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Development of the alluvial fan of the Stryi River and its Late Glacial incision in the foreland of the Eastern Carpathians (Western Ukraine)

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ABSTRACT:

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The article presents the stages of development of the alluvial fan of the Stryi River (tributary of the Dniester River), which is the largest alluvial cone in the foreland of the Eastern Carpathians. The alluvial fan has a diverse morphology and complex structure, and its formation is the result of the accumulation and erosion activity of several rivers. In order to reconstruct the evolution of the alluvial fan, geological cross-sections of the Stryi, Svicha and Dniester river valleys were made on the basis of archival drillings and field research. The stratigraphy of the alluvial fills is based mainly on morphological (morphostratigraphic) criteria and the correlation of terrace levels with those of adjacent areas. Fluvial sediments from the Late Glacial and Holocene were dated by the radiocarbon method, which allowed the determination of the age of fan dissection. The main factor controlling the course of accumulation and erosion on the alluvial fan was climate change. The accumulation of alluvial covers was preceded by phases of erosion, which generally fell at the end of the glacial periods (late glacial) and the beginning of the interglacials. Differences in the depth of dissection of the strath and the thickness of the accumulated alluvial sediments in the northern and southern parts of the fan may be the result of different tectonic movements and/or the transport capacity and size of river discharges. In the Late Glacial (Alleröd-Younger Dryas) and the Early Holocene the alluvial fan was dissected to a depth of 10–15 m due to the erosion of the Stryi and Dniester rivers.

Key words: Alluvial fan; Late Glacial incision; Stryi-Zhydachiv Basin; Western Ukraine.

INTRODUCTION

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

Skvarchevska (1956) separated seven terraces within the Carpathian foreland section of the Stryi river valley. Terraces V–VII are located outside the alluvial fan of the Stryi, within the Drohobych Plateau and Morshyn Plateau. Terraces I–IV were formed inside the valley bottom, and their alluvial sediments form the alluvial fan of the Stryi (Table 1). The accumulation of the alluvial series of the Stryi

Age	Terrace system	Skvarchevska (1956) Stryi valley	Kravchuk (1999) Dniester valley	Huhmann *et al.* 2004 Dniester valley	Stryi-Zhydachiv Basin (own research)		
		Height (m)	Height (m)	Height (m)	Terrace	Height (m)	Age
				4–5 (7 levels)	flood-plain	4–5	Holocene (2–3 levels)
	I	2.5–3.0	2.5–4.0	7 (NT2)	I	5.5–7.0	Late Glacial
Upper (Late) Pleistocene	II	4–5	7–12 8–15***	10–15 (NT1)	II	10–15	Upper (Late) Pleistocene
Middle Pleistocene	III	15–22	15–20 (25)	30–35 (MT)	III		Middle Pleistocene
	IV	27–43	27–40 35–50***		IV		
Lower Pleistocene	V	50* 50–70**	50–70	55-65 (HT)	V	50	Lower Pleistocene

Table 1. Heights and ages of river terraces in the upper Dniester valley and Stryi river valley. * Stryi-Svicha interfluve, ** Stryi-Tysmenyca interfluve, *** Gofhstein (1962), HT – High terrace, MT – Middle terrace, NT1 – older Low terrace, NT2 – younger Low terrace (Huhmann *et al.* 2004).

fan which is 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) believed that the largest areas in the Stryi-Zhydachiv Basin are occupied by terraces I and II (Table 1). According to him, the thickness of the alluvial sediments in the Basin reaches 30 m, which is a maximum sediment thickness for the entire eastern Carpathian foreland zone. The significant thickness of channel alluvial sediments in the alluvial fan of the Stryi may be associated with the tectonic lowering (subsidence) of the Basin (Gofshtein 1964).

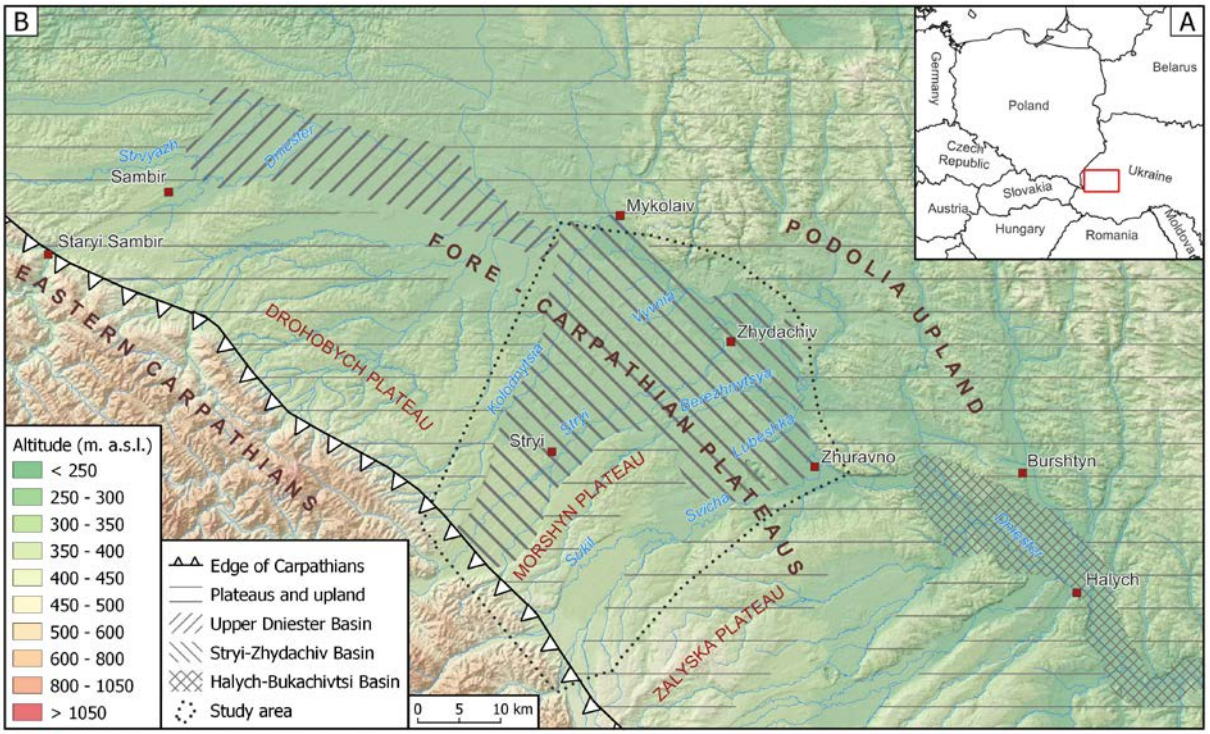
A similar system of Pleistocene alluvial fans occurs in the foreland of the Western Carpathians. These fans were deposited in the Sandomierz Basin by the Carpathian tributaries of the Vistula River (alluvial fans of the Raba, Dunajec and Wisłoka rivers) (Gębica 1995, 2004; Starkel 2001, 2014). In the upper Vistula valley the alluvial fans were formed both in the foothills section of the river and in the Subcarpathian Basin (Oświęcim Basin) (Niedziałkowska *et al.* 1985; Niedziałkowska and Szczepanek 1993–1994; Starkel 2001; Wójcik 2010; Lindner and Marks 2013). Among them, the largest is a vistulian alluvial fan of the upper Vistula river, which is covered with silts (Niedziałkowska and Szczepanek 1993–1994).

In the upper Dniester valley, at the margin of the Carpathians below terrace II with loess cover there is a system of gravel fans with a height of 10–11 m and 5–6 m above riverbed, which have been dated to the Late Glacial and Holocene (Gębica *et al.* 2016). These cones have no continuation in the Upper Dniestr Basin, because the Basin is filled almost entirely with Holocene peats underlain by thick series of alluvial Pleistocene sediments (Text-fig. 1B). In the Dniester river valley (downstream of the Stryi-Zhydachiv Basin) Huhmann *et al.* (2004), based on radiocarbon dating of subfossil trunks, fragments of woods in alluvial sediments and the degree of soil maturity, determined the age of NT1 terrace (10–15 m above river channel) to the Upper Pleniglacial (LGM), and the terrace NT2 (7 m above river channel) to the Late Glacial (Younger Dryas) (Table 1). Taking into account the results of these studies and the dating of the Holocene alluvial fan of the Stryi river in Zhydachiv town (Gębica *et al.* 2023), an attempt is made to correlate the terraces and alluvial sediments of the Stryi alluvial fan with dated profiles in neighbouring areas. An important, so far unsolved problem in the Late Pleistocene evolution of the Basin is also the determination of the age of dissection of the alluvial fan of the Stryi river.

The aims of this study were as follows: (1) analysis of the morphology and structure of the fan, (2) reconstruction of the stages of the alluvial fan development (3) determination the age of dissection of the fan.

STUDY AREA

The study area is located in the Eastern Carpathian foreland (Western Ukraine) in the Subcarpathian part of the upper Dniester river catchment (Text-fig. 1). 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 (mega) alluvial fan, whose length is 40 km and whose width between the Kolodnytsia river valley and the Svicha river valley is about 40 km (Text-figs 1B, 2). The fan has a complex (composite) morphological and geological structure. It consists of several (inserted) alluvial fills, in the accumulation of which the Stryi river

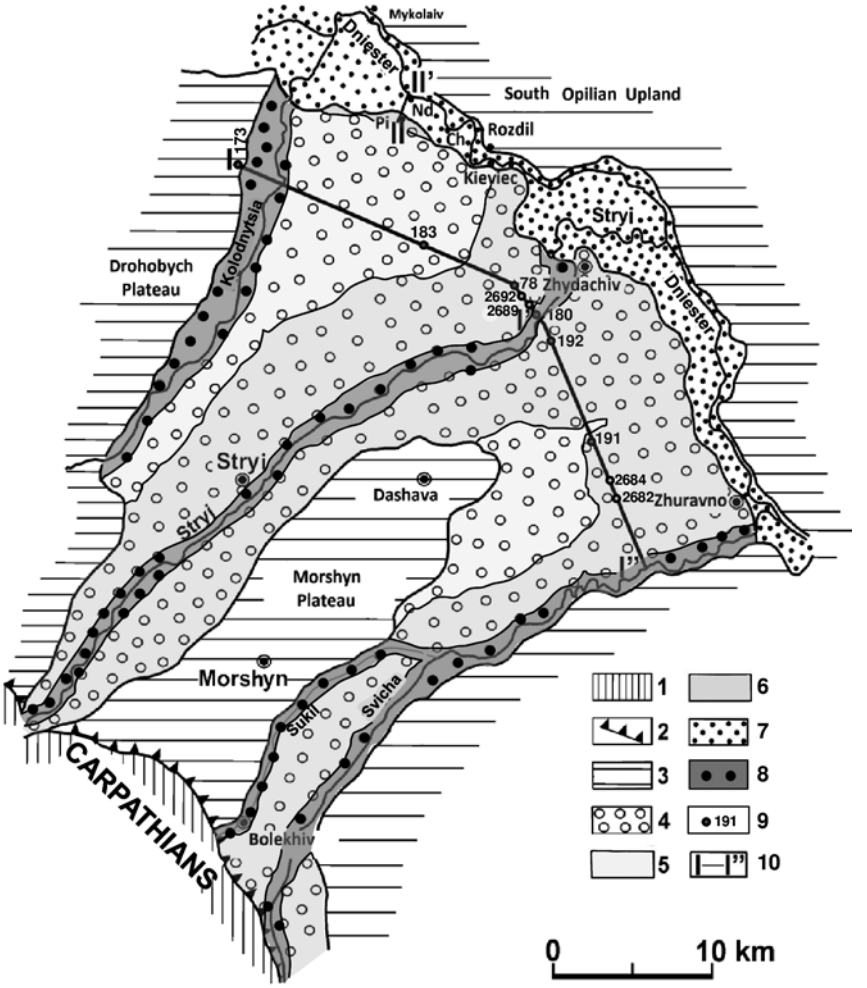


Text-fig. 1. Location of the study area: A – on the map of Central Europe, B – on the foreland of the Eastern Carpathians.

played the greatest role, with a smaller share played by the Kolodnytsia river. Probably, the Dniester river also took part in the formation of the northern part of the fan. A smaller fan in the southern part of the Basin was deposited by the Svicha and its tributary the Sukil river (Text-figs 1, 2). The apex of the fan begins at the river outlet from the Carpathians at an altitude of 350 m a.s.l., and 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 in some places by the edge of terrace II which is 15 m in height and was formed due to the erosion activity of the Dniester. The fact of the deep cutting (dissection) of the fan by the channel of the Dniester has not yet been explained.

The Stryi-Zhydachiv Basin is located in the Carpathian Foredeep which is filled with Badenian and Sarmatian sediments deposited in the so-called external zone of the Carpathian Foredeep Basin (Ney *et al.* 1974). The border of the Stryi-Zhydachiv Basin with the Carpathians is a clear morphological edge that runs along the front of the Skole unit thrusting into the inner zone of the Carpathian Foredeep (Text-fig. 1B) (Ney *et al.* 1974). The eastern border of the Basin with the Podolia Upland is basically consistent with the faults and flexures that separate the Carpathian Foredeep from the SW edge of the Eastern European Platform (Gierasimov *et al.* 2005). In the basement of the Carpathian Foredeep Basin, which includes Cambrian sediments, there is a system of faults parallel to and perpendicular to the Carpathian thrust front, which were probably reactivated in the younger complex of Neogene sediments (Krzywiec 2001). The Carpathian Foredeep consists of three structural-facial units: Boryslav-Pokuttya, Sambir and Bilche-Volytsya, which are characterized by thrust-and fold structure (Gierasimov *et al.* 2005). The course of the folds of these units is consistent with the direction of the Carpathian thrust, i.e. from north-west to south-east. However in the present relief of the Basin they are not visible, because they were eroded as a result of the erosion activity of the Carpathian tributaries of the Dniester river and are covered in the Basin with thick alluvial sediments, and in the plateaus with gravels and loess.

Another tectonic element of the Carpathian Foredeep consists of transverse dislocations. They divide the Carpathian Foredeep area into several tectonic blocks, but they are also not reflected in the present relief of the Basin. Only the middle section of the Stryi river (between the Carpathians and Stryi town) is formed along one of these faults (Shakin ed. 1977).



Text-fig. 2. Alluvial fans of the Stryi and Svicha rivers in the Stryi-Zhydachiv Basin (for location see Text-fig. 1). 1 – Carpathians, 2 – Edge of Carpathian, 3 – Plateaus and upland, 4 – Pleistocene alluvial fan (in general), 5 – Lower Pleistocene terraces, 6 – Middle and Upper (Late) Pleistocene terraces, 7 – Holocene terraces of the Dniester and Stryi Rivers (with meandering channels), 8 – Holocene terraces of the Stryi, Kolodnytsia, Sukil and Svicha Rivers (partly with braided channels), 9 – Number of drillings (Sources data: Saksiejev and Shedenko 1968a, b; Denisevič *et al.* 1968; Gierasimov and Gierasimova 1970), 10 – Geological cross-section lines (I – I'-I" and II – II'); Nd – Naditychi II profile (in this site the samples for radiocarbon dating were taken), Pi – Pisochna, Ch – Chernyca;

The sources of Stryi river are located in the Eastern Bieszczady Mts. at an altitude 1122 m a.s.l.. Up to its junction with the Dniester river, the Stryi has a greater length, i.e. 236 km (including the pre-Carpathian section which is 65 km long). The basin area is 3060 km^2. The average discharge of the Stryi at a distance of 17 km from its junction with the Dniester river is 45.2 m^3/s, and the maximum recorded discharge was 890 m^3/s (Perhach and Gamonia 2016). For comparison, the average discharge of the Dniester river in the area of Zhydachiv town is 124 m^3/s (Huhmann *et al.* 2004). Between the Carpathian margin and Zhydachiv town, the Pleistocene alluvial fan is cut by the braided channel of the Stryj with a width of 200–700 m and a channel gradient of 2.3‰ (Text-fig. 2). A system of inserted gravel terraces with a height of 2 m and 4 m stretches along this channel for a distance of 10 km from the margin of Carpathians (Gębica *et al.* 2023). Downstream of Zhydachiv town, due to the small gradient (0.6‰), the Stryi flows in a meandering channel 50–100 m wide 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. 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.).

According to the latest stratigraphic subdivision table of the Quaternary system (Cohen and Gibbart 2019), the Pleistocene is divided into Early (Lower) (2.58–0.78 Ma – mln years BP), Middle (0.78–0.13 Ma BP) and Upper (Late) Pleistocene (0.13–0.011 Ma BP). The Holocene covers the last 11,7 ka cal BP. The Scandinavian ice-sheets during the early Middle Pleistocene (Sanian 1; Elsterian I and Sanian 2; Elsterian II Glaciations), covered the northern part of the Dniester basin at the foot of the Carpathians (Lindner and Marks 2015). The edge of the ice-sheet of the Sanian 2 Glaciation was located about 30 km north-west of the Stryi river valley (Łanczont *et al.* 2019). During the early Middle Pleistocene glaciations the river system was transformed into the ice-marginal valley (so-called SubCarpathian Trough) draining proglacial waters through the Dniester valley to the Black Sea (Lindner and Marks 2015). Terrace V was formed in the upper Dniester valley during the Lower Pleistocene (Table 1) or during the early Middle Pleistocene (Ferdynandovian Interglacial and Sanian 2; Elsterian II Glaciation) (Lindner and Marks 2015; Łanczont *et al.* 2010, 2019). Terraces II– IV were formed in the valleys of the Dniester and Stryj 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 Glacial (Vistulian) and Holocene.

MATERIALS AND METHODS

The geological cross-sections of the alluvial fan of the Stryi were made on the basis of the descriptions of the archival drillings made as part of the preparation of the geological maps on the scale of 1:50 000 (Saksiejev and Shedenko 1968a, b; Denisevič *et al.* 1968; Gierasimov and Gierasimova 1970). In these works there are descriptions of geological drillings reaching depths from 100 to over 200 m, however apart from giving the thickness and lithology of the deposits, there are no detailed stratigraphic subdivisions. The age of the alluvial sediments was generally assumed to be Quaternary. Based on the published analysis of the material from these drillings, it was possible to determine the thickness of the alluvial deposits and to separate genetically different types of sediments: alluvial, slope, aeolian, organogenic.

The determination the age of the terraces developed in the Stryi-Zhydachiv Basin was carried out taking into account their correlation with terraces occuring in the much better studied Upper Dniester Basin (Jacyšyn *et al.* 2011; Jacyšyn 2016) and Halych-Bukachivtsi Basin (Huhmann *et al.* 2004; Gębica and Jacyšyn 2021) (Text-fig. 1B, Table 1). The Stryi and Upper Dniester Basin are separated by the valley of the Kolodnytsia river, which facilitates the correlation of terraces developed in both Basins. In order to determine the thickness and stratigraphy of the Holocene fan of the Stryi River in the area of Zhydachiv, our own drillings were made. The results of these analyses are presented in a separate publication (Gębica *et al.* 2023).

Data from archival drillings do not allow for the reliable subdivision of sandy-gravely-boulder alluvia with a thickness from several to several dozen meters. We relied on the examined profiles of terraces older than terrace V, located in the neighbouring plateaus: Drohobych, Morshyn and Zalyska Plateaus (Bogucki *et al.* 2016; Jacyšyn 2016; Jacyšyn and Khrypta 2019). The age correlation can also be made using the profiles of terraces III and IV in the Svicha river valley, which form the southern edge of the Basin (Jacyšyn *et al.* 2016).

Data obtained from archival drillings in the Stryi-Zhydachiv Basin also make it possible to reconstruct (identify) erosional socle levels, which can be interpreted as erosional platforms (strath) and fossil edges, that separate the steps between terraces. The interpretation of the fan structure on the basis of archival drillings has been verified by our own research – the mapping of terraces, and the surveying of the elevations of terraces above riverbeds.

In the Naditychi II profile the organic sediments filling the fossil channel of the Dniester were dated by the radiocarbon method, which allowed the determination of the age of dissection of the alluvial fan in the northern part of the Stryi-Zhydachiv Basin (Table 2). Radiocarbon dating was carried out using the liquid scintillation counting (LSC) technique at

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%)
Naditychi II-1	3.07	organic mud	palaeochannel fill	MKL-546	11830±180	14090–13320	12141–11371 BC
Naditychi II-2	3.67–3.72	trunk	palaeochannel fill	MKL-1277	10890±80	13057–13028 13001–12726	11108–11079 BC 11052–10777 BC
Naditychi II-3	3.74–3.78	organic mud	palaeochannel fill	MKL-547	12050±230	14902–13482	12953–11533 BC

Table 2. Radiocarbon dates from palaeochannel of the Dniester River valley in the northern part of the Stryi-Zhydachiv Basin.

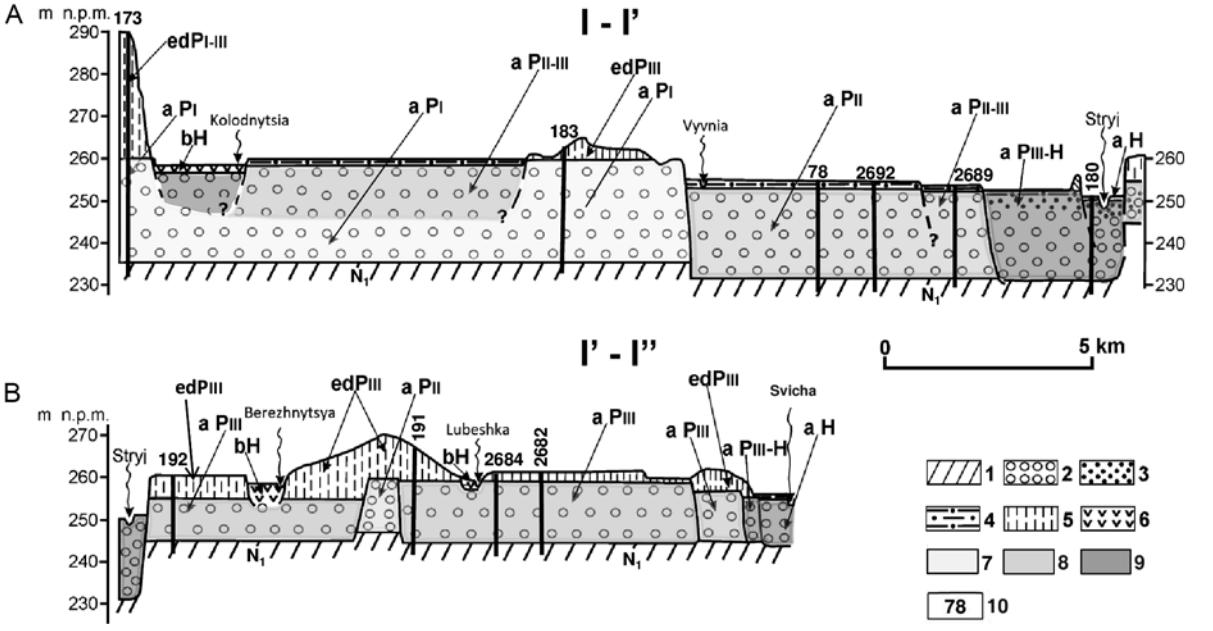
the Laboratory for Absolute Dating in Skała near Kraków, Poland (Lab. code MKL). Radiocarbon dating results were calibrated using OxCal 4.4 software (https://c14.arch.ox.ac.uk/oxcal.html) and the IntCal 09 calibration curve (Reimer *et al.* 2020) (Table 2). The dates in this paper are presented in radiocarbon years before present (^{14}C BP).

RESULTS

The alluvial fans of the Stryi, Kolodnytsia and Svicha Rivers

In the northern part of the Stryi-Zhydachiv Basin three morphological components of the alluvial fan can be distinguished: Kolodnytsia river valley, interfluves of the Kolodnytsia-Vyvnia and Vyvnia-Stryi rivers.The area on the interfluve of the Kolodnytsia-Vyvnia rivers is occupied by terrace V (Text-fig. 3A). The fragment of the fan located between Vyvnia and the Stryi river is built by an inserted alluvial series younger than terrace V. The boundaries of these morphological elements are consistent with the course of the Stryi and Kolodnytsia rivers, and their formation is due to the erosion and accumulation activity of these rivers. The heights of the surface of the fan gradually increase downstream from 2–4 to 15–25 m above the river channel.

The northern part of the Basin is filled with alluvial sediments with a thickness of 20–25 m (Text-fig. 3A). In the bottom lies a 15–23-metre thick cover of gravel alluvia, covered with sands and alluvial loams of overbank origin with a thickness of 2–5 m (Gierasimov and Gierasimova 1970; Denisevič *et al.* 1968; Saksiejev and Shedenko 1968a, b). In the area of the villages of Chernyca and Kieviec, on the edge of the fan (terrace II) with a height of 10–12 m above the Dniester channel, loess-like silts with a thickness of about 5 m outcrop. Along the Stryi channel there is a floodplain with a width of 0.4–0.5 km at the edge of the Carpathians, increasing to 0.8–1.2 km at a distance of 36 km from the edge of the Carpathians, within which alluvia with a thickness up to 25 m have been found (Denisevič *et al.* 1968; Gierasimov and Gierasimova 1970). In the area of the 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 Stryi and Dniester river channels (Denisevič *et al.* 1968; Gierasimov and Gierasimowa 1970; Gierasimov *et al.* 1974). The thickness of Holocene sediments (on the top of the



Text-fig. 3. Geological cross-sections of the alluvial fans. A – In the northern part of the Stryi-Žhydachiv Basin (along the I – I' line). B – In the southern part of the Stryi-Zhydachiv Basin (along the I' – I'' line, for location see Text-fig. 2). 1 – Miocene, 2 – gravel, 3 – sand, 4 – silty sand, 5 – loess, 6 – peat, 7 – Lower Pleistocene terraces, 8 – Middle and Upper (Late) Pleistocene terraces, 9 – Late Glacial and Holocene terraces of Stryi, Svicha and Kolodnytsia, 10 – number of drilling (Sources data: Saksiejev and Shedenko 1968a, b; Denisevič *et al.* 1968; Gierasimov and Gierasimova 1970). Origin and facies of sediments: a – alluvial, e–d – aeolian-delluvial, b – biogenic (organogenic). Age of deposits: N_1 – Neogene, PI – Lower Pleistocene, PI-III – Lower, Middle and Upper Pleistocene (undivided), PII – Middle Pleistocene, PII-III – Middle and Upper (Late) Pleistocene (undivided), PIII – Late Pleistocene, PIII-H – Late Pleistocene and Holocene, H – Holocene.

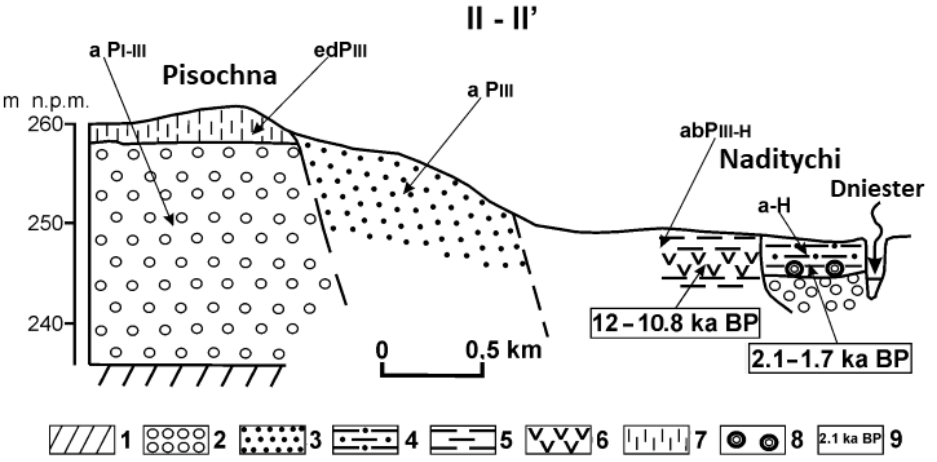
gravels) varies from 5 to 9 m. Miocene clays were found at a depth of 10.5 m. They are overlain by gravels of uneven top surface, cut by palaeotroughs of a depth of 2–4 m, filled with sands 1.5–3.0 m thick (Gębica *et al.* 2023).

In the southern part of the Stryi-Zhydachiv Basin several alluvial fills can be distinguished, referring to the course of the Stryj, Svicha and Dniester and their tributaries: the Berezhnytsya and Lubeshka Rivers (Text-figs 1, 2, 3B). The oldest sediments are the Early Pleistocene alluvia of terrace V, which is developed the foot of the eastern slope of the Morshyn Plateau (Denisevič *et al.* 1968; Gierasimov and Gierasimova 1970). Due to the continuous (extensive) cover of loess, it is practically impossible to separate the Pleistocene terraces younger than terrace V on the basis of morphological criteria. The gravelly-sandy alluvia of about 10–15 m thickness, are probably dated to the Middle and Upper Pleistocene, and younger alluvial fills to the Late Glacial and Holocene (Text-fig. 3B). The alluvia are covered in the upper part with a loess thickness of 5–10 m, the age of which has not yet been determined**.**

The strath of the alluvial sediments in the southern part of the Basin is on average 7–13 m higher, than in the northern part of the Stryi-Zhydachiv Basin. As in the northern part of the fan, the strath descends below the river channel of the Dniester, Stryi and Svicha. An important statement is the fact, that the southern part of the Basin is filled with almost half the thickness of alluvial sediments (up to 10–15 m), which are covered with a continuous cover of loess with a thickness of 5–10 m (Text-fig. 3B).

Dniester River valley

The floor of the Dniester river valley is separated from the fan of the Stryj by a distinct erosion edge, which in some places is 15 m high. From the east and north-east, the bottom of the Dniester valley is limited by the edge of the South Opilian Upland with a height of 15 to 80 m, and a maximum of 100–110 m (Text-fig. 2). The bottom of the Dniester valley is filled with alluvia of the Pleistocene and Holocene terraces. The largest area is occupied by terrace II with a height of 15–20 m above the Dniester channel, covered with loess, originating from the Upper Pleistocene (Text-fig. 4). Below terrace II there is a sandy terrace with a height of 10 m above the Dniester river. The Holocene terraces consist of 2–3 levels of floodplain with a width varying from 3–4 km north of Pisochna to 0.3 km near Rozdil (Text-fig. 2). The width increases again to 4–5 km in the area of Zhydachiv town, and towards the south it decreases to 1.2 km in the area of Zhuravno town. In the bottom of the Dniester valley, a floodplain with a height of 4–5 m above the Dniester and Stryi channels is best developed. The surface of the floodplain is cut by numerous oxbow-lakes, and in the northern part by canals and drainage ditches. In places, fragments of terrace I rise above the floodplain with a height of 5.5–7 m above the Dniester and Stryj riverbed. The floodplain in the northern part has built alluvia with a thickness of 8–10 m, while in the southern part the thickness of alluvial sediments increases to 16–20 m. The lower part of the profiles is made up of channel alluvia (gravels and pebbles) with a thickness of 8–17



Text-fig. 4. Geological cross-section of the Dniester river valley in the northern part of the Stryi-Zhydachiv Basin (along II – II' line, for location see Text-fig. 2). Lithology: 1 – Miocene clay, 2 – gravel and sand, 3 – sand, 4 – silty sand, 5 – silt and clay, 6 – peat, 7 – loess, 8 – subfossil trunk, 9 – radiocarbon date (conventional years in ka BP). Origin and facies of sediments: a – alluvial, ed – aeolian-deluvial, b – biogenic (organogenic). Age of deposits: N_1 – Neogene, P I-III – Lower, Middle and Upper (Late) Pleistocene (undivided), PIII – Upper Pleistocene, P III-H – Upper (Late) Pleistocene and Holocene, H – Holocene

Text-fig. 5. Upper part of the palaeochannel fill of the Dniester river at the depth of 0.2–3.0 m in the Naditychi II profile (for location see Text-fig. 2). Organic deposits are overlain by floodbasin black clays and silts and silty-sandy deposits of the natural levees (Photo P. Gębica).

m. In the upper part the channel alluvia is overlain by overbank sediments (sands, silts and clays) and palaeochannel fill sediments (peat, mud and clay) with a total thickness of 4–5 m.

On the cross-section of the Dniester valley, in the northern part of Stryi-Zhydachiv Basin, below the sandy terrace, the floodplain is developed (Text-figs 2, 4).

In the undercuts of the floodplain with a height of 4–5 m above the riverbed, in the profile of Naditychi the sediments of the fossil Dniester channel were described (Text-figs 4–6). The description from the top includes:

– 0.0–1.5 m – sandy silt with thin layers of sand, in the bottom horizontal layers of silt and sand
– 1.5–2.53 m – mud (silt) gray, in the lower part clayey silt
– 2.53–2.76 m – silty clay with a lot of Fe-Mn concretions
– 2.76–2.86 m – organic black clay with Fe-Mn concretions in the bottom
– 2.86–3.53 m – organic brown mud bedded with fragments of wood, deformed (folded) in the lower part
– 3.53–3.67 m – organic mud gray and yellow in the bottom with fragments of wood
– 3.67–3.74 m – peat darkbrown good decomposed with fragments of wood, in the top part small tree trunks with a diameter of 10 cm
– 3.74–3.79 m – organic mud lightbrown, good decomposed with grains of sand
– 3.79–3.92 m – mud graybrown with fragments of water vegetation
– 3.92–4.52 m – mud gray with ferruginous vertical precipitations (rhizoconcretions) and remnants of water vegetation

The filling of the Dniester fossil channel consists at the bottom of silts and organic sediments with tree trunks, covered with clays and sandy silts representing the natural sediments of levees (Text-figs 5, 6). Radiocarbon dating of organic mud from a depth of 3.74–3.78 m gave a result 12050±230 BP (MKL-547) (Table 2). A piece of wood from a depth of 3.67–3.72 m was dated at 10890±80 (MKL-1277). A sample of organic mud from a depth of 3.07 m was dated at 11830±180 (MKL-546) (Table 2). The samples from the bottom and top of the organic series have a similar age, which is confirmed by

Text-fig. 6. Bottom part of the palaeochannel fill of the Dniester river in the Naditychi II profile (for location see Text-fig. 2). Organic deposts with fragments of wood and small trunks at the depth of 3.0–3.9 m were dated at Alleröd-Younger Dryas (photo P. Gębica).

Text-fig. 7. Subfossil tree trunks buried in overbank deposits of the Dniester river in the Naditychi I profile at the depth of 2.7–3.8 m. Radiocarbon dates from subfossil trunks (2120±40 BP (MKL-542), 1680±40 BP (MKL-541), indicate that the accumulation of overbank deposits took place in the Roman period (photo P. Gębica).

the calibration results of both samples in the range of 14902–13320 cal BP. However they are significantly older than the date obtained from the trunk (13057–12726 cal BP) (Table 2). The dating results indicate, despite the age inversion, that the organic sediments filling the Dniester fossil oxbow-lake accumulated in the Alleröd or at the beginning of the Younger Dryas. The younger alluvial fill consists of overbank sediments with tree trunks which accumulated during the floods dated to the Roman period (Text-figs 4, 7).

DISCUSSION

The development of the alluvial fans from the Lower to the Late Pleistocene

The history of the development of the alluvial fans in the Stryi-Zhydachiv Basin dates back to the Lower Pleistocene. In the Lower Pleistocene the northern part of the basin was drained by the system of Stryi and Kolodnytsia Rivers, which accumulated the alluvial cones on the interfluves of the Kolodnytsia – Vyvnia. The Dniester drained the north-east and east part of the Basin. The activity of the Stryi with the Kolodnytsia and Dniester rivers at that time is associated with the accumulation of V terrace sediments (Table 3) (Skvarchevska 1956; Kravchuk 1999).

In the southern part of the Basin, the Svicha river accumulated in the Lower Pleistocene the alluvia of V terrace (Jacyšyn *et al.* 2016). In the Middle Pleistocene the channel of the Stryi river moved to the south-east, while the Kolodnytsia drained the north-western edge of the Basin until the Late Pleistocene. Alluvia III and IV terraces from the Middle Pleistocene were inserted in to the gravel cover from the Lower Pleistocene. In large areas between the Stryi and Svicha rivers, the alluvia of these terraces is covered by loess 1–5 m thick, therefore reconstruction of the course of erosion and accumulation processes during this time is very difficult (Table 3). In the Upper (Late) Pleistocene the Stryi river moved further to the south-east and accumulated alluvia of II terrace.

Stratigraphy		Paleomagnetism		MIS	Stages of terrace formation
Holocene		Brunhes		1	Formation of 2-3 levels of the floodplains in the Dniester and Stryi River valleys
Pleistocene	Upper (Late) Pleistocene			2	Accumulation of "cold" alluvia of the II terrace Dissection of the II terrace Beginning with the accumulation of alluvial sediments of the I terrace
				3	The course of fluvial processes is not definitively recognized.
				4	The course of fluvial processes is not definitively recognized.
			Blake	5	Formation the strath of the II terrace. Accumulation of "warm" alluvial sediments of the II terrace
	Middle Pleistocene			6	The course of fluvial processes on the alluvial fan of Stryi River in the Stryi-Zhydachiv Basin and in the upper Dniester valley is difficult to reconstruct
				7	The course of fluvial processes on the alluvial fan of Stryi River in the Stryi-Zhydachiv Basin and in the upper Dniester valley is difficult to reconstruct
	Lower Pleistocene			8	Accumulation of alluvial sediments of the IV terrace
				9	
				10	
				11	Dissection of alluvial sediments of the V terrace. Formation the strath of the IV terrace
				12	Scandinavian ice sheet in the upper Dniester basin. Alluvia of V terrace was covered by glacial till. Accumulation of peryglacial alluvial sediments.
				13–15	Accumulation of the "warm" alluvial sediments of the V terrace.

Table 3. Main stages of the Pleistocene-Holocene evolution of the Stryi and Dniester river valleys. Sources: Łanczont and Bogutskyj 2002; Huhmann *et al.* 2004; Łanczont and Boguckyj 2007; Jacyšyn and Bogutskyj 2008; Gębica *et al.* 2023.

The channel of the Dniester, pushed by the alluvial fan of the Stryi River, moved eastwards to the edge of the South Opilian Upland. In the Dniester valley in the area of Pisochna sandy alluvia was accumulating, building up a terrace with a height of about 10 m above riverbed. Its age at the present state of research is difficult to determine. Dating of the NT1 terrace (10–15 m above the Dniester riverbed) in the Halych-Bukachivtsi Basin has shown that the terrace was formed in the Upper Pleniglacial (MIS 2) (Huhmann *et al.* 2004). In the Kolodiiv profile located in the valley of the Sivka river (tributary of the Dniester), channel alluvia of the II terrace was accumulating during the cold stage (MIS 6), and palaeochannel deposits accumulated in the Eemian and Early Glacial (MIS 5) (Łanczont and Bogutskyj 2002). Thus, the alluvia terrace II in the Kolodiiv profile is much older than the alluvia terrace NT1 in the Dniester valley.

Late Glacial incision of the Stryi alluvial fan

In the Late Glacial and Holocene the alluvial fan was cut to a depth of 10–15 m by the channel of the Dniester and Stryi. The results of dating of the fossil Dniester channel, suggests that the dissection of the alluvial fan of the Stryi River occured in the Alleröd or at the beginning of the Younger Dryas, ca. 11–12 000 years ago (Text-fig. 4). It is difficult to determine whether it was a braided or meandering channel. The presence of silts, clay and organic sediments in the floodplain (Text-figs 5, 6) could determine the development of a sinous or a meandering channel. The tree trunks in the organic sediments testify to the occurence of forest vegetation, which favoured the incision of Dniester channel. Because in the described profile to a depth of 4.5 m no channel sediments (the bottom of the filling of the palaeochannel) were captured, it should be assumed that the erosion in the Late Glacial descended below the present Dniester riverbed. Younger alluvial fills are represented by insertions of the overbank sediments with tree trunks dated to the Roman period (Text-figs 4, 7). On the Holocene alluvial fan in the Zhydachiv town area the oldest fossil channel of the Stryi river located 2 m below the present riverbed has been dated to the Younger Dryas. On the other hand the large-radius Stryi palaeochannel located in the marginal part of the floodplain is younger and dates back to the Early Holocene (Gębica *et al.* 2023). Similar radiocarbon dates confirming the incision of the terrace II before the Younger Dryas in the Dniester valley downstream of the Stryj-Zhydachiv Basin were obtained by Huhmann *et al.* (2004) (Text-fig. 1, Tables 1, 3). However the age of the alluvia of terrace I (NT2) 5.5–7 m above the Dniester riverbed, determined by Huhmann *et al.* (2004) to the Younger Dryas seems too young (underestimate) because the radiocarbon date comes from the fill of the large-radius palaeochannel of the Dniester, which undercuts terrace NT2. Dating of the overbank sediments of this terrace at 13010±180 BP (MKL-2264), if is not overestimated, indicates that dissection of the terrace II (NT1) may have already occured at the termination of the LGM (Gębica and Jacyšyn 2021).

The role of tectonic movements in the development of the alluvial fans in the Stryi-Zhydachiv Basin

The occurence of transverse tectonic dislocations in the bedrock (basement) of the Basin, which divide the Carpathian Foredeep area into several tectonic blocks, is not reflected in the modern relief of the Basin. However, it is assumed that the middle section of the course of the Stryi river is founded on such one fault (Shakin ed. 1977). This fault also separates two large tectonic blocks, which differ in the amplitudes of their tectonic uplifts. This is registered by the differences in the location (height) of strath terraces and the thickness of alluvium between the southern and northern part of the Stryi-Zhydachiv Basin. The strath of the terraces in the southern part of the Basin is on average 7–13 m higher, than the strath in the northern part of the Basin. The southern part of the Basin is filled with nearly twice as much thickness (10–15 m) of alluvial deposits as its northern part. This may provide the evidence for the existence of differential tectonic movements in the Basin (Gofshtein 1964). On the other hand, differences in the elevation of straths and the thickness of alluvial sediments in the northern and southern part of the Basin, can be explained by the transport capacity (river competence) and volume of river discharges. The fluvial action of the two largest rivers: Stryi and Kolodnytsia in the northern part of the Basin, has resulted in deeper dissection of the straths and thicker accumulation of alluvial sediments. In the southern part of the Basin, the Svicha and its tributary the Sukil river deposited a smaller alluvial fan, and the dissection of the strath did not reach as deep as in the northern part of the Basin.

CONCLUSIONS

The alluvial fan of the Stryi river has a composite morphological and geological structure. The forma-

tion of the fan is the result of the accumulation and erosion activity of the largest Carpathian tributary of the Dniester – the Stryi river. A smaller fan in the southern part of the Stryi-Zhydachiv Basin was deposited by the Svicha river. The main factor controlling the course of accumulation and erosion on the alluvial fan of the Stryj river was climate change. The accumulation of gravel covers from the Lower to Late Pleistocene was preceded by the phases of erosion (dissection) of the alluvial fan, which generally fell on the end of the glacial periods (late glacial) and the beginning of the interglacials.

The differences in the thickness of sediments and the elevation of strath between the northern and southern part of the Stryi-Zhydachiv Basin can be explained by the larger transport competency and discharges of the Stryi and Kolodnytsia, compared to the Svicha River. It is not unlikely that the accumulation of the thick series of alluvial sediments in the northern part of the fan was influenced by tectonic movements lowering (subsiding) the Stryi-Zhydachiv Basin. The dissection of the alluvial fan to a depth of 10–15 m took place in the Late Glacial (Aleröd-Younger Dryas) and in the Early Holocene. The correlation of the age of the sediments in the southern and northern part of the Basin is difficult due to the continuous blanket of loess, which has covered the older relief in the bottom of the Stryi and Svicha valleys.

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