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River response to climate and sea level changes during the Late Saalian/Early Eemian in northern Poland – a case study of meandering river deposits in the Chłapowo cliff section

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Abstract

Fluvial sediments in the Chłapowo cliff section were studied in order to reconstruct their palaeoflow conditions and stratigraphical position. Lithofacies, textural and palaeohydraulic analyses as well as luminescence dating were performed so as to achieve the aim of study. Sedimentary successions were identified as a record of point bar cycles. The fluvial environment probably functioned during the latest Saalian, shortly after the retreat of the Scandinavian Ice Sheet. Discharge outflow was directed to the northwest. The river used the older fluvioglacial valley and probably was directly connected to the Eem Sea. Good preservation and strong aggradation of point-bar cycles were related to a rapid relative base level rise. The meandering river sediments recognised showed responses to climate and sea level changes as illustrated by stratigraphical, morphological and sedimentological features of the strata described. The present study also revealed several insights into proper interpretation of meandering fluvial successions, in which the most important were: specific lithofacies assemblage of GSt (St, Sp) → Sl → SFrc → Fm (SFr) and related architectural elements: channel/sandy bedforms CH/SB → lateral accretion deposits LA → floodplain fines with crevasse splays FF (CS); upward-fining grain size and decreasing content of denser heavy minerals; estimated low-energy flow regime with a mean depth of 1.6–3.3 m, a Froude number of 0.2–0.4 and a sinuosity of 1.5.

Keywords: point-bar succession, meandering fluvial system, Quaternary geology, fluvial sedimentology, Eemian Sea

1. Introduction

In the Pleistocene glacial record, meandering rivers were not so widespread as were braided rivers, in areas affected by advances of the Scandinavian Ice Sheets. During this period, conditions for the evolution of meandering river patterns in valley systems were provided in times marked by proper environmental settings, mostly during interglacials (Vandenberghe, 2001, 2003; Huisink et al., 2002; Vandenberghe & Woo, 2002).

Complete cycles of meandering rivers can be preserved only under specific conditions, the most important of which include: topography of the palaeovalley system, sediment supply, flow characteristics, climate, available accommodation space, eustatic sea level fluctuations or tectonic movements and position of the ice sheet margin (Blum & Tornqvist, 2000; Mol et al., 2000; Catuneanu, 2006; Toucanne et al., 2009; Blum et al., 2013; Ghinassi et al., 2014). During field work, a Pleistocene succession with well-preserved point-bar sediments was encountered in the Chłapowo cliff section. The present study aimed to: 1) reconstruct palaeoflow conditions of an ancient meandering river, 2) recognise the palaeogeographical setting and age of the system, and 3) discuss the reasons behind the good preservation of fluvial strata.

2. Geological setting

The study area is situated in the central part of the southern Baltic coast, 35 km to the north of Gdynia (Fig. 1), and covers the Chłapowo cliff section along the coastline between the towns of Władysławowo and Jastrzębia Góra. Smaller outcrops also exist in erosional ravines that cut into the cliff. Quaternary sediments cover Eocene, Oligocene and Miocene deposits with a total thickness of approximately 120 m. Eocene and Oligocene strata, deposited in an epicontinental sea, comprise mudstones, sands and muds, in places enriched in amber (Kramarska et al., 2002; 2008). Miocene sediments are represented by quartz-mica sands and lignite and attain a thickness of *c.* 80 m, including up to 30 m that are accessible at several places along the cliff (Marzec & Woźny, 1972). Lithofacies analysis showed the strata to have originated in a low-energy fluvial environment and their sedimentation probably occurred within a meandering system (Moskalewicz & Sokołowski, 2014). Miocene layers are found underneath a 30-m-thick Pleistocene series, the base of which is formed by a distinct erosional boulder pavement of Scandinavian erratics. Pleistocene sediments change laterally within the cliff outcrop; however, their upper part commonly includes a 2-m-thick till layer, while other parts are generally dominated by sands and gravels, forming two series of fluvial deposits. The lower, gravelly succession was interpreted as a record of a braided river system with a westerly outflow (Moskalewicz & Sokołowski, 2014). The overlying sandy fluvial strata are the subject of the present study. The stratigraphy of these sediments has not yet been well established, although TL dating (162.9±24.4–322.2±48.3 ka) indicates that they are assignable to the Saalian glaciation (Olszak, 1996).

3. Methods

Sandy sediments in the Chłapowo cliff section were subjected to lithofacies, grain size, heavy mineral and palaeohydraulic analyses. A lithofacies code that follows Miall (1996) and Zieliński (1998) is defined in Figure 2. For each lithofacies type identified in the field, at least one sediment sample was collected for laboratory analysis. Sieving was done to obtain grain-size distributions and median values. The medium-grained (0.18–0.25 mm) sand fraction was also subjected to heavy mineral analysis, involving separation by sodium polytungstate at a specific density of 2.85 g/cm^3 and identification of minerals under a petrographic microscope. A minimum of 300 transparent minerals were identified in each sample. Opaque minerals were also counted to compare their percentage to that of transparent minerals. Determination of the absolute age of sediments used a TL dating method at Gdansk laboratory to verify previous data (Olszak, 1996). The methodology applied follows that of Fedorowicz

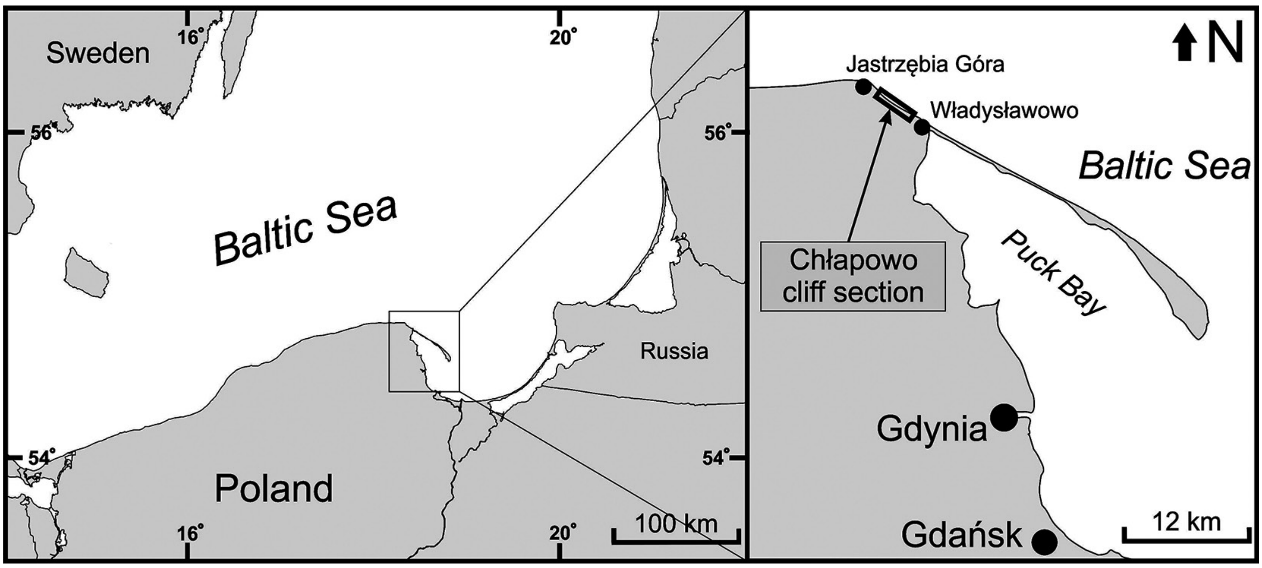

Fig. 1. Location of the Chłapowo cliff section.

et al. (2013; see detailed discussion in Fedorowicz, 2006).

Palaeohydraulic parameters were estimated on the basis of the thickness of sedimentary units measured, in combination with grain size and palaeocurrent data. Most geometric parameters of meandering palaeochannels can simply be reconstructed by a study of sedimentary successions during field work (Williams, 1984; Bridge & Tye, 2000; Ito et al., 2006; Khan & Tewari, 2011; Ghinassi et al., 2014). Equations were chosen in consideration of the type of palaeochannel pattern recognised in ancient fluvial strata. None of the parameters presented was measured directly, due to insufficient outcrop width (except for directional analysis and thickness). Ghinassi et al. (2014) discussed this problem, and showed that values obtained by empirical equations allowed an adequate approximation of channel geometric features.

Directional analysis was performed so as to estimate channel sinuosity and mean palaeocurrent vector (Bridge et al., 2000). Channel sinuosity (sn) was calculated using the following empirical equations:

$$sn = 4.84/(4.84\text{-}fi^2)$$

where fi is half of the maximum palaeocurrent range in radians. The mean palaeocurrent vector was computed according to the standard method (Tucker, 2003).

To determine mean channel depth (D) we used the following formula due to a partially eroded point-bar cyclotheme, which involves its thickness (T_{PB}):

$$D = 0.65\ T_{PB}$$

We used the coefficient 0.65, related to further erosion and compaction of sediment, as the mean value from formulas applied by Cotter (1971), Morton & Donaldson (1978), Allen & Mange-Rajetzky (1982) and Bridge & Tye (2000).

The thickness of point-bar deposits, interpreted as the bankfull channel depth (Bridge & Tye, 2000), was used to estimate channel belt width (CBW), following Bridge & Mackey (1993) and Ito et al. (2006):

$$CBW = 59.9\ T_{PB}^{\ 1.8}$$

Channel width (W) was calculated as a function of mean depth (D) and channel sinuosity (sn), following Williams (1986):

$$W = 96\ D^{1.23}\, sn^{-2.35}$$

Meander wavelength (L) was approximated according to Leopold & Wolman (1960):

$$L = 10.9\ W^{1.01}$$

Mean annual discharge (Q) was calculated from Schumm's (1972) formula:

$$Q = W^{2.43}/18(W/D)^{1.13}$$

One of the challenges in interpretation of ancient fluvial systems is to determine the palaeoslope of the channel. Most small outcrops do not provide any opportunity for direct measurements. A relationship between slope, discharge and channel depth was proposed by Leopold & Wolman (1957a, b, 1960), but later variations that also involve grain size diameter can be used successfully to derive other parameters from the thickness of strata. We used Ferguson (1987) formula to approximate palaeoslope (S):

$$S = 0.0049\ d_{50}^{\ 0.52}\, Q^{-0.21}$$

The roughness coefficient (n) was approximated according to Maizels (1983):

$$n = 0.039\ d_{50}^{\ 0.167}$$

The flow velocity of stream (V) was determined with the Gauckler-Manning formula:

$$V = (R^{0.067}\, S^{0.5})\ n^{-1}$$

where R is the hydraulic radius interpreted as mean flow depth (D), due to the cross-sectional geometry of the meandering channel.

The velocity obtained was used to calculate the Froude number (Fr), where g is acceleration due to gravity:

$$Fr = V\ (gD)^{-0.5}$$

4. Results

Three depositional units (U1-U3) were investigated in the central part of the cliff section (Fig. 2) on the basis of major erosive boundaries and lithofacies successions. TL dating (Fig. 2, Table 1) shows that these sediments could be linked to the period from the late Saalian glaciation to the start of the Eemian interglacial. Results of dating showed an interval age of 120±18–265±40 ka. However, the oldest date (265±40 ka) is not representative. Due to the high sedimentation rate, sediment probably was not adequately zeroed, which led to an increase of the age of the strata. Details of palaeohydraulic parameters are presented in Table 2. Sinuosity, calculated for all three units together, amounted to 1.5. The other palaeohydraulic parameters are described below.

4.1. Unit 1

Unit 1, with a mean thickness of 4.2 m, comprises a succession of St→Sp→Sl lithofacies capped by a 20-cm-thick SFr lithofacies (Fig. 2). The St lithofacies attains a maximum thickness of 3 m. The Sl lithofacies, with some organic detritus, is eroded in the upper part. With an erosional boundary that is overlain by a mud layer (Fm) of variable thickness, ranging from several to 30 cm. In turn this is overlain by a *c.* 20-cm-thick layer of well-sorted fine sands with ripple cross-lamination (SFr). This layer is truncated by a second erosional boundary. Median grain size decreases upwards in the unit, from 0.22 mm in the St lithofacies to 0.19 mm in the upper part of the Sl lithofacies and 0.05 mm in the SFr lithofacies. Heavy mineral analysis shows a predominance of garnet (40%), pyroxene (31%) and amphibole (17%). The ratio of opaque to transparent minerals attains a mean value of 0.44. The

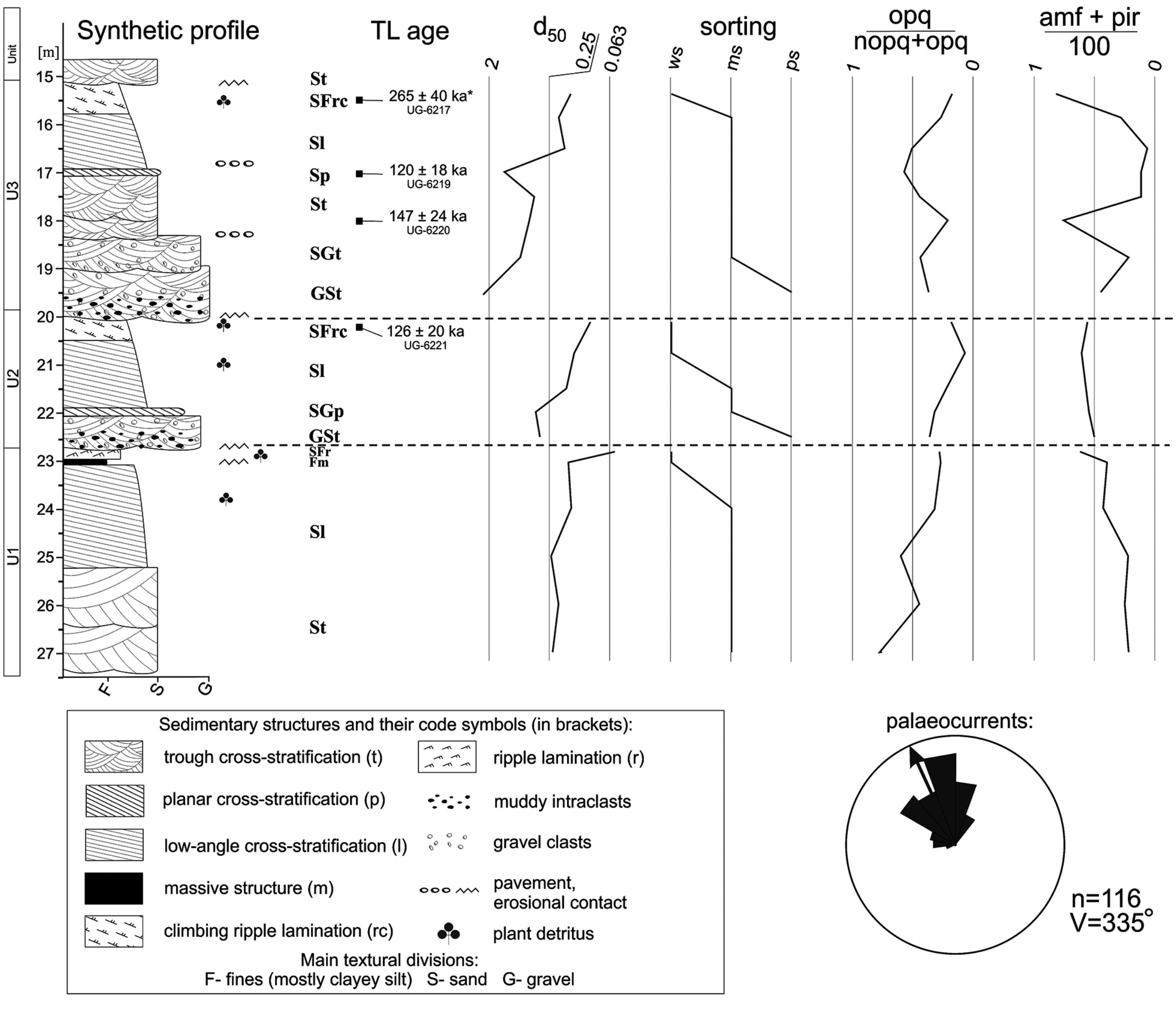

Fig. 2. Sedimentological characteristics of the Chłapowo cliff section. D_{50} is median grain size in mm; sorting is presented as: ws – well sorted, ms – moderately sorted, ps – poorly sorted; opq/nopq+opq is the ratio of opaque heavy mineral content; amf+pir/100 is the ratio of amphibole and pyroxene total content, being an index of less resistant heavy mineral content. Note the specific trends within individual sedimentary units. * – This date is not representative; the sediment probably was not adequately zeroed.

Table 1. TL dating results provided by the Gdańsk laboratory with radionuclide concentrations (Bq/kg) and dose rate, equivalent dose and TL age.

TL sample & depth [m]	No lab. UG	^{226}Ra [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]	Dose rate d_r [Gy/ka]	Eq. dose d_e [Gy]	TL age [ka]
CH – 15.5	6217	4.7±0.4	5.2±0.4	523±37	1.54±0.14	407.8±41.6	265±40
CH – 17.0	6218	4.2±0.3	6.6±0.4	601±38	1.72±0.16	206.9±22.1	120±18
CH – 18.0	6220	4.4±0.3	6.5±0.4	472±35	1.46±0.15	214.0±23.1	147±24
CH – 20.2	6221	6.1±0.4	8.4±0.5	470±38	1.49±0.16	188.1±19.3	126±20

opaque mineral content generally displays an upward-decreasing trend, while amounts of pyroxene and amphibole increase upwards, form 32% in the St lithofacies to 76% in the SFr lithofacies. Palaeocurrent analysis indicates a mean palaeoflow direction to the NNW. The mean depth of the palaeoflow was estimated at 2.9 m, bankfull depth at 4.5 m, mean velocity at 1 m/s and the Froude number at 0.19.

4.2. Unit 2

Unit 2 is formed by a GSt→SGp→Sl→SFrc lithofacies succession with a total thickness of 2.5 m (Figs 2 and 3). Within the poorly sorted, coarse-grained sediments (GSt, SGp), which attains a median grain size of 0.38–0.44 mm, numerous muddy intraclasts of upward-decreasing frequency and diameter (maximum 11 cm) were recorded. Fine-grained sediments in the upper part of unit 2 are partially eroded. The median grain size of the Sl and SFrc facies ranges between 0.12 and 0.19 mm. Pyroxene (41%), amphibole (27%) and garnet (27%) are the commonest heavy minerals. Towards the top of the unit, the content of opaque minerals, with a mean ratio of 0.25, generally decreases, in contrast to the slightly increasing frequencies of pyroxene and amphibole. Palaeocurrent analysis indicates a mean palaeoflow directed to the north. The mean depth of the palaeochannel is estimated at 1.6 m, bankfull depth at 2.5 m, mean velocity at 1.6 m/s, and the Froude number at 0.39.

Table 2. Palaeohydraulic parameters calculated for point-bar sediments in the Chłapowo cliff section. [1] – input data.

Unit	U1	U2	U3
Paleocurrent range [degrees][1]		248-34	
Thickness of point-bar succession, T_{PB} [m][1]	4.5	2.5	5.0
Median grain size, d_{50} [mm][1]	0.179	0.254	0.726
Sinuosity, sn		1.5	
Mean depth, D [m]	2.9	1.6	3.3
Bankfull depth, $D_{max}=T_{PB}$ [m]	4.5	2.5	5.0
Width of the channel, W [m]	139	67	158
Channel belt width, CBW [m]	898	312	1085
Meander length, L [m]	1587	765	1809
Mean discharge, Q [m^3/s]	114	23	152
Slope, S [‰]	0.74	1.24	1.44
Mean flow velocity, V [m/s]	1.0	1.6	2.3
Froude number, Fr	0.19	0.39	0.40

4.3. Unit 3

Unit 3 has an erosional basal contact. The unit comprises gravelly and sandy sediments, 5 m in total thickness, with a preserved succession of GSt→SGt→St→Sp→Sl→SFrc (Fig. 3A). Two lines of boulders, which are concordant with the lithofacies bedding, are present within the succession (Fig. 3E). Sediments of the trough cross strata, 3 m in thickness, are poorly sorted in the lower part, but sorting becomes better upwards. They also include a large number of muddy intraclasts which display, similar to unit 2, an upward-decreasing frequency and diameter. The median grain size of the strata varies from 2.48 mm in the GSt lithofacies to 0.14 mm in the SFrc lithofacies. Heavy mineral analysis reveals a predominance of garnet (43%), pyroxene (28%) and amphibole (22%). The ratio of opaque to transparent minerals attains a mean value of 0.37. Within the trough cross strata, heavy mineral contents are variable. In the upper part of the succession the ratio of opaque to transparent minerals shows a decreasing trend, while amounts of less resistant minerals greatly increase. Palaeocurrent analysis indicated a mean palaeoflow direction to the northwest. The mean depth of the palaeochannel is estimated at 3.3 m, bankfull depth at 5 m, mean velocity at 2.3 m/s, and the Froude number at 0.4.

5. Discussion

5.1. Palaeoenvironment and palaeohydrology

Gravels and coarse sands with trough cross-stratification (GSt, SGt) are interpreted as bedforms that developed in the deepest part of a channel (Fig. 4B). Poor sorting of these sediments suggests a high-energy flow and relatively rapid sedimentation (Ghazi & Mountney, 2009; Ghinassi et al., 2014). An abundance of muddy intraclasts provide evidence of fluvial reworking of floodplain deposits.

The GSt and SGt deposits in units 2 and 3 are overlain by sand with a planar cross-stratification (Sp) lithofacies that may be a record of waning flow. This lithofacies represents small migrating transverse bars or sand waves (Allen, 1964; Todd & Went, 1991).

The medium-grained sand with trough cross-stratification (St) in units 1 and 3 is related to the formation of three-dimensional dunes in a relatively deep channel zone – the thalweg (Allen, 1964;

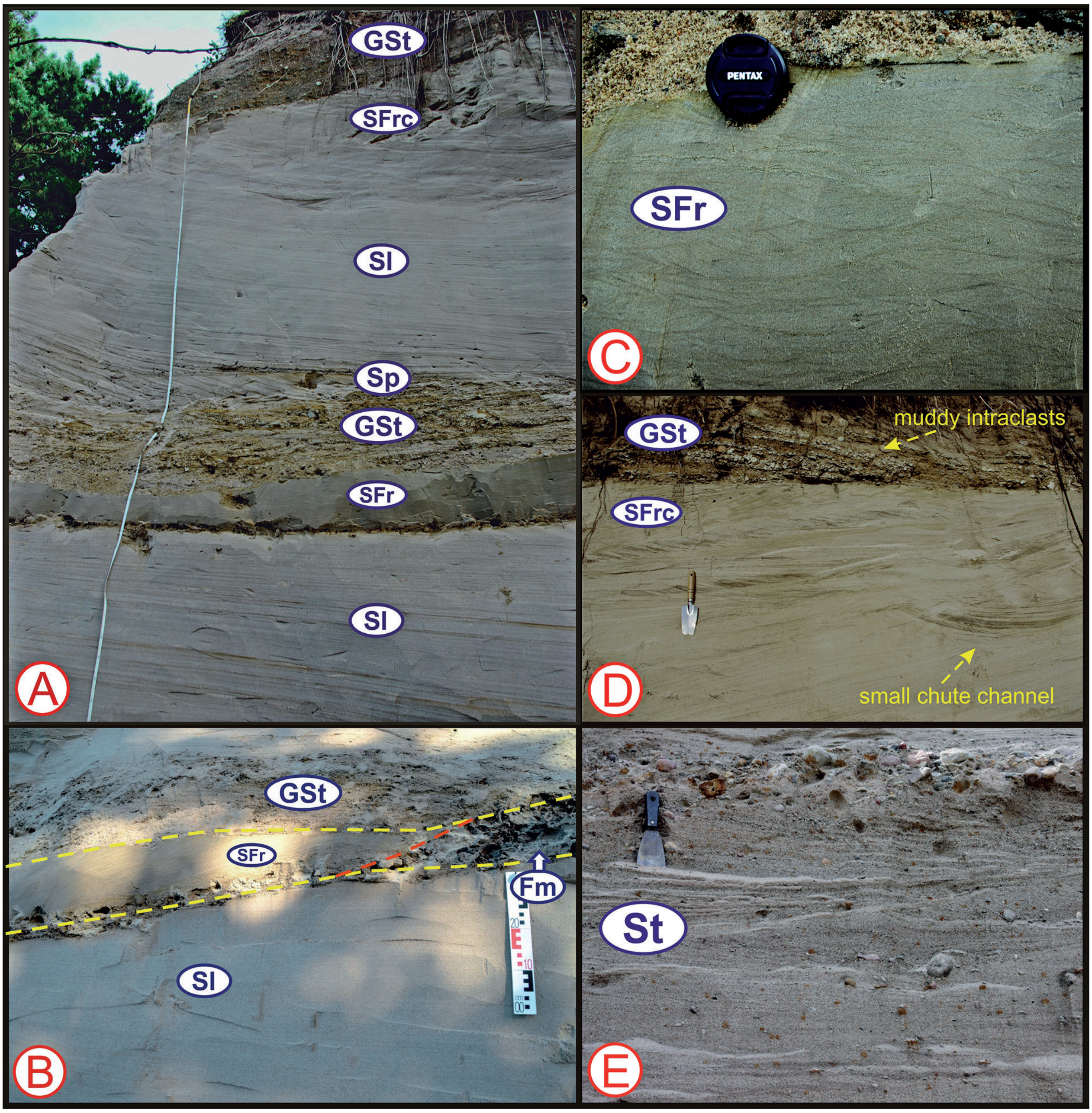

Fig. 3. Photographs showing particular features of point-bar sediments.
A – Transition of lithofacies within sedimentary cycles. Each cycle begins with trough cross-stratified gravels and sands, passing into sands of planar, low-angle cross-stratification and climbing-ripple cross-lamination. Fine overbank lithofacies are also preserved; **B –** Lateral contact of Fm overbank lithofacies (right side) with SFr lithofacies interpreted as part of a crevasse splay; **C –** Internal structure of crevasse splay deposits; **D –** Upper part of point-bar cycles with a small-scale chute channel and climbing-ripple cross-lamination. Note the high content of intraclasts in the lithofacies above the erosional boundary; **E –** Internal features of trough cross-stratification without intraclasts.

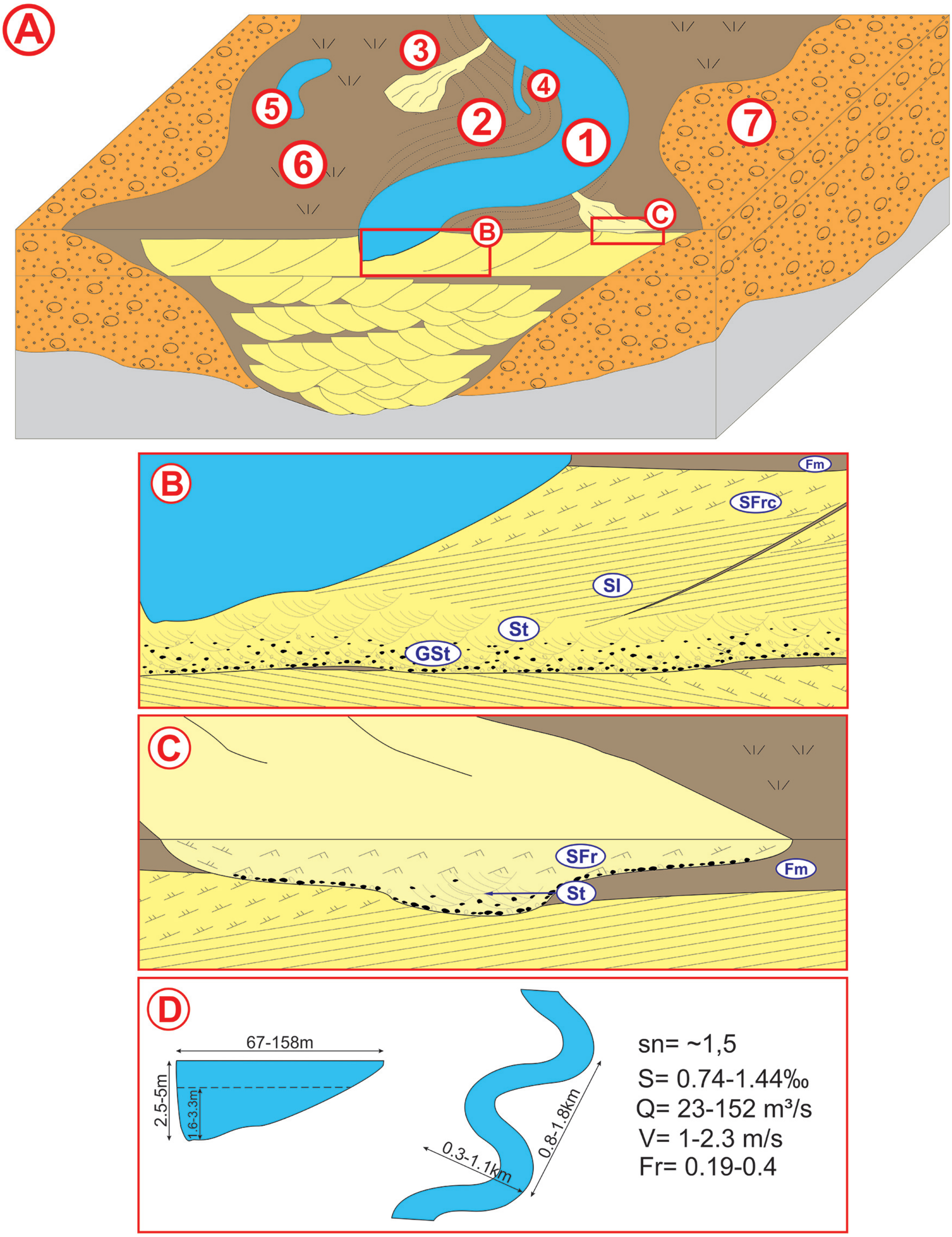

Fig. 4. Interpretative model of the sedimentary environment interpreted.
A – General view of the most important architectural elements: 1- channel, 2 – point bar, 3 – crevasse splay, 4 – chute channel, 5 – cut-off meander, 6 – poorly vegetated muddy floodplain, 7 – older terrace; **B –** Lithofacies succession indicating a typical cycle of meandering river; **C –** Conceptual model of crevasse splay lithofacies; **D –** Most important palaeohydraulic parameters and channel geometry dimensions. All figures are not to scale.

Ashley, 1990; Collinson, 1996). The lack of muddy intraclasts and medium sand may reflect sediment supply at the time of deposition, and probably is not related to a change of flow conditions.

Medium sands with planar, low-angle cross-stratification (Sl) were formed in the transition zone between deep and shallow parts of the channel. The medium sand texture, good sorting and normal grading, suggest a gradually decreasing flow energy vertically in the deposits. Lithofacies Sl was developed mostly under subcritical flow conditions, as a record of washed-out sand waves (Miall, 1996).

Fine silty sands with climbing-ripple lamination (SFrc) are evidence of low flow energy and sedimentation in shallow parts of the channel. The Sl and SFrc lithofacies occasionally include small troughs in their upper parts (Fig. 3), presumably associated with bending flow and development of small-scale chute channels (Ghinassi, 2011; Grenfell et al., 2014).

Massive muds (Fm) are interpreted as fine floodplain overbank deposits, developed in flood periods via suspended sediment transport and deposition. Poor preservation of the Fm lithofacies is linked to the reworking of fluvial sediments from the effect of lateral channel migration within an aggrading depositional environment. This explains why complete overbank successions with palaeosoil horizons are absent.

The SFr lithofacies is interpreted as part of a crevasse splay (Farrell, 2001; Van Huissteden & Kasse, 2001). The lower boundary of this lithofacies was erosional; however, median grain size (0,05 mm) and well-sorted sediment indicate relatively slow and low-energy transport. The superposition to the Fm lithofacies and the erosional contact between them is also important. Palaeocurrents measured within the SFr lithofacies showed different directions of palaeoflows to the channel deposits, with a deviation of about tens of degrees. This interpretation is supported by the widespread, yet discontinuous abundance of this lithofacies within the entire fluvial succession exposed in the Chłapowo cliff section. All these features indicate river flow entering the proximal part of the floodplain. The general concept of crevasse splay formation is presented in Fig. 4C.

Particular units provide a record of cyclic sedimentation, commonly observed in fluvial systems. Successions similar to GSt (St, Sp)→Sl→SFrc→Fm (SFr) have been widely described for meandering river sediments of different ages (Collinson 1996; Miall 1996; Zieliński 1998). In Miall's (1985, 1996) terminology, the succession described above corresponds to the following transition of architectural elements: channel/sandy bedforms CH/SB → lateral accretion deposits LA → floodplain fines with crevasse splays FF (CS).

Meandering processes imposed permanent reworking of sediments, resulting in the low preservation potential of fine floodplain deposits. Abundant intraclasts in trough cross strata are fragments eroded from the floodplain indicative of lateral erosion of fine-grained floodplain deposits. If the sedimentary record covers only channel sediments, correct lithofacies-based interpretation of a fluvial environment may be hindered, as lower parts of sedimentary cycles in braided and meandering rivers could be similar in some respects. For example, both can include St and Sp assemblages, being a record of migrating sand bedforms in the channel (Allen, 1964; Crowley, 1983; Leleu et al., 2009), which is noted primarily in the comparison of straight segments (thalweg zones) of meandering rivers and deep sand-bed braided rivers (Stewart, 1981). Another similarity is the presence of the Sl lithofacies, formed either as the upper part of point bars or as low, washed-out central bars in sand-bed braided rivers (Cowan, 1991).

Sedimentary cycles of meandering rivers display upward-fining trends (Nanson, 1980), related to the distribution of flow energy in relatively deep channels with varied bottom morphology. Coarser particles of sand and gravel were deposited in the thalweg, while finer fractions aggraded in the upper parts of point bars. Heavy mineral analysis indicates that abundances of more/less resistant minerals vary within cycles, showing an enrichment of pyroxenes and amphiboles in the upper parts of cycles. The content of non-opaque minerals increases upwards in the cycles, in contrast to the generally denser opaque minerals (Mange & Maurer, 1992). Heavy mineral distribution depends of the energy that is required for their transport. If the upper parts of sedimentary cycles are eroded, heavy mineral composition is similar in meandering and braided river sediments (Zieliński & Goździk, 2001), particularly when such meandering rivers functioned in a cold, post-glacial period. In that case, the content of particular heavy minerals should be interpreted carefully on account of a marked relationship between their composition and river pattern evolution (Weckwerth & Chabowski, 2013).

A relationship between the trend of fining-upward grain size (one of the main indicators of meandering fluvial environments) and increasing amounts of less resistant minerals, e.g. of amphibole and pyroxene groups was established during the present study. Both gradual, vertical trends as recorded in sedimentary successions are valuable indicators of decreasing flow energy (more precisely, shear stress) that may be related to a meandering style of sedimentation.

Palaeocurrent data obtained for particular units show great dispersion in all directions. However, values obtained only from cross-stratified deposits suggest a relatively consistent palaeoflow vector, with distribution attaining several tens of degrees in the northerly and northwesterly direction (Fig. 2). Such results can be interpreted as a complex multi-directional flow, most likely associated with a meandering rather than a braided river pattern (Ghazi & Mountney, 2009; Salamon & Zieliński, 2010; Fustic et al., 2012). Results of channel slope estimates (0.74–1.44‰) most likely could not be linked to a braided system. However, with reference to Hartley et al. (2010), identification of single sinuous, multiple sinuous or sinuous-to-braided channel patterns seems to be more appropriate. Sinuosity, estimated at 1.5, is a lower boundary value for sinuous rivers (Rust, 1978; Miall, 1996) and may be identified with meandering rivers (Teisseyre, 1985, 1991; Zieliński, 2014). During mean stages, the depth of the channel was 1.6–3.3 m, discharge 22.9–151.6 m^3/s and flow velocity 1–2.3 m/s. The estimated palaeohydraulic parameters (Tab. 2, fig. 4) show that the river functioned within a low-energy system with subcritical flows. The flow regime changed during flood periods, but values presented indicate a meandering rather than a braided fluvial environment.

5.2. Causes of aggradation and sedimentation style

Lithofacies assemblages and preliminary stratigraphical allocation suggest that the river functioned in a cold period, shortly after the Saalian glaciation. Mojski (2005), who summarised investigations of Quaternary sediments in Poland, opined that the morphological surface of Polish Lowlands was partially re-organising following successive glaciations and that most major rivers in Poland generally had constant and comparable outflow directions through the entire Quaternary period.

The river probably evolved in the same valley from a braided pattern during a period of transformation from glacial to interglacial settings. Kozarski & Rotnicki (1977) showed a braided river development at the end of glaciation in the Prosna valley in the Polish Lowlands. Later, a river with large meanders came into being, which then evolved into a medium-scale meandering system. Similar observations in western Europe and North America were made by other authors, who proved that low-energy meandering patterns arose mostly after deglaciations under climatic and sea level changes (Kozarski et al., 1988; Mol, 2000; Blum & Tornqvist, 2000, Gibbard & Lewin, 2002; Kasse et al., 2003). The regional evolution of river patterns with reference to glaciation events and sea level changes is presented in Figure 5.

We deduced that fluvial sediments preserved in the Chłapowo cliff section represent the downstream part of a regional river (*c.* 150–200 km long) with relatively strong flow power. The depth of the river and the determined discharge values surpass modern examples (e.g., Piaśnica, Łeba and Łupawa). This suggests that the river had a diverse discharge network with a lot of tributaries, probably constituting one of the major regional rivers that extended at least from the Pomeranian Lakelands to the Eem Sea.

Based on recent views on Eem Sea palaeogeography (Funder et al., 2002; Head et al., 2005; Makowska, 2009), the transgression reached the area close to the study site. However, there are not enough data on Eem Sea deposits on the northern and western ends of Chłapowo cliff. Reconstructions of river valley system in Poland also show that river systems with an outflow directed to the north-northwest may not have been possible (Marks, 2005; Makowska, 2009). Meandering fluvial sediments recognised in the Chłapowo cliff section demonstrate that existing palaeogeographical models may need to be revised; however, more data from other sites are essential for a proper palaeogeographical reconstruction.

Subsequent fluvial cycles with a similar record of thickness, geometry and lithofacies succession, with minor presence of an overbank subenvironment and a lack of palaeosols, indicate an aggradation stacking pattern (Blum & Tornqvist, 2000). Sediment supply to the Eem Sea was probably high, due to early erosion in the young post-glacial landscape. The river functioned during a cold period, which is demonstrated by the weak chemical erosion of heavy minerals (i.e., high content of pyroxenes and amphiboles) and the lack of organic matter within the overbank lithofacies. Therefore, according to Blum & Tornqvist (2000), when considering stratigraphical, morphological and sedimentological responses, a direct influence of climatic changes on the evolution of the river pattern, probably was less important than of sea level change.

As a rule, the final phases of deglaciations were associated with rapid rises in relative sea level (Rohling et al., 1998). Between the Late Saalian and Ear-

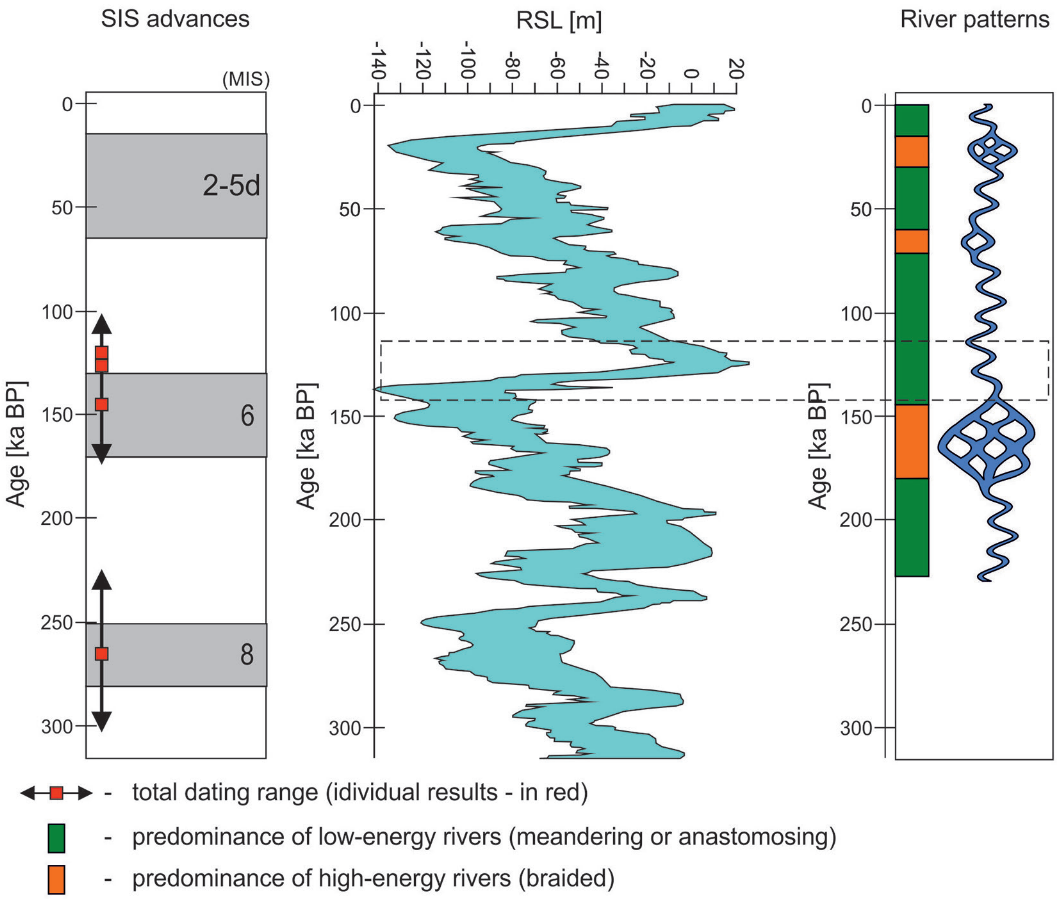

Fig. 5. Compilation of data on advances of the Scandinavian Ice Sheet in Poland, associated relative sea level (RSL) changes and response of fluvial pattern evolution. Glacial episodes (grey colour), correlated with marine isotope stages (MIS), are based on the revised stratigraphic scheme of the Pleistocene of Poland (Lindner et al., 2013). The graph of RSL changes is based on Rohling et al. (2012), who used curves of Waelbroeck et al. (2002), De Boer et al. (2010) and Rohling et al. (2009). Fluvial pattern evolution refers to Central Europe. Data based on the present work and on Krzyszkowski (1990), Mol (2000) and Zieliński (2007). The timespan of processes described in the present study is marked by a dashed rectangle.

ly Eemian sea level rose with a minimum value of 80 m, probably more (about 100–120 m; Rohling et al., 2012, fig. 5). Such a great change led to formation of the Eem Sea, and later, rapid marine transgression onto lowlands in the south (Makowska, 2009; Marks et al., 2014). Deglaciation also led to vertical crustal movements. The Baltic basin was uplifted as a consequence of glacio-isostatic rebound (Forsstrom et al., 1988). During the Late Saalian/Early Eemian the study area situated near the margin of the ice mass. This suggests that the rate of glacio-isostatic uplifting was similar to that during the Late Weichselian/Holocene period, probably surpassing modern rate, which is estimated in the central part of Baltic basin to be 2–4 mm *per annum* (Ekman & Makinen, 1996; Rosentau et al., 2012).

Sea level changes and crustal movements impacted geological processes and the sedimentary record in the Baltic region, including terrestrial environments (Van Andel & Tzedakis, 1996; Marks, 2005; Mojski, 2005). The fluvial deposits studied here showed an aggradation stacking pattern of a downstream fluvial system with well-preserved point-bar cycles. The rate of sea level rise must have compensated the rate of glacio-isostatic uplift of the intracontinental basin to fulfil accommodation space requirements (Coe & Church, 2005a, b). Therefore, strong aggradation with a high preservation potential of point-bar sediments must have resulted mainly from relative sea level rise controlled by global climate changes during the Late Saalian/Early Eemian.

6. Conclusions

The present study provides an interpretation and discussion of Pleistocene fluvial sediments in the Chłapowo cliff section. Lithofacies and palaeocurrent analyses, as well as preliminary dating, provide the basis for the following conclusions.

The sediments investigated formed in a meandering river environment with river outflow directed to the northwest. According to results of palaeohydraulic analysis, the river is interpreted to have been of medium scale, with a mean depth of *c.* 1.6–3.3 m, a mean palaeoflow velocity of 1–2.3 m/s and a sinuosity of 1.5. Formation of a meandering river pattern was made possible by a low-energy gradient and moderate flow amplitudes.

Fieldwork revealed several specific records of point-bars: 1) sharp erosive bases of successions (i.e., palaeochannel bottom surface); 2) general lithofacies succession of GSt (St, Sp)→Sl→SFrc→Fm (SFr) and related architectural elements: channel/sandy bedforms CH/SB → lateral accretion deposits LA → floodplain fines with crevasse splays FF (CS); 3) scattered palaeocurrent directions within cycles; 4) abundance of muddy (floodplain-derived) intraclasts and their upward-decreasing content in channel facies.

Distinction of a meandering river pattern is easier if the upper portions of sedimentary cycles are fully preserved. Textural and mineralogical analyses appear to be useful in identification of meandering river environment as well, revealing the following upward trends within point-bar sediments: 1) grain size fining; 2) increasing content of less resistant heavy minerals; 3) decreasing content of opaque heavy minerals.

The river functioned at the end of the Saalian and at the start of the Eemian, shortly after the retreat of the Scandinavian Ice Sheet, as deduced from TL dating and overlying position of the Weichselian till. In our opinion the good preservation and strong aggradation of point-bar cycles were related to a rapid relative base level rise. The influence of sea level rise on the formation of the river pattern probably was more important than the direct impact of climate change.

Identification of a Late Saalian/Early Eemian meandering river system with outflow directed to the north-northwest implies that existing models of the extent of the Eem Sea and of the regional river network may need revision by addition of data from other study sites.

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