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Facies and statistical analyses of a crevasse-splay complex at the Tomisławice opencast lignite mine in central Poland

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Abstract

The studied crevasse-splay complex, situated within the 1st Mid-Polish lignite seam (MPLS-1), ranks amongst the best-developed and most readily accessible for direct research of all hard coal and lignite occurrences worldwide. The sandy-coaly sediments constituting it required a number of field and laboratory tests. However, the present article focuses solely on sedimentological and statistical analyses of sediments along a selected key section, the most important results of which are presented below. First of all, data obtained in previous sedimentological studies have been confirmed, in that individual segments of this complex represent both subaerial and subaqueous types of crevasse splays. On the one hand, their sediments are characterised by an extremely high content of coalified organic matter, reaching 20–40 wt.% in some samples; on the other, these crevasse splays are composed of fine sands with a median and mean grain size of 0.15 mm. In addition, the remaining statistical parameters (standard deviation, skewness and kurtosis) indicate a very good sorting of these sands, no significant so-called 'tails' and a better sorting close to the sediment mean grain size value, respectively.

Keywords: fluvial environment, crevasse splay, crevasse-splay microdelta, lignite seam, Middle Miocene

1. Introduction

Crevasse splays are known to occur in various sedimentary settings (e.g., fluvial, deltaic) and are always located in close proximity to river channels. They form in overbank areas by breaching natural levees during the initial stages of a flood. Crevasse splays occur in both modern and ancient successions, and are common in siliciclastic and coal-bearing strata (Guion, 1984; Smith et al., 1989; Bristow et al., 1999; Michaelsen et al., 2000; Makaske, 2001; Bridge, 2003; Boggs, 2012; Zieliński, 2014; Burns et al., 2019; and references therein). Crevasse splays usually appear as single forms or as complexes consisting of two or more superimposed splays. They may significantly differ in size (from several square metres to >220 km^2; Rahman et al., 2022), in shape (lobate, dendritic) and in thickness from centimetres to >20 m (Horne et al., 1978; O'Brien & Wells, 1986; Mjøs et al., 1993; Bridge, 2003; Gulliford et al., 2017; Millard et al., 2017; Widera et al., 2023).

The opencast lignite mines managed by the Konin Lignite Mine contained an exceptional number of exposed crevasse-splay sand bodies (Widera, 2016, 2017, 2020; Widera et al., 2017a; Chomiak et al., 2019; Wachocki et al., 2020, 2023). Most likely these represent the most diverse and best-developed crevasse splays known from lignite occurrences globally (Widera et al., 2022, 2023). The interseam siliciclastics from the Tomisławice opencast lignite mine comprise four, and locally five, layers of sand which form a crevasse splay complex. A preliminary sedimentological and statistical analysis of grain size distribution along a selected key section of the opencast mine is described and discussed herein.

The present study should be treated as a supplement to the paper prepared by almost the same team of authors (Widera et al., 2024). However, in the current contribution we focus on issues (organic content, statistical parameters of grain size) that have not been treated in detail previously. Therefore, its main aim is to provide a detailed description of the selected field section, the so-called key section, by specifying the basic facies features and parameters for the organic-siliciclastic sediments present there. The distribution of organic matter contents along this section is added. Finally, the following three issues are briefly discussed: 1) the exceptionally high concentration of organic matter, 2) the dominant massiveness of the sediment, and 3) the uniqueness of sample T29.

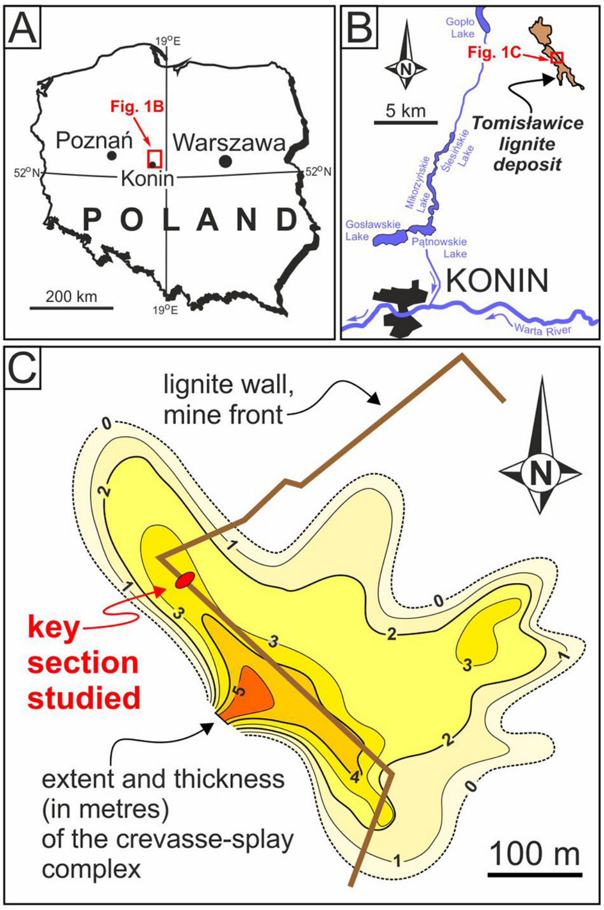

Fig. 1. Locality maps. **A, B** – Study area within Poland and the Tomisławice opencast lignite mine. **C** – The studied key section against lignite faces in August 2022 and extent of the mapped crevasse-splay section (co-ordinates 52°28'11.5"N, 18°30'48.3"E).

2. Geological setting

The Tomisławice lignite deposit, located close the town of Konin in central Poland (Fig. 1A, B), fills a shallow and fault-bounded graben of up to 20–30 m deep, although its tectonic origin is poorly expressed in some parts (Fig. 2). The graben belongs to the Konin Elevation (Widera, 2021, 2022), which is a central fragment of the Mogilno Trough, and this in turn is part of the Szczecin-Miechów Synclinorium (Żelaźniewicz et al., 2011).

In the study area, the Mesozoic (Late Cretaceous) bedrock consists of marls and limy sandstones, while Paleogene deposits are represented only by marine glauconitic sands of early Oligocene age, and the Neogene is much more complete lithostratigraphically (Fig. 2). The last-named succession includes two main lithostratigraphical units, that is, the Koźmin Formation at the bottom and the Poznań Formations on top (Piwocki & Ziembińska-Tworzydło, 1997; Widera, 2022). The Koźmin Formation encompasses sub-lignite siliciclastics such as fluvial sands and coaly sands with lignite intercalations. In contrast, the Poznań Formation is only residually preserved and locally consists of the lower Grey Clays Member and the upper Wielkopolska Member (Chomiak et al., 2019; Wachocki et al., 2023).

The Grey Clays Member comprises the first Mid-Polish lignite seam (MPLS-1) and the so-called 'grey clays' resting locally on top. The MPLS-1 is currently extracted only in the Tomisławice opencast mine. It is of Mid-Miocene age and up to 11.8 m in thickness, with an average of 6.9 m. The Wielkopolska Member ('green and flamy clays') has been recognised in the field, but not penetrated in most boreholes. Exceptions are boreholes BT-4 and T-116, where the Neogene clays are present within the Quaternary sediments (Fig. 2). Currently, it is believed that the 'green and flamy clays' of the Wielkopolska Member accumulated between the late Mid-Miocene and the earliest Early Pliocene as channel-fill muds and sands, and overbank muds (Widera et al., 2017b, 2019; Maciaszek et al., 2020; Zieliński & Widera, 2020; Kędzior et al., 2021).

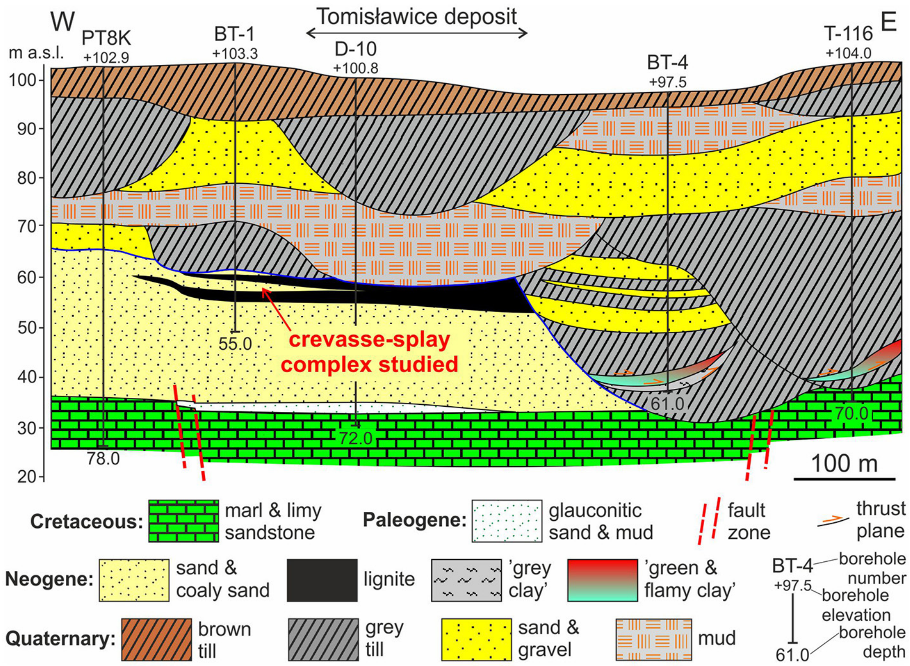

Fig. 2. Latitudinal geological cross-section through the Tomisławice lignite deposit. Note the lignite seam divided into two by the examined crevasse-splay complex in the vicinity of borehole BT-1 (after Wachocki et al., 2023, slightly modified).

The Neogene succession is capped by Quaternary deposits which are very diverse in terms of thickness as a result of erosion and glaciotectonic processes, ranging between 35 and 60 m. The Quaternary, mainly of Pleistocene age, includes such glaciogenic sediments as glacial tills, fluvioglacial sands and gravels, as well as fluvioglacial-lacustrine muds (Fig. 2).

3. Material and methods

The crevasse-splay sand bodies studied at the Tomisławice opencast lignite mine were very well exposed in 2022 and 2023. These siliciclastic sediments, which divided the exploited first Mid-Polish lignite seam (MPLS-1) into two, could be directly observed from a distance during field work. The exposed complex of sand bodies exceeded 450 m in length and attained a thickness of up to 4 m in a SE–NW direction. In a SW–NE direction, it measured >100 m in length and 0–3 m thickness (compare Figs. 1C and 3).

Geological field studies were carried out and included a sedimentological investigation of the key section, the results of which are presented herein. A letter code was used to simplify the description of clastic and clastic-organic facies (Table 1). The sedimentary and deformational structures of the deposits examined and identified in the field were named after various researchers (Miall, 1977; Allen, 1982; Bridge, 2003; Boggs, 2012; Collinson & Mountney, 2019).

A total of 29 samples from siliciclastic levels were collected for further laboratory tests. The latter included grain-size analyses, using the sieving method, and determination of organic contents by burning all samples in a muffle oven at 550°C. In addition, basic graphic statistical parameters were cal-

Table 1. Codification of crevasse-splay facies used in the present paper.

Code	Facies
Sm	sand with a massive structure
SCm	coaly sand with a massive structure
Sh	sand horizontally stratified
SCh	coaly sand horizontally stratified
SCh(d)	coaly sand horizontally stratified and deformed
Sp	sand with a planar cross-stratification
Sp(d)	sand with a planar cross-stratified and deformed structure
SCp	coaly sand with a planar cross-stratification
SCp(d)	coaly sand with a planar cross-stratification and deformed structure
SCr(d)	ripple cross-laminated and deformed coaly sand
Sr	sand with ripple cross-laminattion
St	sand with a trough cross-stratification
SCt	coaly sand with a trough cross-stratification

culated with a SIEWCA grain-size program. Finally, standard nomenclature was applied to the description of grain sizes of deposits investigated (i.e., median, mean grain size) (Wentworth, 2022), while for other parameters (i.e., standard deviation, skewness and kurtosis) Folk and Ward (1957) were followed.

4. Results

4.1. Deposits comprising the crevasse-splay complex

4.1.1. Description

The crevasse-splay complex is finger-shaped, ~0.4–0.6 km in size (length, width) and up to 5 m thick as documented by borehole data. The studied key section is 3.8 m in height (compare Figs. 2–4). The section lies on top of the lower bench of the MPLS-1, which is currently being mined for electricity production by the Konin Lignite Mine at the Tomisławice opencast lignite mine. Overlying the key section are residually preserved Neogene 'clays' (up to 0.8 m) and the upper bench of the MPLS-1 (up to 1.7 m) (compare Figs. 3A, B and 4).

In general, fine-grained sandy-coaly and sandy facies dominate in this key section. However, these are separated by thin (up to 0.6 m) layers of lignite. All analysed samples contain organic matter (dispersed organics and plant roots or rootlets) in amounts ranging from 0.2 to 40.3 wt.%, that is, >5 wt.% in five samples, 5–≥1 wt.% in fifteen samples, and ≤1 wt.% in nine samples (Fig. 4C). However, several sandy-coaly (SCm, SCh, SCh(d), SCp, SCp(d), SCr(d)) and sandy facies (Sm, Sh, Sp, Sp(d)) were distinguished macroscopically in the field (Fig. 4B). In addition to these, other facies (Sr, St, SCt), which will not be characterised in detail in the present paper, have been identified in close proximity to the key section studied (Fig. 5).

4.1.2. Interpretation

Massive coaly sands and sands are prevalent in the key section (Fig. 4B; Table 1). The SCm and Sm facies can be interpreted in two ways. First, they may have resulted from a sudden deposition from a hyperconcentrated flow (Nemec, 2009). Secondly, this apparent massiveness could additionally have been caused by good sorting (see Table 2), as well as by roots of peat-forming plants (Boggs, 2012; Gulliford et al., 2017). Facies SCr(d) probably formed during tractional deposition resulting from migration of small-scale bedforms, for example, ripples (e.g., Widera, 2016; Widera et al., 2024). An attempt to explain the deformation process of this facies is explained below.

Horizontally stratified facies (SCh, Sh) were most likely deposited as a non-channelised sheet flow. At the time, the water flowed over the entire surface of the crevasse splay, thus creating an upper-stage plane bed (Allen, 1982; Bridge, 2003; Boggs, 2012; Zieliński, 2014; Collinson & Mountney, 2019). In general, both these massive and horizontally stratified sediments should be associated with accumulation under subaerial conditions, namely, on the 'dry' surface of a Mid-Miocene mire and not in standing water (Widera et al., 2022).

The planar cross-stratified facies (Sp, SCp) should be interpreted completely differently. In view of the fact that these facies extend laterally over a length of 200–300 m and the lamination within them is inclined unimodally (towards the N–NNE) at an angle of up to 35°, they represent a former microdelta with typical 'prograding splay deposits' (Mjøs et al., 1993; Bristow et al., 1999; Zieliński, 2014; Chomiak et al., 2019). Therefore, they probably accumulated in shallow lakes or ponds that existed in the area of the Mid-Miocene mires of central Poland (Widera, 2016; Widera et al., 2017a, 2023, 2024; Chomiak et al., 2019, 2020; Wachocki et al., 2020; Dziamara et al., 2022).

It is worth paying attention at this point to deformations in the lower part of the microdelta, that is, its bottom set layers – facies SCh(d) and SCr(d) (compare Figs. 4B and 6). These most likely resulted from reversed density gradients or unequal loading. This means that an unstable (heterolithic, liquefied) substrate was syn-depositionally deformed, for example, by the above-mentioned migrating ripples (Anketell et al., 1970; Allen, 1982).

4.2. Statistical parameters of grain size

4.2.1. Description

Among the statistical parameters considered here, equal results were obtained for median and mean grain sizes. In both cases, grain sizes range from 0.12 to 0.20 mm, while the average value for all samples analysed is 0.15 mm (Fig. 4C; Table 2).

Most of the standard deviation values are fairly even (0.28–0.56 phi), with the exception of sample T29 (0.93 phi). Indeed, eight samples have values of <0.35 phi. However, the mean value of all 29 samples is 0.41 phi. The skewness and kurtosis results fall within a wide range, which is influenced by the above-mentioned sample T29. Generally speaking, the calculated mean values of the two parameters are 0.021 and 1.232, respectively (Table 2).

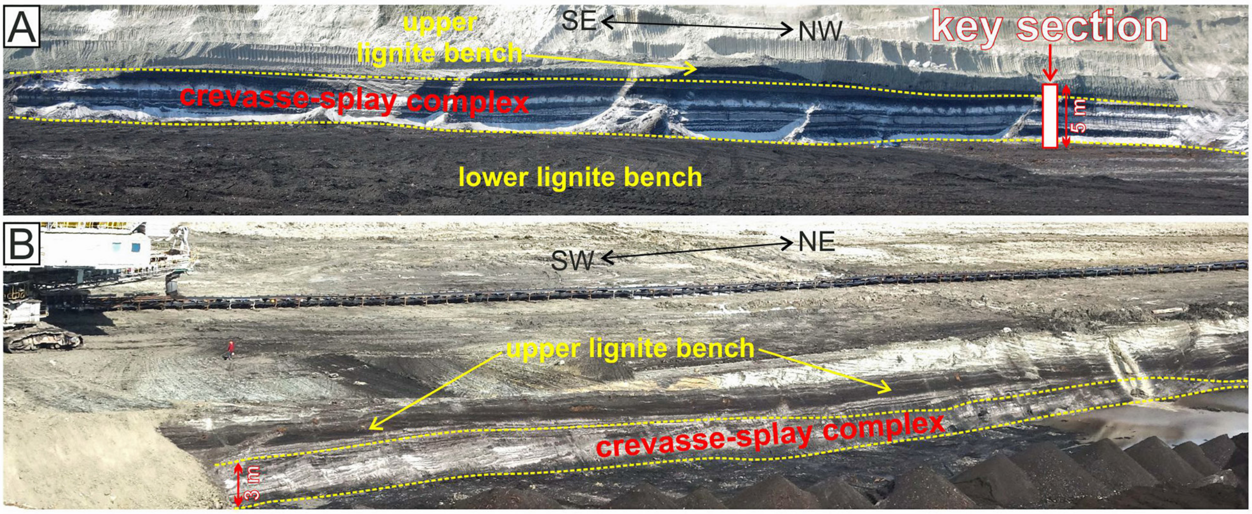

Fig. 3. Broad view of the crevasse-splay complex from the Tomisławice opencast lignite mine with location of the studied key section. **A** – western exploitation face (August 2022). **B** – northern exploitation face (September 2022). For location mine fronts see Figure 1C.

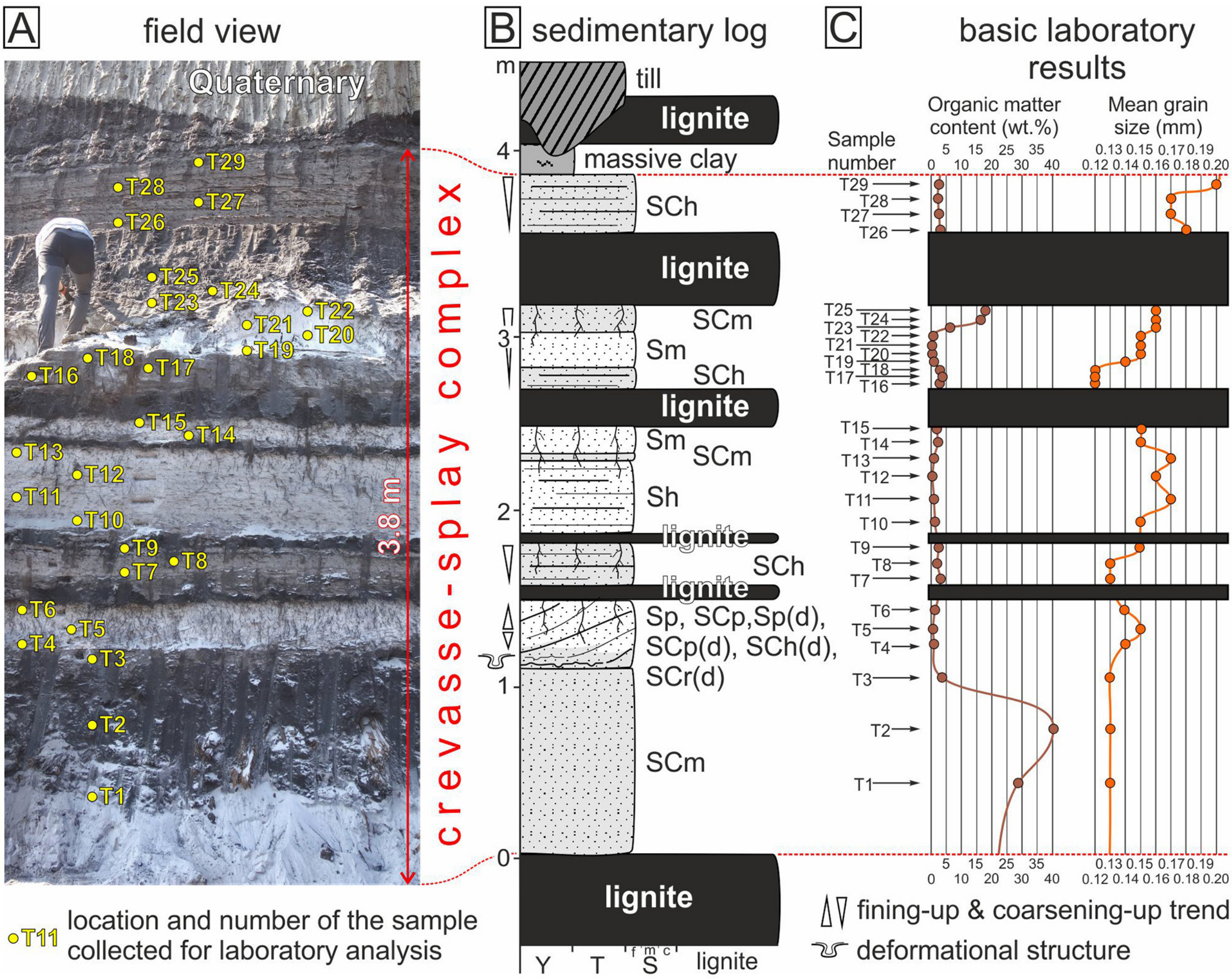

Fig. 4. Sedimentology of the studied key section. For location of the key section see Figures 1C and 3A; for explanations of facies codes see Table 1.

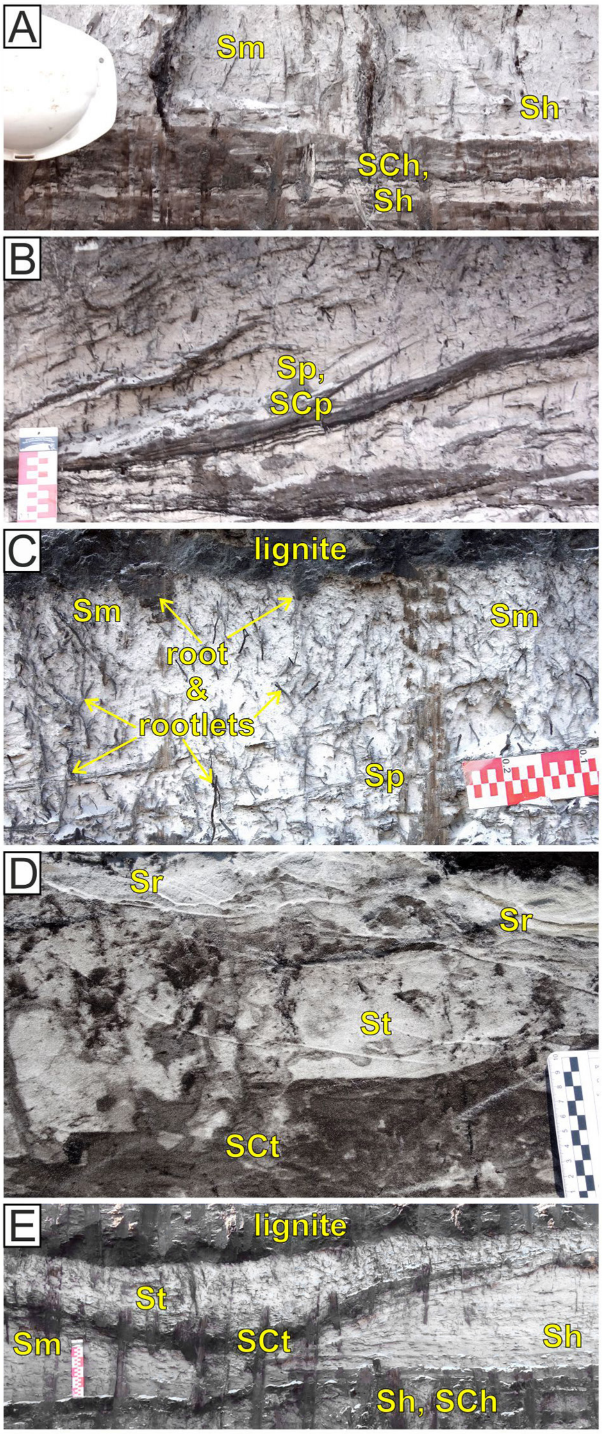

Fig. 5. Examples of some facies in the vicinity of the examined key section. For explanations of facies codes see Table 1.

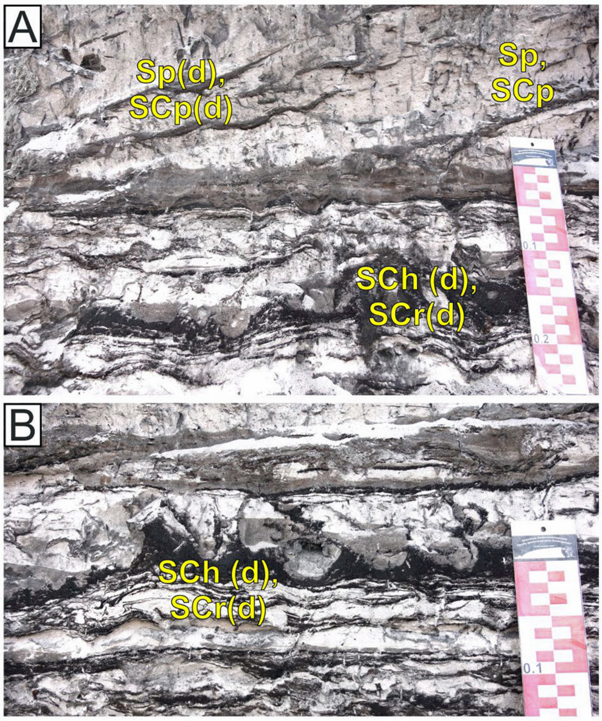

Fig. 6. Examples of deformed sediments in the vicinity of the examined key section. For stratigraphical position of deformations see Figure 4B; for explanations of facies codes see Table 1.

4.2.2. Interpretation

The sediments of the examined crevasse-splay complex represent fine sands (Table 3). The two lower layers of sand, as well as the fourth one, are characterised by a weak coarsening-up trend, that is, coarsening towards the top of the key section (Fig. 4C). This can be explained by the progradation of the crevasse splay due to a higher-energy water flow (Fielding, 1984), or by the erosion of the natural levee and enrichment with coarser grains (Gębica & Sokołowski, 2001). In general, the sands analysed are well sorted, and eight samples are even very well sorted, as suggested by standard deviations of <0.35 phi. Sample T29, which is moderately sorted, is also an exception in this case (standard deviation of 0.93 phi) (Tables 2, 3).

The average graphic skewness shows a symmetrical grain-size distribution. This means that the sands examined do not have so-called ‘tails’ of fine (coarse skewed, positive) or coarse (fine skewed,

Table 2. Average values of basic grain-size statistical parameters obtained for 29 samples from the key section of the crevasse-splay complex at the Tomisławice opencast lignite mine in central Poland.

	Median grain size (mm)	Mean grain size (mm)	Standard deviation (phi)	Skewness	Kurtosis
Range	0.12–0.20	0.12–0.20	0.28–0.93	−0.443–0.222	1.0036–4.605
Mean	0.15	0.15	0.41	0.021	1.232

Table 3. Statistical grain-size ranges and their descriptive terminology (Wentworth, 1922; Folk & Ward, 1957; Blott & Pye, 2001).

Mean grain size (mm)	Sediment name[1]	Standard deviation (phi)	Sorting name[2]	Skewness value	Skewness name[2]	Kurtosis value	Kurtosis name[2]
0.1–2	very coarse sand	< 0.35	very well sorted	+0.3–+1	very fine skewed	<0.67	very platykurtic
0.5–1	coarse sand	0.35–0.5	well sorted	+0.1–+0.3	fine skewed	0.67–0.9	platykurtic
0.25–0.5	medium sand	0.5–0.7	moderately well sorted	+0.1–−0.1	symmetrical	0.9–1.11	mesokurtic
0.125–0.25	fine sand	0.7–1	moderately sorted	−0.1–−0.3	coarse skewed	1.11–1.5	leptokurtic (peaked)
0.063–0.125	very fine sand	1–2	poorly sorted	−0.3–−1	very coarse skewed	1.5–3	very leptokurtic
		2–4	poorly sorted			>3	extremely leptokurtic
		>4	extremely poorly sorted				

[1] – after Wentworth (1922), [2] – after Folk & Ward (1957); ranges of mean values of statistical parameters obtained in the present study and their names are shaded.

negative) grains. However, 17 samples are characterised by positive phi values (>0), while 12 others have negative ones (<0). The average graphic kurtosis is peaked, that is, leptokurtic (Tables 2, 3). In other words, such a shape of the kurtosis curve reflects a better sorting close to the sediment mode (central portion of grain-size distribution) than in the 'tails' (Folk & Ward, 1957; Blott & Pye, 2001).

5. Discussion

The fine sands of the crevasse-splay complex studied contain an exceptionally high concentration of organic matter relative to sediments of other crevasse splays. This applies to all examples from coal/lignite-bearing areas globally, as described in the literature (e.g., Horne et al., 1978; Fielding, 1984; Guion, 1984; Michaelsen et al., 2000; Widera et al., 2022, 2023; and references therein). This exception can be explained in two ways. Either it is the result of separation of each splay by a lignite layer or, alternatively, it could have resulted from redeposition of the coalified plant matter from the natural levee and the proximal part of the mire (compare Figs. 1C and 4B).

The massiveness of the sediments also requires a brief discussion. Here, it is associated with good sorting and a post-depositional destruction of the original stratification. The first is indicated by the similar shapes of curves of statistical parameters analysed (compare Tables 2, 3 and Fig. 7). The second, and more probable, reason for the massiveness of the sediments may be linked to numerous roots and rootlets of peat-forming vegetation present in each layer of the crevasse-splay sands (see Figs. 4, 5).

Sample T29 differs significantly from the others in terms of its basic statistical parameters. This is very enigmatic, because this sample was not obtained from the filling of the distributive channel, for example (Fig. 4A). At this stage of the research,

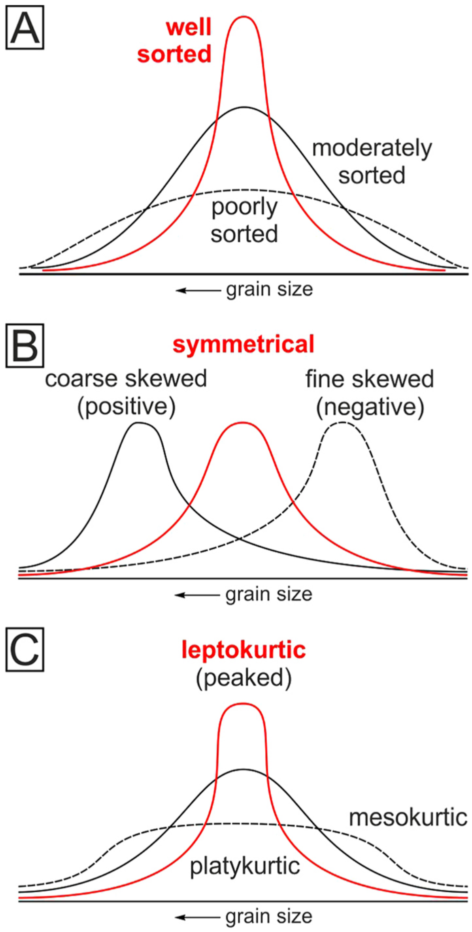

Fig. 7. Various types of graphic curves for standard deviation, skewness and kurtosis. Curves characteristic of average values of deposits examined are marked in red; compare with data contained in Tables 2 and 3.

this phenomenon may be explained by a temporary increase in water flow energy over the entire surface of the uppermost crevasse splay – facies SCh (Fig. 4B).

6. Conclusions

The crevasse-splay complex from the Tomisławice opencast lignite mine ranks amongst the best-developed ones on record from the lignite-bearing Miocene of Poland and even amongst the globally best-known to date, as described in the literature. It locally encompasses up to five superimposed crevasse splays that are separated by thin lignite beds. The total extent of these splays is ~0.2 km^2 in plan view and their thickness ranges from 0 to >5 m. In general, sandy-coaly and sandy facies with a massive, horizontal or planar lamination dominate within the deposits examined.

The massive facies occurring in the key section may have resulted from a sudden deposition; alternatively, it could have been caused by roots of peat-forming vegetation. The horizontally laminated facies formed as a non-channelised sheet flow, while the planar cross-stratified facies are interpreted as being typical of crevasse-splay microdelta fronts. These arose under both subaerial and subaqueous conditions. In the first case, they accumulated in flowing water, while in the second, they formed in standing water, that is, in lakes or ponds occurring on the surface of the Miocene mires.

Finally, the deposits studied contain an exceptionally large amount of coalified organic matter, including dispersed organics, as well as the roots or rootlets of plants. Despite this, they are well-sorted, fine sands with symmetrical skewness and leptokurtic kurtosis. This clearly confirms that those grains are best sorted around the graphical mean's grain-size value.

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