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# Peat formation dynamics in the meandering fluvial system of the Mudstone Series (Middle Pennsylvanian), Upper Silesian Coal Basin, Poland

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The Mudstone Series (Langsettian–Duckmantian) in the Upper Silesian Basin of Poland is contemporaneous with the main coal-bearing interval of tropical Pangea. The strata were deposited in a continental setting outside the direct reach of glacioeustatic sea-level oscillations. Facies and architectural analyses of the unit provide evidence that the principal depositional environment of the Mudstone Series was a meandering fluvial system with channel belts that followed the NNE-striking basin axis. Amalgamation of these channel belts resulted in laterally widespread sheet-like sandstone bodies up to several tens of metres thick with internal erosional surfaces, which are sandwiched within dominantly fine-grained floodplain facies bearing coal seams. About 24–71 coal seams of the Mudstone Series are at least locally >1 m thick and economically important. Peat swamps formed by paludification of widespread floodplains that were dissected by active channels and upon which there were shallow lakes. Petrographic analysis indicates that the precursors of most coal beds were wet forest to mixed peat swamps colonised by arborescent – shrubby vegetation, whereas herbaceous peat-forming wetlands were subordinate and concentrated in the eastern, less subsiding part of the basin. Coal seams derived from forest to mixed peat swamps are dominated by bright coal lithotypes composed of vitrinite/vitrite which, together with intercalated clastic bands and an ash yield of 17 wt.%, suggest a high degree of waterlogging and a rheotrophic character for most peat swamps. Local coal bands rich in fusain lenses may record a temporarily lowered water table when the exposed surface was prone to wild fires. Although forest swamps generally occupied proximal parts of the floodplains, mixed peat swamps preferred distal areas that were less affected by active fluvial channels. Coal resulting from forest swamps is characterised by alternating bands of thick telinite and collotelinite derived from arborescent vegetation. Mixed peat swamps generated coal with a higher proportion of collodetrinite and inertodetrinite rich in sporinite derived mostly from shrubby plants. Herbaceous vegetation resulted in dull coal lithotypes only: durain, clarain-durain and durain-clarain, composed of detrital macerals, mainly inertodetrinite, vitrodetrinite and sporinite.

Key words: Late Carboniferous, tropical Pangea, depositional environment, coal-bearing succession, stratigraphic architecture, coal facies.

## INTRODUCTION

The Upper Silesian Basin, one of the largest coalfields in Europe, provides a valuable opportunity to study a variety of sedimentary palaeoenvironments, including seashores with barriers, fluvial systems, deltas and lakes (Podio and Wieja, 1960; Doktor and Gradziński, 1985; Mastalerz and Smyth, 1988; Gradziński and Doktor, 1996; Doktor et al., 1997, 1999; Doktor and Gradziński, 1999; Gmur et al., 1999; Kędzior, 2001, 2008, 2016; Gmur and Kwiecińska, 2002; Doktor, 2007; Opluštil et al., 2019, 2024). Until now, the Mudstone Series (Langsettian–Duckmantian) in the Upper Silesian Basin has been studied separately from the perspectives of sedimentology (Doktor and Gradziński, 1985) and coal composition and its properties (Krzeszowska, 2004; Gorol, 2004; Adamczyk et al., 2014; Parzentny and Róg, 2020; Kędzior and Teper, 2023; Sosnowski and Jelonek, 2023). The sedimentary environment is one of the key factors controlling peat accumulation. Recognising the sedimentary environments of coal-bearing sequences is thus important for understanding the geometry of coal beds including seam thickness, continuity, splitting, as well as quality parameters such as ash yield and sulphur content. This research is one the first attempts to characterise the clastic depositional system of the Mudstone Series and its effect on

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peat accumulation. The main objective of this study is to integrate the results of analysis of the clastic (dominantly fluvial) depositional system with data on the composition and geometry of the coal seams to characterise their peat swamp hydrology and prevailing type of vegetation. This, in turn, will help to better understand the spatial variability and temporal dynamics of the depositional systems represented by the Mudstone Series. This goal requires studying the interplay between the peat swamps and co-existing fluvial channels based on examination of the transition between the phytogenic deposits (coal) and the clastic deposits of contemporaneous channels. Achievement of those targets requires careful identification and correlation of individual coal beds and observations of their transition to contemporaneous channel deposits, which is not always easily accomplished based on data from boreholes located between mining fields. Therefore, these analyses only focus on mining areas where the identification of coal seams was verified by underground observations yielding a large concentration of data. The results improve our understanding of the formation of peat swamps in the meandering fluvial system of the Mudstone Series (Langsettian–Duckmantian), one of the principal coal-bearing units in the Upper Silesian Basin.

## GEOLOGICAL SETTING OF THE BASIN AND STRATIGRAPHIC POSITION OF THE MUDSTONE SERIES

The Upper Silesian Basin (USB), situated along the Polish-Czech border (Fig. 1A, B), is an erosional relic of a large sedimentary basin formed in the eastern part of the Variscan foreland of the Moravo-Silesian thrust and fold belt on the Brunovistulicum block (e.g., Kotas, 1995; Kalvoda and Bábek, 2010). The total composite thickness of the coal-bearing succession in this foreland basin reaches 8500 m; however, due to eastward migration of the depocentre and post-Carboniferous erosion, the maximum thickness in any one place does not exceed 4000 m (Kotas, 1995). A complete succession of the coal-bearing strata is only preserved in the larger Polish sector of the basin, where it is divided into four large units (Fig. 1C), traditionally called “series” (Dembowski, 1972). With the exception of the oldest Paralic Series, the overlying three units, the Upper Silesian Sandstone, Mudstone, and Kraków Sandstone series, lack marine fauna and are of continental origin.

The concept of the Mudstone Series, the target of our study, was introduced by Dembowski (1972) and further developed by Porzycki (1972). The lower boundary of the Mudstone Series is located at the Hubert freshwater faunal horizon (Porzycki, 1972), whereas the upper boundary is marked by a lithological change from a succession of dominantly floodplain facies to coal-bearing strata dominated by thick, poorly sorted sandstones of the Kraków Sandstone Series (Doktor, 2007). The maximum thickness of the Mudstone Series exceeds 2000 m near the western edge of its present-day range, and reduces significantly towards the east due to decreasing subsidence on approaching the eastern margin. The full original thickness is preserved only in the central and eastern parts of the basin where it is overlain by the Kraków Sandstone Series (Fig. 1C); in other places, preservation is incomplete due to post-Carboniferous erosion. The Mudstone Series is divided into the Załęże Beds (Langsettian) and the Orzesze Beds (Duckmantian), with the boundary between them in the roof of the Stanislaw freshwater faunal horizon accompanied by a tuffogenic band. The number of coal seams in the Mudstone Series varies spatially, with a maximum of 150 coal beds, of which up to 70 locally reach economical significance and are mined. Numbering of the coal seams increases towards the base of the series (Doktorowicz-Hrebnicki and Bocheński, 1952). The oldest coal seams are numbered 407–327 of the Załęże Beds and are overlain by coal beds 326–301 of the Orzesze Beds.

The predominance of fine-grained (mudstone) siliciclastic deposits above coarse-grained sand bodies and the presence of numerous siderite nodules distinguish the Mudstone Series from the underlying and overlying units. A composition and provenance analysis of the sandstones by Świerczewska (1995) indicate a recycled orogen as the source area, with a dominance of metamorphic rocks. The sideritic nodules, typically several centimetres in diameter, are commonly concentrated in clusters or horizons a few to about ten centimetres thick. In the coarse-grained deposits, nodules commonly occur as redeposited intraclasts in conglomerates interpreted as channel lags (Doktor and Gradziński, 1985; Doktor et al., 1997). Plant macro- and microfossils are abundant in the Mudstone Series (cf. Kmiecik, 1995; Kotasowa and Migier, 1995). Faunal remains are typically sparse, except in a few widespread lacustrine horizons (e.g., Hubert and Stanisław freshwater faunal horizons). The fauna is represented by the remains of thin-shelled bivalves accompanied by phyllopods, ostracods, polychaetes, scales and bones of fish, and rare insect wings (Musiał et al., 1995).

Until the 1970s, interpretation of the Mudstone Series was limited to the very general interpretation of a fluvial origin for the sandstone bodies (Unrug and Dembowski, 1971), and for the possible existence of large freshwater lakes (Porzycki, 1972). Later studies of Radomski and Gradziński (1978, 1981), Kotas (1977), and Doktor and Gradziński (1985) interpreted deposition of the Mudstone Series on an extensive low-gradient alluvial plain drained by high-sinuosity meandering rivers, which transported mainly suspended fine-grained particles. These authors also interpreted the vertical changes in facies to be controlled by autocyclic processes. The fine-grained sediments were primarily deposited on vegetated floodplains, with a smaller proportion in shallow and short-lived floodbasin lakes. Sand was mainly deposited in major fluvial channels and in overbank areas as crevasse splays, i.e., in crevasse channels and proximal splay areas. Peat swamps formed in poorly drained areas of distal floodplains, under conditions of considerably reduced clastic supply (Doktor and Gradziński, 1985). The large-scale changes of the sand/mud ratio are attributed to an interplay of the basin subsidence rate and the rate of clastic sediment supply from the Variscan orogen (Gradziński, 1982), with the lateral and vertical variation in phytogenic accumulation controlled mainly by fluvial autogenic factors (Doktor and Gradziński, 2000).

## DATA AND METHODS

The data used in this article comes from more than 230 boreholes, former brickyards and underground mine galleries. The information was used to construct geological cross-sections, maps and diagrams illustrating the stratigraphic architecture and petrographic composition of selected coal seams. Several study methods were employed. They are briefly described below.

### FACIES ANALYSIS

The description of facies and their associations is based on the previous studies of Doktor and Gradziński (1985), who documented deposits of the Mudstone Series in numerous temporary exposures (mostly brick pits), boreholes, and mine galler-

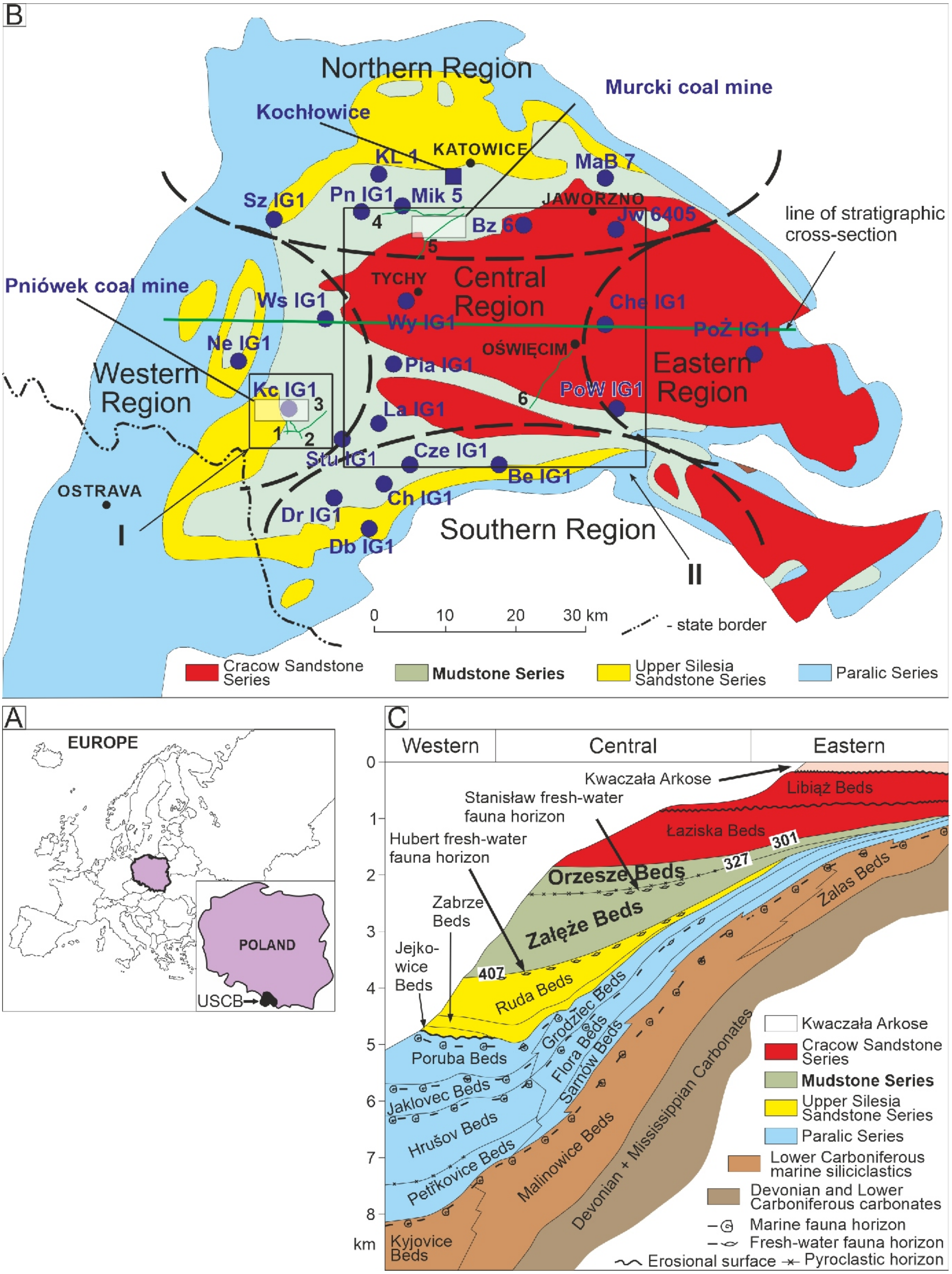



**Fig. 1. Location maps and stratigraphy of the study area, distribution of boreholes, coalfields, and exposures yielding data for coal facies analysis, and location of correlative cross-sections over the Upper Silesia Coal Basin map of Kotas (1994)**

**A** – location of the Upper Silesia Coal Basin in Europe; **B –** simplified geological map of the Upper Silesia Coal Basin (based on Buła and Żaba, 2005); **C** – stratigraphic cross-section of the coal-bearing succession of the Upper Silesia Coal Basin (after Kotas, 1995); I – area mapped in Figures 14 and 15; II – area mapped in Figures 16–18; note, arabic numbers indicate location of Figures 7–12: 1 – Fig. 7, 2 – Fig. 8, 3 – Fig. 9, 4 – Fig. 10, 5 – Fig. 11, 6 – Fig. 12

ies. Based on distinctive lithological features, including composition, grain size, bedding characteristics, sedimentary structures, and the presence of coalified plant material, Doktor and Gradziński (1985) distinguished 12 lithofacies. They determined the scale of an individual lithofacies by considering the variability of the succession and conducting a detailed local study, describing the lithofacies at a scale of 1:100. We provide here a slightly modified version supplemented by data from detailed descriptions (1:100 scale) of 22 boreholes (Fig. 1B) with total core length >10,000 m. Facies are defined based on: (i) sediment grain-size and its variation; (ii) sedimentary structures; (iii) the shape and composition of clasts and framework/matrix relationships; (iv) the nature of bed contacts; and (v) the preservation and taphonomy of fossils. The facies described are grouped in facies associations that are thought to be genetically or environmentally related (Collinson, 1969). According to Walther's Law, as depositional environments migrate laterally, the sediments of one environment come to lie on top of sediments of the adjacent environment. Thus, a two-dimensional picture of the depositional architecture can be built on the basis of the vertical variability of the lithofacies.

## STRATIGRAPHICAL ARCHITECTURE OF THE MUDSTONE SERIES

Strata of the Mudstone Series do not form suitable exposures, but a dense network of boreholes covers their area of preserved extent. Selected boreholes were used to construct several cross-sections to visualise the architecture of the coal-bearing fluvial strata. In the Mudstone Series, there are only a few easily identifiable and widespread correlation markers. The most important of these is the Hubert freshwater faunal horizon, the top of which marks the base of the Mudstone Series. The second marker is a tuffitic layer associated with the Stanisław freshwater faunal horizon, the latter defining the boundary between the Załęże and Orzesze Beds. Using coal seams as correlation horizons is problematic because the seams in each mine are numbered independently of those in neighbouring mines. As a result, the same coal can have different numbers in different coal mines. Correlation of coal seams among mining fields, therefore, requires confirmation by mining works (Gradziński, 1994) or construction of correlation panels between neighbouring mines.

## ANALYSIS OF COAL SEAM THICKNESS AND GEOMETRY

Data on the thicknesses of various sedimentary bodies (e.g., coal beds and sandstone lithosomes) were extracted from mining maps and boreholes and plotted onto an Excel spreadsheet. The collected data were, in turn, used to construct thickness maps for selected coal seams, supplemented by thickness maps for clastic deposits overlying or underlying the coal seams studied, or their stratigraphic equivalent where coal is not developed (e.g., tuff in the coal seam 328). Thickness maps of clastic intervals include the package up to the first prominent change in lithology. Individual packages thus represent the thickness of the fine-grained or coarse-grained clastic facies below/above a coal seam. For the purpose of reconstructing the geometries of coal-bearing strata based on archival drilling materials, a simple classification of in-channel deposits, based on their thickness, was applied. Based on analysis of the thickness range of sandstone channel bodies by Gibling (2006), it has been arbitrarily assumed for the purpose of this work that sandstone bodies with a thickness of at least 1.5 m are treated as fluvial channel deposits, while those that are thinner represent crevasse channels or the proximal parts of crevasse splays. First-hand observations in mine galleries by the authors and coal mine geologists provided additional information on thickness changes of the coal seams related to differential compaction and the interaction of coal with contemporaneous fluvial channel deposits.

## MACRO- AND MICROPETROGRAPHIC ANALYSIS OF THE COAL SEAMS

To reconstruct the hydrological character of the peat swamps (e.g., ombrotrophic/rheotrophic) represented by the Mudstone Series, and their prevailing vegetation type (arborescent/herbaceous), lithotype, microlithotype and maceral analyses supplemented by sulphur and ash yield data of coal seams from selected boreholes and coal mines were carried out. These boreholes and mines were located in (i) western; (ii); (iii) central; (iv) southern, and (v) eastern regions of the basin (Fig. 1B).

Lithotype analyses of coal seams of the Orzesze and Załęże beds were performed on one borehole for each of the five above-mentioned regions (Table 1). The lithotype terminology proposed by Lipiarski (1975) and further refined by Pokroński (1994) was used. The vertical succession of the lithotypes provided information on the hydrological history of the peat swamp precursors of the coal beds (Diessel, 1992; Taylor et al., 1998). Six hydrological types of peat swamps (see Figs. 17, 18 and Sup. Fig. 5), characterised by their prevailing type of vegetation and degree of waterlogging, were defined as associations of lithotypes and their textural features (Pokroński, 1994). The lithotype composition and their vertical order roughly reflect the vegetation components. Bright and banded bright coals composed of vitrain are interpreted as originating from forested, continuously wet swamps (telmatic swamps) whereas bright coal with thin bands of durain with fusain lenses indicate relatively drier forest swamp. In contrast, dull coal varieties (banded and banded dull coals) are interpreted as originating from herbaceous swamps (Kalkreuth and Leckie, 1989).

Determination of the microscopic components (macerals and microlithotypes) of the coal samples was performed with a *ZEISS* Axioscope under reflected light using immersion lenses at 200x and 500x magnification. Quantitative analysis of macerals was carried out according to the recommendations of the International Committee on Coal Petrology (ICCP; Stach et al., 1982). ICCP nomenclature (Stach et al., 1982; Taylor et al., 1998) was used to describe the microlithotypes and macerals. Maceral analysis was performed on individual lithotypes from two coal seams sampled in mine galleries (seam 403/1 in the Pniówek coal mine and seam 330 in the Murcki coal mine) and for the coal seam in the Kochłowice exposure. Both coal seams sampled in the Pniówek and Murcki coal mines were also studied for microlithotypes. This analysis was further applied to channel samples representative of the full thickness of particular coal seams sampled from 22 boreholes located in all parts of the USCB (Fig. 1B).

The maceral composition of coal seams 403/1 (Pniówek mine), 330 (Murcki mine), and from the Kochłowice exposure was used to calculate the GI (Gelification Index). This indicates the degree of waterlogging of the peat swamp, and the TPI (Tissue Preservation Index) as a proxy for identification of the type of vegetation and/or intensity of decomposition (Diessel, 1986, 1992). Plotting these indices against the x- and y-axes defines the peat-forming sub-environments and character of the vegetation.

The microlithotype composition of coal beds was plotted on the facies diagram of Hacquebard and Donaldson (1969). It defines four types of peat-forming environments: (i) ombrotrophic

Table 1

**Facies and facies associations of the Mudstone Series and their interpretation**

| Lithofacies table based on Doktor and Gradziński (1985) | | | |
|---|---|---|---|
| Lithofacies association | Lithofacies | Description | Interpretation |
| In-channel deposits | **CGi** infraformational conglomerate | Infraformational clast content >10%, clast composition: mudstone, coal and sideritic nodules, clast and matrix-supported, massive texture, mainly no clast gradation, less common normal or reverse gradation, sharp or erosional boundary with underlying deposits of the SL, Scd, and SH lithofacies, thickness up to several decimetres | Channel lag deposits from strong currents within fluvial channels. Short transport indicated by presence of non-resistant mud clasts (Jackson, 1981; Kędzior and Popa, 2013; Kędzior, 2016; Widera et a., 2019). |
| | **Scd** coalified plant debris-rich sandstone | Abundant large coalified plant remains (mainly stems and branches) embedded within fine- to medium-grained sandstone, wavy laminated or massive texture, associated mainly with CGi and SL lithofacies, thickness up to several decimetres | Large size of the plant remains and the absence of the lightest plant fragments (leaves) associated with sand sediments are indicative of deposition from strong currents. According to Gradziński et al. (1982), this is the result of successive immobilisation and burial of heavy, water-saturated plant fragments dragged along the bottom or moved above the river bed. |
| | **SH** planar parallel-stratified sandstone | Fine to medium-grained sandstones with primary horizontal lamination with lamina thickness up to 0.3 cm, thickness of the deposits up to 20 cm, usually covered by SR lithofacies | Texture is indicative of plane-bed transport and deposition of sand in the upper flow regime (Harms et al., 1982). Flood peak discharges with the flow too shallow for formation of dunes and with velocity too high for ripples (Miall, 1996; Bridge, 2003; Collinson et al., 2006). |
| | **SM** massive sandstone | Fine to medium-grained sandstones, well sorted, texturally massive or solitary, blurred streaks/laminae, when trending to SL, SH or SR lithofacies – quantity and visibility of the laminae increase, thickness varies from decimetres up to 2 m | Generated by hyperconcentrated flows driven by torrential flood and heavy water runoff or tectonic factors affecting water-laden deposits (Costa, 1984; Guzzetti et al., 2008; Norhidayu et al., 2016; Widera, 2017) or local sediment gravity flows (Jones and Rust, 1983; Wizevich, 1992) related to bar incision (Hodgson, 1978), or to development of small gullies resulting from bank collapse (Miall, 1996). |
| | **SL** large-scale cross-stratified sandstone | Fine to medium-grained sandstones, large-scale trough and planar tangential cross-stratification, lamina-set thickness up to several decimetres, 20–300 cm coset thickness, dip of laminae 20–30°, thickness of the lithofacies varies from several centimetres up to several metres, usually associated with SM, CGi, Sci and SR lithofacies | Deposits of transitional part of lower to upper flow regime (Harms et al., 1982) with subaqueous dunes (Ashley, 1990) as a component of migrating channel bars and bedforms of the late-stage thalweg channel-fill (Collinson, 1970; Bridge, 2003) indicating confined, channelised flow. |
| | **SR** ripple cross-laminated sandstone | Fine to medium-grained sandstones and siltstones ripple cross-laminated, 1–4 cm individual set thickness, 10–200 cm coset thickness, lamination usually marked by coalified fine plant detritus, mainly cosets of trough type, rare climbing ripples A and B-type sensu Jopling and Walker (1968), thickness of the lithofacies varies from several decimetres up to 3 m, usually connected with SL and HE lithofacies | Record of migration of ripples due to weak currents of lowest part of low flow regime (Harms et al., 1982). Climbing ripples are related to high rate of suspended grain deposition relative to the rate of ripple migration (Harms et al., 1982; Collinson et al., 2006). |
| Transitional zone deposits (Levee, abandoned channel, flood plain, point bar) | **HE** interbedded mudstones and sandstones with small-scale sedimentary structures | Heterolithic association composed of ripple laminated fine-grained sandstone and siltstone lenses and laminae interbedded with wavy- and planar-laminated mudstones and siltstones, variable mudstone/sandstone ratio from muddy sandstone if sandstone layers prevail to coarse-grained mudstone with sandstone lenses, thickness of the association varies from 10 cm up to 2 m, usually associated with SR and FH, transitional association between SR and FH lithofacies | Deposits of sand-starved muddy slack-water with unsteady pulsatory sand supply, episodic tractional delivery of sparse sand by weak currents insufficient to cover a muddy substrate. Although typical of submerged distal natural levees and overbank floodplains with slack-water ponds, it also occurs in abandoned river channels (Allen, 1963; Miall, 1996; Bridge, 2003) or high on point bars. |
| Overbank deposits | **FW** wavy laminated mudstone and claystone | Wavy to lenticular laminated mudstones and claystones with more or less elongated thin siltstone lenses, some with subtle ripple cross-lamination, 2–3 cm coset thickness, thickness of the lithofacies varies from several decimetres up to 4 m, usually associated with FM and FS lithofacies | Deposition of suspended material and from sporadic weak traction currents (small isolated ripples), typically of distal floodplain ponds and oxbow lakes of abandoned river channels (Miall, 1996; Bridge, 2003). |
| | **FH** planar-laminated | Planar parallel laminated fine-grained siltstones, mudstones and claystones with very thin and | Deposits of a sand-devoid slack-water environment with fluctuating supply of |

Tabl. 1 cont.

| | | | |
|---|---|---|---|
| | mudstone and siltstone | laterally stable laminae, thickness of the lithofacies varies from several decimetres up to 10 m, usually associated with FM and FS lithofacies | suspended muddy to silty load, typical of distal floodplain ponds and oxbow lakes of abandoned river channels (Miall, 1996; Bridge, 2003). Lacustrine environment indicated by fresh water faunal remains. |
| | **FM** massive mudstone and claystone | Mudstones and claystones with no mesoscopically recognisable sedimentary structures, in some parts visible subtle lighter bands, thickness of the lithofacies varies from about ten centimetres up to 10 m, usually associated with FW, FH, FS and C lithofacies | Deposition of muddy suspension in stagnant water or from very slow currents, typical of distal floodplain ponds and oxbow lakes of abandoned river channels (Miall, 1996; Bridge, 2003) or shallow lakes if fresh water fauna preserved. |
| | **FS** root re-worked mudstone and claystone | Mudstones and claystones with abundant coalified root system remains, strongly homogenised with no or faint primary lamination, numerous slickenside surfaces, thickness of the lithofacies up to several decimetres, usually occurs below C lithofacies, in some cases embedded within other mudstone lithofacies | Depositional conditions similar to FW, FH and FM lithofacies: vegetated ponds of distal floodplains free of sand supply (Rust, 1978; Bridge, 2003), substrate of lush vegetation, fossil soils. |
| | **C** coal and coaly shale | Mainly banded humic coal, carbonaceous shales and rare sapropelic coal, some thin clastic bands (mainly mudstone lithofacies) embedded within C lithofacies, thickness of the lithofacies varies from 1 cm up to 5 m, occurs directly above FS lithofacies | Sand-devoid peat and mixed peat-clastic swamps located on distal floodplains with variable and usually negligible mud supply of slack-water suspension. Association with FS lithofacies indicates autochthonous nature of the phytogenic material accumulations. |
| **L Lacustrine and lacustrine deltaic deposits** | | Mainly brownish grey, massive and parallel flat-laminated mudstones containing thin-shelled bivalves, thickness of the fauna-bearing layers highly variable (5–330 cm) interbedded with flat laminated dark grey coarse-grained mudstones and ripple cross-bedded fine-grained sandstones 30–150 cm thick arranged into coarsening upwards sequences. Fauna-bearing intervals up to 7 m in thickness embedded between humic coal beds | Deposition in relatively quiet waters. Quiet-water deposition of suspended mud and silt occurs during normal river discharges, with interbeds of coarser sediment supplied during large river floods, when crevasse splays form. Coarsening-upwards sequences are related to crevasse splay deltas (Elliot, 1974; Gersib and McCabe, 1981). The grain size of sediment within crevasse splays reflects transport in the parental river tract, and can even include coarse sands (Orton, 1995). Subtle lamination needs protection from high clastic input and strong bottom currents and lack of bioturbation (e.g., Degens and Stoffers, 1976; Stoffers and Hecky, 1978; Yuretich, 1979; Demaison and Moore, 1980; Crossley, 1984; Cohen, 1984). |
| **T** pyroclastics | | Tonsteins and tuff/tuffite beds, mesoscopically massive or with faint lamination, light to medium dark grey, brownish grey in colour, thickness varies from a few millimetres up to 70 cm, associated with various lithofacies, best preserved in coals and mudstone lithofacies | Ashfall deposits preserved typically in peat swamps (tonsteins) or intercalated in floodplain strata (tuff beds) some are locally or partly redeposited (tuffite). |

peat bog, which are purely rain-fed, not influenced by mineral-rich groundwater or surface water; (ii) forest-type peat bog in telmatic and limnotelmatic zones; (iii) herbaceous peat bog of telmatic and limnotelmatic zones; and (iv) open-water zones. Two other microlithotype-derived facies indices were used and based on modified microlithotype assemblages defining the tops of the Hacquebard-Donaldson facies diagram. The Forest Facies Index (FFI) is defined as the ratio between microlithotypes (FFI = vitrite + inertite + clarite (spore-poor) + vitrinertite/clarite (spore-rich) + clarodurite + duroclarite + durite + carbominerite) indicating a forest-like character of the fen and components derived from herbaceous vegetation. The Waterlogging Index (WLI) expresses the proportion of microlithotypes indicating high groundwater level versus microlithotypes (WLI = clarodurite + durite + carbominerite/inertite + vitrinertite + durite (spore-poor) indicating peatland drying (see Figs. 17 and 18). For the FFI, values >2 are inferred to indicate a peat bog dominated by arborescent vegetation. Values between 0.5 and 2 indicate peat accumulation in a swamp with a mixed vegetation assemblage, whereas values >0.5 suggest a herbaceous-type swamp. A higher water table is reflected in increased values of the WLI, whereas values <1 indicate a low or fluctuating water table in the peat swamp.

## RESULTS

### LITHOFACIES OF THE MUDSTONE SERIES

In their classic work, Doktor and Gradziński (1985) distinguished 12 lithofacies in the Mudstone Series. These were broadly subdivided into three facies associations, which correspond to three main sedimentary zones represented by river channel, overbank and peat swamp deposits, described briefly below. Their facies scheme is here adopted and supplemented by the facies association of lacustrine and lacustrine delta deposits. In all, we define 14 facies grouped into three facies associations (Table 1).

CHANNEL DEPOSITS

*Description:* Deposits that accumulated within fluvial channels are dominated by well-sorted, fine- to very fine-grained sandstones, with subordinate medium-grained sandstones and some interbeds of infraformational conglomerate composed of redeposited siderite nodules and mudstone clasts (see Doktor and Gradziński, 1985; Fig. 2). Channel deposits form sequences up to 30 m thick, but their average thickness is ~5 m. The bases of the channel units are usually erosional, commonly accentuated by the presence of intraclasts concentrated in horizons that may occur several times in thicker sequences. Sandstones generally display large scale cross-bedding with subordinate asymmetrical ripple lamination. The channel facies associations are usually arranged into fining-upwards sequences (Fig. 2). The thickness, succession of lithofacies, and sedimentary structures, which include lateral accretion surfaces, of the channel bodies show the greatest similarity to deposits of meandering (cf. Doktor and Gradziński, 1985) and partly also of anastomosing rivers (cf. Gradziński et al., 2005; Kędzior et al., 2007).

*Interpretation:* Accumulation of the sandstone bodies took place under general aggradation of the alluvial plain. The thickness of the sandstone bodies, the lithofacies sequence (CGi/SM/SH-SL-SR), and the set of sedimentary structures (epsilon cross-stratification, ripple cross- and flaser bedding) are usually arranged as fining-upwards sequences, typical of sediments that accumulated within low-gradient river channels of high sinuosity. The sandstones mainly accumulated in the form of side bars and, as a result of lateral migration of the meander belt, the laterally continuous sandstone bodies can be traced in individual exposures up to a distance of almost 100 m, while abandoned channel deposits were also recognised (Doktor and Gradziński, 1985).

OVERBANK DEPOSITS

*Description:* Channel deposits comprise only a small proportion of the Mudstone Series strata. The remainder are referred to as ‘overbank deposits’. This group includes sandstones that are <1.5 m thick, as well as siltstones, mudstones and phytogenic deposits. Overbank deposits can be significantly thicker, locally exceeding 100 m. Sandstones classified as overbank deposits occur within thick packages of fine-grained deposits and lack coarse grains. These are typically fine-grained SR lithofacies sandstones and heterolithic deposits (HE) bearing a variety of current structures. Fine-grained deposits, mainly mudstones, are dominantly massive (FM lithofacies), and can be bioturbated (FS lithofacies). Wavy laminated mudstones (FW lithofacies) and flat laminated mudstones (FH lithofacies) are less common. A characteristic feature of overbank deposits is the widespread occurrence of gradational transitions between individual lithofacies. Analysis of the vertical succession of lithofacies indicates the presence of sequences with both normal and reverse grain-size gradation. Vertical stacking of overbank lithofacies (Fig. 3) indicates the existence of four sub-environments (Doktor and Gradziński, 1985):

– Crevasse splays and crevasse channels usually consist of 2–5 m-thick bodies composed of fine-grained sandstones with siltstone and mudstone interbeds, locally arranged into coarsening-upwards sequences occurring within thicker fine-grained packages.
– Natural levees represented by assemblages several tens of centimetres thick of heterolithic sandstones and siltstones with ripple and lenticular lamination, commonly showing bioturbation and root traces.
– Shallow floodplain lakes and ponds recorded as relatively thin and laterally restricted successions of mudstones. These deposits lack roots but contain allochthonous plant remains. In some cases, the lacustrine deposits are overlain by coarsening-upwards sequences, which usually begin with massive mudstones passing upwards into laminated mudstones, heterolithic deposits, ripple-laminated sandstones, and finally by mudstones with root-reworked mudstones.
– Distal floodplains are represented by several-metres-thick successions of alternating fine-grained facies, with diverse sedimentary structures that indicate variable but generally weak currents (wavy, flaser, lenticular, and horizontal lamination, as well as massive beds), commonly interfingering with splay deposits. Root traces of wetland vegetation are typical.

*Interpretation:* Natural levees characterised by variable topography formed along the channels of low-gradient rivers. During high water levels (floods), depressions in the levees were the main routes for the dispersion of sediment from channels and onto floodplains, where it was deposited as crevasse splays. Deposits of crevasse channels and splays, and natural levees typically dominate in proximal parts of floodplains. Distal floodplains are devoid of the sandy fraction and are typically dominated by the deposits of clastic swamps, distal crevasse splays, and periodic lakes (see Doktor and Gradziński, 1985; their fig. 21). Where the distal part of a splay fed into a lake or pond, it forms a crevasse splay delta. Such sediments are associated with terminal splay and characterised by increase of the grain size and arranged into coarsening-upwards sequences (e.g., Elliott, 1974; Gersib and McCabe, 1981). Sedimentary structures (or their macroscopic absence) in the fine-grained deposits (e.g., massive, horizontally and wavy laminated mudstones, and thinner layers of ripple-laminated fine-grained sandstones and siltstones) indicate the predominance of deposition from suspension, only subordinately accompanied by weak traction currents. The occurrence of thick (up to 7 m) packages composed of a single lithofacies (FM, FW), or hydrodynamically closely related lithofacies, indicates the long-term prevalence of similar depositional conditions. The clastic material was deposited as suspended particles in overbank areas during floods. Deposition occurred not only during floods, but also after floodwaters had receded, such as in flood basins and ephemeral ponds where the water table persisted. Overbank deposits typically contain carbonised roots, but in some cases the mudstones lack root traces, which may indicate deposition in lacustrine environments, small ponds, or flood basins.

PALUSTRINE DEPOSITS

*Description:* These deposits are represented by several centimetres to >1 m thick beds of humic coal and/or intercalated carbonaceous mudstone occurring within fine-grained floodplain deposits derived from coarse-grained channel facies. Thin bands of sapropelic coal are intercalated in the coal beds. The deposits underlying coal beds are commonly densely rooted by *Stigmaria*, the rooting organ of lycopsid trees. Fine-grained, thinly bedded and locally laminated mudstones above the coal seams, which are devoid of roots and bear abundant plant remains, indicate that the cessation of peat accretion was due to drowning of the peat swamp. Clastic partings comprising rooted mudstones, with or without a coaly admixture, are present in many coal beds. The coal seams also are commonly split. Major coal seams are laterally widespread, although their correlation between boreholes is problematic due to the limited availability of correlation markers. Such markers

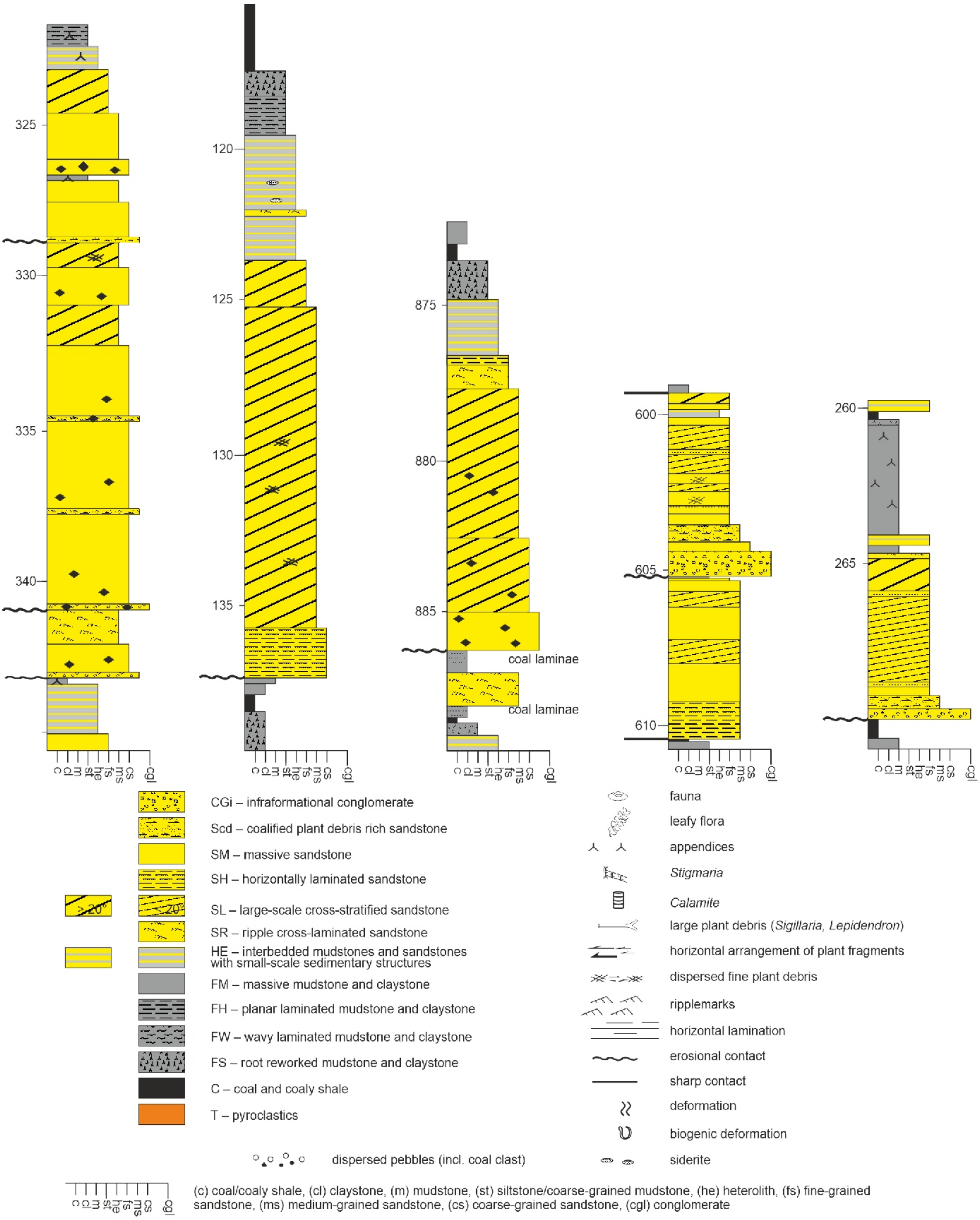



**Fig. 2. Examples of in-channel strata in the Mudstone Series**

Paniowy IG1 borehole with interpretation of the sedimentary environment

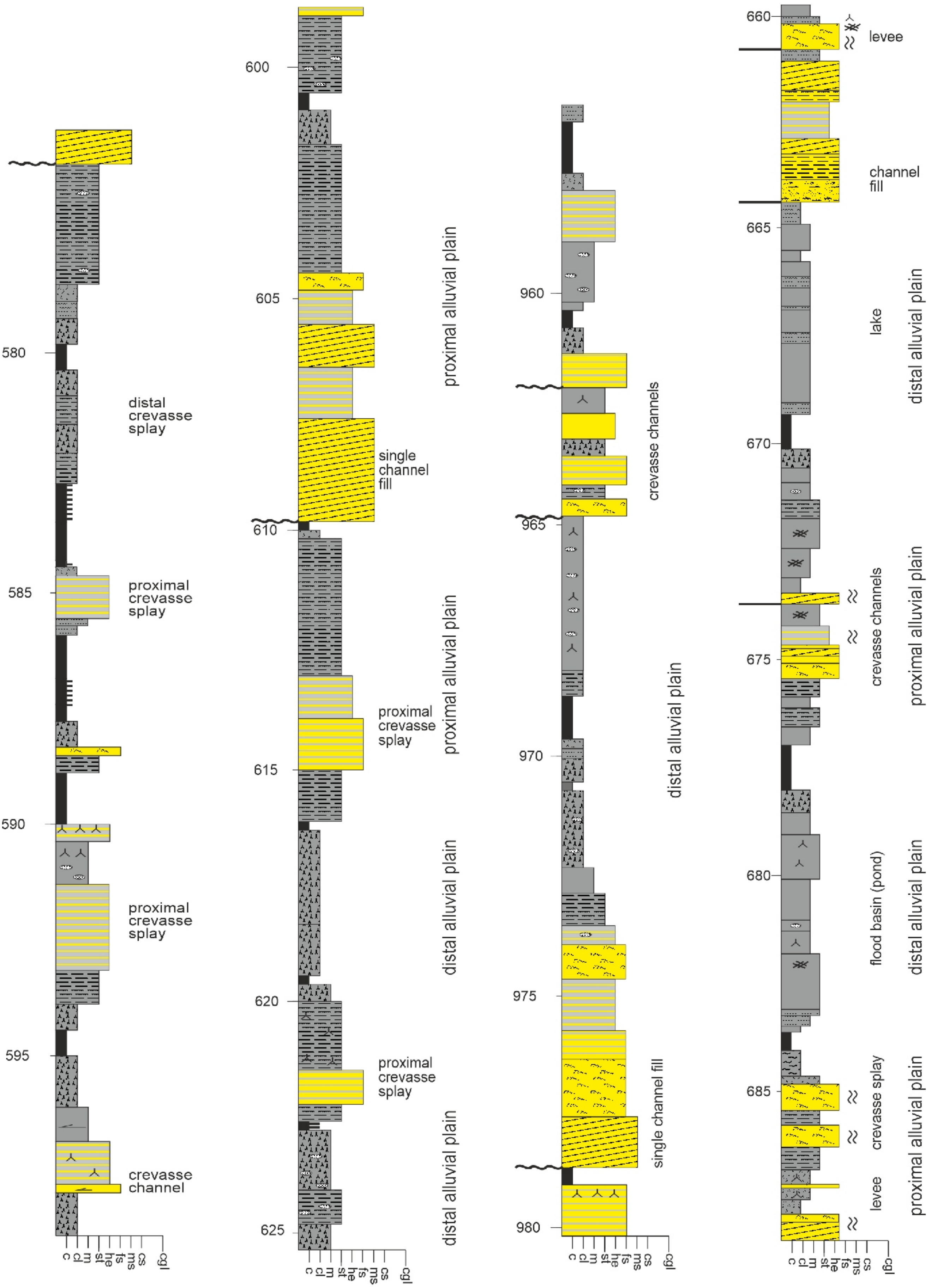



**Fig. 3. Examples of overbank strata in the Mudstone Series**

A–C – Paniowy IG1 borehole with interpretation of the sedimentary environment; D – Warszowice-Pawłowice 43 (WP 43) borehole include several tonsteins and tuff/tuffite beds (cf. Kuhl, 1955; Porzycki, 1972; Łapot, 1992), and the Stanislaw and Hubert faunal bands. In addition, variations in coal seam thickness and the effects of local wedging result in the discontinuous distribution of seams and their concentration in isolated patches (cf. Figs. 5–7 and Sup.Figs. 1–3).

*Interpretation:* Peat formation was typically restricted to areas of reduced clastic input. Mechanisms to restrict clastic material may have included relatively high natural levees or the baffling of flood waters by lush vegetation surrounding the river banks. Long-term peat accretion generating thick peat layers was related to water-table rise likely driven by a combination of various mechanisms. Besides long-term basin subsidence (Doktor and Gradziński, 1985), there would have been other allogenic mechanisms such as climate (Opluštil et al., 2013, 2019, 2022; Noorbergen et al., 2018) and autogenic factors such as local tectonics, avulsion or peat compaction (Doktor and Gradziński, 1985). Cited climatic models suggest that peat accretion was initiated by the transition from a seasonal to ever-wet climate mode, resulting in an upstream reduction of clastic input, a rising groundwater table, and subsequent paludification and peat formation. The cessation of peat accumulation could have been linked to increasing seasonality. Under a seasonal climate mode, higher aggradation of the fluvial channels exceeded peat accretion, which resulted in channel instability and avulsion that introduced clastic sediments into adjacent peat swamps (Noorbergen et al., 2018; Opluštil et al., 2022). It cannot be excluded also that base level changes related to sea level oscillations in the North Variscan Foreland Basin played a role. However, this hypothesis is currently difficult to test because connection between the USB and North Variscan Foreland Basin during the Pennsylvanian is not proven. Rooted mudstones intercalated within coal seams represent short-term extraordinary flooding events at millennial or longer scales, resulting in a temporary interruption of peat production and its subsequent recovery. Major flooding events could also have resulted in coal splitting. The dominantly banded (humic) character of coals underlain by rooted beds, and the presence of roots in some clastic partings, indicate that the precursors of the coal seams were swamps where peat formed by the humification and accumulation of autochthonous plant remains (e.g., Teichmüller, 1989; Diessel, 1992; Taylor et al., 1998). The occasional presence of sapropelic coals indicates that peat swamps either passed laterally from or gradually evolved into ponds, where plant detritus was deposited on an anoxic bottom. The local presence of clastic partings or increased ash yield (generally >10 wt.%) in the form of mud-sized clastic deposits indicates the coexistence of peat swamps with clastic sources, principally active fluvial channels. Some parts of the coal beds, or intervals within them that have a high ash yield and/or intercalated clastic partings, formed in rheotrophic peat swamp systems. By contrast, inner parts of the peat swamps or intervals composed of low-ash coal (<5 wt.%) may have formed in either planar rheotrophic systems with reduced clastic input, or in mesotrophic or ombrotrophic peat swamps with a water table elevated above the regional groundwater table (Smith, 1962; Littke, 1987; Diessel, 1992; Opluštil et al., 2018, 2024; Zieger and Littke, 2019).

#### DEPOSITS OF LARGE PERMANENT LAKES

*Description:* In contrast to the floodplain pond deposits, large lakes bear a fresh-water fauna, are of great lateral extent and thus are of stratigraphic importance. The best examples of widespread freshwater faunal horizons are the Hubert and Stanisław levels (Musiał et al., 1995), although it should be noted that faunal remains were not found in each borehole. The Hubert faunal horizon is composed of various fine-grained lithologies, which host a relatively poor bivalve assemblage with *Curvirimula belgica* (Hind) (with the *longa, triangularis* and *alta* morphological forms), *C. tesselata* (Jones), *C. orbiculata* Tabor, *Anthraconaia lenisulcata* (Trueman), *Naiadites rudensis* Tabor, and *Carbonicola* sp. The Stanisław freshwater faunal horizon assemblage is even more sparse, with *Curvirimula belgica* (Hind), *C. orbiculata* Tabor, and a single *Carbonicola silesiaca* Tabor only (Musiał et al., 1995). Fauna in this horizon, situated at the Załęże/Orzesze Beds boundary (Westphalian A/B boundary), is not common and is only recorded in a few boreholes. The bivalve remains occur within massive mudstones of variable thickness, ranging from 10–330 cm. Mudstones bearing the freshwater fauna (termed here as 'shells-containing') are usually dark grey, horizontally laminated with varve-like alternations in colour, contain scattered solitary silty laminae, and break with a characteristic conchoidal fracture. The alternation of the colour bands and indistinct lamination in the mudstones reflect changes in organic matter content and subtle grain-size variations, resulting in conchoidal and slabby splitting. The mudstones lack root traces and only solitary carbonised plant fragments were observed. In general, the shell-containing beds do not form a single layer, but instead are interbedded with silty mudstones, siltstones, and heterolithic and other fine-grained deposits. The colour banding associated with conchoidal fracture are decisive features for recognising such shell-containing mudstones, even if faunal remains themselves have not been noted. An interval containing several shell-containing horizons can reach up to 8 m in thickness. In most cases, humic coal beds of variable thickness underlie the shell-containing beds. These underlying coals are mostly composed of thin-banded bright lithotypes, in some cases with fusain lenses, and are interbedded with thinner intervals of micro- to medium-banded dull lithotypes. Above a shell-containing layer, grey mudstones, with distinct planar lamination transitioning upwards to indistinct lenticular and flaser bedding, have often been noted. These overlying strata contain solitary or sparse plant detritus and axial fragments, and in some cases sideritic nodules up to 5 cm in diameter.

*Interpretation:* The lake deposits were mainly deposited from suspended load transported by rivers, whereas wind-blown dust and volcanic ash were limited. The predominance of suspended load occurred because the landscape was probably covered by dense vegetation, whereas volcanic ash beds are nearly absent in lacustrine deposits of the Mudstone Series. Quiet-water deposition of suspended mud and silt occurred during normal river discharge, with interbeds of coarser sediment supplied during large flood events, when crevasse splays formed. The grain size of sediment within crevasse splays reflects that carried by the parental river tract, and can include coarse sands (Orton, 1995).

For the lacustrine deposits of the Mudstone Series, the occurrence of a humic coal bed directly below shell-containing mudstones is indicative of drowning of the peat swamp by flood waters. In other cases, the shell-containing deposits have been recognised as having covered a densely vegetated floodplain (mudstones with well-developed coalified root traces, leaves and stems), suggesting a transition from a distal floodplain to floodbasin environment. In only a few cases, sapropelic deposits were noted below lacustrine facies, and are interpreted as representing a flood basin with bottom anoxic conditions and limited clastic supply. An increased supply of coarser-grained sediment, including fine-grained sand, caused the basin to become shallower, which in turn allowed vegetation to colonise the area. Evidence for this progression is shown by the pres-

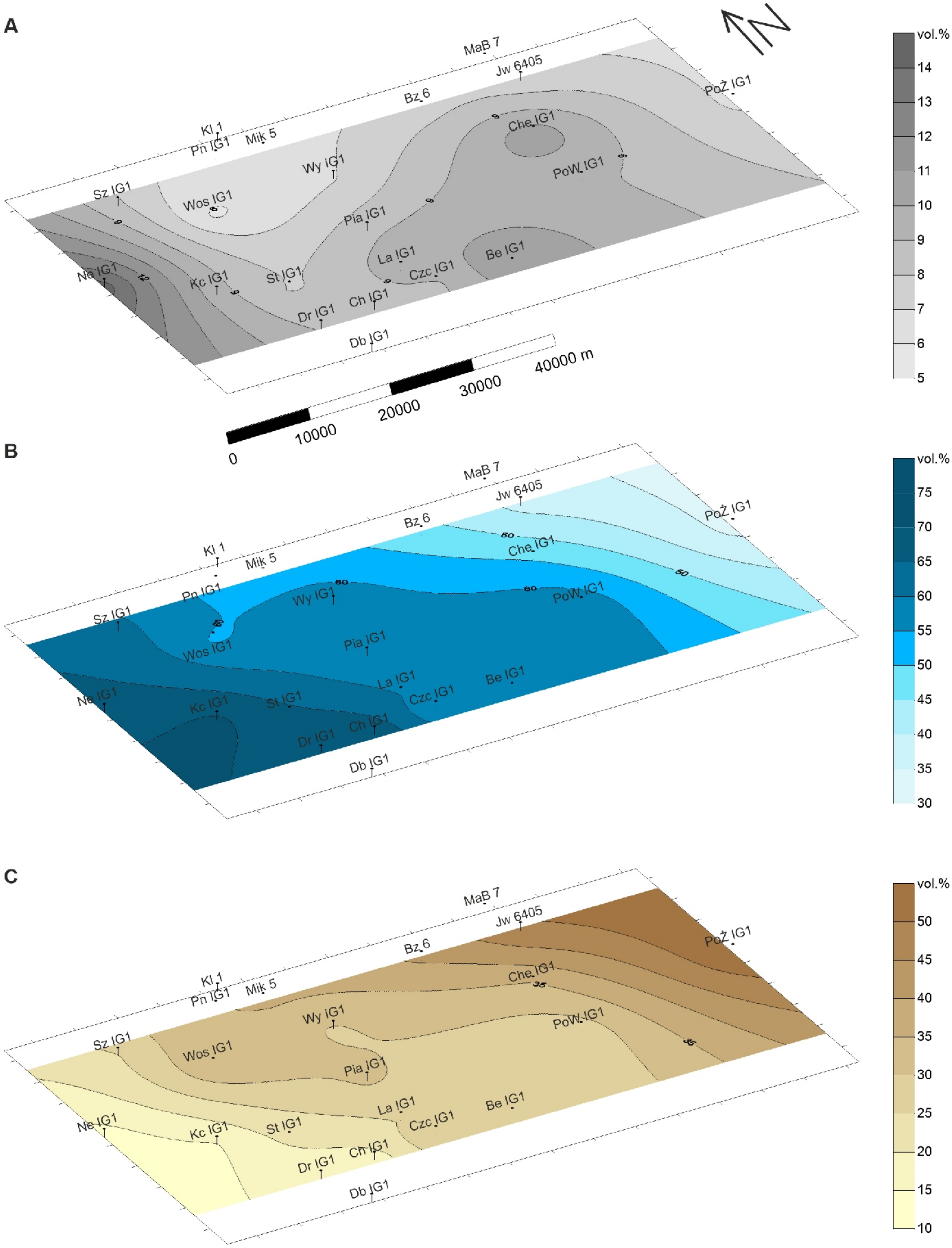



**Fig. 4. Proportion of phytogenic and clastic strata in the Mudstone Series in the Main Syncline area**

**A** – coal content; **B** – fine-grained clastic deposits; **C** – sandstone content. See Figure 2 for borehole distribution in the Main Syncline area

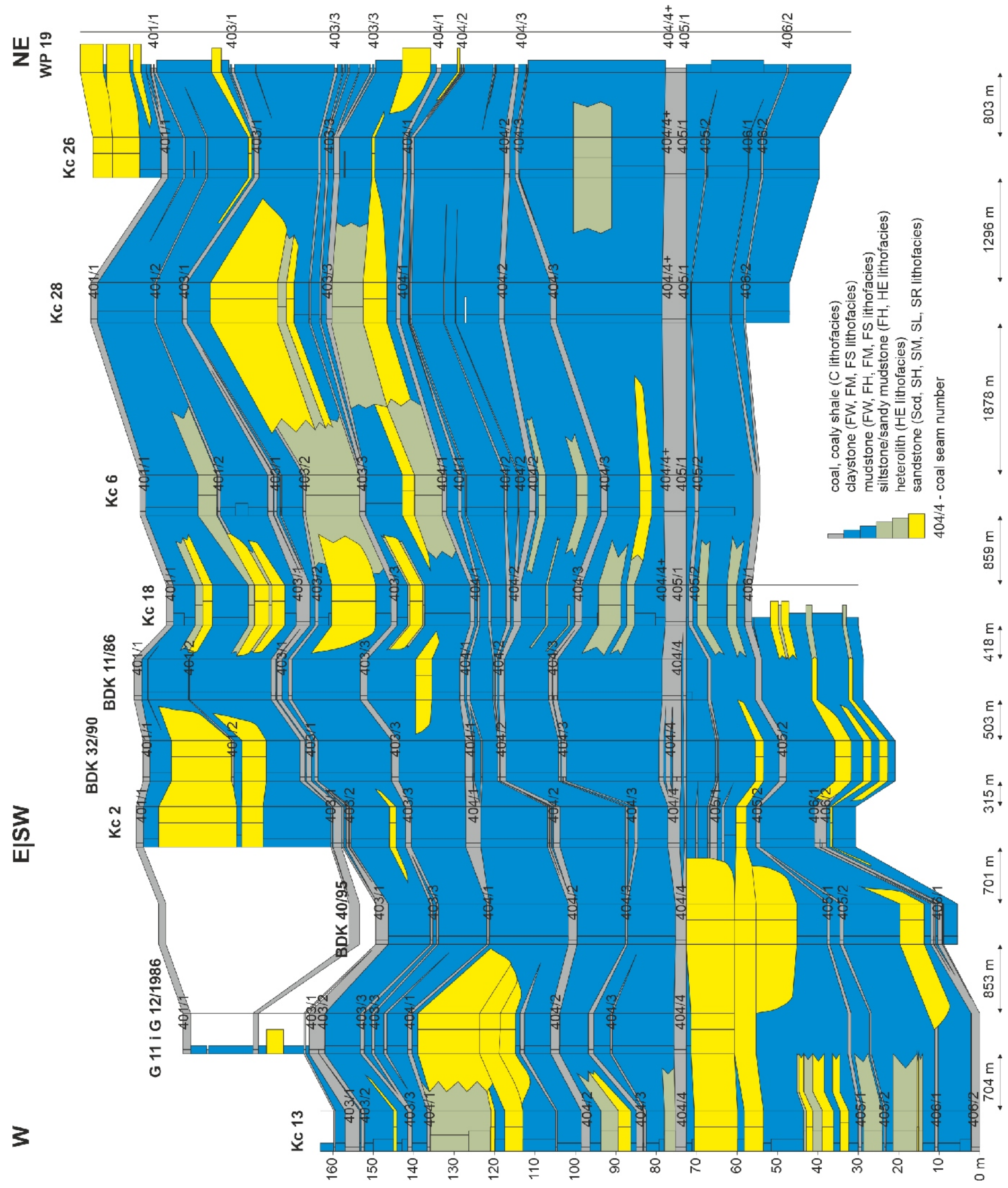



**Fig. 5. Correlative cross-section D–D’**

Base of the Mudstone Series. Pniówek coal mine, southwestern part of the Main Syncline

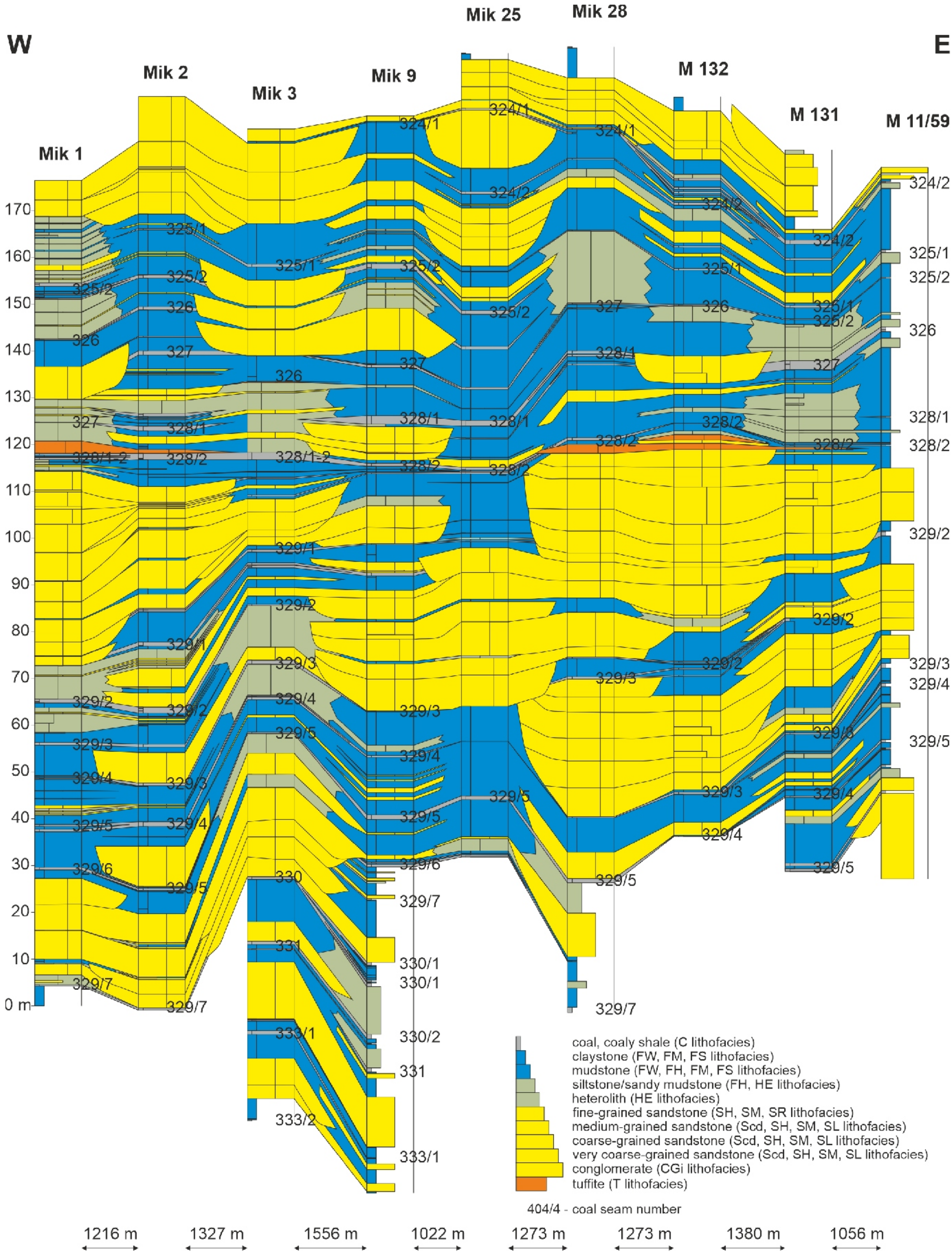



**Fig. 6. Correlative cross-section C–C'**

Orzesze/Załęże Beds boundary. Murcki coal mine, northern part of the Main Syncline

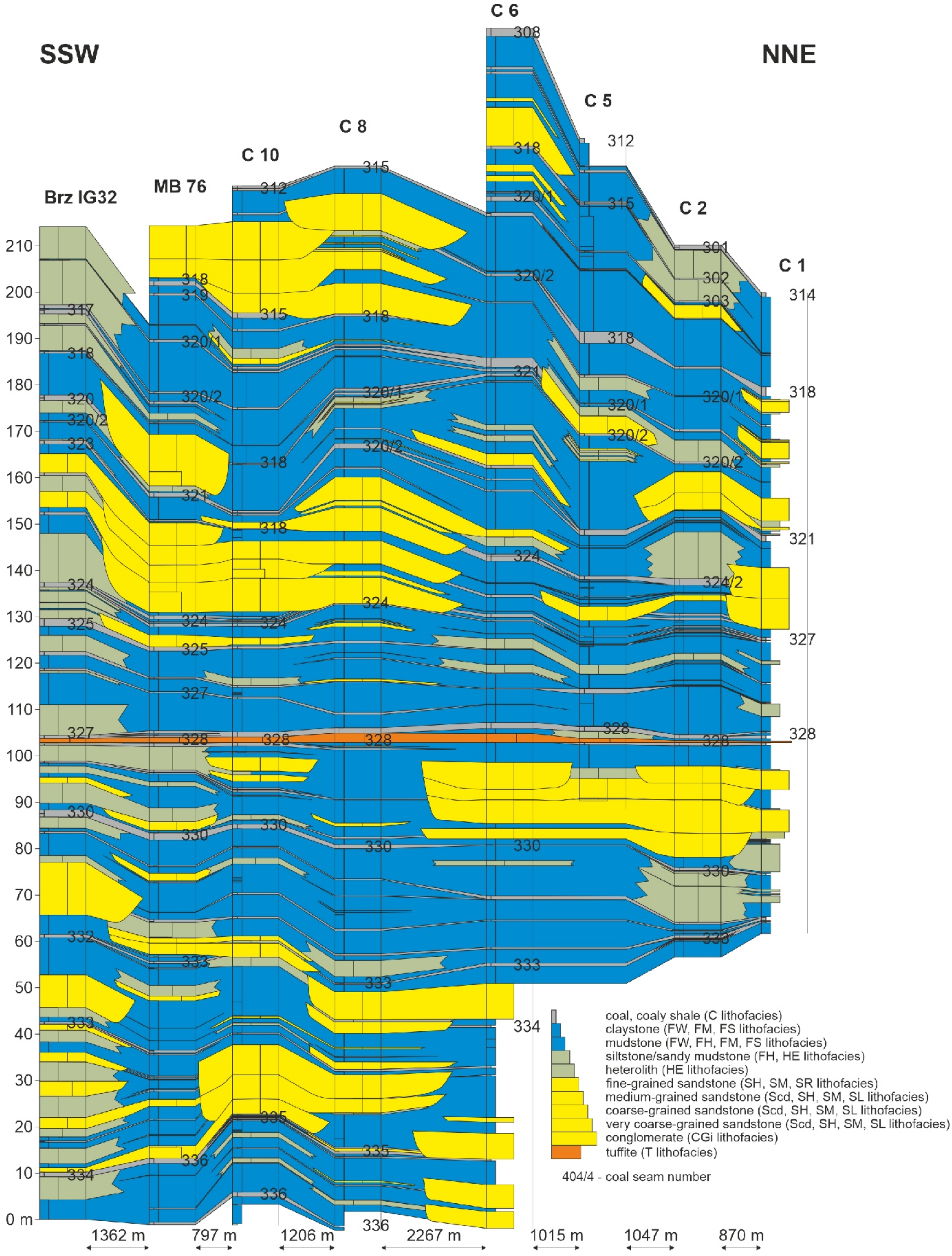



**Fig. 7. Correlative cross-section F–F'**

Orzesze/Załęże Beds boundary. Czeczott and Ziemowit coal mines, southern part of the Main Syncline ence of siltstones and heterolithic deposits with root-disturbed, primarily planar lamination. Minor and laterally impersistent lakes probably represented small ponds formed on the nearest poorly drained parts of the floodplain. The origin of large near-basin scale lakes represented by shell-containing deposits of the Hubert and Stanisław faunal horizons can be only speculated. These are correlated with the base and top of the Langsettian substage. It suggests a hypothesis that they may represent a distal response to the major marine transgressions used in the west European belt of paralic coalfields to define regional substage boundaries (e.g., Owens et al., 1985).

### BASIN-SCALE FLUVIAL ARCHITECTURE OF THE MUDSTONE SERIES

The Mudstone Series is characterised by the alternation of two lithosome groups: one fine-grained and the other coarse-grained. The coarse-grained lithosomes include channel facies forming thick sandbodies, whereas the fine-grained lithosomes consist of laterally persistent deposits of the overbank, palustrine and lacustrine facies associations. The proportion of both groups varies spatially. In western parts of the basin, fine-grained rocks typically constitute 60–80 vol.% of the whole succession, whereas subordinate coarse-grained deposits represent ~20–30 vol.% and coal beds make up 3–9 vol.%. Towards the east, the proportion of coarse-grained facies increases to 54 vol.%, whereas fine-grained facies including coal decrease to 46 vol.% (Fig. 4).

The thickness of individual sandstone bodies increases from <10 m in the western part of the basin to 15–20 m (rarely up to 35 m) in the eastern part. Thicker bodies consist of amalgamated channel-fills. Based on the width/thickness ratio defined by Friend (1983) and Gibling (2006), cross-sections and maps of sandstone thicknesses were used to identify ribbon- and sheet-like sandstone bodies in the Mudstone Series (Figs. 5–7, 12, 13 and Sup.Figs. 1–3). The ribbon-like (channelised) sandstone bodies have width/depth (W/T) ratios of <15 and are usually multi-storied, reflecting the multi-stage filling of fluvial channels. Each storey is separated by an erosional surface, suggesting cyclically repeated phases of erosion of previously accumulated sandstones and the deposition of sediments within the same meander belt. Simple fills formed during a single depositional act occur occasionally. These simple fills have a lesser thickness and smaller lateral extent compared to multi-storey bodies (Fig. 7).

The cumulative thickness of fine-grained strata, comprising overbank, lacustrine facies associations, and phytogenic deposits varies from a few tens of metres to about 150 m, with typical values between 30 and 100 m. Mean values change both spatially and stratigraphically. Packages 15–80 m thick are typical of the lower part of the Mudstone Series (Fig. 5 and Sup.Figs. 1, 2), whereas those in the middle part are thinner (Figs. 6, 7 and Sup.Fig. 3). The mudstone-dominated successions are typically composed of lithosomes several metres thick that are stacked in 15–20 m (<30 m) thick successions separated by mud-sand heterolithic deposits, thin sandstone bodies, or coal seams (Fig. 7). Heterolithic strata are composed of horizontally laminated sandy mudstones with thin interbeds of planar and ripple-laminated fine-grained sandstones. Intercalated in the mudstone-dominated packages are <3 m-thick fine- to medium-grained sandstone bodies deposited as crevasse channels or crevasse splays (Fig. 3). Based on cross-sections (Figs. 6, 7 and Sup.Figs. 1, 2), a lateral change from channel to overbank deposits can be observed, which is typical of meandering rivers. These transitions start with a thick package of sandstone bodies passing laterally into heterolithic deposits and sandy mudstones (levees), and then to mudstones and locally to claystones deposited on a floodplain. On the opposite bank, a sandstone body passes into siltstone or claystone (Fig. 5 – boreholes Kc 28 and Kc 6, depth 120–140 m; Fig. 6 – borehole Mik-9, depth 120 m and borehole Mik-3, depth 150 m). This observation suggests bank erosion on one side of the channel and simultaneous deposition of clastic sediments on a point bar and floodplain on the other side.

Coal seams are important architectural elements in the Mudstone Series. Coal seam thickness varies from a few centimetres in most cases to >6 m (Fig. 5 and Sup.Fig. 1). Changes in coal seam thicknesses are only exceptionally related to post-sedimentary erosion, and in these instances are marked by a reduced thickness or even complete removal, and also by the presence of fluvial channel deposits in the roof of the seam (Figs. 6, 7 and Sup.Fig. 1). Most thickness variations are related to depositional processes during peat accumulation (Fig. 8). Major coal seams (>1.5 m thick) are of relatively large (at least 10 km) lateral extent, whereas thinner seams usually occur as discontinuous irregular lenses. The continuity of coal seams can be locally disrupted by contemporaneous fluvial channels that disturbed peat accumulation in zones that are several kilometres wide and developed due to the flat relief of the flood plain area (Porzycki, 1972; Doktor and Gradziński, 1985). Such instances are marked by the presence of clastic bands/interbeds that commonly result in a coal bed being split into two or more benches (Fig. 5 and Sup.Figs. 1, 2). However, correlation of individual benches between boreholes is often difficult (Fig. 7). Less common is X-shaped splitting, which occurs where a coal seam is split in opposite directions over a short distance, usually towards the east and west (Sup.Fig. 1).

Doktor and Gradziński (1985) explicitly described the sedimentary accumulation environments of the Mudstone Series as being associated with meandering river systems, while noting that some rivers or river sections may be associated with anastomosing rivers. While it is difficult to rule out the presence of an anastomosing system based on analysis of cross-sections, the large quantity of sediment and its thickness on the floodplain may have been the result of an increase in accommodation space, which would have resulted in the presence of isolated and confined channels. Flooding became more frequent due to rising sea levels (Wright and Marriott, 1993). The observations suggest that only immature soils are present, which may support the idea that the image obtained from the cross-sections is related to the activity of low-gradient rivers of anastomosing type. The change in the proportion and thickness of sandstone bodies at the boundary of the Załęże/Orzesze beds may be related to the varying rate of basin subsidence. A comparison of the Langsettian and Bolsovian successions in the Netherlands and Kentucky (USA) indicates that the rate of basin subsidence influences stratigraphic architecture (van den Belt et al., 2015). In general, areas with a high rate of subsidence show a succession dominated by mudstone with a small amount of sandstone, while areas with a moderate rate of subsidence record sandstone bodies 10–20 m thick. However, at this stage of the research, it is not possible to demonstrate whether accommodation space was tectonically controlled on a regional scale or related to regional or local changes in the erosional base. Similarly, it is not possible to assess whether the predominance of fine-grained deposits is related to the type of source area, the gradient of the alluvial valley (and thus the competence of the flow), climatic factors (the amount and distribution of precipitation over time) or a combination of these factors.

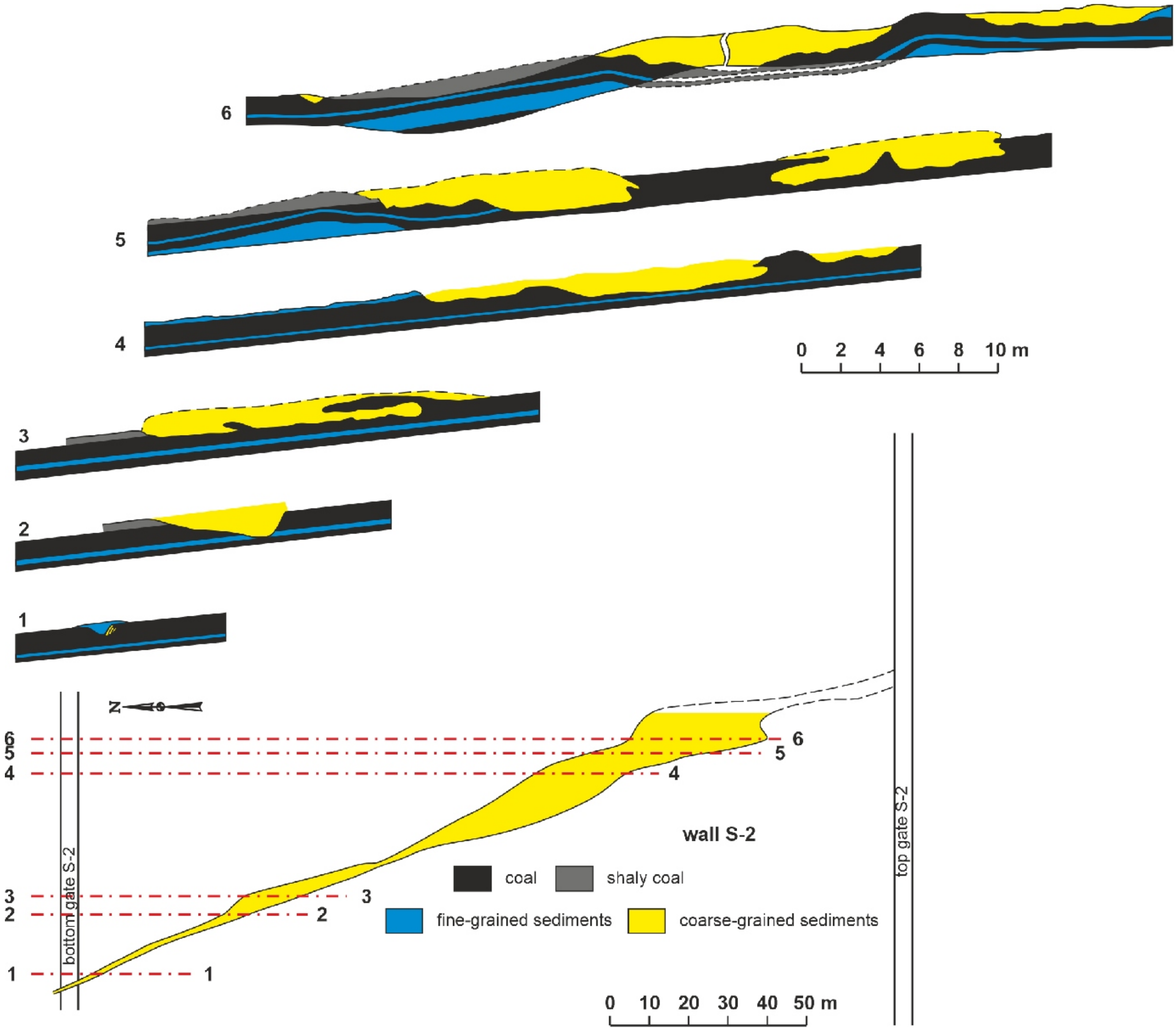



**Fig. 8. Erosive features in coal seam No. 359/1 (Załęże Beds) observed in underground galleries**

FLUVIAL ARCHITECTURE OF SELECTED STRATIGRAPHIC INTERVALS

A better understanding of lateral changes in the architecture of the Mudstone Series is provided by a comparison of cross-sections made at two stratigraphic intervals. The first includes the boundary between the Załęże and Orzesze beds at two different locations: in the Murcki and Czeczott coal mines. The second includes the lowest part of the Załęże Beds in the area of the Pniówek mine (Fig. 1B).

In the Murcki coal mine, located in the northern part of the Main Syncline, the interval is dominated by coarse-grained channel deposits. These strata form thick packages characterised by a complex internal structure and are of large lateral extent. Overbank deposits are either as equally represented as, or are slightly subordinate to, abundant heterolithic facies. Coal seams are rare and usually thin, and locally may be partly or completely washed out due to post-sedimentary erosion (Figs. 5–8 and Sup.Figs. 1–3). As a result, coal seams rarely form laterally persistent horizons that can be traceable between boreholes over large distances. The high proportion of coarse-grained rocks suggests close proximity to, or even a location within, the main channel zone that was situated in the most subsiding part of the basin. In the Czeczott coal mine, ~25 km to the south-east, this interval is dominated by overbank deposits, mainly mudstones with subordinate heterolithic deposits (Fig. 7). Here, coal beds are numerous, some of them being up to 2.5 m thick, rarely eroded, and thus of much greater lateral extent than in the Murcki mine.

More details of the architecture of coal seams and their relationship with entombing clastic deposits can be deduced from cross-sections constructed for the interval containing coals 405–404/4 and for the stratigraphically younger interval of coal 328.

The interval of the lower Langsettian coals 405–404/4 is located ~80–100 m above the base of the Mudstone Series. In the area studied of the Pniówek coal mine (Fig. 1B), coal 404/4 initially splits into two benches (cf. Sup.Figs. 1 and 2). The thickness of the clastic interval between the benches (Fig. 9A) and net content of sandstones (Fig. 9B) point to the close proximity of a SW–NE-striking channel tract zone that is broadly parallel to the axis of maximum subsidence. The zone of maximum sandstone thickness is <2 km across, and the sandstone content generally exceeds 50 vol.%, with a maximum reaching 90 vol.%. Sandstones are essentially absent outside of this zone.

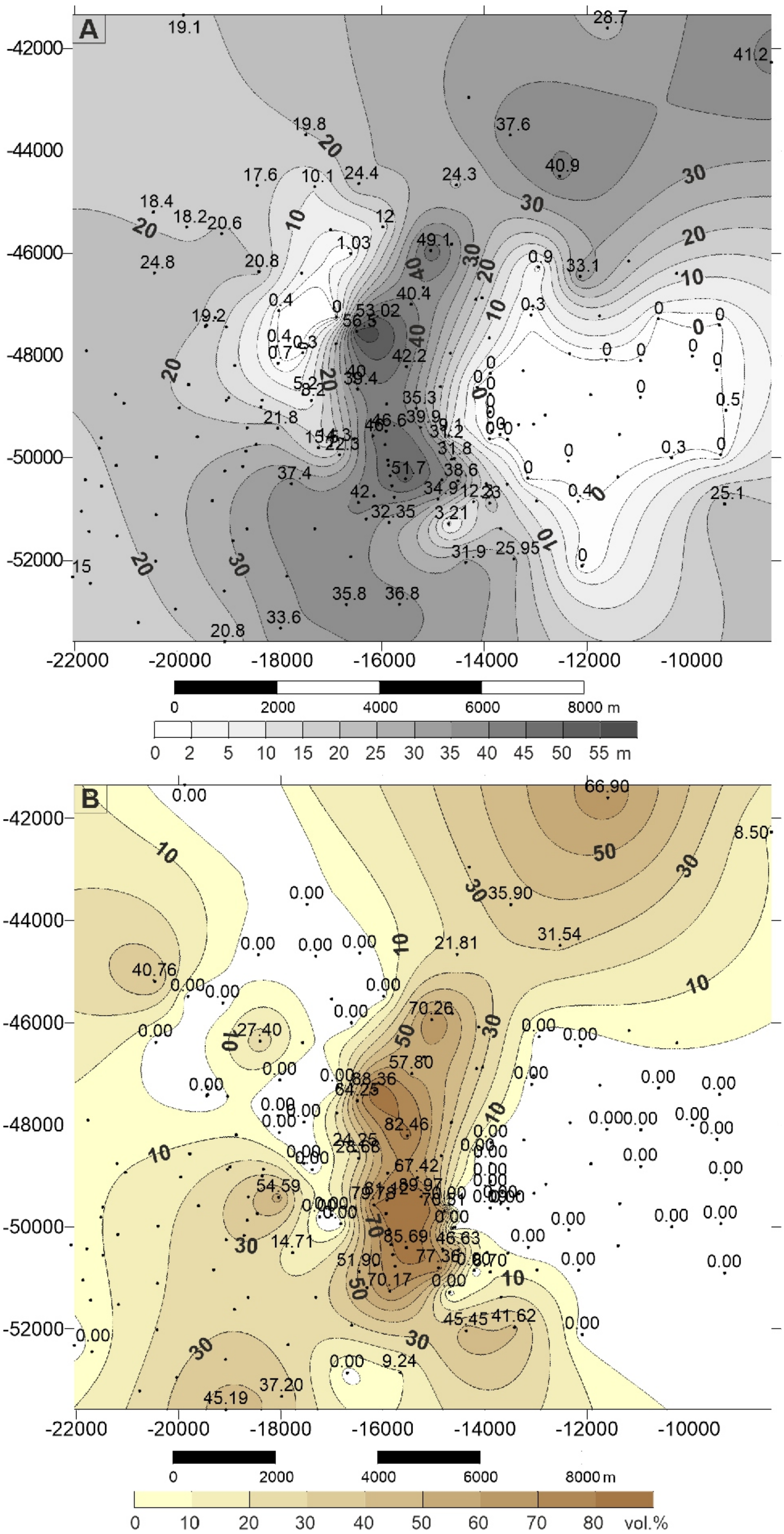



**Fig. 9. Thickness and proportion of sandstone in the interval between the top of coal seam 405/1 and the base of coal seam 404/4**

**A** – map of sandstone thickness (in m); **B** – map of sandstone proportion (in %). The mapped area is shown in Figure 2, as the rectangle marked with the letter A

Overbank deposits entombing coals 405/1 and 404/4 locally contain intercalated bodies of channel sandstone. Bodies found below coal 405/1 form an arc-shaped zone several metres thick extending N–S (Fig. 10A). West of this bend, there are smaller sandstone bodies, which in size and shape resemble oxbow lakes. In contrast, a sandstone body up to 35 m thick between seams 405/1 and 404/4 is straight and trends NNE (Fig. 10B, cf. Figs. 7, 9B and Sup.Fig. 2).

Another sandstone body situated above coal 404/4 resembles a sinuous channel zone up to 12 m thick entombed in overbank facies up to 30 m thick (cf. Figs. 5 and 10C). This latter sandstone body is probably a simple ribbon-type channel-fill, resembling a narrow meander belt that probably trends eastwards, then turns towards the south before changing direction again to the east and north-east. Finally, maps of sandstone thickness probably show a portion of a meander belt running SSW–NNE and following the basin axis. The meander belt appears to be surrounded by a zone of crevasse splays, an interpretation supported by the decreasing thickness of sandstone deposits and their gradual replacement by fine-grained overbank deposits. Clastic supply from the fluvial channel formed a broad zone where coal 404/4 splits into a series of benches, inconsistently numbered during mining work (cf. Sup.Fig. 2).

The younger study interval includes coal seam 328 and an associated tuffite layer (Figs. 6, 7 and Sup.Fig. 3), which marks the boundary between the Orzesze and Załęże beds (Langsettian/Duckmantian boundary). Although discontinuously preserved (Fig. 11), emplacement in a geological instant implies that the spatial distribution of facies directly below and above the tuffite records the position of sedimentary environments at the moment of ash fall and immediately after its deposition. Analysis of strata directly overlying the pyroclastic bed show the presence of a fine- to medium-grained sandstone body up to 5 m (max. 10 m) thick with a meandering pattern, broadly following a sub-N–S course (Fig. 12A). A coal seam up to 1.5 m thick is located mainly in the south part of the area near the meander belt, which corroborates the coexistence of active river channels and peat swamps. The coexistence of both environments implies that migrating river channels undercut the peat swamps on their concave banks, while depositing point bar sediments on their convex banks at the same time.

Beneath the pyroclastic horizon, and entombed in fine-grained siliciclastic deposits, a meandering sandstone body that is ~2–3 km wide (Fig. 13B) and mostly <7 m (max. 30 m) thick trends in a sub-N–S course. Coal seams are scattered into several isolated areas and their thickness typically varies between 0.5 m and 2 m (max. 3.4 m). The temporal evolution of the meander belt and associated floodplain can be deduced from three successive facies maps constructed for intervals 1, 3, and 5 m below the tuffite (Fig. 13). These maps not only show changes in the position of the meander belt, but also its gradual widening at the expense of floodplain clastics and associated peat swamps.

## LITHOFACIES ANALYSIS AND PETROGRAPHIC COMPOSITION OF COAL SEAMS OF THE MUDSTONE SERIES

Coal lithofacies analyses were performed on 431 coal seams from the Załęże Beds (388 coal seams) and Orzesze Beds (43 coal seams) encountered in five boreholes located across the study area: Paniowy IG1 (Pn IG1), Krzyżowice IG1 (Kc IG1), Piasek IG1 (Pia IG1), Poręba Wielka IG1 (PoW IG1), and Drogomyśl IG1 (Dr IG1) (Fig. 1B). The results are given in the Supplementary material (Sup.Figs. 1–4, 5) and summarised in Table 2.

The Załęże Beds in the northern, central and western sectors (see Fig. 1B) are characterised by an almost equal percentage of forest- and mixed-type peat swamps. Only a minor number of coals represent the herbaceous type, whereas forest-type peat swamps predominate in the southern part of the basin. The eastern sector is markedly different, with a relatively high number of the coals representing herbaceous-type peat swamps and only a minor proportion of forest-type peat swamps (Table 2).

There are fewer analyses of the coals from the Orzesze Beds, these being only performed on three boreholes from the northern (Pn IG1), central (Pia IG1), and eastern (PoW IG1) sector. In borehole Pn IG1, the majority (63 vol.%) of the coals represent forest-type peat swamps. Phytogenic material from the borehole Pia IG1 mainly accumulated in mixed-type peat swamps and only 5 vol.% represent the forest type. The eastern sector (borehole PoW IG1) is characterised by a high number of coals from mixed-type peat swamps, with minor contents of forest (22 vol.%) and herbaceous (11 vol.%) types (Table 2). Comparison of the Załęże and overlying Orzesze beds shows a shift towards a greater proportion of mixed-type peat swamps in the northern, central, and eastern sectors. An increase in herbaceous-type peat swamps in the central region, and a decrease in herbaceous-type swamps in the eastern region, can be observed.

### LITHOTYPES

Coal seams studied in the Mudstone Series consist of irregularly alternating bands of bright and dull coal lithotypes. Bright coal lithotypes (vitrain to clarain) predominate, with transitional vitroclarain (>35%) and clarovitrain (28%) being most abundant (Fig. 14). Duroclarain and clarodurain make ~18% and 12 %, respectively, whereas the remaining microlithotypes comprise <5%. Intercalated clastic partings are mainly carbonaceous shale or mudstone, which together make up 7% of the sections of the coals studied.

### MICROLITHOTYPE-BASED COAL FACIES ANALYSIS

Among the microlithotypes, all coal seams studied of the Mudstone Series are volumetrically dominated by vitrite, at 45% on average, whereas the remaining monomaceral microlithotypes, inertite (8%) and liptite (<1%), are subordinate. Among the bimaceral microlithotypes, clarite volumetrically predominates (almost 7%), while vitrinertite (5%) and durite (3%) are less frequent. Trimacerites are dominated by duroclarite (17%), with less clarodurite (4%) and vitrinertoliptite (<1%). The average carbominerite content is 7%. Plotting the microlithotype composition of coal seams in the 22 boreholes studied on the facies diagram developed by Hacquebard and Donaldson (1969) shows that the coal seams mostly originated from peat that accumulated in wet forest peat swamps of the telmatic and limnotelmatic zones (Fig. 15).

In order to reconstruct hydrological changes in the peat swamps throughout the sections studied of the Mudstone Series, several microlithotype-based indices and analytic parameters were applied. These include the: (i) Forest Facies Index (FFI); (ii) Waterlogging Index (WLI); and (iii) ash and sulphur contents. These parameters were determined separately for the Załęże and Orzesze beds in the borehole sections, which are concentrated in five different regions of the basin (see Fig. 1B).

**Facies of the Załęże Beds coal seams**

In the northern region, coal seams of the Załęże Beds were analysed in seven boreholes: Szczygłowice IG1 (Sz IG1), Paniowy IG1 (Pn IG1), Kłodnica 1 (Kl 1), Mikołów 5 (Mik 5),

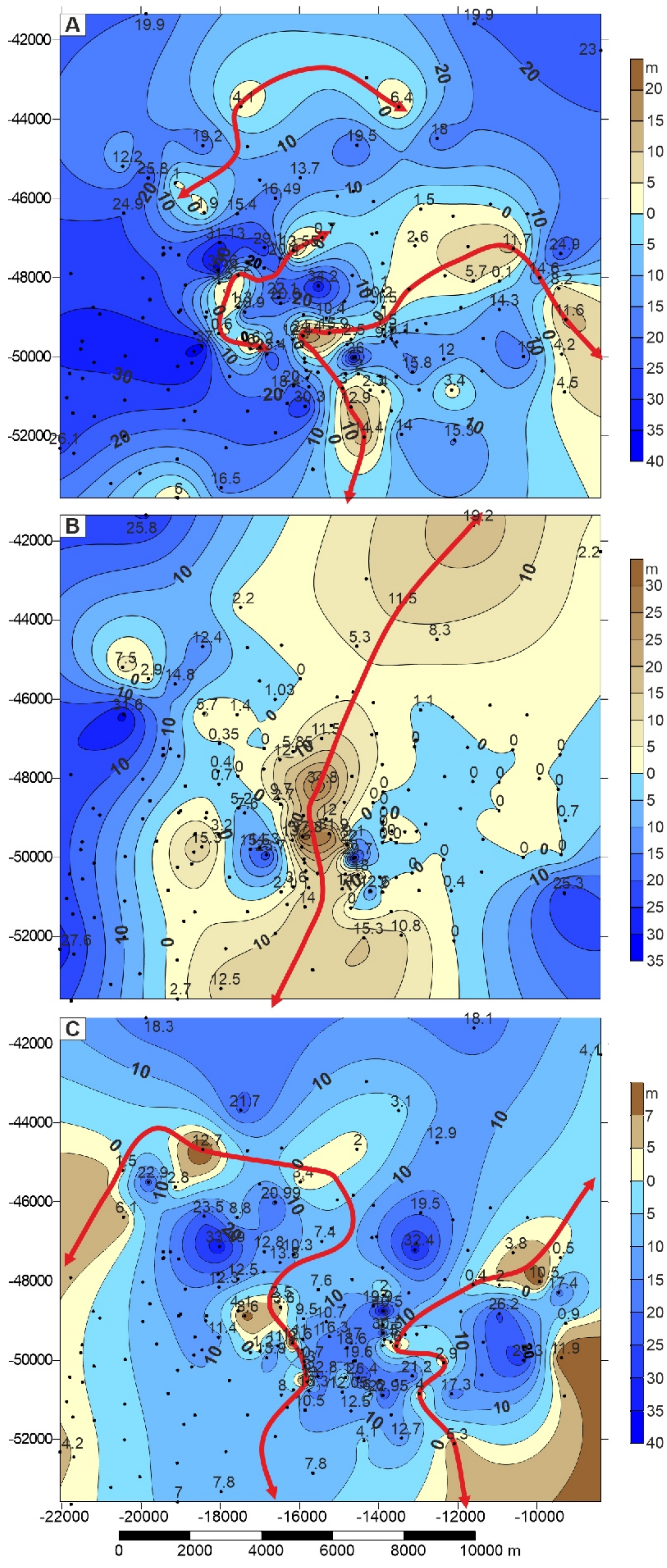



**Fig. 10. Thickness of the stratal packages underlying and overlying coal seam405/1 and overlying coal seam 404/4**

**A** – map of the thickness and lithology of deposits beneath coal seam 405/1; **B** – map of the thickness and lithology of deposits above coal seam 405/1; **C** – thickness of the second sedimentary package overlying coal seam 404/4. The mapped area is shown in Figure 2, as the rectangle marked with the letter A. Thickness of fine-grained deposits are in blue, sandstones in yellow

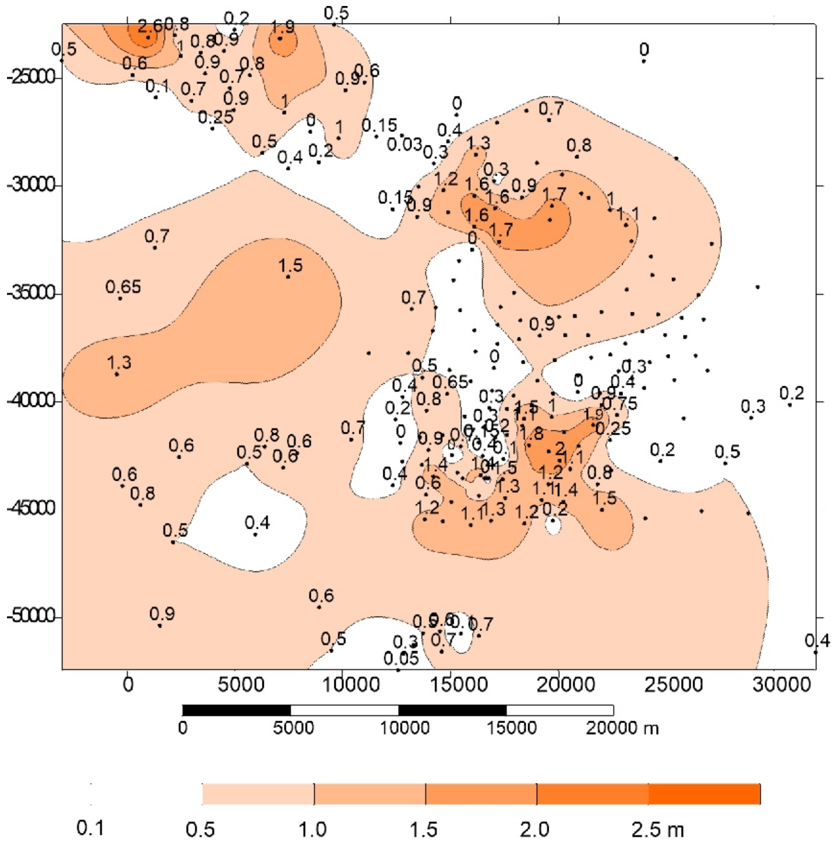



**Fig. 11. Thickness map of the pyroclastic layer at the Orzesze/Załęże Beds boundary**

The mapped area is shown in Figure 2, as the rectangle marked with the letter B

Brzezinka 6 (Bz 6), Maczki Bór Biskupi 7 (MaB 7) and Jaworzno 6405 (Jaw 6405). However, complete sections of the Załęże Beds were only found in the boreholes Pn IG1 and Bz 6. In the western region, deposits of the Załęże Beds were studied in the boreholes Niedobczyce IG1 (Ne IG1), Krzyżowice IG1 (Kc IG1), Woszczyce IG1 (Wos IG1) and Studzionka IG1 (St IG1). Ne IG1, Kc IG1 and St IG1 only encountered the lower part of the beds (406/3–349/1 seams), while Wos IG1 penetrated the interval between coals 347/2 and 328 in the upper part. In the central region, the coal seams of the Załęże Beds were examined in the boreholes Łąka IG1 (La IG1), Piasek IG1 (Pia IG1) and Wyry IG1 (Wy IG1). The La IG1 section represents the lower part of this unit. The boreholes Wy IG1 and Pia IG1 contain complete sections of the beds. Deposits of the Załęże Beds in the eastern region were analysed in the boreholes Chełmek IG1 (Che IG1) and Poręba Wielka IG1 (PoW IG1). The borehole Che IG1 contains coal seams 406–334, whereas the coal seams in the borehole PoW IG1 could not be precisely identified. In the southern region, coal seams of the Załęże Beds were analysed in the boreholes Drogomyśl IG1 (Dr IG1), Dębowiec IG1 (Db IG1), Chybie IG1 (Ch IG1), Czechowice IG1 (Cz IG1) and Bestwina IG1 (Be IG1). A complete section of this unit is found in boreholes Dr IG1 and Be IG1. In the remaining boreholes, coal seams could not be identified with precision.

*Forest Facies Index (FFI):* In the northern region, the highest FFI values (>2) were recorded in coals from boreholes Pn IG1, Kl 1 and Bz 6. These values indicate forest-type peat swamps. In the other boreholes in this region, conditions favoured mixed-type peat swamps (Sup.Fig. 6A). FFI values in the northern regions are generally higher than in the southern regions, especially in the lower part of the Załęże Beds, where most of the coals probably formed in forest-type peat swamps (Sup.Fig. 6B). However, in borehole Ws IG1, FFI values indicate mixed-type peat swamp conditions during the deposition of the upper part of the Załęże Beds. The highest FFI values have been calculated in the central regions (Sup.Fig. 6C), with small excursions in the curves towards values indicative of mixed peat swamps. The eastern and southern regions are characterised by lower FFI values, generally below 2 (Sup.Fig. 6D, E), which is typical of mixed peat swamps and some herbaceous peat swamps. No uniform trend in change values' has been observed; however, increasing or decreasing values over time have been noted in some cases, as in borehole Kc IG1, where FFI values decrease upwards, while the opposite trend has been observed in borehole Ne IG1 (Sup.Fig. 6B).

*Waterlogging Index (WLI):* In the northern region, the eastern part (boreholes BZ 6, MaB 7 and Jaw-6405; see Fig. 1B for location) was characterised by a low or fluctuating water table in the peat swamp (WLI values <1). To the west, evidence of a higher water table in the peat swamps can be observed (Sup.Fig. 7A). The western and central regions were characterised by a relatively stable, low water table, with only short excursions towards a higher water table. One exception is the upper part of the Załęże Beds in boreholes Ws IG1 and Wy IG1, which show that WLI values were higher (Sup.Fig. 7B, C). The WLI is high and corresponds with lower FFI values. In the eastern region, only two boreholes in the west yielded data for WLI calculation. Evidence of a higher degree of waterlogging was only found in the borehole Che IG1 (Sup.Fig. 7D). In the southern region, WLI values indicate increased waterlogging in peat swamps in the upper part of the Załęże beds (Sup.Fig. 7E), similarly to the western and central regions.

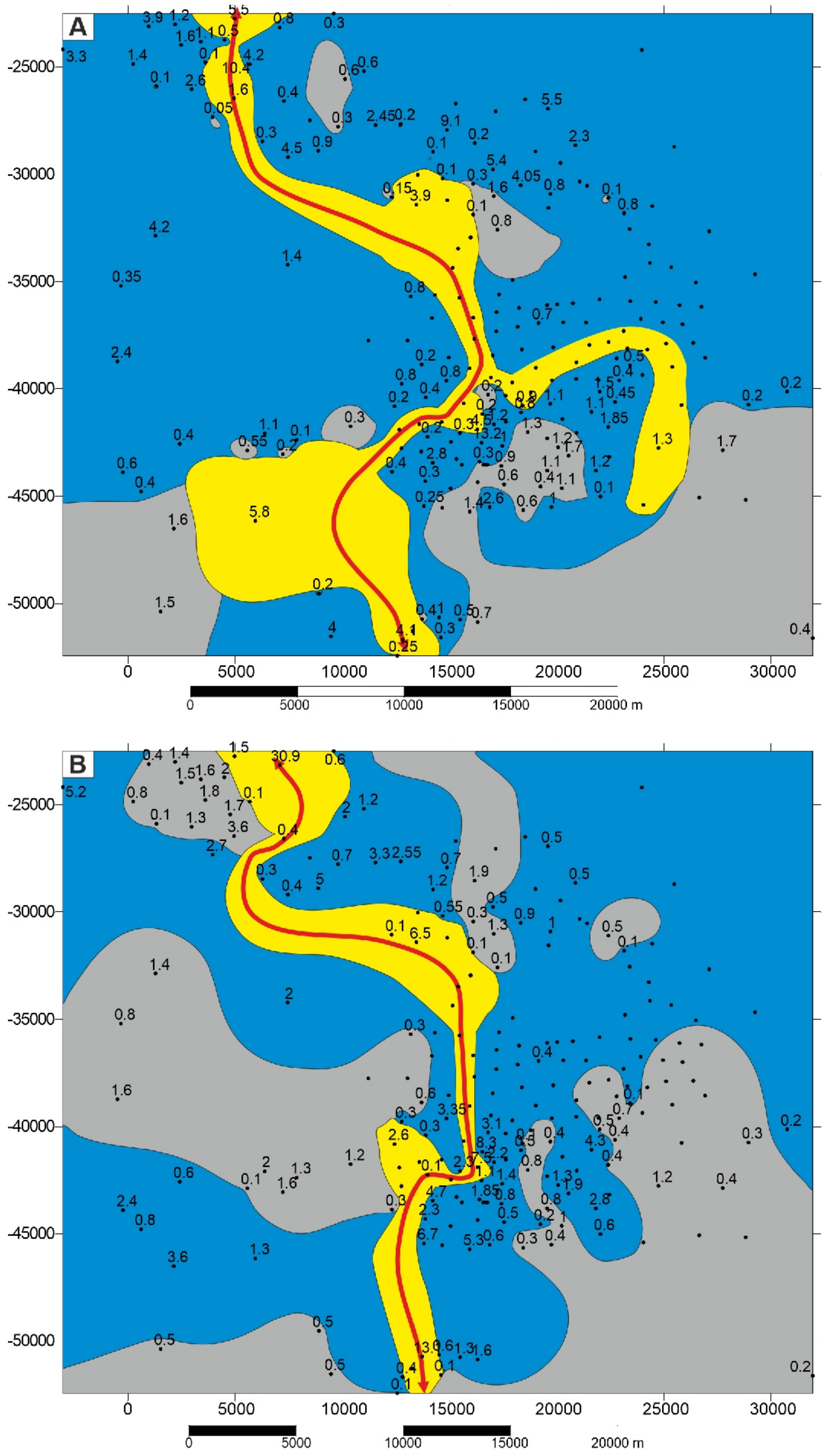



**Fig. 12. Thickness of the first stratal package underlying and overlying the pyroclastic layer**

**A** – map of the thickness and lithology of deposits above the pyroclastic layer; **B** – map of the thickness and lithology of the deposits beneath the pyroclastic layer. The mapped area is shown in Figure 2, as the rectangle marked with the letter B. Thickness of fine-grained deposits in blue, sandstones in yellow, coals in grey

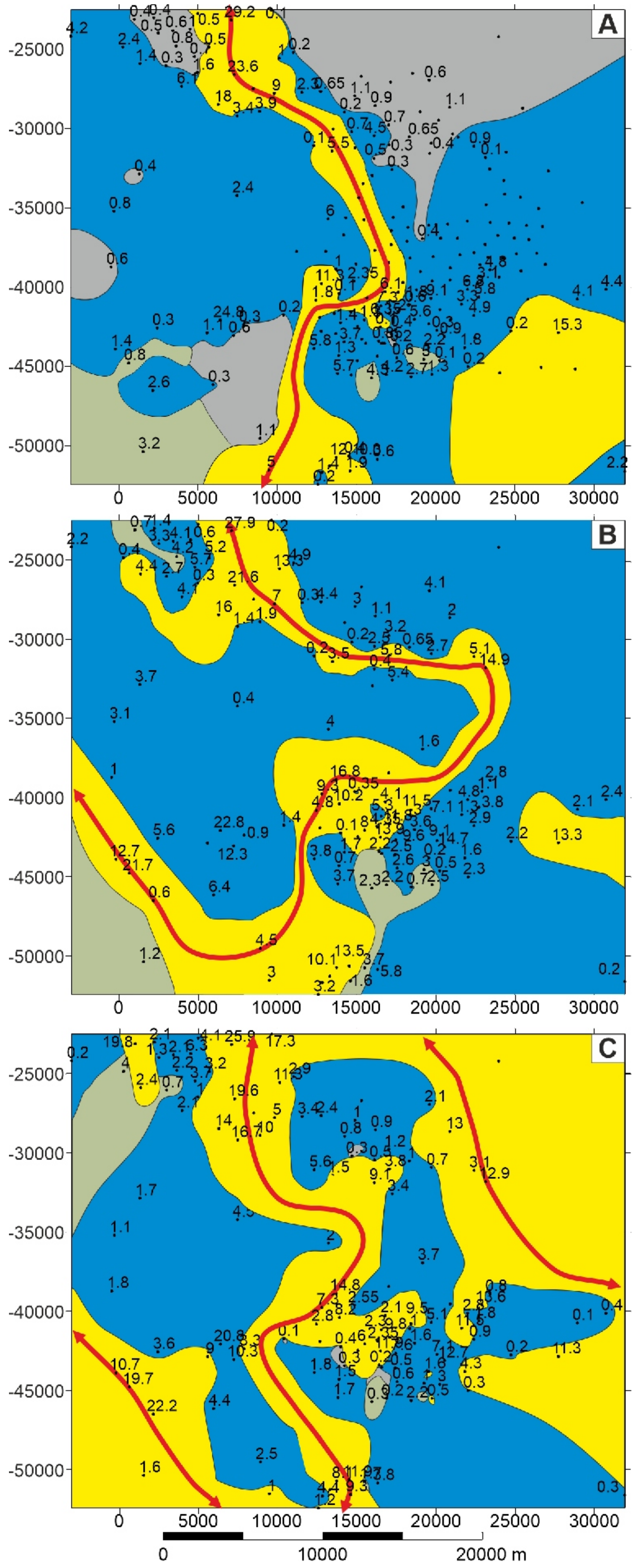



**Fig. 13. Distribution of sedimentary environments around the pyroclastic layer**

**A** – cut 5 m below the base of the pyroclastic horizon; **B** – cut 3 m below the base of the pyroclastic horizon; **C** – cut 1 m below the base of the pyroclastic horizon. Yellow indicates the area of sandstone accumulation (in-channel sediments), green the area of sedimentation of thin interbeds of siltstone and sandstone (proximal floodplain), blue the area of siltstone accumulation (distal floodplain), grey the area of peatland. The red line marks the course of the meander belt. The mapped area is shown in Figure 2, as the rectangle marked with the letter B

Table 2

**Coal seam thickness and peat swamp characteristics based on the coal lithofacies analysis of the coal seams of the Orzesze and Załęże beds**

| | Orzesze Beds | | | Załęże Beds | | | |
|---|---|---|---|---|---|---|---|
| Borehole | Number of coal seams analysed | Coal seam characteristics | Coarse- and fine-grained intervals | Number of coal seams analysed | Coal seam characteristics | Coarse- and fine-grained intervals | Comparison |
| Paniowy IG1 (Pn IG1) | 8 | Thickness varies between 50 and 100 cm, except for one coal >1 m thick; five of eight coal (62.5% seams) were formed in forest peat swamps | Not performed | 118 | 90% coal seams with thickness <100 cm (~60% <50 cm and ~30% 50-100 cm); 51% forest-type peat swamps (mostly <50 cm thick), 40% mixed-type peat swamp, 10% herbaceous-type peat swamp; higher number of mixed peat swamps in thick (>100 cm) seams | Less frequent and thinner coal beds in coarse-grained intervals and formed in forest-type swamps, commonly with indications of drying (fusain); thicker and mostly formed in wet forest peat swamps in the floodplain-dominated intervals | Generally thinner coal seams in Załęże Beds, phytogenic material accumulated mostly in forest-type peat swamps during deposition of the whole Mudstone Series succession |
| Krzyżowice IG1 (Kc IG1) | 0 | Not performed | Not performed | 73 | 5–260 cm thick, mean value 63 cm; 50% coal seams with thickness <50 cm thick and 15% is >100 cm thick; 48% forest-type peat swamps, 48% mixed-type peat swamps, 4% herbaceous-type peat swamps | Lack of thick coal seams (<100 cm thick) in coarse-grained strata; herbaceous-type restricted only to floodplain-dominated intervals | |
| Piasek IG1 (Pia IG1) | 17 | 5% forest-type peat swamps (50 cm thick), 70% mixed-type peat swamps, 25% herbaceous-type peat swamps (<50 cm thick) | Not performed | 93 | 44% forest-type peat swamps, 46% mixed-type peat swamps, 10% herbaceous-type peat swamps; lack of forest-type peat swamps in coal seams with <100 cm in thickness; predominance of thin coal seams representing mixed-type peat swamps | Strong variation in lithological structure did not allow the distinction of distinct intervals with the dominance of fine- and coarse-grained sediments | Change of peat swamp type from forest and mixed in the Załęże Beds to mixed and herbaceous in the Orzesze Beds |
| Poręba Wielka IG1 (PoW IG1) | 18 | 22% forest-type peat swamps (<1m thick), 72% mixed-type peat swamps (50–100 cm thick), 11% herbaceous-type peat swamps (single coal bed >1 m thick) | Not performed | 19 | 16% forest-type peat swamps, 50% mixed-type peat swamps, 34% herbaceous-type peat swamps; seams >50 cm thick formed mostly in mixed peat swamps; thinner coals are the result of peat accretion in forest and/or herbaceous peat swamps | No clear correlation was observed between peat swamp types and thicknesses of coal seams with lithological character of entombing clastic intervals | Relatively stable peat accretion conditions during deposition of the entire Mudstone Series |
| Drogomyśl IG1 (Dr IG1) | 0 | Not performed | Not performed | 85 | 60% forest-type peat swamps, 36% mixed-type peat swamps, 4% herbaceous-type peat swamps; most of the coals of low and medium (<50 cm and 50-100 cm respectively) thicknesses (43% and 34% respectively) | No clear correlation between lithological character of clastic intervals and stratigraphic distribution of coals formed in the forest or mixed peat swamps; no clear correlation between the thickness of the seams and lithology of the deposits surrounding seams | |

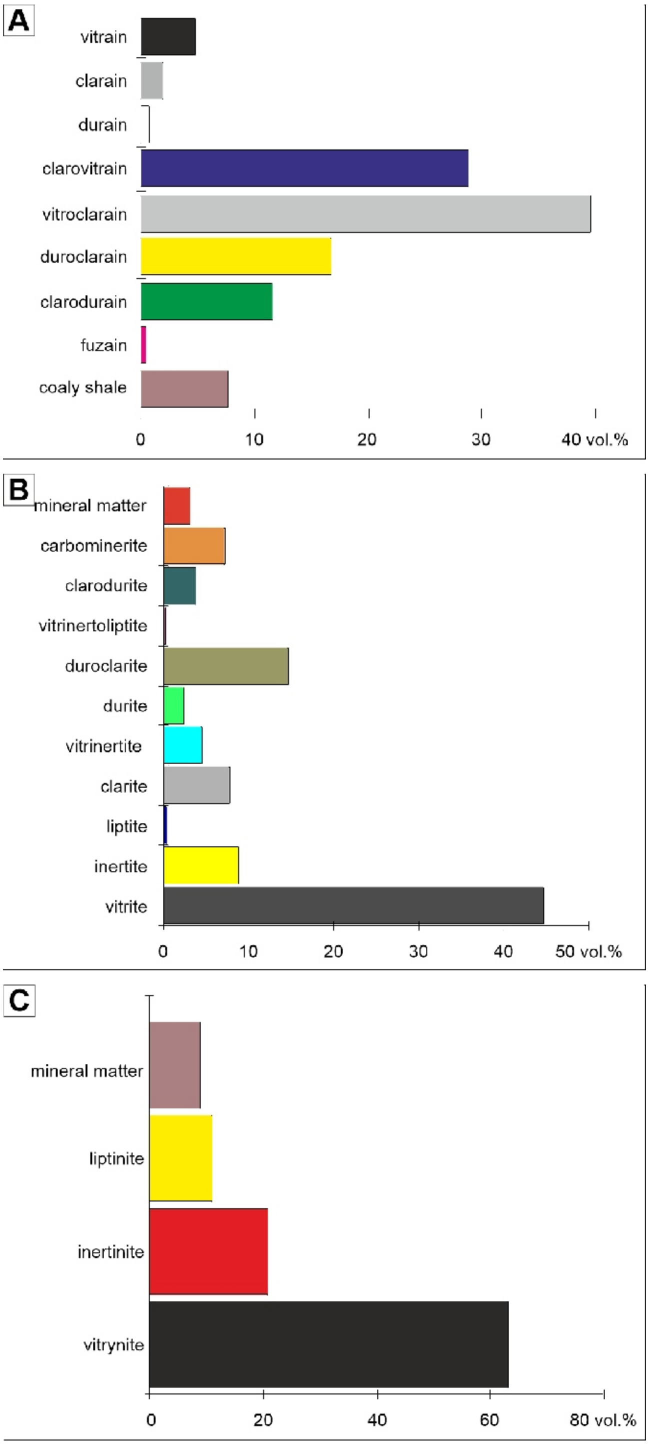



**Fig. 14. Petrographic composition of the coal seams analysed of the Mudstone Series**

**A** – lithotypes; **B** – mean microlithotypes; **C** – mean maceral groups

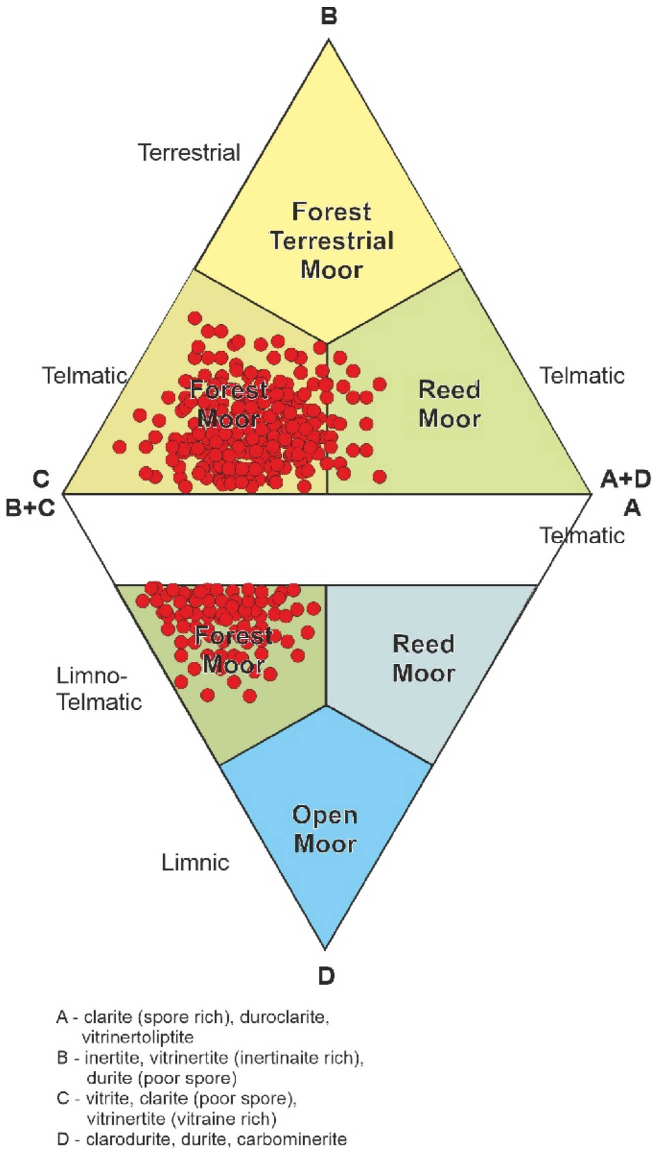



**Fig. 15. Haquebard and Donaldson's (1969) facies diagram for coals of the Mudstone Series**

*Ash yield and sulphur content:* The ash yield and sulphur content varies considerably and shows no clear pattern or trends. In many cases, it does not correlate with FFI or WLI. Exceptions have been observed in the northern region, where high ash yield is typical of coal seams with low FFI values (Sup.Fig. 6), and in the central region, where an increase in ash yield (Sup.Fig. 8C) is associated with higher WLI values in the uppermost part of the Załęże Beds (Sup.Fig. 7C). In most cases, the ash yield does not exceed 20 wt.% (Sup.Fig. 8A–E), with exceptions in boreholes Mik 5 in the northern region (Sup.Fig. 8A) and WS IG1 in the western region (Sup.Fig. 8B). Sulphur content is low, rarely exceeding 2 wt.%, and does not usually show significant variation in the boreholes studied (Sup.Fig. 8A–E).

### The facies of the Orzesze Beds coal seams

*Microfacies analysis:* This was performed on coal samples taken from boreholes at the following locations: Paniowy IG1 (Pn IG1) and Mikołów 5 (Mik 5) in the northern region; Brzezinka 6 (Bz 6) in the western region; and Woszczyce 1 (Ws IG1), Piasek IG1 (Pia IG1) and Wyry IG1 (WyIG1) in the central region. Chełmek IG1 (Che IG1), Poręba Żegoty (PoZ IG1) and Poręba Wielka IG1 (PoW IG1) in the east, and Drogomyśl IG1 (Dr IG1), Dębowiec IG1 (Db IG1), Chybie IG1 (Ch IG1), Czechowice IG1 (Cz IG1) and Bestwina IG1 (Be IG1) in the south. No data from the southern region were used for the FFI and WLI calculations. The Orzesze Beds have only been completely recorded in boreholes Ws IG1 and Wy IG1 in the western and central regions (the area of maximum thickness of the Orzesze Beds). Boreholes in the eastern region recorded a reduced thickness of this unit, and in the case of the boreholes Chełmek IG1 and Poręba Żegoty IG1, the Mudstone Series remains undivided. In the remaining boreholes, the thickness of the Orzesze Beds decreased due to post-Carboniferous erosion.

*The Forest Facies Index (FFI):* Values of the FFI indicate that the coals of the Orzesze Beds formed almost exclusively in forest and mixed peat swamps. The variation in peat swamp types is best exemplified in the boreholes Ws IG1 and Wy IG1 in the western and central regions (Sup.Fig. 9A). In boreholes characterised by an incomplete thickness of this unit, the coals in borehole Pn IG1 were formed in forest peat swamps, whereas the borehole Mik 5 only contains mixed peat swamp facies. Coals from borehole Bz 6 originated in both forest and mixed peat swamps, with the latter being dominant (Sup.Fig. 9A). In the western region, coals mainly formed in mixed peat swamps, except in the upper part of the unit, where forest peat swamps were more prevalent (Sup.Fig. 9A). In the central region, coals formed primarily in forest peat swamps (Sup.Fig. 9A). In the eastern region, the coals suggest an origin in mixed peat swamps (Sup.Fig. 9A). No evident trend in the change of peat swamp types can be deduced based on the spatial distribution of the boreholes.

*Waterlogging Index (WLI)*: WLI values were calculated for boreholes Ws IG1 and Wy IG1, where the maximum thickness of the Orzesze Beds is recorded. This allows vertical changes in the water table level in peat swamps to be tracked (Sup.Fig. 9B). These coals mainly formed in mixed peat swamps, except in the upper part of the unit, where forest peat swamps were more prevalent. The change in the upper section of the Orzesze Beds is accompanied by a decrease in WLI values and an increase in ash yield and sulphur content (Sup.Fig. 9C). Comparing the shape of the curves shows that there were almost no synchronous changes in these two boreholes. In regions where the thickness of the Orzesze Beds is reduced (in the north and east), the WLI values are generally low (Sup.Fig. 9B), indicating a low or fluctuating water table in the peat swamp.

*Ash yield and sulphur content:* The increased ash yield and sulphur content in the western and central regions is accompanied by a shift towards a low or fluctuating water table in the peat swamp. This up-section change in the Orzesze Beds is accompanied by a decrease in the waterlogging index and an increase in ash yield and sulphur content (Sup.Fig. 9C). Ash yield generally increases with elevation in the sections studied. The highest sulphur concentrations were found in seams of the lower part of the section in the borehole Wy IG1 (Sup.Fig. 9C). In the eastern region, WLI values (Sup.Fig. 9B) and ash yield values (Sup.Fig. 9C) are low in all three boreholes (Che IG1, PoW IG1, PoŻ IG1), except in the upper part of the Orzesze Beds in borehole PoW IG1 (Sup.Fig. 9C). In the northern region, the highest degree of waterlogging (Sup_Fig. 9B) and a high ash yield were observed in the coal in borehole Mik 5 (Sup.Fig. 9C).

### Interpretation of facies analysis

Generalisation of the results of the microlithotype-based facies analysis outlined above shows that coal seams derived from forest peat swamps in the Mudstone Series were mostly concentrated in the central and western regions and in the western part of the northern region (Fig. 16). Mixed peat swamps prevailed in the eastern part of the northern region and in the eastern and southern areas. Peat swamps dominated by herbaceous vegetation were mostly observed in small isolated patches in the southernmost and north-eastern parts of the Main Syncline area (Fig. 16). Higher levels of waterlogging broadly correlate with mixed and herbaceous peat swamps. Increased ash yield is connected to a higher value of waterlogging index in the peat swamps, and is more frequent in coals formed in mixed peat swamps. Relatively small changes in sulphur content in the coal seams analysed do not show any significant correlation with the peatland types identified in the Orzesze Beds. These low sulphur values are in agreement with the continental location of the peat swamps outside the reach of marine incursions (e.g., Diessel, 1992).

#### MACERAL-BASED COAL FACIES ANALYSIS

Two coal seams of the Mudstone Series, coal 403/1 from the Pniówek mine and coal 330 from the Murcki mine, were selected for detailed maceral analysis. In both sections, macerals of the vitrinite group comprise volumetrically over 50% on average (Figs. 17 and 18). Collotelinite and collodetrinite are most common. The average content of inertinite is >30% and liptinite is 14%. Inertinite is mainly represented by fusinite and semifusinite, whereas liptinite is dominantly sporinite. In both coal seams, the vitrinite content increases up the profiles (Figs. 17A and 18A). In seam 403/1, a higher collodetrinite content was found in the middle part of the section. The content of inertinite and liptinite generally decreases in the upper parts of the sections (Fig. 17A).

The Gelification Index (GI) increases, although irregularly, up the coal seam sections, which indicates an increasing degree of waterlogging during peat swamp evolution. The Tissue Preservation Index (TPI) also increases towards the top of the coal seams, which refers to an increasing proportion of forest vegetation, or to a lower intensity of decomposition of plant tissues (Diessel, 1992). The TPI increase further implies that plants of tree habit were better adapted to growth in conditions of rising groundwater level. Only in the central part of the section of coal seam 403/1 is there an increased proportion of herbaceous vegetation, which indicates a mixed swamp character (Fig. 17B).

The petrographic composition of the coals, calculated TPI/GI indices, and their position within the facies diagram of Diessel (1986, 1992), point to the conclusion that these coals primarily formed in wet forest peat swamps (Figs. 17 and 18). This interpretation is supported by the high degree of waterlogging and gelification (GI), as well as by the predominance of tree-like vegetation and of macerals of the vitrinite group. The middle part of seam 403/1 probably formed in a mixed peat swamp, as suggested by interbedded laminae composed of macerals typical of forest type peat swamps (e.g., telinite and collotelinite layers) and those representing herbaceous peat swamp communities (e.g., collodetrinite with inertodetrinite and sporinite). In the lower part of seam 330, a thin band of coal derived from a herbaceous peat bog was identified. This band is dominantly composed of collodetrinite and detrital macerals such as inertodetrinite, vitrodetrinite and sporinite. At the top of seam 403/1, intervals of carbonaceous shale were deposited in a clastic swamp. The characteristic microscopic features of this clastic swamp deposit are the occurrence of coal laminae composed mainly of telinite and collotelinite, and laminae of claystone.

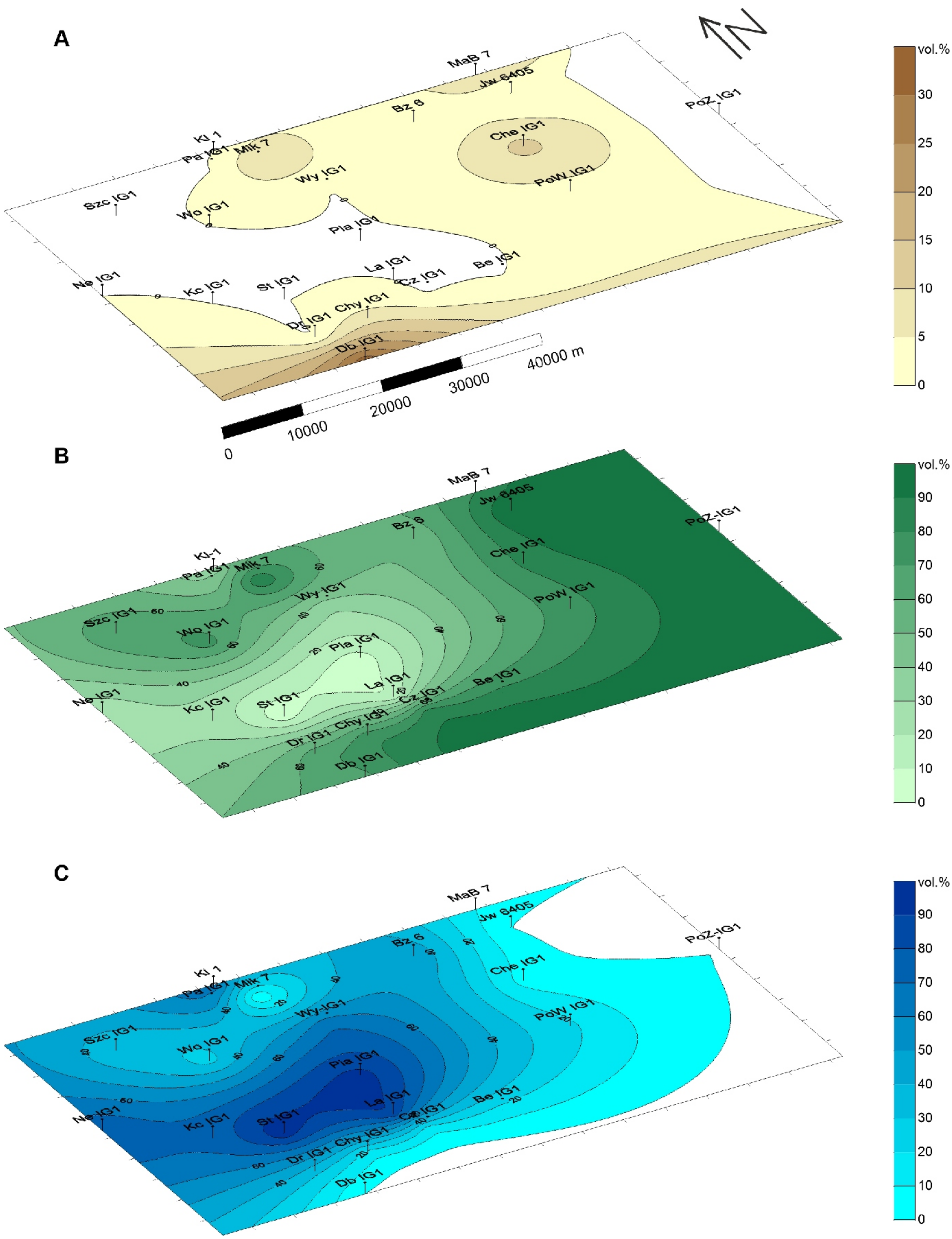
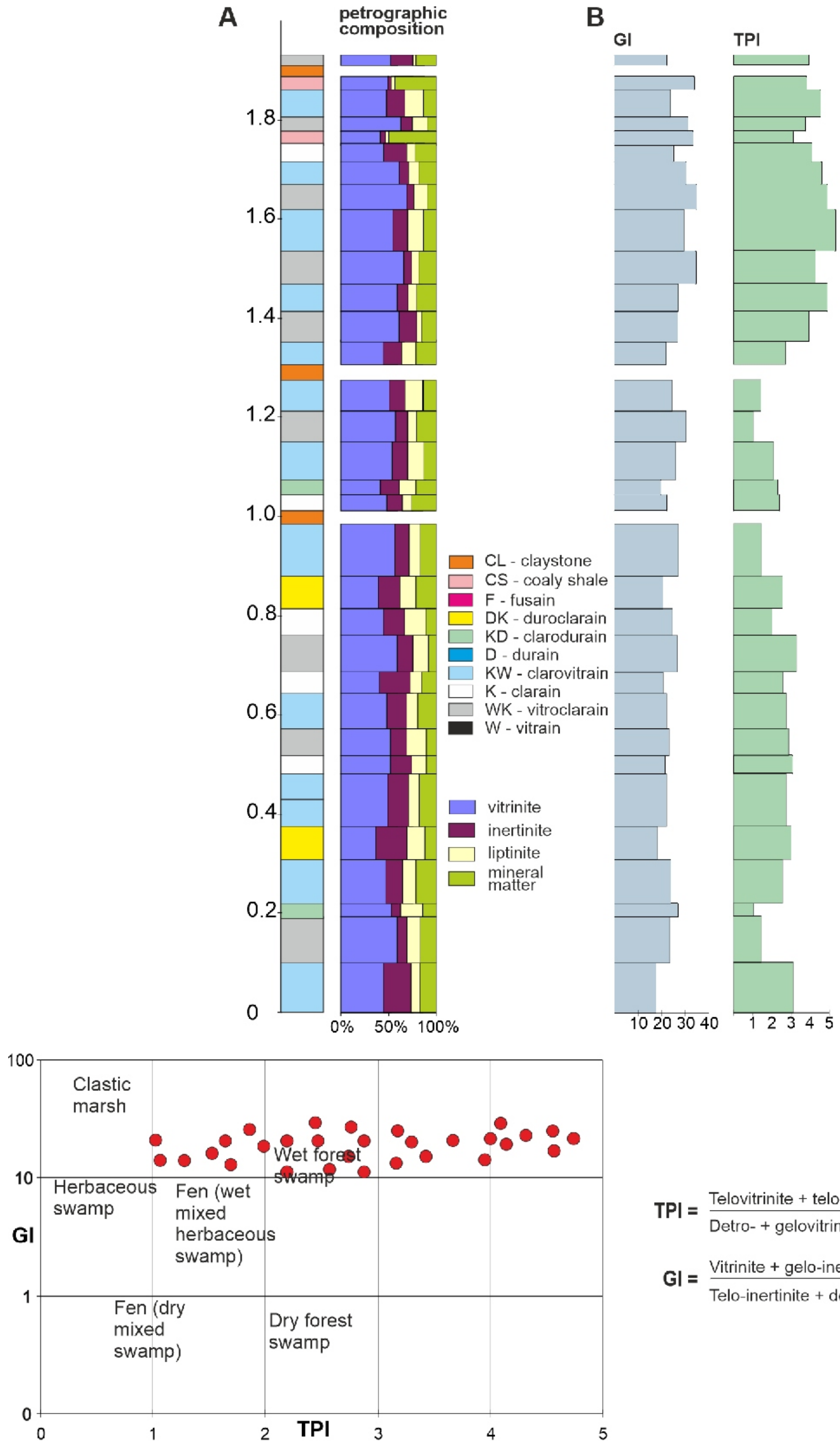



**Fig. 16. Distribution of peatswamp types in the Mudstone Series in the Main Syncline of the Upper Silesia Coal Basin**

**A** – proportion of herbaceous type peatswamps; **B** – proportion of mixed type peatswamps; **C** – proportion of forest type peatswamps




$$TPI = \frac{\text{Telovitrinite + telo-inertinite}}{\text{Detro- + gelovitrinite + detro- + gelo-inertinite}}$$

$$GI = \frac{\text{Vitrinite + gelo-inertinite}}{\text{Telo-inertinite + detro-inertinite}}$$

**Fig. 17. Coal seam 403/1 in the Pniówek coal mine (SW part of the Main Syncline)**

**A** – petrographic composition; **B** – conditions of coal formation

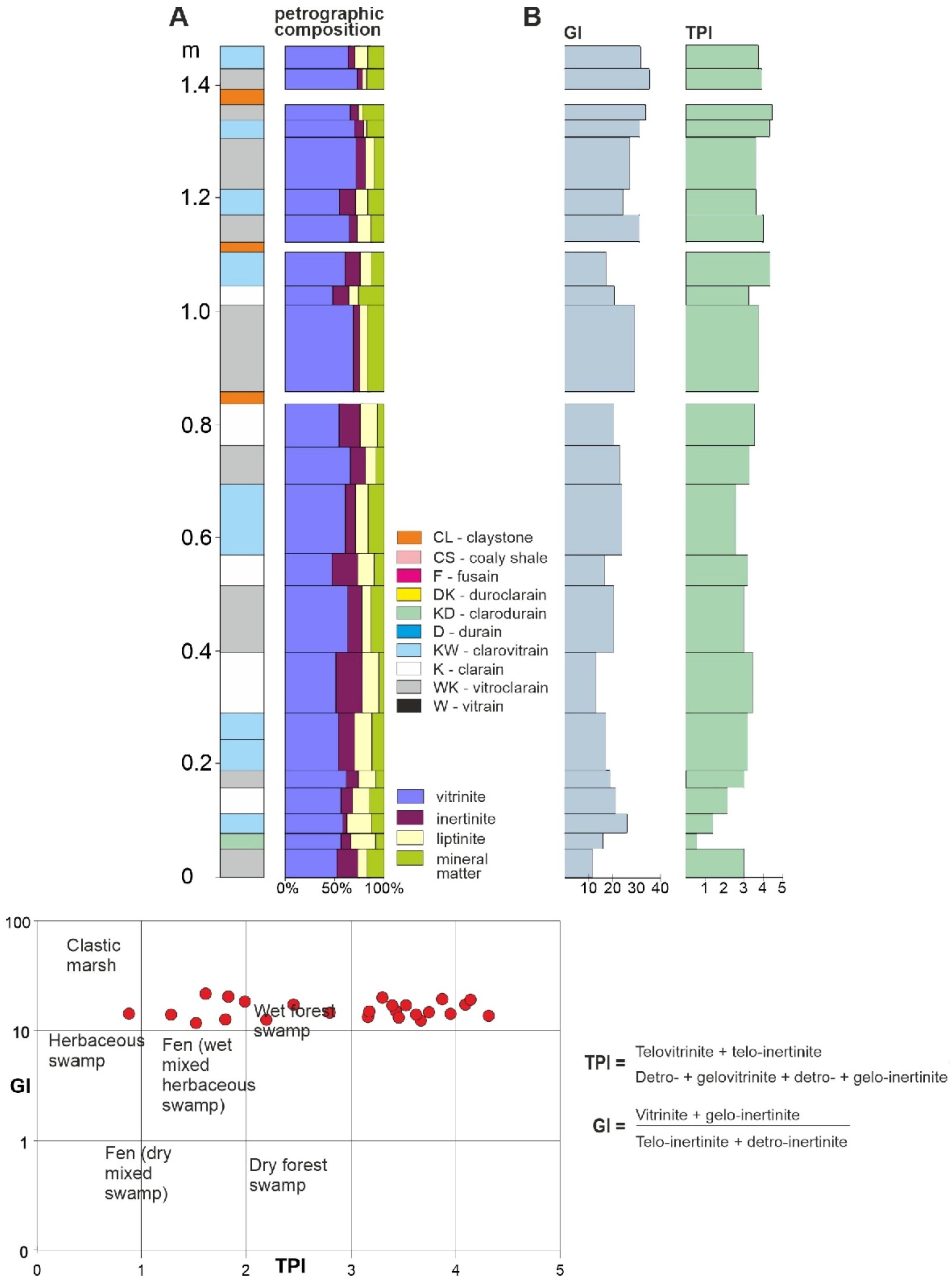



**Fig. 18. Coal seam 330 in the Murcki coal mine (N part of the Main Syncline)**

**A** – petrographic composition; **B** – conditions of coal formation

Maceral analysis of a coal seam exposed in the Kochłowice brickyard was performed on samples from the unsplit coal and from both benches (Fig. 19A). The dominant group of macerals in all three sections is vitrinite (~50% of petrographic composition in all samples), represented mainly by collotelinite. Fusinite is the most abundant maceral in the inertinite group, whereas liptinite is the least represented maceral group. Calculated GI and TPI plotted on a Diessel (1992) facies diagram shows that the unsplit coal and its benches formed in wet forest peat swamps (Fig. 19B). The unsplit coal (Koch 17–19 samples), as well as its benches show a similar trend of increase in the degree of waterlogging, which is marked by increasing GI. This is in agreement with increasing ash yield and decreasing proportion of inertinite in the same direction in all three sections, pointing to rising water table, introduction of clay suspension and drowning of peat swamp, as indicated by upright lycopsid stumps in the roof of the coal. A simultaneous minor decrease in the TPI values may likely indicate reduced "tree density". However, all the TPI values are extremely high, exceeding the limits of the original Diessel (1992) facies diagram. Similarly, high values were calculated for contemporaneous (=Duckmantian) coal seams in the Lower Silesian (=Intra-Sudetic) Basin by Opluštil et al. (2013). This may be potentially explained by the origin of TPI and GI facies indices defined for Permian coals of Gondwana Province characterised by different types of vegetation (Dai et al., 2020). Analysis of the coal in the Kochłowice brickyard also indicates that the buried part of the peat swamp was recolonised by a vegetation type similar to that in the upper part of the unsplit peat swamp.

## DISCUSSION ON DEPOSITIONAL SETTING AND DYNAMICS OF PEAT ACCRETION

In the Upper Silesian Basin, the Mudstone Series (Langsettian–Duckmantian) represents a stratigraphic interval bearing ~150 coal seams. This unit is contemporaneous with the main coal-bearing units in other major coal basins in Europe and North America, which were located in the equatorial region of Pangea (e.g., Nádaskay et al., 2025).

The coal-bearing succession was deposited in a fluvial setting with subordinate shallow lakes. Channel fills composed of fine- to medium-grained sandstone up to 35 m thick are entombed in predominantly claystone and mudstone floodplain deposits. Interpretation of a meandering fluvial system as the principal depositional environment is based not only on the dominance of floodplain strata, but also is evident from the ribbon-like geometry of some thick sandstone bodies. These meander belts are usually 4–5 km wide and follow the NNE-striking basin axis. Where meandering fluvial channels migrated laterally, sheet-like sandstone bodies of significant (at least 5 km) lateral extent were formed. Such bodies are characterised by a complex internal structure, with erosional surfaces commonly marked by thin conglomerate interbeds. By contrast, sandstone lithosomes not exceeding 1,5 m in thickness are mostly interpreted as crevasse channels or splays deposited within the proximal floodplain. This lateral migration may be related to changes in sediment supply upstream, such as periods of increased clastic input related to tectonic events or climate change, as hypothesised by Opluštil et al. (2019) and Laurin et al. (2024). Alternatively, it could be linked to changes in the base level downstream, related to sea level changes. This would suggest that the basin is not high above sea level, supporting the hypothesis that major lacustrine horizons in Upper Silesia are a distal response to sea level rise. The lower boundary of the Mudstone Series is placed at the top of a freshwater faunal horizon, which is also Namurian/Westphalian boundary. This boundary in the western part of the Variscan foreland is marked by the Subcrenatum (=Sarnsbank) marine band (Owens et al., 1985).

The coal seams of the Mudstone Series are typically between a few centimetres and 1 m thick, but exceptionally may exceed 6 m. Peat swamps developed on extensive floodplains that were dissected by active channels and interspersed with shallow lakes. Most peat swamps were established by paludification of the floodplain as wet forest swamps, and stigmarian horizons beneath almost all coal seams point to their autochthonous origin. The rare occurrence of sapropelic coals indicates that phytogenic sedimentation in floodplain ponds only took place occasionally. Changes in thickness within individual seams are related to floodplain topography, the interaction between peat swamps and active fluvial channels, or are associated with early post-sedimentary erosion of compacted peat/coal. Lake deposits usually occur directly on or just above peat swamp (coal) or clastic swamp deposits (carbonaceous mudstone), which indicate the flooding of the peat swamp area and the development of sedimentation in lake conditions. The occurrence of coarsening-upwards sequences (FH-FW-HE-SR lithofacies) above lake deposits indicates the development of a crevasse splay delta/terminal splay associated with flood-water conditions. As a result, coal seams or coal zones composed of several benches of split coal are usually discontinuous and consist of isolated 'patches'. During extraordinary flooding events, sandy bands were deposited in parts of the forest peat swamp adjacent to the channel, while the finer fraction was carried by flood waters to distal parts of the swamp and intercepted there by herbaceous vegetation. Such a mechanism may explain the presence of numerous clastic partings and the occurrence of carbonaceous shales in the coals.

The high degree of waterlogging, demonstrated by a high vitrinite content, the presence of clastic bands, and a mean ash yield of 17 wt.%, point to the rheotrophic character of most peat swamps, although some low-ash intervals with increased inertinite content may also represent ombrotrophic types (Diessel, 1992). Petrographic (lithotype, maceral and microlithotype) composition and calculated facies indices show that the precursors of most coal beds of the Mudstone Series formed in wet forest to mixed, i.e., arborescent- to shrubby-dominated vegetation swamps, whereas peat-forming wetlands with purely herbaceous vegetation were subordinate. The higher rate of subsidence in the western part of the basin adjacent to the orogenic belt resulted in generally higher waterlogging of the peat swamps, which were predominantly colonised by forest to mixed swamp vegetation. In contrast, mixed and subordinate herbaceous swamps were typical of the less subsiding eastern and southern parts of the basin, which were situated on more stable basement (see Fig. 16). Bright coal lithotypes (vitrain, clarain-vitrain and thick-banded vitrain-clarain) rich in vitrinite, mainly colotelinite, dominate coal seams formed in wet forest peat swamps. The vegetation of these swamps was primarily composed of arborescent/woody lycopsids (Gradziński and Doktor, 1995). Mudstone, carbonaceous shale, and bands of high-ash coal intercalated in the coal beds suggest a high water table and peat swamp inundation from contemporaneous active fluvial channels on centennial and millennial scales. The presence of lepidodendrid lycopsid-dominated wet forests in proximity to active fluvial channels has also been documented in the Herrin Coal in the Illinois Basin (e.g., Phillips and Peppers, 1984; DiMichele and Phillips, 1994). However, during prolonged periods of lowered water table, the wet forest peat swamp was locally replaced by relatively dry forest swamp prone to wildfires (Scott and Glasspool, 2006; Glasspool and Scott, 2010), as indicated by fusain lenses and laminae embedded in bright coal lithotypes (vitrain, clarain).

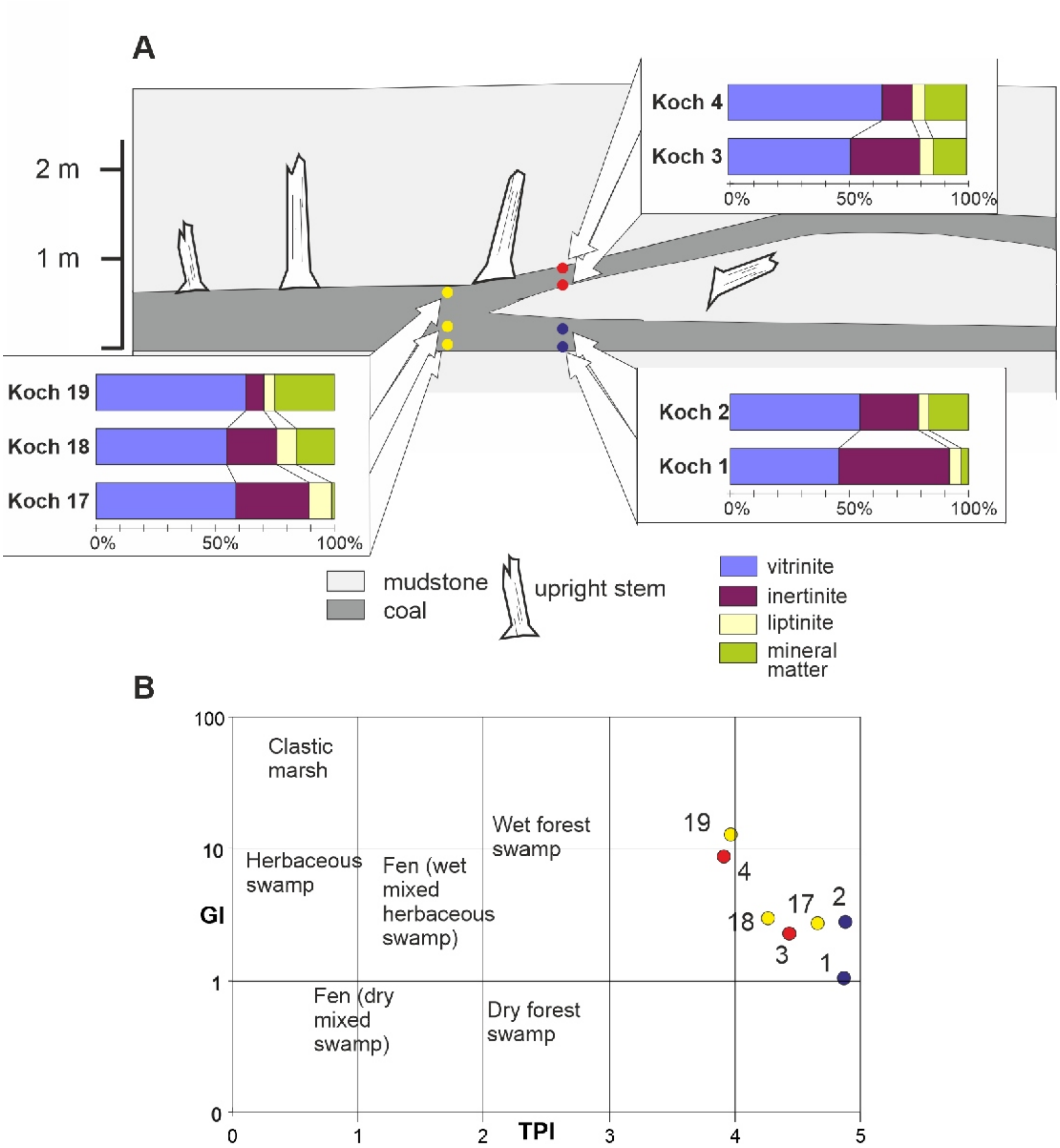



**Fig. 19. Petrographic composition and conditions of coal formation of the Kochłowice exposure (N part of the Main Syncline)**

**A** – location of samples and their petrographic composition; **B** – facies diagram for the seam studied

Mixed peat swamps mainly occupied distal parts of floodplains less affected by active fluvial channels, as indicated by less frequent clastic partings. These swamps represented a transition between forest and herbaceous types, as their vegetation contained a higher proportion of subarborescent and herbaceous plants. Mixed vegetation is indicated by the presence of clarain with thin vitrain laminae. Microscopically, such coals are characterised by an alternation of thick telinite and collotelinite bands generated from arborescent vegetation and layers of collodetrinite and inertodetrinite rich in sporinite derived mostly from herbaceous vegetation. These mixed peat swamps were more abundant in the eastern part of the Upper Silesian Basin. On elevated areas within the mixed swamps (ombrotrophic stage), or during longer periods of a lowered water table, a dry mixed plant community locally formed. The resulting coal bands are low in ash yield but rich in fusain lenses and laminae expressed as having increased fusinite and semifusinite contents. Least numerous were herbaceous swamps dominated by herbaceous vegetation that grew along the lake coast or in the floodbasin situated in areas of limited clastic input. The resulting coal seams are rich in dull coal bands consisting of detrital macerals, mainly inertodetrinite, vitrodetrinite and sporinite.

## CONCLUSIONS

The lower Middle Pennsylvanian Mudstone Series in the Upper Silesian Basin is contemporaneous with the main coal window of tropical Pangea. However, apart from major paralic basins, the Mudstone Series was deposited outside the reach of glacioeustatic sea-level oscillations in a continental setting. This study of the sedimentary geology and analyses of coal petrology has improved our understanding of the palaeoenvironments in which the Mudstone Series and its coal seams formed. The results can be summarised as follows:

- The principal depositional environment of the Mudstone Series was a meandering fluvial system with the predominance of floodplain sediments.

- Meander belts of major fluvial channels were commonly 4–5 km wide, followed the NNE-striking basin axis, and were concentrated along the western basin margin, where the greatest subsidence occurred along the Moravo-Silesian thrust and fold belt. Lateral migration and/or avulsion resulted in the formation of laterally widespread sheet-like sandstone bodies up to 35 m thick with internal erosional surfaces.
- Isolated narrow channel-fills were amalgamated into a broad belt of sand bodies, and transitional forms between these end-member types. In all cases, avulsion was an important process during deposition of all of these architectural types, with significant changes likely dependent on local subsidence rate. Higher subsidence rates resulted in a vertical stacking (aggradational) pattern, whereas lower rates tended to result in lateral migration and the formation of sheet-like channel bodies.
- Variation in thickness of individual seams was related to floodplain topography, peat swamp and fluvial channel interactions or to post-sedimentary erosion.
- The peat swamps evolved on widespread floodplains dissected by active channels and shallow lakes. Coal seams are therefore discontinuous, although individual groups may consist of laterally widespread horizons.
- For the most of the peat swamps, a high degree of waterlogging and a rheotrophic character is suggested, with temporarily lowered water tables when the exposed surface was prone to wildfires.
- Precursors of most coal beds were wet forest to mixed (arborescent/woody- and shrubby vegetation-dominated) peat swamps, whereas herbaceous peat swamps were subordinate and more common in the eastern less subsiding part of the basin. Mixed peat swamps mainly occupied distal parts of floodplains that were less affected by active fluvial channels. Herbaceous swamps were dominated by shrubby to herbaceous vegetation growing along the lake coast or in the floodbasin.

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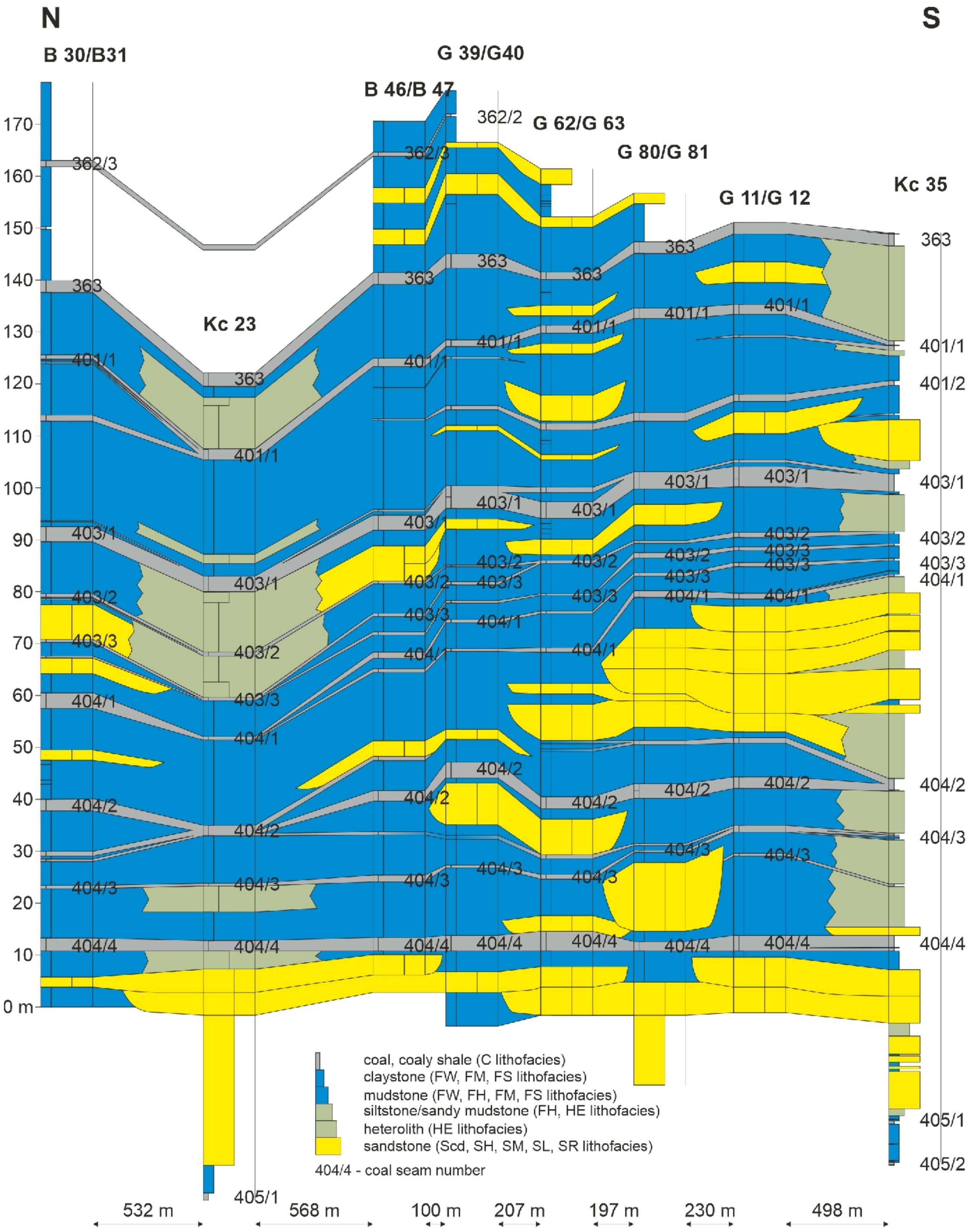
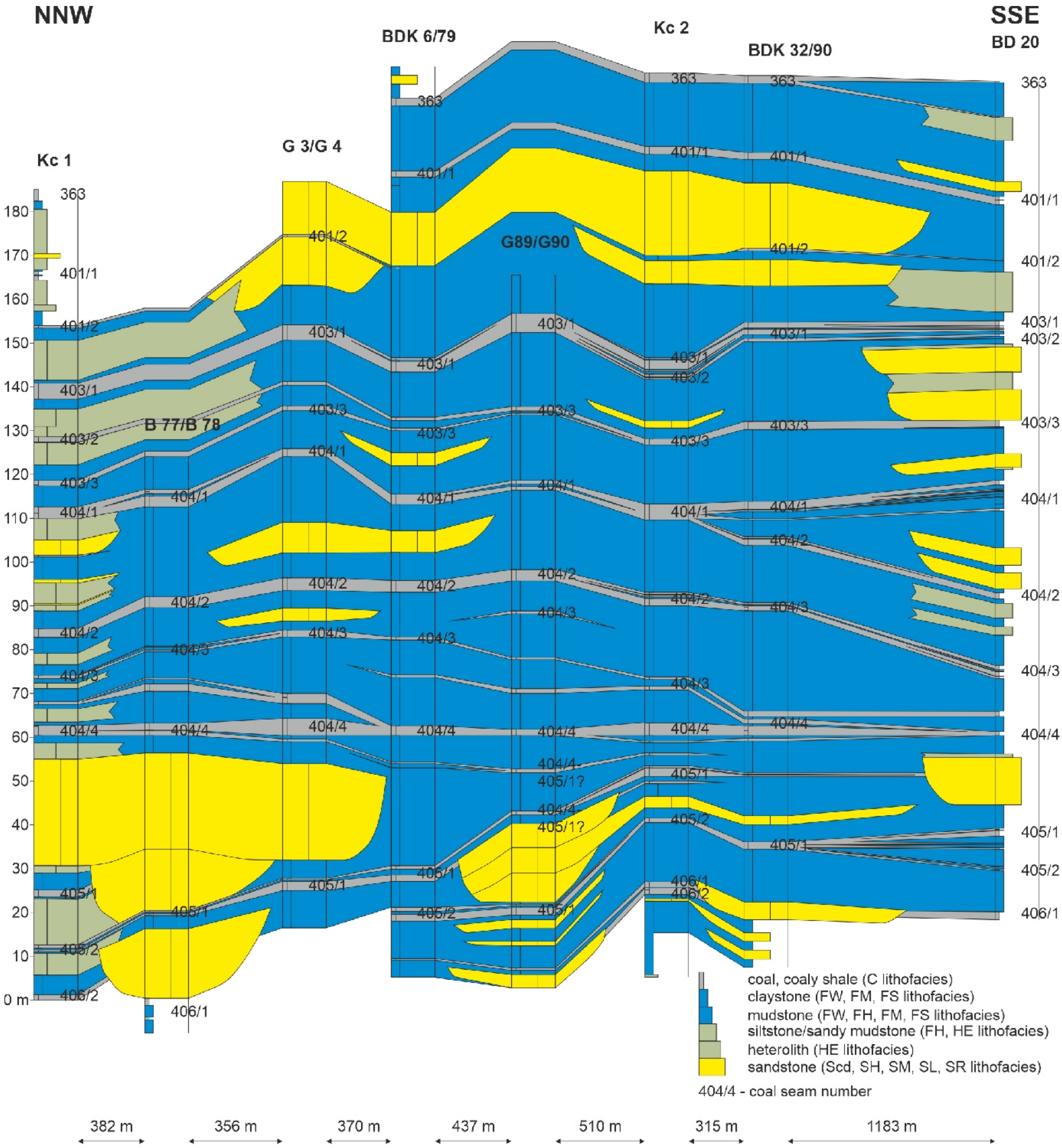


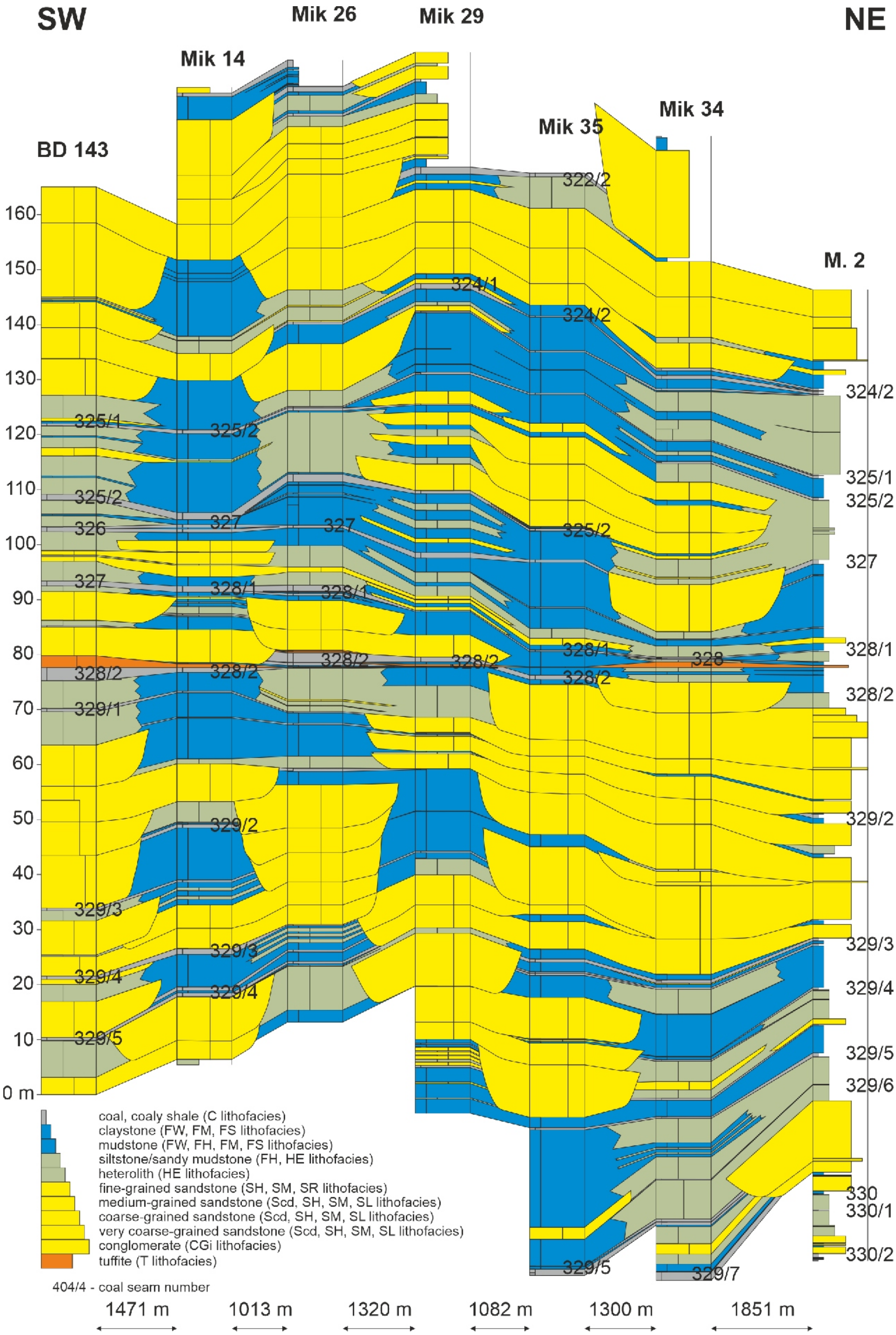

**Supplementary Fig. 1. Correlative cross-section A–A'**

Base of the Mudstone Series. Pniówek coal mine, southwestern part of the Main Syncline



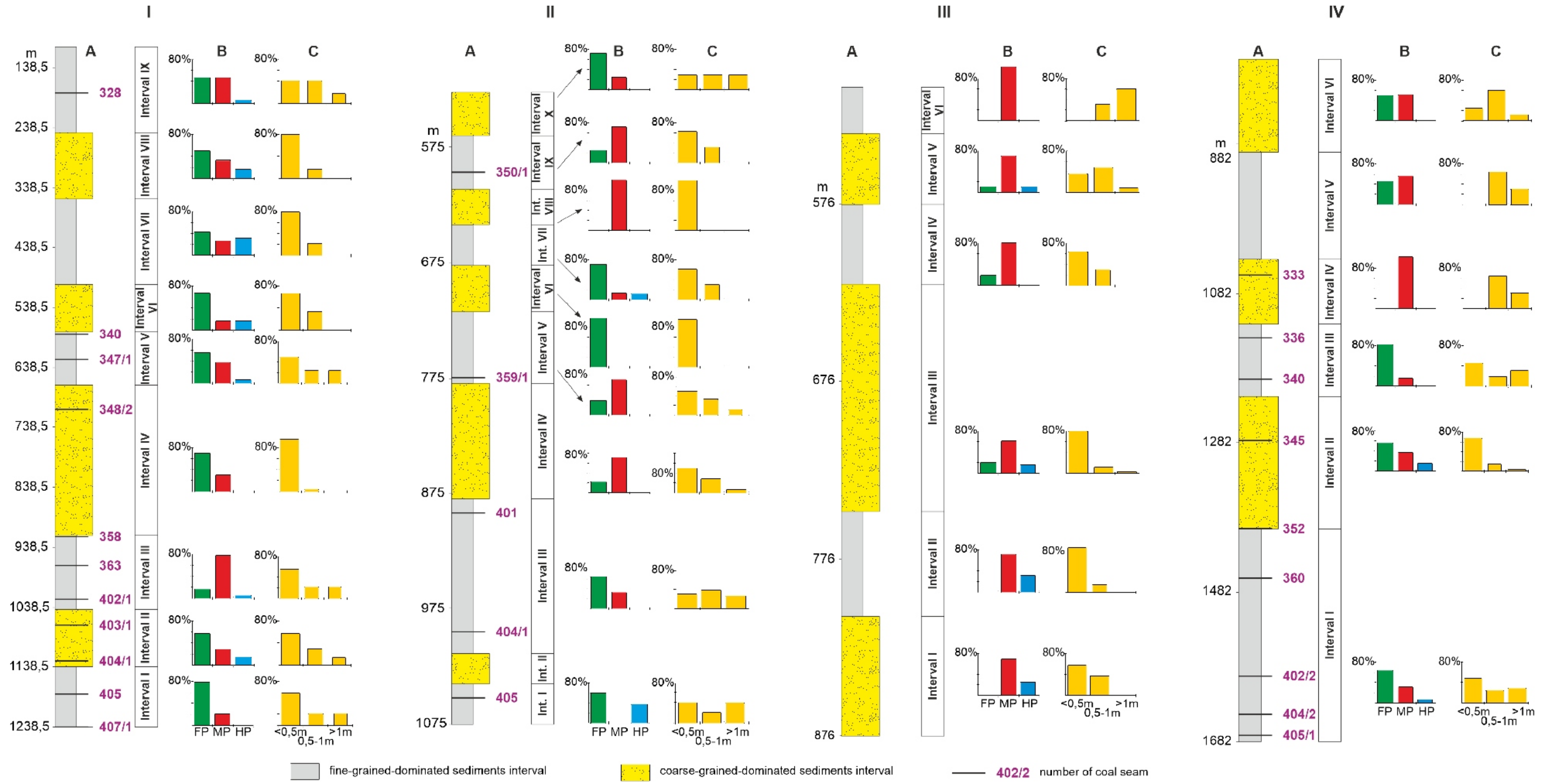

**Supplementary Fig. 2. Correlative cross-section B–B'**

Base of the Mudstone Series. Pniówek coal mine, southwestern part of the Main Syncline



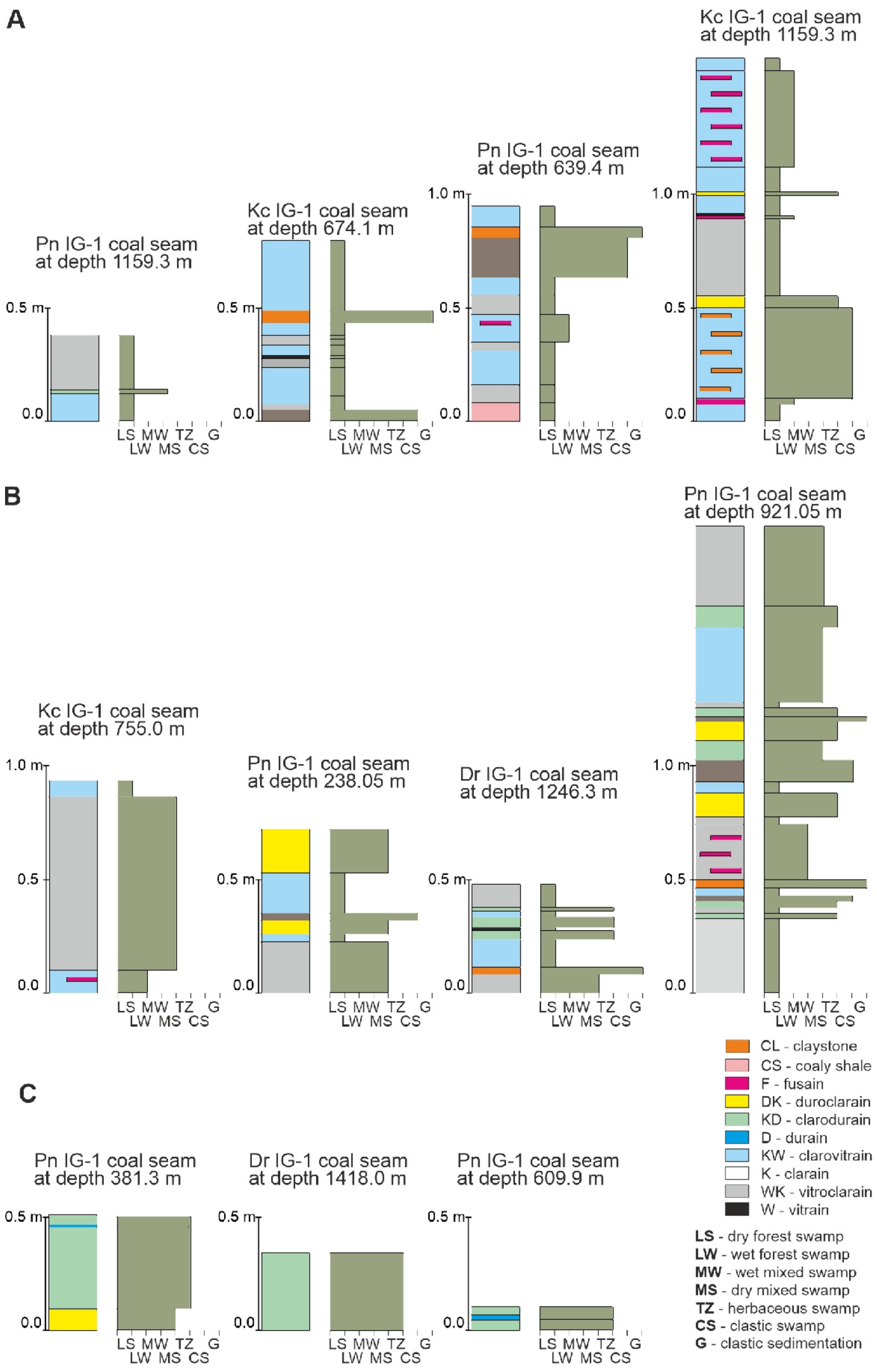

**Supplementary Fig. 3. Correlative cross-section E–E'**

Orzesze/Załęże Beds boundary. Murcki coal mine, northern part of the Main Syncline



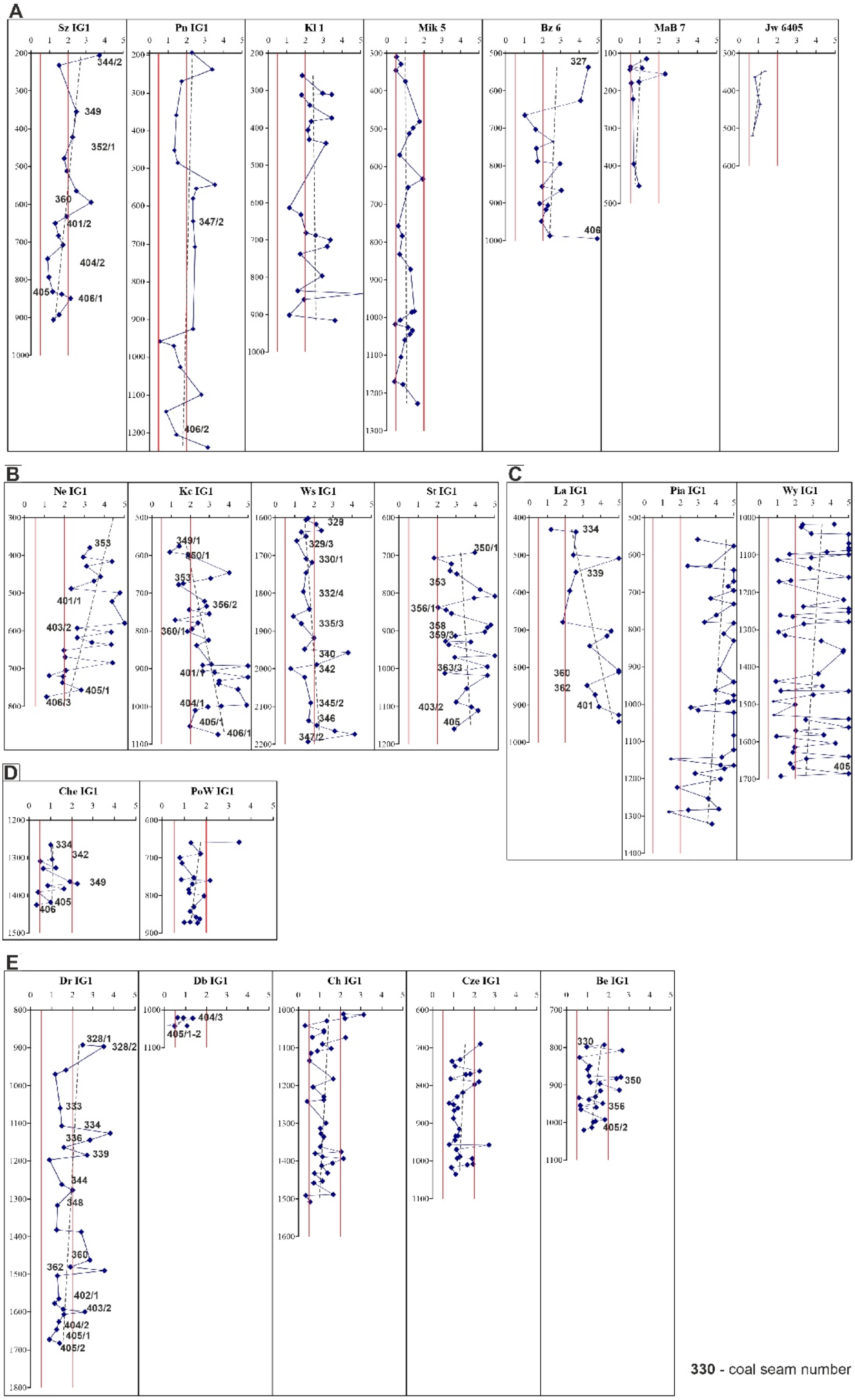

**Supplementary Fig. 4. Variability of coal seam environment and thickness in the Mudstone Series**

**I Paniowy IG1 borehole section: A** – coarse- and fine-grained intervals; **B** – histogram of the number of coal seams representing three types of peatland: (FP) forest-type peatbog, (MP) mixed-type peatbog, (HP) herbaceous-type peatbog; **C** – thickness histograms of coal seams; **II. Krzyżowice IG1 borehole section**: **A** – coarse- and fine-grained intervals; **B** – histogram of the number of coal seams representing three types of peatland: (FP) forest-type peatbog, (MP) mixed-type peatbog, (HP) herbaceous-type peatbog; **C** – thickness histograms of coal seams; **III. Poręba Wielka IG1 borehole section**: **A** – coarse- and fine-grained intervals; **B** – histogram of the number of coal seams representing three types of peatland: (FP) forest-type peatbog, (MP) mixed-type peatbog, (HP) herbaceous-type peatbog; **C** – thickness histograms of coal seams; **IV. Drogomyśl IG1 borehole section: A** – coarse- and fine-grained intervals; **B** – histogram of the number of coal seams representing three types of peatland: (FP) forest-type peatbog, (MP) mixed-type peatbog, (HP) herbaceous-type peatbog; **C** – thickness histograms of coal seams



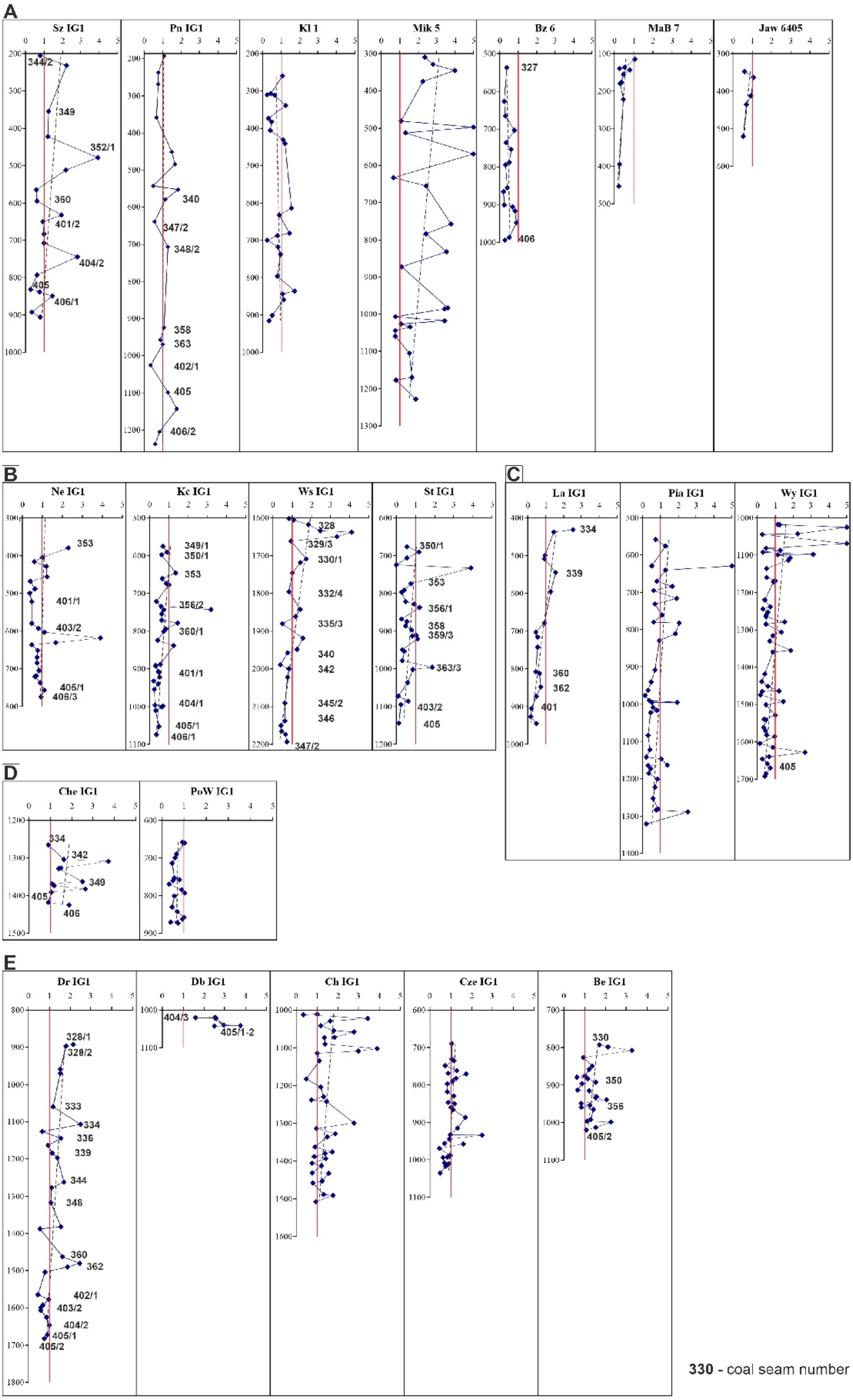

**Supplementary Fig. 5. Examples of lithofacies profiles of selected coal seams from the Mudstone Series**

**A** – coals formed under forest-type peatland conditions; **B** – coals formed under mixed-type peatland conditions; **C** – coals formed under herbaceous-type peatland conditions



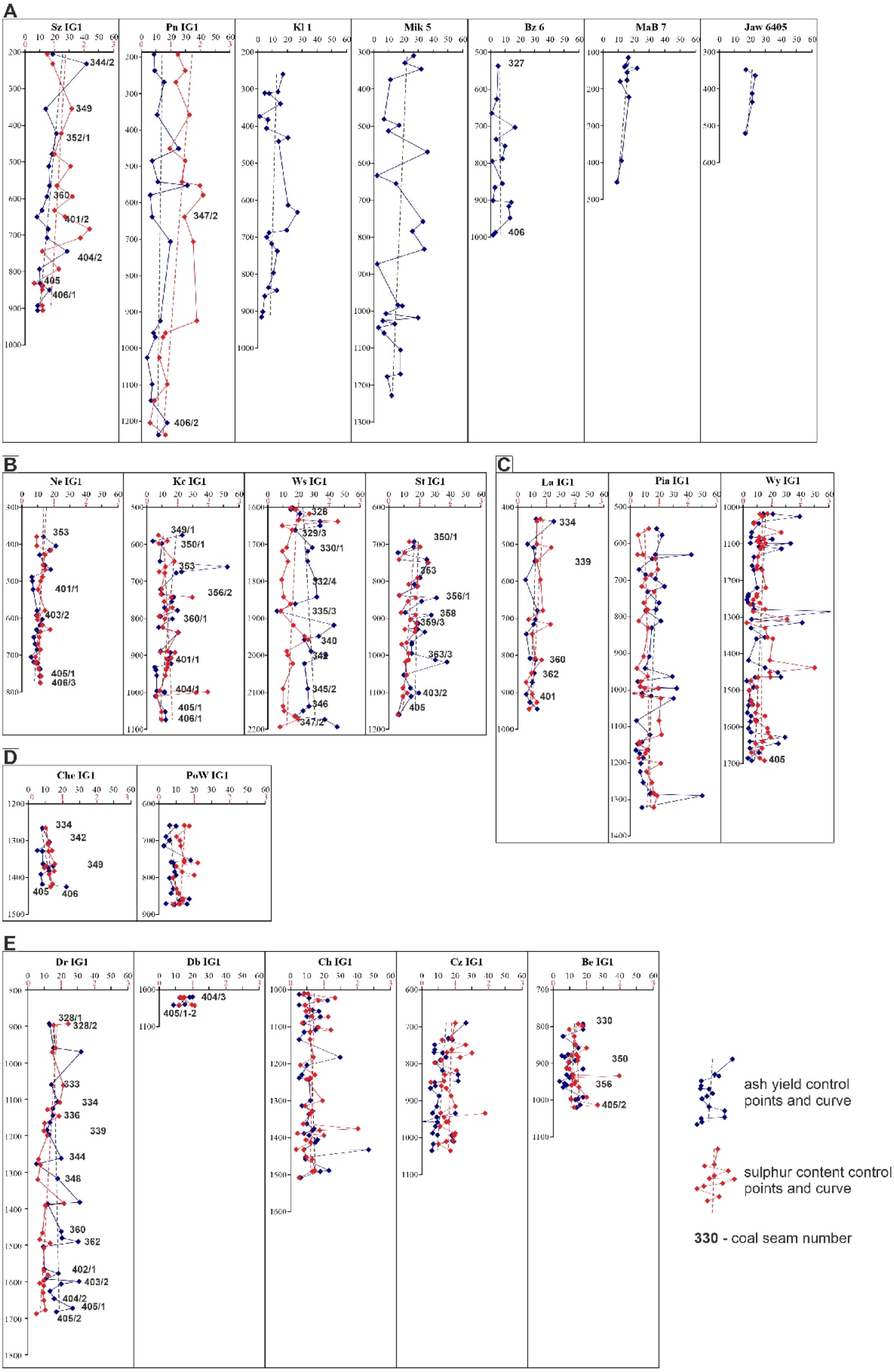

**Supplementary Fig. 6. Variability of forest facies (FFI) and waterlogging (WLI) index values in the Załęże Beds coal seams**

**A** – northern region: SzIG1 – Szczygłowice IG1 borehole, PnIG1 – Paniowy IG1 borehole, Kl 1 – Klodnica 1 borehole, Mik 5 – Mikołów 5 borehole, Bz 6 – Brzezinka 6 borehole, MaB 7 – Maczki Bór Biskupi 7 borehole, Jw-6405 – Jaworzno 6405 borehole; **B** – the western region: NeIG1 – Niedobczyce IG1 borehole, KcIG1 – Krzyżowice IG1 borehole, Wos IG1 – Woszczyce IG1 borehole, St IG1 – Studzionka IG1; **C** – central region: La IG1 – Łąka IG1, Pia IG1 – Piasek IG1, Wy IG1 – Wyry IG1; **D** – eastern region: Che IG1 – Chełmek IG1, PoW IG1 – Poręba Wielka IG1; **E** – southern region: Dr IG1 – Drogomyśl IG1, Db IG1 – Dębowiec IG1, Ch IG1 – Chybie IG1, Czc IG1 – Czechowice IG1, Be IG1 – Bestwina IG1



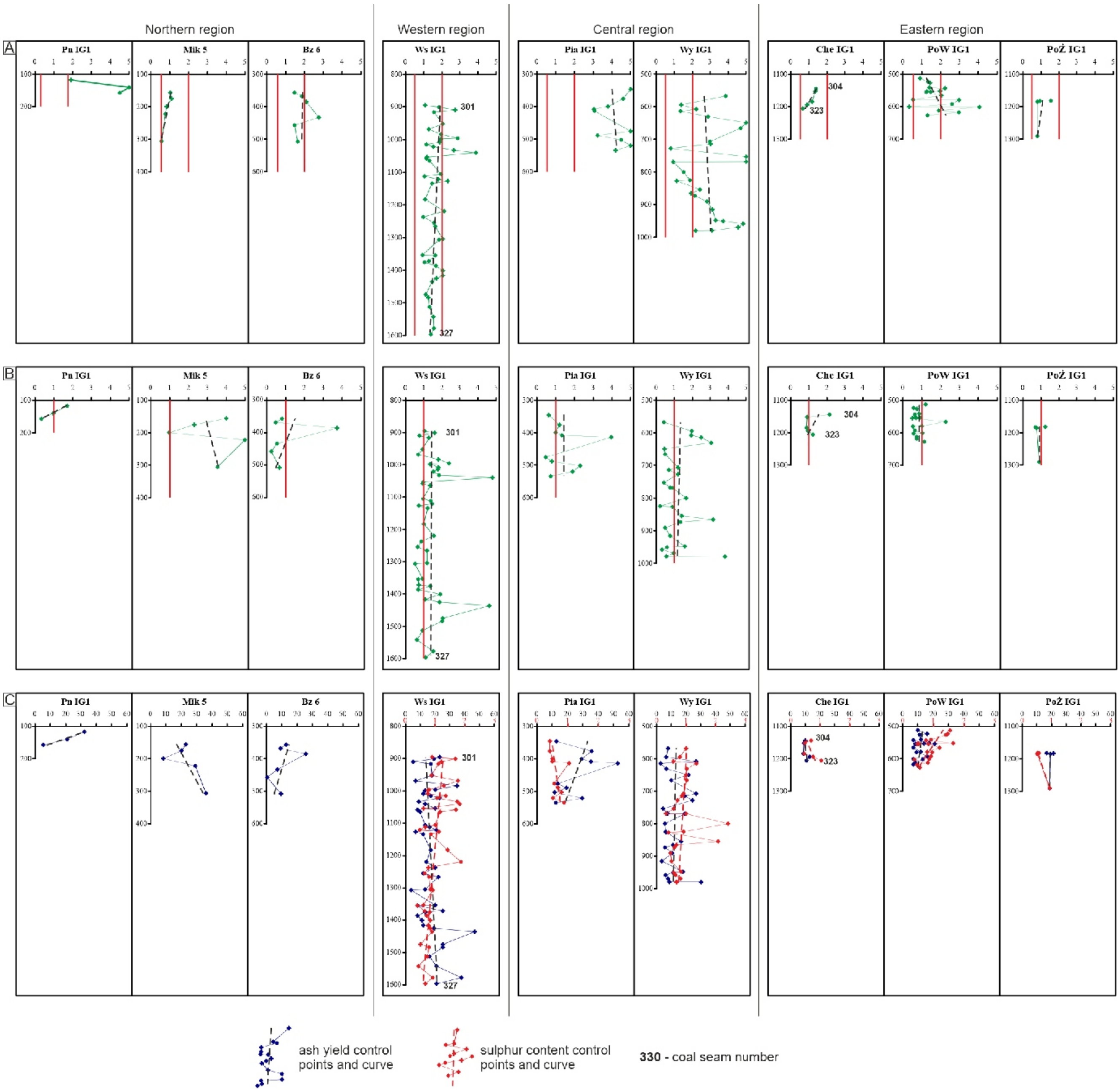

**Supplementary Fig. 7. Variability in the values of the waterlogging index (WLI) in coal seams of the Załęże Beds**

**A** – northern region: SzIG1 – Szczygłowice IG1 borehole, PnIG1 – Paniowy IG1 borehole, Kl 1 – Klodnica 1 borehole, Mik 5 – Mikołów 5 borehole, Bz 6 – Brzezinka 6 borehole, MaB 7 - Maczki Bór Biskupi 7 borehole, Jw-6405 – Jaworzno 6405 borehole; **B** – western region: NeIG1 – Niedobczyce IG1 borehole, KcIG1 – Krzyżowice IG1 borehole, Wos IG1 – Woszczyce IG1 borehole, St IG1 – Studzionka IG1; **C** – central region: La IG1 – Łąka IG1, Pia IG1 – Piasek IG1, Wy IG1 – Wyry IG1; **D** – eastern region: Che IG1 – Chełmek IG1, PoW IG1 – Poręba Wielka IG1; **E** – southern region: Dr IG1 – Drogomyśl IG1, Db IG1 – Dębowiec IG1, Ch IG1 – Chybie IG1, Czc IG1 – Czechowice IG1, Be IG1 – Bestwina IG1




**Supplementary Fig. 8. Variability of ash and sulphur content in the coal seams of Załęże Beds**

**A** – northern region: SzIG1 – Szczygłowice IG1 borehole, PnIG1 – Paniowy IG1 borehole, Kl 1 – Klodnica 1 borehole, Mik 5 – Mikołów 5 borehole, Bz 6 – Brzezinka 6 borehole, MaB 7 - Maczki Bór Biskupi 7 borehole, Jw-6405 – Jaworzno 6405 borehole; **B** – western region: NeIG1 – Niedobczyce IG1 borehole, KcIG1 – Krzyżowice IG1 borehole, Wos IG1 – Woszczyce IG1 borehole, St IG1 – Studzionka IG1; **C** – central region: La IG1 – Łąka IG1, Pia IG1 – Piasek IG1, Wy IG1 – Wyry IG1; **D** – eastern region: Che IG1 – Chełmek IG1, PoW IG1 – Poręba Wielka IG1; **E** – southern region: Dr IG1 – Drogomyśl IG1, Db IG1 – Dębowiec IG1, Ch IG1 – Chybie IG1, Czc IG1 – Czechowice IG1, Be IG1 – Bestwina IG1




**Supplementary Fig. 9. Variability of microlithotype-derived facies indices and ash and sulphur content of the Orzesze Beds**

**A** – forest facies index (FFI) values; **B** – waterlogging index (WLI) values and **C** – ash and **D** – sulphur content in coal seams of the Orzesze Beds in the northern region: PnIG1 – Paniowy IG1 borehole, Mik 5 – Mikołów 5 borehole, Bz 6 – Brzezinka 6 borehole; western region: Wos IG1 – Woszczyce IG1 borehole; central region: Pia IG1 – Piasek IG1 borehole, Wy IG1 – Wyry IG1 borehole; eastern region: Che IG1 – Chełmek IG1 borehole, PoW IG1 – Poręba Wielka IG1 borehole, PoŻ IG1 – Poręba Żegoty IG1 borehole