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Variation of coal quantity accumulated in the Mississippian to Pennsylvanian coal seams (Upper Silesia and Lublin Coal basins, Poland): a reflection of changes in climate and CO_2 availability

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Many coal seams of varied thickness and aerial extent occur in the Upper Silesia and Lublin basins within Mississippian and Pennsylvanian coal-bearing deposits. Well-documented data on coal quantity in the seams identified allows visualization of their variation within the stratigraphic succession and analysis of the time-dependent coal accumulation process. Some characteristic features of this variation were observed. Coal seams of the Mississippian age (Serpukhovian, Paralic Series), formed within a near-shore environment, most often constitute small resources. There were only two intervals of increased coal accumulation in seams of >100 million tons, in the lower and uppermost parts of the Paralic Series. Within the Pennsylvanian coal-bearing succession of terrestrial fluvio-lacustrine origin, a specific, wave-like pattern of seam resource variations and four intervals of increased coal accumulation are observed. In the Lublin Coal Basin, the Lublin Beds only, deposited during the Late Bashkirian, are coal-bearing, in which a bell-shaped pattern of seam resource variation in the stratigraphic succession is observed. The location of enhanced coal accumulation events in the stratigraphic succession suggests their repetition at ~1–4 My intervals. The characteristic features of the quantitative variation in these coal seams may be correlated with glacial-interglacial and climate humidity changes, and interpreted as a response to variable volcanogenic CO_2 supply.

Key words: coal seams, resources, Carboniferous, climate.

INTRODUCTION

Changes in the Earth's climate even in the distant past have been of interest from the perspective of forecasting climate change today. For this reason, much attention has been paid to the Carboniferous glacial episodes (Cleal and Thomas, 2005; DiMichele, 2014; Pfefferkorn et al., 2017). These are well-documented in Earth history (Veevers and Powell, 1987), but their course is debated. Extensive reviews of this topic were provided by Calder and Gibling (1994), Fielding et al. (2008a, b), Montañez and Paulsen (2013), Isbell et al. (2012), Eros et al. (2012), Montañez (2022) and the references therein.

In the area of Gondwana three main phases of continental glaciation have been distinguished, of approximate durations was 360–345, 326–312 and 298–285 Ma (Isbell et al., 2003). Glaciations in the northern hemisphere are less marked, probably due to the development of sea ice cover only (Eros et al., 2012). Much data indicates that a number of shorter periods of glaciation interspersed with interglacial warming can also be distinguished, ranging in duration from 1 to a few million years (Fielding et al., 2008a, b; Eros et al., 2012).

During the late Mississippian and Pennsylvanian ice ages, the Euro-America area, located in what was then the equatorial zone, was an area of lush vegetation, extensive peat-bog development and coal seam formation (Cleal and Thomas, 2005; DiMichele, 2014). However, establishing their relationship to glaciation phases is difficult due to the regional variation and time-varying position of glaciation centres and forested areas, caused by the movement of continental plates (Cleal and Thomas, 2005; Isbell et al., 2012). Sea level-dependent base-level and climate variations are of most importance for the formation of favourable conditions for lush vegetation and the formation of extensive peat-bogs, the sites of formation of the present coal seams (Falcon-Lang, 2004; Cecil et al., 2014). Climate modification is also reflected in the type of vegetation cover (DiMichele et al., 2010).

Cyclic variation of sedimentary environments is an important feature of Carboniferous coal-bearing successions. It is expressed by repeated succession of clastic sediments, often carbonate sediments, coal seams and sedimentary breaks. It is thought to have been caused by global eustatic sea level fluctuations due to the temporally varying extent of ice caps that tied up significant amounts of water (Phillips and Peppers, 1984;

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Heckel, 1990, 1994; Hampson et al., 1999). These in turn were a response to climate changes explained by variations in parameters of the Earth's orbit, described by the Milankovitch cycle, in particular with periods around 100 and 400 ky (Heckel, 1990, 1994; Davydov et al., 2010; Van den Belt et al., 2015; Chesnel et al., 2016; Feulner, 2017; Jirasek et al., 2018). Periodic fluctuation of solar activity may also be admitted (Crowley and Baum, 1992). However, these views are contested because the non-synchronous development of glaciations and their limited spread in different areas does not explain the scale of recorded eustatic movements (Isbell et al., 2003). The reasons for the cyclic changes in sediments composition were not only periodic general climate changes but also tectonic movements in the source areas (Haeckel, 1994; Castelltort and Van den Driessche, 2003). On a regional scale, cyclic variations in sedimentation may also have been caused by palaeogeographic changes (Frank et al., 2008), linked to continental plate movements and tectonic processes at their margins (Bruckshena et al., 1999). These processes also influenced changes in the circulation of oceanic and atmospheric currents. They are thought to have caused long-term, few-million-year-scale changes in climate and sedimentary conditions (Ross and Ross, 1987; Chesnut, 1994; Scheffler et al., 2003).

The occurrence of favourable conditions for the development of peat-bog vegetation and its persistence should be reflected in the variation in the amount of accumulated carbon in individual seams. This was noted by Phillips and Peppers (1984) and Scott and Stephens (2015). However, the study of cyclicity of sedimentation of coal-bearing series and its causes has not yet considered changes in the amount of accumulated coal over time. Van den Belt et al. (2015) demonstrated only the increased coal accumulation in the Westphalian B and C (Duckmanian and Bolsovian stages) of the Netherlands and Kentucky.

A detailed inventory and compilation of data on hard coal resources in individual seams in the Upper Silesian and Lublin Coal Basins in Poland make possible the analysis of their differentiation in the stratigraphic succession, as described below, and allow its interpretation in relation to global climatic changes.

GEOLOGICAL LOCATION OF THE STUDY AREAS

The study area is the Polish part of the Upper Silesian Coal Basin and Lublin Coal Basin (Fig. 1).

The Upper Silesian Coal Basin (USCB) is a foredeep of the Moravian-Silesian Variscan fold belt and located to the west of it (Kotas, 1995; Jureczka and Kotas, 1995; Kędzior et al., 2007). The basin is underlain by Precambrian formations covered by Paleozoic sediments, in particular Carboniferous coal-bearing strata. The coal-bearing formations is >4000 m thick in the western part of the basin and decreases to ~1000 m in its eastern part, outwards from the orogenic front (Fig. 2). The coal-bearing strata are underlain by Lower Carboniferous Flysch sediments (Culm Formation).

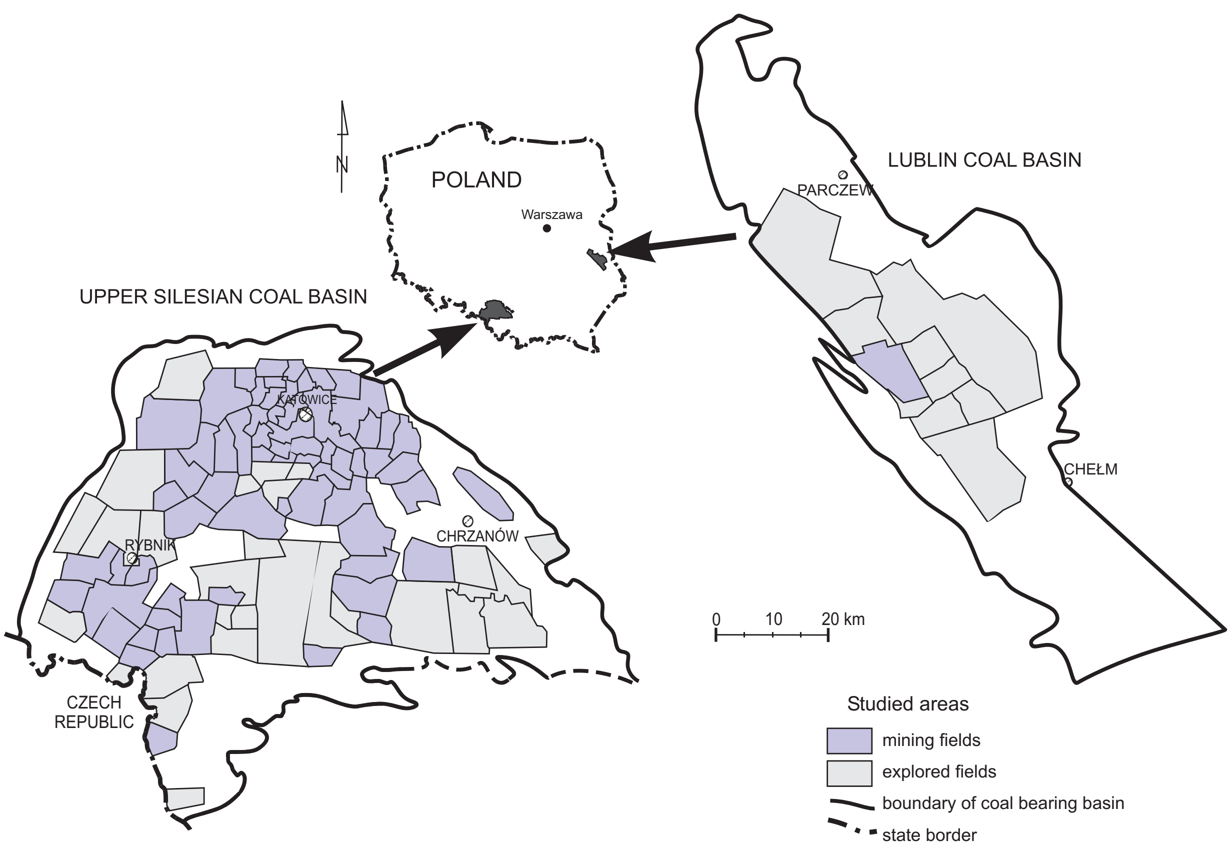

Fig. 1. Coal basins in Poland and location of the coal-mining fields and explored areas ("coal deposits"): boundaries as at the time of resource evaluation

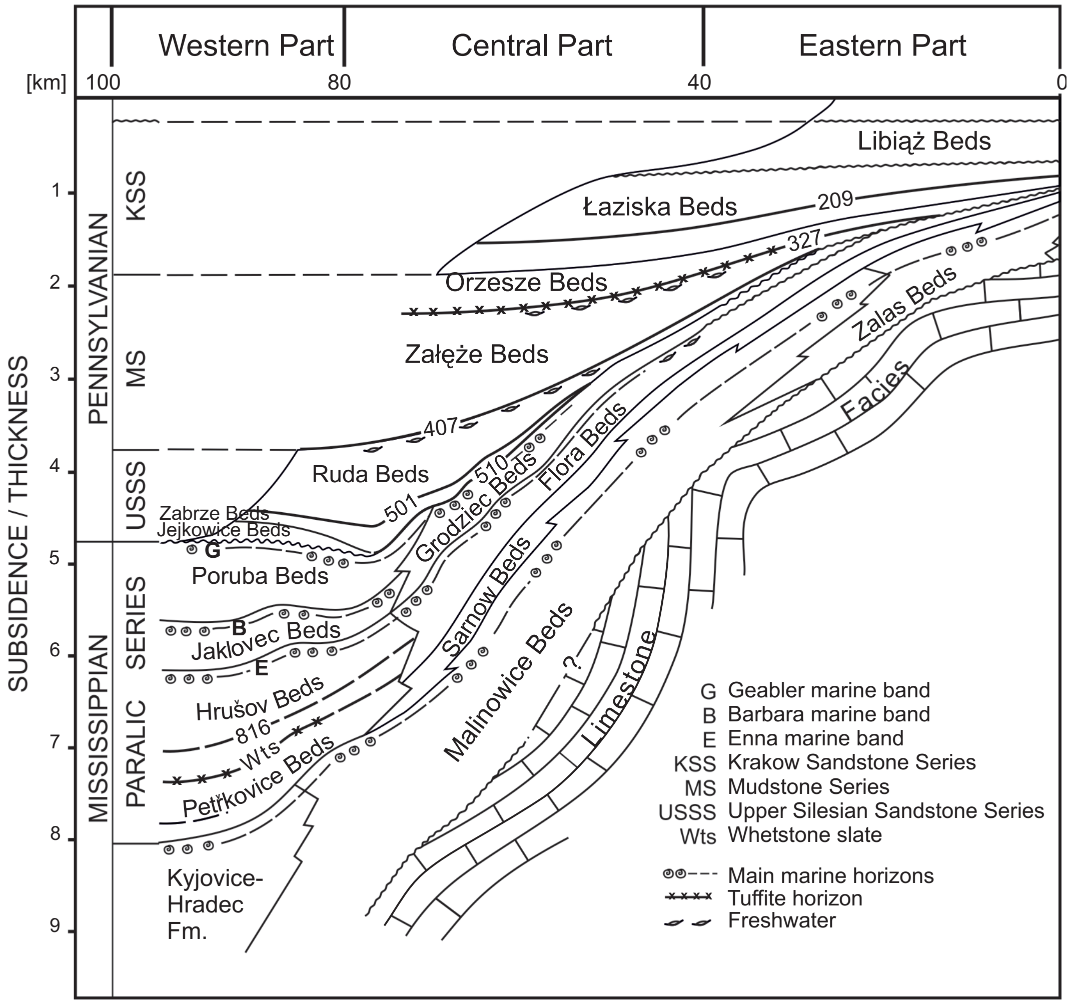

Fig. 2. Model of subsidence of coal bearing formations in the USCB (according to Kotas, 1985, 1995)

For detailed stratigraphic subdivision see Table 2

Coal-bearing formations were formed at the end of the Mississippian Subperiod, in the Serpukhovian, and lower and middle Pennsylvanian (Bashkirian and Moskovian) stages. Coal seams occur in four lithostratigraphic units. These are, from the bottom (Fig. 2 and Table 1): “Paralic Series” formed in the Mississippian Subperiod, in which interbeds of clays with marine fauna (marine bands) are present, and successively in the Pennsylvanian Subperiod: “Upper Silesian Sandstone Series”, “Mudstone Series” and “Krakow Sandstone Series”, which comprise terrestrial, alluvial and lake sediments. Within these “series”, based on palaeontological and palaeobotanical criteria, a number of “beds” are distinguished (Table 2). The Paralic Series is separated from the younger ones by a stratigraphic gap related to tectonic movements of the orogenic Erzgebirge phase around the Mississippian-Pennsylvanian boundary and locally occurring unfossiliferous Jejkovice sandstones. Stratigraphic gaps are also found in the Lower Pennsylvanian, Upper Silesian Sandstone Series, at the boundary between the Zabrze (Saddle, Anticlinal) and Ruda Beds, and within the Krakow Sandstone Series at the boundary between the Łaziska and Libiąż beds (Kędzior et al., 2007). The border between the Łaziska and Libiąż beds is also marked by a fundamental change in the floral assemblage (Kotasowa, 1979).

The coal-bearing formations within the boundaries of the Upper Silesian Basin are cut by numerous faults and in the western part they are folded. In the southern and central parts of the basin the coal-bearing formations are overlain by Neogene deposits, mostly clayey, up to several hundred metres thick, and in the southeastern part of it additionally by overthrusted, folded Paleogene-Cretaceous flysch deposits. In the northern part of the basin, only a discontinuous overburden of Triassic sandstones, limestones and dolomites is present above the Carboniferous formations. Quaternary glacial and fluvioglacial deposits up to some tens of metres occur throughout the area.

Historically documented coal mining escalated in the second decade of the 18th century. Approximately 20 billion tons have been mined to modern times. In the last decade of the 20th century a number of old mines, where coal mining was no longer economically viable, were closed. The total proven and estimated (demonstrated, indicated and inferred) coal resources, including those mined to a depth of 1000 m, amount to ~100 billion tons (Nieć and Młynarczyk, 2014), with additional

Table 1

Coal seams in the USCB and LCB (following Sermet, 2018, for detailed stratigraphic subdivisions see Table 2)

Coal basin	Stratigraphy	Lithological "Series"	Local stratigraphy ("Beds")		Maximum thickness of coal-bearing formations [m]	Total number of coal seams and partings	Maximum total coal thickness [m]	Coal seam numbers	Number of seams with thickness over			
									1 [m]	2 [m]	3 [m]	6 [m]
USCB	Pennsylvanian	Krakow Sandstone	Libiąż		560	38	48	111-119	26	1	-	-
			Łaziska		1080			201-216		5	3	-
		Mudstone	Orzesze*	Orzesze	2000	158	112	301-327	71	4	1	-
				Załęże				328-364				
			Ruda*					401-406		18	7	-
		Upper Silesian Sandstone		Ruda	810	61	80	407-420	23			
			Zabrze (Saddle, Anticlinal)		140			501-510		10	9	5
	Mississippian	Paralic***	Poruba		1100	263	99	601-630	8	-	-	-
			Jaklovec		350			701-723	11	3	-	-
			Hrušov		1300			801-848	26	1	-	-
			Petřkovice		760			901-920	12	-	-	-
LCB	Pennsylvanian	Lublin Formation (Beds)			400	49	30	369-399	17	up to 4**	1**	-

* – former mining subdivision, ** – locally, *** – Ostrava Formation in the Czech part of the USCB

hypothetical resources, to the depth of 1300 m, of ~25 billion tons (Jureczka et al., 2020). The total original resources of the basin, including those at depths below 1,300 m, can be estimated at 150 billion tons, not accounting those eroded before the Neogene-Quaternary.

The Lublin Coal Basin (LCB) was discovered in the second half of the 20th century. It comprises an elongated syncline within the Paleozoic sediments that overlie the Precambrian basement in the marginal zone of the East European Platform. They are arranged almost the main coalbearing formation,100–400 m thick. Their stratigraphic position similar to that of the Mudstone Series in the USCB. In the lower part of the coal-bearing Lublin Formation there is a mudstone bed with brackish-indicating *Dunbarella* fossils (Krzeszowska, 2015), which marks the boundary between the Westphalian A and B. In the older Carboniferous strata only a few insignificant coal seams are present and limestone interbeds occur. Their presence makes it possible to distinguish eleven sequences (cyclothems) in the Serpukhovian and lower Pennsylvanian, up to the beginning of the Westphalian B, (Porzycki and Zdanowski, 1995). Across the whole basin, the coal-bearing formations are overlain by Jurassic and Cretaceous sediments, mainly marls and limestones with a thickness of 700 to 800 m. Indicated and inferred coal resources in the LCB, including mined coal, are ~12 billion tons (Sermet, 2018).

Within the basins studied, numerous coal seams of varying thickness and area of occurrence are present. The coal seams identified that occur across the whole area of each basin are consistently marked with a three-digit symbol (Doktorowicz-Hrebnicki and Bocheński, 1952; Dembowski et al., 1964). The first digit indicates the stratigraphic position of the seam (according to the traditional European division of the Carboniferous). The remaining two digits indicate the location of the seam in each stratigraphic unit from its roof to the floor (Table 1).

DATA AND STUDY METHODS

The assessments of coal quantity herein i.e. coal tonnage, named here as resources without any economic designation, within individual seams in the Polish part of the Upper Silesian and Lublin Coal Basins, are based on their detailed evaluation within the boundaries of all coal-mining fields and explored areas, defined as separate "coal deposits" (Fig. 1). Bituminous, black coal resources in both basins have been well-recognized, documented and systematically reported. The data used in this study were those provided by geological documentation of mining fields and areas where coal resources were described in reports of borehole-based exploration results, stored in by the Polish Geological Institute – National Research Institute in the National Geological Archive in Warsaw.

The term "coal seam" here means a unit comprising coal layers with barren interlayers of claystone or mudstone, the thickness of which does not exceed that of the individual coal layers. The term "seam resources" refers to the amount of coal,

Table 2

Stratigraphy of the USCB and LCB (Dembowski, 1972; Kędzior et al., 2007; Wagner, 2008; Kędzior and Opluštil, 2009; Waksmundzka et al., 2009; Cleal et al., 2009; Lucas et al., 2022)

Stratigraphic subdivision					Upper Silesia Coal Basin			Lublin Coal Basin
International		Western Europe			Local stratigraphy "Beds"*	Lithological Series	Boundary coal seams (s) and marker beds	Local stratigraphy*
Pennsylvanian	Gzhelian 289.9-303.68 Ma	Stephanian	C		Kwaczala arkoses			
	Kasimovian 303.68-307.02 Ma		B					
			A	Cantabrian	Hiatus			
	Moscovian 307.02–315.15 Ma	Westphalian	D	Asturian	Libiąż	Krakow Sandstone	s.111 -s. 119	
					Leonian Phase		Leonian Phase	Magnuszew Formation
			C	Bolsovian	Łaziska		s. 202-s. 218	
	Bashkirian 315.15- 323.4 Ma		B	Duckmantian	Orzesze	Mudstone	s. 303-tuffite horizon	Lublin Formation
			A	Langsettian	Załęże		s. 327-s. 406 and limnic faunistic horizon (Hubert)	Dęblin Formation Kumow Member
		Namurian	C	Yeadonian	Ruda	Upper Silesian Sandstone	s. 407–s. 420	
				Marsdenian	?		?	
			B	Kindescoutian	Zabrze (Saddle)		s. 501–s. 510	
			A	Alportian	Jejkowice sandstone	Hiatus (Erzgebirge Phase)		
Mississippian	Serpukhovian 323.4-330.4 Ma			Chockerian				
				Arnsbergian	Poruba (Upper Grodziec**)	Paralic (shale-sandstone)	Marine horizon Gaebler and s. 601-s. 630	Dęblin Formation Bug Member
					Jaklovec (Lower Grodziec**)		Marine horizon Barbara and s. 701-s. 723	Terebin Formation
				Pendleian	Hrušov (Flora**)		Marine horizon Enna and s. 801-s. 848 and Whetstone slate horizon	
					Petřkovice (Sarnów**)		Marine horizon Nanetta and s. 901–s. 915	
	Visean				Kyjovice (Malinowice, Zalas**)	marine horizon Štur Flysch, marine beds		
					Carbonate facies**			Huczwa Formation

* – stratigraphic location of unit boundaries approximate, ** – eastern part of USCB

including barren partings, which is not >5 cm thick and the total ash content does not exceed 20% (on average it is between few and ten or so %).

The resources of each seam, identified by a three-digit symbol, were calculated separately within the boundaries of individual mining fields and explored areas. The basic criterion adopted for defining the boundaries of the area in which the resources were calculated was the thickness of coal in the seam exceeding 0.6 m. The estimation of resources was based on the results of measurements of seam thickness in mine workings and in cored exploratory boreholes, drilled with at spacings of 500–4,000 m, to a depth >1000 m, arranged in a more or less regular grid. The area of occurrence of each seam was divided into a number of blocks, limited by mining or geological boundaries. The resources of each block were calculated as:

$$Q_b = F_b \cdot m_b \cdot \gamma$$

where: F_b – block area, m_b – average thickness of coal in seam, which was based on measurements in boreholes and mine workings located within and adjacent to the block boundaries, γ – coal bulk density (usually 1.3 t/m^3).

The total resources of each seam are the sum of the resources of all blocks located within the boundaries of the seam occurrence. Previously exploited resources were not included. They mostly came from the thickest seams. The variation in initial resource amount was therefore probably more pronounced than currently described.

The resources analysed differ from those currently reported due to continued mining and the closure of a number of mines. However, the purpose of the study is the interrelationship of resources of individual coal seams, regardless of their declining quantity.

The data on resources of individual seams identified across the whole area of the basin make it possible to describe their differentiation depending on their location in the stratigraphic succession. This was visualized by means of appropriately scaled bars arranged in a stratigraphic sequence. The actual distance between the seams has been neglected because it changes within the basin, increasing towards its central part (Fig. 2). Such presentation shows the trend of changes in the coal accumulation process (anthracogenesis, by Stopa, 1968) during the formation of the whole coal-bearing succession.

Coal resources were estimated to a depth of 1,000 ±100 m within the boundaries of individual mining fields and explored areas. These are not the total resources of the seams, which also occur at greater depth, but it can be assumed that the interrelationship of seam resources within the deeper parts of the basin will be similar.

RESULTS OF THE SEAM RESOURCE ASSESSMENT

UPPER SILESIAN COAL BASIN (USCB)

In the Polish part of the USCB there are ~520 coal seams and layers, with a total thickness of ~339 m. Of these, 242 seams were marked (named) with a three-digit number and among these 234 are considered mineable in some area (Table 1). Splitting of seams can locally increase their number. Split seams are identified by an additional digit, e.g., 358/1, 358/2.

The identification and stratigraphic position of the seams across the whole area of the basin is unquestionable in the case of those that are distinguished by their outstanding thickness and those that are located in the vicinity of rock layers with specific characteristic lithological features, which constitute marker horizons. Such marker horizons are pyroclastic or fauna-rich (especially marine) rocks. The identification and continuity of such seams throughout the basin is corroborated by mining data.

Splits, washouts and pinching of seams disrupt and hinder their correlation, especially those that are thin or occur close together. Identification of such seams can be uncertain. This is evident at the boundaries of mining fields or explored areas, where the same seam may be marked with a different but usually close numerical symbol. Such difficulties particularly affect seams 301–364 (in the Orzesze and Załęże Beds), which often occur over a limited area (Doktor and Gradziński, 1985). For this reason, general data on the resources of individual low-thickness seams not located in the vicinity of marker horizons should be considered as approximate.

Coal seams are unevenly distributed in the coal-bearing series. Their thickness varies from <0.6 to ~20 m. The most common are seams <1.5 m thick. Thicker seams occur mainly in the Upper Silesian and Krakow Sandstone Series and also in the lower part of the Mudstone Series. Only 19 seams are >3 m thick, and only 5 of these >5 m thick. The Zabrze (Saddle) Beds are characterized by outstanding, large resources, with seam 510 up to 24 m thick in the northeastern part of the USCB. Towards the centre of the basin it gradually splits into a bundle of seams of smaller thickness, separately numbered 501-510. The reported total resources of individual seams evaluated up to the depth of 1000 m vary from ~1 to 2700 million tons.

The varied area of occurrence of particular lithostratigraphic units of the coal-bearing series (Figs. 2 and 3) affects the total resources of the enclosed seams, but not the general picture of their mutual differentiation.

There is a distinct difference in the seam resources in the Mississippian (Serpukhovian) Paralic Series, formed under coastal-marine, deltaic conditions, and those formed in the Pennsylvanian fluvial-lake environment of an alluvial plain (Figs. 4 and 5).

In the Paralic Series, the coal seams formed in a deltaic environment are usually thin and have relatively small demonstrated resources, due to a limited area of occurrence at up to 1000 m depth in the Polish part of the USCB (Fig. 3). Coal seams with resources >100 million tons are scarce and indicate an episodic increase in coal accumulation. Two such periods can be distinguished: the formation of seam 816 at the base of upper part of the Hrušov Beds, and of seams 610, 615 and 620 in the uppermost part of the Paralic Series, within the Poruba Beds (Fig. 4).

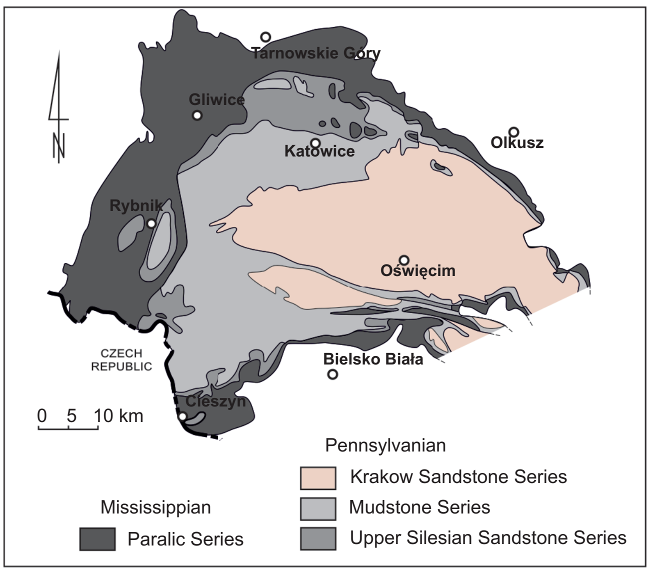

Fig. 3. Simplified geological map of USCB: coal-bearing formations below the unconformable post-Carboniferous cover (according to Jureczka, 2017, simplified)

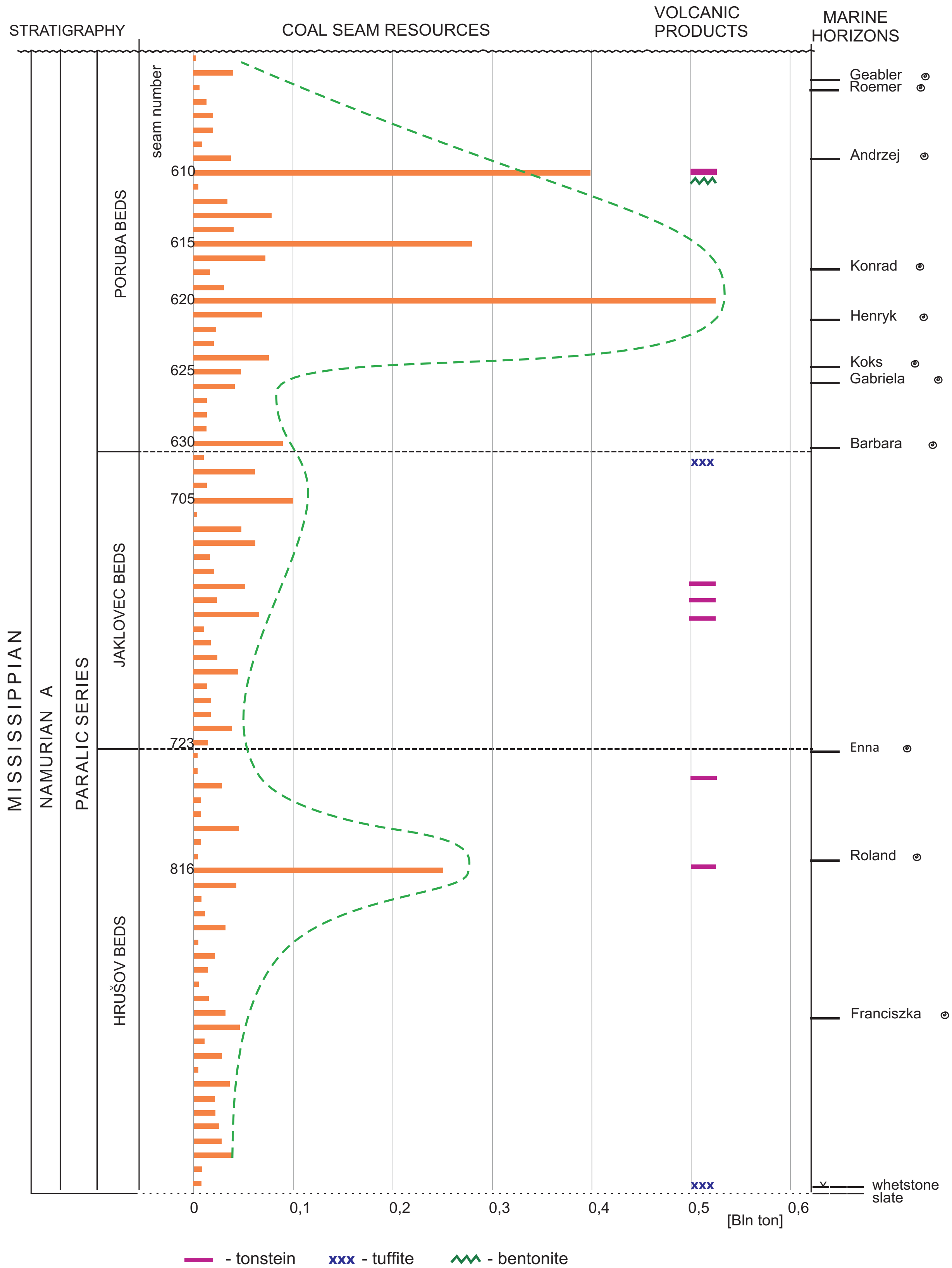

Fig. 4. Resources of coal seams in the Serpukhovian, Paralic Series; USCB

The true distance between seams, which is variable within the basin boundaries, has not been taken into account; only the numbers of selected seams are shown; location of volcanic products according to Ryszka and Gabzdyl (1986); coal resources variation trend is marked by dashed line

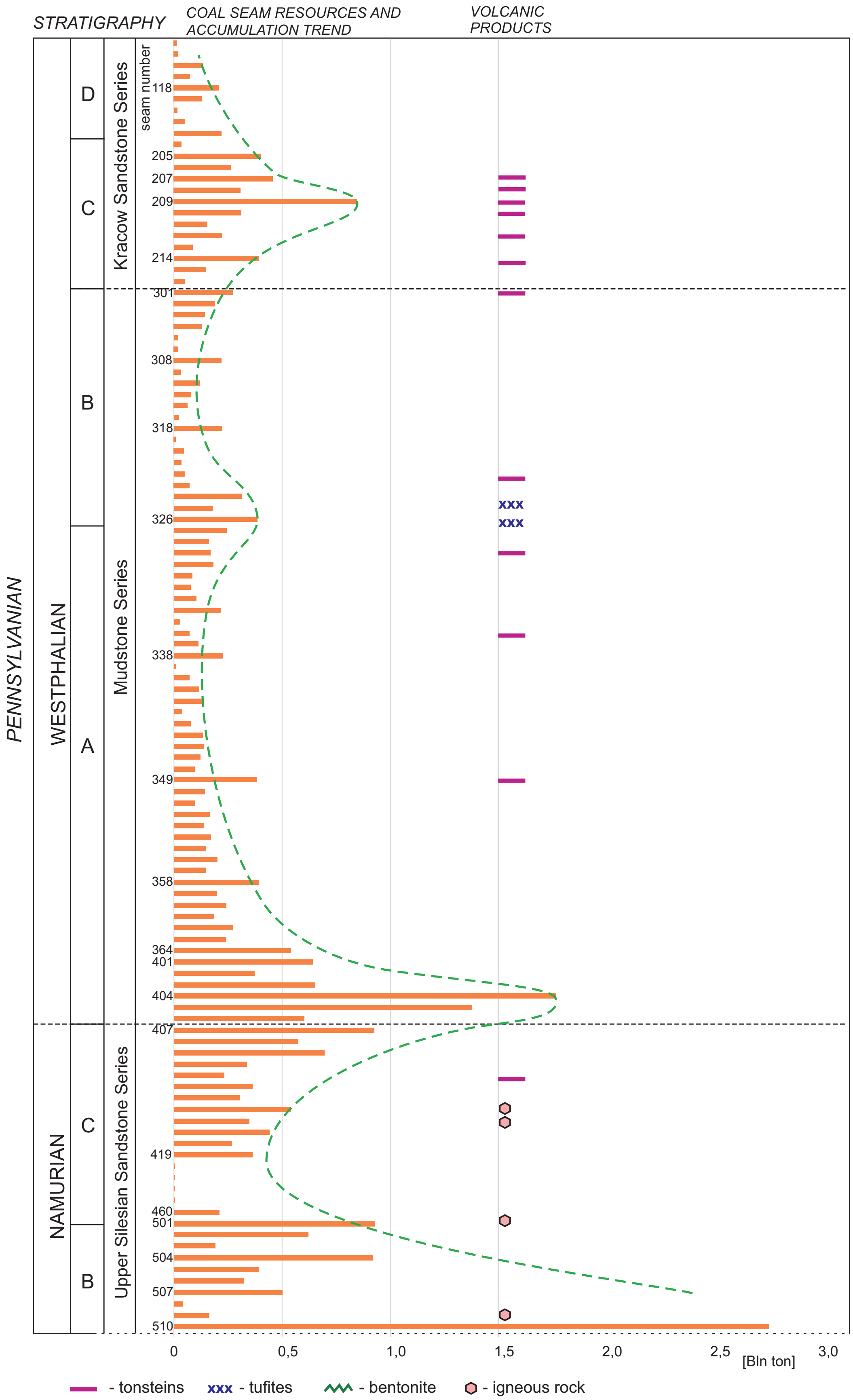

Fig. 5. Reources of coal seams, in Pennsylvanian (Bashkirian and Moscovian) formations; USCB

The true distance between seams, which is variable within the basin boundaries, has not been taken into account; only the numbers of selected seams are shown; location of volcanic products according to Ryszka and Gabzdyl (1986); coal resources variation trend is marked by dashed line

In the Pennsylvanian coal-bearing series formed in the fluvial-lake environment of an alluvial plain (Kędzior et al., 2007), against the background of random oscillatory fluctuations in coal seam resources, long-term trends and specific regularities of their diversification are noticeable (Fig. 5). This consists of the appearance of seams with increasing resources up to the climax value, respectively in seams 405–404, 326 and 209, and then their gradual reduction. Periods of increased coal accumulation occur within the Upper Silesian Sandstone Series, at the boundary between this series and the Mudstone Series and in the Krakow Sandstone Series. In a less pronounced manner such a period is marked within the Mudstone Series (Fig. 5).

A special case is the seam "510" which has the largest resources in the USCB. It occurs at the base of the Pennsylvanian series, and was formed after a sedimentary gap caused by orogenic movements (the Erzgebirge phase of the Hercynian orogeny) at the Mississippian-Pennsylvanian boundary. The higher-lying, younger seams in the Zabrze (Saddle) Beds have progressively lower resources.

LUBLIN COAL BASIN (LCB)

Across the whole Lublin Coal Basin 17 coal seams with thicknesses of 0.6–3.8 m were identified (Porzycki and Zdanowski, 1995). Only eight of them are sufficiently continuous and have a thickness of 1.3–1.8 m in different parts of the LCB. Five seams have resources of >1 billion ton (Fig. 6). In the variation of coal seam resources, two phenomena can be noted:

- alternating occurrence of seams with smaller and larger resources;
- the trend of the seam resources changes, with small resources in the oldest seams, then their rapid growth until they reach the highest value, and then their gradual decrease in the younger and younger seams.

This is similar to the pattern of seam resources variation seen at a similar stratigraphic position in the Mudstone Series of the USCB, at the Orzesze and Załęże beds boundary.

DISCUSSION

The location of coal seams in the stratigraphic succession of the coal-bearing series, their horizontal spread and thickness, and therefore the amount of accumulated organic matter (resources) depend on autogenic (intra-basinal) and allogenic (extra-basinal) factors (Calder and Gibling, 1994; Cecil, 2003). Conditions necessary for the formation of coal seams, especially those with large resources, are (Stopa, 1968; Dembowski

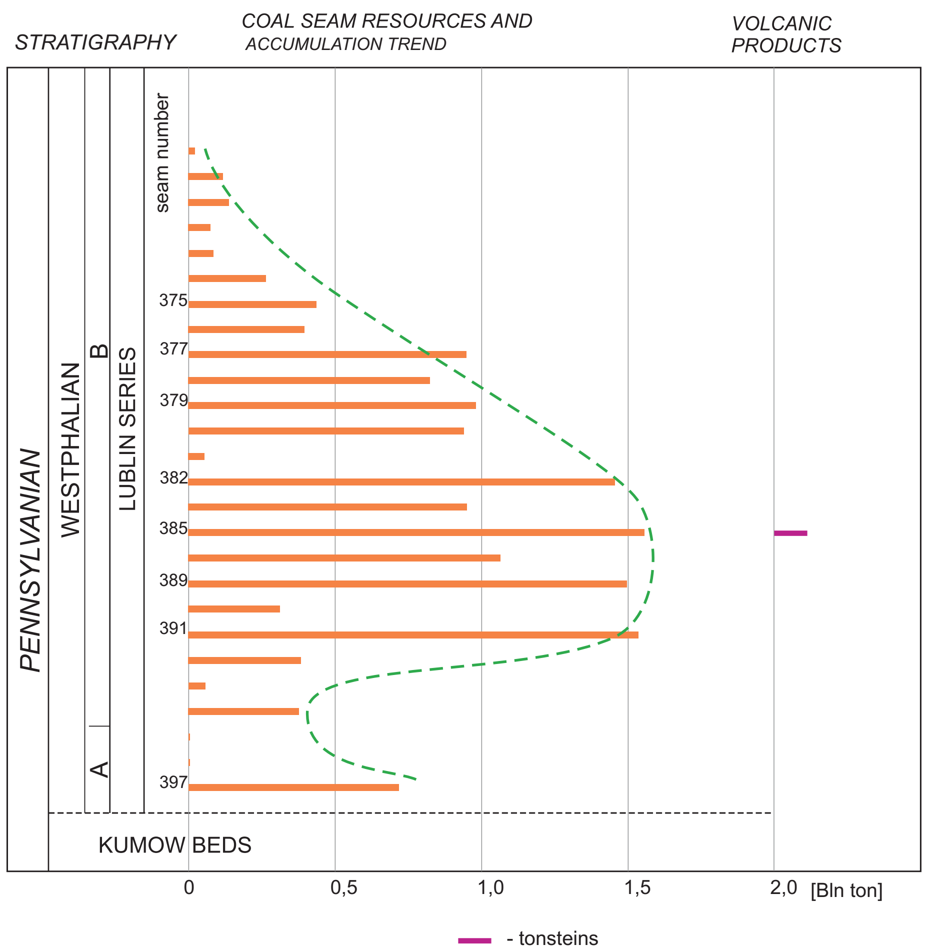

Fig. 6. Coal resources in the LCB (the true distance between seams, which is variable within the basin boundaries, has not been taken into account); only the numbers of selected seams are shown; volcanic products according to Lipiarski et al. (1993); coal resources variation trend is marked by dashed line

and Unrug, 1970; Aitken, 1996; Bohacs and Suter, 1997; Hampson et al., 1999; Kędzior, 2008; Probierz et al., 2012):

– terrain morphology suitable for the formation of extensive peat bogs;
– stable hydrological conditions, and a high water table, necessary for long-term existence of the peat bogs;
– humid climate and CO_2 concentrations in the atmosphere favourable to lush vegetation;
– subsidence of the area on which the peat bog exists, but slow enough that there was no fundamental change in the sedimentary environment and in the conditions of the peat bog formation;
– negligible erosion processes related to changing layout of the river channel network during and after peat bog creation.

Sedimentological studies of the coal-bearing succession in the USCB (Doktor and Gradziński, 1985; Kędzior et al., 2007) indicate that two types of seam can be distinguished:

– those occupying a well-defined position in the profile of a coal-bearing series and identifiable over an extensive area, of substantial thickness ranging from a few to >10 metres, indicating the presence of extensive long-term peat bogs; these seams are therefore distinguished by their considerable resources;
– those occurring in a limited area, discontinuous, usually thin; found in different areas, indicating a patchy distribution of original peat bogs; several such seams, situated in a similar stratigraphic position, can be identified as the same one and marked with the same symbol (number).

Increased basin subsidence in the western part of the USCB caused the splitting of many seams in that direction (Kotas, 1995; Probierz et al., 2012). In addition, the splitting of seams and their local washouts were also caused by the migration of riverbeds (Kędzior, 2008 and cited literature). Such features of the seams mean that the data on resources assigned to seams identified by a specific number are often related to their bundle located in a similar stratigraphic position (Doktor and Gradziński, 1985; Gradziński, 1994).

The described variation of coal quantity accumulated in individual seams arranged in stratigraphic succession indicates the occurrence of long-term trends during their formation. These appear against a background of irregular and short-term changes, which are interpreted as the effect of local variations of the sedimentary environment within the basin that favour peat bog formation (Dembowski and Unrug, 1970; Gradziński et al., 1995; Valero Garces, 1997). This is determined by local landscape features, drainage patterns (Calder and Gibling, 1994) and migration of riverbeds that may result in local short-term sedimentary changes and irregularly occurring variations in the resources of successive coal seams (Tucker, 1997; Doktor, 2007; Kędzior, 2008). Cyclical changes in the sequence of coal-bearing sediments reflect climatic changes over longer time periods and diastrophic processes associated with tectonic events (Klein and Willard, 1989; Izart and Vauchard, 1994; Heckel, 1994; Tabor and Poulsen, 2008). The connection between cyclical changes in sedimentary processes and tectonic movements was a focus of particular attention in earlier studies (Bubnoff, 1960).

The sedimentary cyclicity of Carboniferous coal-bearing formations is usually considered in terms of sequence stratigraphy (Gastaldo et al., 1993; Aitken, 1996; Hampson et al., 1999; Waksmundzka, 2010; Kozłowska and Waksmundzka, 2020), in turn astronomically driven. This is most clearly evident in a deltaic environment via periodic marine transgressions and is documented by transgressive-regressive sedimentary sequences, among which coal seams appear. Sequence boundaries are also defined by depositional gaps (Eros et al., 2012). It is also thought (Hamilton and Tadros, 1994) that in nonmarine basins the boundaries of sedimentary successions may be defined by thick coal seams that occur over a wide area, which are formed in the absence of clastic deposition.

During the Carboniferous icehouse period, cyclical climate changes were marked by ice cap extent changes in the polar regions, particularly in Gondwana. The observed cyclicity of sedimentation, in particular with periods of around 100 and 400 ky, is explained as the result of glacio-eustatic processes following climate changes associated with cyclic variation of the Earth's orbital parameters described by the Milankovich cycle (Heckel, 1990, 1994; Wright and Vanstone, 2001; Feulner, 2017; Van den Belt et al., 2015 and literature cited). Climate oscillations resulted in periodic appearance of conditions favouring the formation of extensive peat bogs in deltaic areas and on alluvial plains during glacial recession and periods of high water levels (Falcon-Lang, 2004; Falcon-Lang and DiMichele, 2010). The changes in climate and water level determine the intensity of vegetation and the rate of coal accumulation in the seams (Van den Belt et al., 2015).

In the Lublin Basin, cyclic sedimentation in paralic deposits accumulated during the Serpukhovian is clearly marked (Skompski, 1996, 2003; Waksmundzka, 2010). Based on limestone intercalations Skompski (1996) suggested 500 ky sedimentary cycles. Waksmundzka (2010) found 11 depositional sequences from the Namurian A up to Westphalian B, associated with eustatic sea level changes. Their roughly estimated duration is ~15 My, considering the general age framework. The Lublin Formation presenting one depositional sequence (Waksmundzka, 2010), probably deposited during ~1 My. Geochemical study of this formation suggests a warm climate during its deposition but with some arid episodes (Krzeszowska, 2019) of some hundreds of kiloyear probable periodicity.

In the Upper Silesian Coal Basin, peat bog development occurred in a coastal-marine, deltaic environment during the Mississippian (Gradziński and Doktor, 1996; Kędzior et al., 2007). Within the Paralic Series the cyclical changes of sedimentary conditions are marked by the occurrence of claystones with a marine fauna (marine horizons) with non-marine mudstone interbeds (Matl, 1971; Gastaldo et al., 2007). This allows the recognition of five megacycles (Kotas and Malczyk, 1972) and as many as 54 shorter cycles (Gastaldo et al., 2009), of ~100 ky duration (Jirásek et al., 2018). During the Pennsylvanian, deposition of the coal-bearing series took place far from the sea-shore, on an alluvial plain (Gradziński et al., 2005; Kędzior et al., 2007), but in the varied sedimentary framework. The deposition of the Upper Silesian and Krakow Sandstone series is considered to have been dominated by a braided river environment, whereas the deposition of the Mudstone Series was dominated by meandering and anastomosing rivers and shallow ephemeral lakes (Doktor and Gradziński, 1985, 2000; Doktor et al., 1997; Kędzior et al., 2007). In the case of both sandstone series, increased clastic material input was caused by tectonic movements in the source area located at the basin margin (Gradziński et al., 1995; Paszkowski et al., 1995). The cyclical changes of sedimentary conditions in the Pennsylvanian is less clear, but is marked by repeated sedimentary sequences (Dembowski and Unrug, 1970) and changes in grain size and depositional environment of the clastic sediments (Doktor et al., 1997). Clear sequence boundaries also mark stratigraphic gaps (Table 1; Kędzior, 2016).

The resource variations of coal seams in the Upper Silesian Coal Basin, described in the stratigraphic succession from the Mississippian to Pennsylvanian, reveal 6 periods of increased coal accumulation independently of short and episodic changes. Distinctly increased coal accumulation events occurred in the early and declining stages of the Serpukhovian (late Pendleian and late Arnsbergian respectively). During the Pennsylvanian, increased coal accumulation and formation of high-resource seams occurred during the formation of the lower part of the Upper Silesian Sandstone Series (Namurian B-Kinderscoutian), at the boundary of that series and the lower part of the Mudstone Series (upper Namurian C, Yeadonian and lower Westphal A, lower Langesetian), and within the Krakow Sandstone Series (Westphalian C, upper Duckmantian). Less clearly, an episode of increased coal accumulation is also marked in the Mudstone Series, at the Westphalian A and B (Langesatian and Duckmantian) boundary.

In the Lublin Basin, within the Lublin Beds formed during the Middle Pennsylvanian (at the Westphalian A and B boundary), a single interval of increased coal accumulation is visible. It may be compared with a less well-defined interval in the Mudstone Series in the USCB at the same time.

The exact age of individual coal seams is not known, but a general age framework of their formation can be estimated. In the lower part of the Paralic Series, at the bottom of the Hrušov Beds there is a whetstone horizon level whose age is 327.3 Ma (Jirásek et al., 2013). The age of deposits formed in the marine environment at the end of the Mississippian is ~324 Ma (Davydov et al., 2010; Pointon et al., 2012; Jirásek et al., 2018). The time of deposition of Pennsylvanian coal-bearing formations (Bashkirian and Moscovian) is between 323.4 and 307.02 Ma (Lucas et al., 2022). However, in the USCB, it is shorter due to a depositional gap at the Mississippian-Pennsylvanian boundary which, according to Kędzior (2016), occurred during the Chokerian and Alportian interval (upper Namurian A). Based on the time scale of Davydov et al. (2010) and Pointon et al. (2012) it can be estimated that this gap lasted ~2–3 My. The closing age of the sedimentation of the coal-bearing series is not determined, but it probably occurred before the end of the Moscovian Stage. The uppermost member of the coal-bearing series, the Libiąż Beds, formed during the Westphalian D (Asturian), are separated from the older members by a depositional gap covering the uppermost part of the Westphalian C, as evidenced by a marked change in floral assemblages (Kotasowa, 1979). Sedimentation during the older part of Pennsylvania (up to Westphalian C), took place therefore, roughly between 320 and ~310 Ma. Within the presented age framework, the distinguished two periods of increased coal accumulation in the Serpukhovian and four in the Pennsylvanian periods were repeated every 1 to 4 My or so (Fig. 7).

Long-term, 10^6 year, sedimentary cycles are found in many areas where Upper Carboniferous strata occur. In the USCB, detailed previous sedimentological studies have identified short-term cyclicity in the lithofacies changes of clastic sediments of the Mudstone and Krakow Sandstone Series, and long-term trends in their variation (Doctor et al., 1997). Statistical analysis of variation of sedimentary features shows that the period of their long-term changes was 2.5–2.7 My in the Mudstone Series and 1.25–2 My in the Krakow Sandstone Series. Within the Mississippian coal-bearing Paralic Series (Ostrava Formation) studied in the Czech part of USCB Jirásek et al. (2018) found 0.7 and to ~1.0 My durations of megacycles marked by principal marine bands.

Long-term complex transgressive-regressive cycles of 2–3 My defined by sedimentary sequences have been recognized in Namurian and Westphalian successions in NW Europe and the Moscow Basin (Izart and Vachard, 1994), and in the Donetsk Basin with a period averaging ~1.6 My (Eros et al., 2012). In North America, cycles of 1.2–4 My and an average of 2 My have been observed (Ross and Ross, 1987), and in the Appalachians in the Lower and Middle Pennsylvanian formations with an average of 2.5 My (Chesnut, 1994; Aitken 1996). These are interpreted as the result of climate change and eustatic movements associated with changes in polar ice caps and subsidence from tectonic processes (Izart and Vachard, 1994; Heckel, 1994; Haq and Shutter, 2008). Tectonic movements are considered a most likely cause of regional variation in eustatic processes (Ruban, 2012). The long-term cyclicity of

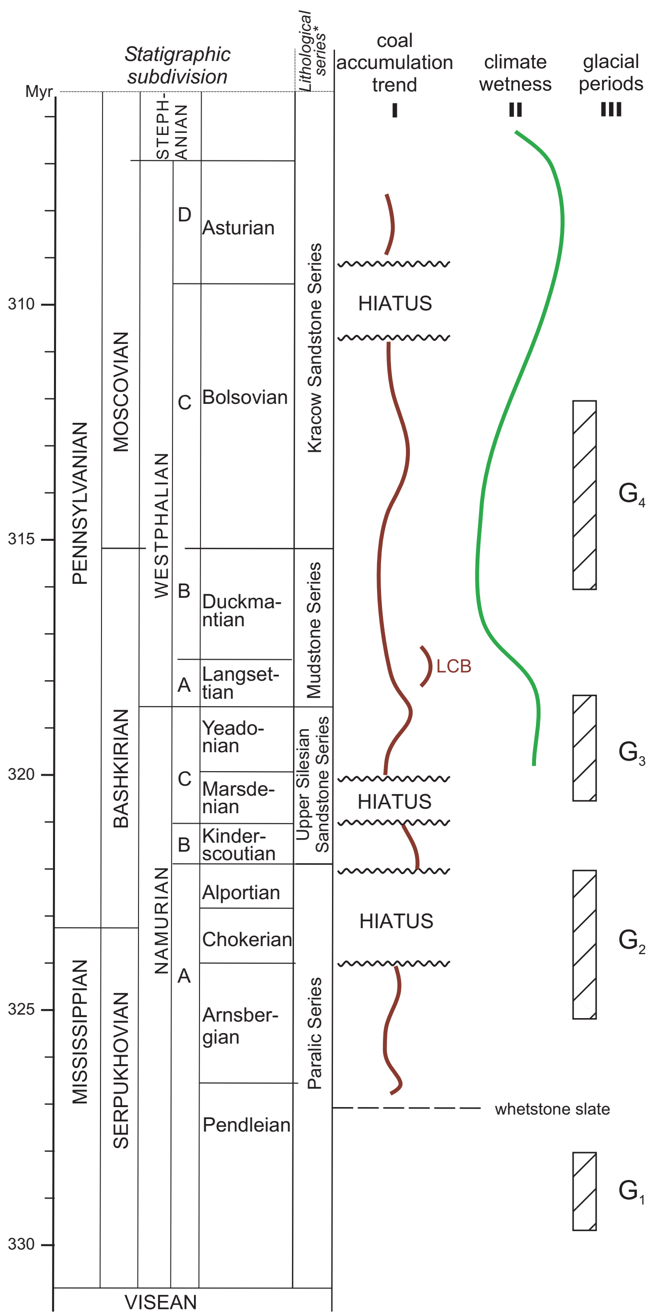

Fig. 7. Time-related coal seam resources variation in the USCB (I) *versus* general climate humidity and glacial periods); time scale according to Davydov et al. (2010), Pointon et al. (2012) modified following Lucas et al. (2022), climate wetness (II) according Phillips and Peppers (1984); glacial periods (III) according to Fielding et al. (2008a, b); * – for local stratigraphy see Table 2

climate variation can be related to long-term changes in the Earth's orbit: eccentricity with a period of 2.6 My and inclination with a period of 1.3 My (Crampton et al., 2018). It is also supposed to be related to changes in cosmic radiation as the solar system moves through the galaxy (Shaviv, 2002). The causes of long-term climate and eustatic process change, however, are still puzzling.

During the well-documented icehouse in the Late Carboniferous (Veevers and Powell, 1987), glacial and interglacial periods are distinguished based on sedimentological and isotopic data ($\delta^{13}C$, ^{18}O) (Montañez et al., 2007, 2016; Fielding et al., 2008a, b; Gulbranson et al., 2010). Their location in time and duration are variously presented (Gulbranson et al., 2010; Eros et al., 2012; Isbell et al., 2012) but indicate long-term climate change over periods of 10^6 years and the occurrence of a humid climate in tropical areas during the glacials, and a dry climate during interglacials (DiMichele, 2014). In the low latitude (equatorial) belt encompassing present-day North America and Europe, intense vegetation development took place, particularly when the climate was humid (Gastaldo et al., 1996; Cleal and Thomas, 2005).

Palaeobotanical data corroborate that during the Mississippian and Pennsylvanian there were repeated periods of humid and drier climate. Phillips and Peppers (1984) observed that these find response in coal resource variations. A humid climate prevailed from the late Mississippian (Namurian A) to Middle Pennsylvanian (Westphalian A) and in the Middle Pennsylvanian-Moscovian (Westphalian C and D), while a less wet climate prevailed from the end of the Westphalian A and in the Westphalian B (Phillips and Peppers, 1984; Cecil et al., 1985). At the same time, 2 glacial periods are distinguished (Montañez and Poulsen, 2013), whose peak occurred at the Serpukhovian-Bashkirian boundary, and at the beginning of the Moscovian. Fielding et al. (2008a, b), based on studies in Australia, distinguished four glacial periods during the Serpukhovian and Pennsylvanian: in the Lower Serpukhovian (lowest Namurian); the final Serpukhovian and Lower Bashkirian (middle Namur); the Middle Bashkirian (highest Namurian-lowest Westphalian); and the Lower Moskovian (upper Westphalian). In Argentina, two glacial periods were determined at that time in the lower Bashkirian and lower Moscovian (Gulbranson et al., 2010). Glacial sediments recorded in different areas of Gondwana at different times, suggest that these were mountain glaciations (Isbell et al., 2012). Their location and equilibrium line altitude were determined by orogenic processes.

A characteristic feature of the variation in the Pennsylvanian coal seam resources formed in the terrestrial environment of the USCB and LCB is the tendency for their periodic increase and, after reaching a local maximum, to gradually decrease. A similar organization of the succession of seam resources in the profile of a coal-bearing series, that is, variations in their thickness and extent, have been observed in other coal basins: the central Appalachian (Aitken, 1996); the Black Warrior in Alabama (Gastaldo et al., 1993); and the Gennedah in Australia (Hamilton and Tadros, 1994). The observed trends in coal seam resource changes in the USCB and LCB suggest that they are driven by long-term gradual changes in climate, as they occur independently of both general changes in sedimentary conditions and in their cyclic short-term variability.

The variation of coal seam resources in the USCB in the Serpukhovian and lower and middle Pennsylvanian and the observed trend of gradual changes in coal seam resources in the Pennsylvanian indicate complex, gradual, long-term climate change and the occurrence of 6 climate periods in this area, favouring lush vegetation and the formation of extensive peat bogs and coal seams. During the period of a less humid climate, formation of the Mudstone Series took place, in which numerous coal seams with smaller resources are present.

The changes described in coal accumulation intensity in the USCB and LCB are generally consistent with global changes in climate and glaciation (Fig. 7). These changes were nearly simultaneous in the tropical equatorial zone in which the two basins were located during the Carboniferous and in the polar areas of Gondwana. The variation in their duration may reflect the observed changes in the location of glaciation centres and their extent (Isbell et al., 2012; Montañez and Poulsen, 2013).

Changes in atmospheric CO_2 content are thought to be the main reason for climate change and glaciation, caused by coal capture in carbonate sediments in the Visean (Dyer et al., 2015), and subsequently in the Serpukhovian and Pennsylvanian in extensive peat bogs (Montañez et al., 2007, 2016; Frank et al., 2008; Montañez and Poulsen, 2013; Wilson et al., 2017). However, this relationship appears more complex. The abundant vegetation development may have resulted from the input of significant amounts of volcanic CO_2 into the atmosphere (Calder and Gibling, 1994; Oyarzun et al., 1999). Numerous signs of concurrent volcanic activity during the sedimentation of the coal-bearing series have been found in the USCB (Figs. 4 and 5). These include (Ryszka and Gabzdyl, 1986; Martinec and Dopita, 1997) tuffites, whetstones, bentonites, igneous intrusions, "tonsteins" (transformed-argillitized volcanic ash interbedded with coal seams), and admixture of pyroclastic material in sandstones (Kowalski and Matl, 1971; Świerczewska, 1995). Signs of volcanic activity have also been found in the LCB (Lipiarski et al., 1993). The exceptional, spectacular formation of seams "510"–"506" of very high thickness, in the USCB, occurred after a period of mountain-forming movements on the Mississippian-Pennsylvanian boundary ("Erzgebirge" phase). These may have been facilitated and supported by high CO_2 contents of volcanic origin. The finding of low $\delta^{13}C$ values near the end of the Mississippian and episodic reduction to ~–5‰ leads to such a conclusion (Bruckschena et al., 1999; Grossman et al., 2002; Saltzman, 2003), as volcanogenic CO_2 is characterized by low $\delta^{13}C$ values, <0‰ (Chiodini et al., 2011). Subsequent carbon fixation by vegetation cover during the Pennsylvanian caused an increase in $\delta^{13}C$ (Mii et al., 2001). The abundant forest cover in the low latitude belt, in turn, caused the binding of significant amounts of atmospheric CO_2 (Berner, 2003; Cleal and Thomas, 2005; Montañez and Poulsen, 2013) and reduced the "greenhouse effect". This favoured the development of an ice cap in the polar zone (Cleal and Thomas, 2005; Frank et al., 2008; Feulner, 2017).

CONCLUSIONS

The variability of coal seam resources in the USCB suggests cyclical long-term, gradual climatic changes in the Serpukhovian and early and middle Pennsylvanian in the area now encompassing central Europe. Periodically, every 1–4 My, there were conditions allowing for lush vegetation development and the creation of extensive peat bogs. These overlapped with short-term climate changes resulting from Milankovitch cyclicity and local autocyclic, intra-basinal changes in sedimentary conditions. The formation of coal seams with large resources could have been favoured in particular by high climate humidity, and periodic changes in the rate of diastrophic movements, as well as the abundance of atmospheric CO_2, the source of which may have been volcanic processes.

Periods of increased coal accumulation intensity in the USCB and LCB in the Serpukhovian and Pennsylvanian periods occurred during the development of glaciations across Gondwana, indicating that global climate change was a common cause. The similar timing of intense vegetation development in equatorial tropical areas and glaciation in polar areas also indicates that the reduction of atmospheric CO_2 by its binding by vegetation was probably compensated by its volcanogenic input.

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