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EVOLUTION OF THE HOLOCENE ALLUVIAL FAN OF THE RIVER STRYI IN THE FORELAND OF THE EASTERN CARPATHIANS (WESTERN UKRAINE)

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Abstract

The research reconstructs the development of the alluvial fan of the River Stryi in the Holocene and dates the phases of increased river activity and their correlation with other valleys in the upper Dniester and Vistula river basins. The age of the palaeochannels and the stratigraphy of alluvial fills are based on radiocarbon dating supported by the results of palynological analyses. The oldest (fossil) palaeochannel of the Stryi was dated to the Younger Dryas. The large-radius meander was abandoned at the end of the Boreal Phase during the period of flood intensification at about 8700 BP. The uneven top of the gravels (cut by palaeotroughs of a depth ranging from 2 to 4 m) indicates that during periods of increased discharges (Younger Dryas, end of the Boreal Phase, late Atlantic and beginning of the Subboreal) the troughs were cut and filled with channel sands. From the beginning of the Subboreal Phase (5400-5300 BP), aggradation of the valley bottom has been predominant, which is manifested not only by the overbuilding of the floodplain but also by the gradual elevation of the channel. The accumulation of sandy-silty overbank sediments dated to about 8300, 5400 and 2800 BP correlates well with the beginning of humid phases and floods in the upper Vistula and upper Dniester basins as well as floods recorded in lakes in the northern foreland of the Alps.

Key words

generations of palaeochannels • alluvial fills • radiocarbon dating • flood phases • Stryi-Zhydachiv Basin • Western Ukraine

Introduction

In the piedmont zone of the Eastern Carpathians in Ukraine there is a system of alluvial fans, the structure and age of which is not precisely known. One of the largest is the Pleistocene alluvial fan of the River Stryi, which occupies most of the Stryi-Zhydachiv Basin (Rudnicki, 1907). A smaller Holocene alluvial cone of the Stryi is inserted in the Pleistocene alluvial fan.

Skvarchevska (1956) separated seven terraces within the Carpathian foreland section of the Stryi river valley. Terraces V-VII developed outside the alluvial fan of the Stryi, within the Drohobych Plateau and Morshyn Plateau. Terraces I-IV developed in the valley bottom, and their alluvial sediments form the alluvial fan of the Stryi. The accumulation of alluvial series of the Stryi fan up to 35 m thick occurred – according to Skvarchevska (1956) – during the Upper Pleistocene and the Holocene. Tsys (1962) stated that the greatest extension within the boundaries of the alluvial fan of the Stryi reaches terrace II. Similarly, Kravchuk (1999) believes that the largest areas in the Stryi-Zhydachiv Basin are occupied by terraces I and II. According to him, the thickness of the alluvial sediments in the Basin reaches 30 m, which is a maximum thickness of sediments for the entire eastern Carpathian foreland zone. The significant thickness of channel alluvial sediments on the alluvial fan of the Stryi may be associated with the tectonic lowering (subsidence) of the Basin (Gofshtein, 1964).

The much smaller Holocene alluvial fan of the Stryi, which is inserted in the Pleistocene cone at the confluence with the River Dniester near the town of Zhydachiv (Żydaczów), was the subject of detailed geomorphological research including sedimentological and palynological analyses and radiocarbon dating. The results of this research were partially published in the scientific monograph of the Ukrainian-Polish seminar in Roksolany (Gębica et al., 2013a). The descriptions of outcrops and drillings as well as radiocarbon dating made it possible to recognise the structure and age of the youngest (Medieval) alluvial fills in the northern part of the floodplain (Zhydachiv Dachas sites or Żydaczów Dacze – denoted in the Figures and Table as ŻD) (Gębica et al., 2013b; Gębica et al., 2016). In the years that followed, drilling was carried out along a transect located on the southern part of the floodplain (Zhydachiv Town cross-section or Żydaczów Miasto – denoted in the Figures and Table as ŻM) where several generations of Holocene palaeomeanders developed. This drilling was carried out in order to identify the age of the palaeomeanders and to reconstruct the development of the Holocene alluvial fan of the Stryj.

In the foreland of the Carpathians, where aggradation generally dominates, we can talk about phases of increased river activity, during which erosion and accumulation processes operate simultaneously. During the floods, troughs are cut and then filled with channel sediments. Research conducted in the upper Vistula river basin showed the presence of inserted series of alluvia, which were dated and correlated with the phases of high flood frequency. Each of these phases, with a duration of 200 to 600 years, was identified on the basis of various indicative changes in sediments and forms (Starkel et al., 1996; Starkel, 2014, Kalicki, 1996; Gębica, 2011): (i) the occurrence of coarse sediments, including the insertion of channel sediments, (ii) the overlapping of flood (overbank) sediments with organic deposits, (iii) covering of the overbank sediments with channel sediments, (iv) the occurrence of accumulations of subfossil trunks, (v) the occurrence of abandoned palaeochannels or of palaeochannel systems abandoned by avulsion.

The main purpose of the article is to present new, yet unpublished, results on the Holocene evolution of the Stryi alluvial fan in the Stryi-Zhydachiv Basin. The detailed aims of this study were as follows: (i) determine the morphology, structure and stratigraphy of the Holocene alluvial fan, (ii) establish the chronology of the phases of increased activity of the Stryi, and (iii) correlate (compare) these flood phases with other valleys in the upper Dniester basin and upper Vistula basin.

Study area

The study area is located in the Eastern Carpathian foreland (Western Ukraine) in the Subcarpathian part of the upper Dniester river catchment (Fig. 1A,B). One of the largest basins in the Eastern Carpathians foreland is the Stryi-Zhydachiv Basin. The majority of the Basin is occupied by a Pleistocene alluvial fan, whose length is 40 km and whose width between the Kolodnytsia river valley and the Svicha river valley is about 40 km (Fig. 1B). The apex of the fan begins at the river outlet from the Carpathians at an altitude of 350 m a.s.l., the distal part of the fan near the mouth of the Stryi where it discharges into the Dniester is located at an altitude of 250 m a.s.l. To the north-east, the fan is bounded by the edge of terrace II which is 15 m in height and was formed due to the erosion activity of the Dniester.

Between the Carpathian margin and Zhydachiv town, the Pleistocene alluvial fan is cut by the braided channel of the Stryi with a width of 200-700 m and a channel gradient of 2.3‰ (Fig. 1B). A system of inserted gravel terraces with a height of 2 m and 4 m stretches along this channel. In the profile of the 4 m cone-terrace (10 km from the Carpathian outlet of this river), two layers of gravel outcrop. The older (bottom) layer is built of ferruginous-cemented and imbricated gravels. The bottom layer is overlain by "fresh" gravels with inserts of muds and overbank deposits up to 0.5 m thick at the top (Gębica et al., 2013a). In the Stryi river channel there are numerous gravel bars with tree trunks and branches accumulated during floods, e.g. in July 2004.

Downstream of Zhydachiv town, the Stryi bypasses a 30-m high erosional hill, then turns east and flows into the Dniester at a distance of 7 km from the town. Due to the small gradient (0.6‰), the Stryi flows in a meandering or slightly sinuous channel 50-100 m wide

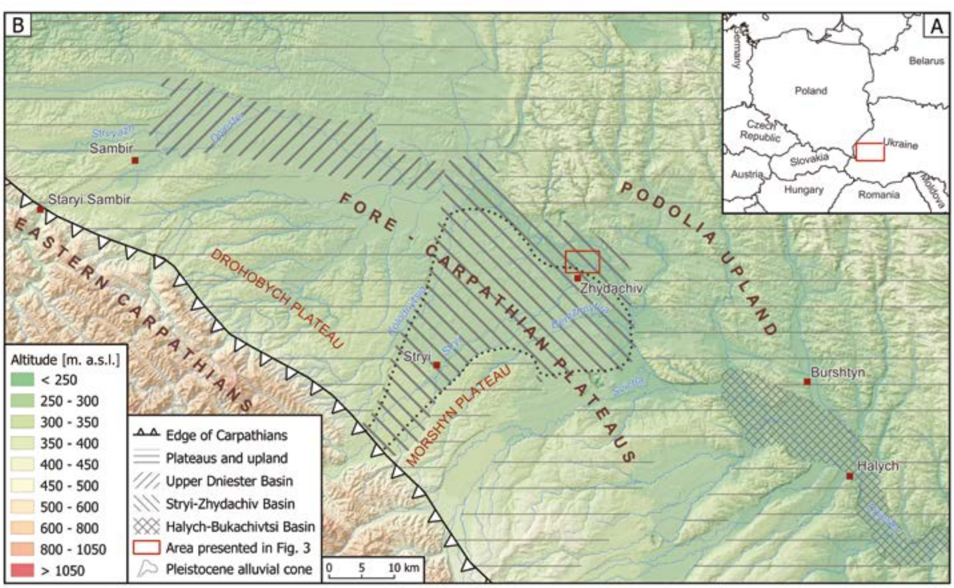

Figure 1. Location of the study area. A – Location marked on the map of Central Europe. B – Main geomorphological elements of relief after Gębica and Jacyšyn (2021, modified) of the Eastern Carpathian foreland (Western Ukraine) with location of study area

Source: Graphic design by Łukasz Chabudziński.

accompanied by 2-3 levels of Holocene floodplain at a height of 2-3 m, 4-5 m and 6 m above the river channel (Fig. 2). The largest of these is occupied by a floodplain 1.5-2.4 km wide and 4-5 m in height (247-246 m a.s.l.), bounded by the edge of Pleistocene terrace II at a height of 10-15 m above the river channel (246-250 m a.s.l.). Terrace I reaches a height of 5.5-7 m above the Stryi and Dniester river channels. The major fragments of this terrace have developed on the left-bank (northern part) of the Stryi river valley near the village of Miezhirichia. Terrace I is also found east of Zhydachiv. The alluvia lie on Miocene clays, and the bottom of the alluvial fills is located at a depth of 9-12 m below the water table in the Dniester river channel (Denisewicz et al., 1968; Gierasimow & Gierasimowa, 1970; Gierasimow et al., 1974).

One can distinguish the systems of palaeochannels with different ages in the southern part of the floodplain in the area of the town of Zhydachiv (Fig. 3): (a) narrow, large radius palaeomeanders (w = 40-50 m, R = 260 m), (b) smaller poorly visible palaeomeanders, (c) larger (w = 40-70 m) and deeper palaeomeanders that developed in the 15-17th centuries based on the dating of subfossil tree trunks (Gębica et al., 2013a) and (d) the largest palaeomeanders with a width of w = 70-100 m, partially filled with water, and cut off during floods in the 19th and 20th centuries (Gębica et al., 2013a). The Stryi-Zhydachiv Basin was not covered by continental glaciation during the Pleistocene. The ice-sheet of the Sanian 2 (Elsterian II) Glaciation, about 500 ka BP, covered the northern part of the Dniester basin at the foot of the Carpathians. The edge of the ice-sheet was located about 30 km northwest of the Stryi river valley (Łanczont et al., 2019). Terraces II-IV were formed in the valleys of the Dniester and Stryi after the Elsterian II Glaciation. Terrace I has a height of 5.5-7 m and a floodplain of a height of 4-5 m above the riverbed was formed in the Late Vistulian and Holocene.

Figure 2. Channel of the River Stryi in the Zhydachiv town. On the left (northern bank) point bar deposits, on the right (southern bank) floodplain at the height of 4-5 m above riverbed

Materials and methods

Geological cross sections, sampling and sedimentological analyses

The description of the outcrops of alluvia with subfossil tree trunks in the southern part of the floodplain was supplemented by a geological cross-section 0.5 km long, constructed on the basis of 16 boreholes (Figs. 3, 4). Sediment cores were collected using a petrol-powered percussion hammer drilling rig, which permitted the collection of core samples using a set of window steel samplers of length 1-2 m and diameter 10 cm. The drilling was conducted along the cross-section line, at an average distance of 20-50 m (between the profiles of ŻM 8 and ŻM 16 the distance was 210 m). The boreholes were drilled to a depth of 7-10.5 metres. During the drilling, a description of cores was made and sediment samples were taken for sedimentological analyses. Samples were collected from each of the logs and from each layer in the profile that differed in lithology. From the 16 logs, seven benchmark profiles were selected, of which 130 samples were taken for grain size analyses. The analyses were conducted in the Laboratory of the Department of Geomorphology of Jagiellonian University in Kraków. Depending on the thickness of the layers described and their lithological differentiation, the number of samples taken ranged from 12 (ŻM 1 profile) to 25 samples (ŻM 13).

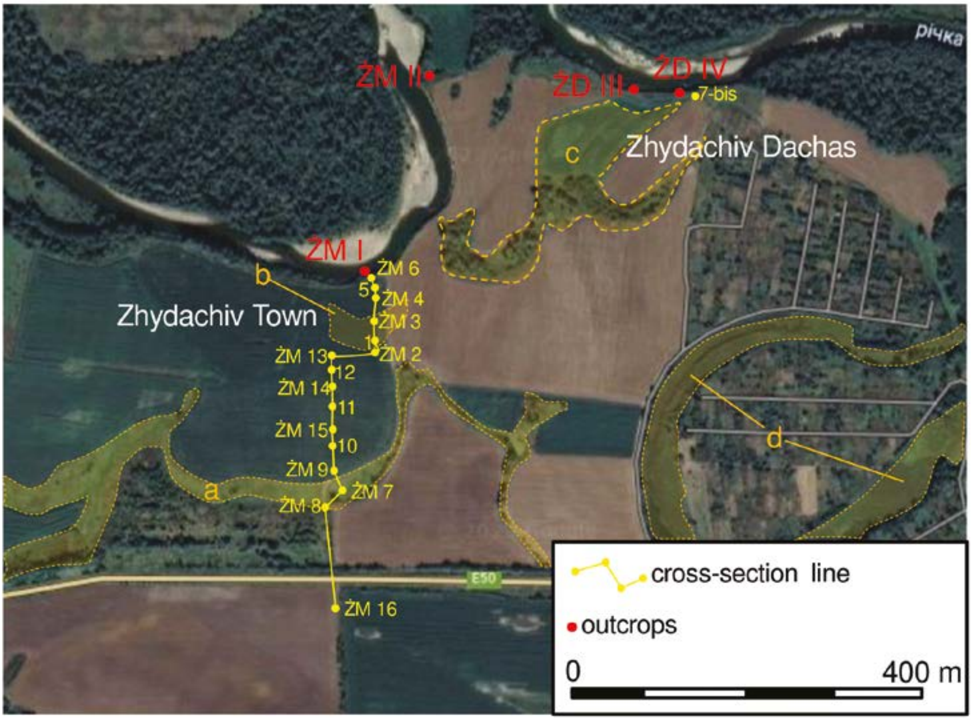

Figure 3. Location map of the geological cross-section with borehole logs examined and outcrops in the Stryi river valley near Zhydachiv Town (Żydaczów Miasto, ŻM) and Zhydachiv Dachas (Żydaczów Dacze, ŻD) (based on Google Earth). Generations of palaeochannels (a, b, c, d) described in the text

At the initial stage of analysis, the samples were dried and the organic detritus was removed and then they were sieved using a mesh size of 1 mm. Sediment samples of grain size diameter above 1 mm were analysed by the sieve method. For samples in which the grain size diameter of particles was below 1 mm, the analysis of deposits was performed by laser diffraction grain size analysis using a Mastersizer 3000. The results obtained after combining both methods were compiled in fraction intervals of half phi. Gradistat software, version 5.11 PL beta, was used to calculate the statistical grain size parameters according to Folk & Ward (1957), such as: mean diameter (Mz), sorting (δ_1), skewness (Sk_1), and kurtosis (K_G). The results of the analyses are presented on the grain size diagrams. Sedimentological analyses were used to distinguish the main types of lithofacies (channel sediments, meander point bars, palaeochannel fill, natural levees and floodbasin sediments), which were presented on a scatter plot of mean grain size (Mz) versus sorting index (standard deviation) (δ_1).

Radiocarbon dating and palynological analyses

The age interpretation of erosional dissection (cuts) and alluvial fills is based on 16 radiocarbon dating results (Tab. 1) supported by palynological analyses of sediments. Table 1 summarises the new, not yet published results of the dating of 9 samples and analyses of the age of 7 samples that were published in conference proceedings (Gębica et al., 2013a). The dated material is mainly organic silt and wood fragments. Radiocarbon dating was carried out using the liquid scintillation counting (LSC) technique at the Laboratory for Absolute Dating in Skała near Kraków,

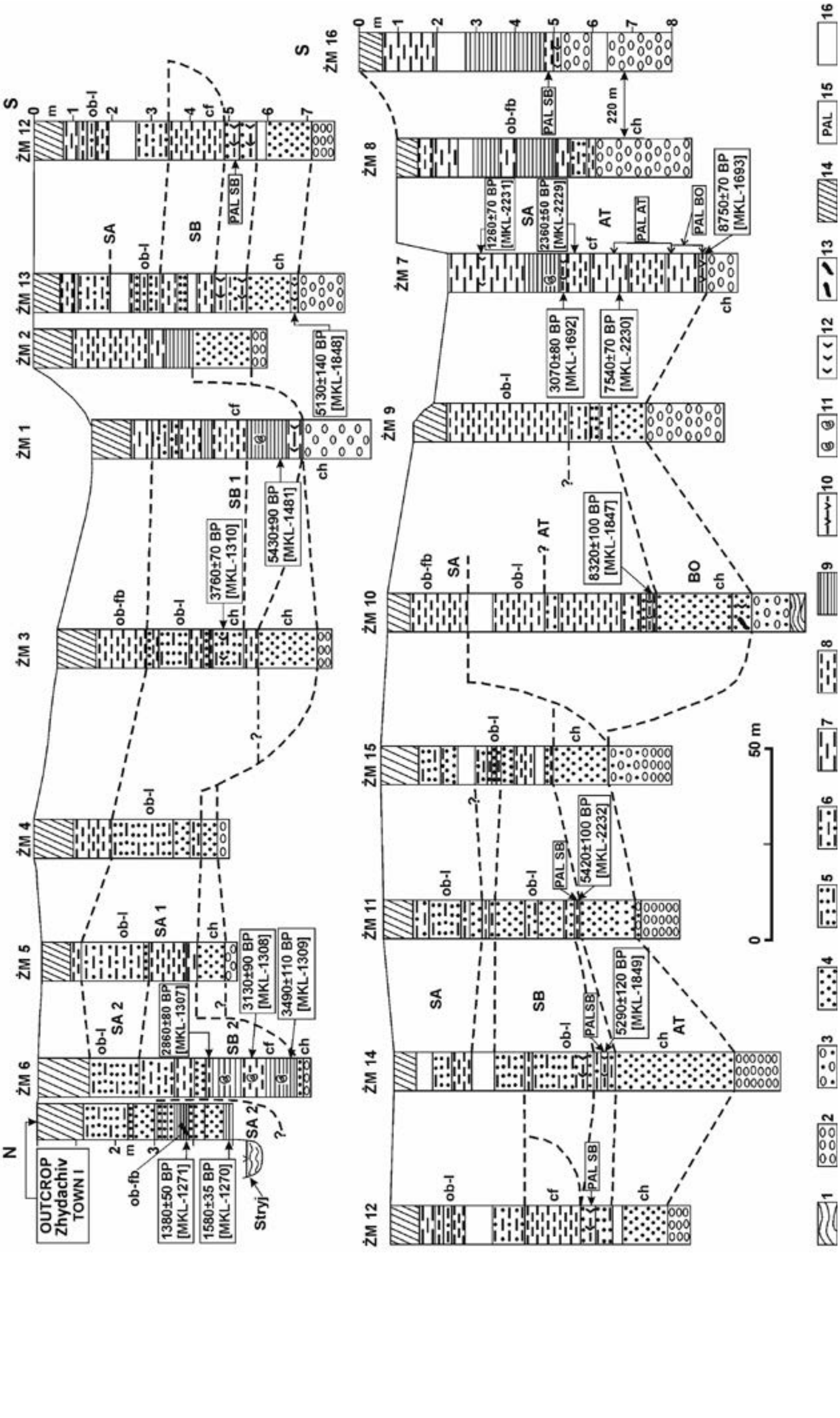

Figure 4. Alluvial fills in the Holocene fan of the River Stryi in the Zhydachiv Town (Żydaczów Miasto, ŻM) cross-section. 1– Miocene clay, 2 – gravel, 3 – gravel with sand, 4 – sand, 5 – silty sand, 6 – sandy silt, 7 – silt (mud), 8 – clayey silt, 9 – clay, 10 – organic silt, 11 – mollusc shells, 12 – organic detritus, 13 – wood, 14 – Holocene soil, 15 – palynological age determination, 16 – lack of sediment core; Denotations of chronostratigraphical periods: BO – Boreal, AT – Atlantic, SB – Subboreal, SA – Subatlantic; Litho-facies: ch – channel deposits, ob-l – natural levee deposits, ob-fb – floodbasin deposits, cf – channel fill deposits

Table 1. Radiocarbon dates from alluvial fan of the River Stryi in the Zhydachiv Town (Żydaczów Miasto, ŻM) cross-section and Zhydachiv Dachas (Żydaczów Dacze, ŻD) profile

Profile name	Depth [m]	Type of material	Facies of deposits	Laboratory No	Radiocarbon age [BP]	Calibrated age [BP] (95,4%)	Calibrated age (BC/AD) (95,4%)
Zhydachiv Town I* (ŻM I)	3.7 4.9	wood wood (oak)	natural levee floodbasin	MKL-1271 MKL-1270	1380±50 1580±35	1390-1180 1540-1390	568-769 AD 410-559 AD
Zhydachiv Town II* (ŻM II)	5.0 5.5	trunk trunk	channel	MKL-1480 MKL-1479	1140±35 1180±35	1170-960 1230-980	780-984 AD 722-969 AD
Zhydachiv ŻM 1*	4.79-4.82 5.3-5.4	organic silt	palaeochannel fill	MKL-1482 MKL-1481	2460±100 5430±90	2735-2315 6385-5995	803-389 BC 4451-4046 BC
Zhydachiv ŻM 3*	4.3-4.4	organic silt	point bar	MKL-1310	3760±70	4380-3925	2457-1978 BC
Zhydachiv ŻM 6*	4.45-4.52 5.58-5.62 6.5-6.55	organic silt organic silt organic silt	palaeochannel fill	MKL-1307 MKL-1308 MKL-1309	2860±80 3130±90 3490±110	3205-2795 3550-3080 4060-3490	1266-836 BC 1614-1130 BC 2131-1529 BC
Zhydachiv ŻM 7	0.85-0.9 3.05-3.10 3.36-3.41 4.35-4.40 6.68-6.73	organic silt organic silt wood organic silt organic clay	palaeochannel fill	MKL-2231 MKL-1692 MKL-2229 MKL-2230 MKL-1693	1260±70 3070±80 2360±50 7540±70 8750±70	1303-1003 3435-3035 2699-2207 8454-8185 10105-9565	648-899 AD 1503-1058 BC 570-358 BC 6505-6236 BC 8181-7597 BC
Zhydachiv ŻM 10	6.8-6.85	sand with organic detritus	overbank	MKL-1847	8320±100	9490-9045	7567-7083 BC
Zhydachiv ŻM 11	5.09-5.11	sand with organic detritus	overbank	MKL-2232	5420±100	6403-5950	4454-4040 BC (94,3%)
Zhydachiv ŻM 13	6.65-6.68	sand with organic detritus	channel	MKL-1848	5130±140	6220-5605	4309-3652 BC
Zhydachiv ŻM 14	5.45-5.51	silt with organic detritus	overbank	MKL-1849	5290±120	6295-5775	4357-3804 BC
Zhydachiv Dachas 7-bis*	7.23-7.26 7.33-7.37	organic silt wood	palaeochannel fill	MKL-1695 MKL-1694	11500±90 10750±100	13505-13155 12890-12430	11636-11218 BC 10955-10489 BC

*^{14}C dates published in Gębica et al., 2013a

Poland (Lab. code MKL). Radiocarbon dating results were calibrated using OxCal 4.4 software (https://c14.arch.ox.ac.uk/oxcal.html) and the IntCal 09 calibration curve (Reimer et al., 2020) (Tab. 1). The dates in this paper are presented in radiocarbon years before present (^{14}C BP).

From the fill of the palaeochannel within Zhydachiv, profile log 7/1, pollen analysis was performed on 14 mineral-organic samples. Samples with a standard volume of 1 cm^3 were collected in the core from a depth of 0.85-0.90 m to 6.75 m. In addition to the benchmark profile ŻM 7/1, palynological analyses were performed for individual samples in 6 other profiles (ŻM 10, 11, 12, 13, 14, 16). The results of pollen analyses from the ŻD 7bis sequence are also included in this study (Gębica et al., 2013b). All samples were boiled in hydrofluoric acid (HF), and then the modified Erdtman acetolysis method was used (Berglund & Ralska-Jasiewiczowa, 1986). Sporomorphs of vascular plants on an area of 400 mm^2 of microscopic preparation were identified and counted from each sample. Initial pollen analyses were performed (preliminary phase) and the results were also subject to initial interpretation. The results of the identification of sporomorphs, and the abundances of individual sporomorphs of plant taxa are presented in a simplified pollen diagram drawn using POLPAL for Windows software (Nalepka & Walanus, 2003).

Results

Characteristics of alluvial fills

A large-radius palaeomeander on the southern, marginal part of the floodplain represents the oldest generation (a) of palaeochannels (Fig. 3). It is 45 m wide and has a radius of curvature R = 260 m. The bottom of this palaeochannel (log ŻM 7) lies at an elevation of 3.5 m above the river channel. Log ŻM 16 is situated on Pleistocene terrace I at an elevation of 6 m above the river channel (Figs. 3, 4). A palaeochannel of smaller size, the older generation (b) (Fig. 3), is very poorly marked on the plain, is located closer to the present-day channel of the Stryi (logs ŻM 1, 3). Palaeochannels of the youngest generations (b, c) are located in the northern and eastern part of the floodplain. The thickness of Holocene sediments (on the top of the gravels) varies from 5 to 9 m. Miocene clays were found at a depth of 10.5 m in log ŻM 10 (Fig. 4). They are overlain by gravels of uneven top surface, cut by palaeotroughs of a depth of 2-4 m, filled with sands 1.5-3.0 m thick. Palaeotroughs are fossil (buried) erosional depressions formed by the Stryi bed cutting into a gravel cover and later filled with channel sands. They are invisible in the contemporary surface of the floodplain because they are covered with a thick blanket of overbank sediments. A series of overbank sediments 4-7 m thick rest on the channel sands, varied in terms of litho-facies and grain size indices. Several Holocene cuts and alluvial fills (inserts) can be distinguished in the cross-section of the floodplain with a height of 4-5 m (Fig. 4):

1. Overbank sediments (log ŻM 16) at the top of terrace I consist of fine-grained silts and clays of floodbasin sediments 5.2 m thick. Similar overbank sediments occur in the ŻM 8 log located on a floodplain undercut by a large-radius palaeomeander. Overbank sediments rest on Pleistocene gravels (made up of pebbles with a diameter of 3-9 cm), the top of which is located at the level of the present-day Stryi river channel. The gravels form a fragment of the alluvial plain, the age of which is difficult to determine at the current stage of research.
2. The fill of a large-radius palaeomeander (log ŻM 7) consists of poorly sorted silts (muds) 6.75 m thick overlying the channel sediments. In the bottom, at a depth of 5-6 m, there are sandy silts (with a sand percentage up to 20%), grading upward into organic clayey silts with a mean grain size diameter (Mz) ranging 5.5-7.1 φ (Figs. 5, 6).
3. A palaeotrough (log ŻM 10) cut in the gravels and reaching a depth of 9.5 m from the floodplain ground surface. The palaeotrough is filled up with channel sands 2.5 m thick. The sands are medium and

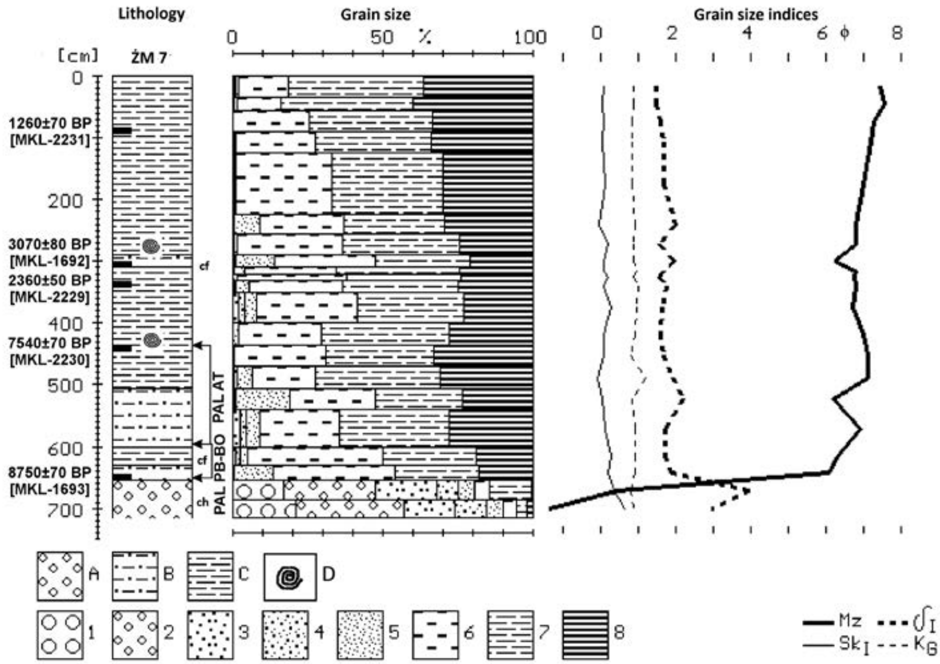

Figure 5. Lithological profile with grain size indices after Folk and Ward (1957) in the Boreal palaeochannel fill (log ŻM 7). For the location of the deposits investigated see Figs. 3, 4; ch – channel deposits, cf – channel fill deposits. Lithology: A – medium gravel, B – sandy silt, C – silty clay, D – mollusc shells. Grain size: 1 – coarse gravel, 2 – medium gravel, 3 – coarse sand, 4 – medium sand, 5 – fine sand, 6 – coarse silt, 7 – fine silt, 8 – clay; PAL – Palynological denotations of chronostratigraphical periods: PB – Preboreal, BO – Boreal, AT – Atlantic

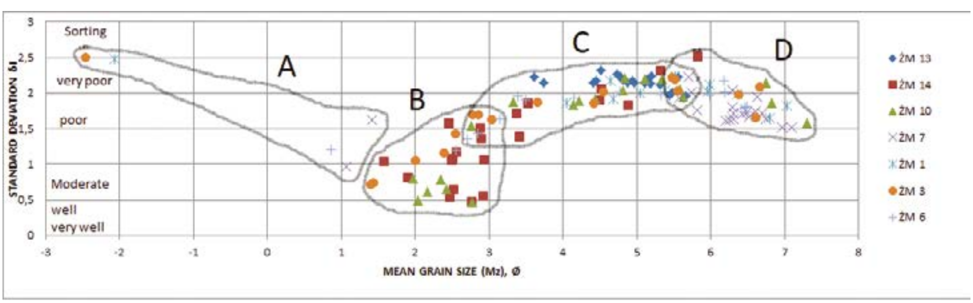

Figure 6. Scatter plot of mean grain size (Mz) versus sorting index (standard deviation) (δ_1) of different types of deposits in the Holocene Stryi alluvial fan; A – channel-lag and bar deposits B – channel- point bar and palaeotrough fill deposits, C – natural levee deposits, D – channel fill and flood basin deposits

well sorted (δ_1 = 0.3-0.8), the mean grain size diameter (Mz) ranges from 1.8 to 2.7 φ (Figs. 6, 7). Channel sands in the ŻM 10 and 9 sequences are overlain by overbank sandy silts and silty sands up to 7 m thick. These sediments are poorly or very poorly sorted (δ_1 = 1.75-2.2), the mean grain size diameter varies from 4.2 to 5.5 φ (Fig. 6).

4. A palaeotrough cut into the top of the gravels (logs ŻM11, 12, 14 and 15) is filled with sand up to 3.3 m thick (ŻM 14) (Fig. 4). The sand filling the trough is well and

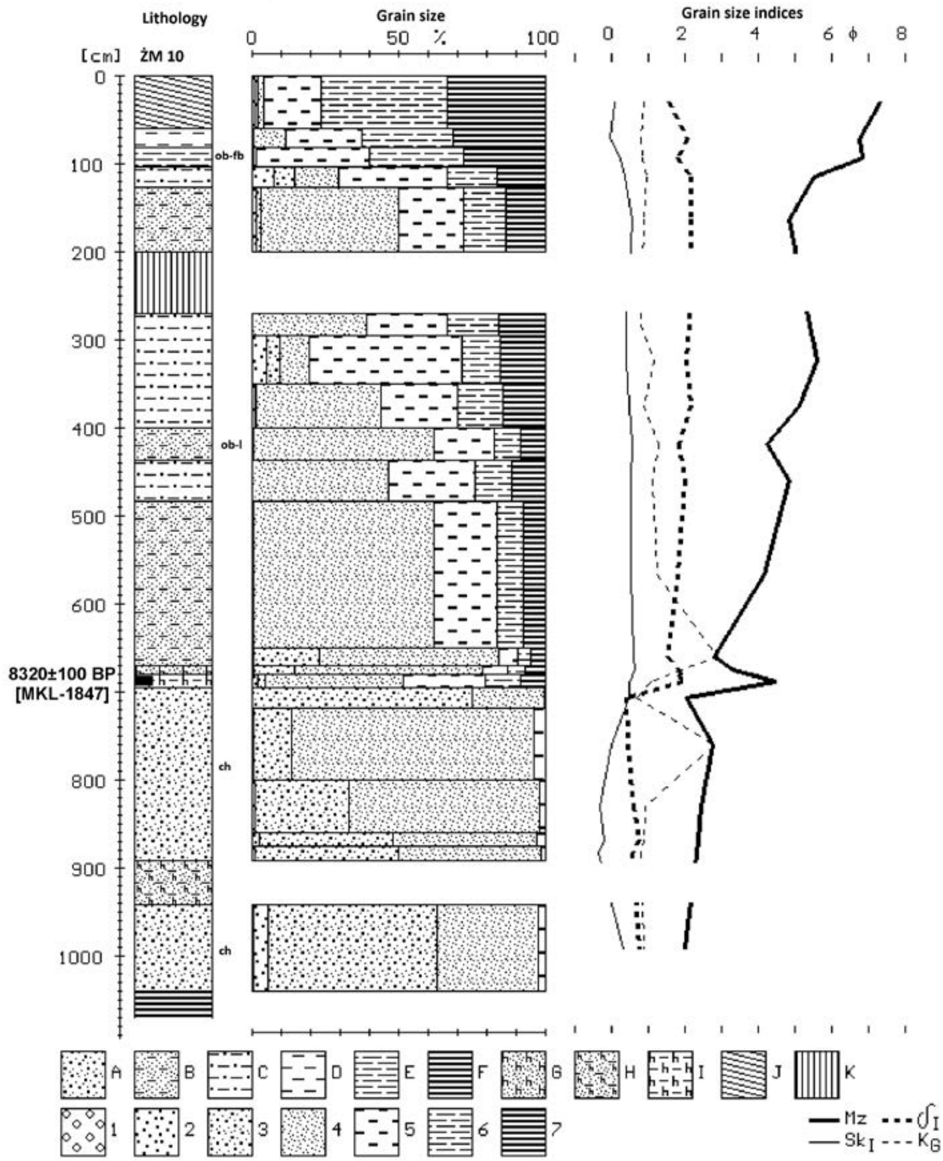

Figure 7. Lithological profile with grain size indices after Folk and Ward (1957) in the Boreal-Atlantic deposits (ŻM 10 sequence). Channel sands filling the palaeotrough are covered with thick natural levee sediments; ch – channel deposits, ob-l – natural levee deposits, ob-f – floodbasin deposits. For the location of the profile investigated see Figs. 3, 4. Lithology: A – medium sand, B – silty sand, C – sandy silt, D – silt E – silty clay, F – clay, G – organic sand, H – organic silty sand, I – organic silt, J – Holocene soil, K – lack of core. Grain size: 1 – medium gravel, 2 – coarse sand, 3 – medium sand, 4 – fine sand, 5 – coarse silt, fine silt, 7 – clay

medium sorted ($\delta_1 = 0.4$-1.0), and the mean grain size diameter (Mz) is 1.5-3.0 φ (Fig. 6). At a depth of 4.9-5.4 m there is a layer of overbank silty sands and silts with organics, covered by silty sands of natural levees 4 m thick (Fig. 4).

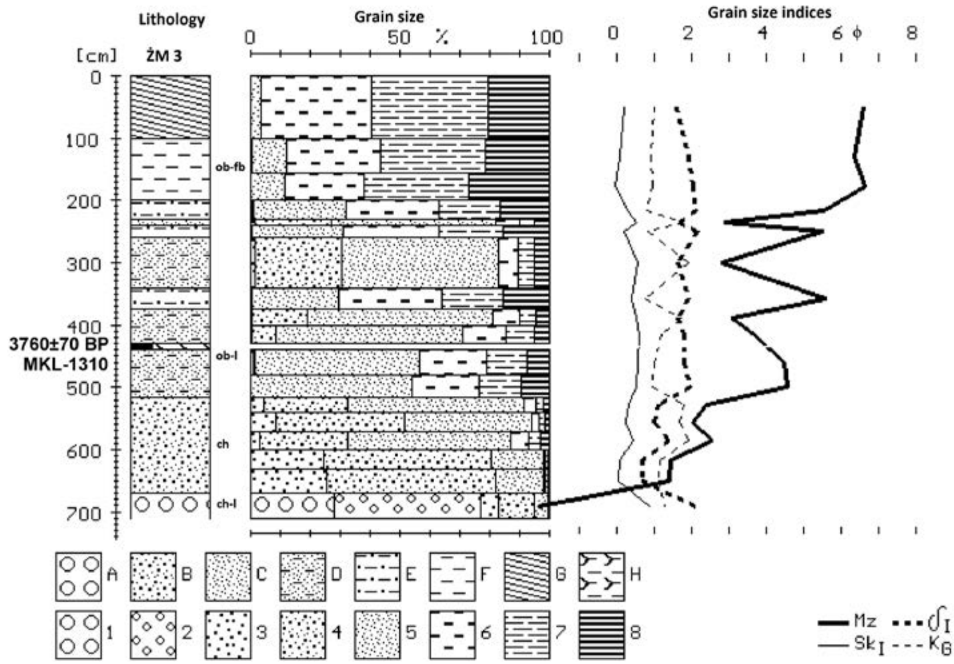

Figure 8. Lithological profile with grain size indices after Folk and Ward (1957) in the palaeochannel point bar deposits of Subboreal age (ŻM 3 sequence). The point bar deposits grade upward in the natural levee deposits; ch-l – channel lag deposits, ch – channel (point bar) deposits, ob-l – natural levee deposits, ob-f – flood basin deposits. For the location of the deposits investigated see Figs. 3, 4. Lithology: A – coarse gravel, B – medium sand, C – fine sand, D – silty sand, E – sandy silt, F – silt, G – Holocene soil, H – silt with organic detritus. Grain size: 1 – coarse gravel, 2 – medium gravel, 3 –coarse sand, 4 – medium sand, 5 – fine sand, 6 – coarse silt, 7 – fine silt, 8 – clay

5. This palaeochannel cut in gravels is filled to a depth of 4.0 to 5.3 m by poorly and very poorly sorted silts (δ_1 = 1.9-2.0) with a mean grain size diameter ranging from 5.4 to 6.0 φ. At a depth of 1.5-4.0 m, a predominance of silty sands (ŻM 1 log) is noticeable, with an increasing mean grain size diameter (from 4.0 to 6.0 φ) (Figs. 4, 6). The point bar deposits of this palaeochannel (log ŻM 3) occurred at a depth of 4.3-5.2 m and are covered by silts (muds) with wood debris filling the oxbow-lake. At the top of the sequence (at a depth of 2.0-4.3 m) there are laminated sands and sandy silts (Mz = 2.8-5.6 φ) of the natural levees, overlain by overbank silty-clayey sediments (Figs. 6, 8).
6. Alluvial sediments with a fossil gravel outlier at a depth of 4.0-4.3 m (logs ŻM 4 and 5) (Fig. 4). Channel gravels are covered by sands and sandy silts of the levee sediments that are 4.2 m thick.
7. The filling of a fossil palaeochannel (log ŻM 6) which is 2.0 m thick, consisting of clayey silts with a mean grain size diameter 5.3-6.5 φ. Sediments filling the palaeochannel are overlain by a series of silts and silty sands (Mz = 2.6-4.8 φ) of the natural levee sediments which are 3.0 m thick (Figs. 6, 9).
8. The sediments filling the palaeochannel or floodbasin comprise silts with a mean grain size diameter of 6.0-7.0 ϕ and bearing fragments of wood debris at a depth of 3.8 and 4.9 m (ŻM I outcrop). They are covered by channel sands (Mz = 1.5-2.0 φ), which, in turn, are overlain by levee sediments (Figs. 3, 4) (Gębica et al., 2013a).
9. Channel sediments with subfossil tree trunks in the ŻM II profile outcropped in the Stryi riverbed (Fig. 3) at a depth

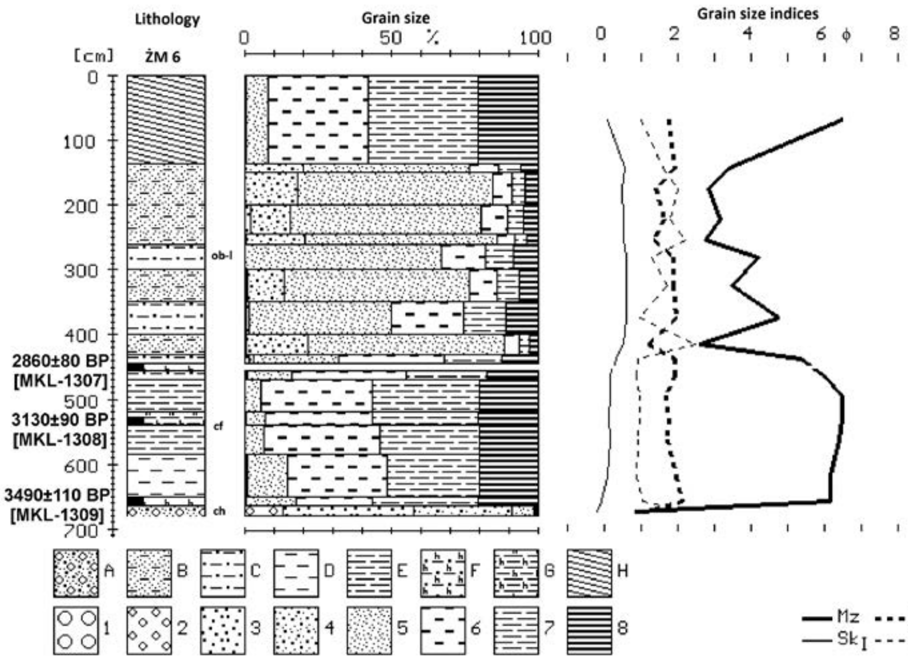

Figure 9. Lithological profile with grain size indices after Folk and Ward (1957) in the fossil Subboreal channel fill (log ŻM 6). Fossil channel fill sediments are overlain by sandy levee deposits of Subatlantic age; ch – channel deposits, cf – channel fill deposits, ob-l – natural levee deposits. For the location of the deposits investigated see Figs. 3, 4. Lithology: A – gravel and sand, B – silty sand, C – sandy silt, D – silt, E – clayey silt, F – organic silt with sand, G – organic silt, H – Holocene soil. Grain size: 1 – coarse gravel, 2 – medium gravel, 3 – coarse sand, 4 – medium sand, 5 – fine sand, 6 – coarse silt, 7 – fine silt, 8 – clay

of 5.2-5.7 m, grading upwards into sandy point bars. The point bars are covered by silty sands, passing toward the top into clayey silts which are 4.7 m thick (Gębica et al., 2013a).

Apart from the cross-section discussed above, subfossil tree trunks were found in several outcrops located to the north-east (closer to the confluence with the Dniester) at the Zhydachiv Dachas site (Fig. 3). On the 6 m high terrace (ŻD IV outcrop) a "black oak" trunk was buried in silts and sands of a palaeochannel fill (Fig. 10). The palaeochannel fills were covered by rhythmically layered silty-sandy flood deposits, grading upward into levee sediments (Gębica et al., 2013a). In the 5 m high terrace (ŻD III outcrop), at a depth of 4.45-4.8 m, the "black oak" trunk was buried under the sands of point bars in the palaeochannel fills (Fig. 3). In the 6 m high terrace (log ŻD 7bis) (Fig. 3), at a depth of 7.1-7.9 m, silts with organic laminae and snail shells were found. These fillings of the

Figure 10. Subfossil "black oak" buried in the Early Medieval palaeochannel fill deposits (ŻD IV sequence). This trunk is located at the level of the present-day Stryi riverbed and is overlain with 6 m of overbank deposits

oldest (fossil) palaeochannel sediments are located below the present-day Stryi riverbed.

Stratigraphy of alluvial sediments

The thickness of the sediments building up the floodplain reaches a maximum of 25 m (Gierasimow & Gierasimowa, 1970; Denisewicz et al., 1968). Our research indicates that only the top part of the sediments, with a thickness of 7-10.5 m, can be dated to the Holocene. The stratigraphy of alluvial fills of the Stryi Holocene cone in Zhydachiv town is based on the results of palynological analyses and radiocarbon dating.

Preliminary palynological analyses

From preliminary palynological analyses, the material provides no basis for a more accurate interpretation, so it is not possible to propose that at this stage of the research. Samples from the Zhydachiv Town 7 (ŻM 7) log from a depth of 6.75 to 6.65 m (Figs. 4, 5) contain relatively high numbers of pollen grains of pine (*Pinus*), birch (*Betula*), with elm (*Ulmus*), hazel (*Corylus*), alder (*Alnus*) and grasses (*Poaceae*). These may represent sediments from the Early Holocene (Boreal Phase) (Fig. 11). A more probable age is the end of the Boreal Phase or the beginning of the Atlantic Phase. The samples from a depth of 5.95 to 4.35 m can be dated to the Atlantic Phase based on the contribution of pollen of such taxa as: *Alnus*), oak (*Quercus*), hazel (*Corylus*) and elm (*Ulmus*), although there are already single pollen grains of hornbeam (*Carpinus*) which played a greater role in forest younger than ca. 4000 years BP (Fig. 11). The samples from depths of 4.35 m, 3.39 m and 3.22 m are very interesting, because significantly increased numbers of oak (*Quercus*) pollen grains were found in them (Fig. 11). Perhaps this is connected with human activity, for example, the felling of selected trees to give more sunlight to the canopy of a single remaining tree which therefore had more possibility of receiving abundant pollen (Nalepka, 2005). In log ŻM 12/1 (Fig. 4), a sample of mud with remains of organic detritus at a depth of 5.25-5.30 m, was dated to the Subboreal Phase owing to the presence of pollen grains of elm (*Ulmus*), oak (*Quercus*), hazel (*Corylus*), and, in particular, hornbeam (*Carpinus*) and beech (*Fagus*). Similarly, in the sequence of ŻM 16/6, in the sample from a depth of 4.83 m (Fig. 4), a high percentage of pollen grains of birch (*Betula*), alder (*Alnus*), oak (*Quercus*), elm (*Ulmus*), hornbeam (*Carpinus*) and beech (*Fagus*) indicates a Subboreal Phase. A similar composition and percentage of tree pollen in this period was recorded in the Velyky Lukavets river valley at the Starunia site in Western Ukraine (Stachowicz-Rybka et al., 2009). In the samples collected from the following logs: ŻM 10/1 at a depth of 6.8-6.85 m, ŻM 11/1 at a depth of 5.09-5.11 m, ŻM 13/2 at a depth of 6.65-6.68 m and in the sequence of ŻM 14/1 at a depth of 5.45-5.51 m, the frequencies of pollen grains were very low and do not provide sufficient material for interpreting the results. Individual pollen grains found in these samples could suggest an age younger than 4500 BP, i.e. including sediments from the Subboreal and Subatlantic Phases, but from a formal point of view such a conclusion could not be sustained. Plant indicators of human activity are practically absent. A sample of silt (mud) with organic laminas in the ŻD 7bis log from a depth of 7.18 m can be classified to the end of the Late Vistulian (Younger Dryas?) or the beginning of the Holocene (Gębica et al., 2013a) due to the occurrence of pollen grains of pine (*Pinus*), birch (*Betula*), stone pine (*Pinus cembra)*, larix (*Larix*), spruce (*Picea*) and willow (*Salix*). Palynological studies of the nearest site, Mainych in the Upper Dniester Basin, indicate the direction of interpretation as far as the above-mentioned phases of the Holocene are concerned (Harmata et al., 2006).

Radiocarbon dating

Alluvial fills and a system of palaeochannels can be dated using the radiocarbon method on the cross-section of Zhydachiv Town (Tab. 1, Figs. 3, 4).

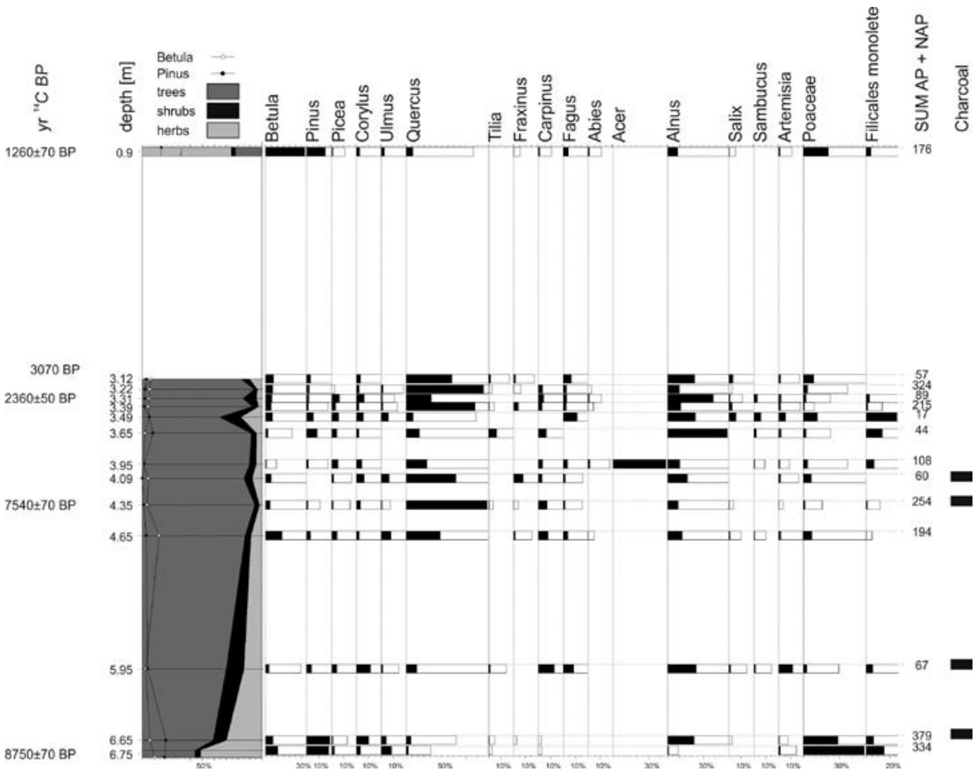

Figure 11. Percentage pollen diagram in log ŻM 7 from the Boreal palaeochannel fill

1. The bottom of the palaeochannel fills in the ŻM 7 log (sample from a depth of 6.68-6.73 m) was dated to 8750±70 BP (MKL-1693), i.e. the end of the Boreal Phase (Figs. 4, 5). A silt (mud) sample from a depth of 4.35 m is dated to 7540 ±70 BP (MKL-2230), which indicates that it originates from the Atlantic Phase. Samples located at a depth of 3.39 and 3.05-3.10 m were dated to 2360±50 BP (MKL-2229) and 3070±80 BP (MKL-1692), which means an age inversion. A clay sample from a depth of 0.85-0.90 m at the top of the palaeochannel fills was ascribed an age of 1260±70 BP (MKL-2231), which indicates the Middle Ages (Tab. 1).
2. In the ŻM 10/1 sequence, a silt sample from a depth of 6.80-6.85 m was dated to 8320±100 BP (MKL-1847) (Figs. 4, 7), i.e. the accumulation of sediments at the top of the palaeotrough occurred at the end of the Boreal Phase or at the beginning of the Atlantic Phase.
3. In the ŻM 11/1 sequence a sample of silt with organic remains from a depth of 5.09-5.11 m is dated to 5420±100 BP (MKL-2232), which means that overbank sediments were accumulated at the end of the Atlantic Phase. In the ŻM 14/1 sequence a silt sample with organic remains from a depth of 5.45-5.51 m was ascribed a similar age 5290±120 BP (MKL-1849) (Fig. 4).
4. A sample of sand with organic remains inserted in gravels at a depth of 6.65-6.68 m in log ŻM 13/2 was dated to 5130 ±140 BP (MKL-1848) (Fig. 4), which marks the beginning of the Subboreal Phase.
5. The bottom of the palaeochannel fill in the ŻM 1 sequence (sample from a depth of 5.3-5.4 m) was dated to 5430±90 BP (MKL-1481) (Fig. 4) which is the end of the Atlantic Phase, i.e. similar to the ŻM 11/1

sequence. The point bar deposits in this palaeochannel were dated to 3760±70 BP (MKL-1310) (Fig. 8).

6. Three samples were dated from the filling of the fossil palaeochannel (log ŻM 6) (Figs. 4, 9). The lowermost sample (at a depth of 6.5-6.6 m) was dated to 3490±110 BP (MKL-1309), middle sample (5.3-5.4 m) to 3130±90 BP (MKL-1308) and a sample from the top of the fills (4.45-4.55 m) – to 2860±80 BP (MKl-1307) (Gębica et al., 2013a). The dating of the bottom samples means that palaeochannel was cut off in the younger Subboreal Phase.
7. Two samples were dated from the Zhydachiv Town I outcrop (Figs. 3, 4). A sample of wood lying in clays at a depth of 4.9 m was estimated to date to 1580±35 BP (MKL-1270) and the wood sample lying in silt and sands at a depth of 3.7 m was dated to 1380±50 BP (MKL-1271) (Gębica et al., 2013a). This means that the overbank sediments were accumulated in the Early Middle Ages (4-6th centuries A.D.).
8. Two subfossil oak trunks in the ŻM II outcrop (Fig. 3), lying at a depth of 5.2-5.7 m in the sands, were dated to 1180±35 BP (MKL-1479) and 1140±35 BP (MKL-1480), i.e. 8-10th centuries AD (Tab. 1) (Gębica et al., 2013a).
9. A sample of organic silt in the Zhydachiv Dachas 7bis log (Fig. 3) from a depth of 7.23-7.26 m showed an age of 11,500±90 BP (MKl-1695), while wood from a depth of 7.33-7.37 m was dated to 10,750±100 BP (MKL-1694) (Gębica et al., 2013a). The date 10,750 BP, indicates that the oldest (fossil) palaeochannel was abandoned in the Younger Dryas.

Discussion

Despite the age inversion in the ŻD 7bis sequence, the dating of both samples indicates that the filling of the oldest (fossil) palaeochannel of the Stryi occurred at the end of the Late Vistulian. This is confirmed by palynological analyses, which determine the time of deposition of the oxbow-lake sediments as the Younger Dryas or the beginning of the Holocene. During the Younger Dryas the Stryi river channel was located 1.5-2 m below the present-day level of the river (Fig. 12).

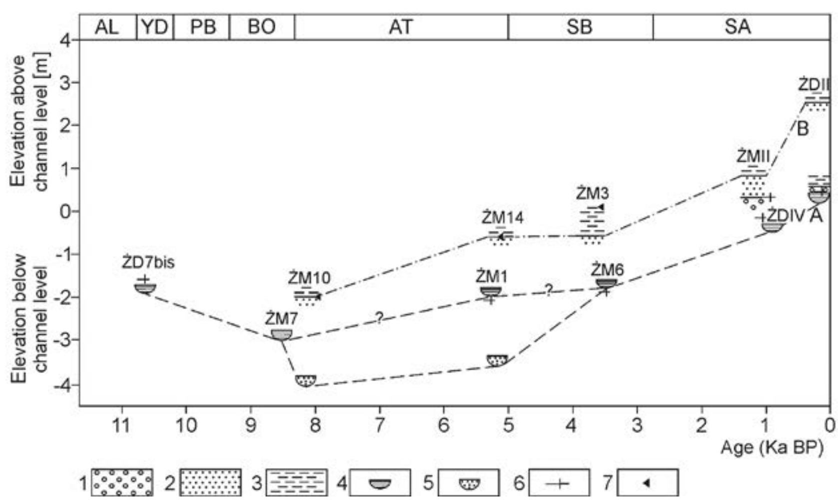

Figure 12. Vertical changes of the channel of the River Stryi during the Late Vistulian and Holocene. 1 – gravel (channel deposits), 2 – sand (point bar deposits), 3 – silt (overbank deposits), 4 – bottom of palaeochannel fill, 5 – bottom of palaeotrough, 6 – radiocarbon dating of palaeochannel fill, 7 – radiocarbon dating of overbank deposits, A – oscillations of the channel level, B – oscillations of the point bar deposits. Explanation of chronostratigraphical periods: AL – Allerød, YD – Younger Dryas, PB – Preboreal, BO – Boreal, AT – Atlantic, SB – Subboreal, SA – Subatlantic

The preserved remains of the palaeochannel fills do not provide the basis for the reconstruction of the size and type of the channel pattern. We do not know whether it was a channel of meandering or braided pattern. Palaeochannels dating from the Late Vistulian (Alleröd-Younger Dryas) are also found in the lower section of the Strvjaž river valley (Fig. 1) at a depth of 6-7 m below the surface of the floodplain (Starkel et al., 2009). The organic sediments of one such palaeochannel were cut and covered with sand deposits, similarly to that of the Stryi in the Early Middle Ages. A fragment of a palaeochannel, probably meandering and formed at the end of the Late Vistulian, was also found in the Dniester river valley in the Naditychi profile located north of the Stryi-Zhydachiv Basin (Gębica & Jacyszyn, 2012). Large-radius Younger Dryas palaeomeanders of the Dniester have been also documented in the Halych-Bukachivtsi Basin (Fig. 1) (Huhmann et al., 2004; Kołaczek et al., 2017; Gębica & Jacyšyn, 2021).

The bottom of the fills of the large-radius palaeomeander of the Stryi (log ŻM 7) was dated to 8700 BP and therefore the channel was abandoned in the Boreal Phase. Abandonment of the meander channel occurred as a result of a neck cut-off, or – more likely in this case – chute cut-off of the meander. The end of the Boreal Phase is probably associated with the accumulation of the top cover of the upper Dniester alluvial fan at the outlet from the Carpathians (near Staryi Sambir town) (Fig. 1), where a fragment of wood in the sequence of the 10 m high gravel terrace was dated to 8720±90 BP (Starkel & Jacyšyn, 2006). Both of the events described above, i.e. the abandonment of the channel of the Stryi in Zhydachiv and the deposition of the gravel of the upper Dniester alluvial cone, occurred during the floods at the end of the Boreal Phase (the beginning of the humid phase is dated to some 8700 BP – Starkel, 2001, 2014). Evidence for the fact that the Stryi channel was active in the Early Holocene can be seen in a deep palaeotrough cut in the gravels and filled with channel sands whose top is dated to 8320±100 BP (Fig. 4, 7). Thus filling of the palaeotrough took place up until the beginning of the Atlantic Phase. Around 8300 BP there was a change in deposition from channel sands to overbank silts in the ŻM 10 sequence. In the fills of large-radius palaeomeanders e.g. of the River San near Stubno in the foreland of the Carpathians (Gębica et al., 2022), or in the alluvial fan of the River Wisłok in the Besko Basin or in smaller basins in the Dynów Foothills area (Gerlach et al., 2019), the covering of organic sediments by overbank sandy or silty-clay sediments is dated from ca. 8400-8300 BP to ca. 7900 BP. The change in deposition from organic to mineral sediments means there was frequent flooding of valley bottoms and/or there were periodical large floods between 8400 and 7900 BP. The thick overbank accumulation during the Atlantic Phase in the sequences of ŻM 10 and ŻM 9 is also confirmed by a date of 7540 BP in the fills of the Boreal palaeochannel (ŻM 7 sequence). Another younger palaeotrough cut in gravels is filled with channel sands from the end of the Atlantic period (ŻM 11, 12, 14 logs). The layer of silt deposited at the top of sand fills was dated to 5420±100 BP and 5290±120 BP (Fig. 4, Tab. 1). This means that both the cutting of the palaeotrough, the bottom of which lies below the present Stryi channel (Fig. 12), and its filling up with sandy bar deposits, were associated with high discharges in the channel (Niedziałkowska, 1991) at the end of the Atlantic Phase. An enhanced activity of the river at the beginning of the Subboreal Phase (the period of wetness and climate cooling about 5400-5100 BP) caused the accumulation of sandy levees. This resembles the alluvial fills in the system of palaeomeanders of the Vistula in the Grobla Forest (Starkel et al., 1991; Gębica, 1995). Similarly, in the Upper Dniester Basin (Fig. 2) the change from organic to mineral deposition in the Majnych peat bog succession was dated exactly to 5410 BP (Starkel & Jacyšyn, 2006). The beginning of this phase in the Alps falls at ca. 5600 BP, and the last episode of raising of the Constanza Lake level is dated to 5300 BP (Magny & Haas, 2004). The age of the sample dated in the ŻM 13 sequence to 5130 BP seems to be underestimated, since the silt inserts located higher in the ŻM 11 and ŻM 14 sequences are older. This does not change the fact that the sandy overbank sediments at a depth of 2.0-5.5 m (ŻM 13 and 12 sequences) were deposited during the Subboreal Phase. This is also confirmed by the results of palynological analyses of the sample at a depth of 5.1-5.2 m in the ŻM 12 log (Fig. 4).

The palaeomeander represented by the lithological successions seen in the ŻM 1 and 3 profiles was cut-off in the older part of the Subboreal Phase (Fig. 4). The radiocarbon date from the bottom of this palaeochannel fill, 5430±90 BP, seems to be too old (overestimated) if one considers that the date of organic remains in the point bar of this bend (ŻM 3 log) is 3760±70 BP (Fig. 8). If the cutting of this channel occurred at the end of the Atlantic Phase (before 5430 BP), then the age of the overbank sediments accumulated on the floodplain (ŻM 11, 12 logs) at the time when channel was active should be older than 5430 BP. The insert of alluvia of the younger part of the Subboreal Phase represents a fossil palaeochannel (log ŻM 6) filled with sediments deposited between 3490 and 2860 BP (Figs. 4, 9). The cutting off of the channel about 3500 BP coincided with the beginning of flood phase in the Vistula river valley dated to 3500-2900 BP (Kalicki, 1996). Therefore, the sand layer at a depth of 3.4-4.3 m in the ŻM 3 sequence probably represents flood deposition in this palaeochannel which was active about 3700 BP. The change in deposition from clay to silty-sandy sediments of the natural levees dated to 2860 BP clearly coincides with the high flood activity during the climate cooling at the beginning of the Subatlantic Phase (Starkel et al., 2013). Floods which occurred about 2800 BP and in the earlier phase of 5400 BP in the northern foreland of the Alps are correlated by Czymzik et al. (2013) with the minima of solar activity. The flood phase of 2800-2400 BP is recorded, for example, in the palaeomeander systems of the Vistula (Kalicki et al., 1996), and in the subfossil trunks falling in the Dniester river valley (Gębica & Krąpiec, unpublished materials). In the lower San river valley near Stubno, the increase in the input of sands to the small-radius Subboreal palaeomeander was dated to between 2850 and 2310 BP (Gębica et al., 2019). The silty-clay sediments dated to 2360 BP in the ŻM 7 palaeochannel sequence were probably deposited far away from the active river channel during the declining wet phase (2800-2400 BP).

The youngest fill on the cross-section is represented by overbank deposits with wood fragments dated to 1580-1380 BP (Zhydachiv Town I outcrop) (Figs. 3, 4), and thus accumulated at the beginning of the Early Middle Ages (4-6th centuries). This correlates well with the flood phases in the lower Strvjaž river valley (5-6th centuries) (Starkel et al., 2009), in the Vistula river valley (Kalicki & Krąpiec, 1996) and in the river valleys of southern Germany (Becker, 1982). Channel alluvia and trunks dated to 1180 and 1140 BP (ŻM II sequence) (Fig. 3) mark the older subphase of the Medieval floods (8-10th centuries). Silty-clayey sediments dated to 1260 BP were deposited at that time in the palaeochannel represented by the ŻM 7 sequence (Figs. 3, 4). Subfossil trunks dated to 1080 BP and 990 BP at the bottom of the overbank series (ŻD IV sequence) (Figs. 3, 10) mark the younger flood subphase (10-12th centuries) (Gębica et al., 2013a, 2016) known from the upper Dniester river valley (Gębica et al., 2013b) and the upper Vistula river valley near Drogomyśl (Niedziałkowska et al., 1985). These two subphases of enhanced river activity, in addition to the wetter climate (2nd half of the 11th century – Steinhilber & Beer, 2011), also have a clear component of human participation. This is supported by archaeological research at the Zudech hillfort (castle) which existed here in the Early Middle Ages on Bazyjówka hill in Zhydachiv town (Korczyński, 2007). Subfossil trunks in the point bars of the youngest generation paleochannel (ŻD III outcrop) (Fig. 3), dated to 490 and 290 BP, indicate an increase in the frequency of floods during the Little Ice Age (14th century – first half of 15th century and second half of the 15th century – 17th century) (Gębica et al., 2013a). Both flood subphases, in addition to the anthropogenic component associated with the beginning of the Wallachian settlements in the Eastern Carpathians (Kukulak, 2004, 2014; Alexandrowicz et al., 2005; Gębica et al., 2013b) coincide with the climate wetting and cooling at the beginning of the Little Ice Age (Steinhilber & Beer, 2011). In the last 2000 years a clear increase (peaks) in the frequency of floods in the following periods: 1400-1100 BP, 800-500 BP and 300-0 BP, was recorded in the lakes of the central Alps (Wirth et al., 2013) and in the Romanian Carpathian river valleys (Radoane et al., 2019).

Conclusions

Studies of outcrops and drilling logs on the cross-section in the Zhydachiv allow us to conclude that the Pleistocene alluvial fan of the Stryi was cut by the Dniester and Stryi channels in the Late Vistulian. After the dissection of the alluvial fan as a result of the lateral migration of the channel of the Stryi, a much smaller Holocene alluvial fan was formed, consisting of cuts and alluvial fills dating from the end of the Late Vistulian to the Subatlantic Phase. The uneven top of the gravels shows that during the periods of increase in the discharges (Younger Dryas, end of the Boreal Phase, the late Atlantic and the beginning the Subatlantic Phase) the palaeotroughs were cut and then filled with channel sands. Probably at the end of the Late Vistulian and in the Early Holocene and the end of the Atlantic period, the bottoms of palaeotroughs lay a few metres below the present-day Stryi riverbed. The sands filling the palaeotroughs were covered with sandy-silty overbank sediments in about 8300, 5400 and 2800 BP, which adequately correlates with the beginning of the humid phases and floods in the upper Vistula basin and upper Dniester basin as well as the floods recorded in lakes in the northern foreland of the Alps. The largest elements in the construction of the floodplain are sediments from the Subboreal Phase. The thickest series of sediments formed during the Atlantic Phase.

From the beginning of the Subboreal Phase (5400-5300 BP) aggradation in the valley bottom took the primary role, which is manifested not only by the overbuilding of the floodplain but also by the gradual elevation of the Stryi river channel. The highest rate of overbuilding (vertical accretion of sediments) of the floodplain took place during the Middle Ages and the Little Ice Age. The Medieval flood phase (9-11th centuries) and floods of the Little Ice Age, apart from climatic causes, have a clear connection with human activity. The Stryi in the Zhydachiv region, like the Dniester downstream of Staryi Sambir, probably remained a braided channel to the beginning of the Early Holocene due to the large hydraulic gradient of channel and the transport of coarse bedload. The large meanders were abandoned in the late Boreal period. The structure and stratigraphy of the alluvial fan of the Stryi shows similarity to the Holocene alluvial fans that accumulated in the foreland of the Western Carpathians, especially the Holocene fan of the upper Vistula in the Oświęcim Basin.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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