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Depositional system of an anastomosing river with low organic content: an example from the Oława Valley, SW Poland

Krzysztof Jan WÓJCICKI[1]

[1] 1 University of Silesia, Faculty of Natural Sciences, Institute of Earth Sciences, Będzińska 60, 41-200 Sosnowiec, Poland; ORCID: 0000-0002-1799-3358

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Large amounts of organic matter (OM) deposited on a cohesive floodplain are considered a typical feature of a low-energy anastomosing river in a humid climate. The Oława River (Silesian Lowland) is a multi-channel fluvial system with laterally stable and low-gradient channels as well as inter-channel islands covered with lush vegetation. Studies in the Oława Valley were designed to determine the forms of occurrence and the conditions of deposition of OM in relation to the main sedimentary subenvironments. The results show a low proportion of OM in the sediments of the Oława floodplain, usually displaying values typical of mineral soils (up to several per cent). In particular, the floodbasin and natural levee deposits have a low content of OM. The rapidly decaying OM there mainly accumulates in epipedons and is dominated by leaf and wood debris. A somewhat higher content of OM was found in the channel alluvia, especially in the rhythmically stratified sediments of the upper part of the river bars. Plant detritus in the form of species-rich wood, bark, remains of leaves, fruits and seeds was deposited directly from the tree canopy or together with mud in the last phase of the flood. The remains of diatoms, porifera and bryozoans are typical of sandier strata. Organic sediments from frequently flooded bars locally contain more rhizodermis and epidermis of amphiphytes. The greatest potential for accumulation and long-term preservation of OM is found in the abandoned channels. The abandoned channel-fills mainly contain the remains of autochthonous wood, rhizodermis and epidermis. The remains of mosses, Cladocera and Chironomidae are characteristic of this sedimentary sub-environment. In general, however, the area occupied by peatlands within the study area is disproportionately low (less than 1%) compared to published examples of anastomosing-river, organic-rich floodplains. In the sections studied, the Oława River thus represents a type of anastomosing system in temperate, humid areas that has been overlooked by classical classifications and is characterised by a low organic sediment content.

Key words: fluvial sedimentology, anabranching rivers, organic material, macrofossil analysis, Holocene.

INTRODUCTION

Low-energy river systems consisting of multiple channel belts with two or more interconnected channels that enclose floodbasins are referred to as anastomosing rivers (Makaske, 2001; Kleinhans et al., 2012). There are many varieties of anastomosing fluvial environment that were originally linked to different climatic zones. Nanson and Knighton (1996) distinguished the following subtypes: 1. hyper-humid, organic in subtropical climates, 2. humid, organo-clastic in subarctic, temperate or tropical climate zones, and 3. mud-dominated in semi-arid climates. Transferring the above to the classification of anastomosing river floodplains (Nanson and Croke, 1992), organic-rich floodplains (suborder C2a) are typical of humid environments, while inorganic (organic-poor) floodplains (suborder C2b) are typical of semi-arid environments. In sedimentological terms, the model of the classic anastomosing river environment is a fluvial type VIII according to Miall (1985). It is a river system where channel bars are relatively rare, natural levees and crevasse splays are well developed and the floodplain is dominated by wetlands, especially peatlands (Zieliński, 2014).

According to the above approaches, vegetation and sedimentary OM (organic matter) play a key role in defining anastomosing systems. There are also alternative interpretations according to which the absence or rarity of OM is due to the high influx of clastic material (i.a. Nadon, 1994; Morozova and Smith, 2003). According to Makaske (2001), there is strong variation in the development of peat among the humid climate anastomosing rivers investigated, predominantly depending on the influx of clastics in relation to floodplain width. Although some of these arguments were already known in the 1980s and 1990s, Nanson and Croke (1992) distinguished between organic-rich and inorganic floodplains because of the significant differences in the hydrology, geomorphology and sedimentology of the anastomosing-channel floodplains of humid and semi-arid regions. According to current knowledge, there are a number of deviations from this model. For example, the peat-forming swamps of the Okavango system, which are rich in OM (McCarthy et al., 1992), are situated on the fringe of the

*E-mail: wojcicki@poczta.onet.pl

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Kalahari Desert in a semi-arid climate. On the other hand, the floodplain deposits of the middle Amazon River (tropical humid) generally contain only thin accumulations of organic material (Rozo et al., 2012). Even more convincing evidence is provided by sections of organic-rich and inorganic floodplains co-occurring in the same climate zone. Studies of organic carbon storage in the headwaters of the River Dee in eastern Scotland (Swinnen et al., 2020) have shown that there is a wide range of OM in adjacent anastomosing river valleys. The average soil organic carbon storage for organic-rich floodplains (suborder C2a according to Nanson and Croke, 1992) was estimated to be 1468.95 ±150.82 Mg ha^{-1}. Such floodplains can therefore be classified among the fluvial systems with the highest organic carbon content. In the case of floodplains classified as suborder C2b, a value more than 10 times lower (142.19 ±21.91 Mg ha^{-1}) was calculated, that roughly corresponds to the mean soil organic carbon storage of braided-river floodplains (Swinnen et al., 2020). Similar discrepancies are observed in anastomosing systems in Poland. The best studied system is the Narew Valley (NE Poland), where the river anastomoses within riverine peatlands (Gradziński et al., 2003; Marcinkowski et al., 2017; Kędzior et al., 2021). In the Obra river valley (western Poland), there is also a thin layer of peat beneath the surface of the floodplain (Słowik, 2014). This is in contrast to the anastomosing sections of the rivers of the upper Odra catchment in southern Poland. In the valleys of the Rivers Kwisa, Bóbr and Oława as well as the River Odra near Opole and Wrocław small amounts of OM have accumulated on their floodplains (see Teisseyre, 1990; 1992).

The main objective of this research was to identify the morphological forms of OM occurrence in the Oława Valley. Quantitative ratios between OM of different origins (wood, leaves, epidermis, periderm, etc.) were determined for the major sedimentary subenvironments of the river floodplain. Completing these objectives opens the field for considerations regarding the conditions for different abundances of OM in the depositional systems of anastomosing rivers found in the same climatic zone. Are the origin, forms and preservation potential of OM similar in organic-rich and organic-poor alluvia? What interactions exist between the vegetation and fluvial processes on the floodplains of anastomosing rivers with low OM content?

REGIONAL SETTING AND STUDY SITES

The Oława is representative of small rivers in warm temperate and humid climates. The catchment area is characterised by a seasonal development of biocoenoses, and a seasonal course of post-sedimentation processes, which occur in the annual rhythm of changes in temperature, humidity, and in the activity of soil organisms. The Oława River (Fig. 1A), which is 91.7 km long and has a basin area of 1167.4 km^2, is an upland river with an average gradient of 2.18 m·km^{-1}. The mean annual discharge of the river in its lower reach is 3.43 m^3·s^{-1} (gauging station: Oława). The hydrological regime of the Oława is traditionally classified as nivo-pluvial, with two maxima: the first occurs in spring, and the second, which is smaller, in summer (Dynowska, 1994). However, the application of a more objective, unsupervised approach to the analysis of hydrological data led Wrzesiński (2017) to rank the Oława among the rivers with the most uniform discharge in the annual cycle (nival, poorly developed regime).

The Oława River has developed a multi-channel pattern in most sections of the valley (Fig. 2), both in its upper course (Teisseyre, 1992; Parzóch and Solarska, 2008) as well as in the middle (Fig. 1B) and lower (Fig. 1C) courses investigated in this study. In the lowest reach of the valley (between Siechnice and Wrocław), the Oława incorporated parts of the Odra oxbow lakes into its channel system. The most important criteria for classifying the multi-thread Oława system as an anastomosing river are the floodplain morphology typical of these rivers, namely multiple interconnected channels that enclose floodbasins, and the lateral stability of the channels (Makaske, 2001; Kleinhans et al., 2012). The morphological profiles of inter-channel islands show their flat or concave-up morphology (Fig. 1D). A concave-up morphology of islands is a fundamental feature of anastomosing rivers, differentiating them from other rivers with multiple channels where convex-up islands are found (Makaske et al., 2017).

The anabranching index, the width/depth ratio and the channel gradient seem to be the most useful parameters defining the planform of the Oława as an anastomosing system (Table 1). The anabranching index (the average count of wetted channels separated by vegetated islands in each of at least 10 cross-sections) calculated on the basis of archived topographic maps (Fig. 2A) is 3.1 in the middle reach (between Wiązów and Osiek) and 2.9 in the lower reach of the river (between Stanowice and Siechnice). These calculations do not take into account dry palaeochannel systems which were abandoned as a result of avulsions in the prehistoric period (Fig. 2B). The width/depth ratio displays values in the range of 3.9–8.1 for the selected palaeochannel cross-sections and 4.8–11.7 for the modern channel. The low values of this indicator as well as the low values of channel gradient (0.00018–0.00082) are typical of anastomosing rivers (Gurnell et al., 2014; Zieliński, 2014). Lyster et al. (2022) demonstrated that the depth/width ratio is sufficient to discriminate between single-thread and multi-thread rivers, suggesting bank cohesion may be a critical determinant of the river planform. The high lateral stability of the Oława channel was confirmed by the analysis of archival maps. The multi-channel Oława system is characterised by varying sinuosity, and this parameter successively decreases for channel belts of later origin (Table 1).

The Oława River drains the glacial and outwash plains of the Odranian Glaciation (MIS8). In addition, Miocene clays and Pleistocene loess as well as limnoglacial deposits occur in the upper and middle parts of the catchment (Michalska, 1992; Winnicka, 2008; Badura et al., 2009; Cwojdziński and Pacuła, 2009). These fine-grained, cohesive deposits may have played a key role in shaping the anastomosing system of the Oława. According to the data of the Detailed Geological Map of Poland (Winnicka, 1985, 2008; Michalska, 1992; Badura et al., 2009; Cwojdziński and Pacuła, 2009), the modern Oława floodplain is mainly covered by clays and muds, with local admixtures of sand (~79.3% of the Holocene valley floor). The Oława floodplain is virtually free of peat and Holocene limnic deposits. Surface peat deposits occupy <0.2% of the floodplain area. Sands and gravels occupy ~20.5% of the floodplain and dominate the lowest section of the valley (Winnicka, 1985). Coarse sands and fine gravels also occur in the Oława channel (approx. 1/3 of the channel deposits in the successions analysed in this study). The significant content of coarse sands and fine gravels in the channel facies is questionable, as bedload transport in a typical low-energy anastomosing river is usually restricted to fine- and medium-grained sands (Zieliński, 2014). Coarser sediments may have accumulated in the valley fill during the Late Pleistocene. They most likely originate from fluvioglacial deposits in the middle and lower parts of the catchment (Winnicka, 1985, 2008; Michalska, 1992). After the Pleistocene-Holocene transition, the reduced channel system was only able to rework gravels locally due to reduced competence in relation to the inherited bounding sediment calibre (Brown et

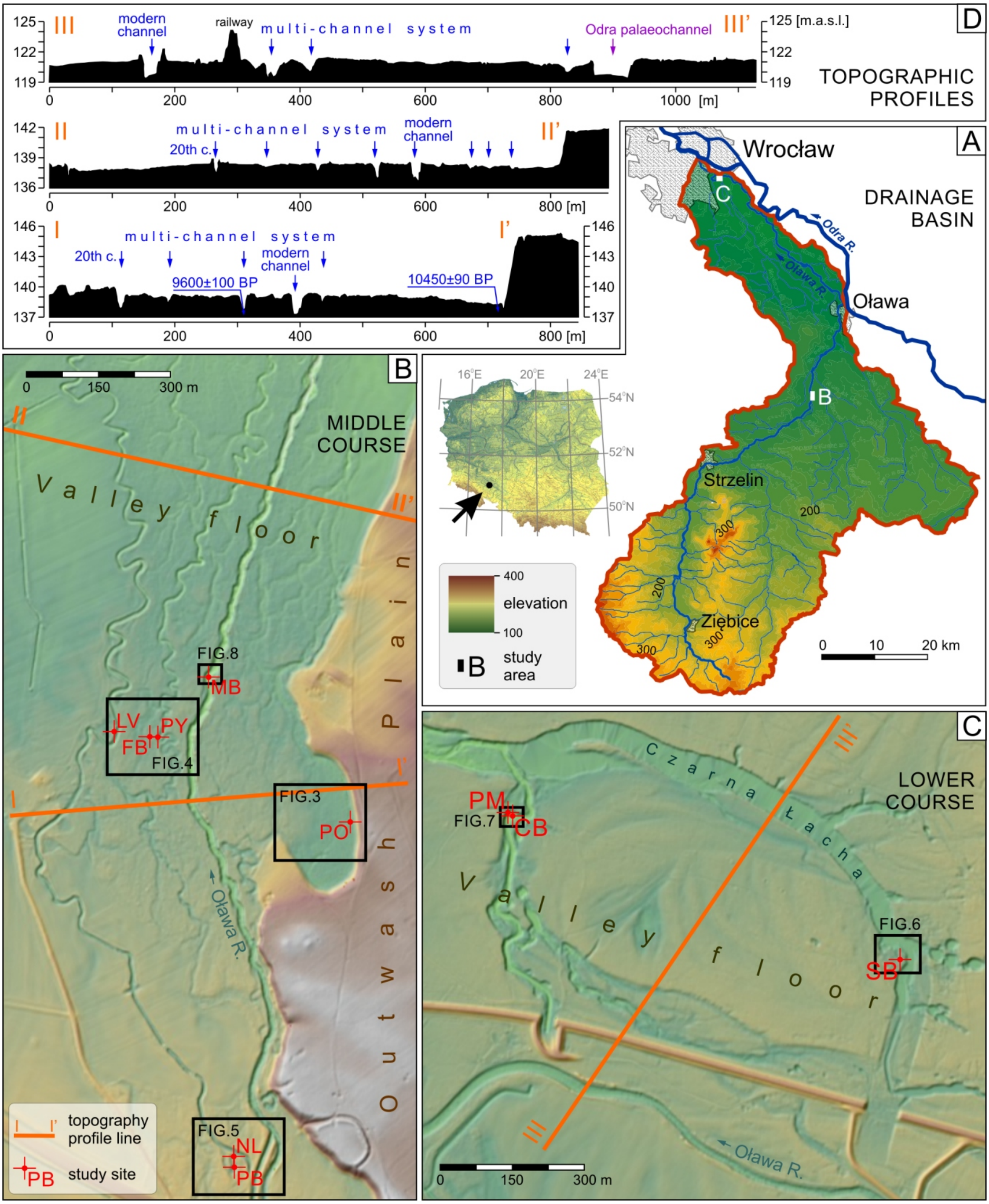

Fig. 1A – location of the Oława catchment; B – location of the study sites in the middle course of the river; C – location of the study sites in the lower course of the river; D – topographic profiles

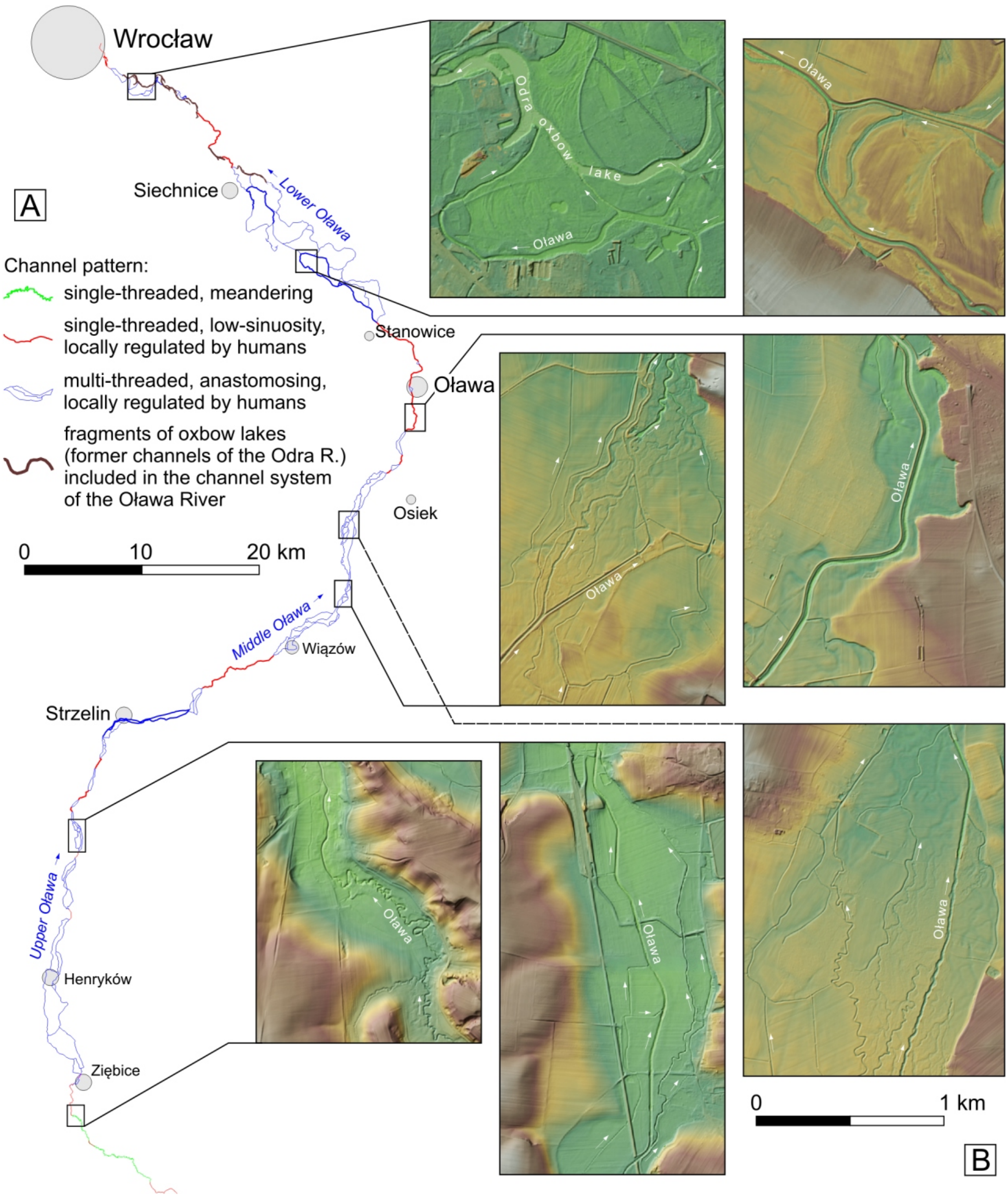

Fig. 2. Channel pattern of the Oława River

A – based on German civil maps at a scale of 1:25000 (1884–1912); **B** – based on digital terrain models of selected valley courses. Note the highly branched Holocene palaeochannel system on the multi-thread sections of the river (with more islands in the inter-channel area compared to archival maps)

Table 1

Selected features of the Oława fluvial system in the sections of the valley studied

Factor	Middle course of the Oława River		Lower course of the Oława River	
	river channels before regulation	modern channel	river channels before regulation	modern channel
Channel slope	0.00043–0.00047	0.00082	0.00018–0.00074	0.00040
Channel sinuosity	1.36–1.52	1.02	1.11–1.29	1.05
Channel width [m]	4–6 (rarely up to 8)	8–10 (rarely up to 14)	6–7 (rarely up to 11)	9–12 (rarely up to 24)
Width/depth ratio	3.9-5.7	4.8-10	4.0-8.1	5.6-11.7
Grain size of channel sediment	sand and gravel		sand and gravel	
Grain size of overbank sediment	silt + clay (rarely fine sand)		silt + clay (rarely fine sand)	

al., 2021). In general, gravel is quite common in the bed material of anastomosing rivers, particularly in alpine locations (Nanson and Croke, 1992; Gurnell et al., 2014). Gravel-bed anastomosing rivers have been described in recent years by Heritage et al. (2016), Liu and Wang (2017) and Gao and Wang (2019).

According to the current state of research, the transformation of the Oława River from a meandering pattern to a multi-channel system is though to have taken place in the Late Holocene under the influence of anthropogenic intensification of soil erosion (Teisseyre, 1994). According to this author, the morphology of the valley is closely related to its geological structure, with wide-bottomed sections within tectonic grabens and narrow-bottomed sections within horsts where the Oława flows in a single, sinuous channel until today. Teisseyre (1992) inferred, on the basis of geological sections, that lateral stabilisation of the channel has occurred in the anastomosing sections since the Middle Ages. At that time (13th century), pond farming began to have an influence on the transformation of the Oława river system (Parzóch and Solarska, 2008). The hydrotechnical system created by the Cistercians survived until the mid-19th century, when most of the canals and ponds were drained. Nevertheless, the length of mill canals in the Upper Oława Valley is 49.6% of the length of the modern Oława riverbed (Parzóch and Solarska, 2008). The anthropogenic changes of the Oława Valley described above refer mainly to the upper part of the catchment. The more natural conservation state of the Oława Valley in the middle and lower course is the result of a dominance of agricultural land and forests in this part of the catchment.

In the Oława channel zone, there are currently many depositional forms, including side (lateral) bars, plug bars, mid-channel bars, and concave-bank and convex bars. Their common feature is a low elevation of the sandy-gravelly sediments of the platform above the average water level of the river. There is no supra-platform typical of meandering channels (Zieliński, 2014). Over time, however, these forms are built up by fine-grained alluvia via vertical accretion, forming accretionary benches. In the middle reaches of the valley, the Oława floodplain is dominated by extensive flood basins with a cover of fine-grained flood deposits up to 1.3 m thick. Natural levees have formed along the two main channels, which were active in the first half of the 20th century, locally reaching a height of over 1 m above the floodplain surface. However, detailed geomorphological analyses did not reveal any crevasse splays in the topography of the valley floor. In its lower course, the Oława uses the marginal zone of the Odra valley, flowing locally through the depressions of large palaeomeanders or crossing their sandy point bars. The thickness of the overbank deposits overlying the channel alluvia reaches 0.6 m on average. This locally thin blanket of vertical accretion deposits is not able to mask the scroll bar topography created by the lateral migration of the Odra meanders.

MATERIAL AND METHODS

The origins of the fluvial forms and sediments in the Oława floodplain were analysed using both geomorphological and sedimentological methods. A digital terrain model created based on high-density LiDAR data was used. Morphometric measurements of landforms were carried out and geological cross-sections were constructed for sediments representing all the depositional subenvironments typical of the Oława floodplain. The sedimentary successions with the highest OM content were selected for detailed investigations, which are described below. A total of 57 exposures and boreholes were analysed. Their depth depended on the thickness of the sedimentary facies investigated. In the case of the channel forms, the boreholes reached coarse-grained sediments in the lower part of the bars. Some of the geological cross-sections penetrate the top of Pleistocene limnoglacial deposits. Sediment samples of water-saturated sediments were collected using a Russian D-sampler. A total of 114 samples were collected for laboratory analysis. Their depth and general lithological characteristics are listed in Tables 3–12. Due to the nature of the drilling, this paper does not contain systematic data on sedimentary structures; however, grain size composition was determined for all samples. The colours of the sediments were determined using Munsell colour charts. In addition, a phytosociological assessment of the current vegetation was conducted during fieldwork. The names of the phytosociological units are given after Matuszkiewicz (2013).

Laboratory work focused on determining the forms in which OM occurs in the alluvia of the Oława River using an optical microscope at 40–1000× magnification. A total of 39 samples containing OM were analysed. Sediment samples were collected for analysis with a volume of 5–10 cm^3. No chemical pre-treatment was carried out, mineral components were also not removed from the samples. The samples were mechanically crushed and mixed with water. A classification based on the structure and morphology of OM (Wójcicki, 2022) was used with respect to the Troels-Smith (1955) system, the groups of plant remains found in peats and limnic sediments (Tobolski, 2000), and with reference to the classification used by Fairbairn (2001). The division adopted permitted the reliable classification of all organic remains present in the individual sediment samples. The proportions of the individual components were

Table 2

Results of radiocarbon dating

Core	Depth [cm]	Laboratory code	14C age [BP or pMC]	Calibrated age [BC/AD (yrs)]	Dated material
PO	29-33	GdS-4562	2990 ±65 BP	1410–1045 BC (94.4%) 1030–1015 BC (1.1%)	peat (mainly *Alnus* sp. wood and *Phragmites australis* roots)
	210-214	GdS-4567	10450 ±90 BP	10725–10045 BC (95.4%)	mainly *Phragmites australis* roots and epidermis
PY	74-76	GdS-4557	8210 ±80 BP	7475–7390 BC (10.7%) 7385–7055 BC (84.7%)	mainly *Salix* sp. wood
	143-148	GdS-4564	9600 ±100 BP	9260–8710 BC (95.4%)	mainly woody detritus and moss remains
FB	160-165	GdS-4558	4810 ±80 BP	3770–3725 BC (3.0%) 3715–3485 BC (76.4%) 3470–3370 BC (16.0%)	mainly tree remains (wood, periderm, leaves)
PB	114-117	GdS-4559	2495 ±75 BP	790–415 BC (95.4%)	mainly woody detritus (including: remains of *Prunus avium*)
NL	218-222	GdS-4563	2770 ±65 BP	1110–1095 BC (1.1%) 1085–1065 BC (1.3%) 1060–805 BC (93.1%)	wood (including remains of *Quercus* sp.) and charcoal
SB	26-29	GdS-4560	113.26 ±0.85 pMC	1958 AD (3.3%) 1990–1995 AD (92.1%)	mainly *Cyperaceae* roots and woody detritus

quantified using the microscopic grid method, with the area occupied by the remains of each morphological group expressed as a percentage (Tobolski, 2000). To estimate the area occupied by the microfossils, a grid dividing the microscope's field of view into 49 squares was used. The results were calculated as an average for at least 15 fields of view. Additionally, the taxonomic composition of the preserved remains was determined, which enabled the reconstruction of the parent sediment-forming communities. Peat categorisation in the article follows the Polish genetic classification (Tobolski, 2000). The OM content of the sediments was approximated using the loss-on-ignition (LOI) method. After initial oven drying at 105°C, the samples were ignited in a muffle furnace for 3 hours at 550°C.

The age determination and calibration of the radiocarbon dates for the purposes of this article were carried out in the Radiocarbon Laboratory in Gliwice using the Liquid Scintillation Counting technique. The date of origin of the youngest channel forms was determined using contemporary cartographic material and archival maps published from the mid-18th century.

OM IN MAJOR SEDIMENTARY SUBENVIRONMENTS – SELECTED EXAMPLES

ABANDONED CHANNEL (PO) SEDIMENTARY SUCCESSION

Site: PO (50°51'20.5"N; 17°14' 51.2"E; 138.3 m.a.s.l.).

Geomorphological situation: Distal floodplain; a peat plain developed in the zone of a Late Glacial abandoned channel at the foot of the outwash plain, which lies up to 9 m above the valley floor (Fig. 3A). The surface of the peat plain is 1 m below the surface of the proximal floodplain.

Vegetation: A richer form of an alder swamp forest (All. *Alnion glutinosae*) dominated by *Alnus glutinosa* and containing, inter alia, *Padus avium*, *Impatiens parviflora, Rubus* sp. (including *Rubus idaeus*), *Iris pseudacorus*, *Galium palustre, Thelypteris palustris* and *Urtica dioica*.

Modern processes: Peat accumulation or peat decay in response to seasonal moisture fluctuations; episodic deposition of fine-grained flood sediments.

Lithology and facies interpretation: Organic sediments filling a former oxbow lake were identified at the site (Fig. 3B). The silty-sandy alluvia (sample PO13), dated to 10,725–10,045 cal BC (95.4%) at a depth of 210–214 cm (Table 2), were originally deposited in an aquatic environment (i.a. remains of freshwater sponges and *Potamogeton* epidermis). Above, sandy, moderately decomposed Phragmiteti peat (samples PO12–9) with a high proportion of reed remains and an admixture of horsetail accumulated (Fig. 3C). This contains the remains of aquatic organisms: *Nymphaeaceae* idioblasts, Porifera needles, Cladocera carapaces with ephippia and Chironomidae head capsules. After terrestrialisation, the wetland was overgrown by swamp forest with *Alnus glutinosa* dominant. The peat samples (PO8–2) are dominated by black alder wood and periderm, with a high proportion of roots and the epidermis of reeds that occupied lower, wetter habitats within the hummock-hollow structure of the forest. Repeated flooding led to silting of the organic sediments (Table 3). At a depth of 61–90 cm (samples PO7–6), the degree of peat decomposition increases and a quantity of charcoal dust is revealed, documenting a peatland fire. In the regenerated forest community, sedges began to assume greater importance. A layer of less decomposed peat at a depth of 29–33 cm was dated to 1410–1015 cal BC (95.5%). In the litter layer (sample PO1), the remains of leaves/leaf epidermis of trees and herbaceous plants form the largest proportion. The leaf flora of *Alnus glutinosa* dominates. The leaves of *Quercus robur*, *Q. rubra* and *Padus avium* are also present.

ABANDONED CHANNEL (PY), FLOOD BASIN (FB) AND NATURAL LEVEE (LV) SEDIMENTARY SUCCESSIONS

Sites: PY (50°51'27.6"N; 17°14'29.9"E; 138.0 m.a.s.l.); FB (50°51'27.8"N; 17°14'28.7"E; 138.8 m.a.s.l.); LV (50°51'28.1"N; 17°14'25.1"E; 139.3 m.a.s.l.).

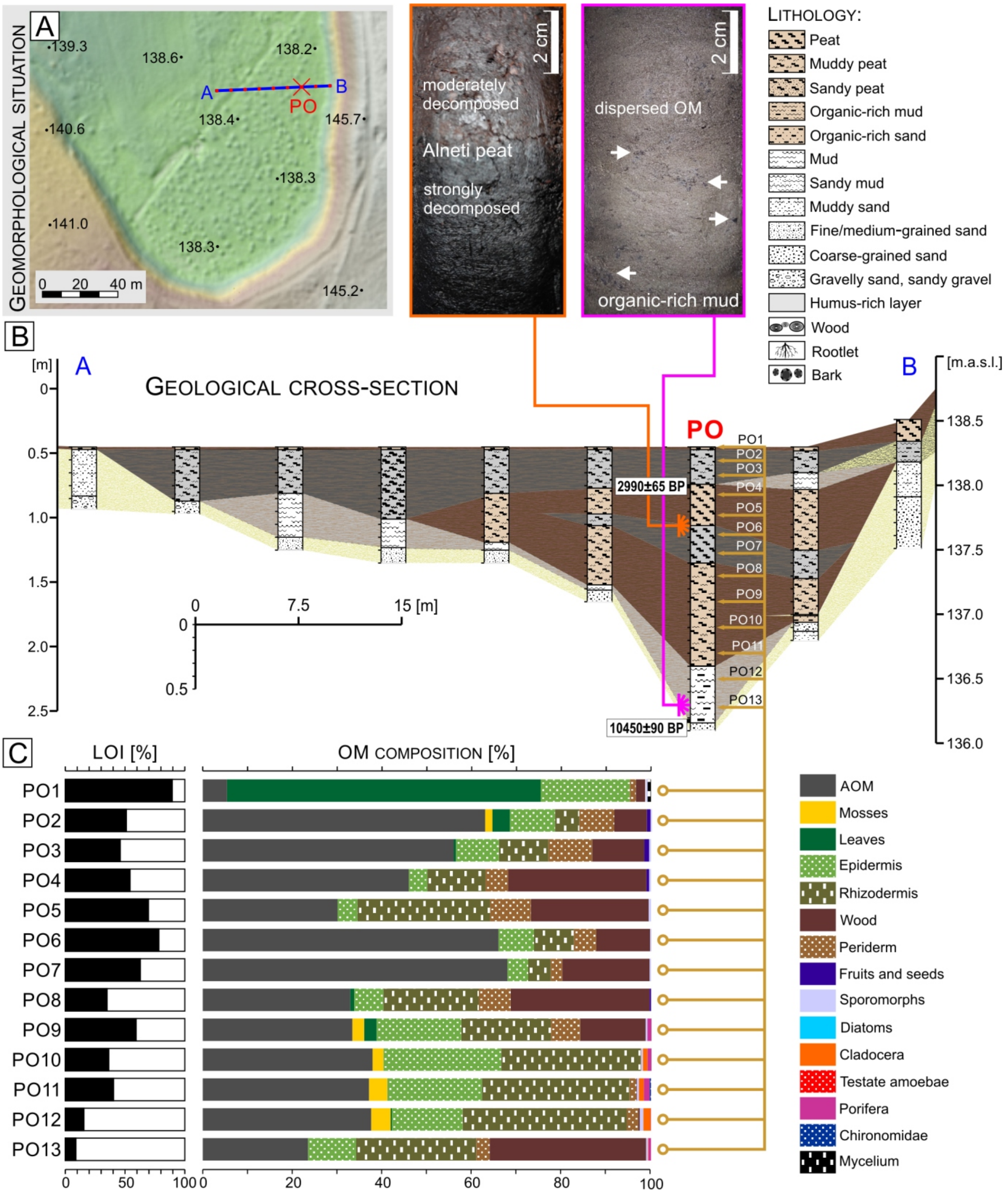

Fig. 3. PO site

A – location of the site on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

Table 3

Lithology of the samples and interpretation of the sedimentary environment for deposits of the PO succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
PO1	0–2	5YR 4/3	89.5	litter	organic accumulation	topsoil
PO2	2–15	2.5YR 2.5/1	51.1	muddy peat	organic accumulation + deposition from suspension	abandoned channel
PO3	15–29	10YR 2/1	46.0	muddy peat		
PO4	29–45	10YR 2/1	54.2	peat		
PO5	45–61	10YR 2/1	69.6	peat		
PO6	61–75	5Y 2.5/1	78.3	peat		
PO7	75–90	5Y 2.5/1	62.8	peat		
PO8	90–110	10YR 2/1	35.0	muddy peat		
PO9	110–130	10YR 2/1	59.4	muddy peat		
PO10	130–150	10YR 2/1	36.4	muddy peat		
PO11	150–170	10YR 3/2	40.4	muddy peat		
PO12	170–190	10YR 3/2	15.6	organic-rich mud		
PO13	190–214	10YR 4/2	8.9	organic-rich mud		
PO14	214–220	2.5Y 6/3	1.2	fine-grained sand	deposition from bedload transport	river channel (thalweg***)

* – according to Munsell Soil Color Charts; ** – loss on ignition; *** – the deepest part of the palaeochannel along its cross-section

Geomorphological situation: Inter-channel area between the Early Holocene channel belt with a small palaeomeander (R_m[1] = 9 m, w_{bkf}[2] = 6 m) and the channel abandoned as a result of river regulation. The latter is bounded by natural levees rising up to 70 cm above the surface of the floodplain (Fig. 4A).

Vegetation: Riverine forest community Ass. *Ficario-Ulmetum minoris* dominated by *Quercus robur, Fraxinus excelsior, Tilia cordata, Corylus avellana, Padus avium, Ulmus minor, U. glabra* and *Acer campestre.* In the seasonally variable layer of undergrowth there are, inter alia, *Galanthus nivalis, Aegopodium podagraria*, *Anemone ranunculoides, A. nemorosa, Corydalis cava, Galeobdolon luteum* and *Allium ursinum.* The treeless depression of the palaeomeander is overgrown by *Corylus avellana* and *Padus avium* shrubs as well as *Urtica dioica, Glechoma hederacea, Galium aparine* and *Alliaria petiolata.*

Modern processes: Soil processes.

Lithology and facies interpretation: The greatest lithological diversity is found in the PY succession (see Fig. 4B and Table 4). This palaeomeander system was abandoned by avulsion probably at the beginning of the Holocene. This is supported by the dating of mud (9600 ±100 BP) from a depth of 143–148 cm (Table 2) deposited between sandy channel alluvia. The process of filling the palaeomeander initially took place in an aquatic environment, as shown by the presence of *Potamogeton* epidermis and *Nymphaeaceae* idioblasts (Fig. 4C). However, the main component of OM in the PY13 sample is *Salix* wood. In addition, many leafless stems of mosses of the class *Bryopsida* are preserved. *Salix* wood also dominates in the organic-rich samples PY7 and PY6. An important component is the *Nymphaeaceae* epidermis. Radiocarbon dating shows that the mixed muddy-organic sedimentation lasted about 1200–2200 years. Above a depth of 74 cm, clayey-silty alluvia were deposited, generally free of OM. Their deposition can be associated with a long period of time (from the 8th millennium BC onwards) during which the river flow may have been episodically triggered in the palaeomeander studied.

In the FB succession the internal structure of the flood basin was analysed (see Fig. 4A, B and Table 5). The Oława alluvia are deposited on grey-blue, silty-clay deposits described as limnoglacial sediments of the Odranian Glaciation (Michalska, 1992). The fluvial succession begins with gravelly sand and transforms to sandy mud with woody detritus dated to the older part of the 4th millennium BC at a depth of 160–165 cm (Table 2). According to radiocarbon dating, the sediments accumulated above appear to represent a period of more than 5,000 years of flood basin development. At a depth of 107–160 cm, horizontal laminated fine-grained sands were initially deposited, with massive muds above. The minimum thickness of the flood basin sediments in the geological cross-section investigated is 1.3 m. These sediments only contain OM in epipedons. The litter layer (sample FB1) is dominated by highly decomposed leaves, including *Quercus robur* and *Corylus avellana* debris. A common find is the fruits of *Alnus glutinosa*. Below this, in the topsoil (sample FB2), a decrease in the proportion of leaves and a relative increase in the proportion of wood were found.

The LV succession (see Table 6) was analysed in an exposure showing the internal structure of the natural levee associated with the Oława channel until the regulation of the river in the 2nd half of the 20th century. It consists of mud and fine-grained sands in a coarsening-upwards succession. Alluvia under the influence of soil processes have a massive structure. They are essentially free of OM. Only at the surface is there an organic-rich litter dominated by the leaves of *Quercus robur*, *Salix fragilis*, *Tilia cordata* and *Carpinus betulus* (sample LV1). Below this, in the topsoil (sample LV2), there is a sharp decrease in the content of easily decomposable leaves and a relative increase in the proportion of more resistant woods and periderms.

[1] – radius of curvature; [2] – channel width

Table 4

Lithology of the samples and interpretation of the sedimentary environment for deposits of the PY

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
PY1	0–10	7.5YR 3/1	7.9	mud	deposition from suspension	abandoned channel
PY2	10–23	7.5YR 3/2	5.3	mud		
PY3	23–40	10YR 3/2	4.1	mud		
PY4	40–56	10YR 3/2	4.6	mud		
PY5	56–74	10YR 3/2	5.2	mud		
PY6	74–86	10YR 2/1	48.8	muddy peat	organic accumulation + deposition from suspension	
PY7	86–97	10YR 2/1	31.0	muddy peat		
PY8	97–109	10YR 3/1	10.2	organic-rich mud		
PY9	109–120	10YR 3/1	9.2	organic-rich mud		
PY10	120–130	10YR 3/1	9.8	organic-rich mud		
PY11	130–140	10YR 3/1	7.4	organic-rich mud		
PY12	140–143	10YR 5/6	1.8	medium-grained sand	deposition from bedload transport	
PY13	143–148	2.5Y 2.5/1	11.9	organic-rich mud	organic acc. + dep. from suspension	
PY14	148–155	2.5Y 3/2	3.3	medium-grained sand	deposition from bedload transport	river channel (thalweg***)

Explanations as in Table 3

Table 5

Lithology of the samples and interpretation of the sedimentary environment for deposits of the FB succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
FB1	0–2	10YR 6/3	42.7	litter	organic accumulation	topsoil
FB2	2–20	7.5YR 4/2	12.0	mud (topsoil)	deposition from suspension	flood basin
FB3	20–40	7.5YR 4/2	6.7	mud		
FB4	40–60	7.5YR 3/2	5.3	mud		
FB5	60–85	7.5YR 3/3	4.2	mud		
FB6	85–107	7.5YR 4/4	3.8	mud		
FB7	107–122	2.5Y 5/4	2.3	muddy sand	rhythmic deposition from bedload transport and suspension	crevasse splay (?) upper part of bar (?)
FB8	122–141	2.5Y 5/4	2.3	muddy sand		
FB9	141–160	2.5Y 6/3	1.8	fine-grained sand		
FB10	160–165	10YR 3/2	5.8	sandy mud with detritus		
FB11	165–173	2.5YR 4/2	2.4	muddy sand		
FB12	173–180	2.5YR 5/2	0.9	gravelly sand	deposition from traction	river channel

Explanations as in Table 3

Table 6

Lithology of the samples and interpretation of the sedimentary environment for deposits of the LV succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
LV1	0–2	7.5YR 5/3	21.8	litter	organic accumulation	topsoil
LV2	2–5	5YR 3/2	5.1	muddy sand	deposition from bedload transport and suspension	natural levee
LV3	5–25	10YR 4/3	2.8	fine–grained sand		
LV4	25–45	10YR 5/3	1.3	fine-grained sand		
LV5	45–65	10YR 5/3	1.6	fine-grained sand		
LV6	65–85	10YR 4/3	2.1	fine-grained sand		
LV7	85–105	10YR 4/3	4.2	mud	deposition from suspension	distal floodplain (flood basin)
LV8	105–125	10YR 5/3	3.8	mud		
LV9	125–145	10YR 5/3	2.8	mud		
LV10	145–165	10YR 5/3	3.7	mud		
LV11	165–180	10YR 4/3	4.2	mud		
LV12	180–200	10YR 5/2	2.1	muddy sand		

Explanations as in Table 3

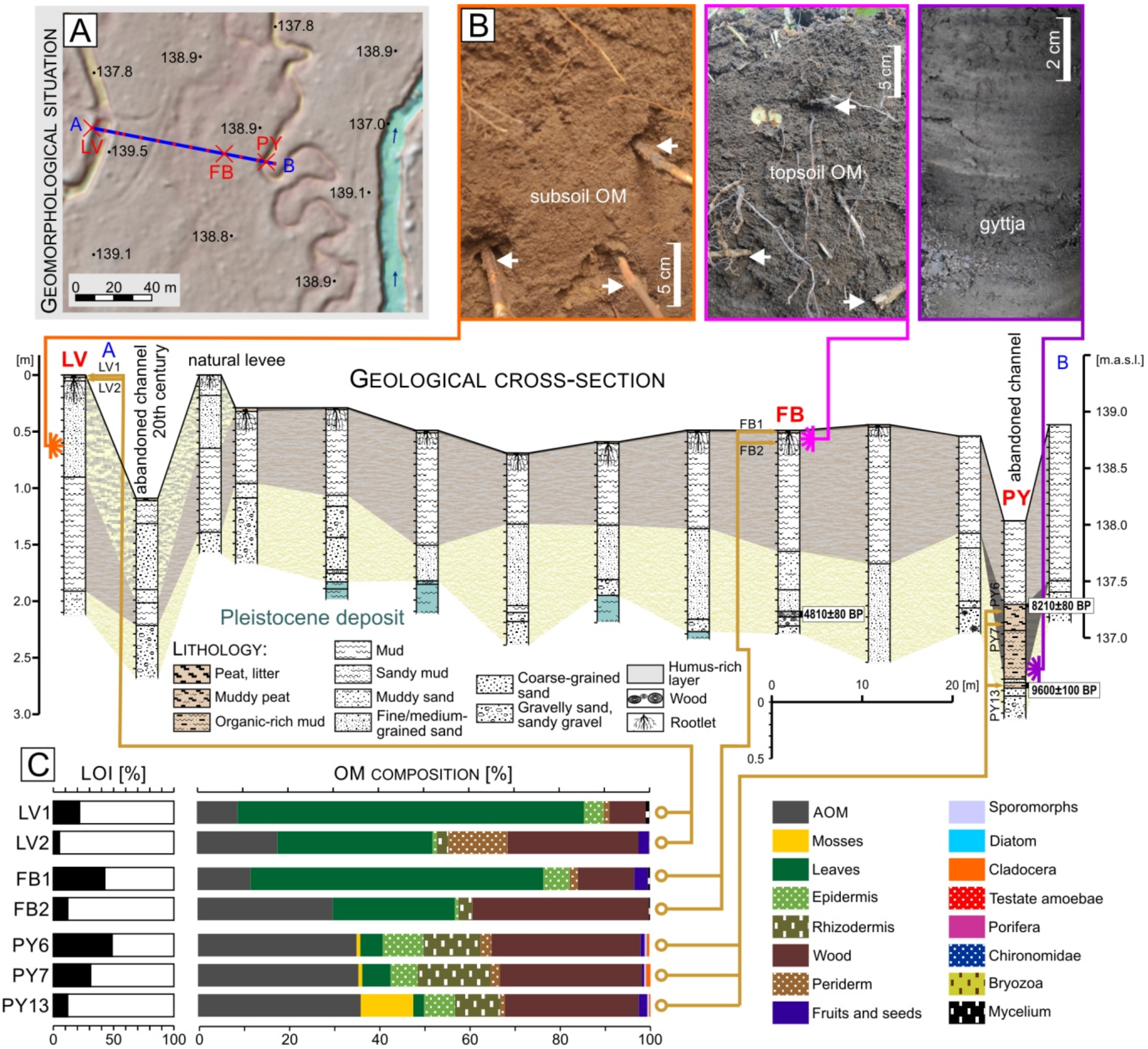

Fig. 4. PY, FB and LV sites

A – location of the sites on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

NATURAL LEVEE (NL), PLUG BAR AND ABANDONED CHANNEL (PB) SEDIMENTARY SUCCESSIONS

Sites: NL (50°50’59.0”N; 17°14’39.1”E; 140.1 m.a.s.l.); PB (50°50’57.9”N; 17°14’39.1”E; 138.5 m.a.s.l.).

Geomorphological situation: The Oława channel, active before regulation, with a natural levee rising to about 1.1 m above the surface of the valley floor and the previously cut palaeomeander (R_m = 12 m, w_{bkf} = 6 m; Fig. 5A).

Vegetation: Riverine forest community Ass. *Ficario-Ulmetum minoris*, dominated by *Fraxinus excelsior* and with the presence of *Ulmus glabra, Quercus robur, Tilia cordata, Acer campestre* and *Padus avium* in the tree and shrub layer together with *Galanthus nivalis, Pulmonaria obscura, Alliaria petiolata, Ficaria verna* and *Stachys sylvatica* in the seasonally variable forest floor.

Modern processes: Soil processes.

Lithology and facies interpretation: The internal structure of the natural levee (NL succession) was identified at the site together with the underlying channel deposits (Fig. 5B and Table 7). In the lower part, sandy-gravelly alluvia were deposited after the meander neck was cut off. They contain wood, including the remains of *Quercus* (sample NL12; Fig. 5C). The dating of detritus and charcoal from a depth of 218–222 cm indicates that the meander cut-off may have taken place at the turn of the second to the first millennium BC (Table 2). Above this, from a depth of 154 cm, there are silty-sandy deposits of the natural levee. The series of these sediments has a coarsening-upward successions. Massive muds and sands bear clear traces of the development of soil processes. The levee sediments contain only traces of organic matter, mainly in epipedons. In samples NL1 and NL4, the wood of root systems, mainly *Fraxinus excelsior*, was found as the main component of OM.

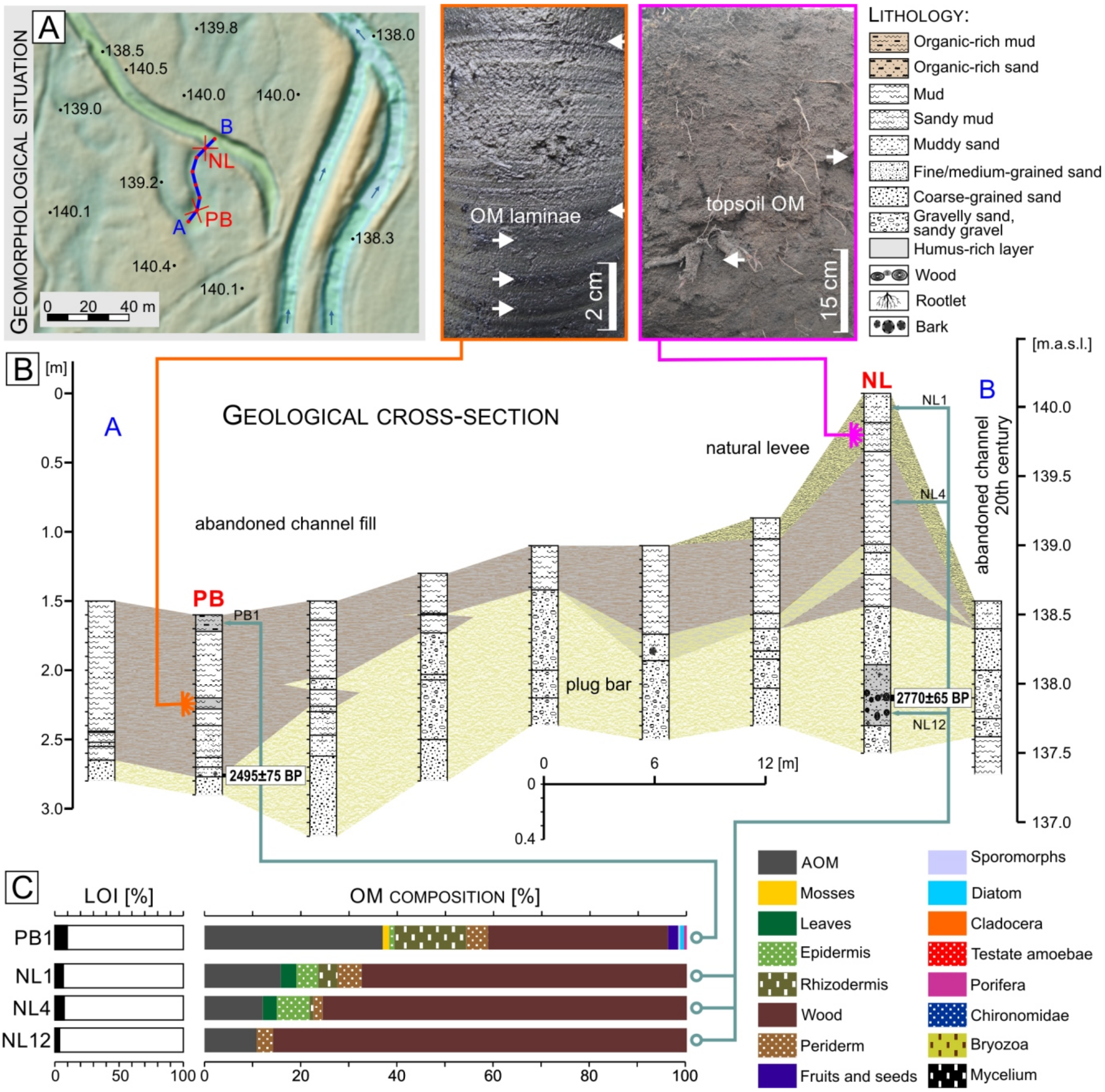

Fig. 5. NL and PB sites

A – location of the sites on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

The geological cross-section along the course of the palaeomeander allowed a reconstruction of the conditions of OM deposition in the first phases after the formation of the oxbow lake. The plug bar deposits consist of a fining-upwards series of gravels and sands, that are essentially free of OM. These coarse-grained alluvia extend to a distance of ~35 m from the meander neck. In this zone, they dovetail with fine-grained muds deposited in the distal part of the palaeomeander. Oxbow lake deposits (PB succession) locally contain an admixture of OM, particularly AOM (amorphous organic matter) and wood of *Fraxinus excelsior*. The dating of woody detritus with remains of *Prunus avium* at a depth of 114–117 cm suggests that the process of palaeomeander filling was initiated in the earlier part of the 1st millennium BC. The overbank alluvia (see Table 8) are accompanied by diatom shells and sponge needles (sample PB1).

SIDE BAR (SB) SEDIMENTARY SUCCESSION

Site: SB (51°02'25.9"N; 17°10'49.4"E; 119.5 m.a.s.l.).

Geomorphological situation: Side bar, in the form of a platform, which is periodically flooded at higher water levels. A place where one of the branches of the River Oława flowed into an old oxbow lake of the River Odra (Fig. 6A).

Table 7

Lithology of the samples and interpretation of the sedimentary environment for deposits of the NL succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
NL1	0–21	10YR 4/3	6.6	muddy sand (topsoil)	deposition from bedload transport and suspension	natural levee
NL2	21–42	10YR 4/2	4.2	sandy mud		
NL3	42–67	10YR 4/2	5.5	mud		
NL4	67–90	10YR 4/3	7.3	mud		
NL5	90–109	10YR 4/3	5.6	mud		
NL6	109–115	10YR 4/2	2.3	fine-grained sand		
NL7	115–131	10YR 4/3	3.5	muddy sand		
NL8	131–154	10YR 4/2	4.2	mud		
NL9	154–175	10YR 4/2	1.1	gravelly sand	deposition from bedload transport (mainly from traction)	channel bar (plug bar)
NL10	175–196	10YR 5/2	0.7	gravelly sand		
NL11	196–222	10YR 3/1	4.2	muddy sand with detritus		
NL12	222–240	10YR 3/2	3.7	muddy sand with detritus		
NL13	240–260	10YR 5/3	1.3	gravelly sand		

Explanations as in Table 3

Table 8

Lithology of the samples and interpretation of the sedimentary environment for deposits of the PB succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
PB1	0–12	10YR 4/2	9.7	organic-rich mud	deposition from suspension + organic accumulation	abandoned channel
PB2	12–20	10YR 4/2	6.2	mud		
PB3	31–50	10YR 4/2	5.9	mud		
PB4	50–68	10YR 4/2	7.7	mud with OM laminae		
PB5	68–80	10YR 4/3	5.3	mud		
PB6	80–103	10YR 4/3	2.3	sandy mud	deposition from bedload transport and suspension	
PB7	103–106	10YR 4/4	1.8	sandy mud		
PB8	106–110	10YR 4/3	1.7	muddy sand		
PB9	110–117	10YR 4/3	2.1	sandy mud		
PB10	117–130	5Y 5/3	1.1	medium-grained sand	deposition from bedload transport	river channel (thalweg***)

Explanations as in Table 3

Table 9

Lithology of the samples and interpretation of the sedimentary environment for deposits of the SB succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
SB1	0-2	10YR 5/3	81.9	litter	organic accumulation	topsoil
SB2	2-11	5YR 3/2	31.3	muddy peat	organic accumulation + deposition from suspension	temporarily dominated by the vertical accretion typical of floodplains channel bar (upper part of side bar)
SB3	11-20	5YR 3/2	32.2	muddy peat		
SB4	20-21	10YR 4/2	3,1	fine-grained sand	rhythmic deposition from bedload transport and suspension	
SB5	21-29	7.5YR 3/2	21.8	organic-rich mud		
SB6	29-48	2.5Y 3/1	5.2	sandy mud with OM		
SB7	48-62	2.5Y 5/4	1.5	fine-grained sand		
SB8	62-72	2.5Y 3/2	8.1	organic-rich mud		
SB9	72-88	2.5Y 4/3	2.2	muddy sand		
SB10	88-100	2.5Y 5/3	2.1	coarse-grained sand	deposition from bedload transport	lower part of side bar

Explanations as in Table 3

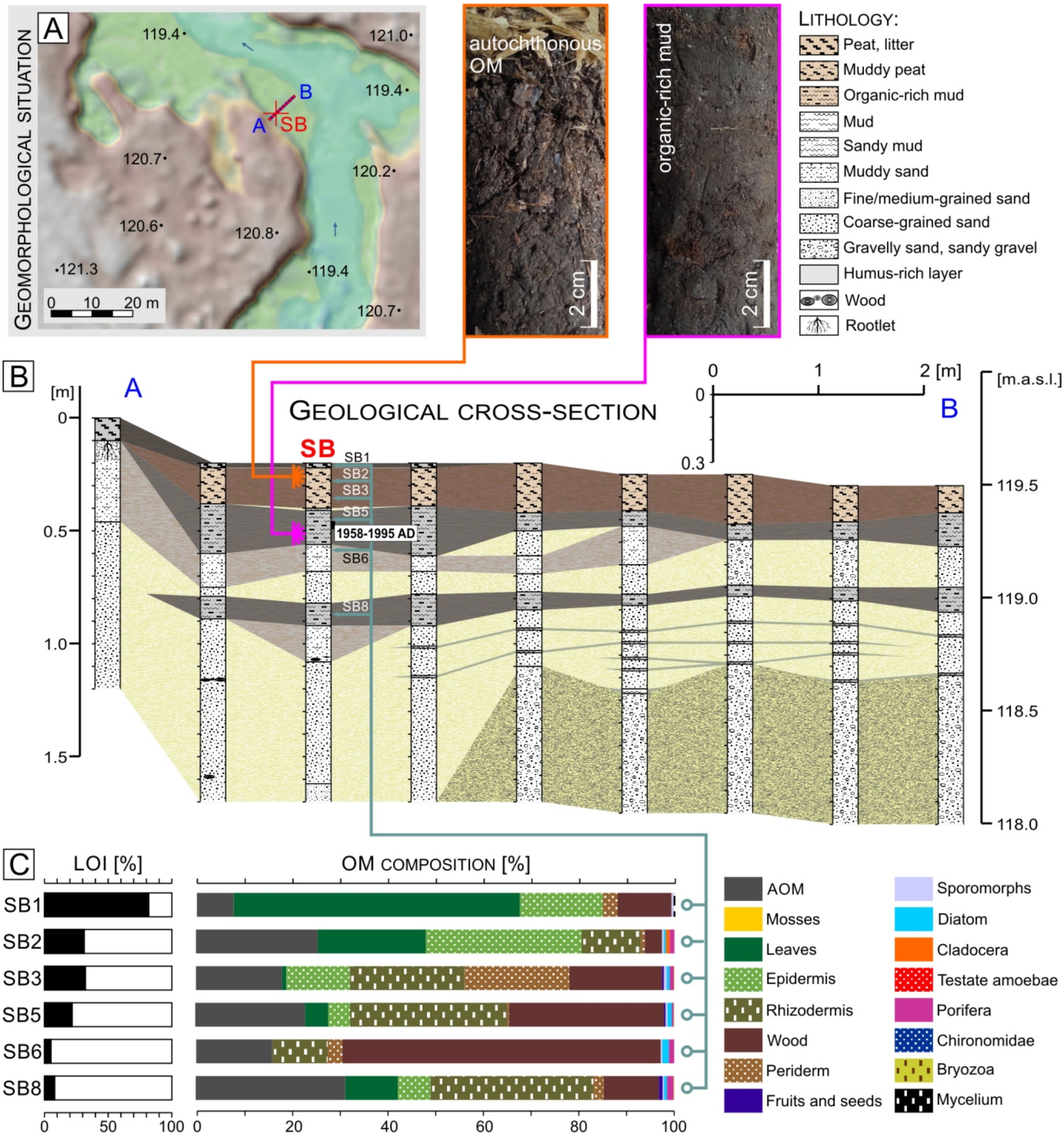

Fig. 6. SB site

A – location of the site on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

Vegetation: All. *Magnocaricion* community dominated by *Carex riparia* with the participation of *Phalaris arundinacea*, *Poa palustris, Scirpus sylvaticus, Juncus effusus* and *Oenanthe fistulosa* and, during inundation, of *Lemna minor* and *Hydrocharis morsus-ranae* invading from neighbouring aquatic communities.

Modern processes: River erosion and accumulation; organic accumulation.

Lithology and facies interpretation: The rhythmically bedded sediments of the side bar were deposited on organic-free coarse sands lying at a depth of 88–142 cm (see Fig. 6B and Table 9). Above this the sand is finer and contains pieces of wood. The sandy-silty layer at a depth of 62–72 cm (sample SB8) is dominated by the remains of the root systems of the rush vegetation (Fig. 6C). In contrast, in the coarser-grained sediments at a depth of 29–48 cm (sample SB6), it was mainly wood detritus that was deposited. Above this, sediments with a high OM content accreted under amphibious conditions and with episodic supply of floodwater mud. Their deposition was most likely initiated in the 1990s (1990–1995 AD with 92.1% probability; see Table 2). Samples SB5, SB3 and SB2 mainly consist of woody detritus and rhizodermis of rush plants (their proportion increases with depth) and epidermis and leaves (their proportion decreases with depth). In the samples studied, the remains of indicators of the aquatic environment have a small but permanent share: diatom shells, needles of freshwater sponges and statoblasts of bryozoans. Their presence testifies to regular flooding of the platform observed during fieldwork. In the litter layer (sample SB1), the remains of leaves and the epidermis of leaves of trees and herbaceous plants form the largest proportion. The leaf flora of *Padus avium* is dominant with *Acer campestre* and *Quercus robur* leaves also present.

CONCAVE-BANK BAR (CB) AND MUD-FILLED CHANNEL (PM) SEDIMENTARY SUCCESSIONS

Sites: CB and PM (51°02'34.8''N 17°10'05.9''E; 118.6 m.a.s.l.).

Geomorphological situation: A mud-filled channel and a concave-bank bar of an active, secondary channel of the Oława River (Fig. 7A).

Vegetation: An aggregation assemblage with *Phragmites australis* dominant invaded by, inter alia, *Lemna minor* during flooding. The reed belt on the landward side borders a forest community dominated by *Ulmus minor*, *Acer campestre* and *Padus avium*.

Modern processes: Accumulation of suspended particles; peat-forming processes.

Lithology and facies interpretation: The succession of sediments in the concave-bank bar is dominated by sandy lithofacies (Fig. 7B and Table 10). At a depth of 82–105 cm, the presence of sandy mud was noted, locally with a significant admixture of OM (sample CB7). In the most recent phase of development of the bar, the importance of organic accumulation increased (samples CB2, CB1). The composition of OM in the individual samples of CB succession is similar. The epidermis and rhizodermis of reeds and sedges predominate (Fig. 7C). Allochthonous components (leaves and woody detritus) from the tree canopy were accumulated synchronously.

The processes of filling the channel (PM succession) occurred in the bend of the riverbed on the distal side of the concave-bank bar. As a result of the reduced flow velocity behind the barrier, grey muds with OM-enriched laminae were deposited on the channel sands (see Table 11). The composition of the layer from a depth of 115–119 cm (sample PM7) is dominated by species-rich wood. In contrast, the mud layer with OM (sample PM1) mainly contains leaves from nearby trees.

MID-CHANNEL BAR (MB) SEDIMENTARY SUCCESSION

Site: MB (50°51'32.5"N; 17°14'35.8"E; 137.4 m.a.s.l.).

Geomorphological situation: Modern mid-channel bar with a length of ~20.5 m and a width of up to 7 m (Fig. 8A).

Table 10

Lithology of the samples and interpretation of the sedimentary environment for deposits of the CB succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
CB1	0–6	10YR 3/2	55.8	organic deposit	organic accumulation + deposition from suspension	temporarily dominated by the vertical accretion typical of floodplains channel bar (concave–bank bar)
CB2	6–19	7.5YR 3/2	24.5	organic detritus with mud		
CB3	19–40	2.5Y 5/6	0.8	coarse-grained sand	deposition from bedload transport and suspension	
CB4	40–60	2.5Y 5/4	1.0	coarse-grained sand		
CB5	60–82	2.5Y 5/3	1.8	fine-grained sand		
CB6	82–87	2.5Y 5/3	2.6	fine-grained sand		
CB7	67–94	2.5Y 4/3	8.1	sandy mud with OM		
CB8	94–105	2.5Y 5/4	2.3	fine-grained sand		
CB9	105–121	2.5Y 6/4	1.3	medium-grained sand		
CB10	121–138	2.5Y 6/3	1.1	medium-grained sand		
CB11	138–150	2.5Y 6/3	1.6	muddy sand		

Explanations as in Table 3

Table 11

Lithology of the samples and interpretation of the sedimentary environment for deposits of the PM succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
PM1	0-11	7.5YR 3/1	21.0	organic-rich mud	deposition from suspension + organic accumulation	mud-filled channel
PM2	11-32	2.5Y 4/2	6.9	mud		
PM3	32-53	2.5Y 4/2	5.3	mud		
PM4	53-74	2.5Y 4/2	6.4	mud		
PM5	74-95	2.5Y 4/2	5.2	mud		
PM6	95-115	2.5Y 4/2	4.6	mud		
PM7	115-119	10YR 4/2	8.9	mud with OM		
PM8	119-128	2.5Y 5/2	2.1	medium-grained sand	deposition from bedload transport	river channel (former thalweg***)
PM9	128-150	2.5Y 6/4	0.8	gravelly sand		

Explanations as in Table 3

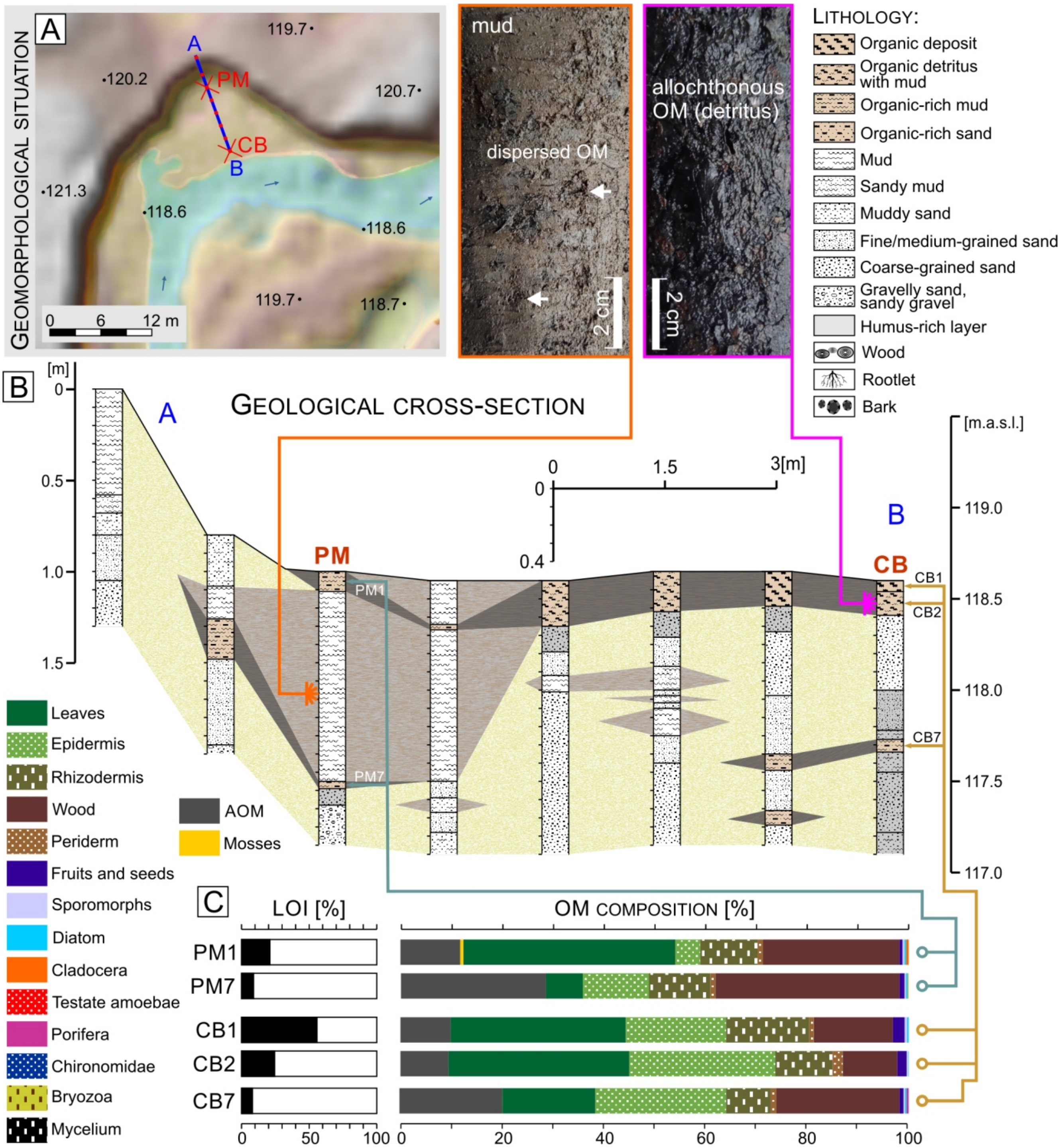

Fig. 7. CB and PM sites

A – location of the sites on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

Vegetation: Initial phase of the Ass. *Phalaridetum arundinaceae* community growing on freshly deposited alluvia. Besides the dominant *Phalaris arundinacea*, the community also includes, inter alia, *Polygonum amphibium* and *Rumex conglomeratus*.

Modern processes: River erosion and accumulation; soil processes.

Lithology and facies interpretation: The formation of the mid-channel bar was most likely caused by a tree falling into the riverbed. The fallen tree triggered the interception of plant detritus transported along the riverbed (Fig. 8B) and forced the deposition of mineral sediments behind the barrier (see Table 12). The result is a large accumulation of species-rich tree remains, mainly composed of wood, leaves and bark (sample MB0) in

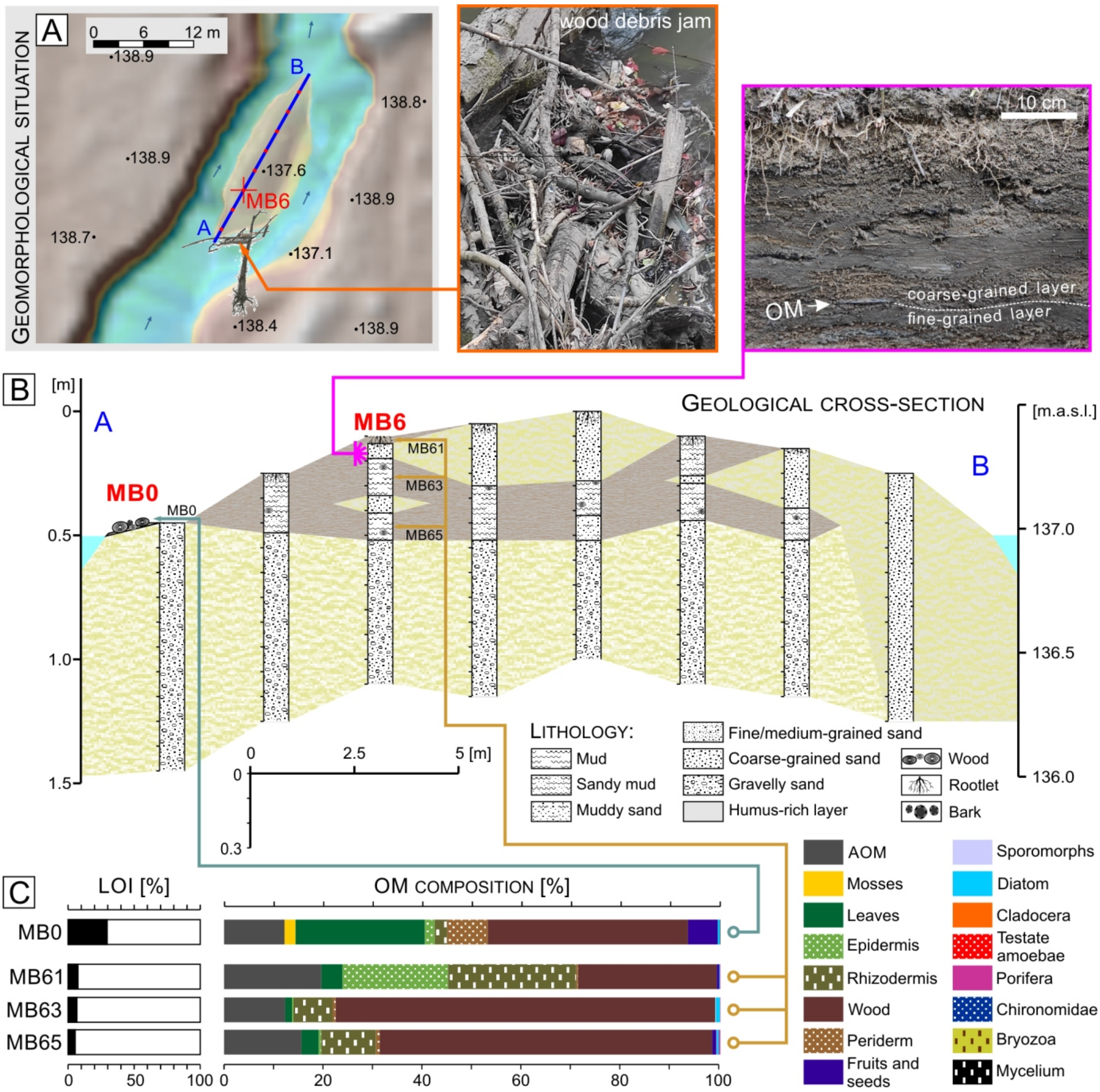

Fig. 8. MB site

A – location of the site on a digital terrain model (the numbers indicate elevation above sea level); **B** – lithology of the sediments, radiocarbon dating and selected photos of sedimentary successions (the background colour on the geological cross-section refers to the colour of the sediment samples); **C** – LOI (loss on ignition) and composition of the organic residues for samples with higher OM contents

the proximal part of the bar (Fig. 8C). Carpological finds also form a relatively large proportion, especially the fruits of *Phalaris arundinacea* and *Urtica dioica*.

In the central part of the bar, the OM content is lower. The basic sedimentary succession in exposure MB6 comprises a rhythmite, consisting of light sandy laminae and dark laminae of silt and fine sand. The latter contain the most OM, but fragments of twigs and acorns were also found in sandy layers at depths of ~90 and 50 cm. It is characteristic that organic detritus accumulates at the upper surface of the layer (sample MB65). This indicates that its deposition occurs at the end of the flood. Samples MB65 and MB63 are dominated by allochthonous OM in the form of species-rich wood. At a depth of 0–3 cm, however, the deposits are heavily overgrown with modern roots. Consequently, the main components of sample MB61, apart from woody detritus, is epidermis and rhizodermis of *Phalaris arundinacea*. This indicates the role of vegetation as an important source of OM in recent alluvia.

OM CONTENT AND DIVERSITY WITHIN THE SEDIMENTARY SUBENVIRONMENTS OF THE OŁAWA VALLEY

Organic material occurs relatively frequently in the sediment samples from the Oława Valley, but mostly as a small admixture of inorganic alluvia. This is reflected in the low values of the mean LOI of the successions investigated: PY – 11.5%, FB –

Table 12

Lithology of the samples and interpretation of the sedimentary environment for deposits of the MB succession

SAMPLE	DEPTH [cm]	COLOUR*	LOI** [%]	SEDIMENT DESCRIPTION	TRANSPORT AND DEPOSITION	SEDIMENTARY ENVIRONMENT
MB0	0–1	5Y 5/2	29.6	mud with detritus	rhythmic deposition from bedload transport and suspension	channel bar (upper part of mid-channel bar)
MB61	0–3	2.5Y 5/3	7.5	mud (topsoil)		
MB62	3–9	2.5Y 5/4	3.1	medium-grained sand		
MB63	9–24	2.5Y 4/3	6.7	mud		
MB64	24–31	2.5Y 4/3	2.3	coarse-grained sand		
MB65	31–42	2.5Y 3/2	5.4	mud		
MB66	42–60	2.5Y 4/3	1.8	gravelly sand	deposition from traction	channel bar (lower part of mid-channel bar)
MB67	60–80	2.5Y 4/3	1.2	gravelly sand		
MB68	80–100	2.5Y 4/3	0.8	gravelly sand		

Explanations as in Table 3

7.5%, MB – 6.5%, LV – 4.6%, NL – 3.9%, PB – 4.4%, SB – 18.9%, CB – 9.2%, PM – 6.8%. Only in the PO succession is the content of OM high, typical of peatlands (mean LOI = 46.3%). The mean LOI value for 114 samples analysed (see Tables 3–12) was 12.8%. For comparison, the average LOI content for 75 samples from the meandering Ruda valley (organic-rich sediment successions were selected for analysis, similarly to the Oława valley) was 24.2% (Wójcicki, 2022). This is chiefly a result of the more frequent presence of peat in the fills of the abandoned channels (mean LOI – 57.3%) and flood basins (mean LOI – 27.6%) of the Ruda River. The LOI content in the sediments from the Ruda valley thus proved to be significantly higher compared to the sediments from the corresponding environments in the Oława valley (Table 13). No Holocene peat deposits were found in the Oława valley, except in the depressions of the abandoned and modern channels. Compared to the organic-rich floodplains of the anastomosing rivers, they occupy a very small area, less than 0.2% of the valley floor (see Fig. 9). Therefore, the depositional system of the Oława River does not meet the criteria (abundant organic and lacustrine deposits, peat formation and lacustrine sedimentation as one of the main depositional processes, and lakes and peat swamps as one of the main landforms) that would allow it to be classified as an organic-rich floodplain (C2a) according to the classification of Nanson and Croke (1992).

Despite its relatively low share in the structure of the Oława floodplain, OM shows a high genetic diversity (Fig. 10A). Phytoclasts (fragmented plant remains) dominate, especially wood, which is mostly of allochthonous origin in the Oława Valley. In freshly deposited sediments, tree leaves are also of great importance. The proportion of periderm (cortex) does not exceed a few percent. By contrast, the epidermis and the rhizodermis form a significant proportion, especially the remains of the underground organs of herbaceous plants. The

Table 13

Basic features of the analysed facies of the deposits

Sedimentary subenvironment			Inorganic components	Organic components	mean LOI [%]
channel zone	channel bars	side bar	upper part: horizontally stratified fine-grained sand, muddy sand and sandy mud; individual sets from 0.01 to 0.2 m; lower part: coarse-grained sand;	mainly detritus (leaves and wood); autochthonous rhizodermis and epidermis; also diatoms* and Porifera*	11.9
		concave-bank bar	coarse- to fine-grained sand and muddy sand; individual set from 0.1 to 0.4 m;	mainly detritus (leaves and wood); autochthonous rhizodermis and epidermis; also diatoms* and Porifera*	9.2
		mid-channel bar	upper part: rhythmically bedded coarse-grained sand and mud; individual sets from 0.03 to 0.15 m; lower part: gravelly sand;	mainly detritus (wood, leaves, fruits and seeds); autochthonous rhizodermis and epidermis; also diatoms* and Porifera*	6.5
		plug bar	gravelly sand to muddy sand; individual sets up to 0.4 m;	wood debris	2.2
	mud-filled channel		horizontally laminated mud; co-set thicknesses up to 1.2 m;	mainly detritus (wood and leaves); autochthonous rhizodermis and epidermis; also diatoms* and Cladocera*	8.3
floodplain	abandoned channel (oxbow lake)		horizontally laminated mud, sandy mud, muddy sand, sand; co-set thicknesses up to 2.2 m;	mainly peat (wood, rhizodermis and epidermis); also mosses*, Cladocera*, Chironomidae*	22.3
	flood basin		massive mud; up to 1.3 m in thickness;	mainly wood and leaves in topsoil	4.8
	natural levee		fine-grained sand, muddy sand, sandy mud and mud; coarsening-upwards succession; up to 1.5 m in thickness	mainly wood and leaves in topsoil	4.0

* – components that are present in small quantities but have an indicative value for the facies studied

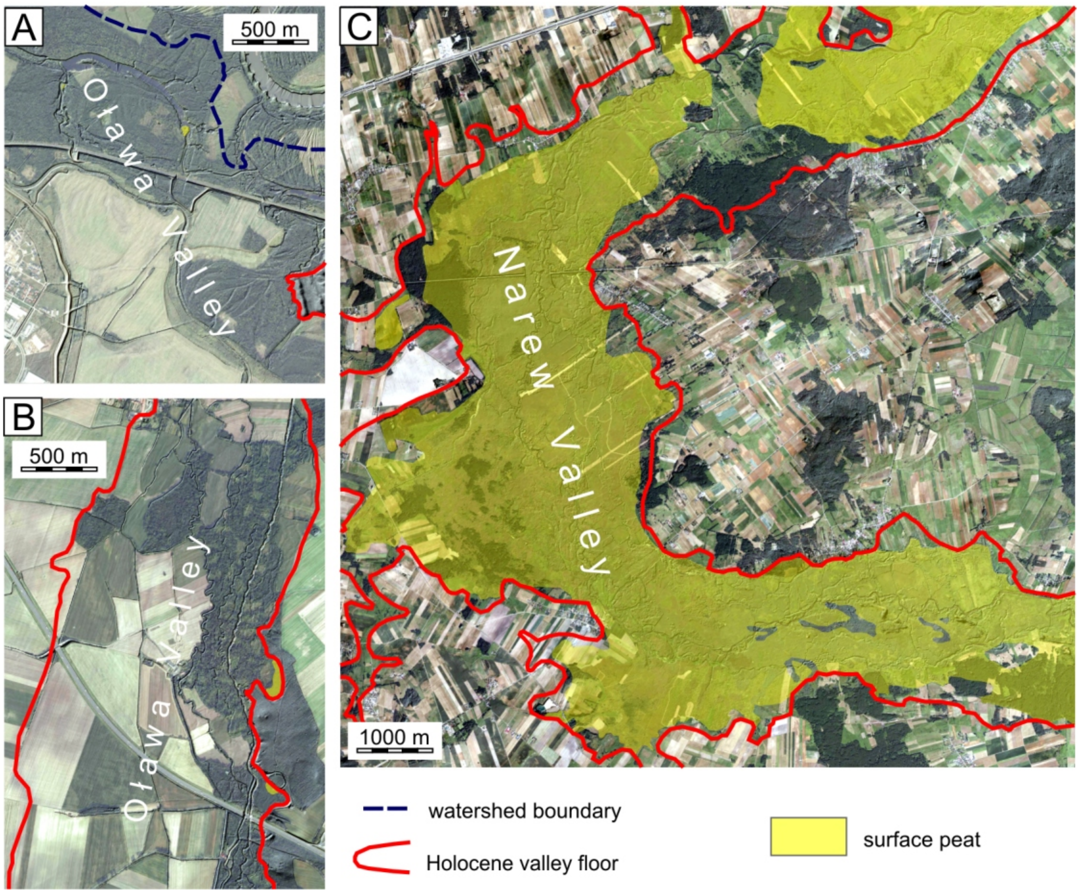

Fig. 9. Proportion of peat on the surface of the Oława floodplain compared to the organic-rich floodplain of the Narew River

A – the Oława valley in its lower course; area occupied by peat according to Winnicka (1985), supplemented by the author; **B** – the Oława valley in its middle course; area occupied by peat according to Michalska (1992) and Winnicka (2008), supplemented by the author; **C** – the Narew valley near Białystok; area occupied by peat according to Butrymowicz (2001)

high percentage of AOM shows that a large proportion of the OM produced in the riverine ecosystem of the River Oława is subject to rapid decomposition. First, the remains of the above-ground organs of the plants, which consist of thin-walled parenchyma cells, are decomposed (Wójcicki, 2022). The rapid degradation affects, inter alia, the above-mentioned tree leaves, which are deposited seasonally.

The proportion of other components (including remains of mosses, fruits and seeds, sporomorphs, Porifera, diatoms, Cladocera, Chironomidae, Bryozoa and thallus of fungi) did not exceed 1 percent in the samples examined. In the sediments of the Oława Valley, the proportion of mosses is very low, the remains of which are a good indicator of *in situ* deposition. The remains of organisms classified as plankton and benthos do not usually contribute much to the composition of OM due to their microscopic size. Instead, they can serve as bioindicators that identify specific sedimentary subenvironments. The presence of diatom remains, spicules of sponges and bryozoan statoblasts is characteristic of flood layers rich in fine sand. The remains of Cladocera and Chironomidae can be associated with undisturbed accumulation in sedimentary basins, especially oxbow lakes. The development of mycelium is characteristic of OM transformations in epipedons.

ORIGIN OF OM IN THE CHANNEL FACIES

The channel sediments of the Oława River show variability in lithofacies, ranging from fine gravel, sandy gravel and sand to sandy-silty rhythmites. In the coarse-grained deposits building large bedforms on the channel bottom, organic particles mainly occur in the form of thick, woody debris. Despite the stable banks, it is not uncommon for trees to fall into the Oława channel. This is encouraged by the structure of the riparian forests that mainly consist of SubAll. *Ulmenion minoris*, i.e. dominated by tall trees that are not adapted to frequent flooding and fluvial erosion. The crowns of fallen trees are a source of woody debris and at the same time act as barriers, trapping coarse organic particles transported downstream. As a result, they can block the channel and may cause avulsion (i.a. Teisseyre, 1992; Bábek, 2018). At the local scale, log jams cause flow redirection, sediment impoundment and bar formation. These processes can lead to the formation of a valley floor with complex local topography which has the character of an anastomosing network (Abbe and Montgomery, 2003).

The greatest genetic variation in OM is associated with the upper, sandy-silty parts of the alluvial bars (Fig. 10B). The River Oława shows similarities with less wet river systems where the

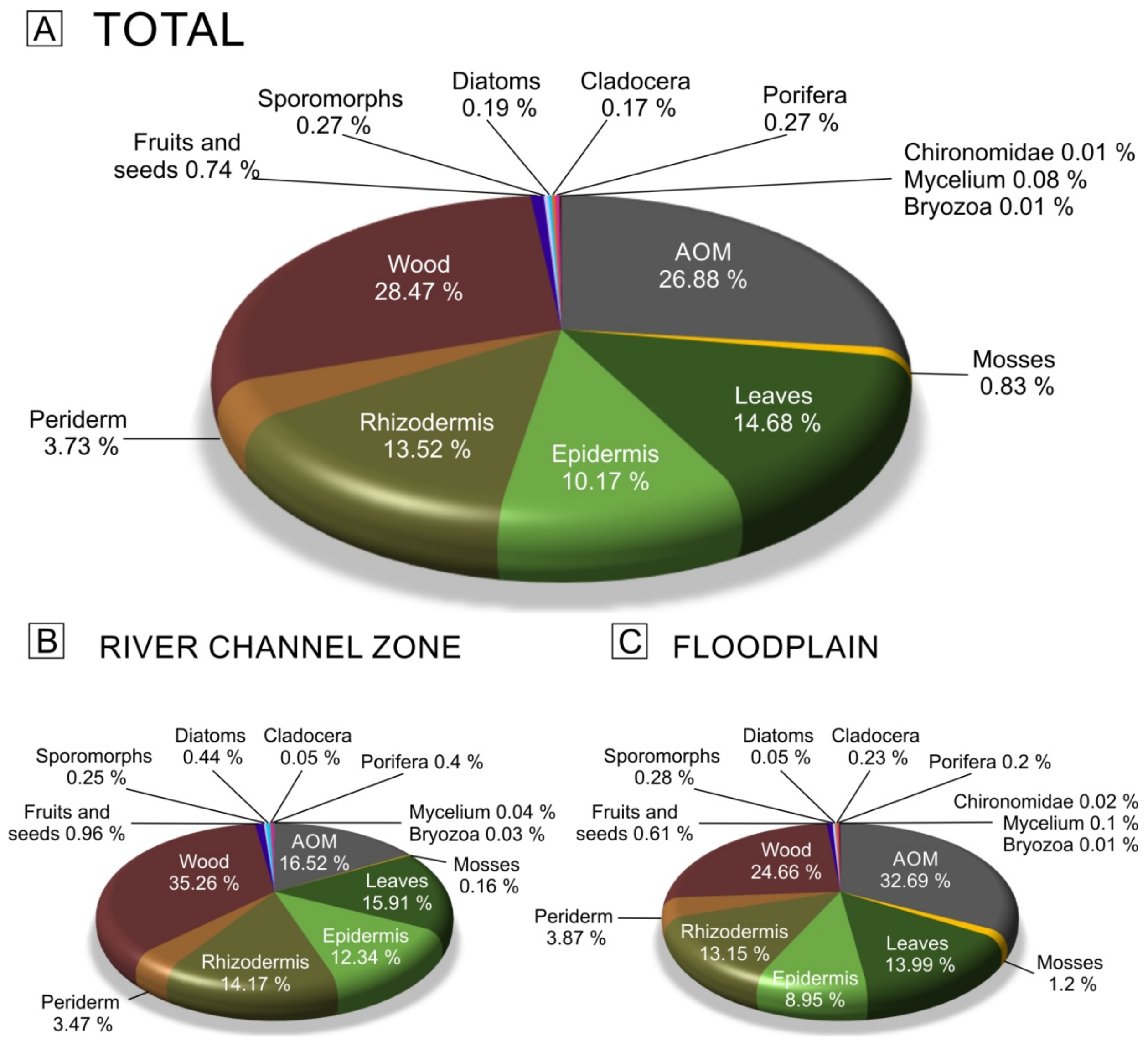

Fig. 10. Contribution of OM forms to sediments within the Oława valley

A – total; **B** – channel facies; **C** – floodplain facies

frequent occurrence of organic litter (including wood and leaf fragments) has been observed in channel sediments (i.a. Smith, 1986; Gibling et al., 1998). Larger pieces of organic detritus were deposited on the surface of the proximal parts of the alluvial bars. They consist of species-rich remains of trees: mainly wood, but also leaves, bark and fruits. They were likely trapped first due to their size, while the finer detritus was transported farther. When water flow is inhibited, fine-grained mud and organic debris, including tiny components such as diatom shells, are deposited on the surface. In zones colonised by vegetation, the detritus can be captured by the shoots of modern vegetation. In addition, the development of soil formation is responsible for post-sedimentary processes of enrichment of alluvial material with epidermis and rhizodermis. This is especially observed in fine-grained laminae, which are rich in nutrients and therefore penetrated by root systems (Wójcicki, 2022). In the case of bars formed in secondary channels, mineral sedimentation can be replaced by organic accumulation. Flooded bars are often colonised by rush vegetation, but even under such conditions the organic sediments mainly consist of allochthonous leaves and wood. Organic detritus can be buried in the banks, strengthening their erosion resistance in a similar way to woody debris (i.a. Abbe and Montgomery, 2003; Bábek, 2018). However, the role of OM in protecting the banks of the Oława appears to be less than in organic-rich floodplains, where reworked peat is very common in channel deposits (i.a. Törnqvist et al., 1993; Gradziński et al., 2003; Kędzior et al., 2021).

ORIGIN OF OM IN THE FLOODPLAIN FACIES

Natural levees with associated crevasse splays are common depositional forms in the proximal floodplains of anastomosing rivers. In the middle reaches of the Oława Valley, distinct natural levees were formed by silty-sandy lithofacies deposited in a generally coarsening-upwards succession. These sediments have a massive structure, ultimately formed under the influence of soil processes that form Cambisols. They usually do not contain OM of alluvial origin, and organic remains mainly occur in epipedons. In the litter level, it is mainly leaves from the crowns of trees that are found. The mineral soil horizons are dominated by the remains of tree root systems. The rapid decomposition of litter with relatively low humus content indicates intensive mineralisation of OM in the eutrophic, aerobic topsoil layer (see Gibling et al., 1998). Natural levees, permanently occupied by rooted vegetation, have an additional effect on the stabilisation of the Oława channel.

The flood basin facies within the distal floodplain is considered the dominant one within the deposits of anastomosing rivers (Kleinhans et al., 2012; Zieliński, 2014). In the Oława Valley, deposition in this sub-environment was mainly of silty-clay deposits. OM occurs rarely, as in the case of natural levees, and then mainly in epipedons. This is usually formed of the remains of leaves in the litter layer (O horizon) and wood in the topsoil (A horizon). Although their accumulation took place amidst the lush vegetation of eutrophic forest communities, the organic remains were subject to intense changes under the influence of soil processes. As a result, the flood basins are filled with secondary massive clayey-silt deposits with traces of post-sedimentary weathering and illuviation. Basically, they do not contain organic detritus of alluvial origin or peat. This clearly distinguishes the Oława system from organic-rich floodplains of anastomosing systems.

Abandoned channels form the most important sub-environment collecting OM in the Oława floodplain. In general, oxbow lakes seem to be an important environment for organic accumulation, both for anastomosing systems in river valleys (i.a. Morozova and Smith, 2003; Rozo et al., 2012) and for anastomosing distributary systems in alluvial fans and deltas (i.a. King and Martini, 1984; Tornqvist et al., 1993; Stouthamer, 2001). However, the amount of organic sediments deposited in this sub-environment in the Oława Valley is generally low compared to the neighbouring valleys of meandering rivers in the Upper Odra basin (Wójcicki, 2013; 2022). The Oława abandoned channels have a sinuosity which varies from meandering sections to almost straight sections. They are partially sediment-filled. In the shallower sections of the abandoned channels with low sinuosity, this is mainly massive silt or fine-grained sand. Lenses of organic sediments occur mainly in the deeper palaeomeander bends in the high-sinuosity sections of the river channel. The main components of OM in abandoned channel-fills are AOM and wood together with the rhizodermis and epidermis of plants, including peat-forming vegetation. The proportion of AOM varies widely in relation to habitat moisture fluctuations, ranging from a few percent to about two-thirds of the total OM. In general, however, preserved phytoclasts outweigh the AOM content in the overbank sediments of the Oława River (Fig. 10C). The abandoned channel-fills are dominated by autochthonous OM components, including single-species wood. However, some of the components are allochthonous (mainly zooclasts and phytoclasts representing the above-ground organs of vascular plants) and were supplied by floodwater (including remains of diatoms and porifera) or come directly from the crowns of trees (some of the leaves). OM in abandoned channel-fills collected in anaerobic environments (aquatic or swampy) and show higher resistance to decomposition.

DEVELOPMENT CONDITIONS OF THE DEPOSITIONAL SYSTEM OF THE OŁAWA RIVER

The question, as posed in the introduction to this article, arises as to how the floodplain of the Oława River has low OM content, while the floodplains of the anastomosing rivers of northern Poland generally show a high biogenic content (Gradziński et al., 2003; Słowik, 2014; Kędzior et al., 2021). Looking at the depositional processes that take place in the channel zone, it is difficult to identify clear differences between these systems. Similarities observed for the Oława and Narew alluvia in the channel zone include: 1) fine clastic sediment together with plant detritus forming laminae within sand; 2) the uppermost part of the channel bars may consist of organic deposits, including peat (see Gradziński et al., 2003).

However, clear differences in relation to organic-rich floodplains can be observed in the structure of the distal floodplain of the River Oława. For the systems described in the literature, facies such as peat bog, backswamp, and lacustrine are typical of this zone (Smith and Smith, 1980; Nanson and Croke, 1992; Makaske, 2001). Farther away from the channels of the Attawapiskat River (humid subarctic), mires exist with up to 0.5 m thickness of grassy peat (King and Martini, 1984). In the Saskatchewan River floodplain (cold temperate humid continental), deposits rich in organic matter mainly form in isolated floodplain lakes, fen meadows and bogs (Smith and Smith, 1980; Morozova and Smith, 2003; Davies-Vollum and Smith, 2008). In the Narew valley (warm temperate transitional), organic deposits cover almost the entire inter-channel areas (see Fig. 9). Cariceti peat and Phragmiteti peat are the most common, while Carici-Phragmiteti peat and Saliceti peat are less frequent (Gradziński et al., 2003). In contrast, the subenvironments of the distal floodplain of the River Oława, especially the widespread flood basins, have a low proportion of OM, and organic remains are rarely associated with peat-forming ecosystems. The source of OM is mainly floristically rich forest SubAll. *Ulmenion minoris*. These communities colonise drier habitats with a lower water table than peat-forming vegetation, lying in the zone with only episodic flooding (Matuszkiewicz, 2005).

The absence of peat in the distal floodplain of the Oława River should not be linked with rapid mineral sedimentation, as suggested by Nadon (1994), Makaske (2001) or Morozova and Smith (2003). Radiocarbon dating shows the average accumulation rates for organic sediments tend to reach higher values than the analogous rates calculated for inorganic deposits. In the PY succession, for example, accumulation of a 74 cm-thick layer of organic sediment took 1.2–2.2 ky, while sedimentation of the same thickness of flood silt could take up to 9.5 ky (see Table 2). Sedimentation of the 160 cm-thick layer of fine-grained sand and mud in the FB succession began 5.4–5.8 ky. An average sedimentation rate of ~0.29 mm/year indicates long intervals between flood episodes, which could be used for peat accumulation under favourable conditions. The absence of further peatlands in the Oława Valley is thus probably related to unfavourable topographical and hydrogeological conditions (see Hare et al., 2017). Firstly, due to the lateral stability of the channels, only a small number of oxbow lakes, which set off mass peat-forming processes in the valleys of the neighbouring meandering rivers (Wójcicki, 2013), were formed. Secondly, the groundwater flowing from adjacent areas only weakly feeds the distal zone of the Oława floodplain. This is due to the small number of erosion edges crossing the aquifers on the valley sides (the site PO is one of the few exceptions). Thirdly, riverine peatlands are often fed by fluviogenic waters, however, in order to maintain a highly organic swamp, bankfull flows need to be relatively frequent (Nanson et al., 2010). In addition, some studies have suggested that avulsion may have played a key role in the formation of organic-rich deposits (Morozova and Smith, 2003; Davies-Vollum and Smith, 2008). In the middle reaches of the River Oława, numerous floods occurred at the turn of the Younger Dryas to early Holocene, which led to considerable aggradation of the valley floor (see Fig. 1: profile I-I'). As a result, parts of the late-Weichselian valley bottom are found 0.6–1.0 m below the surface of the modern floodplain. Vertical stabilisation of the Oława channel system took place in the Holocene. Furthermore, from the 13th century onwards, the process of anthropogenisation of the runoff (changes in the discharge and distribution of high and low water stages in an annual cycle) intensified due to transfer and retention (agricultural drainage system, ponds, millraces) of the Oława water (Parzóch and Solarska, 2008). A particularly strong human influence on the transformation of Central European rivers has been recorded over the last three centuries (Pišút, 2002). Regulation of the Oława River has forced a drop in the local base level and river-bed incision, while anastomosis normally requires a rise in base level (Bábek, 2018). Most likely, the infrequent flooding of the valley floor, as demonstrated by the inhibition of the aggradation rate and the composition of plant communities, was the main determinant for the formation of the Oława depositional system with low OM content. This interpretation is consistent with modelling results for Belgian rivers, according to which the productivity of riverine peatlands seems to be determined to a greater degree by the setting and dynamics of the local river network than by internal peatland processes (Swinnen et al., 2021).

SUMMARY

The depositional system of the River Oława deviates from the classical scheme according to which anastomosing rivers in humid climates form organic-rich floodplains. The characteristic feature of the Oława system is the scarcity of sedimentary facies associated with lacustrine and peat-forming sedimentary subenvironments (including marshes with tall herbaceous vegetation and swamps with forests dominated by black alder or scrub environments of broad-leaved willow). In such a system, the presence of organic sediments with high preservation potential (peat, gyttja) is essentially limited to abandoned channel fills. The geomorphological and hydrogeological conditions (including a paucity of oxbow lakes, resulting from the stability of the channels, a low level of groundwater inflow from gently inclined slopes, limited floodplain inundation, primarily as a result of river regulation and channel incision) should be noted as the limiting factors for peatland development in inter-channel areas. The example of Oława shows that the formation of an anastomosing depositional system does not depend on the amount of OM accumulated on the floodplain. By contrast, anastomosing systems, if they have an aggradational character, create favourable hydrological conditions for the accumulation of organic sediments.

Macrofossil analysis allowed systematic identification of the morphological forms and quantification of the contribution of each OM component observed in sediments of the Oława River depositional system. In general, the organic residues show a moderate degree of decomposition, with the AOM content accounting for about a quarter of the total OM. The analyses showed a clear dominance of material of plant origin. Wood proved to be the most important component of the phytoclasts, accounting for more than a quarter of the total OM in the samples analysed. Leaves, rhizodermis and epidermis reached a proportion of 10–15%. The periderm has a share of a few percent. The proportion of other ingredients, including moss residues and zooclasts, did not exceed 1%. The types of organic debris distinguished were associated with the main sedimentary subenvironments typical of anastomosing systems. In the channel alluvia, especially in the rhythmically stratified sediments of the upper part of the river bars, plant detritus was deposited in the form of species-rich wood, bark and leaf debris, together with fruits and seeds. The remains of diatoms, porifera and bryozoans are typical of sandier layers. Organic sediments from frequently flooded bars may contain more rhizodermis and epidermis. Within the floodplain, abandoned channels have the greatest potential for the collection and long-term storage of OM. Some are filled with peat dominated by the remains of autochthonous wood, rhizodermis and epidermis. The remains of mosses, Cladocera and Chironomidae are characteristic of this sedimentary sub-environment. In the sub-environment of flood basins and natural levees, OM was primarily deposited in epipedons, mainly in the form of leaf and wood debris.

Considering that the content and properties of OM in river depositional systems are highly dependent on local vegetation, studies on the determinants of floodplain development of anastomosing rivers with low OM content in humid climates need to be continued. A more comprehensive picture of the diversity of such systems should lead to a redefinition of the classification of anabranching rivers and their floodplains.

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