sp.	Ericaceae	*P/A*	+	+			
Eucommioipollis sp.	Eucommiaceae: *Eucommia*	*A1*	+	+			
Faguspollenites sp.	Fagaceae: *Fagus*	*A*	+	+			
Fraxinipollis sp.	Oleaceae: *Fraxinus*	*P/A*	+	+	+		
Fususpollenites fusus	Fagaceae: *Trigonobalanus*	*P1*			+	+	+
Intratriporopollenites insculptus	Malvaceae: Tilioidae, Brownlowioideae	*P/A*				+	
Iteapollis angustiporatus	Iteaceae: *Itea*	*P*	+				
Liriodendroipollis verrucatus	Magnoliaceae: *Liriodendron*	*P2/A1*		+	+		
Magnoliaepollenites sp.	Magnoliaceae: *Magnolia*	*P/A1*		+	+		
Milfordia incerta	Restionaceae: *Hypolaena*, *Lepyrodia*	*P*		+	+		
Momipites punctatus	Juglandaceae: *Engelhardia*, *Alfaroa*, *Oreomunnea*	*P2*	+	+	+		
Momipites quietus	Juglandaceae: *Engelhardia*, *Alfaroa*, *Oreomunnea*	*P*					+
Monocolpopollenites tranquillus	Arecaceae: Arecoideae, Coryphoideae	*P*					+

Tab. 1 cont.

Taxon	Botanical affinity	Palaeofloristic element	Lignite seams				
			1st	2nd	3rd	4th	5th
Multiporopollenites maculosus	Juglandaceae: *Juglans sigillata* type	*P2*			+	+	
Myrtaceidites myrtiformis	Myrtaceae: *Myrtus, Callistemon*	*P/A1*			+		
Nyssapollenites sp.	Nyssaceae: *Nyssa*	*P/A1*	+	+	+		
Olaxipollis matthesii	Olacaceae: *Olax*	*P*				+	
Ostryapollenites rhenanus	Betulaceae: *Ostrya, Ostryopsis*	*A1*	+				
Parthenopollenites marcodurensis	Vitaceae: *Parthenocissus, Ampelopsis, Cayratia, Leea*	*P/A1*		+	+		
Periporopollenites stigmosus	Altingiaceae: *Liquidambar*	*A1*	+				
Platanipollis ipelensis	Platanaceae: *Platanus*	*P/A1*			+	+	
Platycaryapollenites miocaenicus	Juglandaceae: *Platycarya*	*A1*		+	+	+	
Polyartiopollenites sp.	Juglandaceae: *Pterocarya*	*A1*	+				
Quercoidites henrici	Fagaceae: *Quercus*	*P2/A1*	+	+	+		+
Quercoidites microhenrici	Fagaceae: *Quercus*	*P2/A1*		+	+	+	+
Quercopollenites sp.	Fagaceae: *Quercus*	*P2/A1*	+	+			
Reevesiapollis triangulus	Malvaceae; Helicteroideae, *Reevesia*	*P*	+	+	+		
Sapotaceoidaepollenites sp.	Sapotaceae	*P*			+	+	
Symplocoipollenites vestibulum	Symplocaceae: *Symplocos*	*P*		+	+		
Symplocospollenites rotundus	Symplocaceae: *Symplocos*	*P*		+	+		
Triatriopollenites rurensis	Myricaceae: *Myrica*	*P2/A*		+		+	
Tricolporopollenites dolium	unknown	*?*				+	+
Tricolporopollenites fallax	Fabaceae	*P/A*		+	+	+	
Tricolporopollenites liblarensis	Fabaceae	*P/A*	+	+	+	+	+
Tricolporopollenites pseudocingulum	Fagaceae?, Styracaceae?	*P/A*	+	+	+		
Tricolporopollenites quisqualis	Fabaceae	*P/A1*			+	+	+
Tricolporopollenites staresedloensis	Hamamelidaceae: *Parrotia, Distylium*	*P2*				+	
Tricolporopollenites villensis	Fagaceae?	*?*		+			+
Vitispollenites sp.	Vitaceae: *Vitis*	*P2/A1*	+			+	

5TH CZEMPIŃ SEAM (LOWER OLIGOCENE)

The 5th Czempiń lignite seam occurs in the form of two isolated patches across a limited area of western Poland, occupying a total area of ca. 7,700 km^2 (Fig. 3A). Its thickness is usually small and does not exceed 1 m. However, lignites of the 5th seam occur also in the overburden of many salt domes in the Polish Lowlands. As a result of synsedimentary salt outflow and/or of subrosion (i.e., salt karst) processes (Kasiński et al., 2009), this seam reaches a considerable thickness in depressions within the salt dome caps. In extreme cases (e.g., the Rogóźno and Wapno salt domes), its thickness may exceed 40 m (Kasiński and Saternus, 2010).

Lignites of the 5th Czempiń seam originated within isolated wetland basins, as shown by their limited extent and thickness (Fig. 3A). Vegetation surrounding the basins was very lush, dominated by the mesophilous mixed forest community. Plants with highly thermophilous requirements dominated: Fagaceae, Fabaceae, Myrtaceae, Eleagnaceae, and Arecaeae (Fig. 4). Marine phytoplankton indicates the paralic character of the swamp basin, with marine influence. The climate at that time, as reconstructed on the basis of plant composition, may be defined as very warm, almost subtropical.

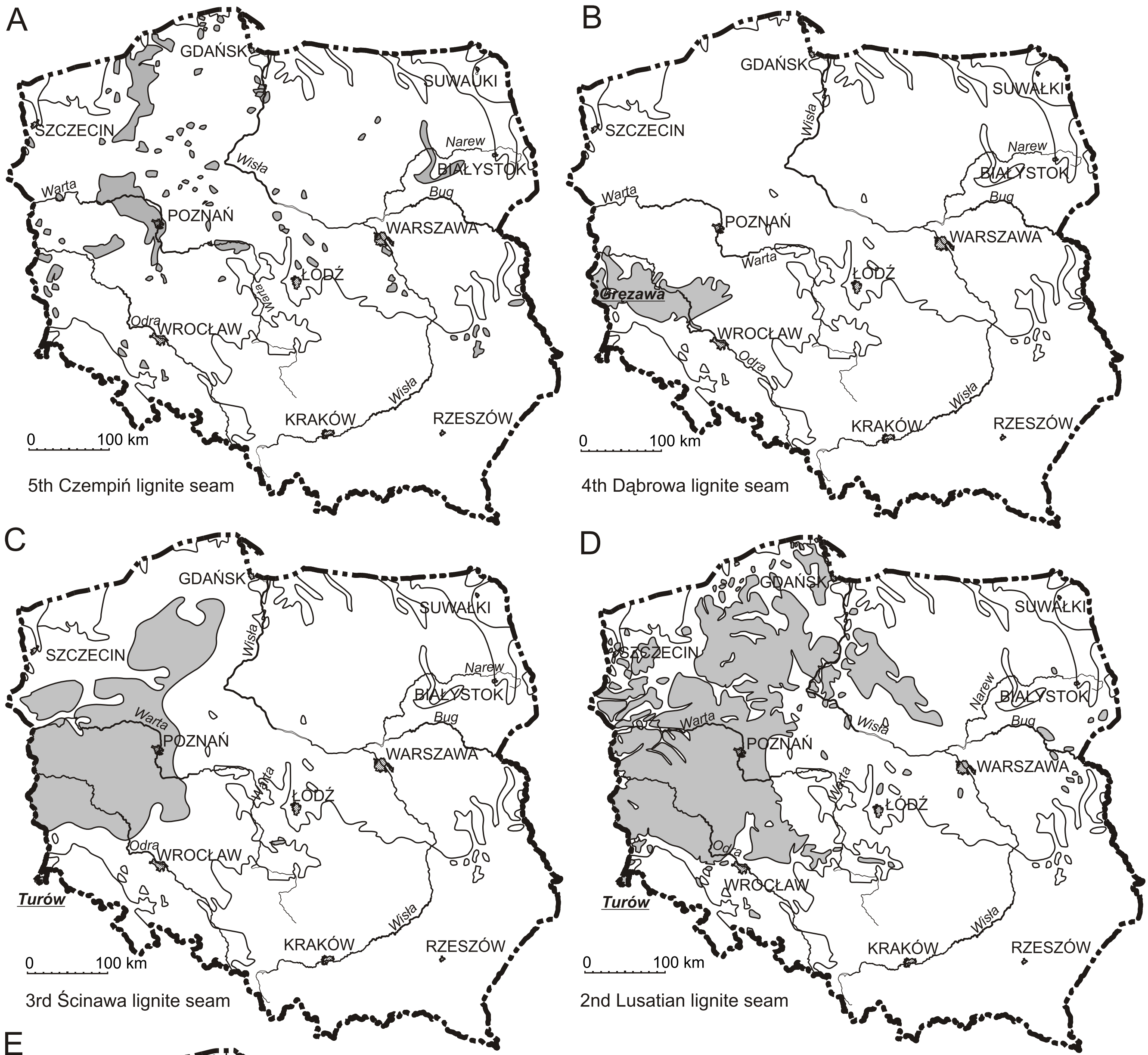
4TH DĄBROWA SEAM (LOWER MIOCENE)

The 4th Dąbrowa lignite seam occurs in southwestern Poland as one compact lobe covering an area of 7,000 km^2 (Fig. 3B; Piwocki, 1998). The seam reaches its greatest thickness in the Legnica-Ścinawa deposit, where it locally exceeds 30 m.

The 4th Dąbrowa seam, clearly recognized in western Poland, was formed in continental conditions in wetlands without marine influence. The rich vegetation was dominated by subtropical plant communities. Two prevalent types of plant communities alternated – peat-forming swamp bushes and mesophilous mixed forests with highly thermophilous plants. The alternation of plant communities was caused by hydrogeological changes – periodical oscillations of the groundwater table, favouring the progressive overgrowth of swamp bushes by a mesophilous forest. The spore-pollen assemblage in the 4th seam represents mainly plants that recently live in a humid subtropical climate (Fig. 5).

3RD ŚCINAWA SEAM (LOWER MIOCENE)

The 3rd Ścinawa lignite seam covers an area of about 30,000 km^2 in southwestern Poland (Fig. 3C; Piwocki, 1992). The seam is usually up to 35 m thick (e.g., Mosty and Ścinawa deposits) and it is much thicker only in the Kleszczów Tectonic Graben – Bełchatów lignite deposit. There, together with the 2nd Lusatian seam, it locally reaches up to 250 m (Piwocki, 1992; Kasiński et al., 2000). The 3rd seam has been fully recognized in the Zittau Basin, where models of sedimentation and of the peat-forming plant succession have been established (Kasiński, 1991, 2000; Kasiński and Ziembińska-Tworzydło, 1998; Kasiński et al., 2010).



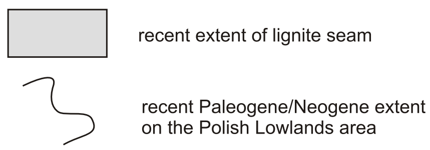


Fig. 3. Geographical extent of major lignite seams in the Polish Lowlands

A – 5th Czempiń seam (after Kasiński and Saternus, 2010); **B** – 4th Dąbrowa seam (after Piwocki, 1998); **C** – 3rd Ścinawa seam (after Piwocki et al., 2004, supplemented); **D** – 2nd Lusatian seam (after Piwocki, 1992); **E** – 1st Mid-Polish seam (after Piwocki, 1992)

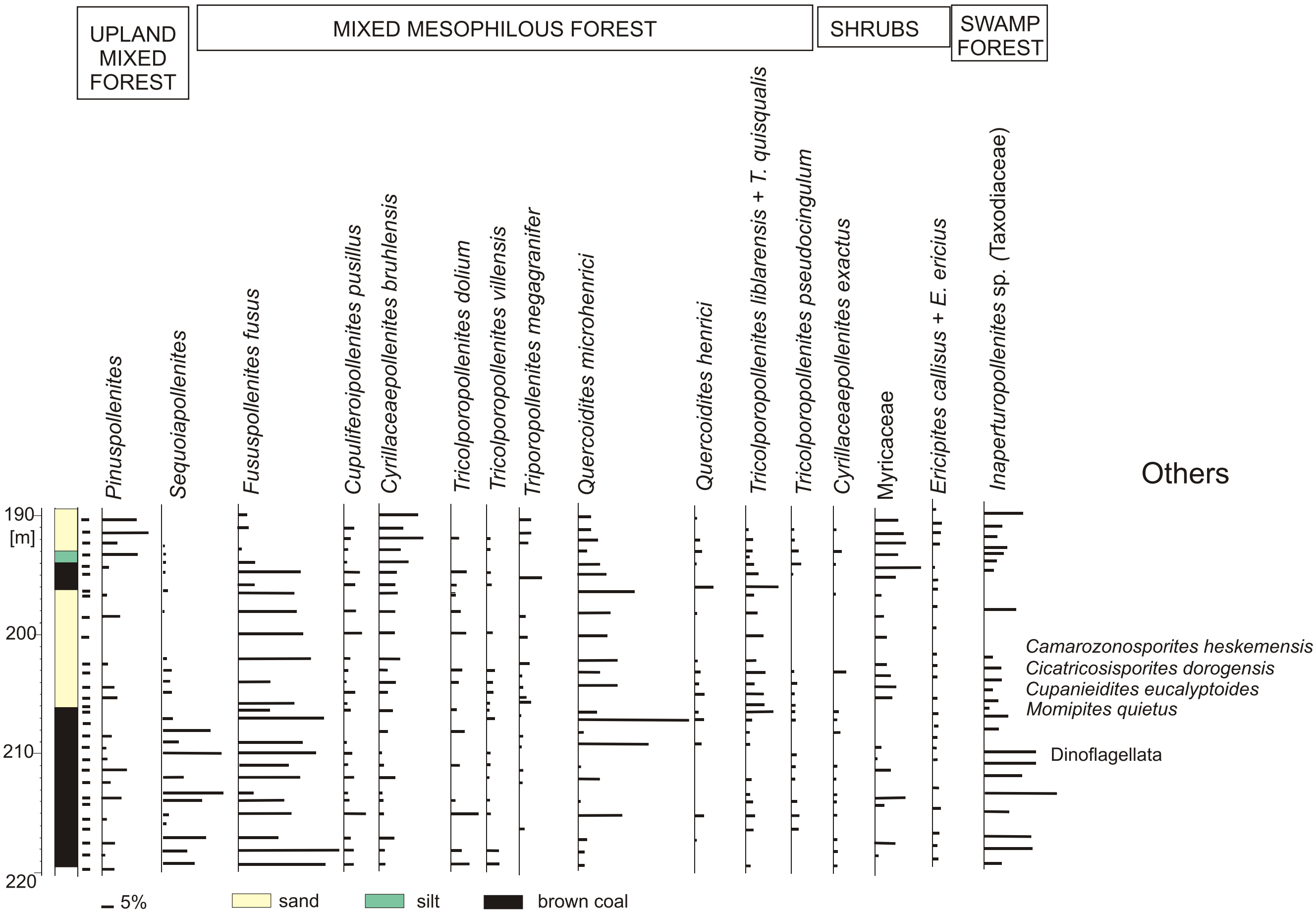


Fig. 4. Pollen diagram of the 5th Czempiń seam in the Warszyce 19 borehole (after Grabowska, 1969, modified)

Sedentation of peat of the 3rd lignite seam was dominated by highly thermophilous forest vegetation with taxonomically rich communities of a mixed mesophilous forest (Fig. 6). Warm-temperate flora had a lower contribution. A warm to subtropical climate prevailed. The origin of the 3rd seam is related to the Middle Miocene climate optimum (cf. Słodkowska and Kasiński, 2016: fig. 9). Accumulation of the peat-forming plant material took place within three different habitats: subaqueous peat-fens, swamp forests and swamp bushes. A reduced humidity then was not favourable for the development of extensive marshes. This is reflected by the smaller thickness and compactness of the seams, although the reasons in this case may also be different, such as lack of accommodation space. A few marine ingressions expressed by the presence of marine phytoplankton have been noted in western Poland at that time (Słodkowska, 2014).

2ND LUSATIAN SEAM (MIDDLE MIOCENE)

The 2nd Lusatian lignite seam occurs across an area of ca. 61,000 km^2 in southwestern and central Poland (Fig. 3D; Piwocki, 1992). The seam is usually up to 40 m thick (Czempiń, Gostyń, Krzywiń, Mosina, Naramowice, Radomierzyce and Szamotuły lignite deposits) and locally reaches up to 250 m within the Kleszczów Graben – the Bełchatów lignite deposit, where it occurs together with the 3rd Ścinawa seam. The 2nd Lusatian lignite seam is also an important correlation horizon, which can be traced across a large area of the Polish Lowlands.

Lignites of the 2nd Lusatian seam originated in limnothelmatic conditions. Marine influence was evident only within the peatlands of western Poland. A very rich pollen spectrum of a mixed mesophilous forest, where subtropical elements are common, is a factor characteristic of this seam (Appendix 1*). High temperature and humidity favoured the lush development of swamp forest communities, usually with *Taxodium*, *Glyptostrobus*, *Nyssa* and a small content of *Alnus*. Warm-temperate taxa in the 2nd lignite seam are more frequent than in the 3rd lignite seam. They are an important addition within a mixed mesophilous forest. Swamp forest and swamp bush communities predominated in the peat-forming vegetation. A warm temperate to subtropical climate prevailed at that time. The large thickness and compactness of the seams points to the high humidity that promoted the development of widespread wetlands.

1ST MID-POLISH SEAM (MIDDLE MIOCENE)

The 1st Mid-Polish lignite seam occurs across an area of ca. 70,000 km^2 in western and central Poland (Fig. 3E; Piwocki,

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1321

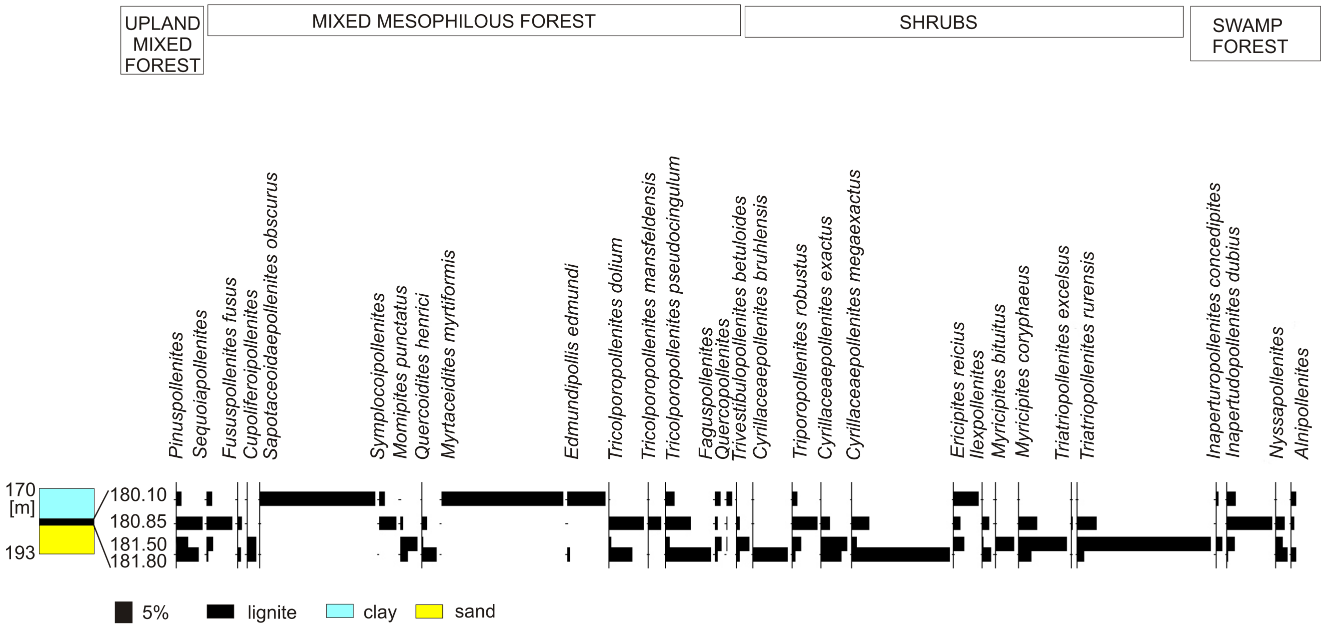


Fig. 5. Pollen diagram of the 4th Dąbrowa seam in the Gręzawa 28 B-bis borehole

1992). This seam is up to 20 m thick in the deposits of the Konin region. The 1st Mid-Polish lignite seam is also an important correlation horizon throughout much of the Polish Lowlands.

Lignites of the 1st Mid-Polish seam formed in continental conditions within swamps and backwaters developed within extensive alluvial plains. Marine influences was evident only within limited areas of western Poland. The plant composition of the mixed mesophilous forest of the 1st seam became progressively depleted in components with high thermal requirements, whereas the significance of riparian forest communities with common warm-temperate plants increased (Fig. 7). Pollen of plants of the cold-temperate climate became progressively more numerous. During the time of the 1st seam sedentation a warm-temperate climate with high humidity prevailed, favourable for the development of extensive marshes, as shown by the fairly uniform character of the lignite seams.

CLIMATE CHANGE – RECORD IN THE LIGNITE-BEARING STRATA WITHIN A CONTEXT OF OCEAN WATER AVERAGE TEMPERATURE

The Early Oligocene anthracogenic period began after the climatic cooling at the Eocene/Oligocene boundary (Pearson et al., 2009). Its termination is associated with climate cooling and aridisation known as the "C4 grassland event" in the Late Miocene (Fig. 8). During 8–4 Ma, the groundwater level changed, which was probably related to the tectonic reshaping of the Carpathians. A decline in the atmospheric CO_2 content below the threshold value occurred also as an effect of the growth of ice sheets in the Northern Hemisphere. As a result, expansion of plants of the C4 photosynthesis type began at that time. Growing seasonality and progressive aridisation caused a lower density of the forest cover and the transition from forest to grassland (Edwards et al., 2010; Singh et al., 2013). After this global ecological event, extensive peat-forming wetlands no longer developed in the European Lowland areas (Osborne, 2008).

During the Early Paleogene, before the cooling at the Eocene/Oligocene boundary, only a few significant lignite occurrences, i.e. Geiseltal (Haubald, 1989; Wilde and Hellmund, 2010) and Helmstedt (Lietzow et al., 1990; Lenz and Riegel, 2001; Riegel et al., 2015) are known in the European Lowlands. Throughout the entire EECO there were perfect conditions for phytogenic matter production: high temperature, i.e. higher than during the main anthracogenic period, and substantial humidity. However, the problem of lignite origin in this case does not refer to the lack of the possibility of production of the phytogenic material, but to the lack of possibility of its preservation in the sediment. This was due to rapid oxidation of this material, already deposited at the surface and in the upper layers of the sediment, in high temperature conditions. In fact, the oxidation rate of phytogenic matter deposited in the soil exponentially increases with rising temperature as shown by experiments (Davidson and Janssens, 2006). Therefore, the lignite-forming process was in most cases constrained by two critical temperature values. Temperatures have to be neither too low nor too high, while high humidity is required during the time of the process (Fig. 9).

Assuming the formation of the 5th Czempiń lignite seam as the beginning of extensive lignite deposition (initial stage) in the Polish Lowlands, and the formation of the 1st Mid-Polish seam as its termination (final stage), the range of mean annual temperatures of these two stages can be determined. Accordingly, the composition of vegetation, reconstructed on the basis of the sporomorph content, was analysed for the seams corresponding to these stages. The coexistence approach method, CA method, was used for the reconstruction of the thermal requirements of fossil taxa (Mosbrugger and Utescher, 1997). This method refers fossil taxa to their nearest living relatives (NLRs) and determines the range of various climate variables, in this case mean annual temperature, in which the contemporary equivalents exist. The range of favourable temperatures for the recent representatives of fossil genera and species of both stages was determined us-

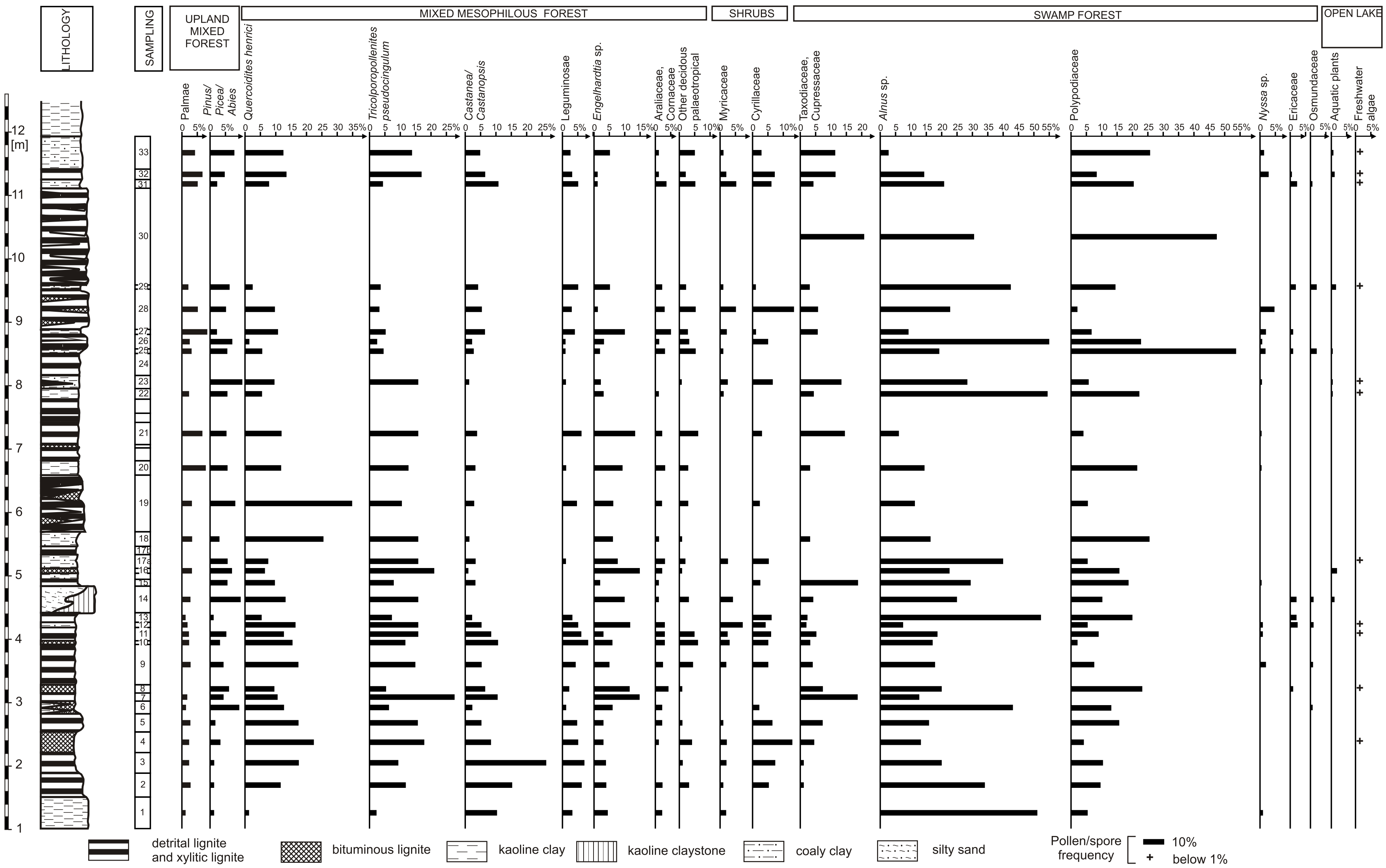


Fig. 6. Pollen diagram of the 3rd Ścinawa seam in the "Turów I" open-pit of the Turów Lignite Mine (after Kasiński et al., 2010, modified)

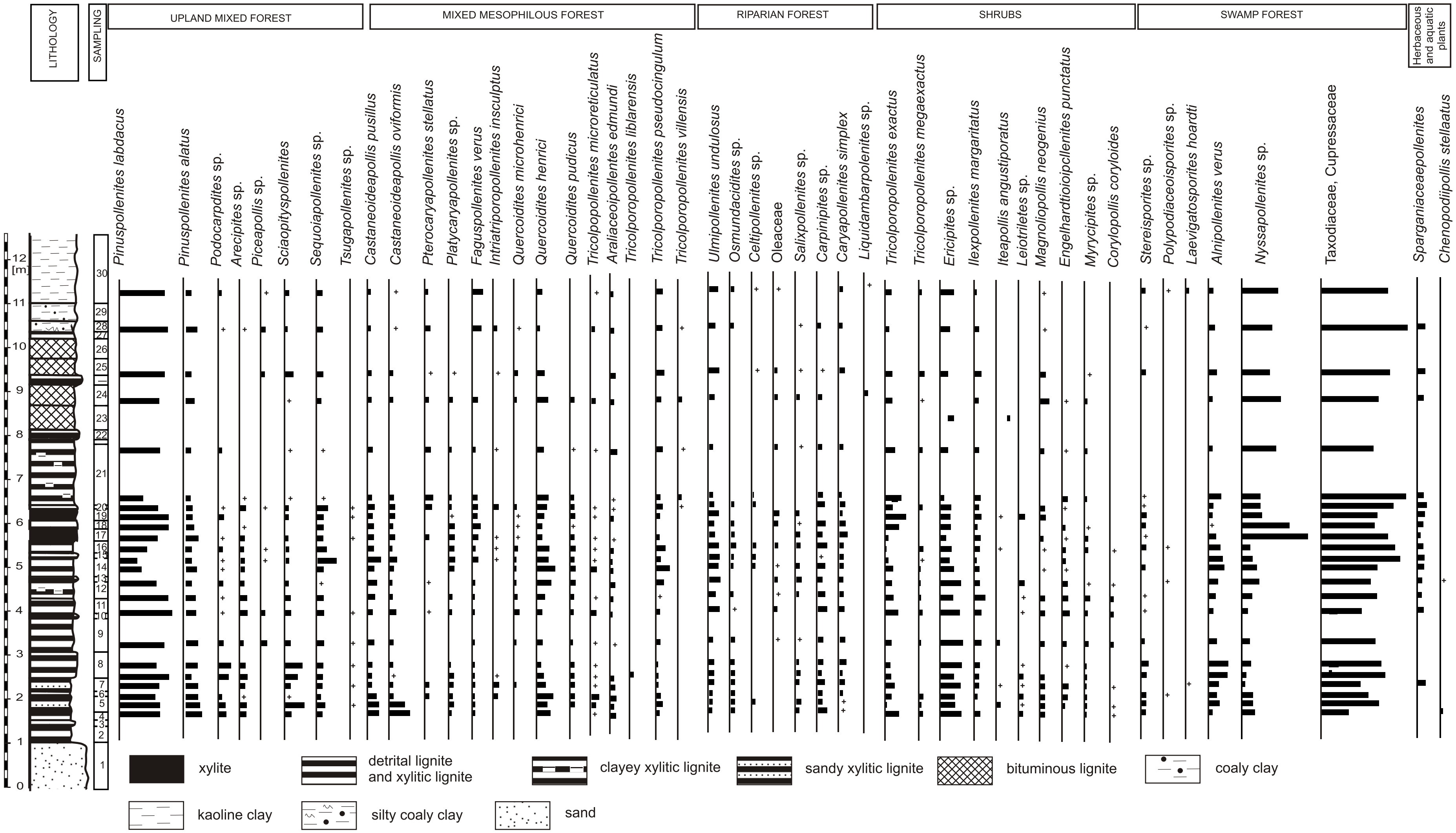


Fig. 7. Pollen diagram of the 1st Mid-Polish seam in the "Jóźwin" open-pit of the Konin Lignite Mine (afer Kasiński et al., 2010, modified)

For other explanations see Figure 6

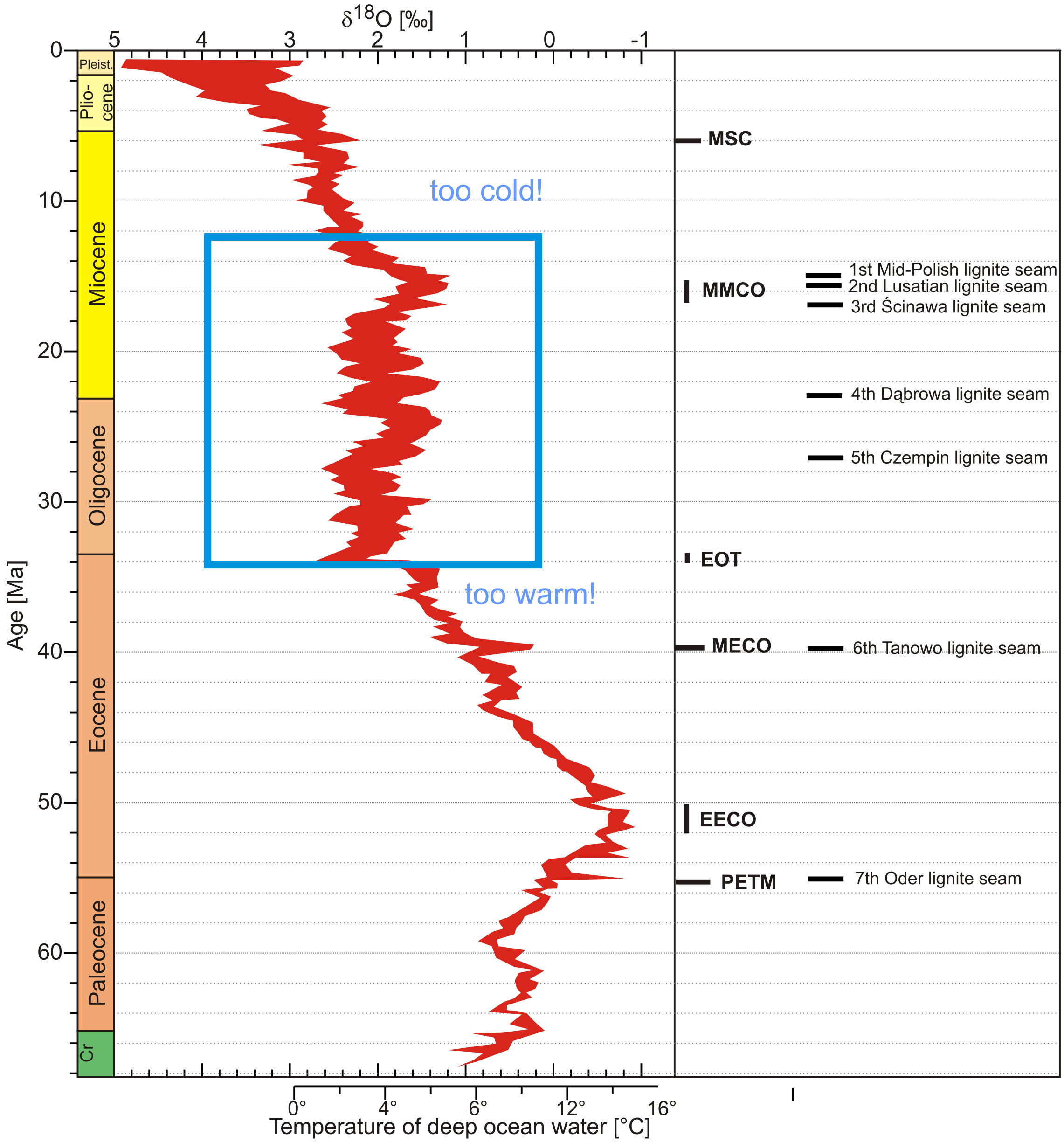


Fig. 8. Periods of increased lignite formation within the context of Cenozoic changes in global marine temperature (oxygen isotope curves after Zachos et al., 2001, 2008)

EECO – Early Eocene Climatic Optimum, EOT – Eocene-Oligocene Transition, MECO – Mid-Eocene Climatic Optimum, MMCO – Mid-Miocene Climatic Optimum, MSC – Messinian Salinity Crisis, PETM – Paleocene-Eocene Termal Maximum

ing the Palaeoflora Database (Figs. 9 and 10; Utescher and Mosbrugger, 2016). For the initial stage of extensive lignite formation (5th Czempiń seam) the temperature is in the range of 17.2–23.9°C, and for the final stage (1st Mid-Polish seam) the temperature is in a slightly lower range of 15.7–19.7°C. Therefore, the range of mean annual temperature, which ensured favourable conditions for the growth and preservation of phytogenic matter, was from about 15.5 to 24°C. Climate conditions prevailing during that time, particularly temperature and humidity, may be related to the recent conditions after the sub-division of Köppen (Köppen, 1900 *fide* Kottek et al., 2006). They correspond to a humid subtropical climate (Cfa type) characterized by hot, usually humid summers and mild winters.

This type of climate currently dominates in the southeastern margins of some continents, such as the southeastern United States, southeastern China, southern Brazil and eastern Australia (Tables 2 and 3).

Such conditions existed during almost the entire period after the cooling at the beginning of the Oligocene (EOT) up to the cooling and substantial drying (C4) in the Late Miocene. At that time, the climatic conditions favoured intense growth of peat-forming vegetation and climate changes did not bring major obstacles to the anthracogenic processes. However, the lignite seams, widely developed in the lowland areas of Europe with a few local exceptions, such as the main lignite seam in the Lower Rhine embayment (Zadwijn and Hager, 1987; Hager, 1993; Schaefer and Utescher, 2014), or the Kleszczów Graben (Kasiński et al., 2000; Piwocki et al., 2004), which correspond to longer stratigraphic intervals) generally do not exist in the form of a single continuous seam corresponding to the whole of the Oligocene and Miocene time (cf. Figs. 2 and 8).

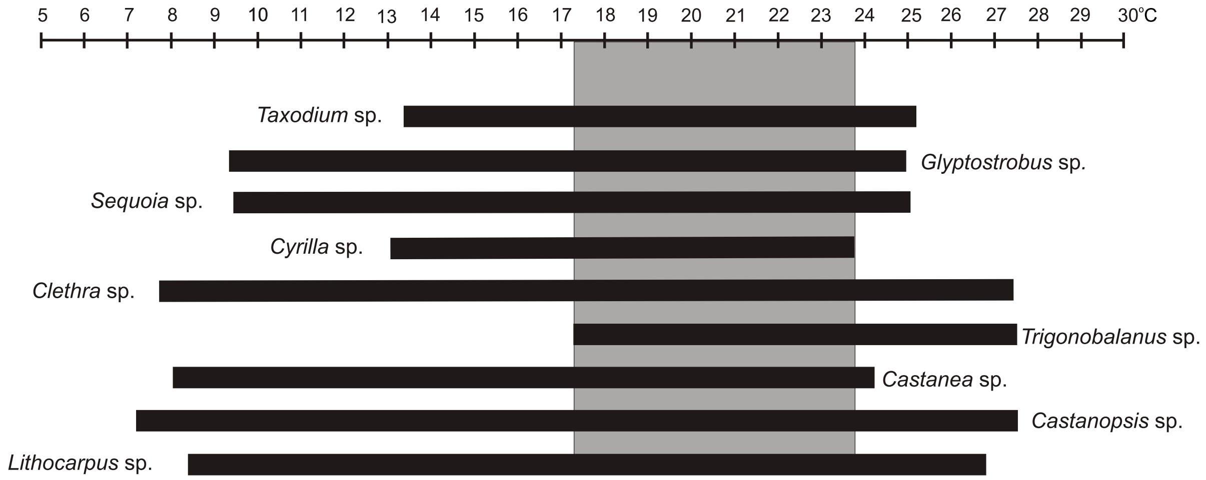


Fig. 9. Mean annual temperature of nearest living relatives (NLRs) based on fossil pollen from the 5th Czempiń lignite seam (after Utescher and Mosbrugger, 2016)

FACTORS CONTROLLING THE PERIODIC CHARACTER OF PHYTOGENIC ACCUMULATION (SEDENTATION)

The accumulation of significant amounts of phytogenic matter, leading to the formation of lignite seams of economic importance, was finally divided into two groups of external factors:

a) climate factors determining the necessary production of phytogenic matter and its preservation in the interval prior to coalification,

b) geodynamic factors controlling the possibility of preservation of phytogenic matter within the sediment and its transformation from peat into lignite during coalification.

The primary role of climate factors is obvious. Sufficient phytogenic matter can be produced only under conditions favourable for vegetation and, therefore, a warm and humid climate is a sine qua non for the extensive production of phytogenic matter. Moreover, climate factors define the time limits (the beginning and end) of extensive anthracogenic processes.

Sedimentary cyclicity is clearly visible in the succession of the Paleogene/Neogene lignite-bearing association, as in all lignite-bearing deposits. This is emphasized by the presence of multiple lignite seams (Kasiński, 1985, 2000). The lignite seams are intercalated with packages of mineral deposits of various thicknesses (Fig. 11).

Biogenic components may be observed at the contact of the lignite seams and mineral sediments. Tree roots grow into the mineral beds below, while their coalified trunks compose the constituents of the lignite seam (Fig. 12A). Above the seam roof, *in situ* tree trunks and stumps may occur within the mineral sediment. They are remains of a swamp forest buried in sand (Fig. 12B).

Geodynamic factors resulting in the distortion of dynamic equilibrium between the rate of lowering of the depositional surface and the rate of phytogenic matter accumulation are responsible for breaks in phytogenic accumulation despite the continuation of favourable climatic conditions (Fig. 13; Bouroz, 1966). Factors determining the lowering of the depositional surface may be auto- or allocyclic (Kasiński, 1983). The autocyclic factors include:

– compaction of the underlying phytogenic deposits (Kasiński, 1983; Widera, 2002, 2015; Widera et al., 2007), deposited during the earlier stages of basin development; the peat/lignite compaction ratio – according to the research noted above – is between 2 and 4;
– subrosion within salt domes, where phytogenic deposits accumulate in the overburden depressions (Meiburg, 1980; Kasiński et al., 2009).

The allocyclic factors include:

– eustatic sea level changes (mostly in the platform areas);
– tectonic subsidence, particularly important in the area of tectonic depressions (grabens), characterized by the highest amplitudes, resulting in large depositional space, wherein – in the case of a long-term dynamic equilibrium – the thickest lignite seams are formed (Kasiński, 1985, 2000, 2004; Hager, 1993; Widera, 2004; Widera and Hałuszczak, 2011);
– regional (epeirogenic) subsidence associated with vertical displacements of the sedimentary basin basement blocks (Kasiński and Piwocki, 2002);
– tectonic salt outflow from the salt dome bodies (Kasiński et al., 2009), where phytogenic deposits accumulate within the overburden;
– rise of the erosional base in the basin margin, which is equal to the relative decrease of depositional surface; simultaneously, it creates more intense erosion of the areas surrounding the peat-forming basin and increased supply of clastic sediments into it.

DISCUSSION

The range of critical temperature values for extensive anthracogenesis does not mean that lignite and coaly deposits were not produced during the Paleogene and Neogene beyond these limits. Due to the difficulties associated with the preservation of organic matter, these deposits usually form much thinner lignite seams with a significant mineral admixture (Pester, 1967; Kuhlmann et al., 2006). However, thick lignite layers could have been formed sporadically even in regions with a fully tropical climate, as in the past, e.g. in northwestern India (Dutta, 2011), and presently, e.g. on the Kalimantan Island (Dwiantoro et al., 2013). This could happen only under specific conditions, ensuring rapid isolation of the deposited sediment from the oxidizing environment, as a result of abrupt burial under mineral deposits or sudden flood with a thick layer of water.

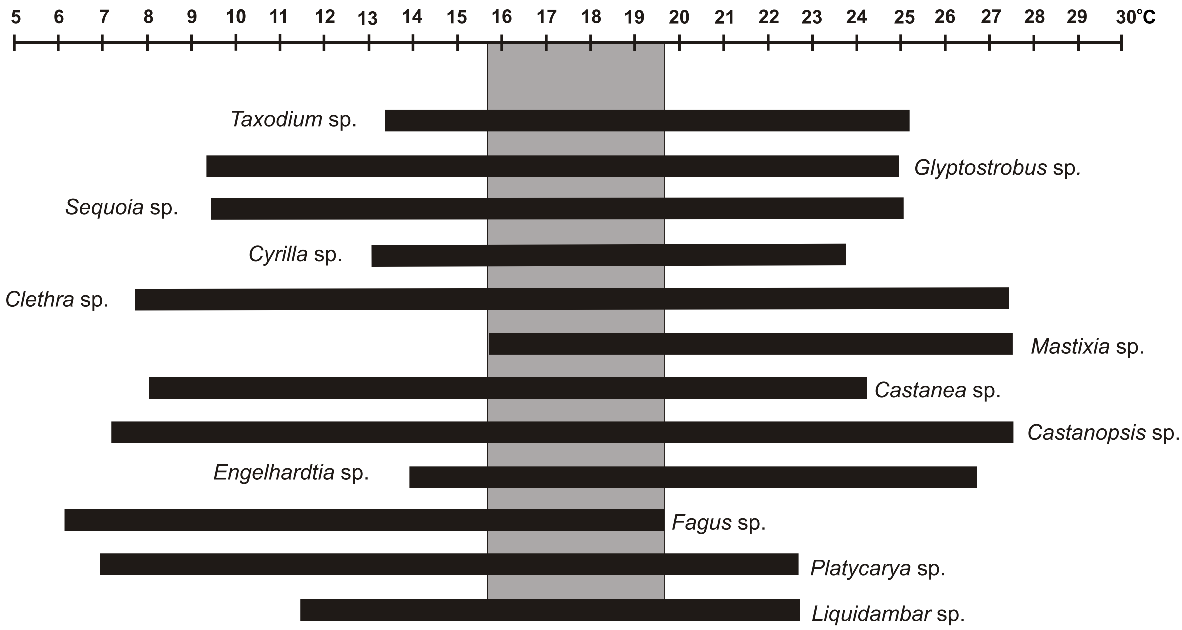


Fig. 10. Mean annual temperature of the nearest living relatives based on fossil pollen from the 1st Mid-Polish lignite seam (after Utescher and Mosbrugger, 2016)

Table 2

Mean annual precipitation and mean monthly precipitation in the driest/warmest months based on fossil pollen from the 5th Czempiń lignite seam (after Utescher and Mosbrugger, 2016)

NLR-taxon	MAPmin	MAPmax	MPdrymin	MPdrymax	MPwarmmin	MPwarmmax
Taxodium sp.	290	2615	0	93	19	227
Glyptostrobus lineatus	222	1864	0	67	3	227
Sequoia sempervirens	222	1613	0	93	3	227
Cyrilla sp.	961	1520	42	56	99	196
Clethra sp.	650	3151	1	165	6	229
Trigonobalanus sp.	1217	3869	7	256	118	297
Castanea sp.	473	2336	2	93	1	304
Castanopsis sp.	397	10798	0	165	1	1100
Lithocarpus sp.	529	10798	0	64	1	1100

Table 3

Mean annual precipitation and mean monthly precipitation in the driest/warmest months based on fossil pollen from the 1st Mid-Polish lignite seam (after Utescher and Mosbrugger, 2016)

NLR-taxon	MAPmin	MAPmax	MPdrymin	MPdrymax	MPwarmmin	MPwarmmax
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Sequoia sempervirens	222	1613	0	93	3	227
Cyrilla sp.	961	1520	42	56	99	196
Clethra sp.	650	3151	1	165	6	229
Mastixia sp.	1096	3293	1	132	28	248
Castanea sp.	473	2336	2	93	1	304
Castanopsis sp.	397	10798	0	165	1	1100
Engelhardia sp.	740	10798	5	152	79	1100
Fagus sp.	376	2648	3	94	5	431
Platycarya sp.	378	2500	1	80	73	431
Liquidambar sp.	619	1823	2	93	5	195

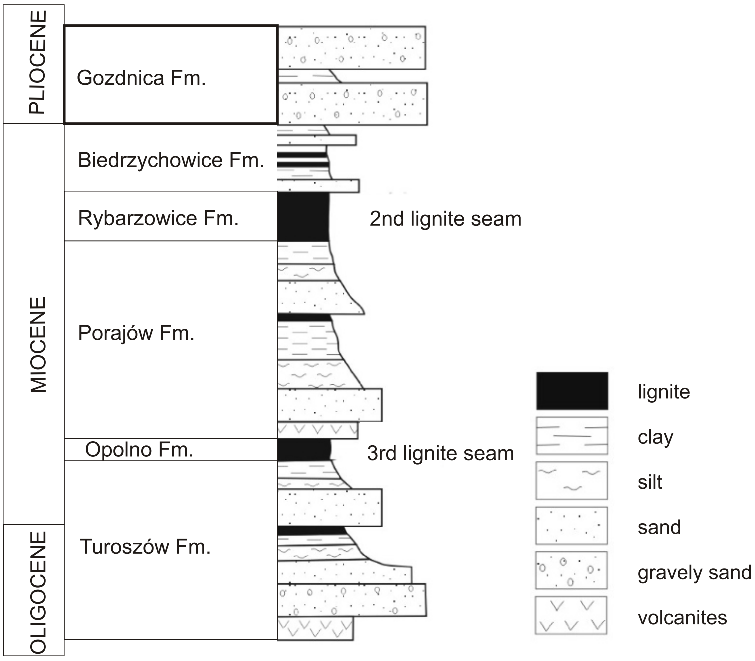

Fig. 11. Generalized profile of the lignite-bearing association in the Zittau Basin, SW Poland

Sedimentary cyclicity caused by alternating beds of phytogenic and mineral deposits (after Kasiński et al., 2010)

The model of a succession of wetland sedimentary environments presented concerns the distal zone of the North Sea Basin, including the area of the Polish Lowlands. Slightly different models of a fen sedimentary succession functioned in more proximal zones, where significant marine influence has been indicated (paralic coal basins). Detailed studies conducted in the Lower Rhine Embayment (Hiltmann, 1976; von der Brelie and Wolf, 1981; Mosbrugger et al., 1994; Huhn et al., 1997) have shown that these sequences can be extremely variable as a result of rapid changes in the groundwater level.

The formation of thick phytogenic successions is usually related to late transgressive systems and early highstands, which are occur particularly commonly in warm climates (Courel, 1989; Chesnut and Greb, 1992; Davies and Hummell, 1994; Diessel, 2004).The application of the nearest living relatives method requires consideration of its restrictions, because it is usually very difficult to clearly identify a contemporary analogue of the fossil species. Progressive evolution and radiation within the genera, i.e. the origin of new species, and a different palaeogeography and atmospheric composition during lignite formation should also be taken into account. During the anthracogenic interval, relatively stable conditions prevailed with a equable content of atmospheric CO_2 higher than the recent level, at 450–500 ppm. The global sea level was about 50 m higher than at present. All these factors might have also affected the prevailing conditions, which were favourable for the formation of extensive wetlands, inter alia, in the Polish Lowlands territory.

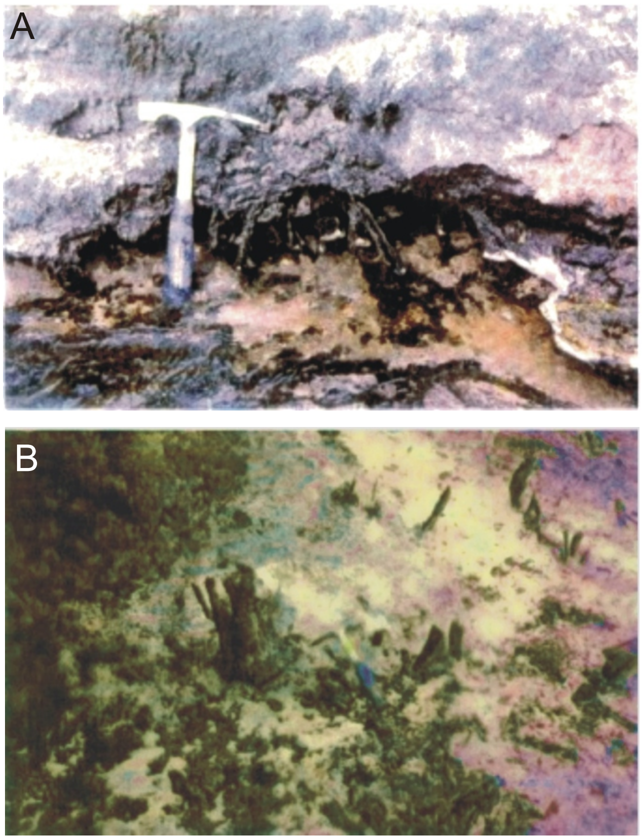

Fig. 12. Contact of a lignite seam with mineral beds

A – tree roots penetrating sands underlying the 1st Mid-Polish lignite seam; **B** – tree trunks and stumps protruding from the sands overlying the 1st Mid-Polish lignite seam; Konin Lignite Mine, "Jóźwin I" open pit, central Poland

CONCLUSIONS

The most intense lignite-forming processes in the Cenozoic of the lowland part of Europe took place during the Oligocene and Miocene. This is an interval showing general consistent "new" flora. In Poland during this time, five main lignite seams from the 5th to the 1st of major economic significance were formed. The interval began from the cooling at the boundary between the Eocene and Oligocene and terminated with the beginning of the aridisation known as the "C4 grassland event" of the Late Miocene. Both critical points are related to the surpassing of temperature limits, which respectively become: (1) too high for the preservation of phytogenic deposits, and (2) too low for the extensive development of the peat-forming vegetation.

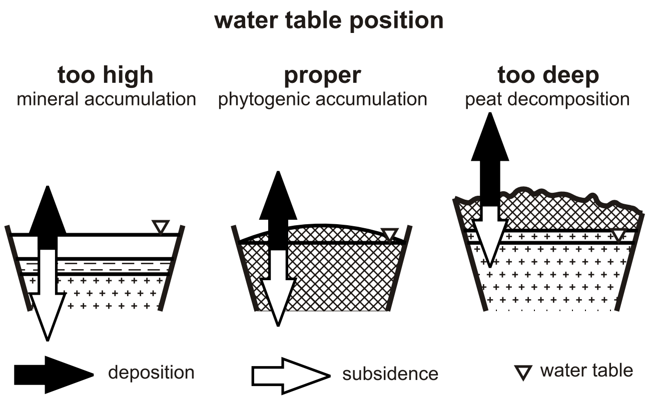

Fig. 13. Impact of a water table position on phytogenic accumulation (sedentation) in a peat-forming area (after Kasiński, 2000)

Climatic conditions favourable for extensive peat-forming vegetation persisted throughout the entire interval of lignite formation. During this period, climatic changes did not pose any major obstruction to the anthracogenesis process. However, in some parts of Europe (e.g., Lower Rhine and Kleszczów grabens) this process was continuous for a much longer time.

Sedimentary cyclicity of the lignite-bearing succession was controlled by auto- and allocyclic mechanisms. Geodynamic factors disrupted the dynamic equilibrium between the lowering of the depositional surface and the phytogenic matter accumulation. Despite the still favourable climate conditions, these geodynamic factors were responsible for gaps in lignite formation. Factors influencing the lowering of the depositional surface include:

– tectonic subsidence,
– salt outflow and subrosion of salt domes (for depressions in the salt dome overburden),
– compaction of underlying phytogenic matter,
– regional epeirogenic subsidence,
– raising of the erosional base.

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