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The interpretative significance of ripple-derived sedimentary structures within an upper Neogene fluvial succession of central Poland

Piotr Maciaszek[1], Lilianna Chomiak[1], Robert Wachocki[2], Marek Widera[1*]

[1]Institute of Geology, Adam Mickiewicz University, Krygowski 12, 61-680 Poznań, Poland;
[2]Konin Lignite Mine; 600-lecia 9, 62-540 Kleczew, Poland;
*corresponding author, e-mail: widera@amu.edu.pl

Abstract

Sedimentary structures discussed in the present study are genetically linked to ripples that consist of pure sand or alternating sand and mud layers. All types of ripple-related structures, such as climbing-ripple cross-lamination and heterolithic bedding, i.e., flaser, wavy and lenticular (nodular), have been identified for the first time in fluvial strata that have been characterised previously as commonly massive. These small-scale bedforms, produced by migrating ripples, have been documented in a fluvial channel of late Neogene age in central Poland. The abundance and co-occurrence of the structures discussed and their spatial distribution provide evidence of their formation under very low-energy conditions, when flow velocity changed markedly, but was often significantly less than 0.5 m/s. Therefore, these ripple-derived sedimentary structures are here recognised as typical of channel fills of an anastomosing river.

Key words: sedimentology, depositional structures, ripples, anastomosing river

1. Introduction

Ripples belong to small-scale bedforms that arise under lower flow regime conditions. In general, their height ranges from 0.3 to 6 cm and their length is in the range of 4–60 cm (Reineck & Singh, 1980; Ashley, 1990). They may be symmetrical or asymmetrical. In the latter case, the stoss slope angle is relatively gentle in comparison to the lee slope angle, which is close to the angle of repose (25–30°) for that saturated with water and the sand and coarse-grained silt particles are 0.02–0.7 mm in size building these ripples. These small-scale bedforms are very diverse in their plan form. This is due to the fact that the first ones created were 2D ripples with straight crests, which together with the increasing flow velocity, are transformed into 3D ones with curved crests (e.g., Allen, 1968; Collinson, 1970; Blatt et al., 1980; Reineck & Singh, 1980; La Croix & Dashtgard, 2015; Baas et al., 2016).

Sandy current ripples are very common in most depositional environments (Allen, 1968; Hunter, 1977; Blatt et al., 1980; Zieliński & Van Loon, 2000; Gruszka, 2001; Hadlari et al., 2006; Gruszka et al., 2012; Allen et al., 2013; Pawłowski et al., 2013; Zieliński, 2014; Kędzior, 2016; and references therein). The ripple cross-lamination indicates only that the water flow was unidirectional for current ripples and flow velocity was less than 1 m/s (Ashley, 1990). In the case of fine sand (0.063–0.25 mm), however, current ripples develop at a flow velocity of < 0.5 m/s (Baas, 1999). Conversely, other types of small-scale cross-lamination that are produced by moving ripples, made of alternating sandy and muddy laminae, are much more interesting as far as their origin is concerned. These specific sedimentary structures are as follows: climbing-ripple cross-lamination, flaser, wavy and lenticular bedding. They are attributed to fluctuations in flow strength, variations in grain size of fine-grained sediments and concentration of suspended particles in flowing to near-stagnant water (e.g., Reineck & Wunderlich, 1968; Środoń, 1974; Ashley et al., 1982; Ashley, 1990; Yokokawa et al., 1995; Martin, 2000; Dalrymple, 2010; Fan, 2013; Zieliński, 2014; Kędzior, 2016), or may depend on the configuration of the depositional surface (Pasierbiewicz, 1982).

Until now, ripple cross-lamination was documented only occasionally within channel-filled deposits that represent an anastomosing river system of late Neogene age in central Poland (Widera et al., 2017). Other specific sedimentary structures, i.e., climbing-ripple cross-lamination and heterolithic bedding (flaser, wavy and lenticular), genetically associated with ripples, are described for the first time in the present paper. Therefore, the major goals of this research are twofold: to document ripple-related sedimentary structures from the palaeochannel of an anastomosing river and to provide evidence of their interpretative significance in term of flow conditions.

2. Geological setting

The channel-filled deposits studied outcrop in the Jóźwin IIB lignite opencast area. This territory covers the northernmost part of the relatively shallow Kleczew Graben, which is situated ~10–20 km north of Konin in central Poland (Fig. 1). The tectonic depression, with Cretaceous limestones at their base, is filled with Neogene and Quaternary deposits. It is worth noting that the entire Paleogene and a significant part of the Pliocene-Pleistocene are covered by stratigraphical gaps (Fig. 2), related to tectonic uplift where erosion prevailed over deposition (Widera, 2007, 2014).

The Cenozoic evolution of the Kleczew Graben began at the Paleogene/Neogene transition. The Koźmin Formation (earliest to middle Miocene), the oldest lithostratigraphical unit, is up to a few tens of metres thick and consists of fluvio-lacustrine sand and silt deposits with lignite intercalations. Strata of the overlying Poznań Formation (late middle Miocene to earliest Pliocene) have traditionally been subdivided into two members, i.e., the lower Grey Clays Member (also termed the Mid-Polish Member) and the upper Wielkopolska Member (Piwocki & Ziembińska-Tworzydło, 1997; Widera, 2007, 2013) (compare Figs. 1C, 2).

The lignite-rich Grey Clays Member comprises mostly the first Mid-Polish lignite seam (MPLS-1), with siliciclastic intercalations, which is currently exploited by the Konin Lignite Mine. This lignite seam covers the middle part of the middle Miocene in age (~15 Ma) (Kasiński & Słodkowska, 2016; Widera et al., 2017), and has an average thickness of 6.6 m. It is currently assumed that the accumulation of peat, which then transformed into MPLS-1, took place in low-lying mires in the overbank zone of the middle Miocene fluvial system (Widera, 2016a, b). Overlying is the mud-dominated Wielkopolska Member, with fluvial channel-fill deposits; the subject of the present research (compare Figs. 1B–E, 2). In the study area, the total thickness of the Wielkopolska Member changes from a few metres to more than 20 m, and the maximum thickness of in-channel sediments attains 5–9 m. The fine-grained deposits (muds) are attributed to the overbank area, while the succession examined is attributed to the channel zone of middle Miocene–earliest Pliocene (< 13.5 Ma) anastomosing river system in central Poland (Widera, 2013; Widera et al., 2017).

The Quaternary cover, with an average thickness of 40–50 m, overlies the Neogene succession (compare Figs. 1C, 2). These deposits are mainly of glaciogenic origin and include glacial tills, fluvioglacial gravels and sands, as well as glaciolacustrine muds and sandy muds (Widera, 2014; Widera et al., 2017).

3. Methods

In the opencast mines, exploited by the Konin Lignite Mine, a few dozens of fluvial palaeochannels within the Wielkopolska Member have been documented. Sediments filling these were characterised by their common massiveness (Widera, 2012, 2013; Widera et al., 2017). In contrast, the palaeochannel that outcropped in 2017 at the Jóźwin IIB lignite opencast mine (Fig. 1D, E), contained a large number of sedimentary structures. During fieldwork, observations and descriptions have been made of small-scale structures that are associated with ripples (Figs. 3–7). Additionally, 27 palaeocurrent measurements were made and 35 samples were collected for laboratory grain-size analyses.

The elongation (strike) of the palaeochannel measured in the summer/autumn of 2017 was 110–290° with a depth of 9 m and a width of 150 m in a southerly-northerly direction. The recalculated true width was ~140 m. The examined ripple-related sedimentary structures were observed in the axial zone of the palaeochannel at about 2.3–2.6, 3.4–4.2 and 6.4–6.8 m above its base (Fig. 1D).

In the present study, the standard grain-size scale is used. According to the field classification of fine-grained deposits mud is defined as a sediment containing > 50 volume percentage of clay and silt (Lundegard & Samuels, 1980). The sediment denominators were subsequently improved according to details from laboratory analyses. A conventional sieving technique has been used for sandy, non-co-

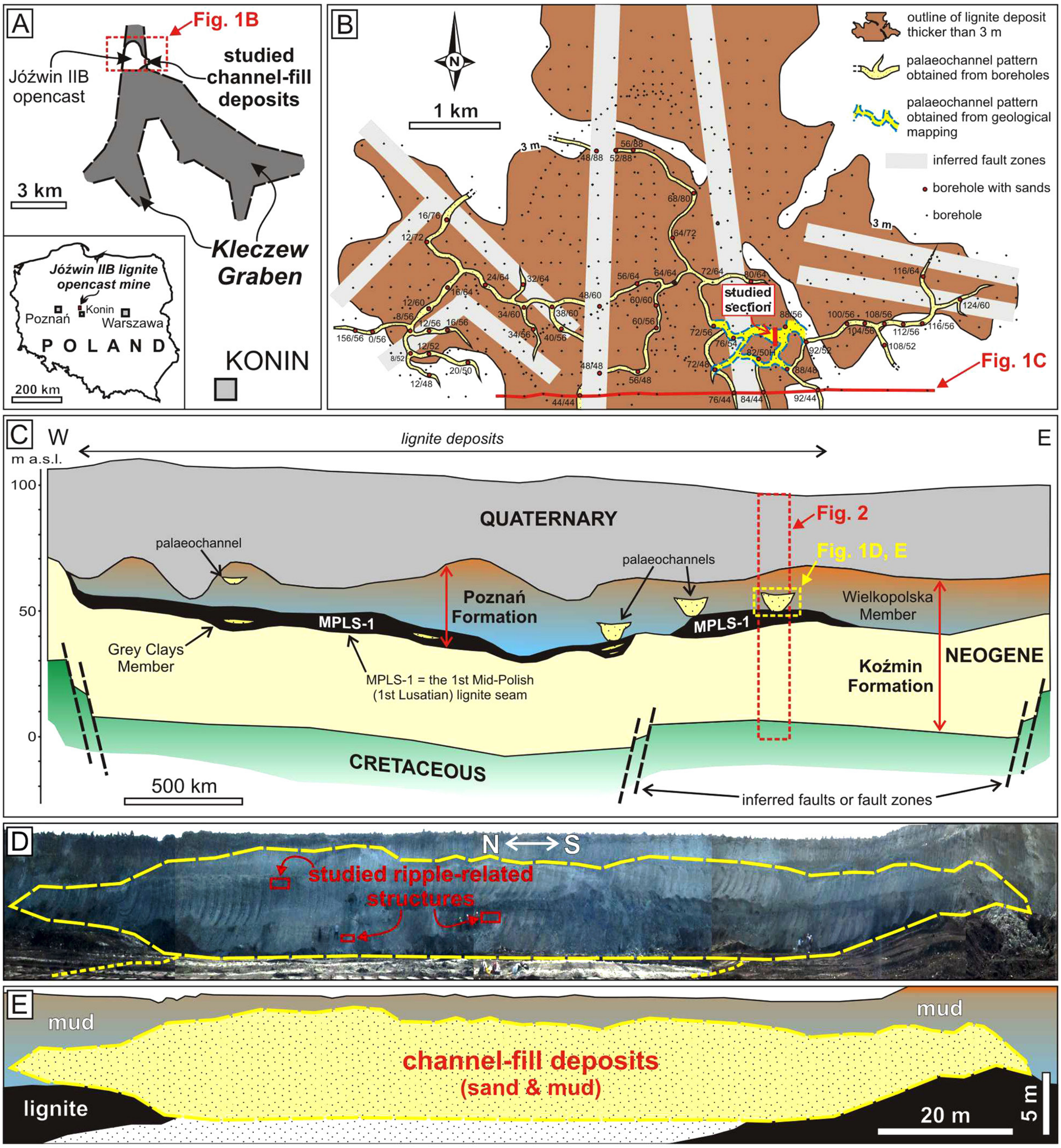

Fig. 1. Locality map and geology of the study area. **A** – Map of the Konin area in central Poland showing the location of the Jóźwin IIB lignite opencast mine in the Kleczew Graben area; **B** – Palaeochannel pattern inferred from borehole data and geological mapping in the area of the Pątnów IV lignite deposits (modified from Widera et al., 2017); **C** – Simplified geological cross-section through the northern segment of the Kleczew Graben (the southernmost part of the Pątnów IV lignite deposits) with the approximate stratigraphical position of the palaeochannel studied (modified from Widera, 2014, Widera et al., 2017); **D, E** – Broad view and corresponding line-drawings of the palaeochannel. Note the location of the ripple-related structures within the palaeochannel examined

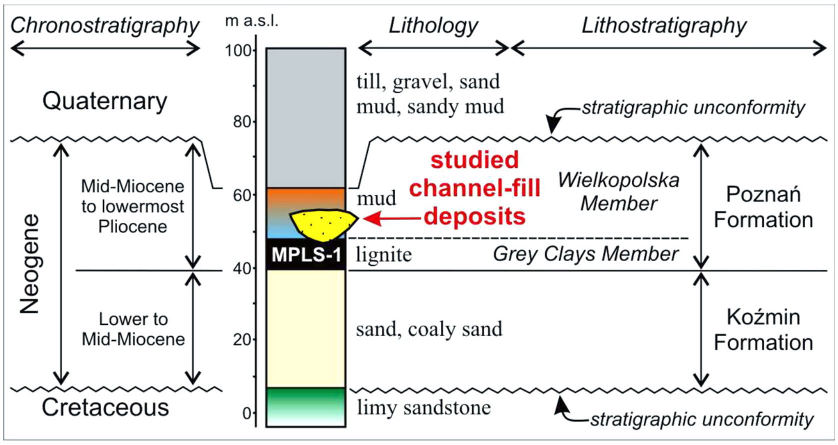

Fig. 2. Stratigraphical sketch of the Cenozoic succession within the Kleczew Graben (modified from Widera, 2007, 2014). Note the stratigraphical position of the examined channel-fill deposits within the muddy Wielkopolska Member of late Neogene age; MPLS-1 – the First Mid-Polish lignite seam; for approximate position of the lithological section see Figure 1C

Table 1. Selected lithofacies associations occurring within the channel-fill deposits that represent a late Neogene anastomosing river system in central Poland

Lithofacies association	Code	Lithofacies	Occurrence & description	Interpretation
Lithofacies association of horizontal lamination*	SMh MSh	Horizontally stratified muddy sand; horizontally stratified mud	Various parts of channel-fill, except its lowermost and uppermost parts. Relatively the largest lateral extent up to a few 10s m, but only up to 0.5–2 dm thick; with flat depositional or erosional base.	Predominantly tractional deposition from bedload transport; lower flow regime without evident erosion of underlying deposits ripples; sporadically upper flow regime (= erosive base); water flow too strong for ripples and too shallow for dunes formation.
Lithofacies association of massive sediments*	Sm SMm	Massive fine-grained sand; massive muddy sand	Both lithofacies are common in all parts of the palaeochannel, especially in its upper part. Up to a few dm thick; massive structure; Sm – low content clay and silt, light grey in colour; SMm – rich in mud admixture, grey in colour; Sm and SMm pass often laterally and vertically to other small-scale lithofacies.	Hyperconcentrated to tractional flow; non- to weak tractional deposition of pure sand or/and sand with a muddy admixture; first, from dense turbulent suspension, and then from weak traction by overbank floodwater drained back to palaeochannel; massive structure is due to well sorting and the lack of colour contrast; in most cases this structure was originally rippled.
Lithofacies association of ripple cross-lamination*	Sr STr SMr	Ripple cross-laminated fine sand; ripple cross-laminated silty sand; ripple cross-laminated muddy sand	All parts of the palaeochannel. Cross-stratified laminae sets are up to 5–6 cm thick and co-set thickness reaches 1–3 dm; Sr – almost pure sand, white in colour; STm – rich in silt, light grey in colour; SMr – rich in mud (clay and silt), grey in colour; these lithofacies form separate beds or co-exist with other small- and large-scale lithofacies.	Tractional deposition from bedload transport as small current ripples; lower part of lower flow regime; this association is very close to association above-described (Sm, SMm), but tractional transport play here more significant role.
Lithofacies association of climbing-ripple cross-lamination**	Src STrc	Climbing-ripple cross-laminated fine sand; climbing-ripple cross-laminated silty sand	Both lithofacies occur occasionally in axial zone of the palaeochannel. Individual cross-strata laminae sets are up to 2.5 cm thick; an angle of climb is < 10°; bases and tops are erosional; this association is underlain by lithofacies Sm and capped by various sandy lithofacies above an erosional surface; climbing-ripple cross-lamination represents the A-type ripple.	Predominantly fine sand (Src) and occasionally a slight admixture of silt (STrc) is transported both in traction and suspension; lower part of lower flow regime; this lamination is formed during periods of waning flow (< 0.5 m/s) in water rich in suspended, mainly sandy load; the A-type ripples are created when the bed-load transport is higher than the suspended-load transport.

Lithofacies association	Code	Lithofacies	Occurrence & description	Interpretation
Lithofacies association of heterolithic bedding**	Sf	Fine sand with a flaser bedding;	Lithofacies are located in various parts of the palaeochannel with exception of its the lower- and uppermost beds. They build up a few upward-fining cycles that are 0.1–0.6 m thick; these lithofacies are sometimes separated by the erosive surfaces; flaser bedding consists of concave-up mud lenses, in the muddy-sandy matrix, which are up to 13.5 cm long and 1 cm thick; wavy bedding is made of thin (up to 0.6 cm) muddy layers, that drape the sandy ripples; nodular/lenticular bedding is built of sandy 'lens-like' nodules (up to 15 cm long and 1.5 cm thick) within the muddy-sandy matrix.	Heterolithic bedding, i.e. flaser, wavy and nodular/lenticular, is formed when water flow changes alternatively; sandy layers (ripples) are deposited when water flow is relatively fast (< 0.5 m/s), while muddy layers are deposited atop the ripples in intervals of slack to almost stagnant water; lowermost part of lower flow regime; this association shows cyclic repetition of lithofacies, which is a record of waning and very low-energetic flow conditions; the erosive surfaces are an evidence of the breaks in deposition and slight erosion.
	Sw	fine sand with a wavy bedding;		
	STn	silty sand with a nodular (lenticular) bedding		

* – lithofacies associations only mentioned in this research; ** – lithofacies associations examined in detail.

hesive deposits (27 samples), whereas for silty-clayey, i.e. muddy, cohesive sediments (8 samples) the areometric method has been applied.

The classification of climbing-ripple cross-lamination used here follows Jopling & Walker, (1968) and Allen (1973). Furthermore, the terminology of heterolithic bedding (flaser, wavy, lenticular) is that of Reineck & Wunderlich (1968). The letter code for sediment description is a compilation of those proposed by various researchers (Miall, 1977; Ghibaudo, 1992; Zieliński, 1995), in part supplemented and modified here. For grain size the following capital letters are applied: S – sand, M – mud, T – silt; while for sedimentary structures such lower-case letters are used: m – massive, h – horizontal, r – ripple, rc – ripple-climbing, f – flaser, w – wavy, and n – nodular, i.e., lenticular. The list of lithofacies recognised in the present paper is shown in Table 1. According to the codification presented herein, for example, the lithofacies code STn means silty sand with a nodular (lenticular) lamination (Table 1).

4. Results

The sedimentary structures that are described and interpreted below have never been observed previously within the upper Neogene fluvial channels in central Poland. To achieve the objectives of the present study, by providing indirect evidence of extremely low-energy depositional environment, first will be characterised lamination resulting from relatively faster water flow and then from the slower one. Thus, according to decreasing flow energy, they are as follows: climbing-ripple cross-lamination, flaser, wavy and lenticular bedding.

4.1. Climbing-ripple cross-lamination

4.1.1. Description

Climbing-ripple cross-lamination (rc) was documented sporadically within the palaeochannel deposits examined. In the present study two sets of climbing ripples are recognised (Fig. 3). Generally, the thickness of individual cross-strata sets is in the range of 1–2.5 cm and the angle of climb is less than 10°. The examples discussed here consist of sets of laminae that are evidently cut by erosion and individual ripples climbing one on the other. In both cases, they consist of fine sand (0.063–0.25 mm) with an admixture of silt (0.002–0.063 mm), although in various proportions. This is manifested in such a way that the lamination is occasionally well visible due to the colour contrast between the more sandy and more silty laminae (Fig. 3A). On the contrary, the lamination is not clear and difficult to document photographically, when the content of grains of < 0.063 mm is negligible, they do not form a continuous laminae and mostly fill pores between sand grains (Fig. 3C).

4.1.2. Interpretation

The development of climbing-ripple cross-lamination (rc), often termed ripple drift cross-lamination, corresponds to a transition from erosional stoss to depositional stoss slopes of ripples. The examples described above (Fig. 3) represent type A of climbing-ripple structures, as distinguished by Jopling & Walker (1968) and Allen (1973). In this case, the angle of climb is smaller than the stoss slope angle of the ripples, which means that their stoss slopes are erosional. Therefore, the lamination interpreted is also referred to as subcritical climbing-ripple cross-lamination (Hunter, 1977).

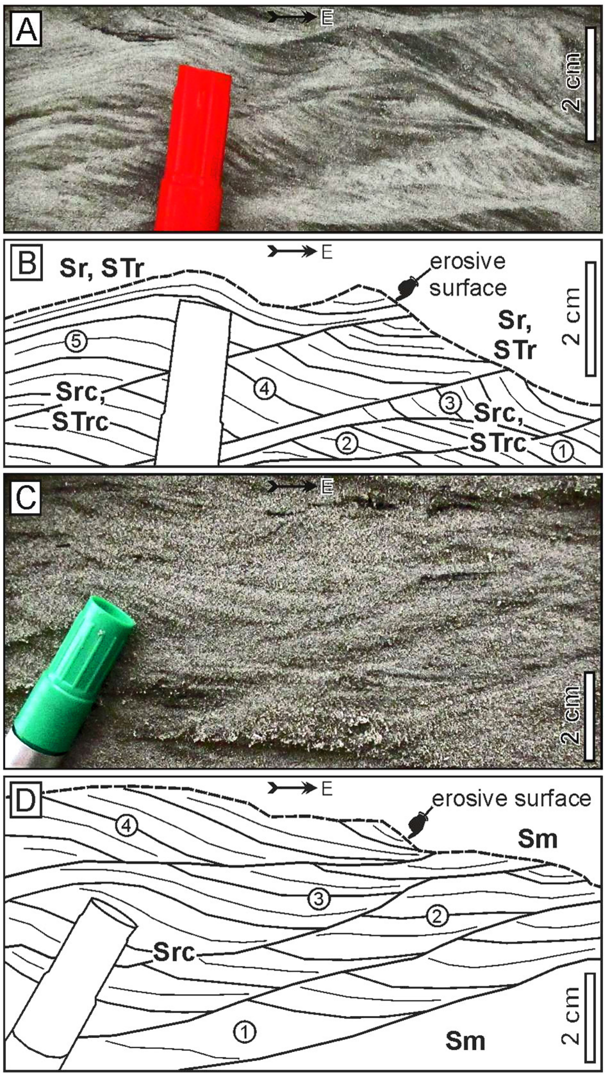

Fig. 3. Climbing-ripple cross-lamination. **A, B** – Sand and sandy-silt with climbing ripples; **C, D** – Sand with climbing ripples. Note the low angle of climb (< 10°) in both examples; flow direction is from left to right, numerals in circles indicate successive generations of climbing ripples; for explanation of lithofacies code see text and Table 1

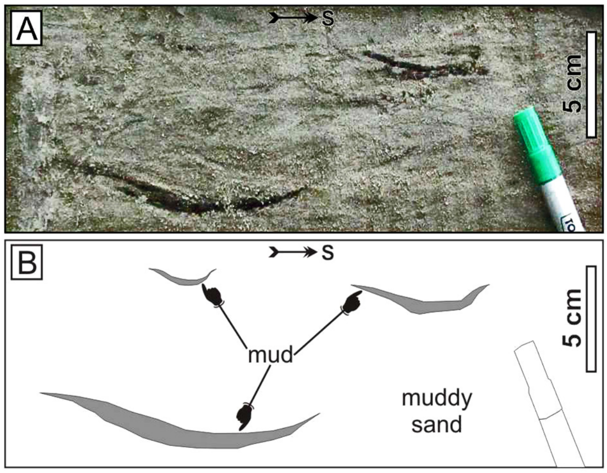

Fig. 4. Flaser bedding. Note the discontinuous muddy layers, consisting of muddy infill of ripple troughs, surrounded by poorly laminated muddy sand. Note that discontinuous 'lens-like' muddy layers surrounded by muddy sand; flow direction is almost perpendicular to the photograph; for explanation of lithofacies code see text and Table 1

Type A ripples with erosional-stoss slopes may be formed when deposition from bedload transport exceeds suspension. Moreover, it is created when ripples receive significant supply of clastic particles from suspension (Jopling & Walker, 1968; Allen, 1973; Ashley et al., 1982).

4.2. Heterolithic bedding: flaser, wavy and lenticular (nodular)

4.2.1. Description

Flaser bedding (f) is located in all three portions of the sedimentary succession studied (Fig. 1D); however, its total thickness is negligible, i.e., 0.1–0.2 m (compare Figs. 4, 7). This sedimentary structure is characterised by the presence of small lenses of mud within more coarsely grained deposits, e.g., muddy sand (Fig. 4). These muddy lenses are concave upwards, up to 13.5 cm in length and up to 1 cm in thickness and they discontinuously fill the depressions (troughs) between poorly visible ripples. They consist predominantly of mud (clay and silt > 50%) and the rest is fine-grained sand, i.e. in the range 0.063–0.25 mm, as laboratory analysis has shown.

Wavy bedding (w) is characterised by alternating, more or less continuous thick sandy and thin muddy layers within the channel-fill deposits studied (Fig. 5). In the present paper, there are two examples of wavy lamination. The first shows the location of wavy bedding at the boundary between sandy deposits at the base and muddy sediments at the top (Fig. 5A, B). The second example presents wavy bedding that is situated within the sandy deposits (Fig. 5C, D). In both cases, the lamination described is marked by muddy layers that are more or less continuous and up to 0.6 cm thick. These muddy layers form a blanket that covers the sandy ripples (Fig. 5).

Lenticular, nodular bedding (n) is the commonest cross-lamination among all small-scale sedimentary structures examined in the present paper. Its thickness (~2.3 m) covers approximately 26% of the channel-filled succession, which attains close to 9 m in thickness (Fig. 1D, E). This type of specif-

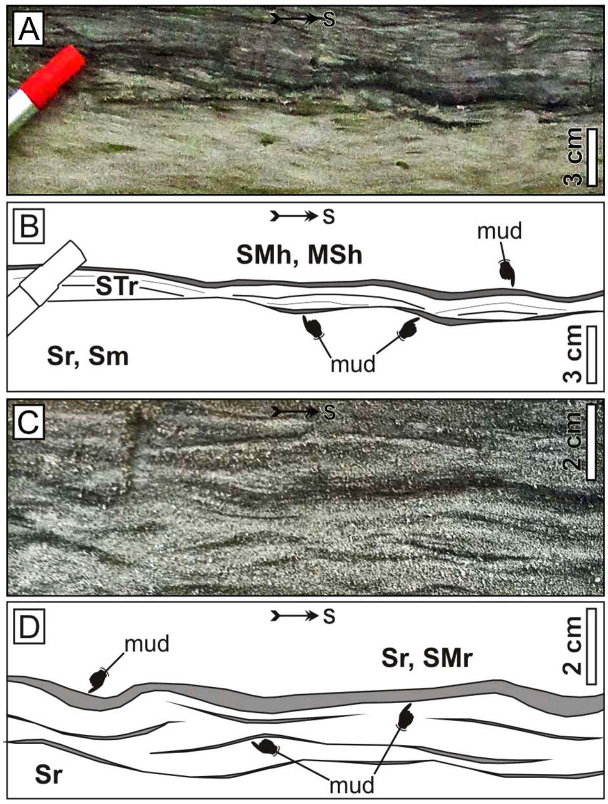

Fig. 5. Wavy bedding. **A, B** – wavy bedding at the boundary between the ripple cross-laminated sands and horizontally laminated muddy-sandy sediments; **C, D** – wavy bedding situated predominantly within rippled sandy deposits with a muddy admixture. Note the relatively continuous muddy layers that drape the sandy ripple structures; flow direction is almost perpendicular to the photograph; for explanation of lithofacies code see text and Table 1

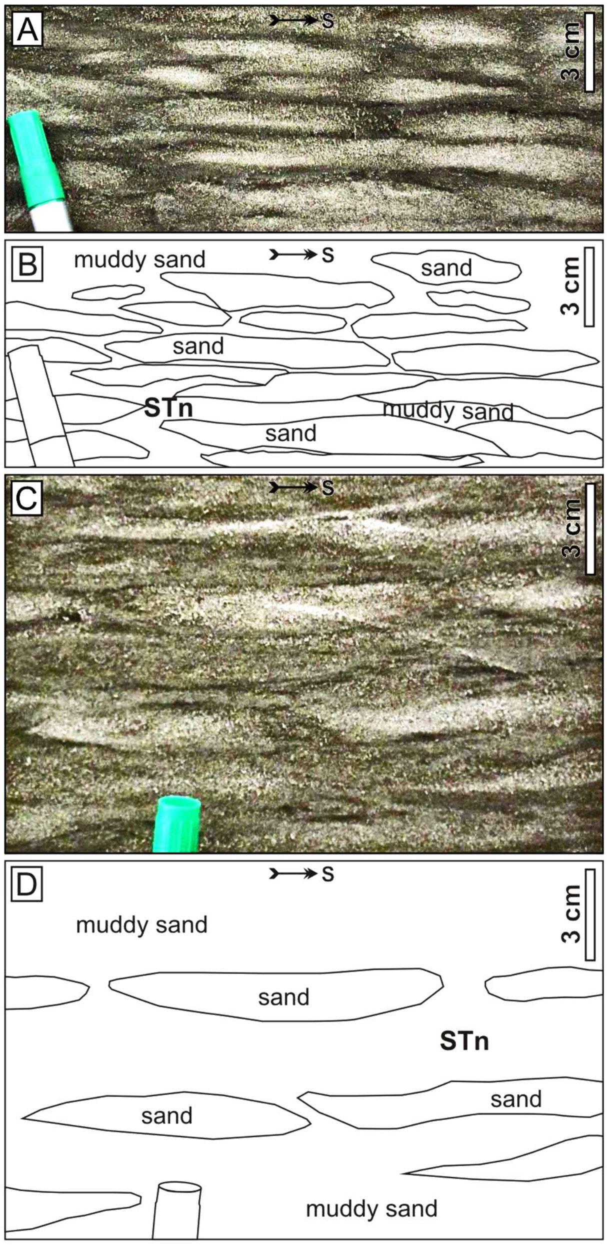

Fig. 6. Lenticular (nodular) bedding. **A, B** – lenticular bedding with a predominance of 'lens-like' sands; **C, D** – lenticular bedding with a predominance of muddy-sandy matrix. Note that 'lens-like' sands are surrounded by muddy sand; flow direction is almost perpendicular to the photograph; for explanation of lithofacies code see text and Table 1

ic lamination consists of 'lens-like' coarser-grained sediments in a matrix of finer-grained material (Fig. 6). In the present case, the lenses (nodules) consist of relatively pure, fine-grained sand, while the surrounding material consists of muddy sand. These 'lens-like', near-symmetrical structures are in fact fossilised ripples, seen parallel to the direction of their migration. The sandy nodules (lenses) are convex both upwards and downwards. Their maximum length and thickness are 15 and 1.5 cm, respectively. These two examples, despite many similarities, differ in proportions between the sandy lenses and sandy-muddy matrix. The first example of lenticular (nodular) bedding is very close to the above-mentioned wavy lamination, because the relative proportion between lenses and their surroundings is almost equal (Fig. 6A, B). In the second example, however, the sandy-muddy matrix takes up several times more surface area than the sandy lenses of the section analysed in detail (Fig. 6C, D). Thus, the latter case represents typically formed lenticular bedding as originally defined by Reineck & Wunderlich (1968).

4.2.2. Interpretation

Differences in the formation of various types of heterolithic lamination are related to water flow velocity and, as a result, to proportions between the

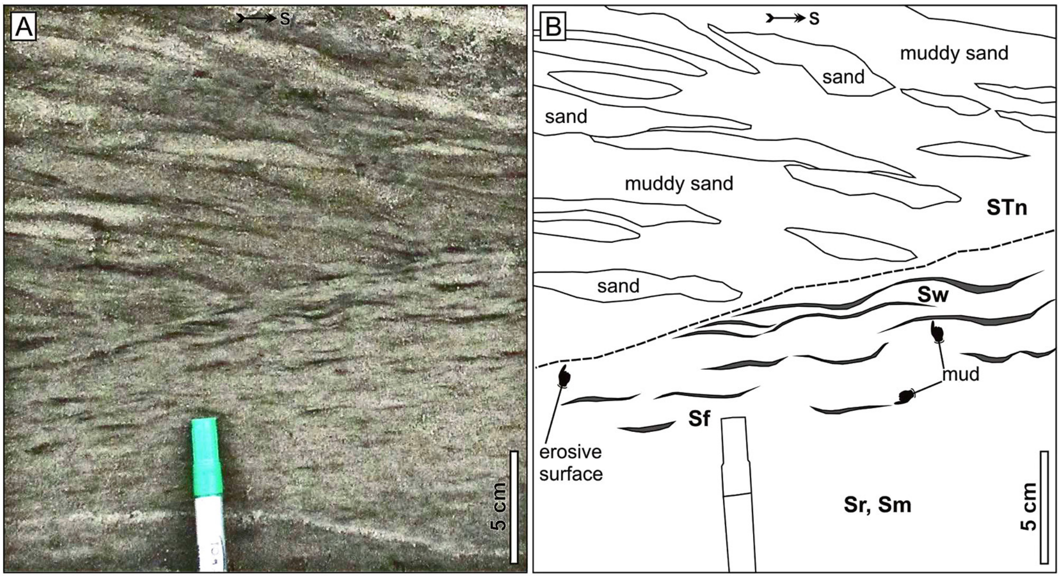

Fig. 7. Co-occurrence of various types of heterolithic bedding. Note the upward transition from flaser (Sf), through wavy (Sw) to lenticular (STn) bedding within the sedimentary succession; flow direction is almost perpendicular to the photograph; for explanation of lithofacies code see text and Table 1

amount of muddy and sandy particles deposited. Therefore, the development and preservation of the sedimentary structures interpreted may occur under alternating relatively fast and slow flow conditions. At extremely low water stages the mud is laid down predominantly from suspension, while during faster-moving water stages the sand-grained particles are deposited mainly from traction (e.g., Reineck & Singh, 1980; Martin, 2000). However, the latest laboratory results show that flow variability is not required to produce deposits that consist of alternating muddy and sandy laminae, i.e. flaser, wavy and lenticular bedding (Baas et al., 2016). Those authors have proved that small bedforms, composed of an admixture of sand and mud and characterised by heterolithic lamination, can be generated under rapidly decelerating flows.

In the case of heterolithic bedding examples shown here, the thickness ratio of sand to mud laminae varies from more than 20 – flaser bedding (Fig. 4), through ~5 – wavy bedding (Fig. 5) to less than 1 – lenticular (nodular) bedding (Fig. 6). Additionally, an even thickness of mud layers in the case of wavy bedding (Figs. 5, 7) provides evidence that the extremely low-energy deposition was not interrupted by significant erosional events (Martin, 2000).

In contrast to the explanation given above, flaser and wavy bedding may also form simultaneously in front of larger bedforms, e.g., 2D dunes, migrating under unidirectional flow conditions (Pasierbiewicz, 1982). In this case, however, the sedimentation surface on which sandy and muddy layers were laid down in the form of lenses and/or waves, must have been originally undulated. Thus, the 'wavy' morphology of the depositional surface may be regarded as a very significant factor to influence the structural development of flaser and wavy bedding (Pasierbiewicz, 1982). In contrast, wavy cross-lamination can be formed during the final phase of the climbing process as type C ripples. Then, ripple migration stops and a muddy blanket atop of ripples is produced in very slow flowing or almost standing water only due to the fact that bed aggradation is caused by fallout from suspension (e.g., Jopling & Walker, 1968; Ashley et al., 1982; Zieliński, 2014).

5. Discussion

The ripple-related sedimentary structures studied may be grouped into ripple to climbing-ripple cross-lamination and heterolithic bedding (Fig. 8). The first group is predominantly homolithic; hence, it is built of pure sand grains and only occasionally contains a slight admixture of finer-grained particles. In contrast, the second group of heterolithic bedding, as the name suggests, is made of lithologically different laminae, i.e., sand and mud (> 50 volume percentage of clay and silt). All of the small-scale structures tested are the result of deposition both from traction and suspension. However, climbing-ripple cross-lamination is formed when processes of traction and suspension occur at the same time (Jopling & Walker, 1968; Allen, 1973; Hunter, 1977; Ashley et al., 1982; Allen et al., 2013).

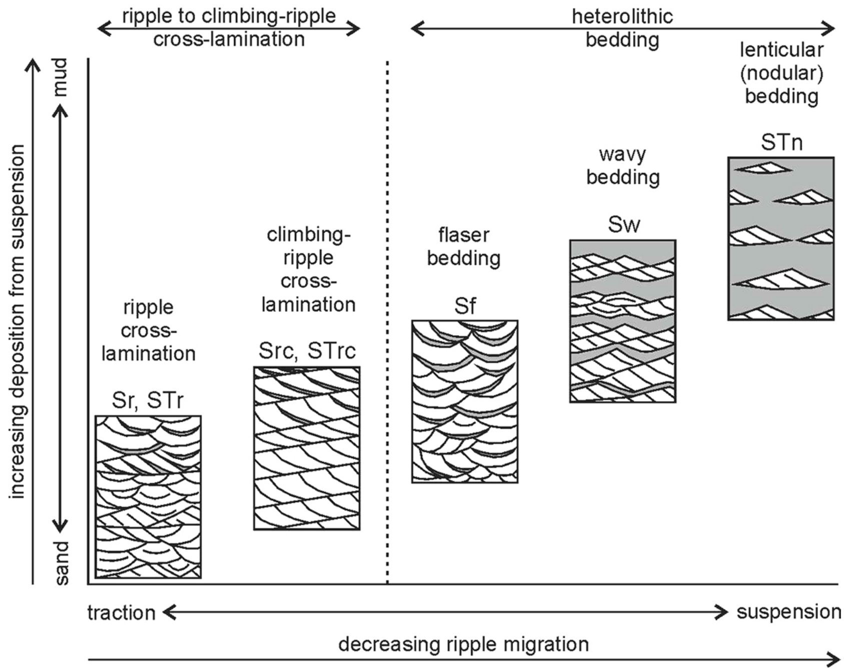

Fig. 8. Simplified diagram showing the relationship between traction and suspension processes, as well as between sand and mud content during formation of ripple-derived sedimentary structures. For explanation of lithofacies code see text and Table 1.

Climbing-ripple cross-lamination is formed during periods of waning flow in water that is rich in suspended sediment load. The climbing ripples studied are characterised by fine sand-grained particles, with a mean grain size of ~0.2 mm. In such a situation, fine sand is transported both in suspension and traction, when flow velocity was less than 0.5 m/s (Baas, 1999).

In the case of heterolithic bedding (flaser, wavy, lenticular/nodular), these two processes occur alternately and/or one substantially predominates over the other (Reineck & Singh, 1980; Yokokawa et al., 1995; Martin, 2000; Dalrymple, 2010; Fan, 2013; Kędzior, 2016). Here can be given at least two exceptions. The first exception explains the genesis of flaser and wavy lamination. Thus, under favourable flow and load conditions, these beddings can also be created simultaneously, as described above (Pasierbiewicz, 1982). The second exception is that given by Baas et al. (2016), who provided experimental evidence that the heterolithic lamination, made of an admixture of sand and mud, can be produced in rapidly decelerating flows. In the case of the late Neogene river system under investigation, this situation may have occurred, for example, when floodwaters returned to the river channels.

Heterolithic bedding does not indicate a specific depositional environment, but provides evidence of its very low energy and the presence of grains of various sizes. In addition, it proves short-term changes from slow current to almost stagnant water. Fine sand is transported during times of a relatively faster-moving flow (< 0.5 m/s), but still very slow, and creates ripples. On the other hand, during intervals of almost stagnant water (~0 m/s) mud, i.e. clay and silt, is deposited between ripples or drapes these. Depending on the proportion between sand and mud, flaser (sand > mud), wavy (sand ≈ mud) and lenticular/nodular (sand < mud) bedding arises, respectively (Reineck & Wunderlich, 1968; Reineck & Singh, 1980) (Fig. 8).

The heterolithic lamination examined has been documented for the first time among upward-fining co-sets of laminae that fill the fluvial palaeochannel of late Neogene age in central Poland. Thus, flaser bedding is located at the base, wavy bedding in the middle and lenticular bedding at the top of these co-sets (compare Figs. 7, 8). This is evidence of episodic repetition of the same sedimentation cycles, which are obviously a record of a low-energy but waning flow. Such upward-fining successions may also be produced by weak storms, episodic floodings, ephemeral or intermittent streams (e.g., Reineck & Singh, 1980; Martin, 2000; Dalrymple, 2010; Fan, 2013; Kędzior, 2016).

Considering the subdivision of fluvial systems only deposits of anastomosing channels can be characterised by water flows from flood stages to extremely low energy. The first of them are documented, among others, by deeply incised (~9 m) the palaeochannel in muddy floodplain – ~8 m and in lignite seam – ~1 m (Fig. 1D, E) and the presence of layers with cross-lamination at various scales; however, such are beyond the scope of the present paper. On the other hand, the above-mentioned very low-energy flows are represented precisely by

Table 2. Comparison of occurrences of climbing-ripple cross-lamination and heterolithic bedding among sediments representing various sub-environments of the main types of rivers

River type	Sub-environments of a river	Selected references
Braided (mainly sand-bed braided river)	braidplain (floodplain): – common in lower parts of the sedimentary successions filling flood basins	Cant (1978), Cant & Walker (1978), Tanner & Hubert (1992), Singh et al. (2013)
	braided channels: – present in secondary channels during final waning stages or in abandoned channels, or in channel pools during low-water stages	Rust (1978), Abdullatif (1989), Rust & Gibling (1990)
	– rare at tops of mid-channel bars or compound bars	Doeglas (1962), Bridge & Lunt (2006)
	natural levees: – present in natural levees of transitional river (braided-to-meandering)	Huisink (1997)
Meandering	meandering channels: – common at uppermost parts of the abandoned channel fills	Kraus & Middleton (1987), Kozarski et al. (1988), Moskalewicz et al. (2016),
	– present in point-bar successions, especially at their tops	Stewart (1981)
	crevasse splays: – present in various parts of the crevasse splays	Allen (1964), Gębica & Sokołowski (2001), Moskalewicz et al. (2016), Burns et al. (2017)
	natural levees: – present in natural levee successions, especially at their tops	Allen (1964), Nemec (1984), Tye & Coleman (1989)
Anastomosing	anastomosing channels: – very common at different levels in the channels, especially in the upper parts of successions	Woodyer et al. (1979), Makaske (1998, 2001), Gradziński et al. (2003a, b)
	natural levees and crevasse splays: – present in these both forms	Nadon (1994), Smith & Pérez-Arlucea (1994)

the specific ripple-derived sedimentary structures studied here, i.e., climbing-ripple cross-lamination and heterolithic bedding (flaser, wavy, lenticular/nodular).

Finally, it should be noted that, in general, the occurrence of climbing ripples, but predominantly heterolithic bedding (Martin, 2000), is seldom reported from fluvial channel deposits (Table 2). In contrast, these ripple-related structures are common in the overbank zone of the sand-bed braided and meandering rivers. Therefore, the relatively high frequency of climbing-ripple and heterolithic structures, within the palaeochannel studied, is characteristic of low-energy anastomosing rivers (Table 2).

6. Conclusions

In 2017, due to mining activity, a palaeochannel within upper Neogene muddy deposits was exposed in the area of shallow tectonic graben in central Poland. Unexpectedly, within the channel-fill sediments, in addition to widespread massive structure and cross-lamination at various scales, appeared sandy-muddy sedimentary structures genetically related to the migration of ripples.

The structures with small-scale cross-lamination examined are characterised by climbing-ripple cross-lamination and heterolithic bedding, that is, flaser, wavy and lenticular (nodular). They formed by deposition from both traction and suspension that may have occurred simultaneously (climbing-ripple cross-lamination) or alternately (heterolithic bedding). These types of lamination are evidence of a very low-energy depositional environment, when flow velocity was from less than 0.5 m/s to almost stagnant water, respectively.

In summary, the presence and preservation of specific ripple-derived sedimentary structures indicate that the flow in the channel changed periodically, but it was still extremely slow. The lamination studied, in particular the heterolithic bedding, formed in very slow flowing to almost stagnant water. Therefore, we believe that among the various types of rivers, only in anastomosing channels do conditions exist for the formation of ripple-derived sedimentary structures as the ones described here.

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