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SEDIMENTOLOGICAL INTERPRETATION OF CREVASSE SPLAYS FORMED DURING THE EXTREME 1997 FLOOD IN THE UPPER VISTULA RIVER VALLEY (SOUTH POLAND)

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Abstract: The paper describes scours and crevasse splays formed at the breaks in embankments of the upper Vistula river valley during the summer 1997 flood. The scours cut into the floodplain composed of fining upward channel and overbank deposits. Erosional furrows have developed locally around the scours. In their vicinity, a thin layer of channel-lag gravel was locally laid down.

Variously shaped crevasse splays were formed: finger-like, deltoidal and tongue-like. Surface relief, vegetation and buildings controlled their geometry and sedimentary features. The lower parts of the deposits consist of fine and medium sands with horizontal and low-angle stratification. Higher in the sequences medium and coarse sands with pebbles display planar cross-stratification. Mud balls and black oak trunks redeposited from older alluvia are common. The whole succession represents sheet-flow sediments with partly channelized flow. Locally, at the top, coarse sands, pebbles, mud balls and boulders embedded in silty-sandy matrix occur, representing slurry-flow deposits. Also present were sediments composed of alternating sands and mud pebbles.

The vanishing flow phase is marked by occasional ripple marks encountered in the top part of the sequence. Around the flow obstacles (plants, buildings) sand shadows were formed, composed of fine and medium sands with horizontal stratification in the lower parts and ripple cross-lamination along with climbing cross-lamination in the upper parts. The top part included medium and coarse sands with planar cross-stratification. Most of the studied sequences showed coarse-upward grading which is not the effect of changes in the energy of flood waters but originates from the supply of all the time coarser material from the successively deepening scours.

Key words: modern river deposits, crevasse splays, Holocene, Vistula valley, Southern Poland

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INTRODUCTION

The July 1997 flood in the Vistula valley was caused by intensive rainfall in the Carpathian part of the Vistula drainage basin. The study area included a reach of the Vistula river valley between the confluences with its two Carpathian tributaries: the Dunajec and Wisłoka rivers (Fig. 1). Here, embankment breaks resulted in formation of interesting erosional (scours) and depositional (crevasse splays) landforms. Their morphology and general conditions of origin are described in a previous paper (Gębica & Sokołowski, 1999). The aims of present study are to give a description of various structures and sedimentation conditions of the crevasse splays.

Erosional and depositional landforms of overbank flooding are well known from both, modern rivers (e.g., Coleman, 1969; O'Brien & Wells, 1985; Farrel, 1987; Florek *et al.*, 1987; Ritter, 1988; Teisseyre, 1988; Gomez *et al.*, 1997; Gębica & Sokołowski, 1999) and ancient deposits (e.g., Cherven, 1978; Fielding, 1984; Doktor & Gradziński, 1985, Smith, 1987; Platt & Keller, 1992; Brodzikowski *et al.*, 1997). Comprehensive descriptions of the crevasses can be found, among others, in: Allen (1965), Elliott (1974), Bridge (1984), Miall (1996) and Zieliński (1998).

CHARACTERISTICS OF THE STUDY AREA

The study area is located in the foreland of the Carpathian Mts., in the upper Vistula river valley, between the mouths of its Carpathian tributaries: the Dunajec and Wisłoka (Fig. 1). The Vistula river valley, cut into Miocene clays, is filled with alluvial terraces of Vistulian and Holocene age

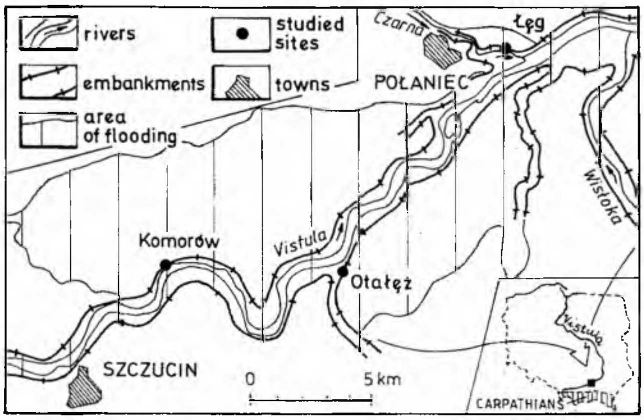

Fig. 1. Location of studied sites against the extent of the July 1997 flood in the Vistula valley (by Gębica & Sokołowski, 1999 – modified, simplified)

Table 1

Lithofacies code – texture codes (by Miall, 1978 with modifications by Zieliński, 1995)

Code	Graining
GS	sandy gravel
SG	gravelly sand
S	sand
SGD	diamictic gravelly sand
S/G	alternating sand and mud pebbles
FS	sandy silt
S	silt

Table 2

Lithofacies code – structure codes (by Miall, 1978 with modifications by Zieliński, 1995)

Code	Sedimentary structures
m	massive structure
h	horizontal stratification
w	wavy lamination
r	ripple cross-lamination
rc	climbing ripple cross-lamination
l	low-angle cross-stratification
p	planar cross-stratification
t	trough cross-stratification
i	very large-scale inclined cross-stratification

(Sokołowski, 1987; Gębica & Sokołowski, 1999). Numerous traces of abandoned channels can be found on the Holocene floodplain, which rises 3–4 metres above the recent river bed. The floodplain is built of channel deposits covered by overbank deposits of total thickness from several to almost 20 metres. The lowermost part of the sequence comprises sandy gravels of mean grain diameter about –2.1 Φ (4.29 mm). Single boulders observed in the bottom originate from the washed-out glacial sediments from Sanian (= Elsterian) Glaciation. Up the sequence, gravelly sands appear followed by sands of mean grain diameter from –0.2 to 2.5 Φ (1.15–0.18 mm). The overlying overbank loams show mean grain diameter between 4.1 and 7.7 Φ (0.058–0.0048 mm). The thickness of these sediments varies from 1 to 5 metres. Abandoned channels are filled with dark, organic-rich clays, muds, gyttja and peat.

The whole reach of the river valley is a farmland. Embankments, 4.5–5 metres high and at a distance of 50 to 250 metres from the river course, frame the river channel. The interembankment zone may accommodate a floodwater of 1% occurrence probability (i.e. of the recurrence interval 100 years). The gradient of the river channel is 0.28‰. During floods the river transports by bedload sediment of mean grain diameter between –0.3 and 2.3 Φ (1.2–0.20 mm). Grains larger than 2 centimetres are very rare.

The embankments were broken on the floodplain, some tens of metres from the channel, always at the point bars of abandoned channels. The direct reason of breaching was liquefaction and suffosional washing of alluvial loams and sands forming the substratum of embankments. It is possible that landslides of the bank slopes might have played some role also. The breaks in the embankments resulted in the formation of scours and crevasse splays. The largest splay was deposited at Komorów site, smaller ones were observed at Otałęż and Łęg sites.

METHODS AND TERMINOLOGY

The studies on the structure of the newly formed crevasse splays have started just after the retreat of flood waters. The fully developed forms could not be investigated. Before the complete drop of water table, technical services have commenced reconstruction of embankments and resilting of scours, which resulted in almost complete destruction of the forms near the scours as well as partial destruction of crevasse splays. Our field work included mapping of the preserved forms. Additionally, over 30 ditches were dug down to the bottom of the crevasse splay sediments. Sediments exposed in the ditches were described and photographed, cross-stratifications were measured and samples were collected for grain-size analyses.

Lithofacies encountered in the crevasse splays were described using letter codes proposed by Miall (1978) and Zieliński (1995, see Tabs 1, 2). Main size fractions were described mezoscopically and named according to the Friedman & Sanders (1978) terminology. Indices proposed by Folk & Ward (1957) were applied in the grain-size analyses. Grain-size analysis was done by sieving but only for sediments devoid of soil aggregates, mud balls and boulders.

Thicknesses of lithofacies were categorized according to Zieliński (1995) as: small scale (<6 centimetres), medium scale (6–30 centimetres), large scale (>30 centimetres) and very large scale (>1 metre).

Noteworthy are mud gravels alternating with sand, labeled with atypical but useful code *S/G,* most accurately reflecting the character of the rock. The gravels form thin (up to several centimetres) layers, composed mostly of soil aggregates (mud aggregates, pedogenic aggregates – see Rust & Nanson, 1989; Maroulis & Nanson, 1996; Gibling *et al.*, 1998). The soil aggregates derived from washing-out of alluvial loams and from the embankments. As the size of typical soil aggregates may be variable, particularly in the areas of intensive agriculture, this term was conventionally limited to the fragments less than 2 centimetres across (gravel diameter).

In the thicker layers – up to a dozen of centimetres – the soil aggregates, mud balls and sporadic pebbles are additional components. Mud balls, occasionally armoured, consist of various materials: alluvial loams, oxbow clays, oxbow loams and loams forming the embankments. Mud balls which sometimes form layers of intraformational gravels or conglomerates were commonly observed in river sediments but were usually described as channel-lag deposits, fillings of erosional furrows and plunge pools or as single fragments (see e.g., Allen, 1964; Williams, 1966; McKee *et al.*, 1967; Karcz, 1969, 1970; Gradziński, 1970; Doktor & Gradziński, 1985; Plint, 1986).

Although density of soil aggregates and mud balls differ from those of sand and gravel grains, all these sediment components reveal a similar behaviour in water current (cf. also Maroulis & Nanson, 1996; Gibling *et al.*, 1998).

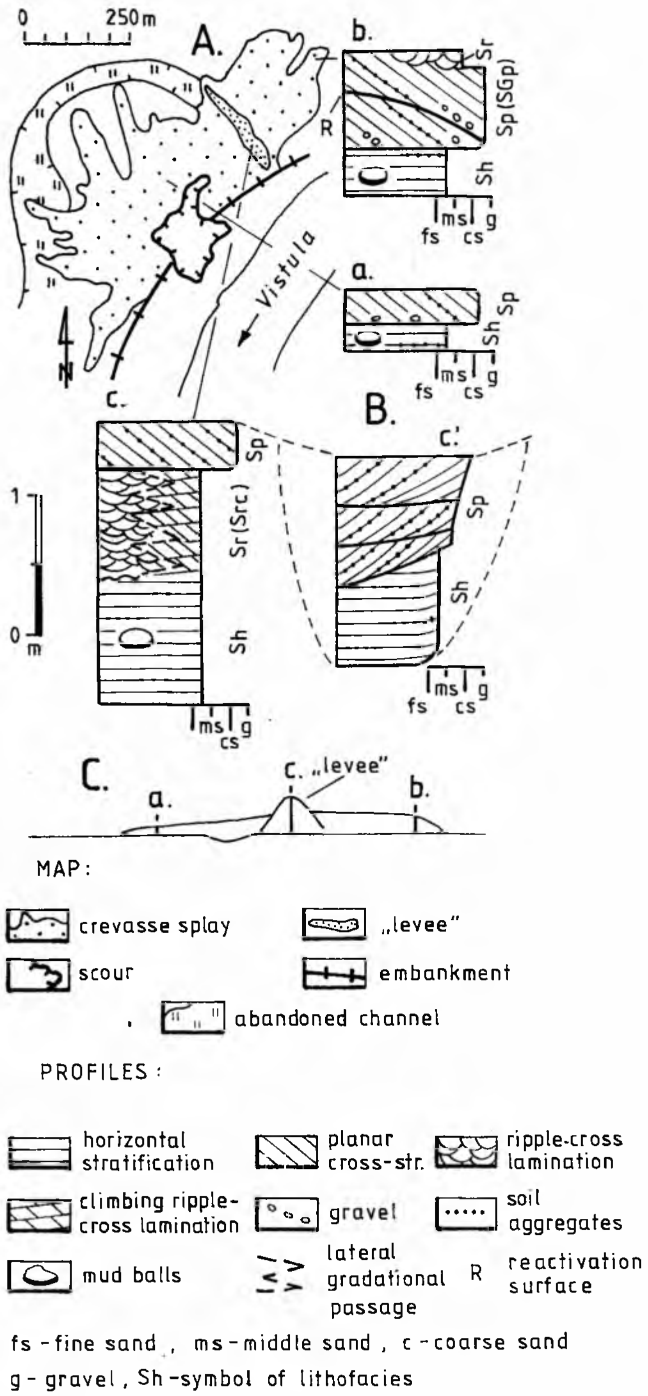

Fig. 2. Scour and crevasse splay (**A**), typical successions of lithofacies (**B**) and schematic (not to scale) profile of crevasse splay in Komorów site (**C**). (A – by Gębica & Sokołowski, 1999 – modified, simplified)

DEPOSITS AND SEDIMENTATION OF CREVASSE SPLAYS

Komorów site

The shapes of crevasse splays vary due to the surface morphology, the presence of buildings and clusters of trees and bushes (Gębica & Sokołowski, 1999). The latter two factors played decisive role in the formation of finger-like shape of the splay in Komorów whose longest, NE-trending finger extends over 600 metres. The generally flat surface of the splay was disturbed by sand shadows behind the buildings or tree clusters. The largest set of connected shadows resembling a natural levee (length 225 m; max. width 35 m; max. height – i. e. elevation of levee crest above floodplain – 2 m) was formed in the eastern part of the splay (Fig. 2A). We are using the term levee, although the described form did not fully correspond to the levee definition (cf. Brierly *et al.*, 1997).

Deposits

In all outcrops the lowermost part of the succession included uniform, fine to medium sand (mean diameter from 1.2 to 2.2 Φ, i. e. 0.43–0.22 mm), well and moderately well sorted (σ = 0.4–0.7). The sand forms a set of medium- and large-scale horizontal stratification (*Sh* lithofacies). It was characteristic of all the splays (Fig. 2B). Stratification was poorly marked although, locally, much more distinct due to the presence of discontinuous laminae, up to 4 millimetres thick, composed of soil aggregates. Locally, the sand graded upward into the *Sl* lithofacies of identical grain-size. Exceptionally, sand did not show distinct structures (*Sm* lithofacies).

Sand contained scarce plant detritus, small trunks of black oaks and mud balls. Mud balls occurred individually or in clusters consisting of several forms ranging from a few

Fig. 3. Komorów site, proximal part of splay, in lower part of profile: substratum of splay deposits (mud), in middle part: horizontally stratified sand (lithofacies *Sh*), at the top: gravelly sand (lithofacies *SGp*). Paddle is 30 cm high

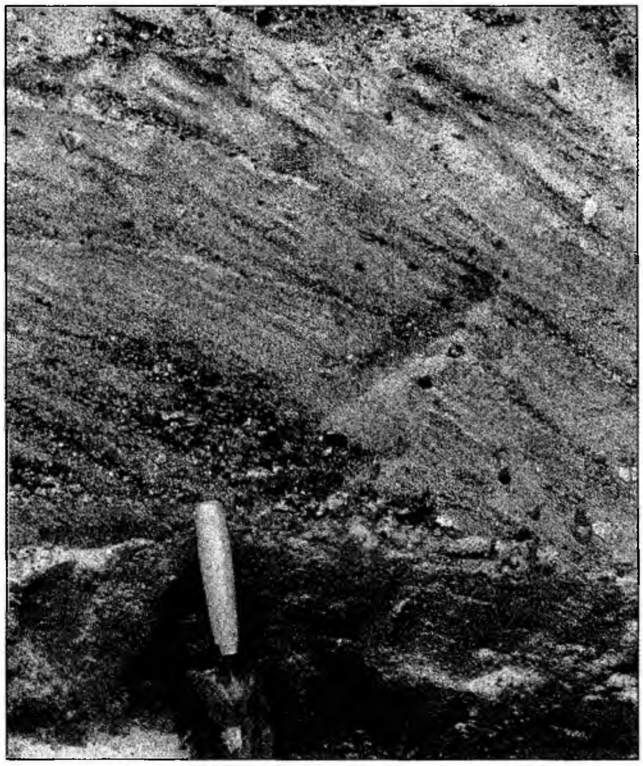

Fig. 4. Komorów site, front of splay, reactivation surfaces. Paddle is 30 cm high

to a dozen of centimetres across. The mud balls of similar size in horizontally stratified sand deposits were reported by McKee *et al.*, (1967).

In proximal splay the thickness of deposits was low – from several to 30 centimetres. In thicker sequences, the *Sh* lithofacies or *Sh* → *Sl* succession (which constitutes about half of the total thickness) were overlain by a single, planar cross-stratification set composed of medium and coarse sand (*Sp*), occasionally with pebbles (*SGp* lithofacies – Figs 2Ba, 3). Maximum dip of laminae whose contacts with set base are angular, may reach 28°. Some laminae are composed of soil aggregates.

Towards the distal splay, the thickness of deposits gradually increased up to about 1 metre. Moreover, structural and textural diversity was also higher. The *Sh* (*Sl*) lithofacies was covered by medium and coarse sand (*Sp* lithofacies) or sand with pebbles (*SGp* lithofacies). The sediments belonging to the *Sp*, *SGp* and *St* lithofacies are apparently coarser-grained than the above described *Sh* and *Sl* ones (mean diameter is from –1.5 to 1.9 Φ i. e. 2.83–0.27 mm) and, at the sometime, poorly sorted (σ = 0.3–2.1).

The sets of planar cross-stratification formed several, distally aggrading layers. Locally, progradation took place, accompanied by formation of reactivation surfaces (Fig. 2Bb) among which erosion surfaces at a lower angle than cross-beds and downstream fining in groups of cross-beds (Fig. 4) were distinct (according to classification of Allen, 1982). Logs of black oaks appeared rarely in the lower part of the sequence causing some irregularities in stratification.

In the upper parts of the sequences, medium- or large-scale *St* lithofacies was a rare component. Locally, the last, uppermost unit was medium-sand *Sr* lithofacies.

Among the textural features of crevasse splays noticeable was the inverse grading with the coarsest grain size in the *Sp* and *St* members and, where ripple marks were present, the pennsymmetric grain-size distribution with the coarsest grains in the *Sp* coset.

Levee sediments forming a ridge located in the eastern part of the splay and composed of several coalesced sandy shadows show different characteristics. Total thickness of these deposits reached about 1.8 m. Lateral variability was clear, which allowed distinguishing two genetically different sediments – sand shadows and inter-shadow channels.

The sand shadows are bulges developed behind trees or bushes, composed of vertical succession of *Sh* → *Sr (Src)* → *Sp (S/Gp)* lithofacies (Fig. 2Bc). The *Sh* lithofacies occurred in the bottom half of the succession, as in other forms. The overlying fine and medium sand (*Sr* lithofacies) and rare *Src* (type A) were obscured and only locally distinct due to rather uniform grain size. Higher in the sequence the *Sr* (*Src*) lithofacies graded into medium and coarse sand (*Sp* or *S/Gp* lithofacies), mostly medium-, rarely large-scale sets (Fig. 5). The inter-shadow channels were filled with sand of *Sh* → *Sp (S/Gp)* lithofacies succession (Fig. 2Bc'). In deposits of *Sp (S/Gp)* lithofacies, miniature deltas with fronts dipping obliquely to the axes of shadows were observed.

Filling of inter-shadow channels up to the level of the shadows caused junction of both forms and development of a ridge transversal to the axes of shadows and inter-shadow channels. Such ridge resembles the natural levee but in both, shadows and inter-shadow channels, coarsening-upward grading and increasing scale of stratification were observed. Thus, these sequences differ from typical natural levees. Moreover, the *FSh, Fh* or *Fw* lithofacies, or sand/mud rhythmites are absent (see e.g., Coleman, 1969; Klimek, 1974; Cherven, 1978; Farrel, 1987).

Sedimentation

At the initial stage the crevasse splay was formed in sheet-flow environment, which is documented by the common occurrence of *Sh* lithofacies in the bottom part of the sequence. Accumulation proceeded in supercritical flow, under the conditions of upper stage plane bed. Apart from the structures, a high flow energy is suggested by the presence of mud balls, up to a dozen of centimetres in diameter. The *Sl* lithofacies formed under similar conditions although its formation mode is not explicit. It might have originated from washed-out dunes (diminished dunes) or from antidunes. The latter interpretation is supported by the observed opposite inclinations of the layers which may suggest the presence of low-angle foresets or backsets. The increasing flow power related to the antidunes can be explained in terms of a diversified flow resistance. During the formation of *Sh* lithofacies, which occupied bottom part of the sequence, the substratum roughness was much higher due to the presence of ploughing furrow-slices and vegetation.

The lack of obstacles on land surface which could disturb the sheet-flow in the close vicinity of the scour caused that the splay developed initially as a form resembling a radiating delta-like fan (Coleman, 1969). The obstacles located in some distance from the scour led to distinct channeling of flow. Material transported by individual streams was laid down in isolated fingers, which, in turn, resemble a single-channel crevasse splay (see Coleman, 1969). Flow channeling is documented also by the *Sp* and *(SGp)* lithofacies, which constitute significant part of the fingers. Dip of laminae in the sets reached as much as 34°, which points to a small depth at crest during their deposition (Smith, 1972) as well as to a low flow rate (Jopling, 1965). The presence of reactivation surfaces may point to local changes in flow intensity and in water depth (Allen, 1982; Collinson, 1986).

In the upper portions of the splays the *Sr* lithofacies appeared (particularly in their distant parts) as a result of vanishing flow. Thickness of deposits increased along the course of stream and reactivation surfaces appeared at the steep margins of the fingers.

The vertical lithofacies sequence of fingers shows many similarities to sequences reported from transverse sand bars (or linguoid bars) of braided rivers. Both resulted from the similar mechanism of growth and decline, controlled by the same factor. Decreasing intensity of flood flow led to the development of prograding-aggrading forms.

The flow obstacles mentioned above were responsible for the formation of sand shadows, particularly those resembling natural levees. They are similar, to some extent, to the forested bank ridges (see Teisseyre, 1988) where flood waters may reach high flow rates. The appearance of *Sh* lithofacies seems to support such an interpretation, at least at the initial stages of development. Identical lithofacies in shadow deposits and in inter-shadow channels points to similar initial flow power. Flow diversity appeared somewhat later. The formation of levees must have been a very quick process – the lack of pebbles indicates that it had to be completed before the scour excavated the coarse material.

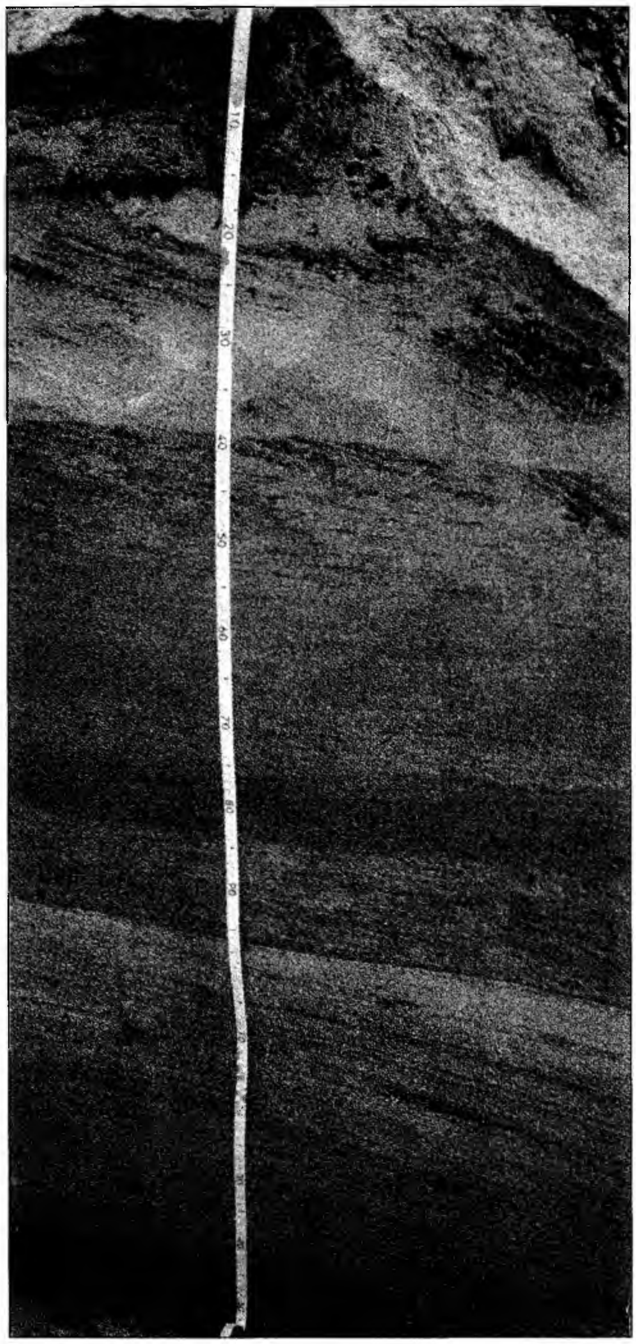

Fig. 5. Komorów site, "levee" deposits, in lower part of profile: horizontally stratified sand (lithofacies *Sh*), in middle part: sand with ripple-cross-lamination (lithofacies *Sr*), at the top: sand with planar cross-stratification (lithofacies *Sp*). Outcrop is 150 cm high

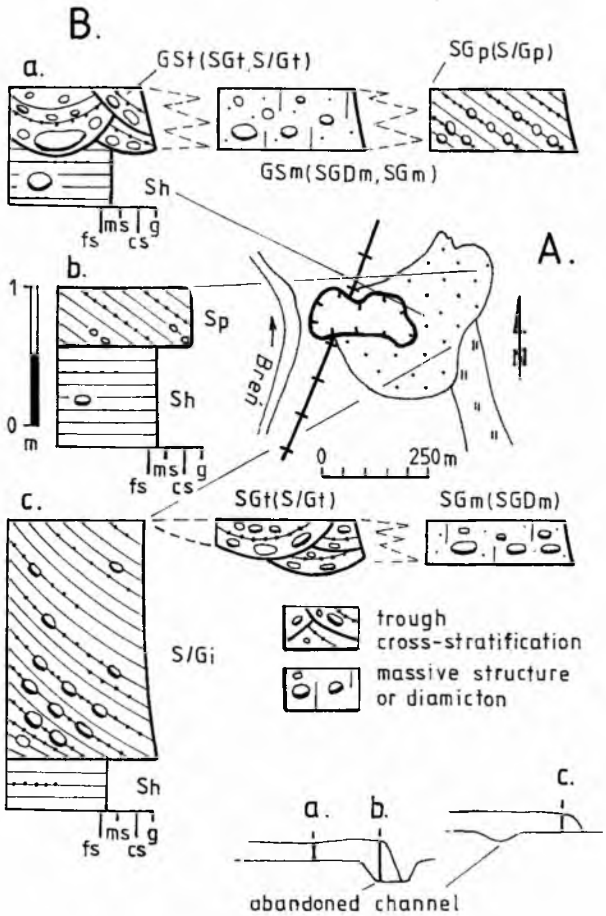

Fig. 6. Scour and crevasse splay (**A**), typical successions of lithofacies (**B**) and schematic (not to scale) profile of crevasse splay in Otałęż site (**C**). Other explanations as in Fig. 2. (A – by Gębica & Sokołowski, 1999 – modified, simplified)

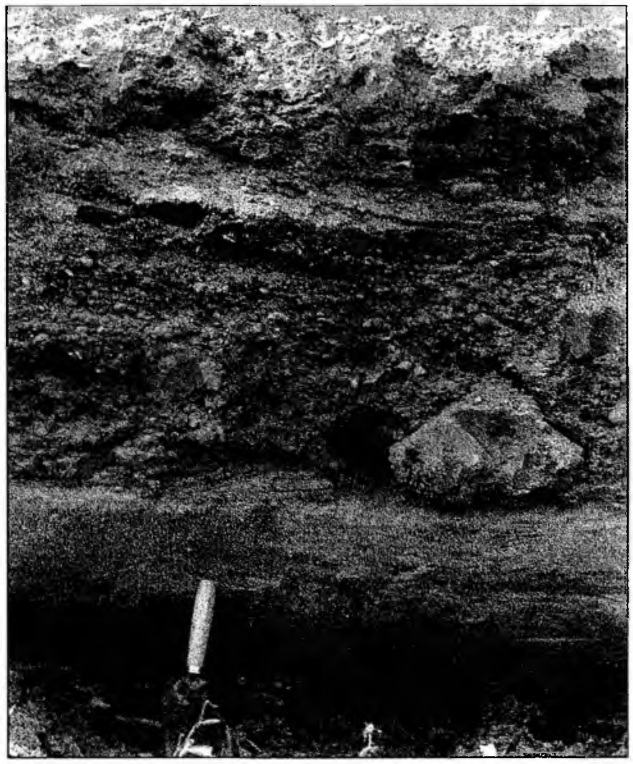

Fig. 7. Otałęż site, middle part of splay, in lower part of profile: horizontally stratified sand (lithofacies *Sh*), at the top: sandy gravel (lithofacies *GSm*) and diamictic gravelly sand (*SGDm*) – slurry-flow deposits. Paddle is 30 cm high

Both the intensive aggradation and rapid deposition are confirmed by the presence of *Src* lithofacies (see e. g. Ashley *et al.*, 1982) and the appearance of *S/Gp* lithofacies in the top.

Otałęż site

The crevasse splay was fan-shaped (Fig. 6A), resembling the radiating delta-like fan (see Coleman, 1969) or deltaic and alluvial cones (see Zwoliński, 1992). The regular shape of the splay resulted from two factors. The first is the lack of pronounced obstacles on the land surface, which would disturb the flow of flood water. The second is the adjustment of the splay to the relief. The existing, meandering abandoned channel highly vegetated by willow thickets and trees (poplars and alders) stopped the accumulation along the arcuated margin. Here, the height of the splay reached maximum (over 2 metres).

Deposits

As the proximal splay was destroyed, the authors could study only its distal parts. Here, the thickness of sediments slightly exceeded 1 metre. Above the sands of the *Sh* lithofacies, which constitute approximately half of the sequence thickness, the sediments of highly variable character were found: coarse sands, sands with gravels and even gravels. According to E. Smolska (pers. comm., 1999), the longer axes of gravel grains did not show any orientation. Instead, the gravels revealed medium- or large-scale trough stratifications, rarely planar cross-stratifications. Lateral transitions were observed to massive structures or diamictic sandy pebbles embedded in silty-sandy matrix. Generally, the *GSm*, *SGm SGDm* and *SGt*, *GSt*, *St*, *SGp*, *GSp*, *Sp* lithofacies were noticed together with the *S/Gt* or *S/Gp* sets (Figs 6Ba, 7). The lithofacies contained numerous mud balls and single boulders. The largest mud ball encountered in the study area was 1.3 m in diameter, slightly flattened and composed of dark, almost black, mud with abundant plant remains which points to the fine deposits of an abandoned channels as material source.

Sediments of the splay front showed diversity controlled by the substratum relief. In places where material was accumulated onto a flat surface and deposition was not affected by plants, the thickness of the splay margin sediments reached almost one metre. In the upper parts of the *Sh* → *Sp* succession, coarser sand with medium- to large-scale planar cross-stratifications was laid down (Fig. 6Bb).

In a place, where the front of deposition reached an abandoned channel with willows, the thickness of sediments slightly exceeded 2 metres. Similarly to other outcrops, bottom part of the sequence was occupied by the *Sh* and *Sl* lithofacies. Above, perfectly developed *S/Gp* and *S/Gi* sets were deposited (Figs 6Bc, 8). Thickness of the set in the point bar of abandoned channel varied from 80 to 110 centimetres and increased to about 170 centimetres in the axial part of the channel. The layers showed distinct changes in deltaic-type inclination grading downward from typical foresets through toesets to bottomsets.

In the top part of the sequence, the *Sm*, *SGm* or *SGDm* lithofacies were locally present, thick at several to almost 30 centimetres. These parts of the splay were usually damaged during embankment reconstruction. Occasionally, normal grading was observed. Laterally, the sediments passed into texturally similar *SGt*, *St* or even *S/Gt* lithofacies.

Close to the distal splay, the preserved fragments of the splay top surface showed diversity due to local, depositional or erosional character. Depositional surface included ripplemarks. Occasionally, whole ripplemarks or their troughs were draped with mud (see Williams, 1966; Karcz & Goldberg, 1967), which represented the *FSw* and *Fw* lithofacies.

Local erosion was suggested by the presence of large (from a dozen to some tens of centimetres across) mud balls resting upon the splay surface and more rare boulders surrounded by current crescent (Allen, 1982). In other places pebble pavements formed on the splay surface, indicated washingout of top layers.

Sedimentation

Development of the crevasse splay at Otałęż differed from that at Komorów. The combined effect of an abandoned meandering channel and vegetation forced the deltaic shape of the splay and led to the maximum thickness of splay deposits in the area of the abandoned channel. Very interesting features are the *S/Gp* and *S/Gi* sets deposited on the outer-splay. As these sets appear close to the margins of an abandoned channel, deposition proceeded due to progradation of an almost classic, Gilbert-type delta. Changes in foreset angles and their transition into classic toesets and bottomsets (S-shaped) in the lower parts of the sequence correspond to the model of Jopling (1965, 1966).

Moreover, both the sandy layers and the mud gravels, commonly formed discontinuous accumulations, lenticular in sections parallel and normal to the current. In horizontal sections both forms were bent and convex towards the current. Considering also the high-angle foresets (locally up to 30°) it is suggested that sandy layers and mud gravels resulted from subaqueous sand-flows (Buck, 1985; Hunter, 1985) developed over dune slip faces. Relatively thick individual foresets can be explained in terms of distinct variability in size and density of grains forming the individual layers (Buck, 1985; White, 1992).

The sediments of very high lithofacies diversity, with large mud balls and boulders, locally encountered in the top of the sequence represent slurry-flow deposits. Low thickness, absence of distinct erosional contacts with the substratum, sheet-like geometry and local fractional grain-size, resemble the sediments described by Nemec & Muszyński (1982) as transitional between debris-flow and stream-flow products, deposited from sheet flows of high density. The authors are of opinion that such conditions may have occurred when a successive fragment of the flood bank collapsed into the scour or, which seems more probable, when a scoured fragment of pre-flood alluvial loams has fallen down. Washout of such material increased sediment concentration within the flow. It seems that the entire crevasse splay from Otałęż formed under predominating sheet-flow conditions. The scale of flow channeling was much lower in comparison to the Komorów splay.

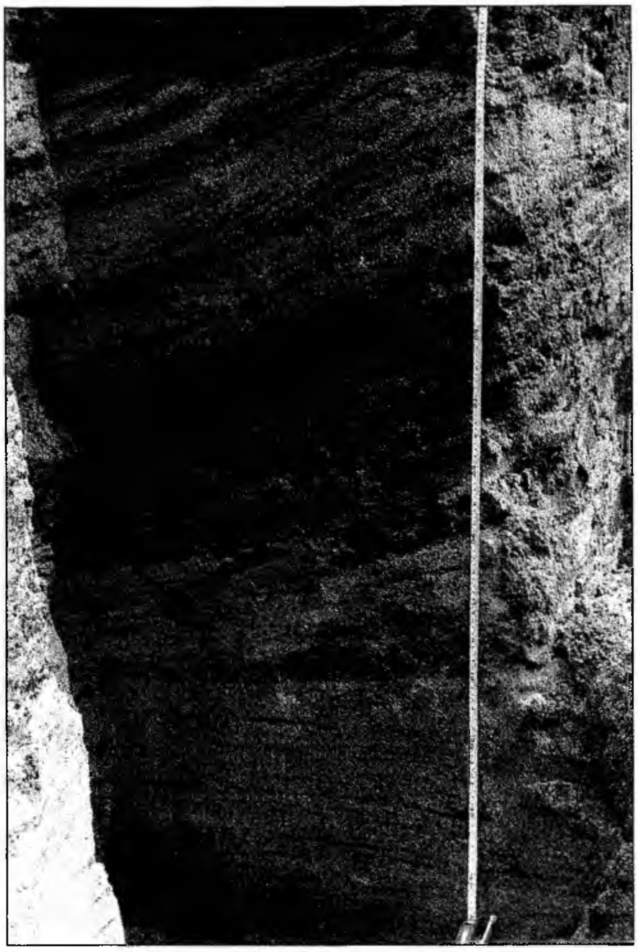

Fig. 8. Otałęż site, front of splay, vertical sequence: in lower part of profile – horizontally stratified sand (lithofacies *Sh*), in middle part – sands and mud gravels (*S/Gp*) – Gilbert-type delta deposits, at the top – *SGm* lithofacies – slurry-flow deposits. Outcrop is 150 cm high

The Otałęż splay provides the best record of the stage of water withdrawal and vanishing of flood. Some initial erosion is indicated by the formation of current crescents around the mud balls and boulders, and pavements on gravel-sand deposits. Somewhat later the lowest-energy sediments of the splays were laid down (i.e. sands with ripple cross-lamination). With almost complete vanishing of the flow, deposition from suspension has started, that resulted in the formation of muds belonging to the *FSw* and *Fw* lithofacies.

Łęg site

At the confluence of the Czarna and Vistula rivers the flood waters were swelled by the Vistula backwater, which resulted in several embankment breaks. A distinct crevasse splay formed at only one break, on the left bank of the Czarna. Development of the splay is an interesting as it ex-

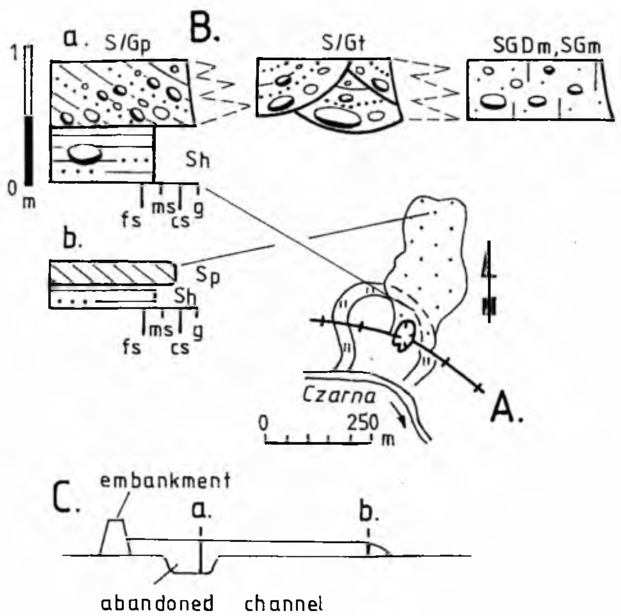

Fig. 9. Scour and crevasse splay (**A**), typical successions of lithofacies (**B**) and schematic (not to scale) profile of crevasse splay in Łęg site (**C**). Explanations as in Figs 2 and 3. (A – by Gębica & Sokołowski, 1999 – modified, simplified)

ceeds the inner part of palaeomeander. Splay deposits initially filled a part of the Czarna abandoned channel, then expanded outside the channel and formed a flat, tongue-shaped splay (Fig. 9A).

Deposits and sedimentation

In the proximal part of the splay located in the Czarna river abandoned channel the deposits were up to 80 cm thick. Above the *Sh* lithofacies, up to 40 cm thick, alternating sands and mud gravels (*S/Gt* and *S/Gp* lithofacies) display medium-scale trough cross-stratification and, less often foresets of planar cross-stratification (Fig. 9Ba). Infrequently the *Sh*, *Sl*, *SGm* and *GSm* lithofacies occupied the bottom part of deposits.

Up the sequence, increasing amounts of mud balls appeared. The largest, somewhat flattened ball reached one metre across. In the upper part of the sequence relics of the *SGm* and *SGDm* lithofacies were preserved, very similar to those found in Otałęż. Unfortunately, the sequence available for studies was incomplete as the uppermost 40–50 centimetres were destroyed during the reconstruction of embankments. Outside of the abandoned channel, the thickness of sediments was usually less than 30 centimetres. Vertical *Sh* → *Sp* succession of lithofacies was common (Fig. 9Bb).

The features described above allow a conclusion that the slurry flow deposits occur in the study area. The most intense sedimentation took place immediately behind the scour due to the obstacle to flow from the abandoned channel scarp and, partly, from vegetation. Therefore, in the abandoned channel the sediments attained their maximum thickness. After flowing through the channel the flood waters lost energy and were channeled. Thus, the splay formed outside the abandoned channel has limited area and low thickness, decreasing distally.

DISCUSSION AND CONCLUSIONS

The splays described above corresponding to overbank deposits only in their position and cannot be regarded as simple analogues of natural landforms (cf. e. g. Allen, 1965; Coleman, 1969; Farrel, 1987; Miall, 1996; Zieliński, 1998). Differences are in more common large-scale sedimentary structures and coarser grain size, which corresponds to that of channel deposits. Even more remarkable differences are: (i) supply of coarse material from deep scours (especially boulders), (ii) intensive washout of overbank fines and soil from floodplain and embankment, which increased sediment concentration within the flow (the presence of slurry-flow deposits) and appearance of soil aggregates, alternating mud gravels and sands as well as mud balls, (iii) high energy conditions of waters abruptly breaking through the high embankments in comparison with waters washingout the lower, natural levees (about 1 m high).

The studied landforms and sediments were deposited in a high-energy environment. The principal factors were: (i) very high hydraulic slope of floodwaters swollen between the embankments and (ii) high water density. In most publications cited above, the horizontally stratified sand lithofacies (*Sh*) was regarded as typical of the crevasse splays. The same is valid for the studied splays, as all of them contain this indicator lithofacies in the bottom of the sequences. This initial stage of splay development is, therefore, represented by sheet-flow deposits formed in supercritical flows, under the conditions of upper stage plane bed.

Other feature common for studied splays is the coarse-upward gradation, which can be linked to the supply of coarser and coarser material during the deepening of the scours. Also McKee *et al.* (1967) suggested that changes in grain size are not necessarily the effects of floodwater dynamics but may result from the type of washedout sediments.

Despite the similarities, the authors conclude that further stages of development of the three studied crevasse splays differed and were controlled by the relief (abandoned channels), vegetation and land development (particularly buildings). These factors provided obstacles to the flood flow and influenced decisively the shapes and ranges of splays as well as deposition and structures of sediments.

Evidently, geomorphic processes active in anthropogenic environment reveal particularly high intensity. Breaking of embankments and the resulting rapid water flow may be, to some extent, compared to small water dam catastrophes. The forms produced during such events cannot be correlated with specific stages of flood development which geomorphic role was discussed by Zwoliński (1992).

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Streszczenie

SEDYMENTOLOGICZNA INTERPRETACJA GLIFÓW KREWASOWYCH UTWORZONYCH W DOLINIE GÓRNEJ WISŁY PODCZAS KATASTROFALNEJ POWODZI W 1997 ROKU

Piotr Gębica & Tadeusz Sokołowski

W badanym odcinku doliny Wisły pomiędzy ujściami Dunajca i Wisłoki (Fig. 1) podczas lipcowej powodzi w 1997 roku doszło do kilkukrotnego przerwania wałów przeciwpowodziowych. W miejscach niektórych przerwań utworzyły się formy erozyjne – wyrwy (krewasy) – rozcinające równię zalewową oraz akumulacyjne – glify krewasowe. Budowa i charakter sedymentacji w obrębie glifów krewasowych są treścią artykułu.

Glify krewasowe miały różny kształt: palczasty, wachlarzowaty i językowaty (Fig. 3A, 6A, 9A). Kształt, podobnie jak charakter osadów i rozwój glifów, były w dużym stopniu podporządkowane rzeźbie powierzchni (głównie meandrowym starorzeczom), zabudowie oraz kępom roślinności drzewiasto-krzewiastej.

Wskaźnikową litofacją osadów glifów krewasowych są drobno- i średnioziarniste piaski horyzontalnie warstwowane (*Sh* – kody literowe litofacji wg Miall, 1978 oraz Zieliński, 1995 – tab. 1 i 2), niewyraźnie przechodzące miejscami w struktury niskokątowych warstwowań przekątnych (*Sl*). Ten typ osadu występuje we wszystkich glifach budując niższą – miejscami do połowy – część profilów (Fig. 3B, 5, 6B, 7, 8, 9B) i powstawał w warunkach zalewu warstwowego (*sheet-flow*) przy nadkrytycznych przepływach górnego płaskiego dna. Miejscami ponad nimi występują osady wiążące się z kanalizacją przepływu (litofacje *Sp*, *SGp* i rzadka *St*), tworzące czasem kilka warstw dystalnie przyrastających. Progradacja zachodziła z wytwarzaniem powierzchni reaktywacji (Fig. 3B, 4), co świadczy o zmiennych warunkach przepływu. W zespołach warstwowań przekątnych pojawiają się szczególne, naprzemianległe warstwy piasków i żwirów. Te ostatnie utworzone są z toczeńców mułowych i agregatów glebowych (litofacja *S/G*).

Spotykana często pionowa sukcesja litofacji *Sh (Sl)* → Sp wykazuje wiele podobieństw do profili łach poprzecznych (lub językowatych) z rzek roztokowych, co świadczy o tym samym czynniku sterującym rozwojem obu typów form: maleniem intensywności przepływu powodziowego doprowadzającego do powstania dużych, progradacyjno-agradacyjnych form.

W depresji starorzecza (Otałęż) profil zdominowała litofacja *S/Gi* (wielkiej skali warstwowania przekątne S-kształtne) wskazujące na progradację delty typu gilbertowskiego (Fig. 7B, 8), której sedymentacja zachodziła w warunkach piaszczystych spływów podwodnych (*subaqueous sand-flow* – Buck, 1985; Hunter, 1985; White, 1992).

W innych miejscach panują ciągłe warunki zalewu warstwowego o wysokiej gęstości (*hyperconcentrate flow*), na co wskazuje pojawianie się osadów typu *slurry-flow* (Nemec & Muszyński, 1982). Mają one niewielką miąższość, przy taflowym pokroju całego członu bardzo zróżnicowanego strukturalnie (litofacje *GSm*, *SGm*, *SGDm* oraz *St*, *SGt*, *GSt*, *Sp*, *SGp*, *GSp* – Fig. 6B, 7, 8).

Opadanie i zamieranie fali wezbraniowej, aż po wytrącanie zawiesiny, wyznaczają ślady opływania (*current crescent*) oraz ripplemarki (litofacja *Sr*) mające miejscami okrywę mułową (*mud drapes* – litofacje *FSw*, *Fw*).

Spotykane najczęściej pionowe sekwencje odwróconego uziarnienia gradacyjnego osadów glifów, nie koniecznie wynikają ze zmian energii przepływów, ale wiążą się z dostępnością poszczególnych frakcji materiału detrytycznego z sukcesywnie pogłębianych wyrw erozyjnych.

Środowisko tworzenia opisywanych glifów krewasowych miało charakter wysokoenergetyczny. Głównym czynnikiem był bardzo duży spadek hydrauliczny wód powodziowych spiętrzonych wałami przeciwpowodziowymi oraz duża gęstość wód, przez co opisanych glifów nie można traktować jako bezpośrednich analogów naturalnych, współczesnych form czy kopalnych osadów (Allen, 1965; Coleman, 1969; Cherven, 1974; Fielding, 1984; Doktor & Gradziński, 1985; O'Brien & Wells, 1986; Farrell, 1987; Smith, 1987; Teisseyre, 1988; Platt & Keller, 1992; Miall, 1996; Brodzikowski *et al.*, 1997; Zieliński, 1998). Opisane tutaj odznaczają się bardziej zróżnicowanymi strukturami sedymentacyjnymi oraz grubszym uziarnieniem, z głazami włącznie, odpowiadając bardziej osadom korytowym. Zróżnicowanie podkreślają też osady *slurry-flow*, mułowe żwiry, znaczna ilość agregatów glebowych oraz dużych toczeńców mułowych, co jest efektem intensywnego rozmywania drobnoziarnistych i bardziej spoistych utworów równi zalewowej i wału przeciwpowodziowego.