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CONDITIONS OF ACCUMULATION AND SEDIMENTARY ARCHITECTURE OF THE UPPER WESTPHALIAN CRACOW SANDSTONE SERIES (UPPER SILESIA COAL BASIN, POLAND)

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Abstract: The Cracow Sandstone Series (upper Westphalian) forms the uppermost segment of the coal-bearing succession that makes up the bulk of the Variscan foredeep-basin fill in the Upper Silesia Coal Basin. The series, up to 1640 m in stratigraphic thickness, consists entirely of non-marine deposits. Fifteen lithofacies have been distinguished in the sediments of this series. The Cracow Sandstone Series is subdivided here in two lithofacies associations. The sandstone association consists mainly of medium- to coarse-grained sandstones that form packages up to several tens of metres thick (max. 140 m), with surfaces of erosion at base. These bodies are separated by less voluminous packages of the mudstone association that consists mainly of mudstones and coal seams, which locally make up the predominant part in the sequences of this association.

The sediments of the sandstone association are believed to have originated within wide channel tracts of distal sandy braided rivers. The sediments of the mudstone association with the interbedded coal seams are interpreted as floodplain deposits. The predominant type of peat bogs, represented now in the coals of the Cracow Sandstone Series, were wet forest swamps. The peat bogs were probably slightly domed and their margins received clastic material from adjacent channels. This resulted in the frequent lateral splitting of the coal seams. The large-scale splitting of seams is associated with lateral transition of fine-grained floodplain deposits into coarse-grained channel deposits.

The vertical alternation of the channel and floodplain deposits is the result of natural processes on an alluvial plain that resulted in shifting positions of depositional environments, first of all avulsion of the whole fluvial tracts.

The coal seams in the Cracow Sandstone Series do not form extensive sheets of persistent thickness, and their geometry depends on the course and evolution of the network of fluvial tracts in the alluvial system. The internal geometry of the Cracow Sandstone Series was controlled to a large extent by differential compaction of sediments, notably by rapid compaction of peat.

Key words: braided fluvial system, fluvial architecture, coal-bearing deposits, Carboniferous, Upper Silesia, Poland.

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INTRODUCTION

The Cracow Sandstone Series is the youngest of the four great informal stratigraphic units distinguished in the coal-bearing succession of the Upper Silesia Coal Basin (USCB). This series, similarly as the two older series, consists entirely of sediments laid down in continental environments. The sediments of this series have been interpreted as fluvial deposits for more than thirty years (Gradziński *et al.*, 1961; Dembowski, 1967, 1972b), but many aspects of their deposition are still little studied. Detailed sedimentological studies have been initiated by the Institute of Geological Sciences, Polish Academy of Sciences. Early results on the sedimentary environment of the Cracow Sandstone Series, based on lithofacies analysis of selected drill cores, were published by Gradziński, Doktor and Słomka (Gradziński *et al.*, 1995).

This paper is a sedimentological study based on a new analysis of much more abundant data acquired in the recent years, mainly from archival borehole descriptions and various coal-mine data. This paper aims mainly at the reconstruction of the environments and conditions of sedimentation and at the presentation of the sedimentary architecture of the studied series.

GENERAL CHARACTERISTICS OF THE CRACOW SANDSTONE SERIES

The Upper Carboniferous coal-bearing succession, of which the Cracow Sandstone Series is a part, occurs in the Upper Silesia Coal Basin (USCB) and is a fill of a Variscan flexural foredeep (Kotas, 1977; Gradziński, 1982) (Figs 1, 2). The stratigraphic thickness of this succession attains 8000 m and decreases from the west to the east (Fig. 2). The sediments of the coal-bearing succession are disturbed by Late Variscan and Alpine faults (cf. Kotas *et al.*, 1983; Kotas, 1985, 1994a, b). The area of the present-day extent of the succession is delineated by boundaries of erosional and tectonic origin. This area is only a fragment of the original, greater sedimentary basin.

The whole succession is divided into four stratigraphic divisions termed "series", which are in turn divided into "beds" (Dembowski, 1972a). This informal division prevails in the research papers on geology and mining in this area as well as in all kinds of archival documents. Attempts

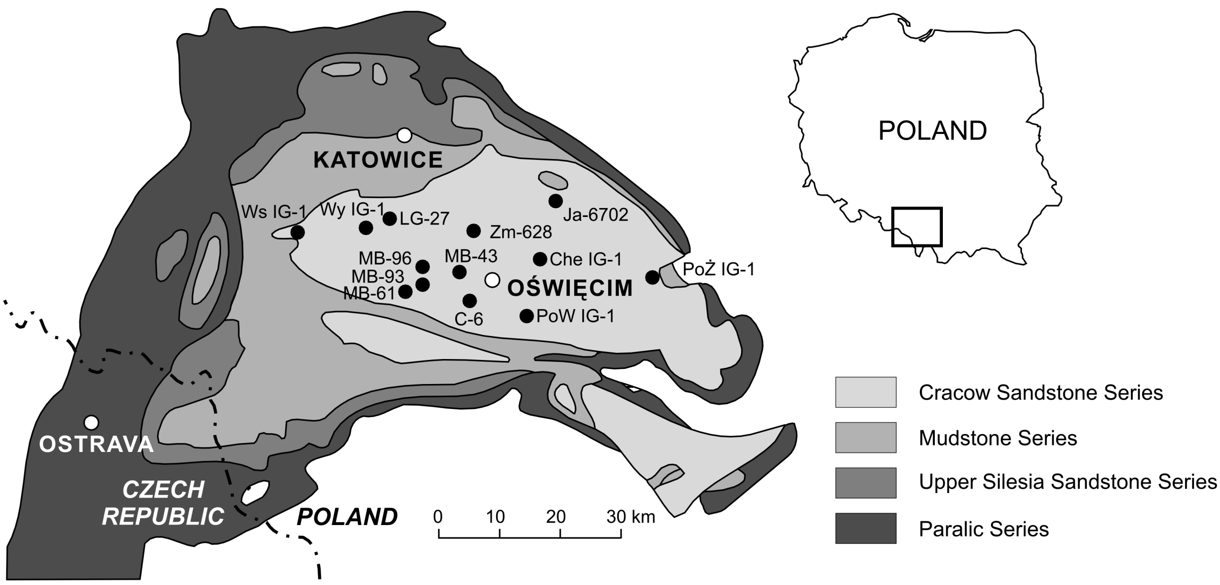

Fig. 1. Location map of the Upper Silesia Coal Basin and position of main PGI boreholes

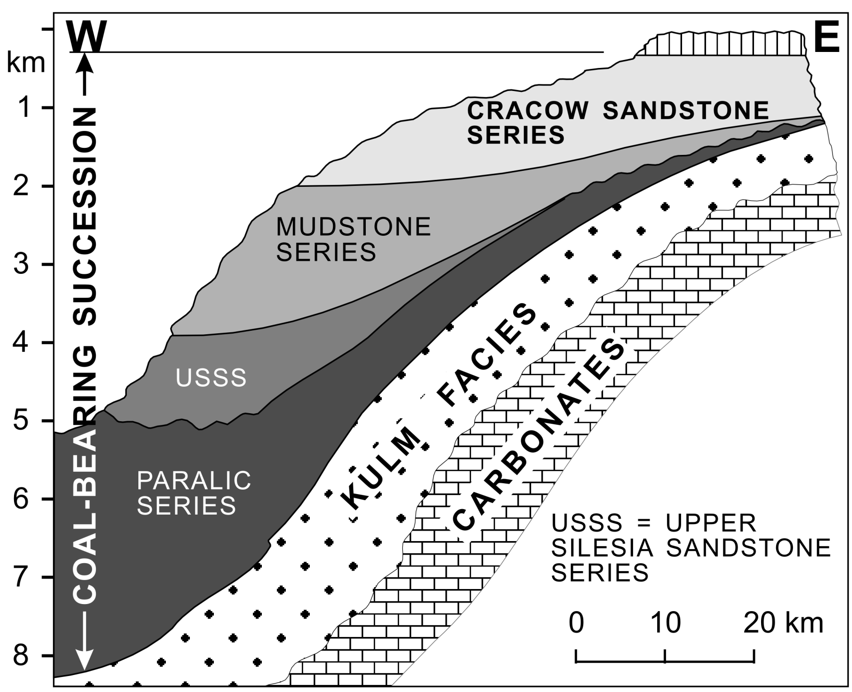

Fig. 2. A schematic lithostratigraphic cross-section through the Upper Silesia Coal Basin (after Kotas, 1994)

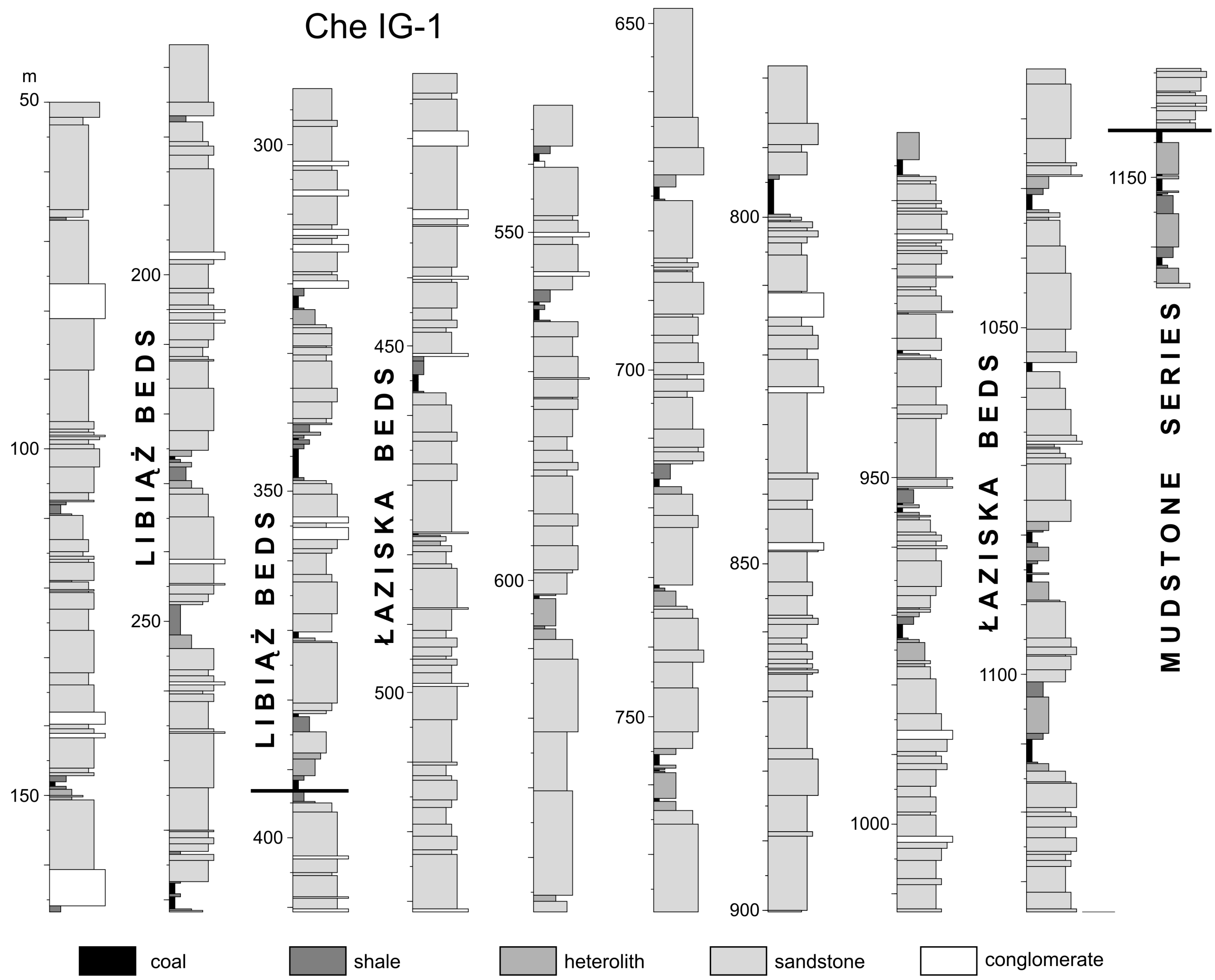

Fig. 3. Generalized lithological log of the Cracow Sandstone Series (based on the section of the Chełmek IG-1 borehole)

at establishing a new, fully formal lithostratigraphic division encounter many difficulties and seem highly problematic (see Gradziński, 1999). For this reason the present author uses here the division and nomenclature of Dembowski (1972a) with some later modifications.

The Cracow Sandstone Series is the youngest of the four series. Two lower-order units are distinguished within it (see Stopa 1957, table 3), now described as the Łaziska Beds and the Libiąż Beds (Dembowski, 1972a, b). They are similar in lithology and are distinguished on the grounds of palaeobotanical data; in practice the boundary between them is being placed arbitrarily (Dembowski, 1967, 1972b).

The described series represents the upper part of Westphalian B (Duckmantian), Westphalian C (Bolsovian) and D (see Kędzior *et al.*, 2007). Kotasowa (1979), basing on her studies of macroflora, postulates a hiatus that encompasses the highest part of Westphalian C (Bolsovian). No lithological changes correspond to this hiatus.

The areal extent of the series is limited to the central and eastern parts of the Coal Basin, and its boundaries are erosional. The sequence is markedly reduced in thickness by erosion over a large part of this area (Fig. 2). Very few outcrops of the Cracow Sandstone Series exist, hence its deposits are known mainly from numerous boreholes and mine exposures.

The lower part of the series (the Łaziska Beds) is generally thickest in the western part of the area and it markedly thins eastward (Fig. 2). The maximum thickness of the Łaziska Beds is estimated at 1080 m, and of the Libiąż Beds at 560 m (Kotas, 1985). However, the maximum total thickness of the Cracow Sandstone Series does not exceed 1200 m in any section (see Fig. 2).

The Cracow Sandstone Series is underlain by the Mudstone Series, composed mainly of fine-grained deposits with subordinate sandstones, mainly fine-grained and interpreted as deposits of a meandering-river fluvial system (Doktor & Gradziński, 1985). The lower boundary of the Cracow Sandstone Series is marked by a sharp change in lithology. This boundary lies at the base of the lowest thick package of coarse-grained deposits characteristic of this series (see Fig. 3). The boundary seems to be generally diachronous, especially in the eastern part of the extent of the series (cf. Gradziński *et al.*, 1995).

Over a small part of its areal extent, the Cracow Sandstone Series is overlain by the Kwaczała Arkose, the youngest stratigraphical unit of the Carboniferous sequence in the Upper Silesia (Rutkowski, 1972). The Kwaczała Arkose is similar in lithology to the underlying deposits of the Libiąż Beds, though it includes more of coarse-grained sandstones and conglomerates. The Kwaczała Arkose lacks coal seams and belongs to the facies type of red beds (Gradziński, 1982). It includes silicified trunks of *Dadoxylon* trees. Both, the age (Stephanian B ?) and the nature of contact of this unit with the Cracow Sandstone Series are not fully clarified. Kotas (1985) includes the Kwaczała Arkose to the Stephanian and suggests that it is separated from the Libiąż Beds by a hiatus that embraces the Cantabrian and Barruelian.

Several tens of coal seams thicker than 10 cm are present within the Cracow Sandstone Series, and about twenty of them are of economic value (Kotas, 1994b). The number of the seams increases generally westward. The coal seams of economic value, usually the thicker ones, are labelled with numbers introduced to the numbering system accepted for the Polish part of the USCB by Doktorowicz-Hrebnicki and Bocheński (1945, 1952). This system is discussed in chapter "Methods"

Coarse-grained sediments clearly predominate in the studied series. They are almost exclusively sandstones, mostly medium- and coarse-grained, sporadically conglomerates. They occur in thick packages, usually a few tens of metres thick. These packages are separated by thinner packages of mostly fine-grained sediments that include numerous coal seams (Fig. 3). Sandstones usually make up 80 to 90 percent of the section thickness, fine-grained sediments from 6.5 to 12 percent, and coals from 2.5 to 6.5 percent. The grain framework of the sandstones consists mainly of quartz (66% on average) and feldspars (22% on average), lithic clasts make up 12% on average (Świerczewska, 1995).

The gravel-grade clasts, mostly 2–10 mm in size, seldom greater, sporadically to 120 mm, are almost exclusively of extrabasinal provenance. They are usually well rounded and they represent a broad spectrum of rocks (Paszkowski *et al.*, 1995). Data of Dembowski (1967, 1972b) suggest that the proportion of gravel-grade clasts slightly increases up the section.

The results of studies on petrographic composition of the sandstones (Świerczewska, 1995) and the rocks that make up the extrabasinal clasts (Paszkowski *et al.*, 1995) indicate that the source areas of the clastic material lay mainly west of the sedimentary basin.

Only scarce data are available to decipher the directions of palaeotransport within the basin. These include scarce measurements of orientation of large-scale cross-stratification (Gradziński *et al.*, 1959, 1961) and maps of coarse clastic proportions in selected stratigraphic intervals (Czekaj *et al.*, 1964). The validity of the latter has been put in question by Gradziński (1980).

PREVIOUS VIEWS ON THE SEDIMENTATION OF THE CRACOW SANDSTONE SERIES

Papers published before 1967 include mainly general statements on the continental origin of the upper part of the coal-bearing sequence, that was then referred to as "Limnic Series", and these studies concerned mainly stratigraphy, palaeontology and general lithology (see Czarnocki, 1947; Stopa, 1957a, b and references there in). Only Dembowski (1967, see page 48–49), in a paper on the Libiąż Beds expressed a view that the sandy sediments in this unit were laid down in fluvial channels or in master channels on alluvial fans, while most fine-grained sediments were laid down by weak currents or as deposits of stagnant waters. In his opinion the coal seams formed by growth of plants in the peat bogs themselves and by supply of plant debris by running water.

Dembowski and Unrug (1970), in a paper dealing with statistical analysis of cyclic sedimentation of the Łaziska beds, expressed an opinion that the multiple repetition of phytogenic sedimentation corresponded to phases of strongly reduced clastic supply to the basin, with the coarse clastics practically not supplied and peat bogs extending over the nearly whole area of the basin. The following phases of clastic accumulation were periods of coarse clastic supply in response to diastrophic movements on the basin margins. The sandstone packets then formed are deposits of fluvial channels and the argillaceous layers are floodplain deposits. In another paper Unrug and Dembowski (1971) accepted the whole upper part of the coal-bearing succession as the deposits of an extensive alluvial plain.

Radomski and Gradziński (1979, 1981) based their sedimentological studies on statistical analysis (using Markov chaines) of the vertical lithofacies sequences in drill cores of selected deep boreholes. These authors concluded that sediments of the Cracow Sandstone Series were laid down on an alluvial plain of predominantly braided rivers. Farther research, based mostly on the analysis of lithofacies sequence in borehole cores, led to the formulation of a general facies model of the studied series (Gradziński *et al.*, 1995).

Another studies, by Gmur and, in part, Doktor, concerned mainly the conditions of growth and the nature of the parent peat bogs of the coal seams in the Cracow Sandstone Series (see Doktor & Gmur, 1999, 2000; Gmur *et al.*, 1999; Gmur & Oliwkiewicz-Miklasińska, 2000; Gmur & Kwiecińska, 2002).

MATERIAL AND METHODS

Data and its sources

The material used for this study comes from various sources, varies in nature as well as in precision and usefulness for sedimentological studies.

The first group of the material used are logs of deep boreholes that penetrated the sediments of the Cracow Sandstone Series. These include in first place logs of nine boreholes drilled by coal industry, the cores from which were described from sedimentological point of view by the present author (with R. Gradziński), usually directly at the drill site. The boreholes were selected from many that were drilled in the second half of the seventies and in the eighties of the past century by Przedsiębiorstwo Geologiczne in Katowice. While selecting, those boreholes were preferred that avoided fault zones and penetrated strata with a minimum dip available. Locations of these boreholes are shown in Fig. 1. The total length of the cores logged in detail is ca. 5000 m.

Similar material comes from final drilling reports on five deep boreholes drilled by PGI (Polish Geological Institute) (Chełmek IG-1, Poręba Wielka IG-1, Poręba Żegoty IG-1, Woszczyce IG-1, Wyry IG-1; cf. Fig. 1). Cores from these boreholes have been described mainly by Z. Buła, with account for generally the same sedimentary features as in the other nine boreholes. The total length of the cores from the Cracow Sandstone Series from these five boreholes amounts to 2700 m.

The second group of material used consists of archival reports on continuously cored boreholes, most of them deep (about 1000 m), drilled during the last half century for the coal industry. The descriptions and divisions on the logs are usually highly simplified; only major lithological types are distinguished there, sedimentary structures are not reported, terminology is inconsistent. As such, usefulness of these reports was limited. The present author went through about 1100 borehole reports and selected 340 for this study, in most cases using only fragments of their sections. Of these, 160 were the base for the thickness maps presented here.

The third group of material are various archival mine data: cross-sections, descriptions of underground boreholes and observations recorded in mine geologists' notebooks. Archives of eight mines that exploit coal from the Cracow Sandstone Series have been used: Siersza, Janina, Jaworzno, Czeczott, Piast, Ziemowit, Murcki and Brzeszcze. This material, though uneven in precision, provides valuable information on geometry of sediments, especially coal seams, many data on local erosion of the coal seams, on the sole and roof rocks etc. Excavation of individual coal seam provides also quite credible data on the lateral continuity of the seams, their depositional termination, splitting etc.

Methods

The methods used by the author have been selected taking into account the accepted goals of the study and the nature of available material.

One of the basic methods was lithofacies analysis. Its main aim was to obtain evidence for reconstruction of sedimentary environments. Because of the lack of surface exposures, the analysis concerned mainly vertical lithofacies sequences distinguished in the cores from deep boreholes. Details of this method are given in chapter "Lithofacies". It should be only stressed here that the field of observation is limited in drill-cores by their small diameter, but on the other hand the cores provide opportunity for tracing changes in sediments in very long continuous vertical sections. The lithofacies analysis was done for the nine boreholes described by the author and for the five PGI boreholes.

For studying the lateral variations of sediments and their 3D geometry the author used mainly the abundant data from mines and archival data documenting the drilling operations by coal industry within the mine fields. Disturbances caused by post-depositional tectonics were not taken into account in construction of the cross-sections and maps presented in chapter concerning "Sediment architecture".

Information accumulated in the progress of this work has been successively added to computerized data base. The thickness maps of the selected elements of sedimentary architecture, maps of barren intercalations in coals, maps of lateral variation of the sole and roof deposits and other diagrams were compiled using computer programs FACJE (see Doktor *et al.*, 1994) and SURFER. Program FACJE was used to determine statistical parameters of the proportions between various lithofacies and lithosomes, and Markov chains were used for analysis of vertical sequences. The author has used the numbered coal seams as marker horizons. The numbering system has been introduced more than fifty years ago to satisfy the needs of the coal industry (Doktorowicz-Hrebnicki & Bocheński, 1945, 1952) and has been in common use since then (Dembowski *et. al.*, 1964). The acceptance of all numbered coal seams as fully credible long-distance marker horizons has encountered sound criticism from Gradziński (1994, 1999, p. 48); in his opinion the numbering and correlation of many seams has been done in a highly arbitrary manner, thus making the identity of the coals seams bearing the same number questionable. The most credible markers are those among the numbered coal seam that include tonstein intercalations, but few of them lie within the studied series (Gabzdyl, 1990; Lipiarski & Muszyński, 2006). Nonetheless, studies of these intercalations have revealed errors in earlier numbering of the same coal seam in two mines (Kuhl & Kruszewska, 1965). The author knows also cases of changing numbers of some coal seams within single mines.

Nevertheless, the present author uses the numbered coal seams, first of all those whose identity has been verified in the best possible way by exploitation within one mine. The conventional numbering of some seams, in accordance with the most recent mining documents, has been used out of necessity on the cross-sections and maps in this paper. It should be stressed, however, that numbered coal seam, are treated herein as local reference horizons and not regional markers within the whole areal extent of the Cracow Sandstone Series.

LITHOFACIES

The lithofacies described in this paper are defined by their features rather than by their origin, but the characteristic features of most lithofacies allow to infer the deposi-

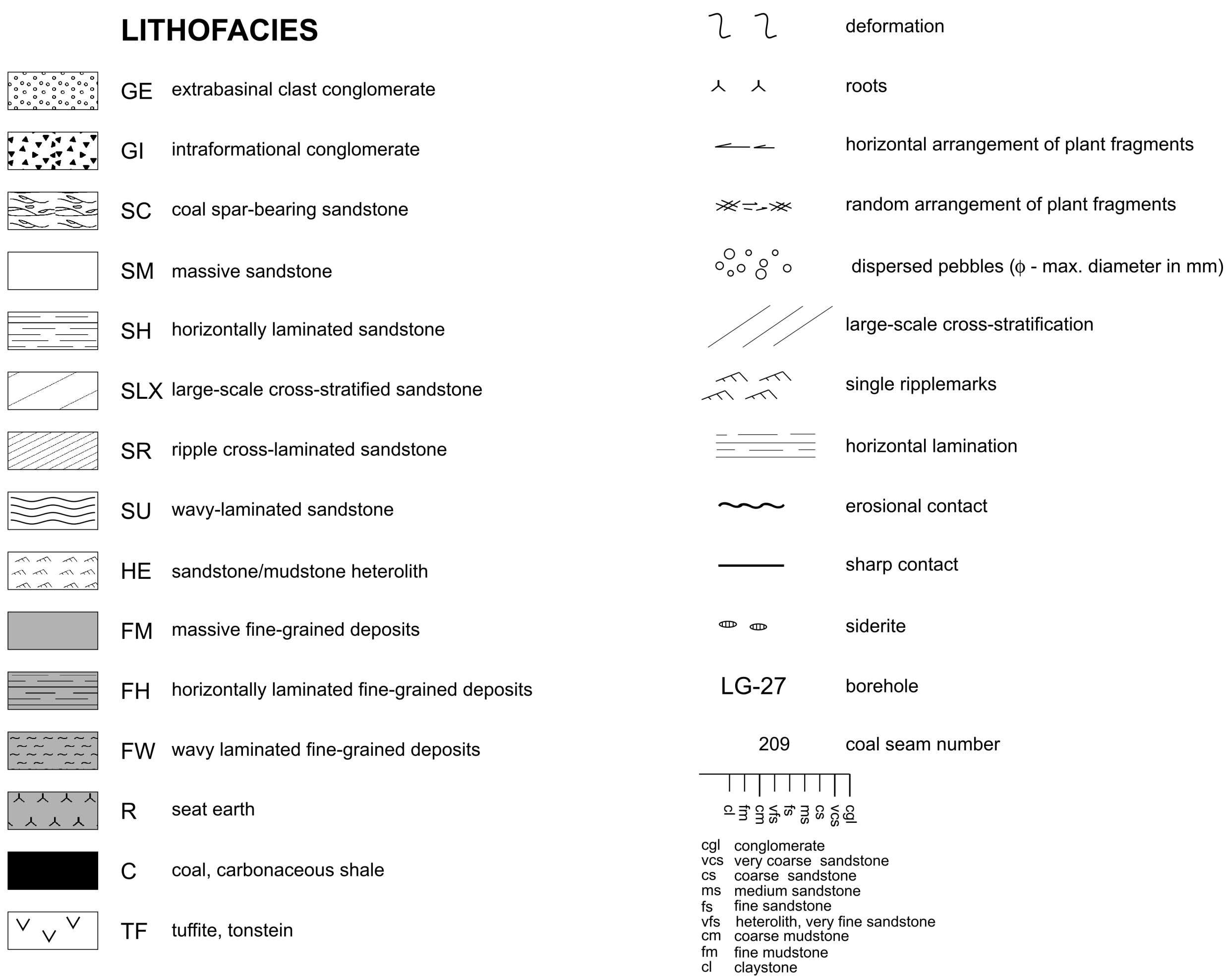

Fig. 4. Legend for the facies sections

tional mechanisms of their constituent sediments. The distinction of lithofacies is based on their mezoscopic characteristics. The lithofacies classification used is similar to that proposed by Miall (1978) for modern and fossil sediments of braided rivers and later used by many authors in papers dealing with alluvial sediments (see e.g., Rust, 1978; Zieliński, 1989, 1992, 1995), including the use by the present author with R. Gradziński (Doktor & Gradziński, 1985 and Gradziński *et. al*., 1995) for the fossil fluvial Carboniferous deposits of the USCB.

The lithofacies classification used here is adapted for the use in the drill cores as the specific type of sediment samples. Drill cores as the source of data call for some adjustment of the descriptions, especially with regard to large-scale cross-stratification. The letter symbols for lithofacies have been adapted for the purposes of this paper, with some modifications to the lithofacies code used in English-language papers.

Fifteen lithofacies have been distinguished in the Cracow Sandstone Series (Fig. 4). The distinction of the lithofacies has been based on various criteria, in most cases on the general grain size of clastic sediments and on characteristic sedimentary structures.

During the core description, each lithofacies was given a letter symbol and such sedimentary features were noted as: presence and type of clasts, mode of grain-size change (coarsening, fining), nature of sole surfaces (gradational, sharp, erosional), presence of siderites, presence and type of plant debris (floated-in fragments, fine detritus, roots), angle of large-scale cross stratification, presence of deformation structures. The lithofacies, their symbols and sedimentary features are listed in Fig. 4. Besides the lithofacies type, also the other sedimentary features noted above were taken into account during the analysis of the vertical succession of sediments. Transitions between sediments of various lithofacies are often gradual, hence the placement of the boundaries is arbitrary in many cases.

The core descriptions were used to produce a graphic lithofacies log at a scale 1:100. Fragments of such logs are shown in chapters “Sandstone Association” and “Mudstone Association”.

Extrabasinal clast conglomerate (GE)

This lithofacies includes conglomerates in which all or most of the gravel grade clasts are exotic (extrabasinal). Nearly all such conglomerates are matrix-supported

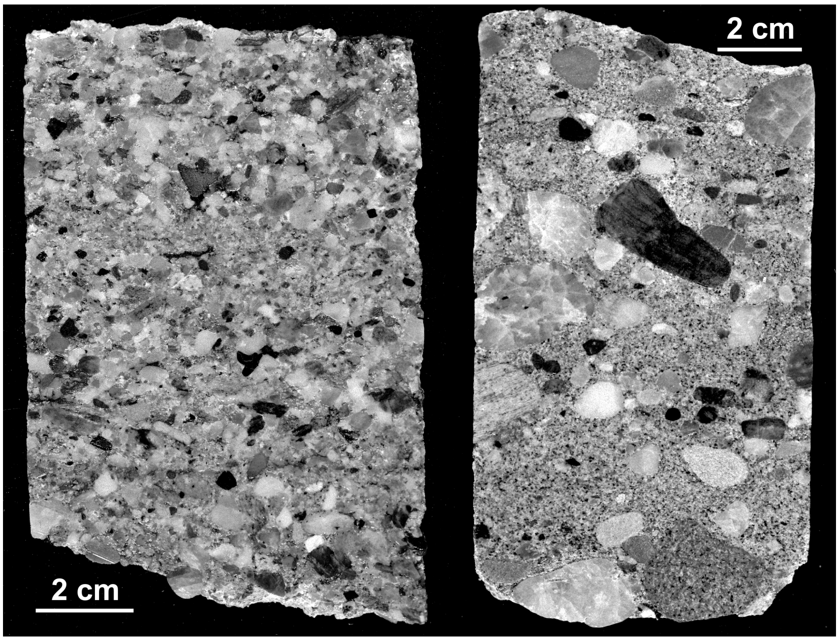

Fig. 5. Extrabasinal conglomerates (GE)

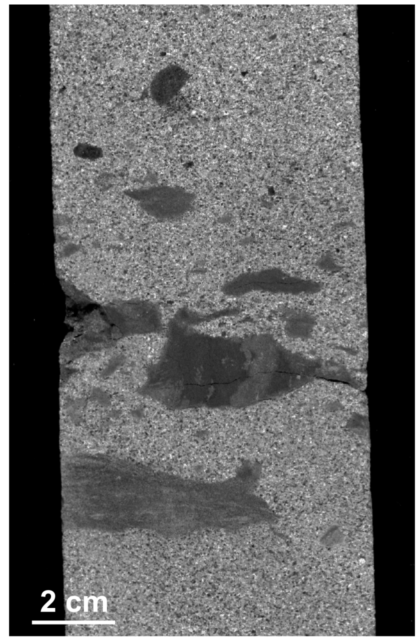

Fig. 6. Intraformational conglomerates (GI)

(Fig. 5). Clast diameters usually oscillate between 1–2 cm, seldom exceed 5 cm, and only exceptionally are greater. Clasts are usually well rounded and consist of very resistant rocks (Paszkowski *et al.*, 1995).

The layer thickness in lithofacies GE usually does not exceed 20 cm. Greater thickness was observed in a few cases, with a maximum of 1.6 m.

Intraformational conglomerate (GI)

In the conglomerates included in this facies gravel-grade clasts are represented mainly by rocks of intrabasinal origin, mostly clasts of mudstones and claystones, less commonly sideritic concretions and sporadically coal clasts. This lithofacies was distinguished when the proportion of such clasts exceeded 10%. The clast diameters usually are of a few centimetres, seldom greater. The clast shapes are variable, similarly as roundness; most clasts are angular (Fig. 6).

The conglomerates in this facies are matrix-supported, with sandy matrix. The layers in lithofacies GI are usually a few decimetres thick.

Coal spar-bearing sandstone (SC)

The distinctive feature of this lithofacies is the occurrence of quite numerous fragments of plants, usually large, preserved as bright coal. They occur as thin, curved, wedging-out streaks, in some cases as closed rings (Fig. 7). The proportion of such coalified fragments is usually not great. For the purpose of lithofacies distinction it was accepted that their proportion has to exceed 8–10% of rock surface in cross-section. The rocks of this lithofacies are distinguished in catalogues of Upper Carboniferous rock types in the Appalachians as *sandstone with coal spars* (Ferm & Melton, 1977).

The layers of this lithofacies are a few decimetres thick at most.

Massive sandstone (SM)

This lithofacies includes sandstones in which no sedimentary structures can be distinguished in mezoscopic observations, so that the rocks is perceived as generally massive (Fig. 8). Nevertheless, microscopic observations in thin sections reveal that sandstone is generally well sorted; diffuse laminae are locally visible due to variation in grain size. It cannot be excluded that the lack of sedimentary structures is only apparent and the use of special methods, such as examination of thin sections in X-rays could reveal various types of stratification (cf. Hamblin, 1962).

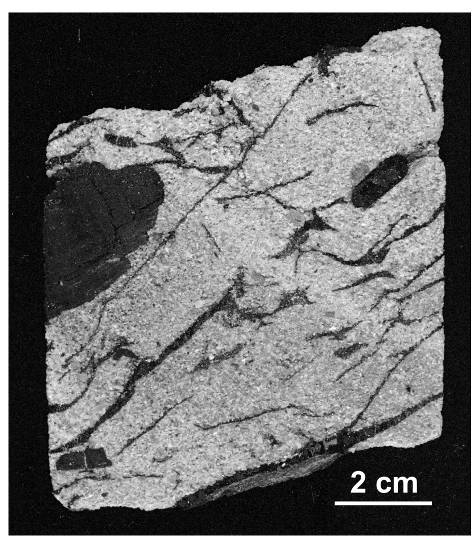

Fig. 7. Sandstones with coalified plant debris (SC)

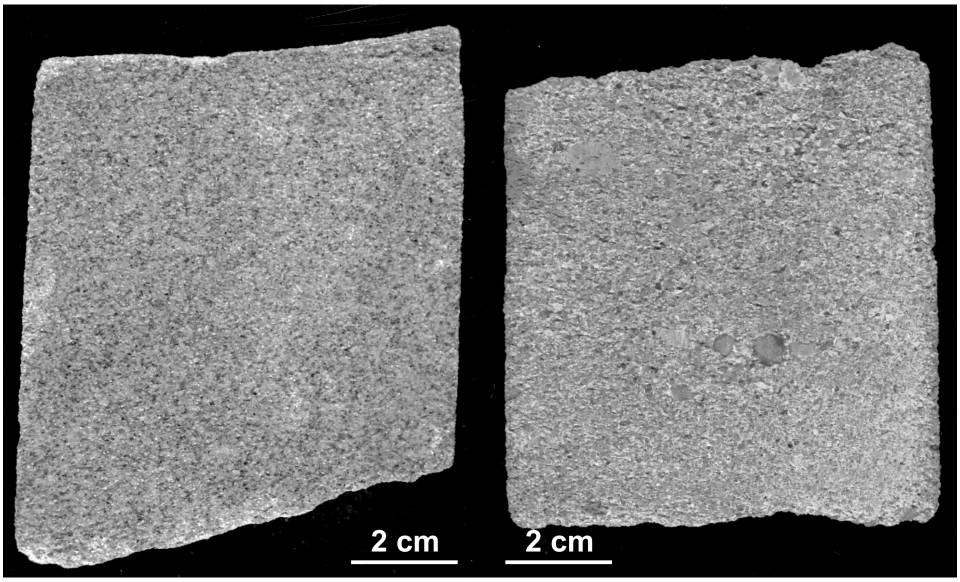

Fig. 8. Massive sandstones (SM)

This lithofacies is represented mostly by medium-grained sandstones and the thickness of its layer varies within wide limits, often attaining several metres; the maximum observed thickness equals 11 m.

The boundaries of lithofacies SM require arbitrary designation because the transitions to other sandstone lithofacies are usually gradual and are manifest only by the appearance of single isolated horizontal or inclined laminae.

Horizontally laminated sandstone (SH)

A characteristic feature of this lithofacies is the presence of planar lamination, originally probably horizontal (Fig. 9). The lamination is marked differences in grain size between individual laminae or within the sections of individual laminae, in some cases it is additionally accentuated by the presence of fine plant detritus. The laminae are usually about one millimetre, seldom a few millimetres, thick.

Most sediments in this lithofacies were probably laid down in conditions of upper flow regime (cf. Harms & Fahnestock, 1965; Harms *et al.*, 1975). It cannot be excluded that planar lamination in the coarser-grained (>0.6 mm) sandstones is related to the conditions of the so called lower plane bed regime (cf. Middleton & Southard, 1978).

The thickness of layers in lithofacies SH usually does not exceed 0.5 m, with a maximum of 2.2 m.

Large-scale cross-stratified sandstone (SLX)

Characteristic of this lithofacies is the presence of large-scale cross-stratification, that is structures composed of sets of originally inclined laminae (Fig. 10). The lamina-

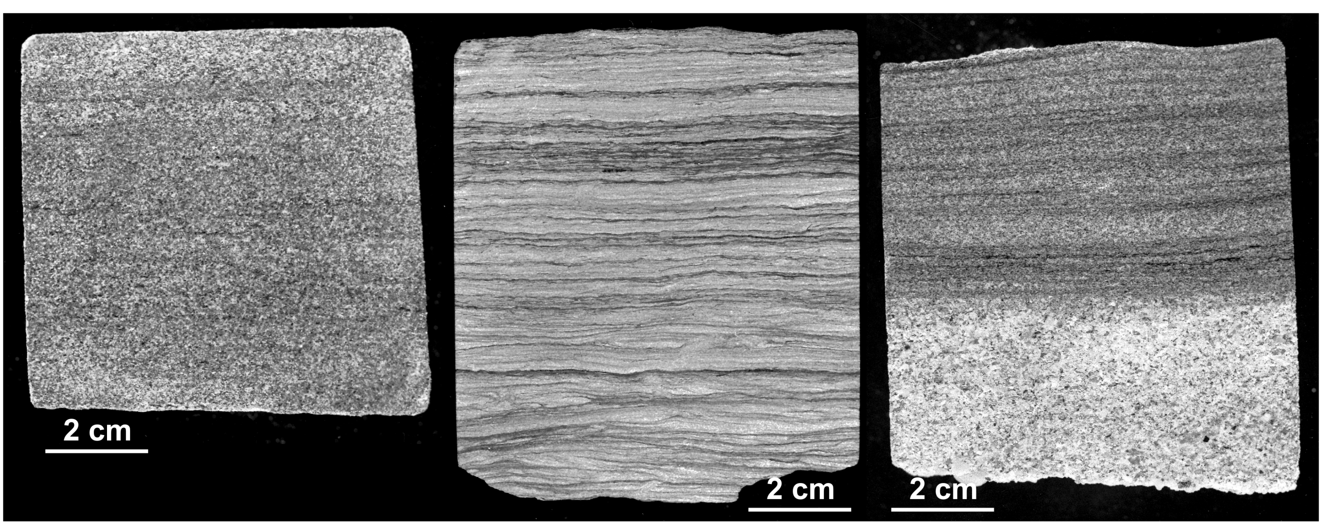

Fig. 9. Sandstones with planar lamination (SH)

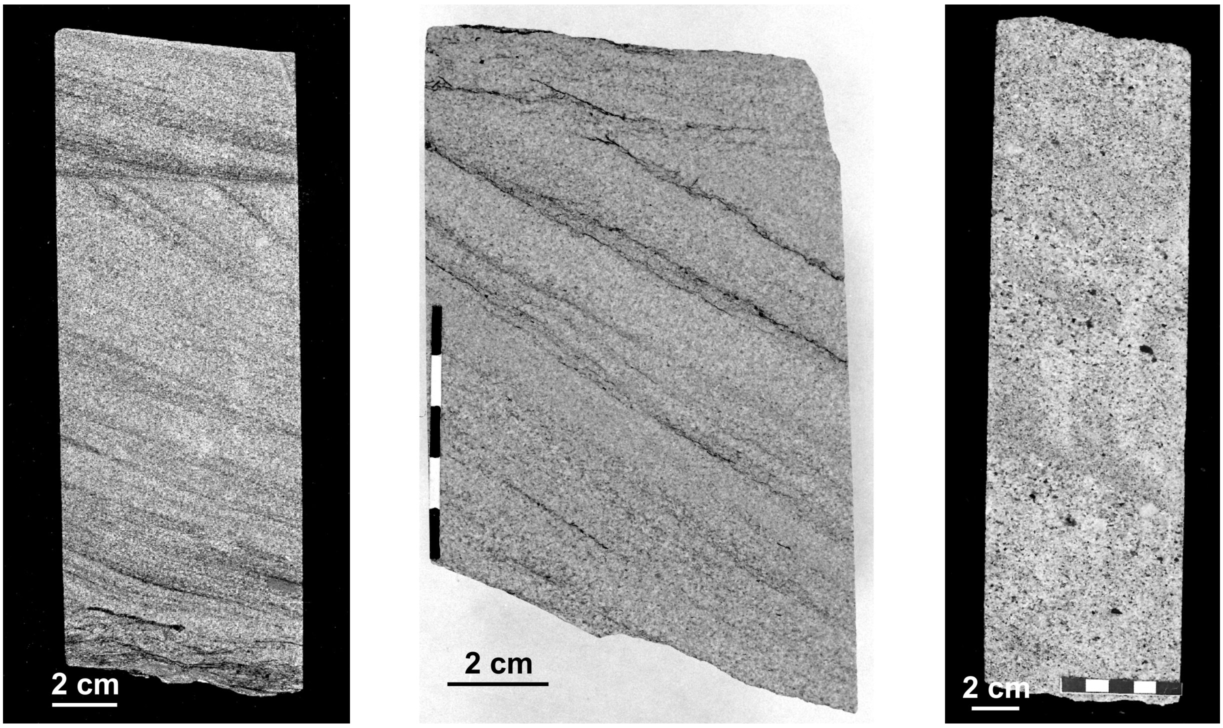

Fig. 10. Sandstones with large-scale cross-stratification (SLX)

tion is visible mainly due to changing grain-size, and is locally accentuated by the presence of granule-sized grains or of plant detritus concentrated on the inclined surfaces of deposition. The thickness of laminae varies within wide limits. Most laminae are a few millimetres thick, but some are a few centimetres in thickness.

The bounding surfaces of laminasets are often difficult to discern in drilling cores. Where they are best visible, they have a form of a surface of discontinuity between the underlying steeply dipping laminae and the overlying less inclined ones. Unlike in surface outcrops, the shapes of the laminasets cannot be determined in cores, hence the distinction of the basic types (trough-shaped and tabular) of large-scale cross-stratification is not possible. For this reason only one lithofacies is distinguished here, which combines sediments with various types of large-scale cross-stratification, therefore also of various origin.

The maximum angle of dip of laminae in sediments of lithofacies SHX attains 30°, and usually is around 20°; it has lower values in the lower parts of the laminasets. Some laminae approach tangentially the basal surface of the laminaset. The thicknesses of individual sets vary within wide limits, from a few decimetres to a metre or more. The layers of lithofacies SHX usually consist of cosets, even up to several metres in thickness. In some cases, single layers composed of a single set of decimetric thickness, are enclosed between layers of other lithofacies.

Ripple cross-laminated sandstone (SR)

The characteristic feature of this lithofacies is the abundance of small-scale cross-lamination (Fig. 11), related to migration of small ripples in conditions of lower flow regime.

The thickness of individual sets vary from a few millimetres to 3–4 cm. The cross laminae are very thin, composed of fine sand, often with admixture of silt, in many cases underlined by the presence of fine plant detritus. The sets often wedge out within the core.

The layers built of lithofacies SR are usually a few decimetres thick, only exceptionally they exceed 2 m.

Wavy-stratified sandstone (SU)

This lithofacies comprises sandstones for which characteristic is the occurrence of single, quite large lenses, built of fine cross-laminae, and separated by bundles of wavy laminae (Fig. 12), in many cases slightly muddy. The cross-laminae within the lenses are often sigmoidally bent. The thickness of the lenses usually exceeds 4 cm. The rock in many places includes dispersed plant debris.

The layer thickness in this lithofacies usually does not exceed 20 cm.

Sandstone/mudstone heterolith (HE)

The rocks attributed to this facies consist of many quite thin (usually a few centimetres) layers of fine-grained sandstone and mudstone (Fig. 13). The distinction of this lithofacies facilitates core description and allows for drawing graphic logs at a scale 1:100. The characteristics of this lithofacies allow for general inferences on repetitive changes in conditions of deposition.

Small-scale cross-lamination is the most frequent structure within the sandstone layers (ripple cross-lamination).

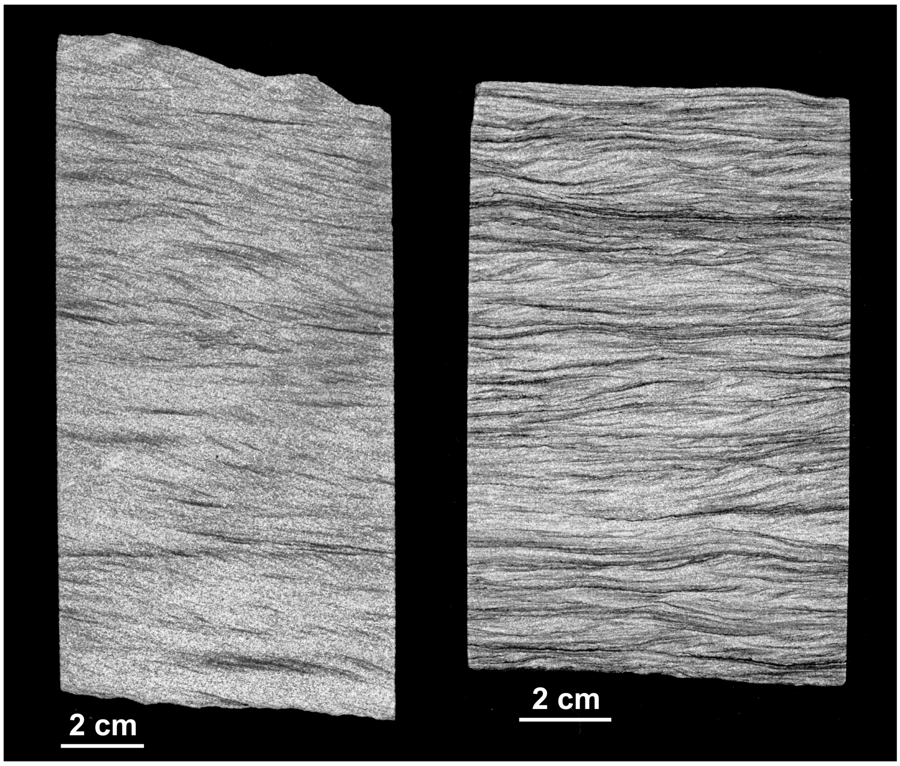

Fig. 11. Sandstones with small-scale cross-lamination (SR)

The mudstone layers usually display wavy or planar lamination, less commonly mudstones are massive, structureless; gradual transitions are common between these sediment types. Proportions between the total thicknesses of sandstone to mudstone layers within the sections of sediments distinguished as lithofacies HE varies within wide limits, more or less 1:3 to 3:1. Depending on it, the rock may be generally described as muddy sandstone or as coarse-grained mudstone with sandstone intercalations.

The thickness of the layers in this lithofacies varies from 10 cm to 1.5 m, sporadically to 3 m.

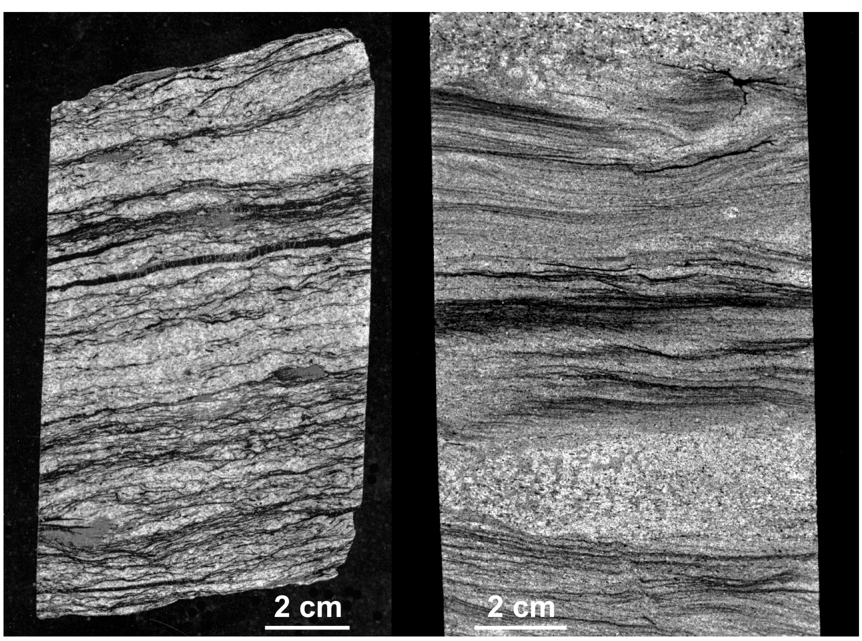

Fig. 12. Sandstones with wavy lamination (SU)

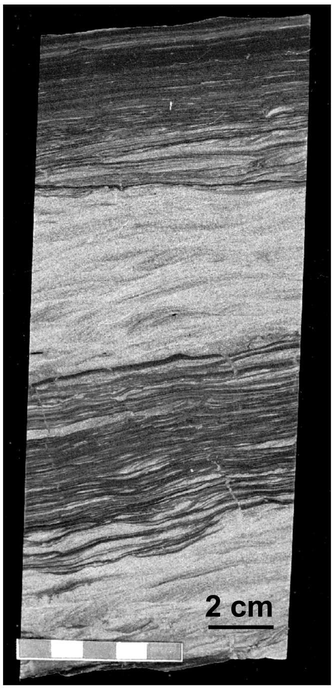

Fig. 13. Heteroliths (HE)

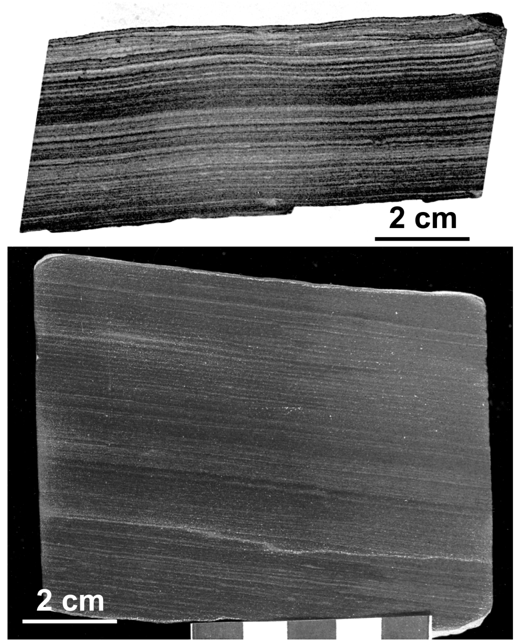

Fig. 14. Fine-grained rocks with flat lamination (FH)

Massive fine-grained deposits (FM)

This lithofacies includes fine-grained rocks, both mudstones and claystones, which observed mezoscopically do not reveal depositional structures. Few indistinct streaks are sporadically discernible due to their slightly different colour. Single greater fragments of plants or plant traces, such as appendixes, occur occasionally in the rocks of this lithofacies.

The layers composed of sediments of this lithofacies may have various thickness, from a few centimetres to 5 m.

Horizontally laminated fine-grained deposits (FH)

This lithofacies comprises mudstones and claystones that feature flat parallel lamination (Fig. 14). Lamination is visible in most cases due to changes in colour. The lighter laminae are composed of coarser grains (silt) than the darker laminae. Usually all laminae are continuous laterally, but some very thin lenticular laminae are wedging out. Flat lamination is often marked by the presence of fine plant detritus or is marked by flat-lying coarser plant debris, usually coalified and strongly compressed.

The layers of sediments in this lithofacies are from a few decimetres to 3.9 m thick.

Wave laminated fine-grained deposits (FW)

Here belong fine-grained rocks (mudstones and claystones), for which characteristic is the presence of irregular lamination, conventionally described as wavy lamination (Fig. 15).

Laminae or bundles of laminae composed of coarser grains (usually coarse silt grade), are usually lighter in shade, often discontinuous and form more or less elongated lenses. Faint traces of cross lamination are discernible within some lenses. Bundles of more continuous laminae, compose of finer-grained sediment, are present between the lenses. Laminae in these bundles are usually slightly wavy, though locally some of them are nearly flat. In general, this lithofacies includes laminated fine-grained rocks (mostly

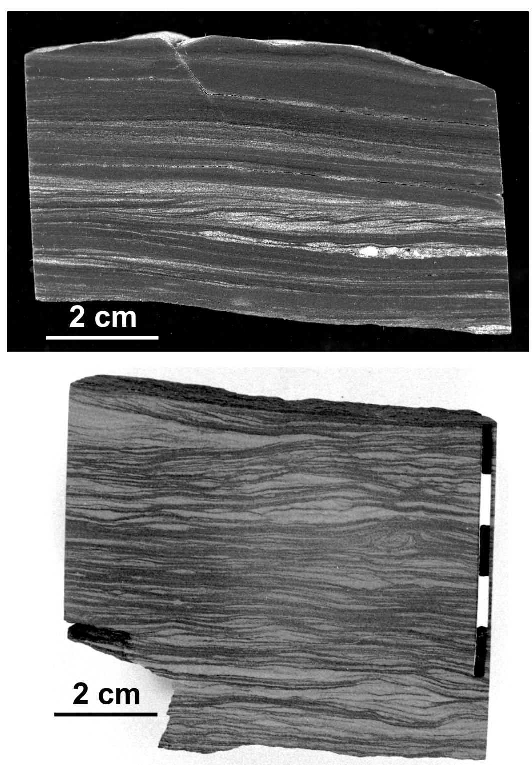

Fig. 15. Fine-grained rocks with wavy lamination (FW)

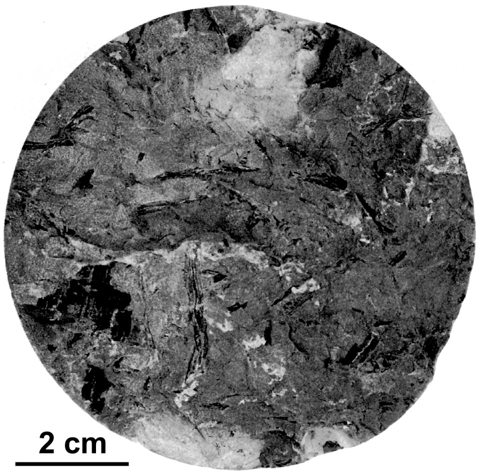

Fig. 16. Seat earth (R)

mudstones, with some claystones), in which lamination cannot be described as flat.

Seat earth (R)

This lithofacies includes fine-grained rocks (mudstones and claystones), exceptionally also sandstones, distinguished by the presence of abundant underground parts of woody plants, that is appendixes and stigmaria. The rocks in this lithofacies usually lack lamination, common are traces of small, variously oriented *slickensides* (cf. Huddle & Patterson, 1961) and bioturbations (Fig. 16).

The seat earth layers are usually a few decimetres thick, with a maximum thickness of 2 m.

Coal, carbonaceous shale (C)

This lithofacies comprises bituminous coal, represented by bright, banded and dull coal varieties and carbonaceous shales. Carbonaceous shales, from a few to nearly twenty centimetres thick, consist of alternating carbonaceous and clayey-muddy laminae rich in organic matter. They are fissile along the boundaries of laminae. This lithofacies includes also thin (up to a few centimetres) intercalations of clastic sediments in coal: thicker intercalations are described as other lithofacies.

The thickness of layers in carbonaceous lithofacies varies from a few centimetres to a few metres.

Tuffite, tonstein (T)

This lithofacies includes various types of tuffites. They usually occur within coal seams. Their colours vary from light to dark grey, some of them are horizontally laminated. The thickness of layers varies from a few millimetres to a few decimetres.

SANDSTONE ASSOCIATION

Two major lithofacies associations have been distinguished in clastic sediments of the Cracow Sandstone Series: the sandstone association and the mudstone association. The latter association is dealt in the following chapter.

Description

The sediments of the sandstone association occur in thick packages built almost exclusively of sandstones, mainly medium- and coarse-grained. The packages are usually 15–35 m thick, exceptionally thinner, many of them exceed 50 m, and attain a maximum of 145 m. Selected examples of packages of sediments belonging to this association are shown in Figs 17–20.

The dominant lithofacies are massive sandstone (SM) and sandstone with large-scale cross-stratification (SLX). The layers of these lithofacies are in many places found alternating in the sequence. The massive sandstone (SM) usually predominates in the sections of individual packages (Fig. 18), and in some cases it attains even 90% (Fig. 19A) of their thickness. Proportion of sandstones (SLX) is usually lower; in most packages they make up ca. 30% of their thickness, but in many cases much less (Fig. 19B).

The lithofacies SM and SLX are usually composed of medium- and coarse-grained sandstones. Both often contain a quite subordinate admixture of small clasts of extrabasinal provenance. The thicknesses of layers of lithofacies SM and SLX oscillates between a few decimetres and a few metres, usually they are 2–3 m thick (Fig. 19B, C).

Cross stratification in sediments of lithofacies SLX is visible mainly due to changes in grain size, less frequently it is accentuated by the presence of granules or plant detritus on inclined depositional surfaces. The thickness of individual laminae varies within wide limits; it is usually millimetric, but occasionally attains a few centimetres. Bounding surfaces of individual laminasets are often poorly discernible in cores; they may be recognized due to differences in dip angles of laminae or due to differences in directions of dip in neighbouring sets of laminae. The measurement of thickness of individual sets is in many cases difficult for the reasons presented above. It seems, however, that sets a few metres thick are not exceptional. The maximum observed depositional dips of cross laminae attain ca. 20°.

Transitions between the layers of lithofacies SM and SLX are in most cases gradational. They are usually marked by appearance or disappearance in the section of single, indistinct inclined laminae, gradually becoming more or less common. The boundaries are better visible when elevated proportion of gravel grade is present in the basal part of a layer of massive sandstone (Figs 19B, 20C).

A third lithofacies characteristic of the sandstone association are conglomerates composed of extrabasinal clasts (lithofacies GE). The extrabasinal conglomerates make up only a few percent in the thickness of the Cracow Sandstone Series. Nevertheless, they occur quite frequently in the section as thin layers, in most cases a few decimetres thick or thinner. Not uncommon are also horizons composed of single isolated clasts.

Quite subordinate are horizontally laminated sandstones (SH), carbonaceous sandstones (SC) and sandstone-

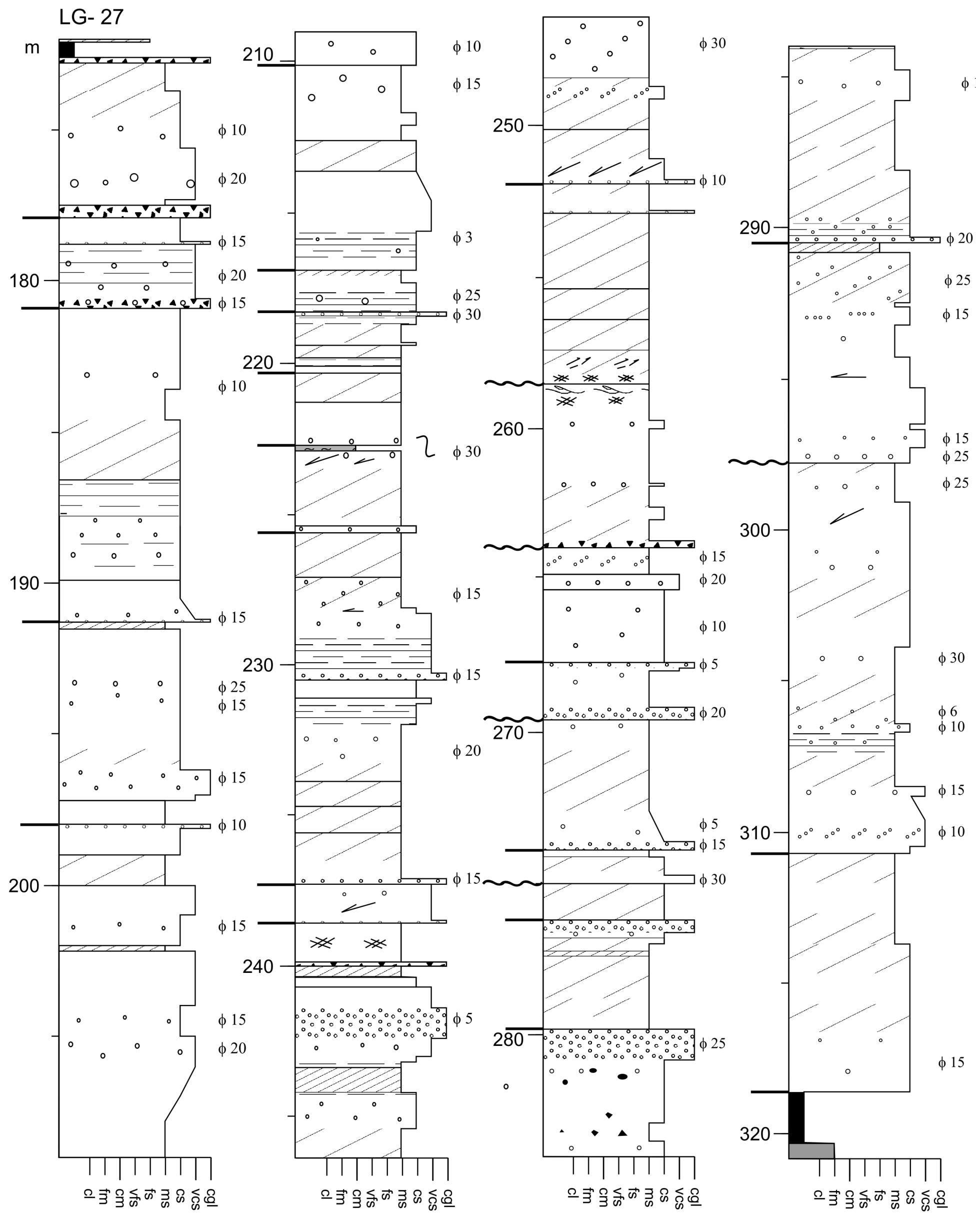

Fig. 17. Example of a 145 m thick package of sandstone association sediments representing a a composite accumulation of channel sediments

mudstone heteroliths (HE). Exceptionally occur thin layers of fine-grained sandstones with small-scale cross lamination (SR); their occurrence is usually limited to the top parts of some sandstone packages (Fig. 20A, C, D). A true rarity are intraformational conglomerates (GI) composed of mudstone clasts (Fig. 20B). The layer thicknesses of the lithofacies mentioned here are small and do not exceed a few decimetres.

Erosion surfaces are difficult to recognize in sediments because of the generally small lithological variability and laterally limited field of observation. It may be supposed that such surfaces are much more common then have been recognized during the core description (cf. Figs 19 and 20). Probably most flat surfaces marked during core description as sharp layer boundaries are probably erosional. The erosional surfaces divide thick sediment packages into smaller intervals.

The intervals separated by more or less distinct boundaries do not display important changes in grain size within them. Upward fining or coarsening of grains is marked in some intervals (see Fig. 20). The thickness of such sequences varies between a few decimetres and a few metres.

Sandstone packages display numerous erosional surfaces that separate single or multiple sequences of fining upward sandy sediments (cf. Figs 17, 19A, 20C) or, less commonly, coarsening upward (cf. Fig. 19 – interval 976 to 940 m, Fig. 20B), composed of alternating layers, mainly of lithofacies SM and SLX.

Bases of sandstone packages as seen in cores, are always clearly marked by a sharp change in lithology ex-

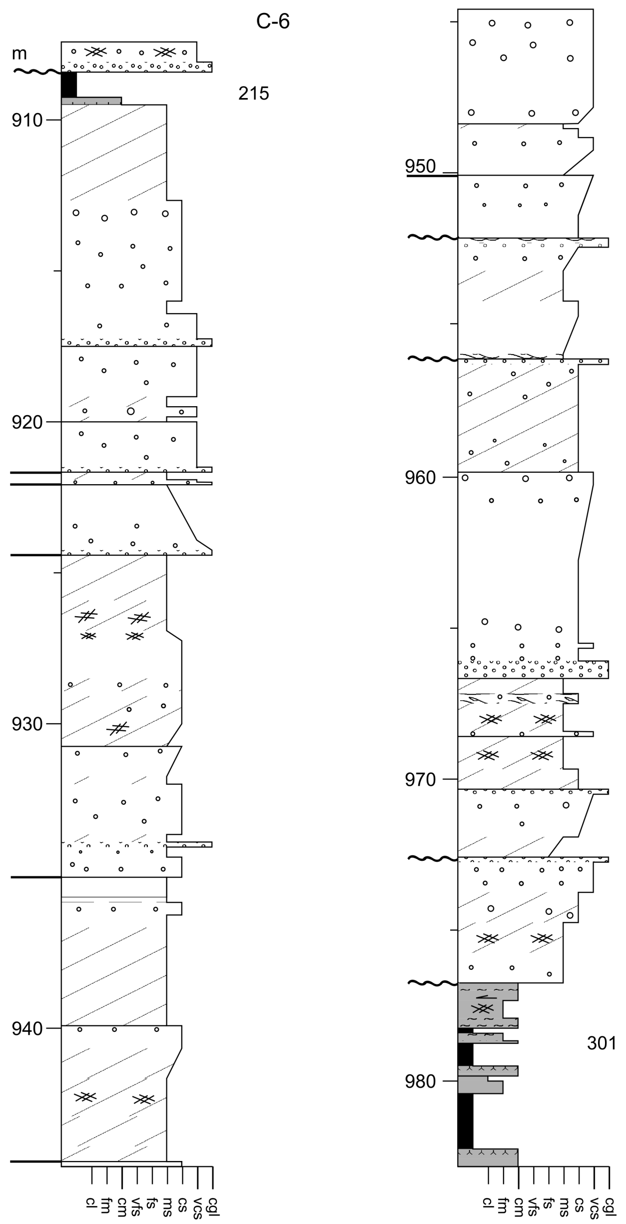

Fig. 18. Example of a package of sandstone association sediments composed of alternating lithofacies SM and SLX. Note short fining-upward and coarsening upward sequences, often separated by erosional surfaces

pressed as a sharp flat contact or an uneven, clearly erosional surface (Fig. 19). Soles of thick sandstone packages, when observed underground, in coal mines, are always erosional. Some sandstone packages start with a thin layer of conglomerate GE (cf. Fig. 19A). The sequence usually starts with sandstone which contains only dispersed gravel-sized clasts, sometimes as single streaks (cf. Figs 17, 18 and 19B), less commonly with sandstones devoid of gravel admixture (Fig. 19C). The sandstones are mostly medium- or coarse-grained, usually massive (SM) and they pass upward to sandstones with large-scale cross stratification (SLX). Large coalified fragments of plants are numerous only in lithofacies SM. In other lithofacies they are rare, in some cases as rings of bright coal. On the other hand, coalified fine plant detritus is common in sandstones of lithofacies SM, SLX and in sandstone/mudstone heteroliths (HE). More notable accumulations of coalified plant debris in sandstones are distinctive characteristics of the sandstone layers attributed to lithofacies SC.

Packages of sandstone sediments usually have distinct upper boundaries, marked by a sharp decrease in grain size and a change in lithology. These packages usually terminate with medium-grained sandstones of lithofacies SLX or SM, sporadically with conglomerates GE, in sharp contact with overlying fine-grained sediments (cf. Figs 17, 18, 19B). Many of the thick packages terminate at top with a thin, up to a few decimetres, sequence with grain size rapidly fining upward and capped with fine-grained ripple-cross-laminated sandstone (SR) or heterolith (HE) grading to overlying deposits of the mudstone association (Fig. 20A, C). Less commonly the grain size gradually decreases upward throughout the whole package, so that the top part consists of fine-grained sandstone with small-scale cross lamination SR and sandstone/mudstone heterolith (HE). Such gradational transition to overlying sediments is more common in packages up to a few metres thick (Fig 20A, D), very seldom thicker.

Interpretation

The sedimentary features of the thick sandstone packages observed in vertical sequences allow to consider these packages as sediments of river channels in which sediment load consisted chiefly of sandy material transported in traction. The predominance of sandy sediments and the small share of fine-grained sediments suggest that these were braided rivers. The very low proportion of gravel in comparison to sand suggests also that the rivers were distal sandy braided rivers (cf. Miall, 1977, 1996). A comparison with the standard, model types of sediment sequences from various modern braided rivers, presented by Miall (1977, 1978) shows greatest similarities of the sequences observed in the Cracow Sandstone Series to the Platte River and South Saskatchewan River types.

Limitations related to the specific conditions of observation in drilling cores do not allow to distinguish the basic types of large-scale cross stratification, that is the trough and planar types, and, in consequence, to infer what kind of bedforms gave origin to the sediments of lithofacies SLX. It may be only supposed that the sediments of this lithofacies could form by migration of large bedforms akin to megaripples (cf. Harms & Fahnestock, 1965; Coleman, 1969; Harms *et al.*, 1975), or even greater bedforms, such as those described by Coleman (1969) from the channels in the lower reaches of the Brahmaputra River. The latter bedforms, described as dunes and sand waves, are up to 8 and 16 m high (Coleman, 1969, p. 190), they form during high water stages and migrate in deep parts of the channels. It is also probable that a part of lithofacies SLX formed in sediments of large bars growing by lateral accretion (cf. Bridge

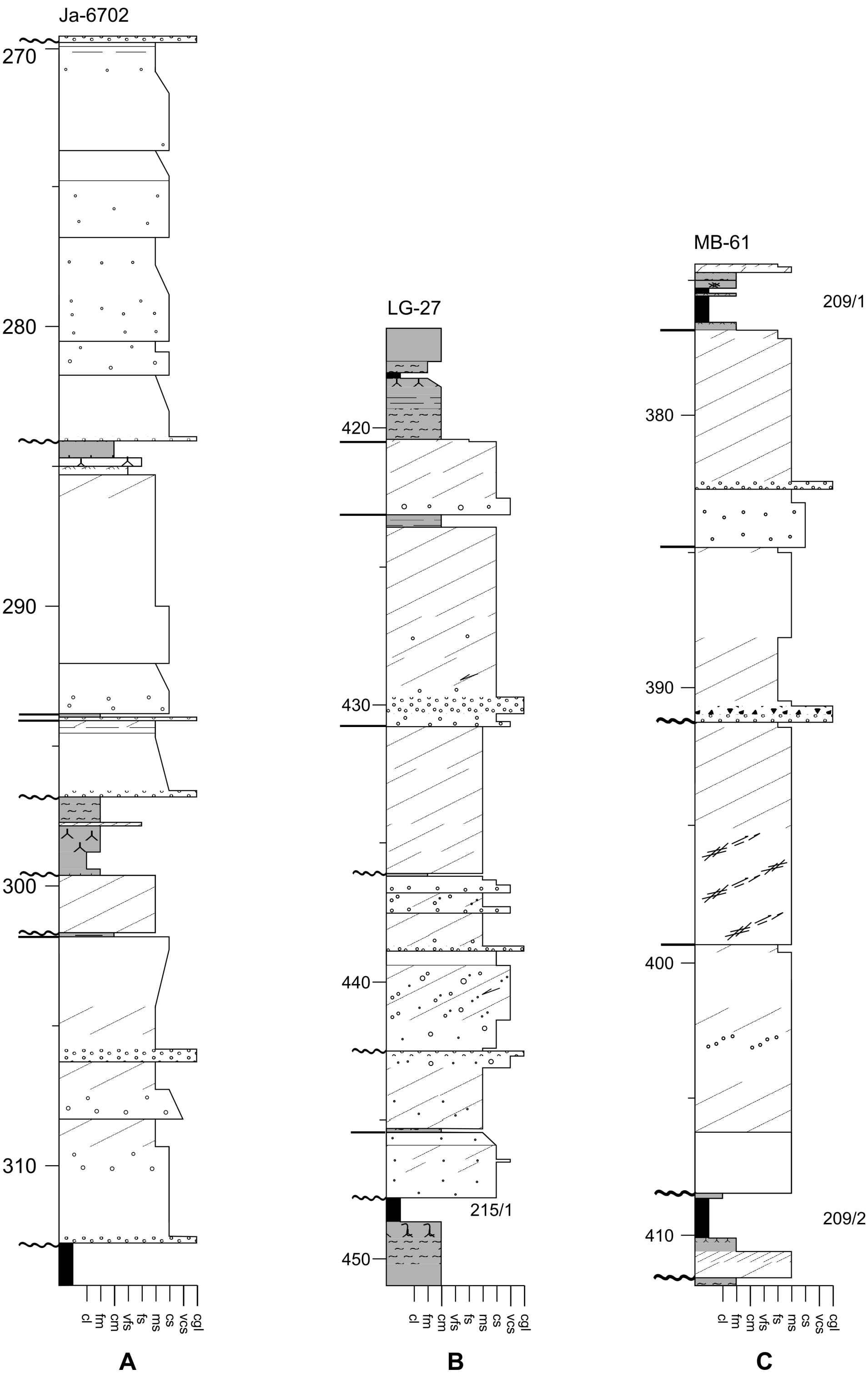

Fig. 19. Examples of sandstone association sediments. **A** – Packages of sandstone association sediments between ten and twenty metres thick, dominated by lithofacies SM, separated by thin, packages of the mudstone association lacking in coal. **B** – A package of sandstone association sediments several tens of metres thick, dominated by lithofacies SLX with conglomeratic intercalations GE. Note numerous erosional surfaces and a rapid change in grain size at the top of sequence. **C** – A package, several tens of metres thick, of sandstone association in typical development (predominance of lithofacies SLX and SM with conglomerate intercalations GE). Note rapid fining upward of grains over a short interval near the top

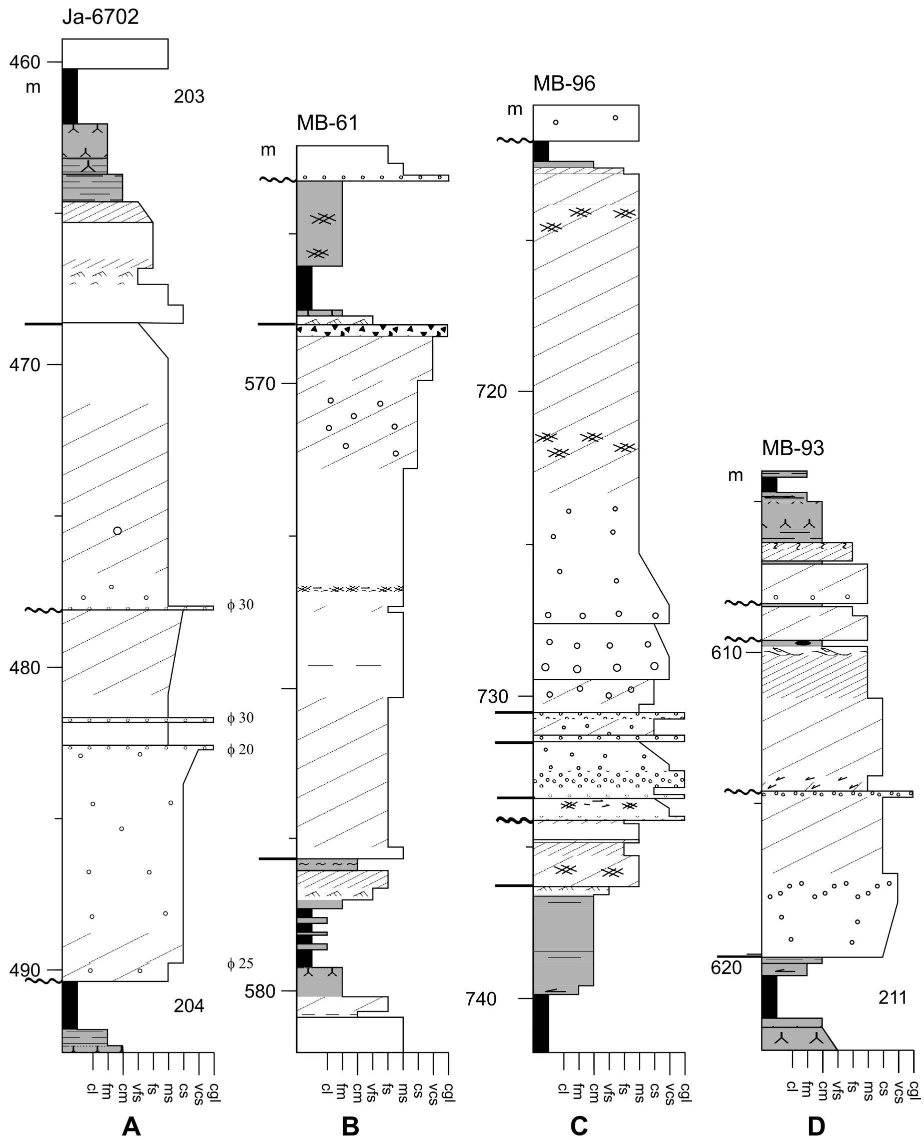

Fig. 20. Examples of sediments of sandstone association, representing deposits of channel tracts. **A** – Package of deposits of sandstone association with coarsening upwards sequences in the lower part, intercalated by conglomerate intercalations and fining-upwards sequences, bounded by erosional surfaces. Note gradual decrease in grain size at the top and gradual transition to the sediments of the mudstone association. **B** – Package of sandstone association with a clear coarsening upward sequence that terminates with a conglomerate intercalation and an erosional surface. **C** – Package of sediments of sandstone association with numerous erosional surfaces and GE intercalations in the lower part, passing upwards to a fining-upwards sequence. **D** – A few metres thick sequence of sandstone association with composite internal structure, generally fining-upwards

et al., 1986; Bristow & Best, 1993; Miall, 1996, tables 4.2, 4.3).

Regardless of the details of the origin of lithofacies SLX, it may be generally concluded that sediments of this type predominate in channel facies of sandy braided rivers, both modern (Coleman, 1969; Smith, 1970; Bridge *et al.*, 1986), and ancient (Smith, 1970; Rust & Jones, 1987; Rust & Gibling, 1990; Wizevich, 1993; Robinson & McCabe, 1997).

It was already mentioned above, that the second of the predominant lithofacies, that is massive sandstones (SM), is composed of sediments whose lack of internal structures is only apparent. Many observed gradual transitions to lithofacies SLX allow to suppose that lithofacies SM consists in fact of sediments with large-scale cross-lamination, mezoscopically unidentifiable on the fresh surface of a drilling core (cf. Hamblin, 1962, 1965). It seems unlikely that the massive nature of the rock would be the result of liquefaction of loose sediment and sliding during the falling of flood waters, as suggested by Jones and Rust (1983) for massive sandstones of the Triassic alluvial sediments of the Hawkesbury Sandstone in SE Australia. Such origin seems to be also contradicted by the often large thickness of the SM lithofacies layers, the lack of discernible deformation structures in their vicinity, and the quite common gradual transitions between lithofacies SLX and SM. It cannot be excluded, however, that some part of the sediments of lithofacies SM formed by sand liquefaction, though there is no clear evidence for this.

It should be noted that the presence of sandstones described as massive or devoid of discernible lamination, hence similar to lithofacies SM, is often noted in fossil sediments interpreted as laid down in channels of sandy braided rivers. Such sandstones, often distinguished as a separate lithofacies or even lithofacies association, are known, among others, from Upper Carboniferous Lee Formation in the Appalachians (Wizevich, 1993) and South Bar Formation in Nova Scotia (Rust & Gibling, 1990; Tibert & Gibling, 1999), from the Triassic Hawkesbury Sandstone Formation in Australia (Rust & Jones, 1987) and the Precambrian Basnaering Formation in N Norway (Røe & Hermansen, 1993). The proportion of such lithofacies in the whole sequence attains even 30% of the total thickness of the whole sequence, and the thickness of layers built of such sediments attains even 8 m. Most of the authors quoted above consider the massive sandstones as the result of slides caused by liquefaction of sediments near the channel margins during the falling stage of floods. Such interpretation seems to be contradicted in some cases by the marked lateral continuity of the massive sandstone layers, visible in mine exposures.

The general paucity of gravel-sized material of extrabasinal provenance is the result of the distal nature of the rivers (cf. Miall, 1977, 1996). The conglomerate layers (GE) present in the Cracow Sandstone Series are few and usually thin; they often display characteristics of channel lag and usually lie above surfaces of erosion. Most conglomerates were probably laid down on the bottoms of the major channels, may be also in local but large depressions that formed at the channel junctions (cf. Bristow & Best, 1993). Some very thin layers of conglomerates or streaks of single clasts may be the result of local winnowing of sand from the tops of sand bars with dispersed larger clasts. Such origin seems to be suggested by surfaces of erosion above the conglomerates (see Figs 18 and 20B – 567 m).

The extremely rare presence of intraformational conglomerates GI within the described channel deposits is best explained by limited amounts of fine-grained sediments laid down within the channel tracts and available for erosional action of the flow.

The great thickness of sandy packages and sedimentary features of intervals within them suggest that these packages are multi-storey accumulations of sediments laid down by many generations of channels. The often large thickness of the individual units and their fairly uniform internal structure suggest, in turn, that the individual channels could be quite deep. Taking into account the fact that the depth of a braided river channel is usually much lower than its width (see Robinson & McCabe, 1997), we may infer that the width of the channel tracts in the depositional environment of the Cracow Sandstone Series had to be large, on the order of some kilometres. The lower reaches of the Brahmaputra River may be referred to as a modern analogue (see Coleman, 1969), the width of its channel tract attains 10 km, and the channel depth attains locally even 40–50 m.

The great thickness of the packages proves also that they were laid down by long-lasting accumulation in the same place, thus suggesting a considerable stability of the whole tract for a longer time.

MUDSTONE ASSOCIATION

Description

The mudstone association, as distinguished in this paper, consists mainly of fine-grained sediments, mostly mudstones with subordinate sandstones, mostly fine-grained. Coal seams are frequent within this association; they are discussed separately in the following chapter "Coals".

The mudstone association occurs in packages that separate much thicker packages of the sandstone association. Selected logs of fine-grained sediment packages are shown in Figs 21 and 22. The mudstone association packages are 2 to 10 m thick in most cases, with a maximum of 28 m (Fig. 21B); thinner packages are sporadic. The mudstone association (together with coal intercalations) makes up 8 to 16 percent of the thickness of the Cracow Sandstone Series. The coal seams alone make up 11 to 54 percent of the total thickness of the association described here (see Fig. 22), and sporadically in some packages they constitute up to 84 percent of their thickness (Fig. 23B).

Lithofacies FM, massive structureless fine-grained sediments (mudstones and claystones), predominates (40–50%) within the mudstone association. Somewhat less important (25–30%) are lithofacies FW – fine-grained sediments with wavy and lenticular lamination – and lithofacies FH – horizontally laminated fine-grained sediments (18–25%). Slight changes in grain-size are common in the mudstones – from coarse-grained to fine-grained mudstones. Quite rare are claystones, which are in most cases massive devoid of discernible internal structure. The sandstone/mudstone heteroliths (HE) are more common than in the sediments of the sandstone association.

The thicknesses of layers of various lithofacies vary within wide limits, but the most common are layers a few decimetres thick. Less common are thicker fragments of sections with homogenous structure; these are usually coarse- and fine-grained mudstones devoid of internal structure (Fig. 21A metres 540–546; Fig. 21C metres 40–62, Fig. 22D). The boundaries between individual lithofacies are in most cases gradual.

A vast majority of coal seams are underlain by thin, usually a few decimetres thick, layers of seat earth (lithofacies R). A few thin layers of seat earth are not overlain by a coal seam. Single stigmaria and appendixes occur also in fine-grained or heterolithic intervals within the mudstone association. Commonly found is also coalified fine detritus of plants, especially well visible on surfaces of lamination, similarly as large pieces of plant debris (see Figs 21C, 22).

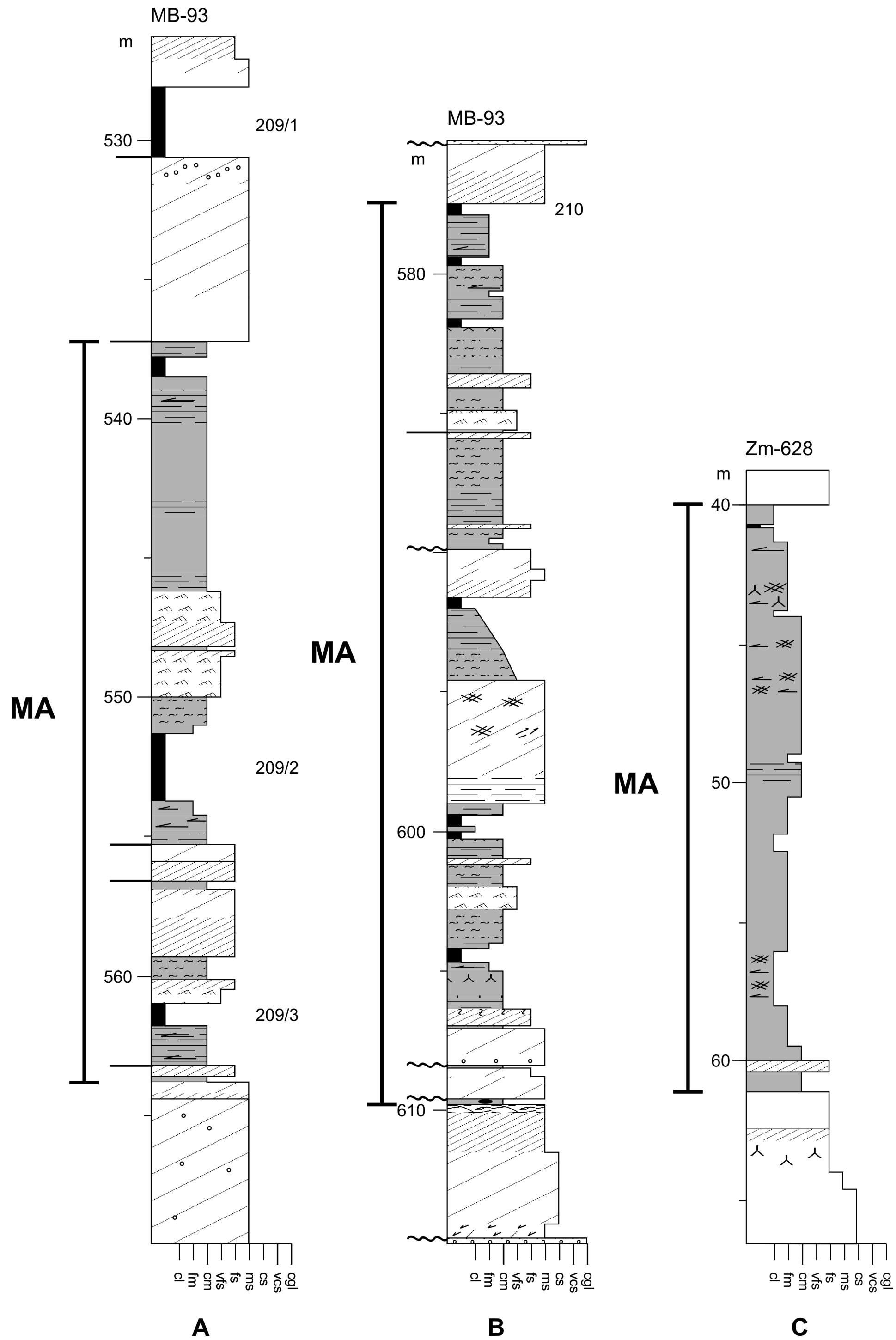

Fig. 21. Examples of sediments of mudstone association. **A** – a 25 m-thick package of sediments of mudstone association with subordinate intercalations of fine-grained sandstone sediments and single thick (up to 3 m) coal seams, representing deposits of a distal floodplain. **B** – Package of sediments of mudstone association with numerous thin intercalations of sandstone sediments and with numerous, usually thin, coal seams, representing deposits of proximal floodplain. **C** – package of sediments of the mudstone association, dominated by lithofacies FM devoid of coal and soil intercalations (R), representing most likely deposits of temporary water basin. MA – mudstone association

The structure of packages of the mudstone association is highly variable in details. The individual packages differ in the number and thickness of the sandstone intercalations (cf. Figs 21 and 22)

The mudstone association includes also intercalations of sandstones, a few metres thick, composed of lithofacies SLX and SR or HE. They usually have sharp, often erosional soles and usually gradational or sharp tops (e.g., Fig

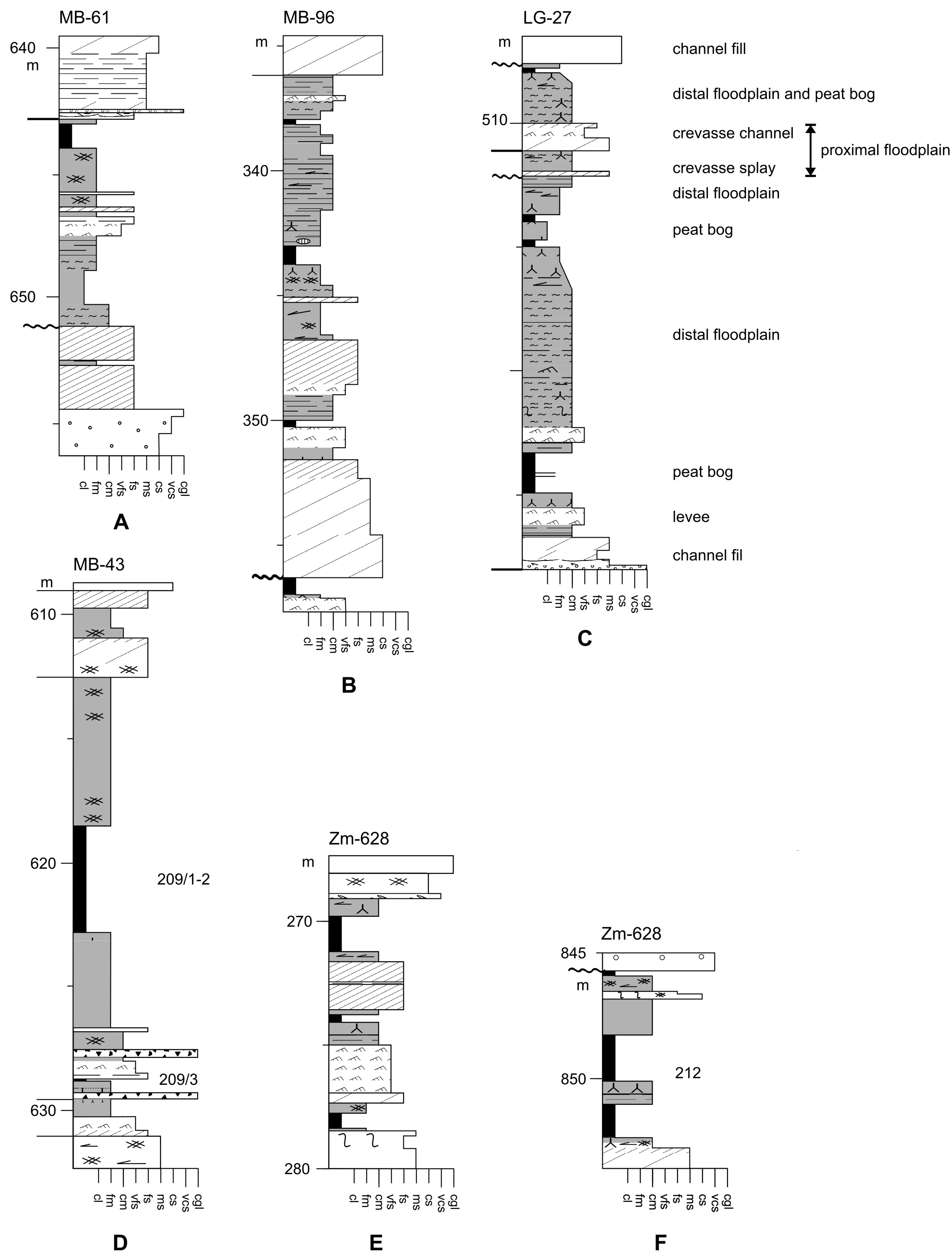

Fig. 22. Examples of the mudstone association, representing extrachannel deposits that correspond to proximal (**A**, **B** and **E**) and distal (**C**, **D** and **F**) parts of the floodplain. Examples of environmental interpretation are given in C

21A. 547–550 m and 555–558 m; Fig. 21B: 589–593 m; Fig. 22B: 347–349 m; Fig. 22E: 271–273 m and 275–277 m).

The mudstone association includes also thin, decimetric, intercalations of sandstones. They consist usually of fine-grained sandstones with small-scale cross-lamination (SR). At top the sandstones usually pass gradually to sandstone/mudstone heteroliths (HE) or mudstones with horizontal lamination (FH) or with wavy lamination (FW) (cf. Fig. 21B: 584 m, 603 m, 607 m; Fig. 22A: 646 m; Fig. 22C:

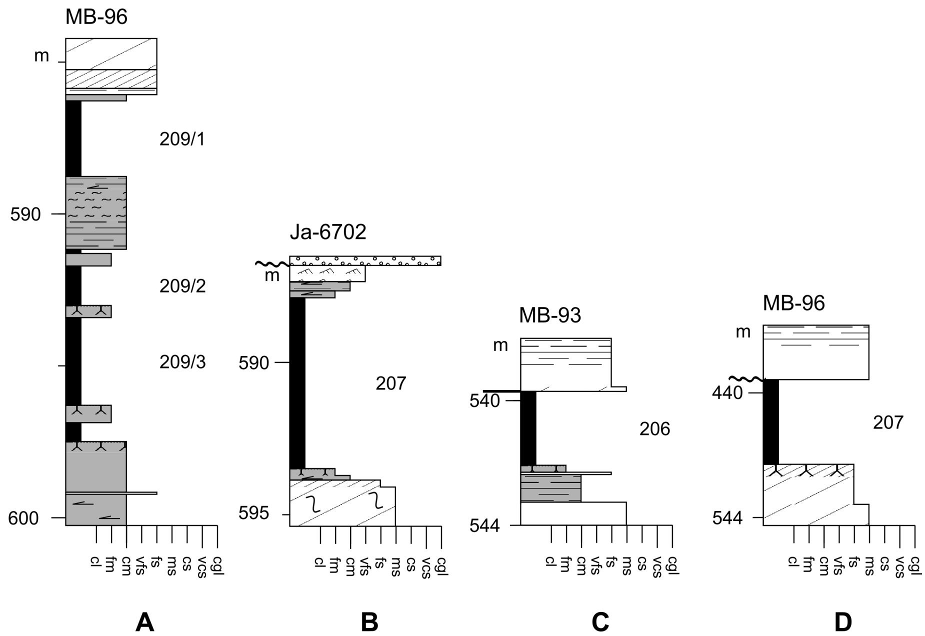

Fig. 23. Examples of sections with coal seams. **A** – example of a coal seam split by numerous intercalations of fine-grained sediments, **B** – thick coal seam overlain and underlain by fine-grained sediments of small thickness, with seat earth (R) at the sole and floated-in plant debris at the top, **C** – coal seam underlain by fine-grained sediments of small thickness, with seat earth, covered at top by sandstones lying on an erosional surface, **D** – a rare example of a coal seam underlain by a zone with roots in sandstone

523 m). Concentrations of the thin sandstone intercalations vary between the sections.

The lower boundaries of mudstone association packages are usually well marked, though they are not erosional. They are marked by a rapid change in grain size, which is perceived as a sharp contact. The boundary between the underlying sediments of the sandstone association and the overlying sediments of the mudstone association is gradational and expressed as gradual but rapid (over a short vertical distance) decrease in grain size and thickness of the sandstone layers in the top part of the lower lying package of the sandstone association (Fig. 21B: 606–610 m).

The upper boundaries of the packages of mudstone association are in most cases sharp, accentuated by a rapid change in grain size (see Fig 21B, C and Fig 22D, E) and are erosional in many cases (Fig. 21A and Fig. 22A, B, C, F).

Interpretation

The mudstone association is usually interpreted as laid down mainly in the extrachannel areas. It consists chiefly of fine-grained sediments accumulated during high water stages in the areas situated away of the zones of active fluvial channels. A common component of this association are layers of coal and akin rocks (lithofacies C), that formed from the plant material accumulated in peat bogs. Their characteristics and interpretation are presented below in chapter "Coal".

Sedimentary features of the sediments in the mudstone association indicate that they were laid down mainly by vertical accretion from material transported in suspension. Intermittent action of weak currents during the deposition of lithofacies FW is proved by locally discernible laminae and intercalations of slightly coarser material (silt, very fine-grained sand), with locally discernible very fine internal cross lamination typical of small ripples. It is very likely that most mudstones and claystones in this association are sediments of flood plains, which are understood after Reinfelds and Nanson (1993, p. 1114), as generally extensive, partly vegetated, practically horizontal parts of alluvial plain, situated in the vicinity of fluvial channels and temporarily inundated during floods.

It cannot be ruled out that a part of the fine-grained sediments are deposits of shallow, long lasting lakes that formed within the areas of deposition of the mudstone association (e.g., Fig. 21C), though no clear evidence for this has been found.

Variation in grain-size of the fine-grained sediments, observed in individual sections may be explained, among other possibilities, as the result of decreasing grain size in transported sediment with increasing distance from an active channel. Such relationship, especially well marked for the fine silt grade, was found, among others, by Guccione (1993) in the modern extrachannel deposits of the Mississippi River and its two tributaries.

Relatively thin accumulations of sandy sediments that occur subordinately in the mudstone association are interpreted as deposits of crevasse splays. The sediments of such origin are usually a characteristic component of sedimentary sequences laid down on alluvial plains of modern rivers of various type (Coleman, 1969; Farrell, 1987; Smith *et al.*, 1989; Ethridge *et al.*, 1999). Such sediments have been described, with detailed characteristics, from fossil alluvial deposits of coal measures by, among others, Horne *et al.* (1978), Obernyer (1978), Flores (1981), Gersib and McCabe (1981), Guion (1984), Doktor and Gradziński (1985) and Mjøs *et al.* (1993).

The comparison of the described deposits of sandy intercalations with the sediments of fossil crevasse splays shows many features in common, which support the interpretation proposed above. The most important among these features are: (a) grain size, distinctly smaller than in channel sediments and coarser than in other sediments of the mudstone association, (b) the usually small thickness of the intercalations, of decimetres or a few metres in most cases, (c) the mass occurrence of sedimentary structures indicative of deposition by currents, including the mass occurrence of small ripples, (d) the occurrence of sharp contacts or erosional surfaces at the base of sequences.

Variations in thickness of sediment packages composed of crevasse-splay deposits are well known in literature. As a rule, the thicknesses of such packages and the grain size decrease with increasing distance from the feeding channel (cf. e.g., Mjøs *et al.*, 1993). The thicker packages, up to a few metres thick (Figs 21A, B; 22A, E), may be interpreted as stacked deposits of several separate splays (cf. Mjøs *et al.*, 1993, p. 172–174). A greater proportion of the crevasse splay deposits in a section of the mudstone association suggests a more generally proximal position of a given section with respect to the feeding channel (cf. Figs 21, 22).

Deposits of natural levees could not be precisely distinguished in the sections of the mudstone association because of the lack of unanimous diagnostic criteria. Another authors apparently have similar problems, as the deposits of proximal crevasse splays have been usually considered jointly with the supposed deposits of natural levees (Jorgensen & Fielding, 1996, table 1).

The number and thickness of sandy intercalations within the mudstone association allow to describe them as deposits of the proximal and distal parts of a floodplain. The sediments laid down in the proximal parts of the floodplain have greater number and thickness of the sandy intercalations, generally interpreted as deposits of crevasse-splays (crevasse channels and natural levees). Less common there are coal seams. The sediments representing more distal parts of the floodplain include scarce and usually thin intercalations of sandy sediments or are devoid of them. More common are coal seams, some of them of considerable thickness (Fig. 23A, B, C).

COALS

Description

The term “coals” is used in this paper in a broad, general meaning and in most cases it describes seams (layers) composed of carbonaceous rocks, that is both, coal and carbonaceous shales that accompany many of the coal seams (cf. lithofacies C). A “seam” is used herein for a coal layer together with the carbonaceous shale intercalations below, within and above it and with thin, subordinate intercalations of clastic sediments. The latter are called by Polish miners *przerosty*. Coals, in the broad meaning presented above, are marked on many drawings and are discussed at many places in the text. Only where the differences between the two mentioned types of carbonaceous rocks is important, the coals and carbonaceous shales are distinguished (Fig. 24).

Coals make up 3–6% of the whole thickness of the series. The coal seams in the whole series are from a few centimetres to a few metres thick, in most cases about 2 m. The maximum thickness, up to 7–10 m, are present mainly in the zones of coal seam coalescence (e.g., seam 209–210 in Siersza mine).

Data on coals from drilling cores are in most cases scarce, cores from coals were in most cases unavailable because of their immediate complete sampling for laboratory investigations. More data on the coal rocks have been obtained by direct observation in the walls of mine galleries and from mine reports.

Coals in the Cracow Sandstone Series are mostly of humic type (Doktor & Gmur, 1999; Gmur & Kwiecińska, 2002) and they display a characteristic banded structure. They are composed of alternating laminae of bright and dull coal. Proportions and thicknesses of individual laminae vary within quite broad limits. Less common are somewhat thicker (up to 10–20 centimetres) layers, build exclusively of bright or dull coal.

Coals in the described series have a high content of ash, between 10 and 18 percent. Ash contents around 30 percent, sporadically even above 40 percent for some coal seams, are given in mine reports. However, these very high values of ash content may be the result of analysis made on channel samples. Acquisition of such samples is often indiscriminate, so that is thin (less than 10 cm) intercalations of clastic sediments are not eliminated from sample, thus drastically increasing the results of ash content analyses. A clear relationship between the coal seam thickness and ash content has not been observed in most cases, though the thickest seam in the Cracow Sandstone Series (207) has the lowest ash content, and many of the thin seams have the highest ash contents encountered.

Coal shales consist of alternating thin laminae of clastic sediment (usually claystone or mudstone) and laminae of bright or dull coal similarly thin. These rock usually display platy fissility. Coal shales usually accompany coal seams, appearing at various levels of the seams (see Fig. 24), but most frequently in their basal parts.

Nearly all coal seams are present within the packages of the mudstone association sediments (Figs 21, 22, 23). In most cases they are a subordinate component in the sections, but locally they prevail (Fig. 23B). Coal seams in the sandstone association are extremely rare and most of these are thin (Fig. 23D).

The thickness of the fine-grained sediments that underlie coal seam varies from above ten centimetres to a few metres, rarely exceeding 10 m. As mentioned earlier, nearly all coal seams are underlain by seat earth (R), less common are

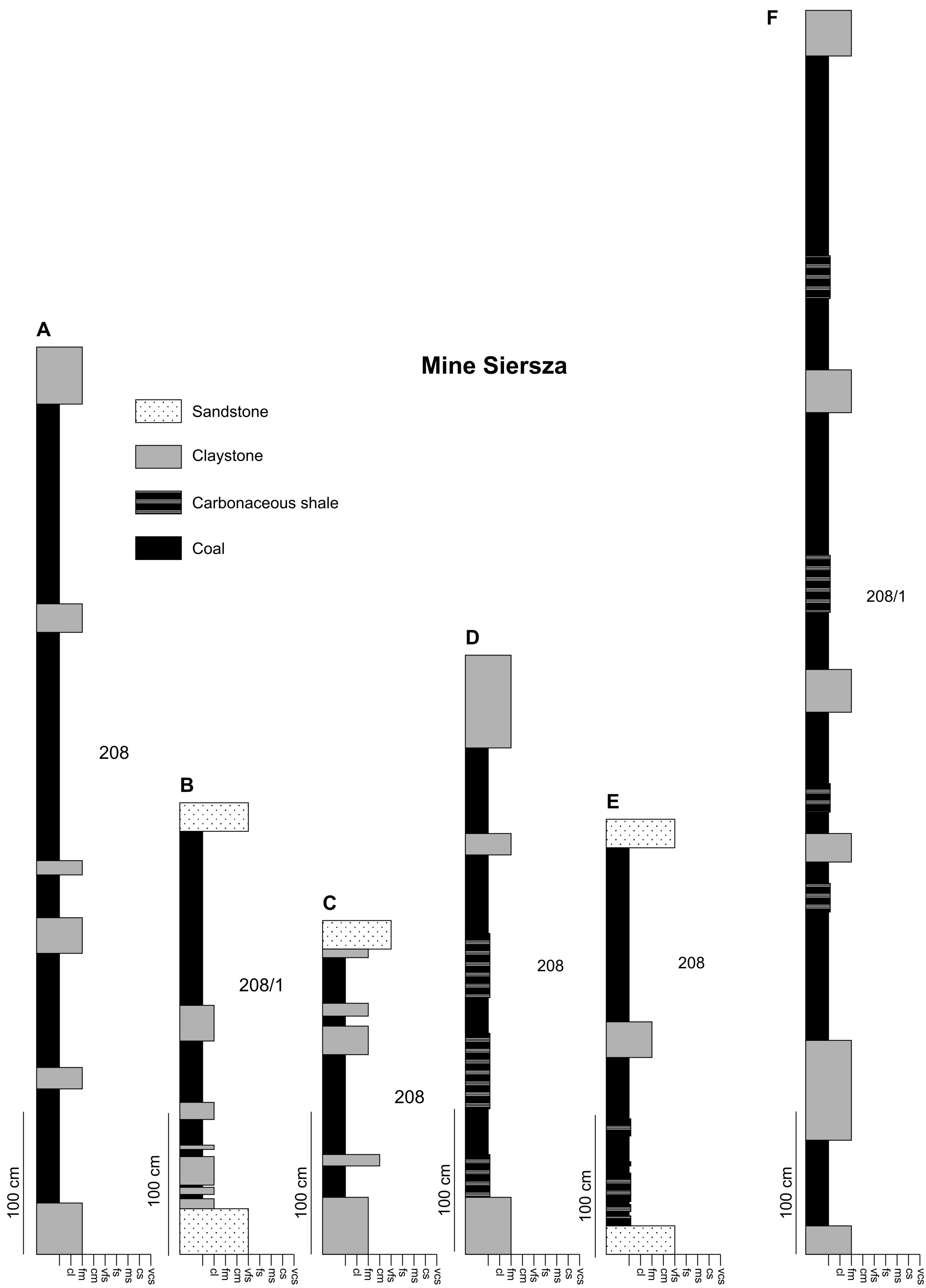

Fig. 24. Examples of coal seams with thin intercalations of fine-grained rocks (**A**, **B**, **C**) and partings of carbonaceous shales (**D**, **E**, **F**)

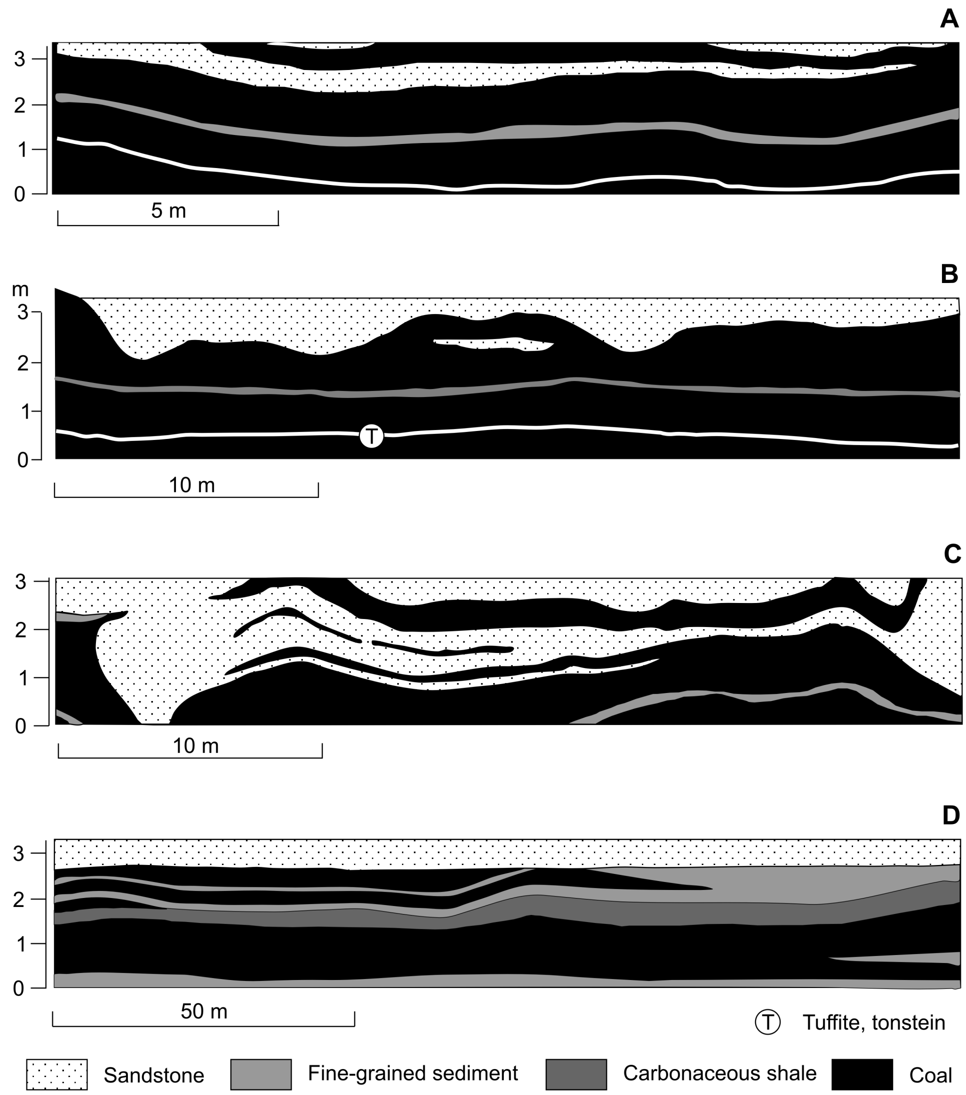

Fig. 25. Examples of partings and intercalations in coal seams. **A** – long, several centimetres thick sandstone intercalations or fine-grained sediments in a coal seam, **B** – long, thin, up to twenty centimetres thick sandstone intercalations of fine-grained sediments and tuffites (T) in a coal seam, **C** – Thick intercalations of sandstone sediments that disturb the thickness of a coal seam and result in its splitting, **D** – Thin partings of fine-grained sediments and coaly shales that continue for hundreds of metres in a coal seam

massive (FM) or laminated (FH) fine-grained deposits; sediments of other lithofacies occur only sporadically.

Some coal seams overlie directly sandstones. In such case direct observations in mine galleries often reveal that the very top of the sandstone has a form of a thin layer of sandstone with abundant coalified plant debris, called *mierzwa* (manure) in the Polish miners' slang.

Coal seams are usually covered by fine-grained sediments, in most cases massive (FM) or horizontally laminated (FH) lithofacies, less frequently by other lithofacies (HE, FW).

When a coal seam is overlain by coarse-grained sediments, that is sandstones of various grade, the top of the coal seam is erosional. The depths of these erosional forms vary, and often attain several tens of centimetres (Fig. 25A and B). In some cases the coal seams were completely removed by erosion. The lateral extents of the wash-outs vary from a few to several hundred metres. In case of extensive washouts, zones of marked decrease in coal thickness or its lack are marked on the coal seam maps (see e.g., Fig. 37). Direct observations in the marginal zones of such washouts often allow to discover deformations related to differential compaction of peat and clastic sediments (Fig. 25C).

A common feature of the coal seams in the Cracow Sandstone Series are partings (binders) – intercalations of clastic sediments in coal (Fig. 26). A common occurrence are thin, centimetric intercalations of fine-grained sediments (mudstones and claystones, quite sporadically fine-grained sandstones) in the form of a series of thin lenses in one coal seam. They disappear and appear at various vertical distances from the top or bottom and they usually continue for a few tens of metres (Fig. 25). Their presence rec-

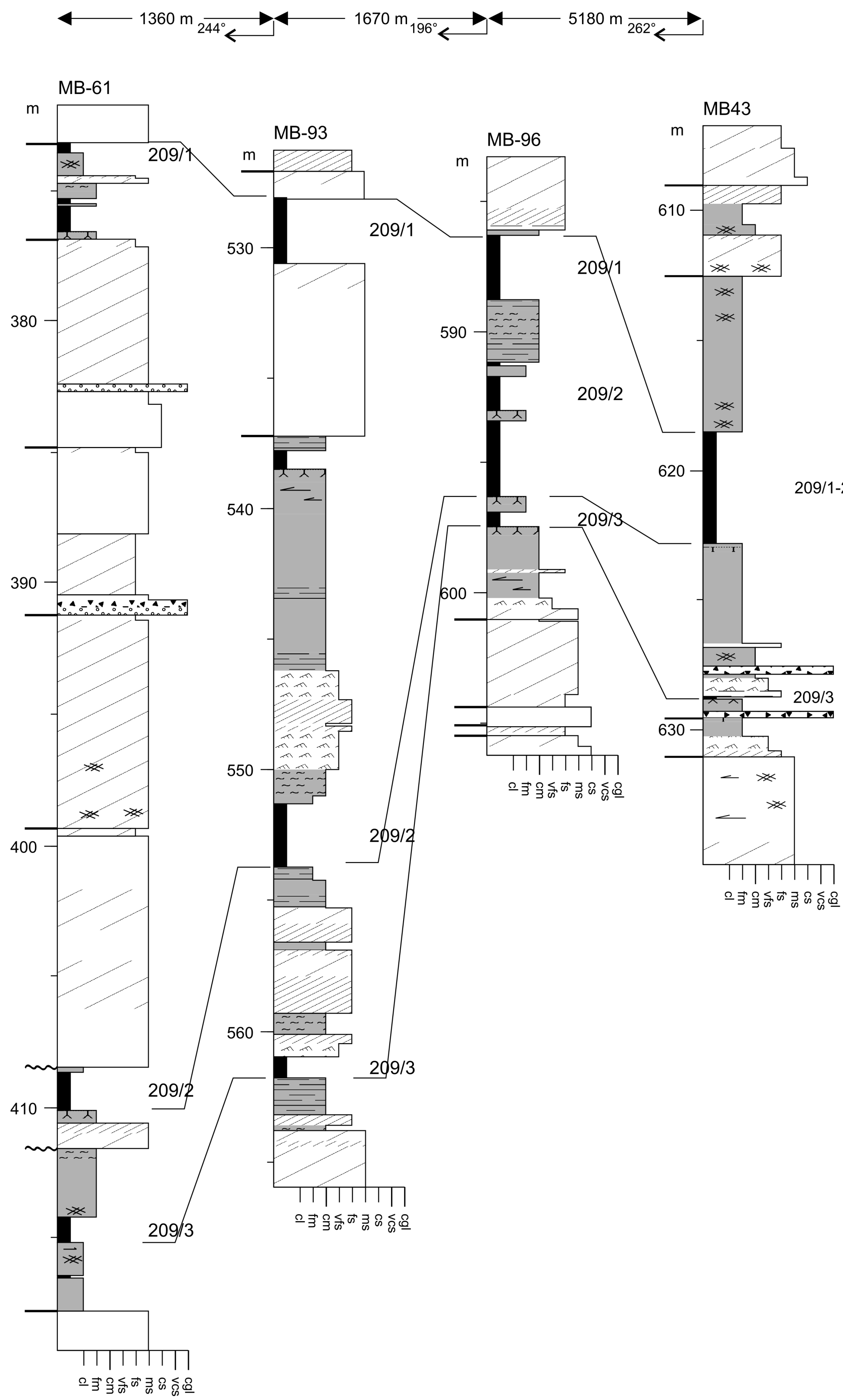

Fig. 26. Example of coal seam (209) splitting over a few hundred metres and the nature of sediments between the coal benches (after Gradziński, Doktor & Słomka, 1995; modified)

ords periods of short-lived small channelized flows through the peat bog, whose transporting power and duration permitted deposition, mainly from suspension, of small amounts of fine-grained sediments. They could be related to periodical flooding and they are a result of deposition from waters leaving the peat bog. The partings of that type, because of their small thickness and extent, do not result in splitting of a coal seam into separate benches.

A specific variety of the partings are those composed of tuffogenic material, in most cases in the form of tonstein (cf. Fig. 25B). Some of them can be traced within a single coal seam for a distance of 15–20 km (Gabzdyl, 1990).

Environmental conditions of peat accumulation of the Cracow Sandstone Series sediments

Coal layers (seams) are the geological record of the presence of peat bogs, that is areas where deposition of phytogenic sediments predominated. Clastic supply to these areas was practically eliminated, with only scarce supply of fine-grained sediment. The results of studies by D. Gmur (Doktor & Gmur, 1999, fig. 47), using nomenclature and facies diagrams of Hacquebard and Donaldson (1969) as well as Diessel (1986) and Pokroński (1994), indicate that the coal seams in the Cracow Sandstone Series were laid down in peat bogs of telematic zone.

The predominant type were wet forest swamps, growing in telmatic zone. These were areas vegetated by woody lycopods growing over extensive, frequently flooded, interchannel areas (DiMichelle & Phillips, 1994). The coals which had their origins in such conditions have mezoscopic structure dominated by lithotypes rich in bright coal (vitrain, claro-vitrain and vitro-clarain). The lack of flow favoured increasingly reducing nature of the environment marked in elevated content of sulphur in coals originated in such conditions (cf. Moore, 1987; Teichmüller, 1989).

Another type of peat bogs that gave rise to the coals of the Cracow Sandstone Series were herbaceous swamps. These were dominated by sphenopsids (horsetails of herbaceous appearance) and herbaceous ferns. Frequent flooding by nearby streams resulted in increased supply of mineral substances to the peat bog, proven by the increased ash contents in the coals that formed in peat bogs of such type. These coals contain more dull coal and are represented mostly by durain, claro-durain and duro-clarain.

Much smaller was the contribution of dry forest swamps in the formation of coals in the Cracow Sandstone Series. The plant assemblages in such swamps included arboraceous lycopods that preferred dryer environments, and some genera of arborescent ferns. The mezoscopic appearance of these coals features the presence of fusine within such lithotypes as vitrain, claro-vitrain or vitro-clarain. The microscopic composition of these coals feature elevated proportions of fusinite and semifusinite, accompanied by macerals from the vitrinite group (Doktor & Gmur, 1999, plates 5c and 5d).

The third type of environment in which the coals of the Cracow Sandstone Series were deposited was that of a wet fen, a type transitional between the forest and herbaceous types. This is evidenced by the plant assemblage composed of lycopods, herbaceous ferns and paralycopods. Such mixed type of plant assemblage is reflected in differentiated petrographic composition of coals formed from such peat bogs. They consist mainly of duro-clarain and vitro-clarain, and the maceral composition includes intercalated thin layers of macerals characteristic of forest-type peat bogs (e.g., laminae of telinite and telocolinite) and thin layers corresponding to the peat bogs of herbaceous type, that is desmokolinite with inertodetrinite and sporinite (Doktor & Gmur, 1999, plate 6a and 6b).

The dry fen variety was scarcely represented among the peat bogs of the Cracow Sandstone Series. They developed on the locally elevated grounds within a wet fen, where peat could undergo temporary drying. Petrographic composition of the coals that formed in these parts of the peat bogs is very similar to that of coals from wet fens, but are enriched in fussin (in mezoscopic view) as well as fusinite and semifusinite (in microscopic view) (Doktor & Gmur, 1999, plate 6c, d).

Analysis of the thickness distribution of coal seams that formed with predominant role of peat bogs of wet forest or herbaceous swamps has shown that the former generally form thinner seams. Coal seams formed with predominant share of herbaceous swamps in are more often the thick ones (cf. Doktor & Gmur, 1999, fig. 48). These seams include less common partings (see Fig. 44) than the seams that formed from peat bogs of wet forest swamp type.

The high content of ash in the seams formed in wet forest swamps is mainly the result of the presence of numerous very thin (1–5 cm) clastic partings. It may be supposed that a limited flow of water, related with a supply of clastic material, occurred temporarily in the areas where this type of swamps predominated, but it did not lead to cessation of peat growth.

The coal seams that formed in the conditions of predominant herbaceous swamp or wet fern are thicker, and the ash content does not derive from the presence of thin clastic parting, but rather from the presence of mineral matter dispersed in coal. This means that the peat bogs grew in conditions of a clastic supply so limited that the partings did not form. The relatively large thickness of these seams indicates longer periods of stable conditions that favoured peat growth.

This may indicate that the channel zones adjacent to the herbaceous swamps had relatively stable margins. It cannot be excluded that vegetation on these swamps provided a quite effective barrier for infiltration that prevented any significant supply of clastic material to the swamp area.

Coal seams in the Cracow Sandstone Series usually start with coals that formed from peat bogs of herbaceous or wet fern type, and they terminate with deposits of dry forest type (Doktor & Gmur, 1999). The predomination of dry forest environments in the top parts of the seams may suggest increased possibility of flood water flow through the peat bog area. The nature of vegetation in the peat bogs of that type could facilitate flow and thus favoured the develop-

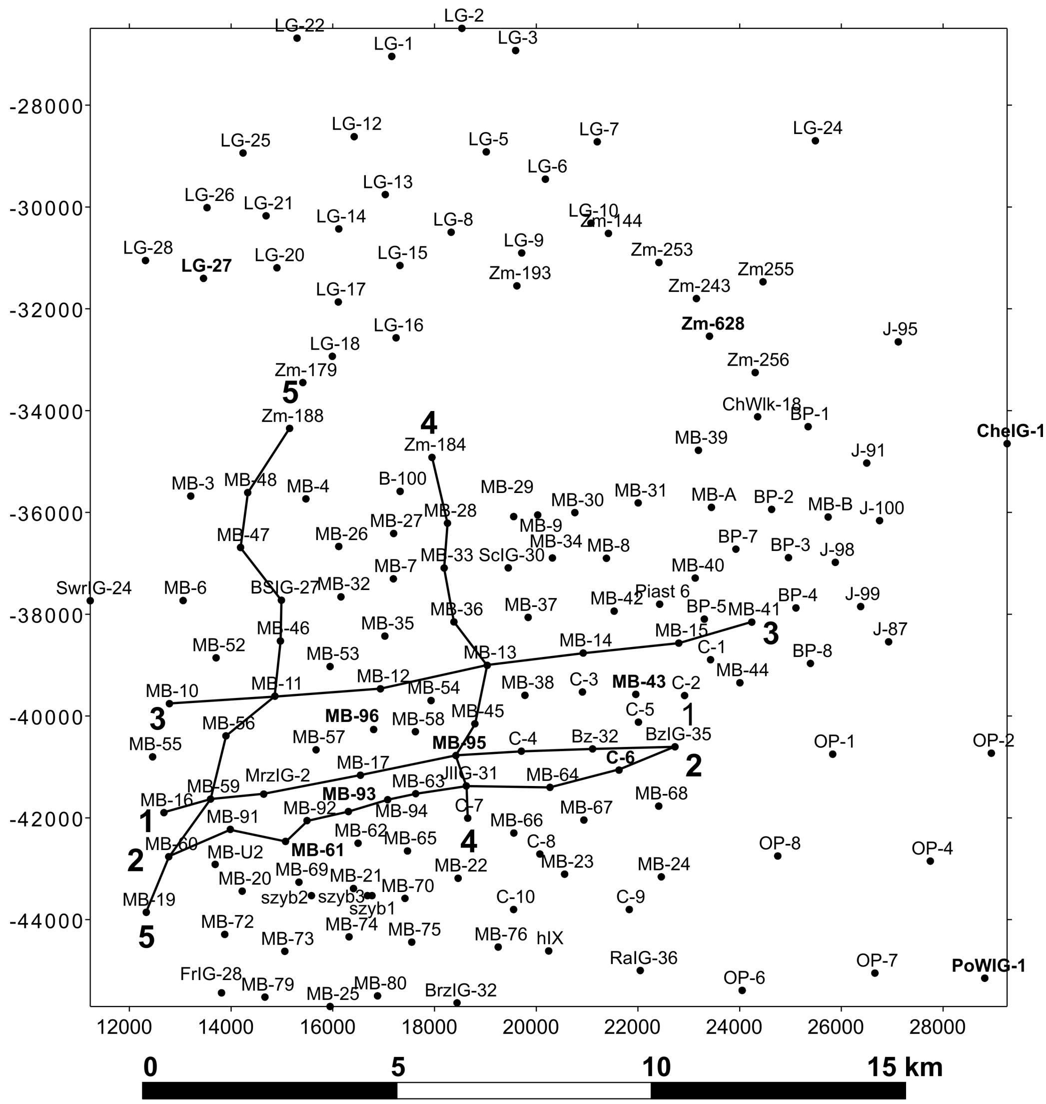

Fig. 27. Location map of the boreholes used for plotting the thickness maps and locations of cross-sections

ment of a new avulsion channel in the area of phytogenic sedimentation.

SEDIMENT ARCHITECTURE

The term "sediment architecture" is used in this paper for depositional architecture, that is spatial geometry of sediment bodies (lithosomes), resulting from sedimentary processes and compaction, without taking into account the results of later, postdepositional tectonics (see Gradziński *et al.*, 2005). For sedimentary successions composed of fluvial sediments, "fluvial architecture" is a synonym (Miall, 1983, 1996; Emery & Myers, 1996, p. 117). Sediment architecture in alluvial successions is studied at various scales (Shanley & McCabe, 1994, p. 546), from relatively small elements (e.g., single accretionary macroforms – Miall, 1985) to large sediment bodies, first of all lithosomes of channel deposits and lithosomes composed of fine-grained extrachannel deposits. In coal-bearing alluvial successions, coal seams are the third major component (cf. Galloway & Hobday, 1996).

As dependable marker horizons are few in the Cracow Sandstone Series, the regional cross-sections based on the dispersed boreholes provide only a general image of the space structure of the whole series (cf. Dembowski *et al.*, 1964; Dembowski, 1972b). From such a point of view, the Cracow Sandstone Series was considered as regularly repeating packages of clastic sediments and coals, more or less parallel to one another. The picture thus obtained is oversimplified, as it does not take into account mutual spatial relationships of the coarse-grained and fine-grained sediments and coals in the series.

Some fundamental problems appear when one attempts to present the spatial geometry of the sediments of the Cracow Sandstone Series in its part preserved to the present. For this reason, the present author presents only selected examples that demonstrate mutual relationships between the lithosomes representing the major lithological varieties of sediment, namely: sandy bodies (sandstone lithosomes), fine-grained sediments and coal seams. These examples are from the area of extent of the Cracow Sandstone Series, fairly well known in consequence of mining works and numerous surveying boreholes. Out of necessity, those numbered coal seams were used as markers, for which their identity is well proven by underground exploitation or a dense network of drilling sections. Postdepositional tectonic faults have been omitted in the presented examples.

Lithosomes of clastic sediments

Several vertical cross-sections and more than ten thickness maps have been drawn to illustrate the sedimentary architecture of the Cracow Sandstone Series. The cross-sections present the structure and mutual relationships between the lithosomes in vertical plane, the thickness maps supplement this picture and allow to trace lateral variations in the lithosome geometry.

The selected area comprises the mining fields of mines: Silesia, Brzezinka, Czeczott, Piast, Ziemowit and Janina, quite well recognized by boreholes and then by mine works. Three nearly parallel cross-sections running east-west and two running south-north have been drawn within this area. Both sets of cross-sections intersect at a nearly right angle (cf. Fig. 27). The sole of coal seam 209, well identified by drilling and mining works in several fields, has been accepted as datum in the cross-sections (Figs 28–32).

The cross-sections through the Cracow Sandstone Series reveal the presence of thick (tens of metres), laterally extensive lithosomes of sandstone deposits. A clear variation may be discerned in the thickness of the sandstone lithosomes. They form lenticular pillows with distinctly wavy shapes of their sole and top surfaces (cf. Figs 30–32). The lower boundaries of the lithosomes, especially of the sandstone ones, are erosional and are incised into the underlying carbonaceous sediments (see Fig. 28 – eastern part and Fig. 29 – in the western part of the section, Fig. 32 – in the northern part) or fine-grained sediments (Fig. 29 – eastern part of the section, Fig. 30 – eastern part and Fig. 31 – southern part).

The sandstone bodies have complex internal structures (see Fig. 31 above seam 209). The cross-sections show also wedging out of some lithosomes and lateral transitions to lithosomes of different lithology. Lithosomes of sandstone deposits often pass laterally to fine-grained sediments by splitting of a sandstone lithosome into many wedging-out sandstone benches (e.g., Fig. 28 above seam 209). The presented cross-sections show also gradual transitions of the sandstone lithosomes to fine-grained sediments, marked in the cross-sections as heteroliths. Such transitions are visible among others above seam 209 in Figs 29–31.

The cross-sections also show that in many cases the lateral extent of sandstone bodies below the coal seams is much smaller than it is the case with the lithosomes above the seams (cf. Figs 28, 29 and 31).

The thicknesses of individual lithosomes change laterally. The thickness maps of the clastic sediments between the coal seams (cf. Figs 34–36) clearly demonstrate distinct zones of thickening and thinning of the lithosomes. This is marked on the cross-sections by the wavy course of the coal seams between them (see Fig. 30). These zones are in general distributed in an irregular way, but with some elongation of the zone of their maximum thickness. A comparison of the course of this zone on several successive maps, showing successively higher inter-coal intervals, reveals a gradual directional change in the course of this zone from SW–NE (Fig. 33) through S–N (Fig. 34) to SE–NW (Fig. 35) and S–N (Fig. 36).

The fine-grained sediments build elongated bodies that accompany the coal seams. They usually lie below the coal seams and usually do not exceed a few metres in thickness (Figs 28–32). They display large lateral extents without abrupt changes in thickness (see Fig. 30, the lithosome beneath seam 209).

The lithosomes of fine-grained sediments above the coal seam as a rule have much smaller lateral extent. They are often bounded by erosional surfaces related to sandstone bodies or pass laterally to sediments of heterolith type, as is seen, among others, above the thicker parts of seam 209 in Figs 29–31.

The cross-sections display also isolated lithosomes of fine-grained sediments, no more than a few kilometres in lateral extent and up to between ten and twenty metres in thickness. They are not accompanied by coal seams in most cases. They are usually bounded by erosional surfaces related to the presence of sandstone lithosomes.

The cross-sections show also wedging out of individual lithosomes and lateral transitions to lithologically different lithosomes. These transitions occur over very short distances in some cases, thus indicating rapid changes in conditions of sedimentation.

The presence of the quite thick pillow-like forms dominated by sandstone sediments may indicate the presence of zones where conditions favourable for deposition of sandstone sediments prevailed for prolonged periods. This may be a record of temporarily stabilized channel tracts of braided rivers. The changes in the elongation directions of the zones with maximum thickness in these bodies may be related in most cases to the changes in the transport directions within the basin, most likely due to migration of the whole channel tracts.

The presence of relatively narrow zones of sandstone sediments beneath the coal seams (see Figs 28, 29 and 31) may indicate gradual cessation of the channel tract and decreasing supply of clastics by this route (see Figs 28 and 29 below seam 209). It may also indicate stabilization of the channel tract, expressed in its considerable thickness relative to its narrow lateral extent (see Fig. 31).

The usually thin lithosomes of the fine-grained sediments that widely underlie coal seams indicate small amounts of fine-grained sediment transported and deposited during deposition of the Cracow Sandstone Series.

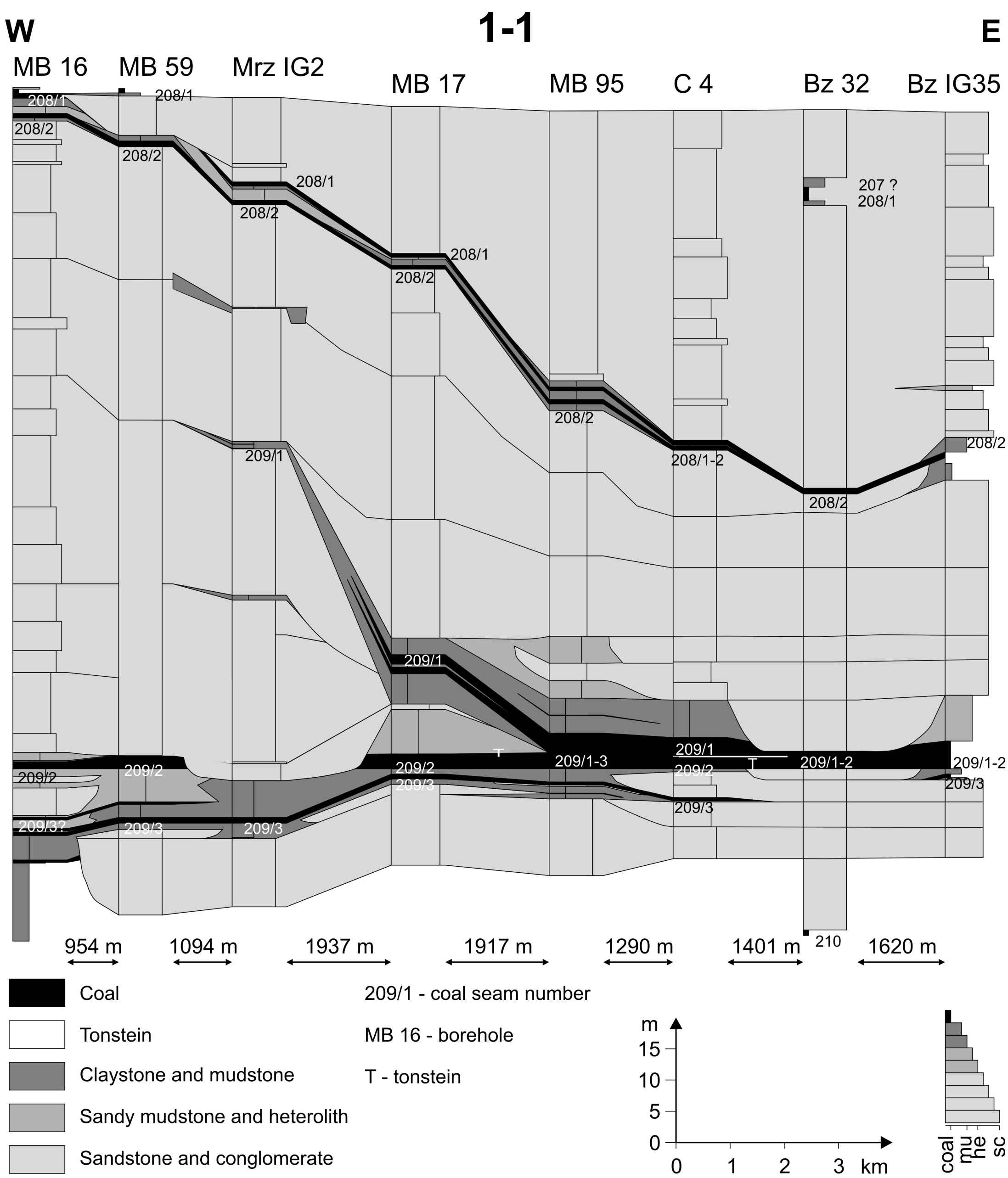

Fig. 28. Lithological cross-section 1-1

Lithosomes of carbonaceous sediments (coal seams)

The coal bodies are an especially characteristic element of sediment architecture because of their lithology. The cross-sections (Figs 28–30) reveal a marked variation of individual coal seams in the Cracow Sandstone Series. They can repeatedly split, fade out, be removed by erosion or be present over a relatively isolated area.

A common phenomenon well apparent on the cross-sections is the presence of partings and splitting of the coal seams. Partings built of clastic sediments that continue over distances of many hundred metres and several decimetres or a few metres thick result in the phenomenon of coal seam splitting, common in the Cracow Sandstone Series. Laterally, intercalations of clastic sediments appear within a seam and in consequence the seam splits in two or more benches (see Figs 24, 25, 26). The miners' practice is to give the benches successive numbers (though not in all cases as one can see in Fig. 29, borehole MB93 or Fig. 32, borehole BsIG27). Labelling some seams in the cross section of one borehole often results in their subsequent correlation on the cross-section solely by its number, without any other valid reason. An example is visible on cross-sections in Figs 28–30 where correlation of the seam labelled 209/1 finds no reasonable justification.

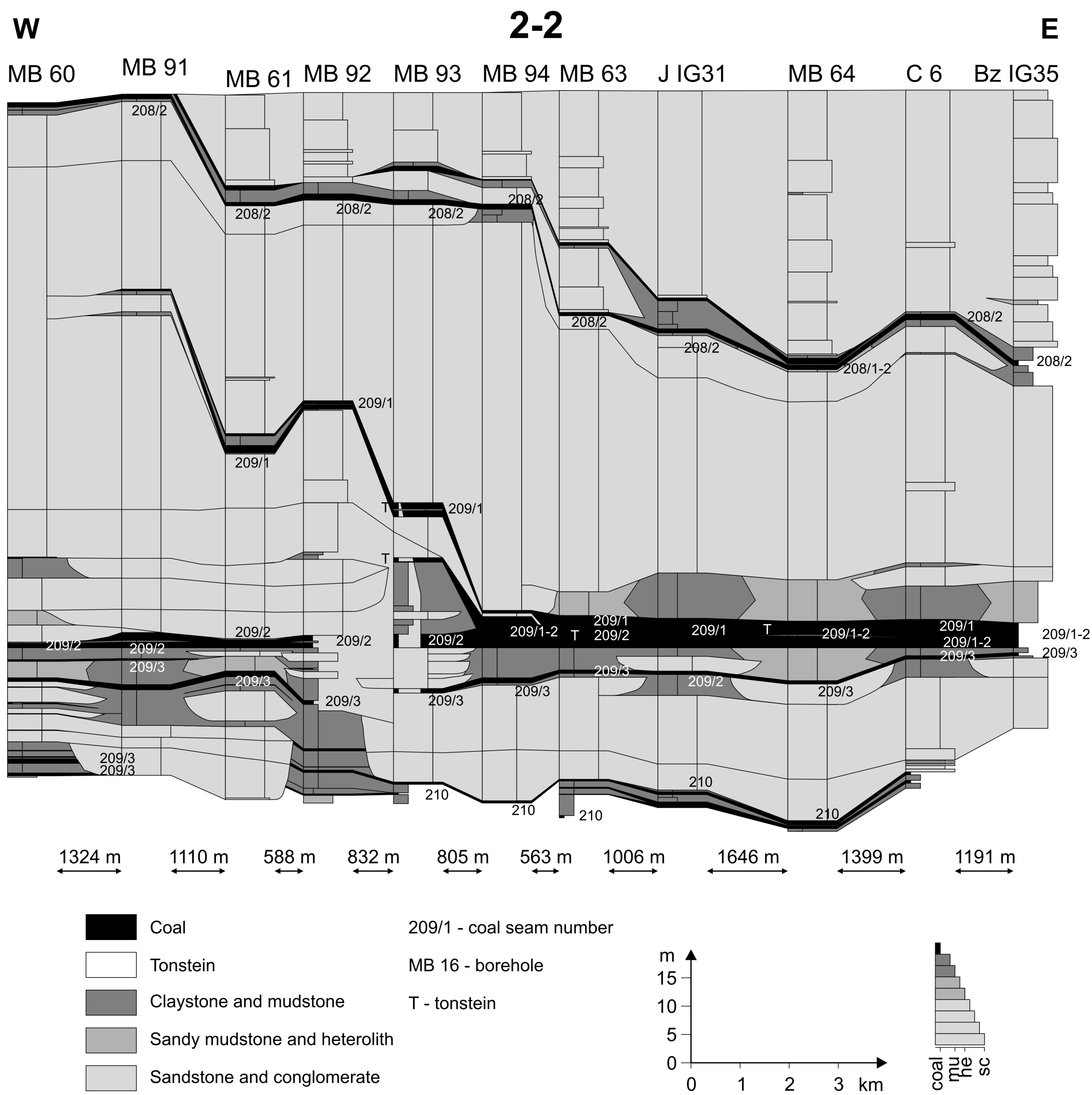

Fig. 29. Lithological cross-section 2-2

The partings built of pyroclastic rocks may be used for identification and correlation of some coal seams. They may be traced within one seam over distances of many kilometres. Within the area selected for this study an example is provided by the tuffite parting within seam 209 (see Figs 28–31).

Those intercalations that have a moderate thickness (of the order of decimetres) are usually composed of fine-grained sediments with abundant roots, and only sporadically of fine-grained sandstone. Some intercalation extend for many hundred metres without any distinct change in thickness, while others have a form of relatively thin lenses that disappear over distances of several tens or a few hundred metres (see Figs 25, 28).

Especially noteworthy are the cases of gradual but rapid thickening of clastic intervals between the benches of a split coal seam (Doktor *et al.*, 1994). The maximum thickness of such intervals documented by mining works exceeds 10 m in many cases, attaining even a few tens of metres (Figs 26, 28 and 29). A significant lateral increase in thickness is usually accompanied by a decrease in proportions of fine-grained sediments within it in favour of coarse-grained sedi-

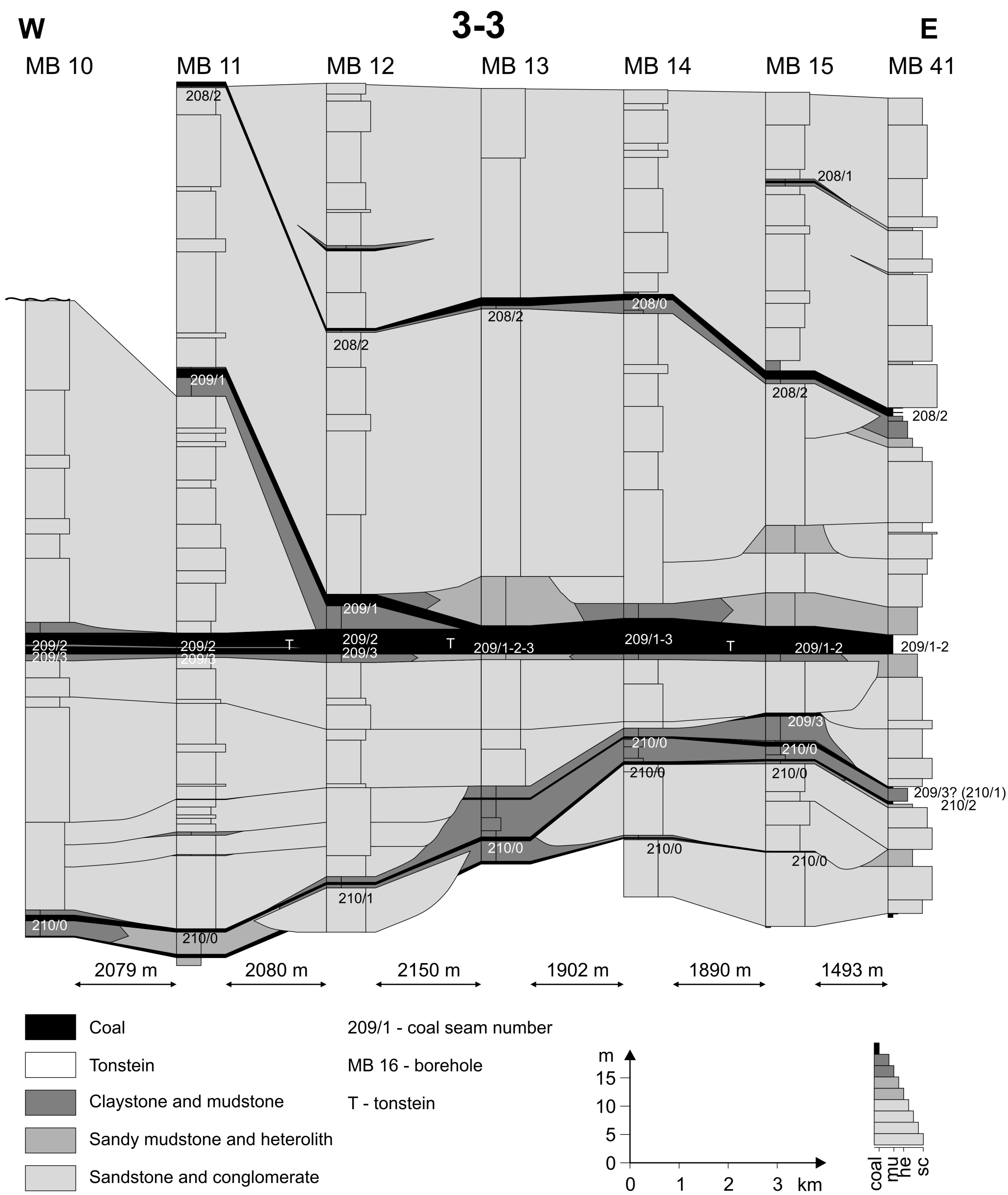

Fig. 30. Lithological cross-section 3-3

ments (cf. Podio & Wieja, 1960). Such changes occur at quite high rates, over distances of hundreds metres or a few kilometres. The intervals tens of metres thick consist almost exclusively of sediments belonging to the sandstone facies (see Fig. 26).

The described above cases of large-scale splitting of coal seams prove that areas with deposition of phytogenic material (peat) were present at the same time with the areas where thick sandstone packages were being laid down. The described here phenomenon of lateral splitting of the coal seams is unequivocally the result of lateral migration of channel tracts. This is marked by the presence of the expanding clastic parting. An abrupt appearance of a thick parting may be a result of avulsion of channel into the area of peat bog in consequence of the difference in the levels of deposition.

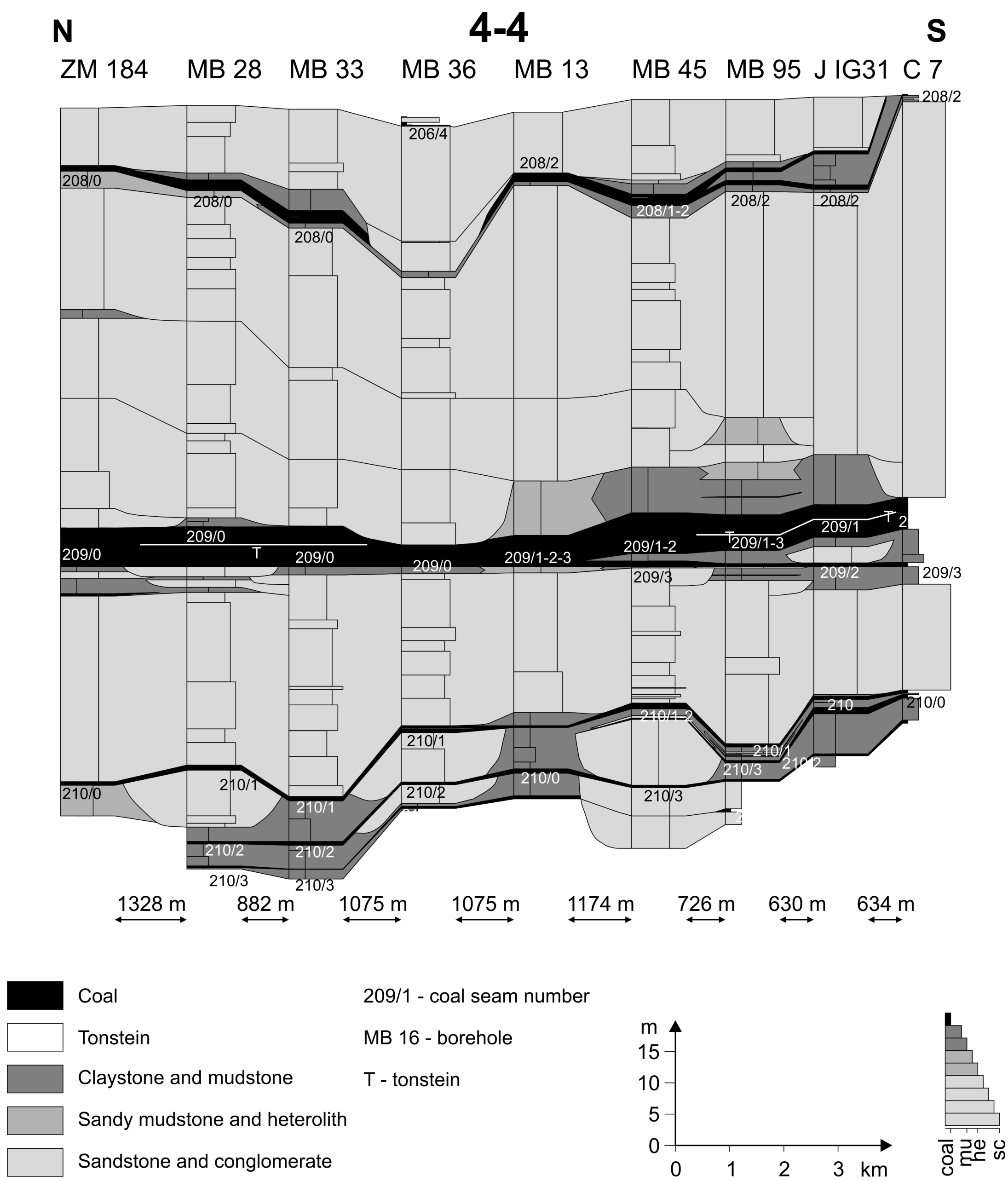

Fig. 31. Lithological cross-section 4-4

It should be noted that case of rapid and multiple splitting have been also observed in such seams (e.g., in the seam labelled as 209, Figs 28–32) that were considered by the earlier authors (Dembowski *et al.*, 1964; Dembowski & Unrug, 1970; Dembowski, 1972b) as "persistent", that is subject to only subordinate splitting and devoid of significant partings, and to which these authors ascribed a role of individual correlation horizons of regional extent.

Changes in thickness of individual, selected coals seams (118, 207, 208, 214, 215 and 216) have been examined on the presented maps that cover an area of ca. 300 km^2 (Figs 37–41). All the seams in the studied area, except for seams 207 and 118, besides the changes in thickness present also zones of complete reduction.

The causes of the local disappearance of the coal seams may be of two types. One – of sedimentary nature – is the lack of conditions leading to establishment of a peat bog. The simplest explanation is the presence of channel tracts through which large amounts of clastics are transported or abundant supply of fine-grained material to the floodplain area. Another factor may be highly variable groundwater level in the extrachannel areas, which also would prevent peat bog formation.

Another cause may stem from processes of erosion. The complete reduction of coal seam thickness as observed on the maps (Figs 37–48) and often registered in the mines, may be related to the so called seam washouts, that is a complete erosion of peat in some area; the erosional surface is in

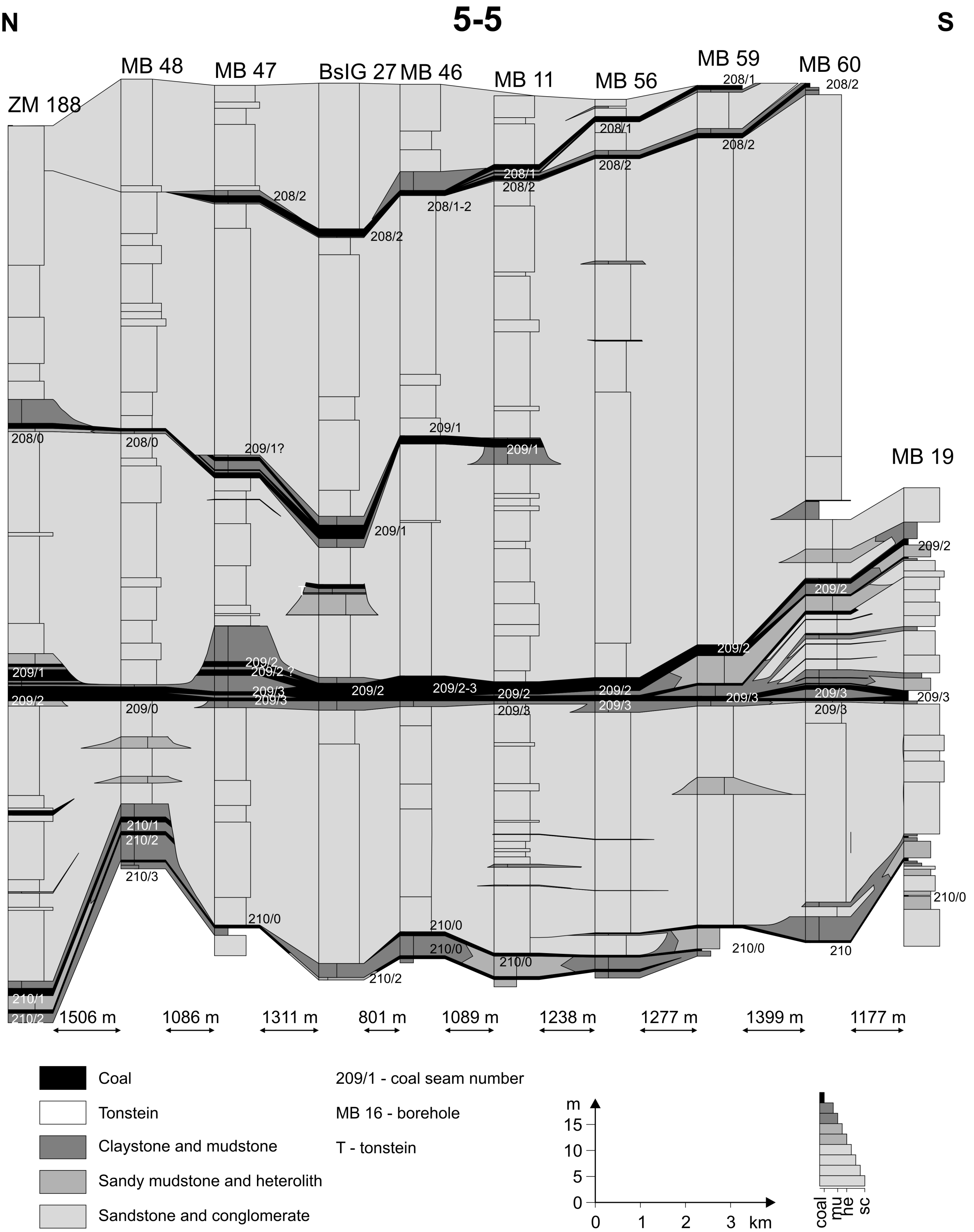

Fig. 32. Lithological cross-section 5-5

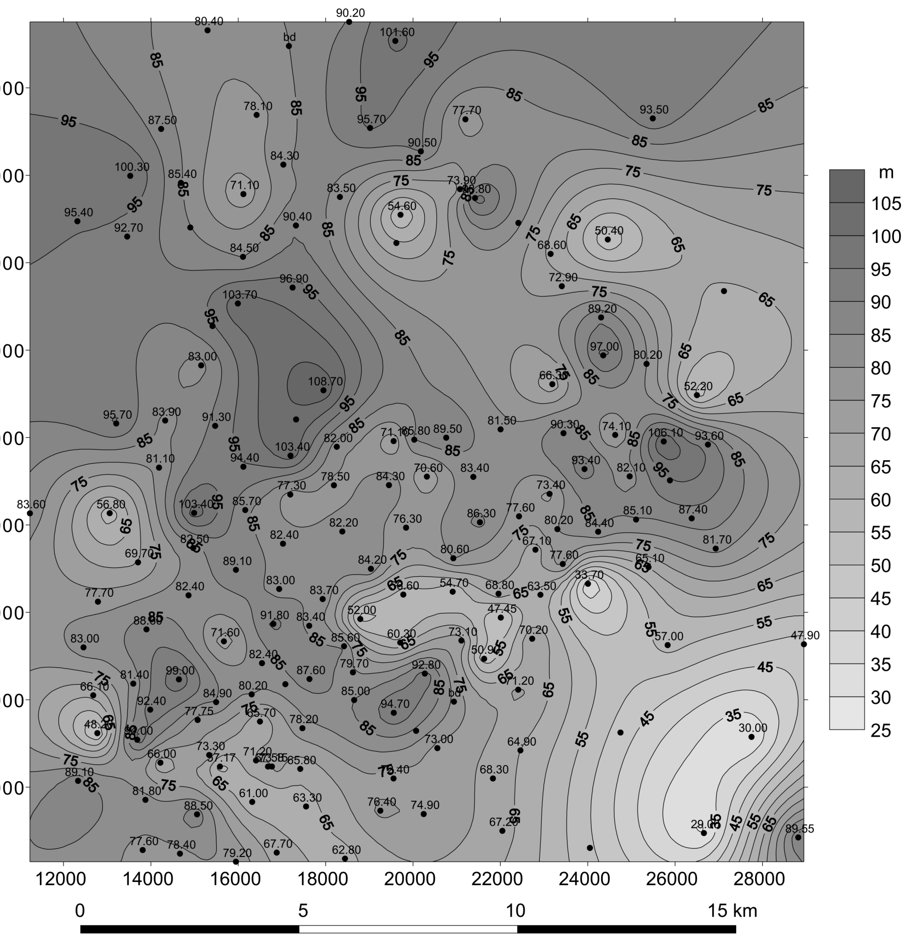

Fig. 33. Thickness map of sediments in the Cracow Sandstone Series beneath seam 215

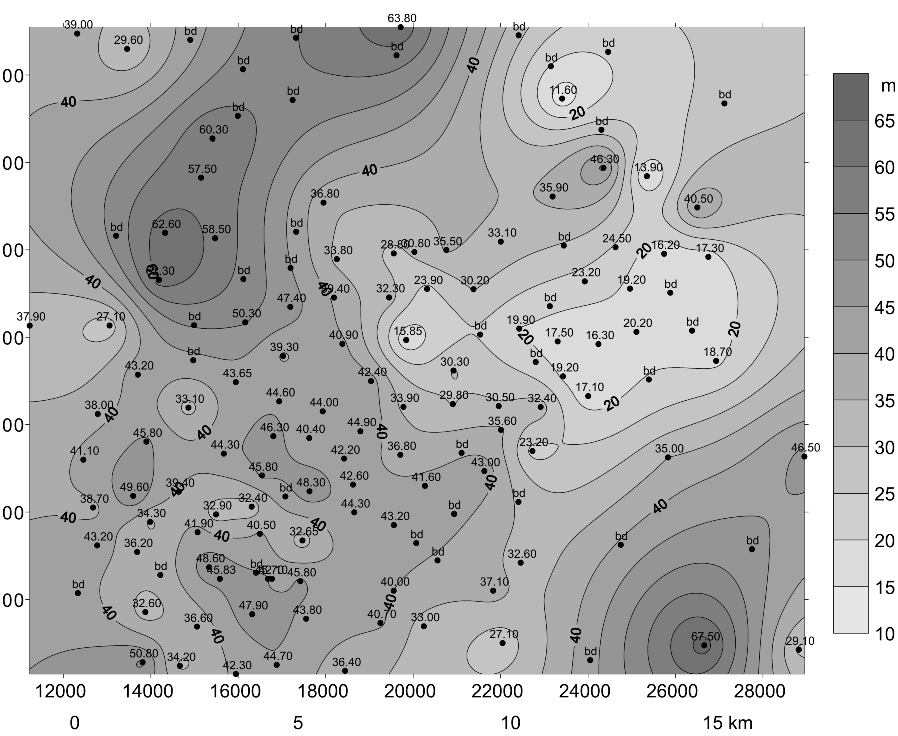

Fig. 34. Thickness map of sediments between seams 215 and 214

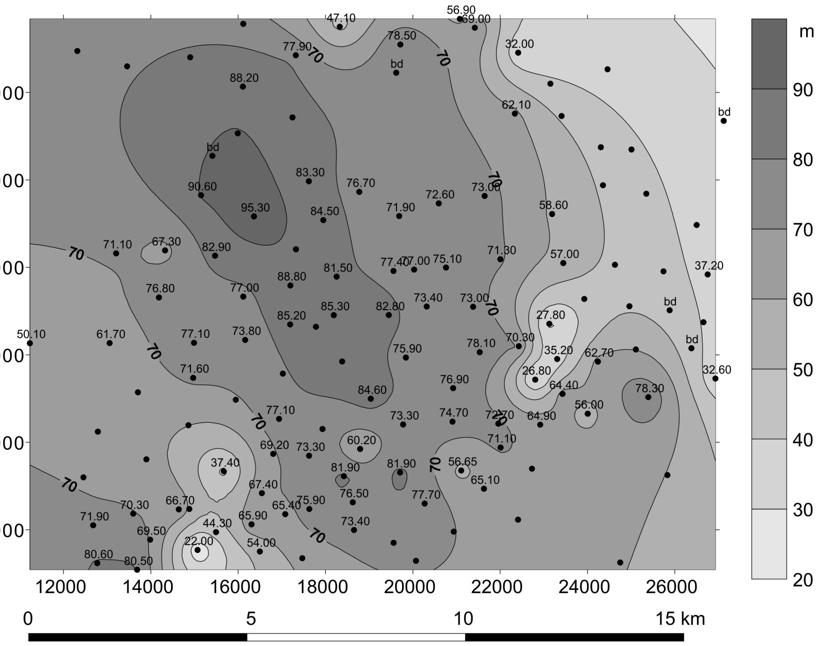

Fig. 35. Thickness map of sediments between seams 208 and 207

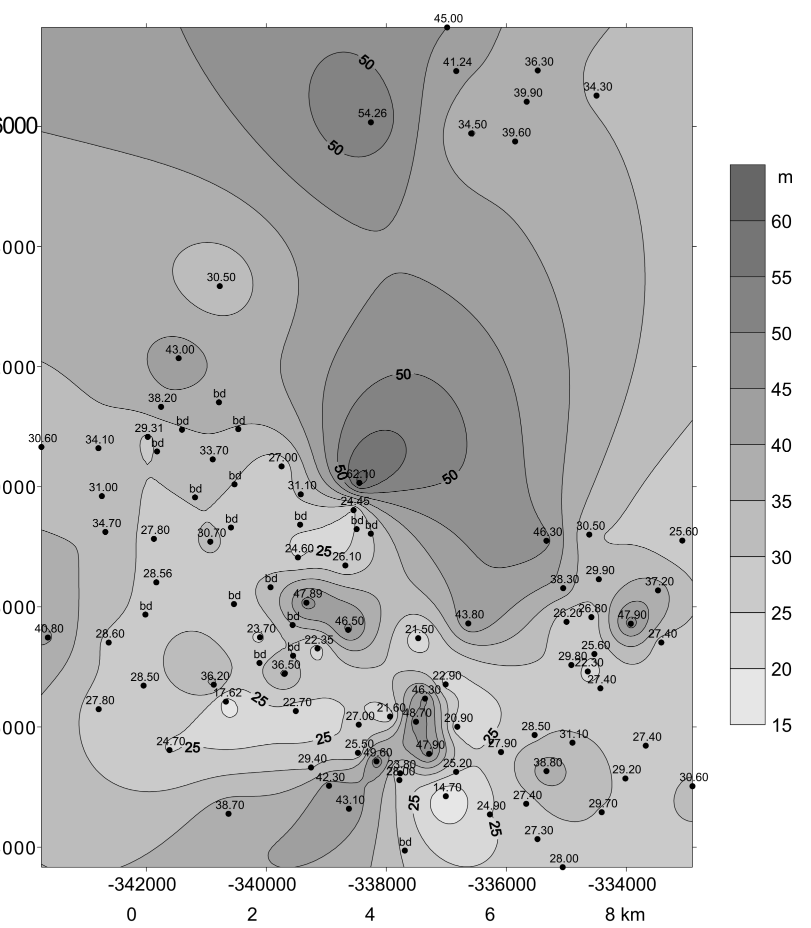

Fig. 36. Thickness map of sediments between seams 119 and 118

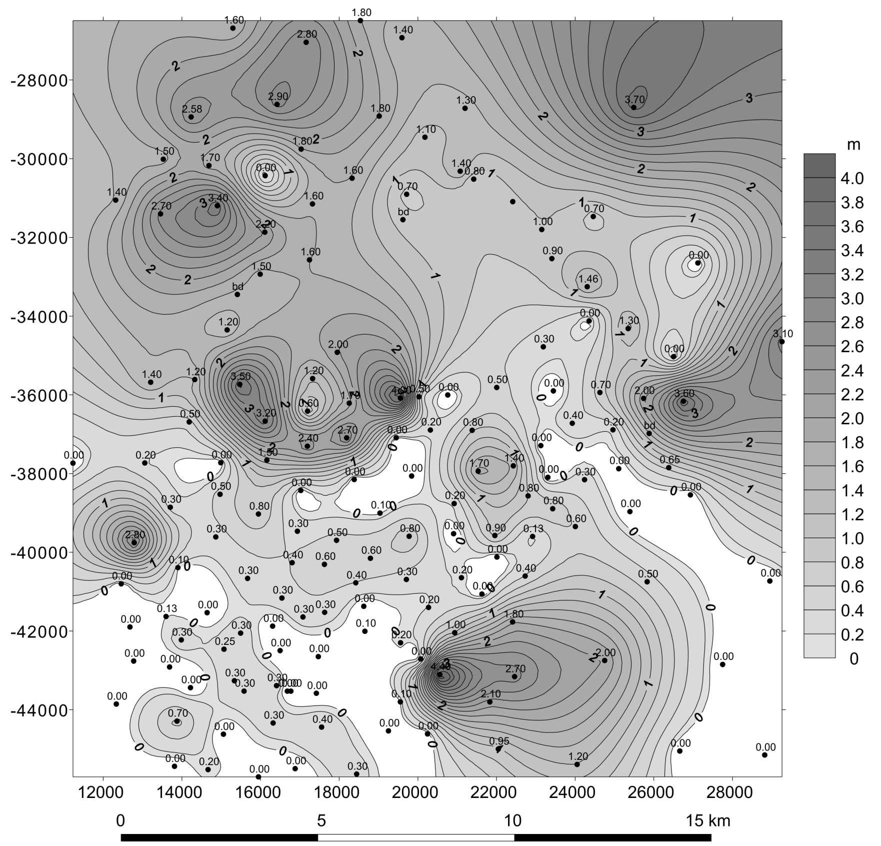

Fig. 37. Thickness map of coal seam 216 over a selected area

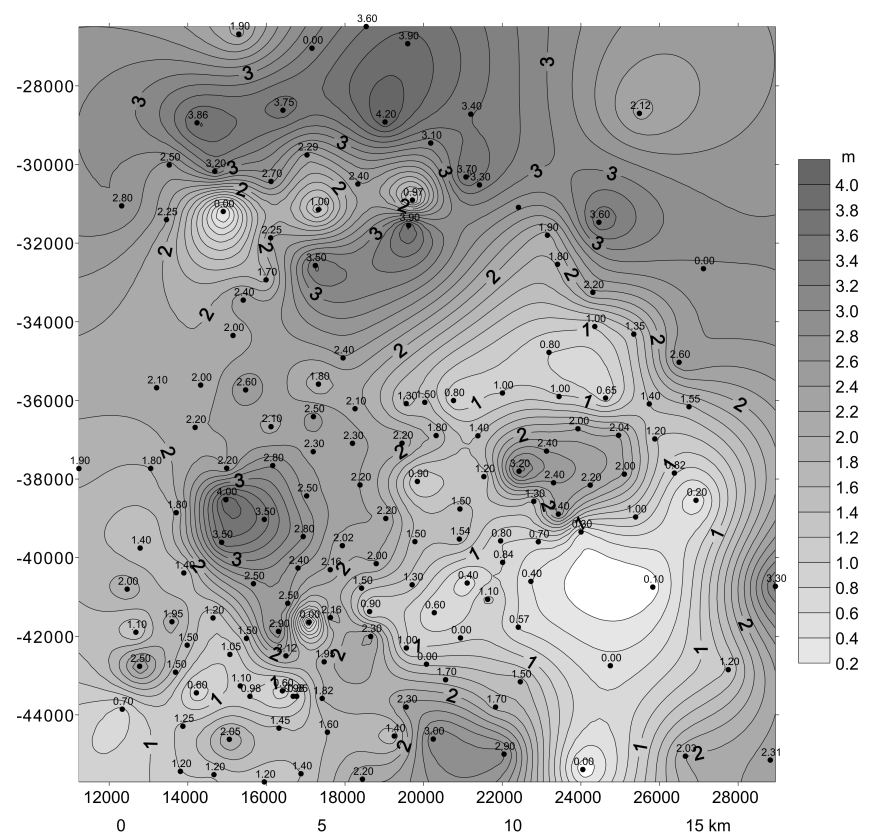

Fig. 38. Thickness map of coal seam 215 over a selected area

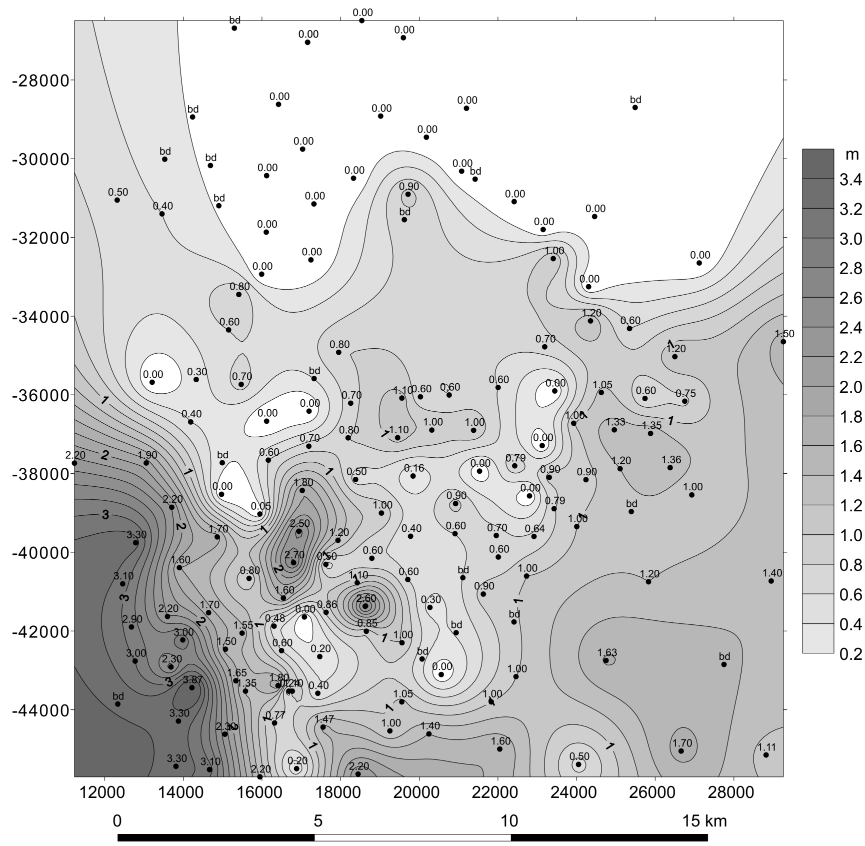

Fig. 39. Thickness map of coal seam 214 over a selected area

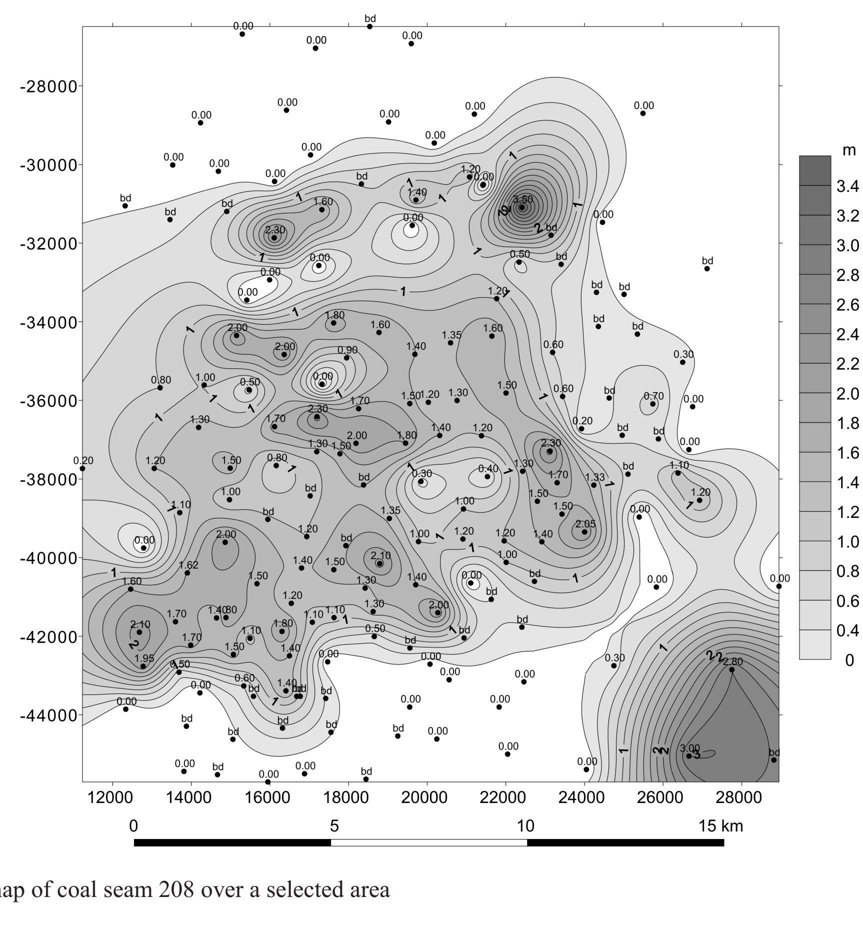

Fig. 40. Thickness map of coal seam 208 over a selected area

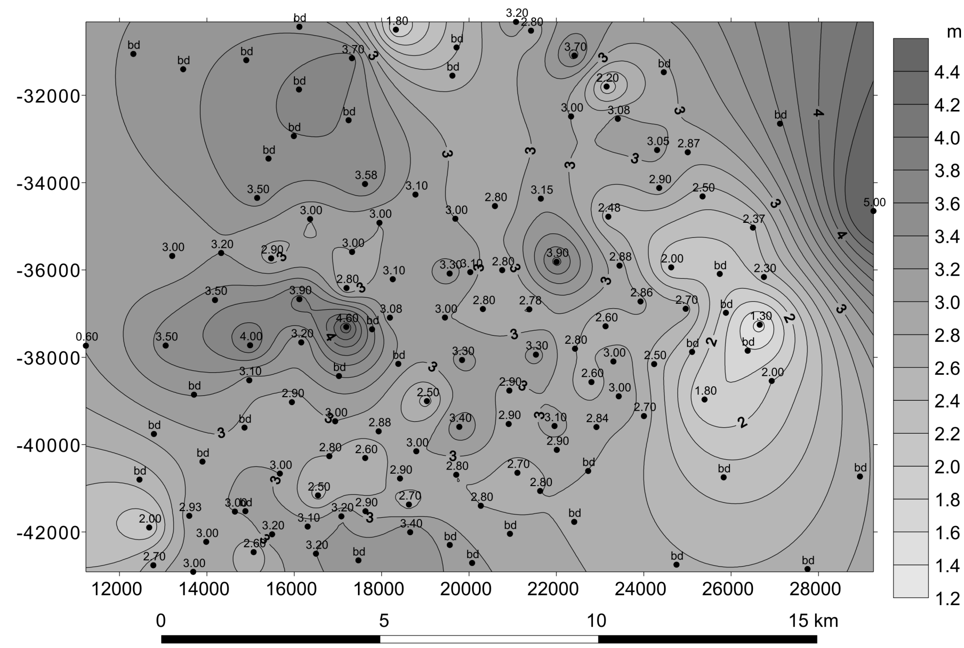

Fig. 41. Thickness map of coal seam 207 over a selected area

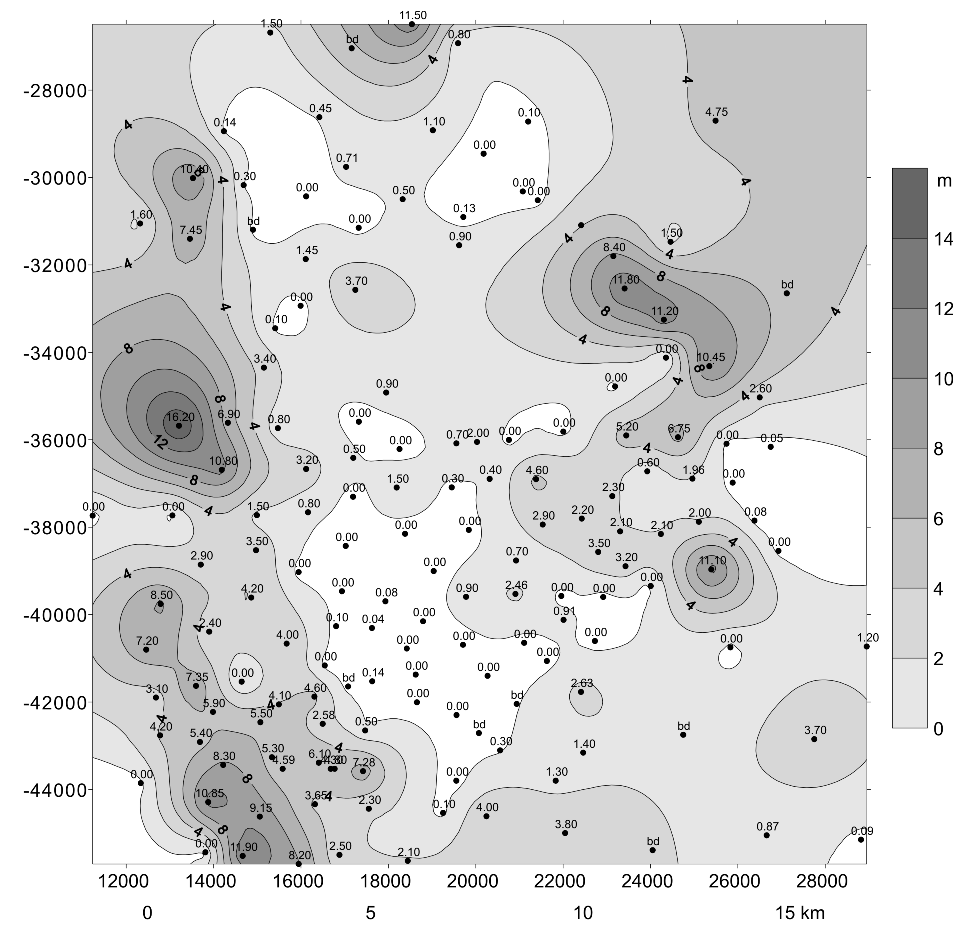

Fig. 42. Map of extent and thickness of clastic partings in seam 215

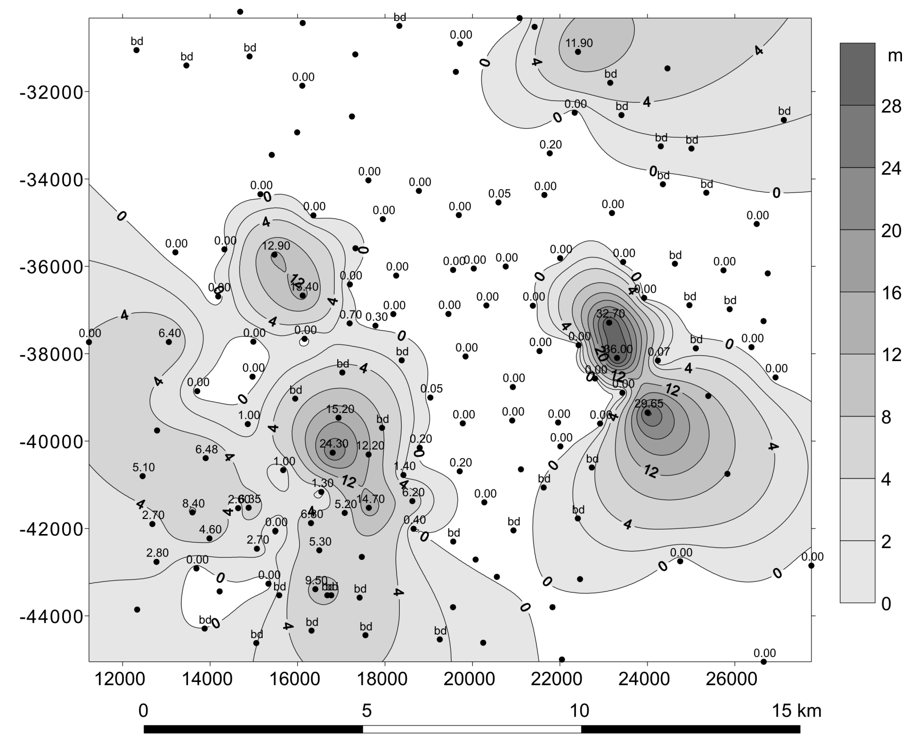

Fig. 43. Map of extent and thickness of clastic partings in seam 208

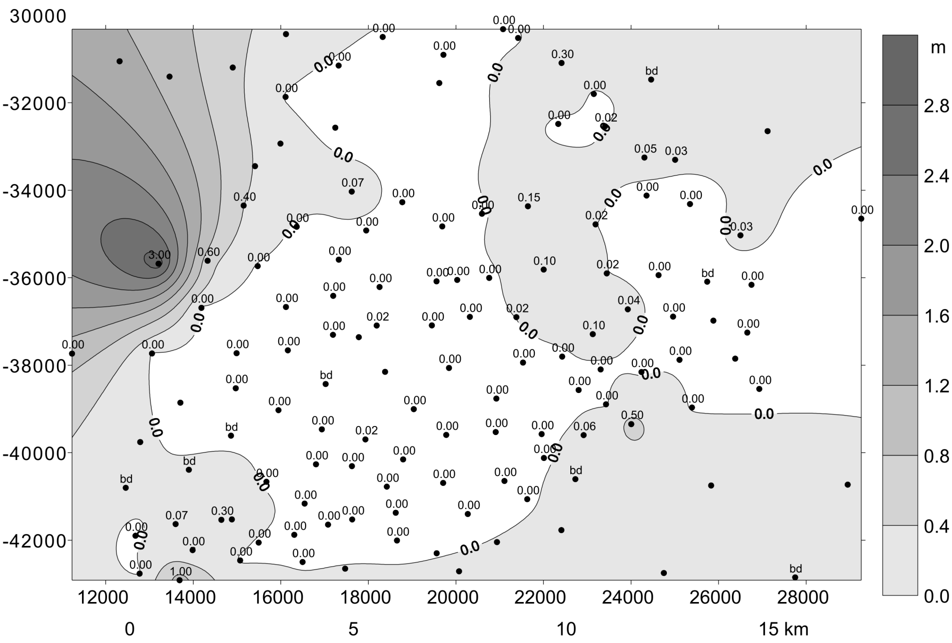

Fig. 44. Map of extent and thickness of clastic partings in seam 207

such cases usually overlain by coarse-grained sediments (see Figs 39 and 46b, 40 and 47b). The whole thickness of peat is removed by erosion when a fluvial channel shifts into the area of a peat bog whose base lies above the base of erosion, in consequence of avulsion or lateral migration. Examples of such complete washout are present in cross-sections 1–5 in seams 209/1, 209/2, 209/3 (see Figs 28–32). The vertical extent of such erosion was not necessarily great. The greatest differences in elevation within the washouts may be related to an especially deep *scorsum*, such as could form locally at the junctions of the major channels (cf. Best, 1988). The width of such zones of erosion found usually at the bases of the thick sandstone packages (see Figs 39 and 46), is variable and attains from a few tens and more metres. In plane view, the zones of greater washouts are usually elongated, have a more or less sinuous course, and in some cases they coalesce (see Figs 37 and 40).

The zones of coal-seam thinning discernible in the maps (Figs 38–41) may be the result of the conditions less favourable for the growth of a thick peat bog, for instance because of frequent flooding or because of covering with fine-grained sediments, which depends, in turn, on the distance from the extent of influence of the channel tracts. The influence of the channel tracts adjacent to the peat bogs is often marked in the greater number or increased thickness of partings in a coal seam (see Figs 42, 43 and 44). A reduced thickness of phytogenic sediments may be also related to the areas where ground level was so intensely lowered by compactional subsidence that the growth of phytogenic sediments did not compensate the difference between the ground level and water level. Shallow lakes could form in such places and they would prevent the peat growth.

The erosional factor may be active here at a somewhat smaller scale than in the cases of complete reduction of a coal seam. Washouts are marked only at tops of coal seams, usually to the depths of decimetres or slightly more. The widths of such erosional depressions, usually found at soles of sandstone packages, are variable and they attain up to few tens or more metres. In plane view, such washout zones are usually elongated, are more or less sinuous and often coalesce (see Figs 38–40). Similar phenomena on a still smaller scale of a few to few tens of metres are registered in the walls of mine galleries (see Fig. 25); it may be thus supposed that these phenomena are quite widespread. Such partial thickness reduction, of coal seams 209 and 209/2, may be seen in cross-sections 1-1 to 5-5 (Figs 28–32).

The fact of peat erosion seems to be corroborated by the presence of the earlier described sediment called *mierzwa* in sandstone sediments below the eroded peat, or the occurrence of so called "spider web", that is sediment of lithofacies SC, in sandstones above coal.

The presence of relatively small areas, on the order of tens square kilometres, where thickness of coal seams may attain several metres should be obviously related to the conditions especially favourable for the establishment and growth of peat bogs (cf. Figs 38, 41). These areas had the clastic supply cut off for a long time. A high level of groundwater that was fed, among others, by infiltration from the zones of channel tracts, fostered the growth of peat, while the rapid growth of peat compensated, in turn, the rapid aggradation in the channel tracts.

GEOMETRY OF SEDIMENTS ASSOCIATED WITH THE COAL SEAMS

Analysis of drilling cores and the thickness maps of the sediments directly underlying coal seams revealed that the coal seams in the Cracow Sandstone Series are in most cases underlain by fine-grained sediments (mudstones and claystones) (see Figs 45–48). These are usually seat earth layers with preserved traces of roots. Much less frequently the underlying fine-grained sediments are massive or laminated and devoid of root traces. The thickness of these sediments varies from above ten centimetres to a few metres, only in few cases it exceeds 10 m.

Much less commonly the coal seams in the Cracow Sandstone Series are underlain by sandstones. In the thickness maps of sediments underlying coal seams they are arranged in narrow elongated zones, a few kilometres wide, which undoubtedly represent ancient channel tracts (Figs 45, 46). They could be abandoned rapidly, for example as a result of avulsion, and for this reason they were the only sediments directly preceding accumulation of phytogenic matter in these places. These could also be sediments of channel tracts, laid down when phytogenic sediments already were being accumulated in the adjacent areas. The small width of the tracts accompanied by the rather large thickness of sediments, on the order of several tens of metres (see Fig. 45a), points to their stabilization and to aggradation of channel sediments compensated by rapid accretion of the phytogenic sediments. Deterioration of the elongated forms, apparent on the maps (see Fig. 46a), leads to conclusion that some smaller tracts were ceasing to be active, so that the whole network was being reduced (see Figs 45a, 48a). These might also be forms related to crevasse splays, periodically encroaching onto the peat bogs; they could be dominated by sandy sediments in proximal zone, close to the channel.

Some coal seams, such as 207, are underlain almost exclusively by fine-grained sediments over large areas, covering a major part of their extent (Fig. 48a). Such seams are in those places thicker (Fig. 41), have a smaller number of partings (Fig. 44) and lack thick and extensive benches.

Numerous sandy bodies are present below seams 215, 214 and 208 over a large area (Figs 45–47). The greater areas they occupy, the more likely is the presence of large-scale splits in these seams. Seams 215 and 208 may serve as examples (see Figs 42 and 43). Those seams that are more widely underlain by sandy sediments (usually representing channel deposits) have more partings and the partings are thicker, and are at the same time thinner themselves (see seam 208, Figs 40 and 43). This seems to confirm the fact of synchronous deposition of the channel sediments and phytogenic material.

Sediments overlying coal seams in the Cracow Sandstone Series include both, fine-grained and coarse-grained lithologies. Above coal seams, the coarse-grained sediments (sandstones) often predominate over fine-grained sediments (see Figs 46 and 48). Coal seams in the Cracow Sandstone Series are often overlain by wide (more than 5 km) sandstone bodies that seem to be deposits of expanding channel tracts (see Figs 46 and 48). They often form extensive sheets, probably resulting from channel migration within the tracts as well as from lateral migration of the whole channel tracts. The sandy sediments over the coal seams attain several tens of metres in thickness, in some cases their thickness even exceeds 100 m (Fig. 45b). In

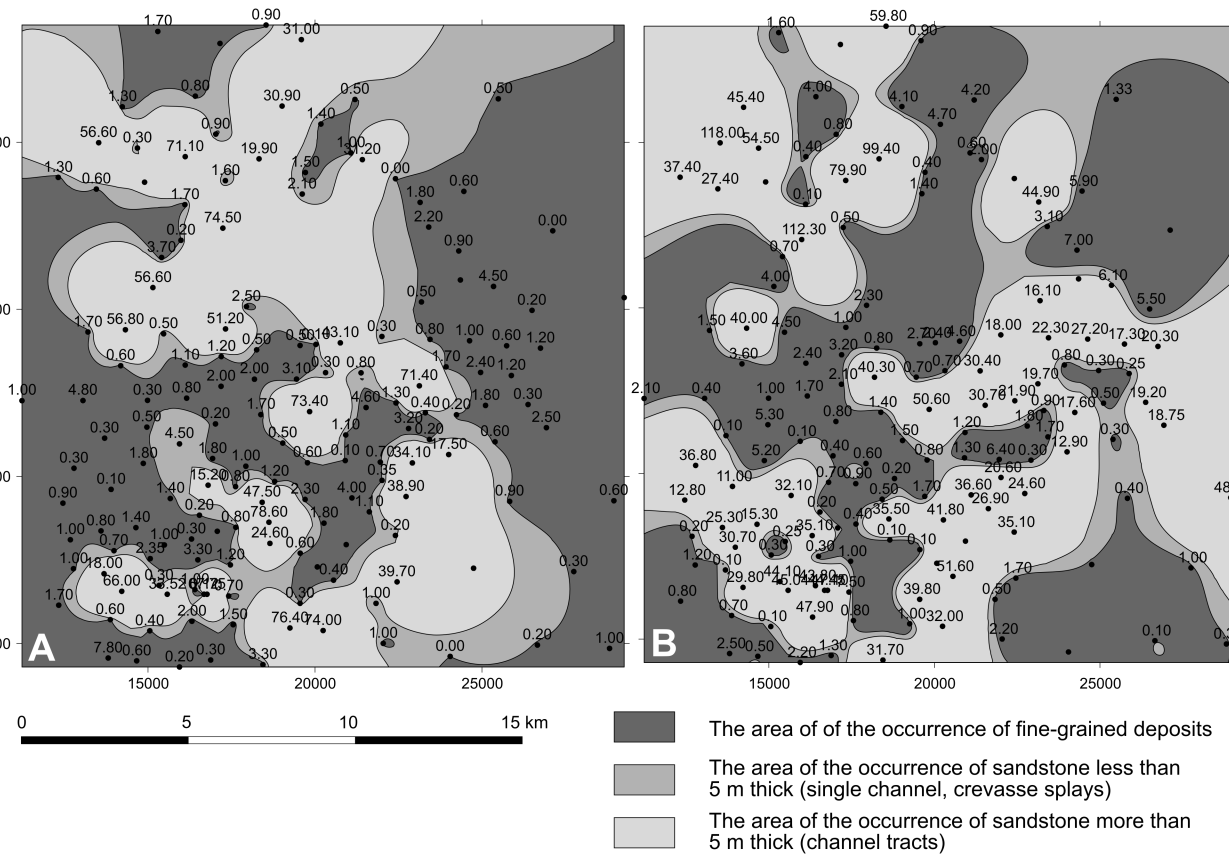

Fig. 45. Thickness maps of coarse-grained and fine-grained sediments over (B) and below (A) seam 215

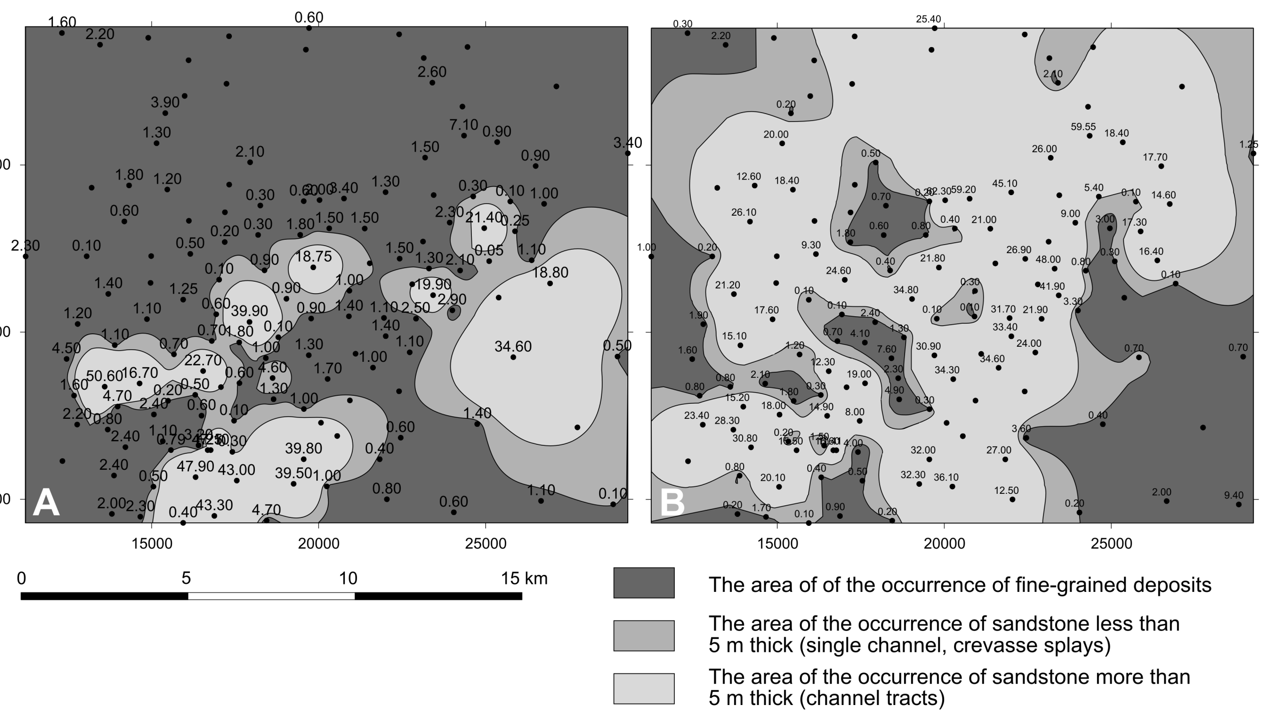

Fig. 46. Thickness maps of coarse-grained and fine-grained sediments over (B) and below (A) seam 214

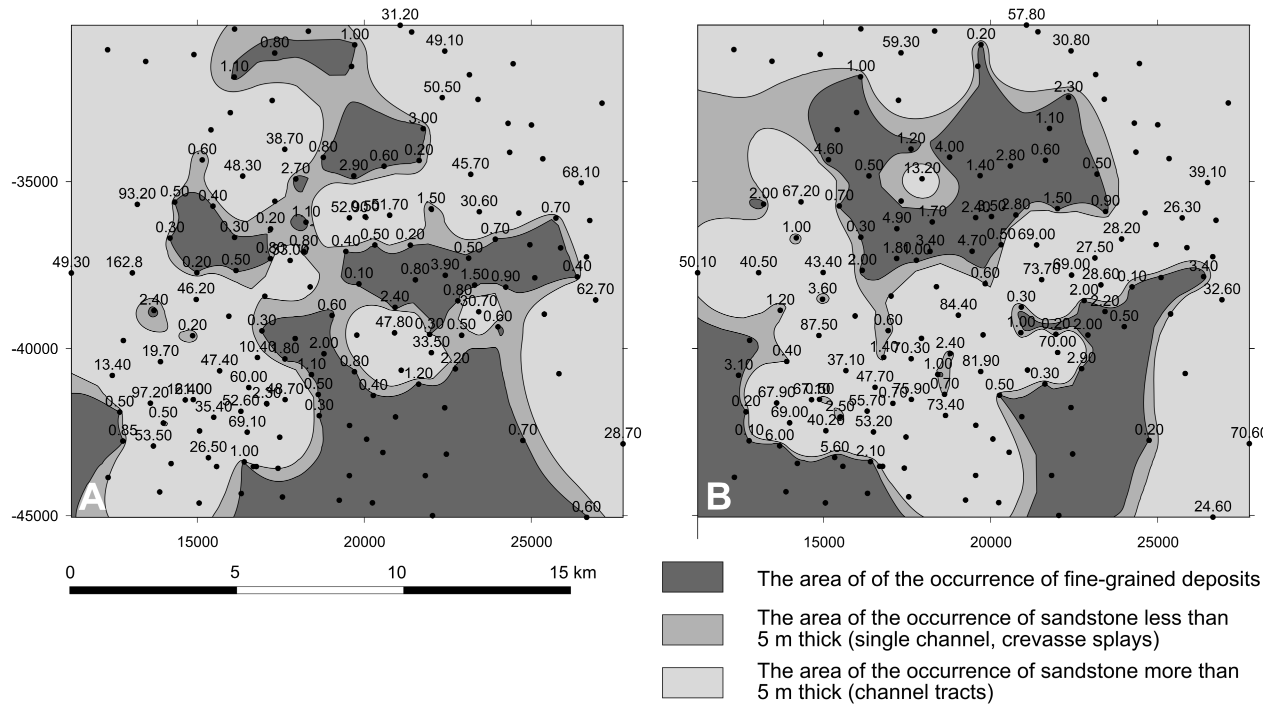

Fig. 47. Thickness maps of coarse-grained and fine-grained sediments over (B) and below (A) seam 207

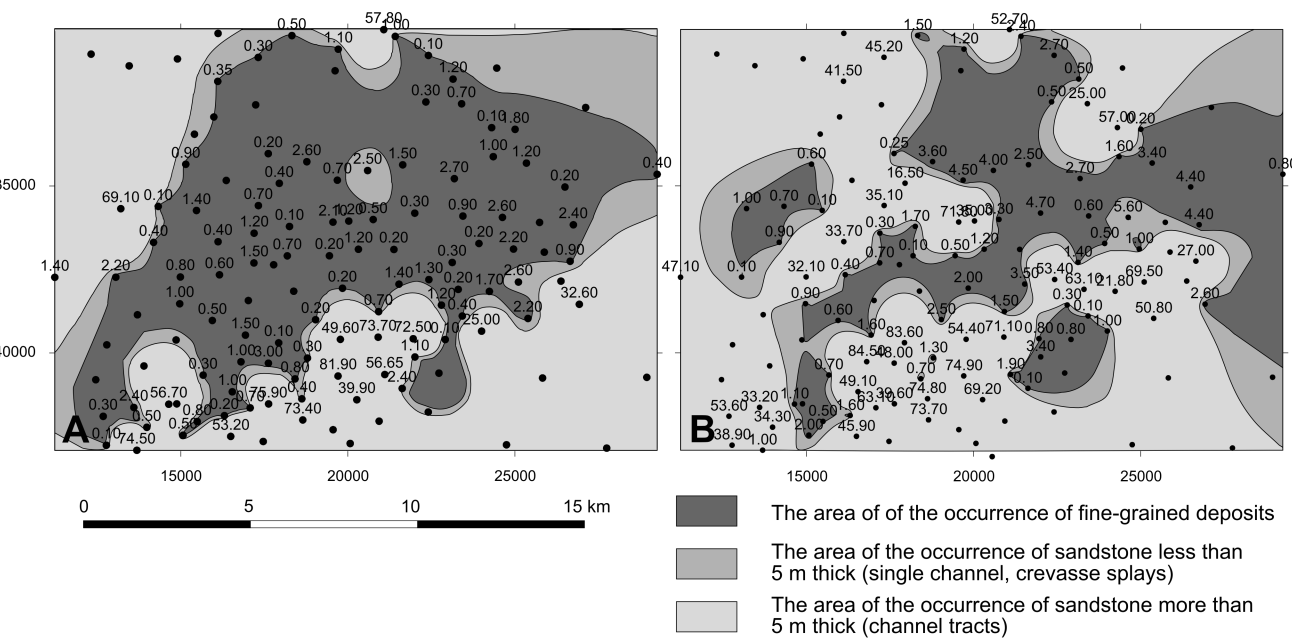

Fig. 48. Thickness maps of coarse-grained and fine-grained sediments over (B) and below (A) seam 208

many cases the soles of these bodies are erosive, and the constituent sediments are of coarse-sand grade with frequent admixture of gravel, with horizontal or large-scale cross-lamination (see Figs 19a, 20b). These bodies have complex internal structures, marked by internal erosional surfaces and oscillatory changes in grain-size (see Fig. 17). Deposition of these sediments was often related with erosion of a peat bog, marked by reduced thickness of the coal seams beneath the sandstone body.

The fine-grained sediments beneath the coal seams are typical extrachannel floodplain sediments. Their thickness usually does not exceed a couple of metres. The less common thicker packages, up to several metres, are probably sediments of intermittent stagnant water bodies of lacustrine type. The attitude of these bodies depends on the pattern of distribution of the channel deposits (see Figs 45b–48b).

Interpretation

The changes in thickness of individual lithosomes discernible in the cross-sections and maps, and the frequent wedging out of these lithosomes, are common and characteristic in coal-bearing fluvial sediments of various age (see Horne *et al.*, 1978, fig. 9; Flores, 1981, figs 18–20, 22; Cavaroc & Flores, 1984, fig. 9; Flores & Hanley, 1984, fig. 2; Dunlop & Bustin, 1987, figs 4–8; Robinson & McCabe, 1997, fig. 6). The generally "wavy" geometry of the lithosomes is explained in the first place by differential compaction of the constituent sediments, that is sand, mud or clay, and peat.

It may be assumed that the depositional surface on which the sediments of the Cracow Sandstone Series were laid down, was generally flat and devoid of significant differences in elevation; this concerns especially the extra-channel areas and the peat accumulations growing on them. Decompaction of sediments and restoration of its successive stages would be extremely difficult. The difficulties stem from the fact that peat undergoes much greater compaction than clastic sediments and, first of all, compaction proceeds in many stages at changing rate (see Thiadens & Haites, 1944; Elliott, 1985; Courel, 1987; Fallini, 1965; Ryer & Langer, 1980). Additional difficulty is related to the fact that the degree of compaction may differ depending on the kind of material making up the peat, and it changes laterally even over short distances (Warwick & Stanton, 1988).

The enclosed cross-sections and thickness maps demonstrate that the sandstone lithosomes (packages) have a form of extensive sheet bodies (*sensu* Friend *et al.*, 1979) with high values of the width/thickness ratio. Bodies of such shape in fluvial deposits are typical of channel deposits of braided rivers, laid down within the channel tracts on an alluvial plain. The presence of such bodies in the Cracow Sandstone Series confirms the opinion expressed earlier that the sandstone packages in this series represent channel deposits of channel tracts of braided rivers (Gradziński *et al.*, 1995, p. 163–164). Geometry of the sandstone lithosomes allows also to exclude the possibility that sediments of this series accumulated on an alluvial plain shaped by anastomosing (cf. Kirschbaum & McCabe, 1992; Nadon, 1994; Makaske, 2001) or meandering (cf. Horne *et al.*, 1978; Gersib & McCabe, 1981; Dunlop & Bustin, 1987) rivers, as seems to be indicated by the lack of numerous elongated and narrow sandy bodies. The narrow sandy bodies observed beneath coals seam could herald transformation of a network of braided channels into stable, narrowing with time, channel tracts. They do not display, however, the long-term stabilization, characteristic of anastomosing rivers and are wider.

The splitting of coal seams, observed in vertical cross-section (Figs 26, 28), seems to unequivocally demonstrate coexistence of the areas of clastic deposition with the areas occupied by peat bogs.

ENVIRONMENT OF ACCUMULATION OF THE CRACOW SANDSTONE SERIES

The Cracow Sandstone Series is generally interpreted as deposits of a braided fluvial system, consisting of coexisting channels tracts and floodplains (Fig. 49). The latter were the site of deposition of both, fine-grained clastics and peat (see Gradziński *et al.*, 1995).

The sandstone association is interpreted as deposits of braided rivers, laid down in channel belts. The braided nature of the rivers is suggested by the predomination of sandstone in the whole series, the relatively low proportion of fine-grained sediments and the nearly complete lack of fine-grained intercalations within the thick sandstone bodies. The braided type of rivers is also suggested by the assemblage of sedimentary features, corresponding well to the assemblage known from channel deposits of modern sandy braided rivers (cf. Coleman, 1969; Cant, 1978; Bristow, 1987; Skelley *et al.*, 2003; Smith *et al.*, 2006; McLaurin & Steel, 2007; Nichols & Fisher, 2007) as well as from fossil sediments interpreted as laid down in such rivers (cf. Rust & Jones, 1987; Rust *et al.*, 1987; Covan, 1991; Browne & Plint, 1994; Cadle & Cairncross, 1993; Skelly *et al.* 2003). An additional argument is provided by the relative broad dispersion cross-strata dips (see Gradziński *et al.*, 1961), a common attribute of braided-river deposits (cf. Coleman, 1969; Rust & Jones, 1987; Browne & Plint, 1994).

A comparison of the sequences observed in the sandstone packages with the model sequences of sediments of modern braided rivers, compiled by Miall (1978), shows the best analogy to the Platte River sequence, which represents a type of distal sandy braided river. Such a type seems to be also indicated by the low proportion and relatively small size of extrabasinal clasts in the bodies in the Cracow Sandstone Series.

The lack of large surface exposures precludes the determination of the size parameters of the channels that formed the braidplain. It may be supposed, however, that the depth of the main channels could reach at least ten metres or more. This seems to be indicated by thick intervals in the sequences of the sandstone packages, composed entirely from medium-grained sandstone, with prevailing large-scale cross-stratification.

The large dimensions of the individual channel tracts, which consisted of channels of various rank, are indicated by the depths of the main channels and the large lateral extent of many sandstone bodies, assessed at some kilometres. This seems to be confirmed by the thickness maps of the sediments underlying and overlying individual coal seams (Figs 45–48). A modern equivalent of an especially wide channel belt is the lower reach of the Brahmaputra River, described by Coleman (1969) and Bristow (1987). According to the latter author, modern sedimentation in this reach "is predicted to produce a sand body of a sheet-like nature

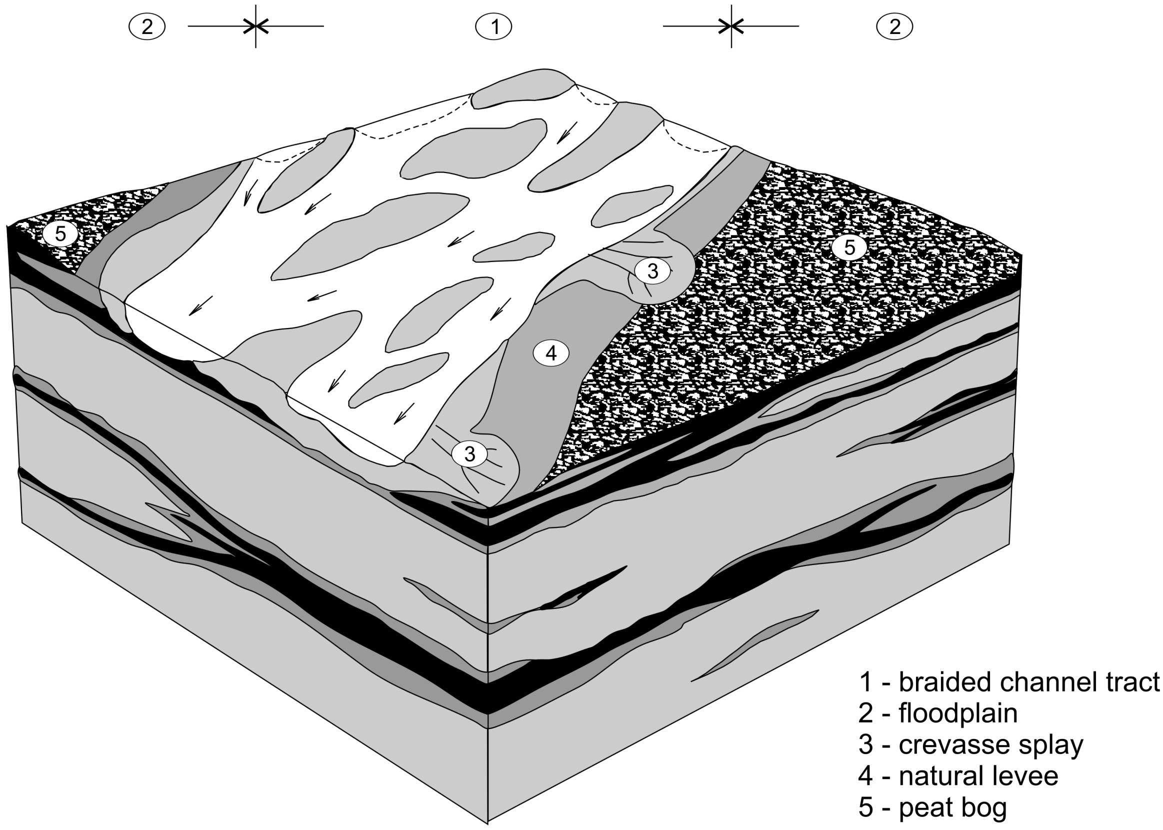

Fig. 49. Model of sedimentary environment of the Cracow Sandstone Series, (after Gradziński, Doktor & Słomka, 1995; modified)

approximately 40 m thick and 20 km wide" (Bristow, 1987, p. 73).

The great thicknesses of many sandstone packages and the features of their sequences indicate that the packages formed by long permanence in a stable position of the same, only slightly migrating, channel tract. One cannot exclude, however, that they formed by stacking of several generations of separate channel tracts, caused by their repetitive avulsion.

Avulsion of channel zones, including braided river channel tracts, is accepted as one of the major processes accompanying the filling of subsiding basins by fluvial systems (Richards *et al.*, 1993, see also Alllen, 1978; Bridge & Leeder, 1979). It is thus quite probable that the channel tracts in the Cracow Sandstone Series significantly shifted their positions, usually encroaching onto the area of the floodplain.

Such avulsion usually resulted in rapid cessation of coarse clastic transport in the abandoned channel belt. In the Cracow Sandstone Series the evidence of such course of events is provided mainly by the rapid changes in sediment grade, commonly observed near the tops of sandstone packages and the sharp contacts with the overlying sediments of the fine-grained facies association.

In consequence of avulsion, the abandoned channel (or a tract of braided channels) gradually became inactive. Transport of sand in the abandoned channel belt gradually ceased, a fining-upwards sequence of sediments accumulated within it, with a generally gradational transition to the overlying fine-grained sediments. The sequences of such type are present in the sections of the Cracow Sandstone Series. Coexistence of the old and new channel may last for a long time, as for instance in the delta of the Rhine and Meuse for ca. 500–1000 years (see Tornquist, 1993; Stouthamer, 2001). The cross-sections through the sediments of the Cracow Sandstone Series present zones of heterolithic sediments (see Figs 32–35) that may be the record of a slow decay of and abandoned channel.

As a consequence of avulsion, a new channel rapidly encroaches onto the extrachannel area where deposition of fine-grained sediments predominated, usually for a long time. In the case of the Cracow Sandstone Series these were mostly areas of deposition of phytogenic sediments.

Processes related to avulsion, poorly studied until recently, are now a subject of detailed studies, as is shown by the increasing number of publications by authors that study this question in the recent years (Jones & Schumm, 1999; Davies-Vollum & Kraus, 2001; Morozova & Smith, 2003; Stouthamer & Berendsen, 2007). Many experiments (computer simulations) have been conducted (e.g., Bridge & Leeder, 1979; Mackey & Bridge, 1995; Makaske, 2001), which demonstrate that there is a positive correlation between the rate of aggradation and frequency of avulsion (the faster the aggradation the more frequent is avulsion). This is confirmed by experiments in an artificial basin (Bryant *et al.*, 1995; Makaske, 2001). One may suppose that exactly such conditions, favouring the occurrence of avulsion, prevailed during the deposition of the Cracow Sandstone Series. The high rate of sediment aggradation favoured frequent avulsion of whole channel tracts, recorded in the sediments of the Cracow Sandstone Series by the common sequences with rapid changes in grain-size at the tops of sandstone packages and sharp contacts with the overlying fine-grained sediments.

One of the factors favouring avulsion in a preferred orientation, described as topographically triggered avulsion (cf. Alexander & Leeder, 1987) could be tilt caused by uneven tectonic subsidence within the Upper Silesia Coal Basin during the deposition of the Cracow Sandstone Series (e.g., synsedimentary faults).

Avulsion could be initiated during especially large floods, when crevasses were cut in natural levees and then rapidly transformed into new channels, as well by obstruction in flow caused by plant jams, shallowing of channels by their overgrowing with plants etc. In general, the time and place are hard to predict, and Bridge and Leeder (1979) suggest that avulsion should be considered as a stochastic process.

It seems that one of the main mechanisms that have shaped the sedimentary architecture of the Cracow Sandstone Series was relatively rare avulsion of the whole channel tracts of a braided river. This is suggested by the specific development of the sediments of this series, with thick packages of channel sediments laid down by braided rivers, accompanied by relatively thick (several metres) coal seams.

Erosion in river channels that invaded the floodplain probably reached small depth. This is suggested by the relatively small vertical extent of the washouts observed in mine works. The deepest vertical extent within washouts may be related to confluences of major channels (see Best, 1988).

The mudstone association is interpreted as floodplain sediments. Mudstones predominated among the fine-grained sediments laid down there. Most mudstones were laid down from suspension during temporary floods. These were in many cases associated with the action of weak currents, giving rise to sediments with wavy lamination. Only some of the mudstones, especially those with faint horizontal lamination, and the flat-lying, compressed fragments of plants were probably laid down in shallow ponds on the floodplain. The ponds could form by sinking of the ground surface below the water table, as a result of subsidence, either caused by compaction or by tectonic movements, not fully compensated by aggradation of sediments.

The relatively rare intercalations composed of fine-grained sandstones or heterolith, present in the fine-grained facies association, are attributed to crevasse splays that formed in the zone adjacent to river channel belts and probably represented the types of crevasse splays described by Coleman (1969) from the Brahmaputra River.

The coal seams formed from the sediments of peat bogs that developed in favourable condition on the floodplain. The presence of root-worked layers beneath most coal seams indicates autochthonous nature of the seams. The studies by Gmur (Gmur *et al.*, 1999) have shown that the coal seams in the Cracow Sandstone Series formed in peat bogs of telmatic zone, and the predominant type were wet forest swamps. The great thickness attained locally by the seams, usually devoid of partings, seems to indicate that such seams were related to slightly raised peat swamps (cf. Staub, 1991; Staub *et al.*, 1991). Close to the channel belts, the sediments of such peat bogs were inundated by flood waters that laid down clastic material, which is marked in the rock record by the presence of the partings that result in splitting of the coal seams.

The most extensive peat bogs probably covered areas of at least hundreds square kilometres. This is proven by the extent of those few coal seams with intercalations of tonstein, which may be accepted as reliable stratigraphic markers. Many peat bogs were probably smaller in area as seems to be indicated by sedimentary terminations of the coal seam, frequently observed in mines, and the variable numbers of coal seams in the borehole sections.

Differentiated compaction of sediments is reflected in the present-day geometry of sediments and it was an important factor controlling syndepositional relief during the successive stages of sedimentation of the Cracow Sandstone Series.

The differences in the scale and rate of compaction were especially distinct between peat and clastic sediments. The scale of peat compaction was many times greater than that of clastic sediments and the reduction in thickness due to compaction occurred much faster, especially when peat became covered with a thick layer of clastic sediment. The original thickness of the individual packages of the floodplain sediments, composed of peat and mud layers, was much greater than their present-day thickness. On the other hand, the original thickness of the sandy channel deposits, practically not subject to compaction, remained almost unchanged.

With the generally prevailing aggradation that compensated tectonic subsidence of the basin, the faster vertical accretion of sediments in the channel belts was balanced in the floodplain areas mostly by peat growth. As a result, the area of deposition of the Cracow Sandstone Series had relief with small differences in elevation and the floodplain areas were only slightly raised above the adjacent channel belt. The thickness of packages of the fine-grained association with the coal seams within them, is a proof of stability of the floodplain areas.

Encroachment of a channel belt on the floodplain area had to initiate compaction of the underlying peat layers, rapid at the beginning. In consequence, the depositional surface was becoming locally depressed, thus favouring rapid vertical accretion of the channel sediments. Such processes provided favourable conditions for great-scale splitting of the peat/coal layers (see Fig. 26).

The general contrast between the Cracow Sandstone Series and the underlying Mudstone Series is caused, before all, by a dramatic and sudden increase in clastic supply to the USCB. The cause of this should be looked for mainly in the rearrangement of the extrabasinal system of supply and initiation of new source areas (see Paszkowski *et al.*, 1995; Świerczewska, 1995). This resulted in the transformation of the earlier meandering fluvial system, characteristic of the Mudstone Series (Doktor & Gradziński, 1985), into the braided fluvial system of the Cracow Sandstone Series.

CONCLUSIONS

The Cracow Sandstone Series is interpreted as deposits of an alluvial plain related to a system of sandy, distal braided rivers. The thick sandstone bodies predominant in the whole series are deposits of wide and relatively stable channel tracts and in most cases display characteristics of stacked, multi-storey accumulations of channel sediments.

The subordinate but common rock bodies composed mainly fine-grained clastic sediments and coal seams are interpreted as accumulated in extrachannel areas.

The phenomena of large-scale splitting of the coal seams and lateral transitions within the parting in coal seams, from fine-grained to coarse-grained sediments, demonstrate that belts of fluvial channels coexisted with the peat bogs situated in the extrachannel areas.

The vertical alternation of the sandstone bodies and the bodies of extrachannel deposits is the result of natural processes acting on the alluvial plain and resulting in migration of sedimentary environments, first of all, the whole channel tracts.

Coal seams in the Cracow Sandstone Series do not form continuous sheets of uniform thickness, and their geometry and lateral distribution depended on the course and development of the network of channel tracts within the fluvial system.

The alluvial plain was relatively flat. Accretion of sediments within the fluvial tracts was compensated by accretion of extrachannel sediments, mainly by the rise of the depositional surfaces of peat bogs.

The general decrease in thickness of the studied series from the west to east is a result of the rate of tectonic subsidence in this direction. The architectural details of the individual sediment bodies were mainly caused by differences in compaction of sediments of different lithology, and also by various processes that controlled sedimentation.

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Streszczenie

WARUNKI AKUMULACJI I ARCHITEKTURA KRAKOWSKIEJ SERII PIASKOWCOWEJ GÓRNOŚLĄSKIEGO ZAGŁĘBIA WĘGLOWEGO (KARBON GÓRNY)

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Krakowska seria piaskowcowa stanowi najwyższą część sukcesji węglonośnej Górnośląskiego Zagłębia Węglowego wypełniającej waryscyjskie, fleksuralne zapadlisko przedgórskie. Seria osiąga 1640 m miąższości stratygraficznej i zbudowana jest wyłącznie z osadów lądowych. W osadach tej serii wyróżniono 15 litofacji oraz dwie, wyraźnie różniące się asocjacje facjalne, określone jako piaskowcowa i mułowcowa. Osady pierwszej z tych asocjacji, złożonej w przewadze z piaskowców średnioziarnistych, dominują w całej serii i z reguły tworzą grube ciała (litosomy), dochodzące nawet do 140 m miąższości. Litosomy te rozdzielone są cieńszymi pakietami osadów asocjacji mułowcowej, w których obok osadów klastycznych, z reguły drobnozianistych, pospolicie występują pokłady węgla, nieraz znacznej miąższości.

Cała krakowska seria piaskowcowa interpretowana jest jako osady rozległej równiny aluwialnej związanej z systemem piaszczystych, dystalnych rzek roztokowych. W obrębie traktów koryt rzek roztokowych powstawały tam ciała piaszczyste, które zazwyczaj wykazują cechy wielopiętrowych nagromadzeń osadów korytowych. Obszary pozakorytowe były miejscem depozycji materiału drobnoziarnistego i miejscem rozwoju węglotwórczych torfowisk; w pobliżu traktów koryt rozwijały się tam też glify krewasowe.

Dominującym typem torfowisk w omawianej serii były wilgotne torfowiska leśne. Pokłady węgla nie mają charakteru ciągłych pokryw o stałej miąższości, a ich geometria i lateralne rozprzestrzenienie zależało od przebiegu i rozwoju sieci traktów systemu rzecznego. Obserwowane zjawiska wielkoskalowego rozszczepiania pokładów węgla i widoczne w tych miejscach lateralne przejścia do osadów korytowych dowodzą współistnienia traktów rzecznych i węglotwórczych torfowisk rozwiniętych na obszarach pozakorytowych.

Litosomy piaskowcowe mają geometrię pokryw, ale o ograniczonym zasięgu lateralnym. Za stosunkowo dużą stabilnością macierzystych traktów koryt przemawia znaczna miąższość tych

litosomów, podobnie jak pospolita, znaczna miąższość pokładów węgla.

Naprzemianległe występowanie w profilach pionowych ciał piaskowcowych i ciał reprezentujących osady asocjacji mułowcowej jest wynikiem naturalnych procesów zachodzących na równinie aluwialnej, które powodowały przemieszczanie się środowisk depozycyjnych, głównie procesów awulsji całych traktów koryt rzecznych.

Architektura sedymentacyjna krakowskiej serii piaskowcowej odzwierciedla przede wszystkim efekty wspomnianych procesów, a w dużym stopniu związana jest też ze zróżnicowaną kompakcją osadów gruboziarnistych, drobnoziarnistych i torfów.