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Application of malacological analysis to reconstruct climate fluctuations and human activity during the Middle and Late Holocene. Research in the valley of the Grajcarek stream (Pieniny Mts., southern Poland)

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ABSTRACT:

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The scope of this analysis included fluvial sediments of the low terrace of the Grajcarek stream in the Małe Pieniny Mts. (Western Carpathians). The structure of the terrace has been surveyed in five profiles. The sedimentary sequence includes alternating layers of gravel and calcareous mud with a maximum thickness of up to 2.2 m. A rich and varied malacofauna has been found in the mud. The age of the sediments was determined using the radiocarbon method. The sediments that make up the terrace cover the younger part of the Middle Holocene and the entire Late Holocene. The analysis of the malacofauna has allowed for the characterization of environmental changes. The most important of them dates back to the Middle Ages and is associated with the phase of intensive settlement in the Pieniny Mts.. It is indicated by deforestation and the related change in the composition and structure of malacocoenoses manifested by the replacement of forest communities by ones with open-country species. Gravel horizons are records of flood periods correlated with wet climatic phases. It is possible to distinguish six such phases covering the following periods: 6600–6100 y cal BP, 5500–5100 y cal BP, 4500–4100 y cal BP, 3200–2300 y cal BP, 2000–900 y cal BP and 400–200 y cal BP. They correspond to the periods of increased fluvial activity of rivers, intensification of mass movements, advances of alpine glaciers and the increase in the water level in lakes.

Key words: Environmental changes; Molluscs; Flood phases; Holocene; Pieniny Mts.; Carpathians.

INTRODUCTION

The Holocene is an interglacial period that began approx. 11,700 years ago (Walker *et al.* 2019). During it, there were a number of climatic fluctuations, usually spanning several hundred years. Their appearance was associated with a variety of factors, often continental or even global in nature (e.g. Mauri *et al.* 2014; Demény *et al.* 2021). As a consequence, warmer phases alternated with cooler ones, and wetter with drier ones. These climatic fluctuations had a significant impact on geological processes. The cooler and wetter phases favored the development of mountain glaciers (e.g. Holzhauser *et al.* 2005; Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011), raising the water level in lakes (e.g. Ralska-

Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Holzhauser *et al.* 2005; Magny *et al.* 2012), or the intensification of mass movements (e.g. Starkel 1997; Alexandrowicz 1997a, 2013a; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002; Soldati *et al.* 2004; Prager *et al.* 2008; Pánek *et al.* 2013). During humid periods, an intensification of fluvial activity is also observed (e.g. Starkel *et al.* 2006, 2013; Hoffmann *et al.* 2008; Gębica 2011, 2013a, b; Wirth *et al.* 2013; Benito *et al.* 2015; Gębica *et al.* 2016; Perşoiu and Perşoiu 2018; Rădoane *et al.* 2019). It manifests in the appearance of erosive surfaces and gravel horizons in the profiles of fluvial deposits. Research on such sediments in the area of the Polish Carpathians has been undertaken for many years (e.g. Starkel *et al.* 2006, 2013; Gębica 2011, 2013a, b; Alexandrowicz 2020). Thanks to them, it was possible to correlate the phases of high fluvial activity with the periods of climate change. Most of these analyzes were concentrated in the valleys of large rivers. Studies in smaller river and stream valleys have not been studied so intensively in this respect.

Mollusc shells are often preserved in fine-grained river sediments (sand and mud), especially those characterized by an increased calcium carbonate content. Such formations are deposited in a relatively low-energy environments, thus limiting the processes of physical breaking of the shells. At the same time, the presence of calcium carbonate protects the shells from chemical dissolution. Gravel layers accumulating in a high energy environment usually do not contain mollusc shells or contain only small, non-determinable shell fragments. This is related to the rapid destruction of shells as a result of their crushing.

Fluvial sediments are often used for palaeogeographic analyzes. These include the reconstruction of the stages of intensification of fluvial processes (based on the sequence of gravel horizons), the palaeoenvironment reconstruction (based on the characteristics of mollusc communities present in the mud horizons) as well as the assessment of the intensity of anthropopressure. The above-mentioned issues will be the subject of the presented study.

STUDY AREA

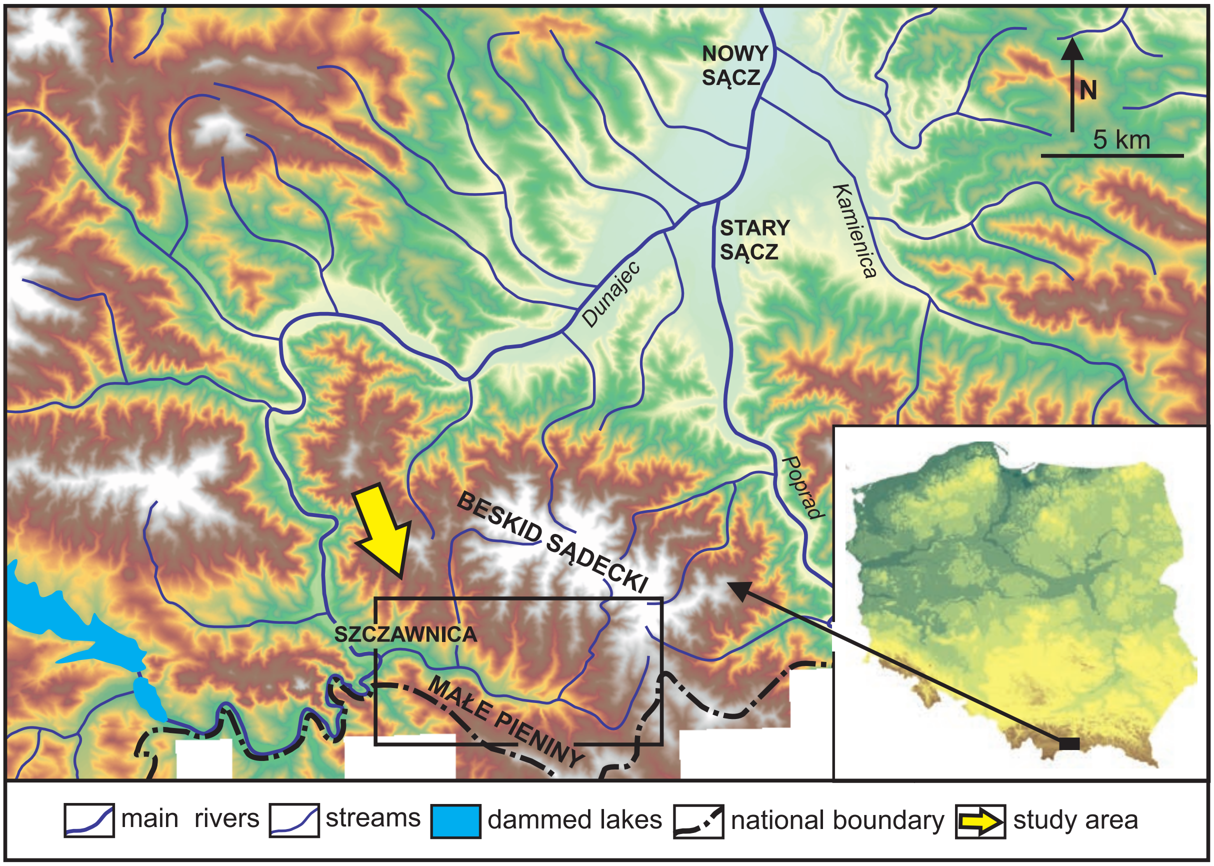
The study area covers the valley of the Grajcarek stream, the right-bank tributary of the Dunajec River (Pieniny Mts, Carpathians). It is a relatively wide, flat-bottomed valley, about 15 km long, separating two mountain ranges: Beskid Sądecki (in the north) and Małe Pieniny (in the south) (Text-figs 1 and 2). The source of the stream is located at an altitude of approx. 950 m a. s. l., and the estuary in the town of Szczawnica (approx. 425 m a. s. l.). The Grajcarek stream valley itself and its northern slopes are built of highly tectonically disturbed flysch sediments representing the Late Cretaceous and Palaeogene. On the southern slopes, strongly deformed and lithologically differentiated limestones (Upper Jurassic–Lower Cretaceous) and variegated marls (Upper Cretaceous) (Jurkiewicz 1994; Birkenmajer and Gedl 2017) are exposed. The older substrate is covered with low-thickness Quaternary sediments. On the slopes of the valley, there are mainly solifuction and weathered covers. In the stream valleys there are river sediments (gravel, sand and mud), and locally also travertine (Gerlach 1966; Alexandrowicz 1997b, 2004).

Along the bed of the Grajcarek stream there is a 2–2.5 m high terrace escarpment. At its bottom, the ground rocks are exposed, forming a rocky socle which alluvial sediments rest on.

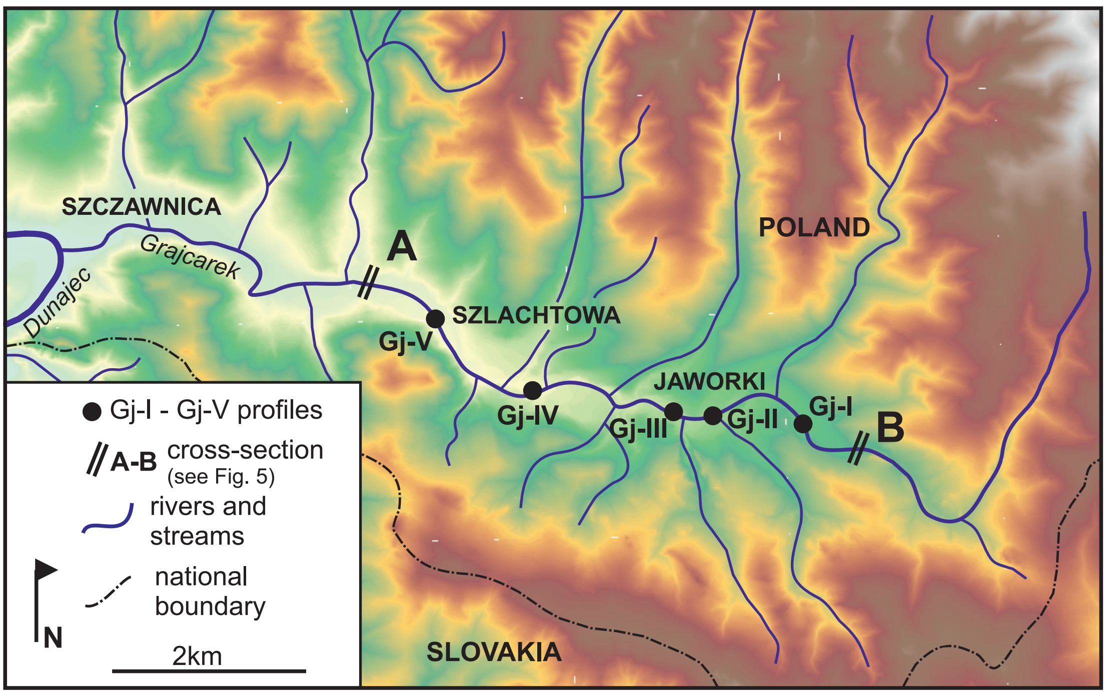
Today, the valley of the Grajcarek stream is almost completely deforested and occupied by arable fields and pastures, as well as by settlements.

MATERIAL AND METHODS

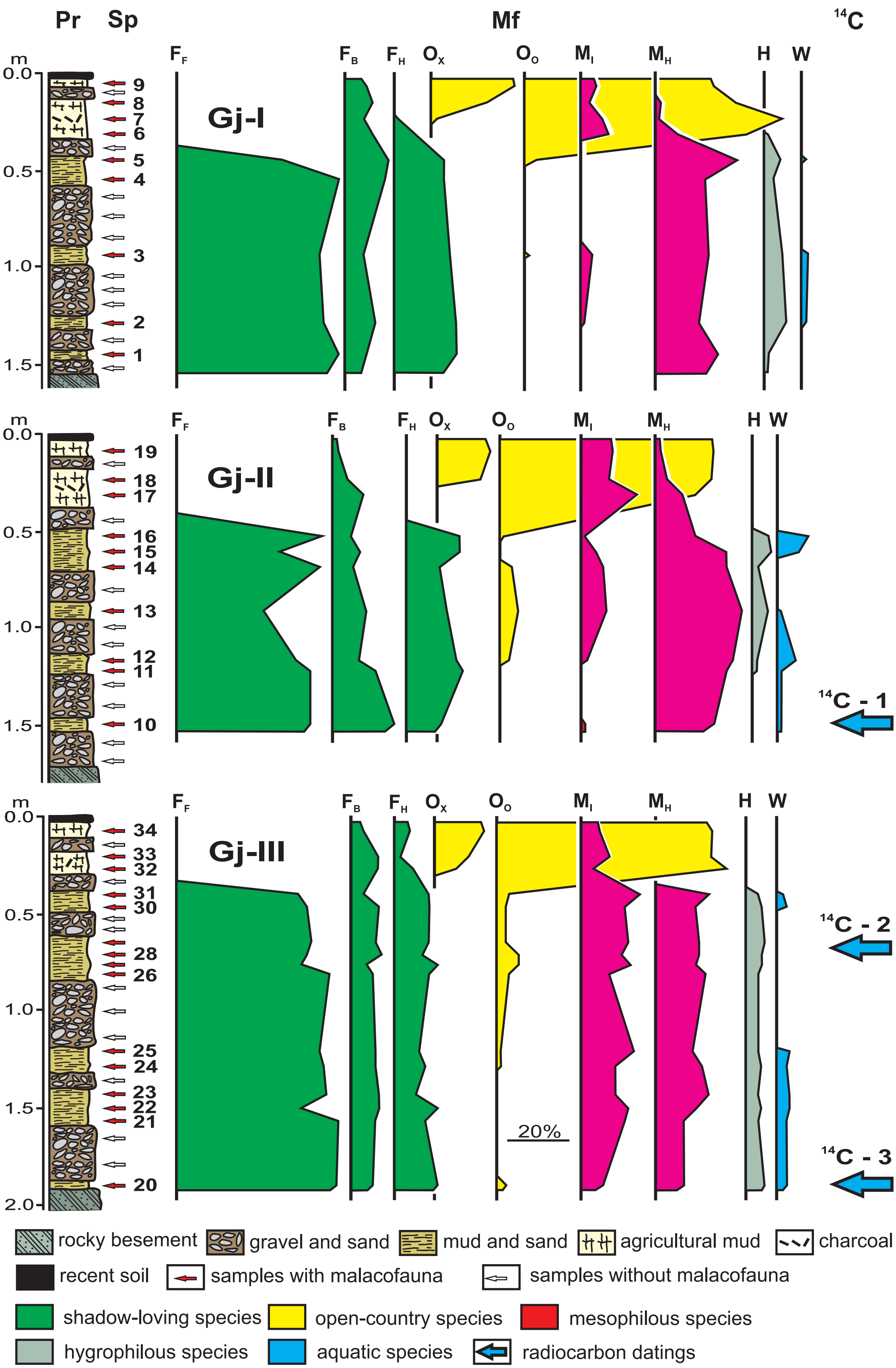
Malacological analyzes in the Grajcarek stream valley were made on the basis of material collected from five profiles (Gj-I – Gj-V; Text-fig. 2). The preliminary results of the fauna analyzes have been included in several regional studies (Alexandrowicz 2004, 2013b, 2020). For the purposes of this study, much more extensive material was used (new profiles and samples, new age determinations). The samples for malacological analyzes included intervals 10–20 cm thick (depending on the lithology of the sediments). A total of 108 samples were taken (62 of which had shell material present). Well-preserved mollusc shells were present only in mud sediments, while the samples of gravel contained few, heavily crushed and undeterminable shell fragments, which were not used in the presented analyzes. After sludging, drying and selecting the shells of molluscs (whole specimens, juvenile forms and those shell fragments which enabled indisputable identification), the taxa were determined using the keys (Wiktor 2004; Welter-Schultes 2012; Horsák *et al.* 2013) and the comparative collection. Malacological analysis was performed using the methods described by Ložek (1964) and Alexandrowicz and Alexandrowicz (2011). Individual mollusc species were classified to ecological groups (according to



Text-fig. 1. General location of the Grajcarek stream valley (map base: www. polska.e-mapa.net).

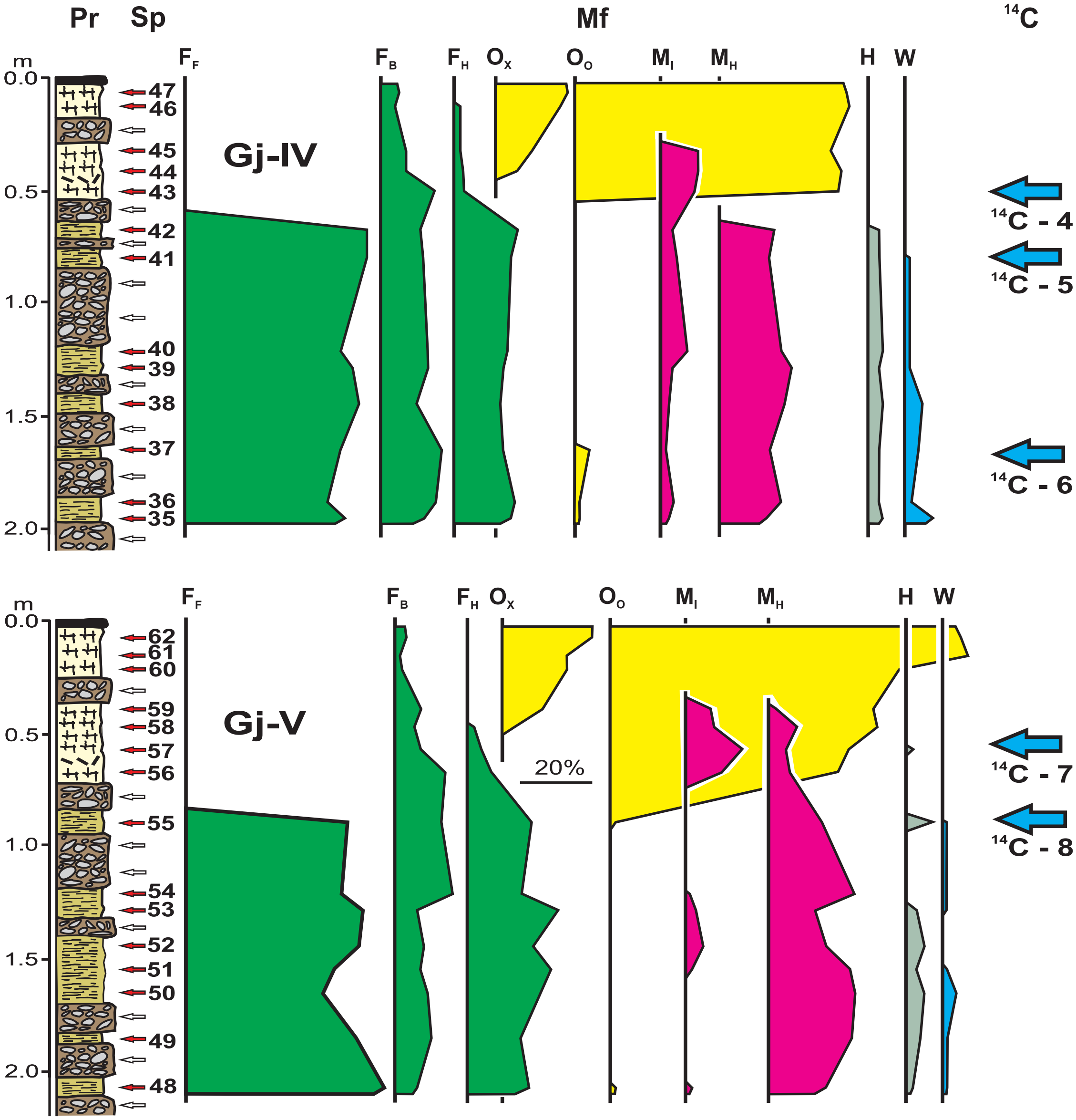


Text-fig. 2. Location of profiles of fluvial deposits in the Grajcarek stream valley (map base: www. polska.e-mapa.net).



Pr Sp
Mf
14C
Gj-I
Gj-II
Gj-III
FF FB FH OX OO MI MH H W
m
0.0
0.5
1.0
1.5
2.0
14C - 1
14C - 2
14C - 3
20%
rocky besement
gravel and sand
mud and sand
agricultural mud
charcoal
recent soil
samples with malacofauna
samples without malacofauna
shadow-loving species
open-country species
mesophilous species
hygrophilous species
aquatic species
radiocarbon datings

the scheme developed by Ložek (1964) with modifications (Alexandrowicz and Alexandrowicz 2011; Juřičkova *et al.* 2014b): forest species (F_F), shade-loving species of rare forests and shrub zones (F_B), shade-loving moist forest species (F_H), xerophilous and underground species (O_X), open-country species (O_O), mesophilous species of medium humid habitats (M_I), mesophilous species of humid habitats (M_H), hygrophilous species (H) and aquatic species (W). The percentage shares of each ecological group in each sample were calculated. This made it possible to construct malacological diagrams which were the basis for palaeoenvironmental considerations. The stratigraphy of the sediments was determined indirectly (by comparing the composition and structure of malacocoenoses with those of neighboring



Text-fig. 4. Lithology and mollusc fauna of fluvial deposits in the Grajcarek stream valley (profiles Gj-IV and Gj-V). For explanations see Text-fig. 3.

← Text-fig. 3. Lithology and mollusc fauna of fluvial deposits in the Grajcarek stream valley (profiles Gj-I – Gj-III). Pr – lithological profiles, Sp – samples, Mf – malacofauna, ecological groups of molluscs (after: Ložek (1964), Alexandrowicz and Alexandrowicz (2011) and Juřičková *et al.* (2014b)); F_F – forest species, F_B – shade-loving species of rare forests and shrub zones, F_H – shade-loving, moist forest species, O_X – xerophilous and underground species, O_O – open-country species, M_I – mesophilous species of medium humid habitats, M_H – mesophilous species of humid habitats, H – hygrophilous species, W – aquatic species, ^{14}C – radiocarbon datings.

sites) and directly (by performing eight age determinations using the radiocarbon method). The radiocarbon datings were based on organic remains separated from sediments: fragments of branches (4 samples), finer plant detritus (2 samples) and fragments of charcoal (2 samples). The results of age determination were calibrated using the OxCal software (Bronk Ramsey 2017) and calibration curve IntCal 20 (Reimer *et al.* 2020). Age determinations were made at the Absolute Dating Methods Center, Institute of Physics, Silesian University of Technology in Gliwice (laboratory reference number: Gd) (2 samples) and at Radiocarbon Laboratory of the Ukrainian Academy of Sciences in Kiev (laboratory reference number: Ki) (6 samples).

RESULTS

Sediment lithology

The low terrace of the Grajcarek stream has a quite uniform structure. Flysch formations appear at the bottom of the Quaternary sediments, forming a rock socle, the roof of which rises several cm above the recent stream level. Fluvial sediments rest on the eroded surface of the socle, with a thickness of up to 2.2 m (Text-figs 3 and 4). Within these formations there are layers of fine- and medium-grained gravel. The dominant component is slightly carved, usually discoidal sandstone pebbles with a diameter of 5–10 cm, accompanied by less numerous limestone fragments. The gravel is characterized by a compact grain framework and a poor, sandy matrix. Imbrication of pebbles is locally noted. Sometimes lenses of coarse sand are also visible. The sediments in question represent the channel facies. They do not contain identifiable molluscs remains, nor fragments of plants (Text-figs 3 and 4). Another type of sediment consist of calcareous gray and dark gray mud containing inserts or lenses of fine-grained, yellowish sands and single sandstone pebbles. Plant remains are often found, usually appearing as fragmented detritus, sometimes forming larger accumulations. Fragments of branches also appear. In these mud, a rich and abundant malacofauna has been found (Text-figs 3 and 4). The roof part of the terrace is made of yellowish, sandy mud with numerous plant remains and fragments of charcoal. Lenses of sand and even fine-grained gravel are locally observed. In these sediments numerous molluscs shells are found (Text-figs 3 and 4). The top of the terrace is made of a thin layer of recent soil.

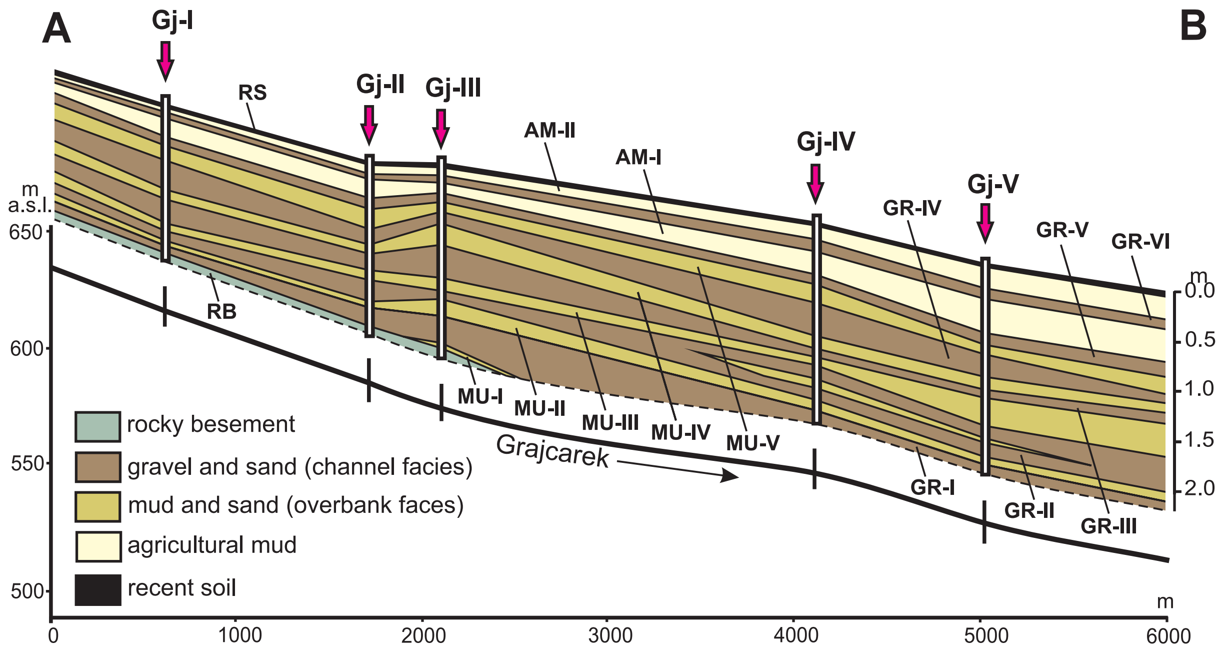
Malacofauna

In 62 samples taken from five profiles (Gj-I – Gj-V) (Text-fig. 2), the presence of 55 species of molluscs was identified (53 species of land snails, 1 species of water snail and 1 species of bivalves). The number of taxa in individual samples ranged from 5 to 44, and the number of specimens from 104 to 930. In total, the shell material included over 15,500 specimens, slug plates and numerous unidentifiable shell fragments. The taxonomic composition of the analyzed fauna within the separated lithological levels (see section Discussion) is presented in Table 1. The taxonomic composition of malacofauna in all analyzed samples is presented in Appendix 1 (available only in on-line version).

The most numerous group of molluscs are shade-loving species (34 taxa) (ecological groups F_F, F_B and F_H). They are the dominant component in the bottom and middle sections of the profiles, even up to 75% of all fauna (Text-figs 3 and 4, Table 1, Appendix 1). Taxa that prefer relatively moist habitats, often found on forested banks of streams (*Vitrea diaphana*, *Vitrea transsylvanica*, *Vitrea crystallina*, *Monachoides vicinus*) are especially common. Noteworthy is the large share of mountain species (Alpine-Carpathian or Carpathian), including Carpathian endemics (*Balea stabilis*, *Vestia gulo*, *Vestia turgida*) (Wiktor 2004; Welter-Schultes 2012). *Helix pomatia* shells, are present in the roof sections of the profiles. Snails typical of open habitats (ecological groups O_X and O_O) appear mainly in the roof intervals of profiles, reaching large numbers here and constituting up to 85% of all fauna (Text-figs 3 and 4, Table 1, Appendix 1). Typical representatives of this group are *Vallonia pulchella* and *Vallonia costata* – taxa living in grassy biotopes of varying humidity. *Cecilioides acicula* should also be mentioned here – a form that leads an underground lifestyle, especially willingly inhabiting arable areas (Wiktor 2004; Welter-Schultes 2012). This taxon can be treated as an index of human agricultural activity (e.g. Alexandrowicz *et al.* 1997, 2019; Alexandrowicz 2004; Čiliak *et al.* 2015). Mesophilous snails (ecological groups M_I and M_H) complement the fauna in question (Text-figs. 3 and 4, Table 1, Appendix 1). Among them, the most important are *Arianta arbustorum* and *Perforetella bidentata*. Both of these species inhabit shaded biotopes of high humidity and are a common component of malacocoenoses living at the bottoms of river and stream valleys. Hygrophilous species and aquatic molluscs (ecological groups H and W) are sparse and are only an accessory component of fauna (Text-figs 3 and 4, Table 1, Appendix 1).

E	Taxon	MU-I	MU-II	MU-III	MU-IV	MU-V	AM-I	AM-II
FF	*Acicula parcelineata* (Cless.)	8	5	15	12	14		
	Platyla polita (Hartm.)	12	34	33	59	70		
	Argna bielzi (Rossm.)	1	4	10	5	16		
	Acanthinula aculeata (Müll.)	12	12	10	30	27		
	Vertigo pusilla Müll.	5	14	6	26	2		
	Ena montana (Drap.)	1	12	4	42	37		
	Cochlodina orthostoma (Menke)		4	5	5	37		
	Ruthenica filograna (Rossm.)	16	41	30	81	45		
	Macrogastra plicatula (Drap.)	6	10	3	40	33		
	Balea stabilis (L.Pfe)	4	8	10	43	24		
	Discus ruderatus (Hartm.)		4		6			
	Discus perspectivus (Mühlf.)	2	6	6	23	29		
	Vitrea diaphana (Stud.)	33	200	185	323	365		
	Vitrea transsylvanica (Cless.)	15	96	91	189	186		
	Vitrea subrimata (Reinh.)	8	59	59	137	134		
	Mediterranea depressa (Sterki)	14	10	22	47	23		
	Aegopinella pura (Ald.)	29	139	89	192	169		
	Semilimax semilimax (Fér.)		12	5	12	12		
	Eucobresia nivalis (Dum et Mort)		8	8	44	45		
	Petasina unidentata (Drap.)	2	86	69	108	152		
	Faustina faustina (Rossm.)	10	70	52	137	92		
	Isognomostoma isognomostomos (Schröt.)	19	180	150	255	252		
FB	*Vertigo alpestris* Ald.		4	2	2	1		
	Alinda biplicata (Mont.)	1	1	2	4	3		
	Aegopinella minor (Stab.)	5	13	22	51	44		
	Frutiticola fruticum (Müll.)	8	64	63	161	103	6	
	Monachoides incarnatus (Müll.)	14	129	98	148	149	4	
	Cepaea hortensis (Stud.)				39	73	3	
	Helix pomatia (L.)						140	43
FH	*Macrogastra tumida* (Rossm.)	2	3	2	16	33		
	Vestia turgida (Rossm.)	6	13	7	9	18		
	Vestia gulo (Bielz)	5	1	7	9	5	2	
	Vitrea crystallina (Müll.)	15	147	160	301	323	12	2
	Monachoides vicinus (Rossm.)	22	150	138	277	233	22	8
OX	*Cecilioides acicula* (Müll.)						120	232
OO	*Vallonia costata* (Müll.)	3		8	22	9	487	320
	Vallonia pulchella (Müll.)	2	3	9	35	23	623	419
	Pupilla muscorum (L.)			1	7	8	106	67
	Vertigo pygmaea (Drap.)	2	2		8	1	88	62
MI	*Cochlicopa lubrica* (Müll.)	8	44	24	88	43	71	26
	Clausilia dubia Drap.		1	2	35	16		
	Punctum pygmaeum (Drap.)	3	20	20	52	29	22	6
	Vitrea contracta (West.)	1	2	3	5	1		
	Euconulus fulvus (Müll.)	8	29	214	34	8	9	
	Perpolita hammonis (Ström)	11	17	24	69	33	17	2
	Vitrina pellucida (Müll.)	1	12	4	10	38	5	1
MH	*Carychium tridentatum* (Risso)	2	41	33	134	111	1	
	Succinella oblonga (Drap.)	5	20	13	60	88	24	2
	Vertigo substriata (Jeffr.)	3			5	1		
	Trochulus villosulus (Rossm.)			16	72	86		
	Perforatella bidentata (Gmel.)	14	126	122	199	151	12	
	Arianta arbustorum (L.)	12	184	169	253	221	12	
H	*Carychium minimum* Müll.	22	80	83	170	149	3	
W	*Galba truncatula* (Müll.)	3	50	28	41	69		
	Pisidium personatum Malm.	8	17	19	3	11		
Plates of slugs			3	5	5	9	24	1
Total species		**44**	**49**	**50**	**55**	**54**	**23**	**14**
Total specimens		**386**	**2192**	**1967**	**4163**	**3889**	**1813**	**1191**
Indeterminate shell fragments		**149**	**787**	**597**	**917**	**759**	**424**	**311**

Table 1. List of species recognized in profiles of fluvial deposits in the Grajcarek stream valley. For explanations see Text-figs 3 and 5.



Text-fig. 5. Longitudinal section of the Grajcarek stream valley (see also Text-fig. 2). MU-I–MU-V – mud horizons (described in text), GR-I–GR-VI – gravel horizons (described in text), AM-I, AM-II – agricultural mud (described in text), RS – rocky basement, RS – recent soil.

DISCUSSION

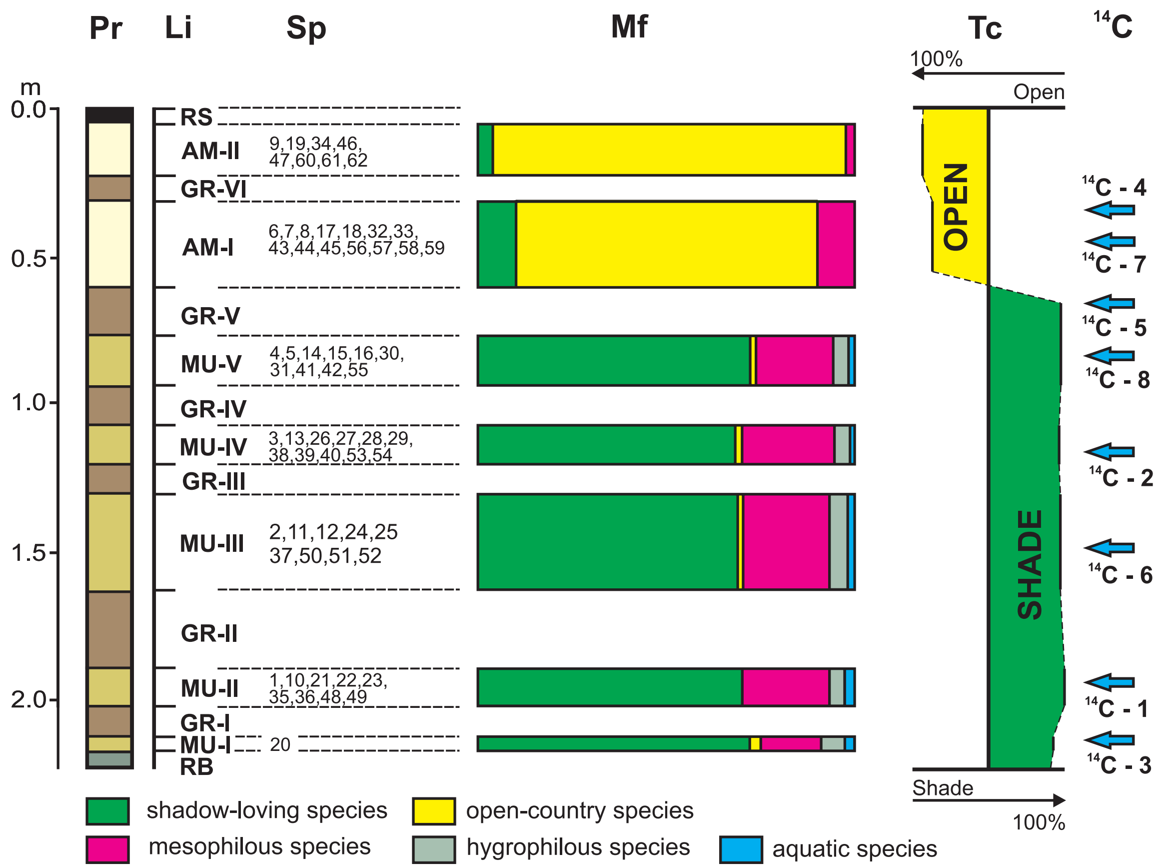
Chronology of fluvial sediments

The low terrace of the Grajcarek stream is well exposed and allows tracking of the course and determination of the mutual relations of the distinguished layers over a considerable distance. It is possible to isolate five gravel horizons separated by four fine-grained sediments containing plant debris and malacofauna (Text-fig. 5). The roof part of the terrace is made up of two levels of yellowish mud separated by a single gravel insert (Text-fig. 5). The presence of molluscs made it possible to characterize the environmental features, while the plant material allowed for radiocarbon datings enabling the determination the age of the sediments.

The oldest, thin mud level (MU-I) is only revealed at the bottom of profile Gj-III (Text-figs 3, 5 and 6). It contains a poor malacofauna with a predominance of forest species, accompanied by mesophilous snails. The share of open-country molluscs does not exceed a few percent (Text-figs 3 and 6, Table 1). Dating performed within the discussed layer determined its age at 6100±90 y BP (7242–7 213 and 7168–6 745 y cal BP; C-3; Text-figs 3 and 6, Table 2) indicating the younger part of the Middle Holocene. The oldest gravel layer (GR-I) is visible in all profiles and, apart from the Gj-III profile, it rests directly on the rock socle. It marks the first episode of fluvial intensification recorded in the low terrace of the Grajcarek stream (Text-figs 5 and 6). Above, there are dark mud (MU-II) with abundant malacofauna with a large share of shade-loving and mesophilous taxa, jointly reaching 85% (Text-figs 3–6, Table 1, Appendix 1). Plant fragments appear in these mud, both highly fragmented detritus and fragments of branches. The age determined by the radiocarbon method at

Date	Age (BP)	Lab code	Age (cal BP)	Material
C-1	5350±80	Ki-10071	6291-5988 (91.4%) 5970-5940 (4.1%)	wood (branch)
C-2	3500±80	Gd-12176	3979-3577 (95.4%)	wood (branch)
C-3	6100±90	Gd-11314	7242-7213 (2.1%) 7168-6745 (93.4%)	plant detritus
C-4	370±30	Ki-10026	504-423 (55.0%) 397-317 (40.4%)	charcoal
C-5	940±30	Ki-9106	925-791 (95.4%)	wood (branch)
C-6	4150±70	Ki-9178	4845-4518 (93.4%) 4469-4448 (2.1%)	plant detritus
C-7	450±40	Ki-10053	545-436 (91.7%) 350-333 (3.7%)	charcoal
C-8	2300±50	Ki-10062	2437-2288 (56.4%) 2277-2153 (39.0%)	wood (branch)

Table 2. Results of radiocarbon datings.

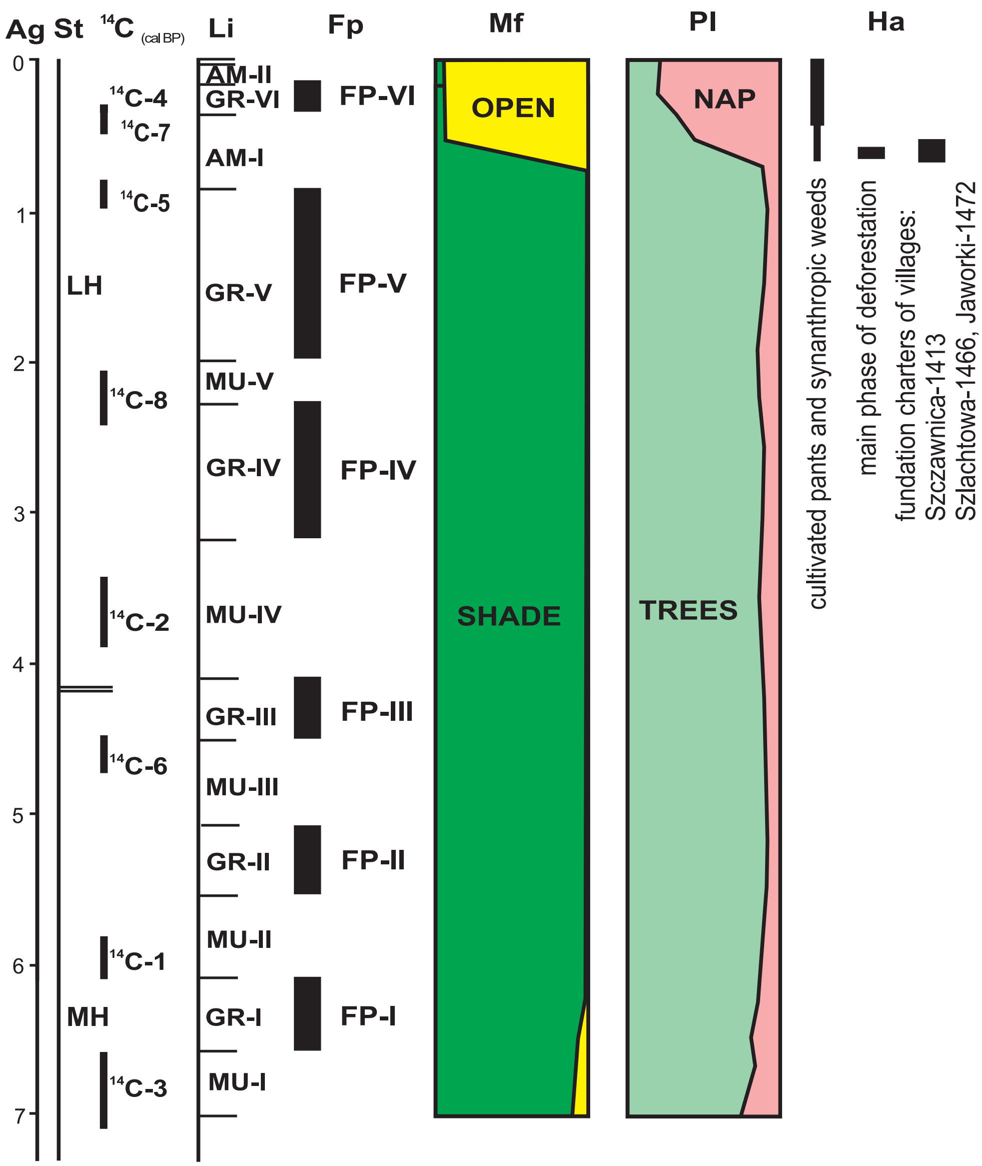


Text-fig. 6. Synthetic lithological and malacological profile of fluvial deposits in the Grajcarek stream valley. Pr – lithological profile, Li – lithology (for explanations see Text-fig. 5), Sp – samples, Mf – malacofauna, Tc – two-component malacological diagram, ^{14}C – radiocarbon datings.

5350±80 y BP (6291–5988 and 5970–5940 y cal BP; C-1) points to the end of the Middle Holocene (Text-figs 3 and 6, Table 2). Above there is another gravel horizon (GR-II). In the lower part of the valley it is separated by a thin insert of dark mud visible in the Gj-IV and Gj-V profiles (Text-figs 5 and 6). The next level of mud (MU-III) contains a numerous malacofauna, reaching as much as 70% share of shade-loving taxa. They are accompanied by mesophilous snails, and the share of other ecological groups does not exceed 10% (Text-figs 5 and 6, Table 1, Appendix 1). The result of the dating done here: 4150±70 y BP (4845–4518 and 4469–4448 y cal BP; C-6) indicates that the layer in question was deposited at the turn of the Middle and Late Holocene (Text-figs 4 and 6, Table 2). The gravel that makes up the GR-III layer is characterized by a higher proportion of sand and finer grained pebbles. The thickness of the discussed level rises down the valley (Text-figs 5 and 6). Mud lying above (MU-IV) contain a rich malacofauna, in which the share of shade-loving species exceeds 75% (Text-figs 3–6, Table 1, Appendix 1). The discussed layer contains accumulations of plant detritus, both fine detritus and twigs. Dating made on the basis of this material: 3500±80 y BP (3979–3577 y cal BP; C-2; Text-figs 3 and 6, Table 2) points to the Late Holocene. The GR-IV layer consists of fine-grained gravel with single larger pebbles and coarse-grained sand lenses. The thickness of this horizon usually does not exceed a dozen or so centimeters (Text-figs 5 and 6). Mud that make up the MU-V level are characterized by a relatively high proportion of fine- and medium-grained sand appearing as discontinuous, lenticular interlayers. The malacofauna is abundant and varied, with shade-loving taxa being the dominant component. The roof of the discussed layer shows clear signs of erosion. On this surface, there is a GR-V layer made of fine-grained gravel and coarse-grained sand (Text-figs 5 and 6). Accumulation of plant debris, mainly fragments of branches, is visible in the roof part. Their age was determined to be 940±30 y BP (925–791 y cal BP; C-5; Text-figs 4 and 6, Table 2). Above this layer, the nature of the sediments clearly changes. Yellowish, sandy mud with single sandstone pebbles appear (AM-I) (Text-figs 3–6). Within this horizon, there are numerous pieces of charcoal, locally forming larger accumulations. Their age was determined as: 450±40 y BP (545–436 and 350–333 y cal BP) – middle part of the layer (C-7) and 370±30 y BP (504–423 and 397–317 y cal BP) – roof part of the layer (C-4) (Text-figs 4 and 6, Table 2). Both dates indicate a relationship between the sediments in question and the Middle Ages. The malacofauna occurring within the AM-I level is significantly different from the fauna recognized in the lower intervals of the analyzed profiles. There is a clear reduction in species diversity and a clear change in taxonomic composition. Shade-loving species are disappearing and are being replaced by open-country taxa, mainly forms typical of grassland habitats. It is also worth emphasizing the presence of *Cecilioides acicula*. The share of open-country snails reaches 85% (Text-figs 3–6, Table 1, Appendix 1). The youngest gravel level (GR-VI) is made of fine-grained gravel with an admixture of sand (Text-figs 5 and 6). The roof of the Grajcarek low terrace is made of yellow, sandy mud with a quite numerous malacofauna with a predominance of open-country taxa (AM-II), covered with a thin layer of recent soil (Text-figs 3–6, Table 1, Appendix 1).

Phases of fluvial activity and environmental changes

Mud-gravel sequences commonly observed in river sediments record changes in fluvial activity. These changes are usually climatically generated and are most often associated with moist and cool periods. This relationship has been confirmed by numerous observations carried out at many sites of river sediments. Another important element leading to the intensification of the fluvial activity is human activity, especially deforestation processes leading to the reduction of natural retention and, as a result, to an increase in the frequency of floods (e.g. Starkel *et al.* 2006, 2013; Hoffmann *et al.* 2008; Gębica, 2011, 2013a, b; Wirth *et al.* 2013; Łajczak *et al.* 2014; Benito *et al.* 2015; Gębica *et al.* 2016; Perşoiu and Perşoiu 2018; Szwagrzyk 2018; Rădoane *et al.* 2019, Alexandrowicz 2019a, b). The Grajcarek Valley is a good example of these phenomena. Based on the conducted analysis, it is possible to distinguish six phases of intensification of the fluvial activity. The two oldest ones, corresponding to gravel horizons GR-I and GR-II, are related to the younger part of the Middle Holocene (FP-I and FP-II phases) (Text-fig. 7). The next phase (FP-III) and the GR-III gravel level representing it falls on the border of the Middle and Late Holocene. All these phases covered periods of several hundred years. The mollusc communities identified in the silt separating the gravel levels representing the period in question are characterized by a large species diversity. The dominant role is played by shade-loving taxa, while forms typical for open habitats either do not occur at all or constitute a small percentage of the community (Text-fig. 7). Such a composition of malacofauna proves that during the Middle Holocene the Grajcarek stream valley (both its bottom and slopes) was covered with forests. The presence of dense forest complexes during this period has been documented in many malacological profiles within the Pieniny Mts. (Alexandrowicz 2004, 2017; Alexandrowicz *et al.* 2016, Alexandrowicz and Soczylas 2017), Podhale Basin (Alexandrowicz 1997b, 2019b, Alexandrowicz *et al.* 2014) as well as in the entire northern Carpathians (Alexandrowicz 2004, 2019a). The results of palynological analyzes carried out on peat bogs in eastern Podhale also indicate the dominance of forest communities, mainly mixed forests (pollen phases: *Ulmus–Tilia–Quercus–Fraxinus* and *Corylus*; Obidowicz 1990; Rybniček and Rybničková 2002). At the same time, there are no traces of human activity in the pollen and malacological profiles. The two younger fluvial phases (FP-IV and FP-V) are related to the Late Holocene and cover periods of several hundred to a thousand years (Text-fig. 7). Gravel horizons GR-IV and GR-V correspond to them. The mollusc communities identified in the mud accompanying the above-mentioned gravel horizons are characterized by high taxonomic diversity, with the dominant component being shade-loving and mesophilous species. The ecological composition of the malacofauna shows the domination of forests throughout the valley (Text-fig. 7). Malacological data from many profiles representing the period in question also record a significant degree of afforestation in this part of the Carpathians (Alexandrowicz 1997b, 2004, 2017, 2019a, b; Alexandrowicz *et al.* 2014, 2016; Juřičková *et al.* 2014a, 2020; Horáčková *et al.* 2015; Frodlová and Horsák 2021). This is also confirmed by the results of palynological analyzes indicating at the same time the deterioration of climatic conditions and an increase in the share of species with lower ecological requirements with a simultaneous decrease in the importance of thermophilous taxa (pollen phases: *Picea–Carpinus–Abies* and *Fagus–Abies*;



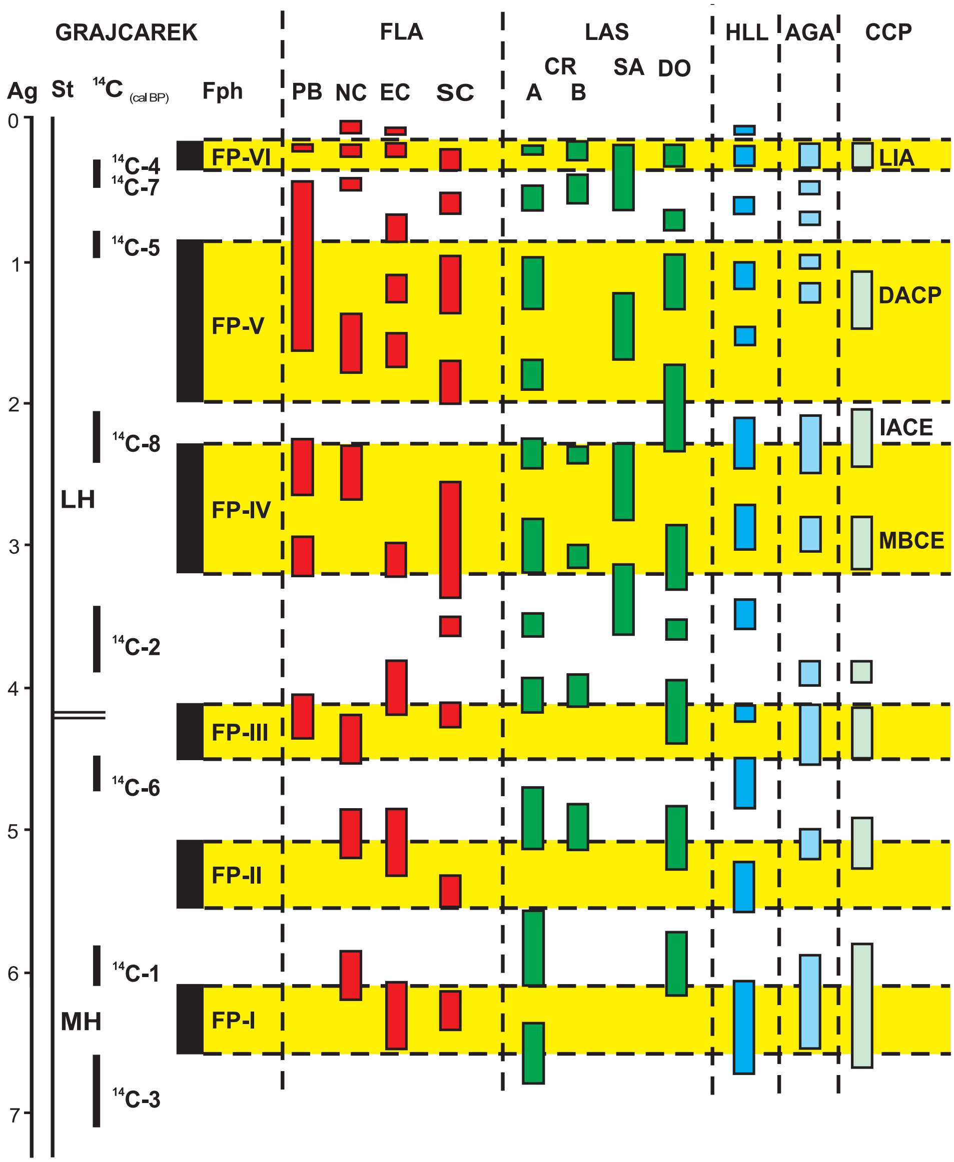
Text-fig. 7. Chronology of periods of increased fluvial activity against the background of malacological, palynological data and the development of settlement in the Grajcarek stream valley. Ag – time scale, St – stratigraphy (after: Walker *et al.* 2019): MH – Middle Holocene, LH – Late Holocene, ^{14}C – radiocarbon datings, Li – lithology (for explanations see Text-fig. 5), Fp – periods of increased fluvial activity (described in text), Mf – malacofauna, Pl – palynological data (after: Obidowicz 1990; Rybniček and Rybničková 2002), Ha – human activity.

Obidowicz 1990; Rybniček and Rybničková 2002). There are no signs of anthropogenic transformation of habitats in the discussed interval. The youngest fluvial phase (FP-VI) and the corresponding gravel level (GR-VI) represent the historical period (Text-fig. 7). The accompanying yellowish mud contain malacofauna of small taxonomic diversity. Its most important feature is the dominance of open-country species, mainly meadow taxa. The presence of *Cecilioides acicula* is also important. The second characteristic feature of the fauna in question is a very small share of shade-loving taxa. An interesting fact is the presence of *Helix pomatia* – a snail that only appeared in the Polish part of the Carpathians in the Middle Ages (Alexandrowicz and Alexandrowicz 2010). The composition and ecological structure of the malacofauna occurring in the upper part of the low Grajcarek terrace indicates a rapid deforestation of the entire stream catchment area. This process was most likely related to the settler development, the formation of human settlements (locations of towns in the valley: Szczawnica 1413 AD, Jaworki 1472 AD, Szlachtowa 1466 AD and agricultural activity (Text-fig. 7)). The development of settlement and related anthropopressure in the Podhale Basin and Pieniny Mts during the Middle Ages is well documented in many malacological profiles described in this area (Alexandrowicz 2013b, 2020). Clear traces of these processes are also visible in the palynological profiles. On the one hand, they are highlighted by the sudden disappearance of tree pollen, indicating rapid deforestation of the area, and on the other hand by the appearance of pollen from cultivated and synanthropic plants (NAP phase; Obidowicz 1990; Rybniček and Rybničková 2002) (Text-fig. 7). Similar rapid changes in the environment under the influence of human activity in the Middle Ages are observed almost in the entire northern part of the Carpathians (e.g. Gębica 2013a, b; Gębica *et al.* 2016; Alexandrowicz *et al.* 2019, Alexandrowicz 2019a, b, 2020; Kołaczek *et al.* 2020; Sobala and Rahmonov 2020).

Local and regional correlation of flood phases

Periods of increased fluvial activity in rivers and streams recorded as gravel horizons appearing within alluvial sediments are usually associated with climatic fluctuations. Periods of increased humidity, usually combined with cooling, leading to intensification of floods, play a special role here. This dependence has been confirmed in numerous studies (e.g. Starkel *et al.* 2006, 2013; Hoffmann *et al.* 2008; Gębica, 2011, 2013a, b; Wirth *et al.* 2013; Benito *et al.* 2015; Gębica *et al.* 2016; Perşoiu and Perşoiu 2018; Rădoane *et al.* 2019). The influence of the periods of dampness and cooling of the climate is not limited to fluvial processes. This is also manifested in fluctuations in the water level in lakes, stages of intensified mass movements and periods of advances of mountain glaciers (e.g. in the Alps) (e.g. Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Starkel 1997; Alexandrowicz 1997a, 2013a; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002, Soldati *et al.* 2004; Joerin *et al.* 2006; Prager *et al.* 2008; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011; Magny *et al.* 2012; Pánek *et al.* 2013). The impact of the climatic factor is therefore at least regional. Another important factor is human activity. The impact of this element is more local. In addition to the undoubted relevance of climatic conditions, inter alia, terrain should be considered important. In general, mountainous areas create less favorable conditions for the development of settlements and, as a consequence, they are settled later. On the other hand, colonization in these areas is usually concentrated in the valleys leading to their rapid transformation, which in turn is well documented by the sequences of river sediments (e.g. Gębica 2013a, b; Gębica *et al.* 2016; Alexandrowicz *et al.* 2019, Alexandrowicz 2019a, b, 2020; Kołaczek *et al.* 2020; Sobala and Rahmonov 2020).

Six phases of intensification of fluvial processes (FP-I – FP-VI) were distinguished in the sequence of sediments making up the low terraces of the Grajcarek stream. The oldest of these (phase FP-I) falls on the period of about 6600–6100 y cal BP. This phase has not yet been identified in Podhale, but it is clearly visible in the fluvial sediments of large rivers in the Western (Starkel *et al.* 2006, 2013) Eastern (Gębica and Krąpiec 2009; Gębica, 2011, 2013a, b; Gębica *et al.* 2016) and Southern Carpathians (Rădoane *et al.* 2019). It also corresponds to the period of intensified mass movements in the Carpathians and Alps (e.g. Starkel 1997; Alexandrowicz 1997a, 2013a; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002; Soldati *et al.* 2004; Prager *et al.* 2008; Pánek *et al.* 2013). The discussed period is also associated with the rise of the water level in lakes (both alpine and lowlands) (e.g. Ralska-Jasiewiczowa and Starkel 1988; Magny, 1993, 2004; Magny *et al.* 2012; Alexandrowicz 2013c) and the slightly marked phase of glacier advancement in the Alps (Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011) (Text-fig. 8). The next phase of greater intensity of fluvial processes is marked in the younger part of the Middle Holocene, covering the period of about 5500–5100 y cal BP (phase FP-II). However, its correlation with regional climate change is relatively weak. Although in some river valleys in the Carpathians there are signs of increased activity (Starkel *et al.* 2006, 2013), it is not a common phenomenon. Similarly, during this period there was no increase in the activity of landslides (Margielewski, 1998, 2006, 2018) and no significant glacier thrusts in the Alps (Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011). On the other hand, an increase in the water level in the lakes is observed, both in the Alpine zone and in the European lowlands (e.g. Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Magny *et al.* 2012; Alexandrowicz 2013c) (Text-fig. 8). The third of the distinguished phases (phase FP-III) falls on the turn of the Middle and Late Holocene (4500–4100 y cal BP). This phase clearly correlates with the period of significant changes manifested in the cooling and moistening of the global climate (4.2 ka event, Bond event 3) (Bond *et al.* 2001). The appearance of gravel horizons is observed in several stream valleys in Podhale (Alexandrowicz 2019b). A significant increase in the intensity of river activity is also common throughout



Text-fig. 8. Local and regional correlation of periods of increased fluvial activity in the Grajcarek stream valley. Ag – time scale, St – stratigraphy (after: Walker *et al.* 2019): MH – Middle Holocene, LH – Late Holocene, ^{14}C – radiocarbon datings, Fph – phases of increased fluvial activity in the Grajcarek stream valley (described in text), FLA – fluvial activity: PB – Podhale Basin (after: Alexandrowicz 2019b), NC – northern Carpathians (after: Starkel *et al.* 2006, 2013), EC – eastern Carpathians (compilation after: Gębica 2011, 2013a, b; Gębica *et al.* 2016), SC – southern Carpathians (after: Perşoiu and Perşoiu 2018; Rădoane *et al.* 2019), LAS – landslides: CR – Carpathians (after: Margielewski 1998, 2006, 2018 (A); Alexandrowicz 1997a, 2013a (B)), SA – Swiss Alps (after: Dapples *et al.* 2002), DO – Dolomites (after: Soldati *et al.* 2004), HLL – phases of high water level in lakes (compilation after: Magny 1993, 2004; Magny *et al.* 2012), AGA – advances of Alpine glaciers (compilation after: Holzhauser *et al.* 2005; Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011), CCP – cold climatic phases (after: Mayewski *et al.* 2004; Mauri *et al.* 2015), MBCE – Middle Bronze Cold Epoch, IACE – Iron Age Cold Epoch, DACP – Dark Ages Cold Period, LIA – Little Ice Age.

the Carpathians and documented at numerous sites (e.g. Starkel *et al.* 2006, 2013; Gębica and Krąpiec 2009; Gębica, 2011, 2013a, b; Gębica *et al.* 2016; Rădoane *et al.* 2019). The discussed period is also associated with the appearance of numerous new landslides and the activation of many older forms both in the Carpathians (Starkel 1997; Alexandrowicz 1997a; Margielewski 1998, 2006, 2018; Pánek *et al.* 2013) and the Alps (Dapples et al. 2002, Soldati et al. 2004, Prager et al. 2008). There is a period of glacier expansion in the Alps (Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011) and the rising of water level in lake reservoirs (e.g. Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Magny *et al.* 2012; Alexandrowicz 2013c) (Text-fig. 8). The FP-IV phase covers a period of approximately 3200–2300 y cal BP. During this time, two cold climatic fluctuations are noticeable. The older ones are in the Middle Bronze Age Cold Epoch, and the younger ones are in the Iron Age Cold Epoch (Mayewski *et al.* 2004; Plunkett and Swindles 2008; Mauri *et al.* 2015). The discussed phase in the valley of the Grajcarek stream corresponds to one gravel horizon with a considerable thickness, while in other valleys it is possible to separate two levels of gravel separated by an insert of sandy mud. The intensification of fluvial processes related to these climate fluctuations, underlined by the deposition of gravel levels, has been described in numerous valleys in the Carpathians (Starkel *et al.* 2006, 2013; Gębica and Krąpiec 2009; Gębica, 2011, 2013a, b; Gębica *et al.* 2016; Rădoane *et al.* 2019). It is also a phase of intensification of mass movements and the related activation of older forms and the emergence of many new ones (e.g. Starkel 1997, Alexandrowicz 1997a, 2013b; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002, Soldati *et al.* 2004; Prager *et al.* 2008; Pánek *et al.* 2013). In this period, the development of glaciers correlated with the Löbben and Göschenen I phases (Holzhauser *et al.* 2005; Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011) is recorded in the area of the Alps. In both alpine and lowland lakes there is a clear rise in the water level (Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Holzhauser *et al.* 2005; Magny *et al.* 2012; Alexandrowicz 2013c) (Text-fig. 8). The FP-V phase covers a period of approximately 2000–900 y cal BP. In the Grajcarek valley it is represented by one gravel horizon. The period in question was characterized by a series of warmer and colder climatic fluctuations, but the traces of the former, unfortunately, have not survived. This can probably be associated with the period of high intensity of fluvial processes, which corresponds to significant climate cooling – Dark Ages Cold Period (Mayewski *et al.* 2004; Helama *et al.* 2017) falling at the end of the period in question (Bond event 1 (Bond *et al.* 2001)). It is likely that it was that the activity of fluvial phenomena significantly intensified during this period, which on the one hand made it possible to deposit a series of gravels, and on the other hand led to the destruction of previously accumulated sediments. Such an interpretation may be indicated by the presence of erosive surfaces within the gravel sequence. Gravel covers of this age are commonly recorded in the stream valleys in Podhale Basin (Alexandrowicz 2013b, 2019b, 2020). They are also described in numerous Carpathian valleys (Starkel *et al.* 2006, 2013; Gębica and Krąpiec 2009; Gębica 2011, 2013a, b; Gębica *et al.* 2016; Rădoane *et al.* 2019). This period is associated with a significant increase in the intensity of mass movements. Numerous new landslides were formed both in the Carpathians and the Alps, and some of the older forms were reactivated (e.g. Starkel 1997, Alexandrowicz 1997a, 2013a; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002, Soldati *et al.* 2004; Prager *et al.* 2008; Pánek *et al.* 2013). Numerous small landslides of that age were also described in the vicinity of the Grajcarek stream valley (Alexandrowicz 1993, 1997a, 2013a). The discussed phase is also associated with the development of Alpine glaciers (Göschenen II phase) (Holzhauser *et al.* 2005; Joerin *et al.* 2006; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011) and the period of high water level in lakes (Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Holzhauser *et al.* 2005; Magny *et al.* 2012; Alexandrowicz 2013c) (Text-fig. 8). The youngest phase FP-VI is in the period of 400–200 y cal BP and corresponds to cooling during the Little Ice Age (e.g. Grove 1988; Bradley 2000; Briffa 2000; Mayewski *et al.* 2004; Matthews and Briffa 2005) (Bond event 0 (Bond *et al.* 2001)). This last cool climate fluctuation led to the formation of the youngest gravel horizon, which is visible both in the sediments of the Grajcarek stream and in the top sections of numerous river sediment sites in Podhale (Alexandrowicz 2013b, 2019b, 2020). Human activity has overlapped with climate change. The rapid demographic growth in the warm period of the Medieval Warm Period (Grove and Swistur 1994) led to significant environmental changes in Podhale Basin and Pieniny Mts., especially extensive deforestation and the appearance of large grasslands (pastures) and arable fields (Alexandrowicz 2013b, 2019b, 2020). Analyzes of river sediments, including those forming the low terrace of the Grajcarek stream and neighboring areas, indicate that during the LIA, anthropopressure decreased, which was probably the result of deteriorating climatic conditions and progressive depopulation (Alexandrowicz 2013b, 2020). The record of high activity in rivers and streams during the LIA is common throughout the Carpathians and is highlighted by the presence of gravel horizons occurring in roof sections of terrace sequences (Starkel *et al.* 2006, 2013; Gębica and Krąpiec 2009; Gębica 2011, 2013a, b; Gębica *et al.* 2016; Perşoiu and Perşoiu 2018; Rădoane *et al.* 2019). It is also a period of intensified slope processes. Several landslides representing this period of time have been described in the Grajcarek stream catchment area (Alexandrowicz 1993, 1997a, 2013a). Numerous manifestations of mass movements (landslides, rubble runoff, etc.) have been documented in all mountain areas in Europe (e.g. Starkel 1997; Alexandrowicz 1997a; Margielewski 1998, 2006, 2018; Dapples *et al.* 2002; Soldati *et al.* 2004; Prager *et al.* 2008; Pánek *et al.* 2013). During the LIA, the expansion of Alpine glaciers is visible, manifested in several consecutive oscillations, largely correlated with periods of solar activity minimums (Holzhauser *et al.* 2005; Joerin *et al.* 2006; Plunkett and Swindles 2008; Ivy-Ochs *et al.* 2009; Nussbaumer *et al.* 2011). The period in question was also marked by an increase in the water level in lakes (Ralska-Jasiewiczowa and Starkel 1988; Magny 1993, 2004; Holzhauser *et al.* 2005; Magny *et al.* 2012; Alexandrowicz 2013c) (Text-fig. 8).

CONCLUSIONS

The sequence of river sediments that make up the low terraces of the Grajcarek stream includes alternating levels of mud and gravel. Rich mollusc communities are associated with fine-grained sediments. The gravel horizons refer to the mainly climatically generated periods of the stream's intensified fluvial activity. The results of the malacological analyzes, lithological observations and radiocarbon dating performed lead to the following conclusions:

- The sedimentary sequence in the Grajcarek stream's low terrace covers the period of the younger part of the Middle Holocene and the entire Late Holocene.
- Malacofauna communities have survived only in fine-grained sediments deposited in a relatively low-energy environment. Shells do not appear in gravel horizons. This is related to the high energy of the sedimentation environment leading to the rapid crushing and removal of the shells from the sediment.
- The mollusc communities recognized in the silt deposits allow for the reconstruction of environmental changes. The malacocoenoses occurring in the sediments of the Middle Holocene and the lower part of the Late Holocene are characterized by the dominance of shade-loving species. This fact proves the high afforestation of the Grajcarek stream catchment area in this period. These observations agree well with the results of malacological studies carried out in adjacent areas, as well as with the palynological data. A completely different malacofauna was identified in the top part of the sedimentary sequence. The most important component of mollusc communities here are open-country species, mainly in grassy biotopes. There are also forms characteristic of arable fields. Radiocarbon dating indicates that this rapid change in environmental characteristics took place in the Middle Ages (12th–14th centuries). During this period, the Grajcarek valley was settled by man. The appearance of larger groups of people forced the acquisition of areas suitable for agricultural use. As a result, there was extensive deforestation leading to a change in the characteristics of natural habitats (forests were replaced by pastures and farmland). It had a very significant impact on the fauna and flora communities living in this area. Similar rapid anthropogenic changes during the Middle Ages are documented in numerous malacological profiles in the Podhale Basin, Pieniny Mts., as well as in other areas of the northern part of the Carpathians. They are also confirmed by the results of palynological analyzes of peat bogs in the western Podhale Basin.
- Gravel horizons represent periods of increased of fluvial activity. There were 6 such phases distinguished in the analyzed sediments. Thanks to the performed age designations, it was possible to approximate their time ranges. They are as follows: 6600–6100 y cal BP (FP–I), 5500–5100 y cal BP (FP-II), 4500–4100 y cal BP (FP-III), 3200–2300 y cal BP (FP-IV), 2000–900 y cal BP (FP-V) and 400–200 y cal BP (FP-VI).
- The above-mentioned phases of intensification of fluvial activity closely relate to climate change, especially to cool and humid periods.
- On a local scale, these phases correlate well with the consequences described from the fluvial formations described in other stream valleys in the Podhale Basin and Pieniny Mts.
- Separate phases also refer to climate changes occurring on a regional (in the Carpathians) and continental scale. They correspond to the periods of intensified fluvial processes, intensified mass movements, glacier advances in the Alps and rising water levels in mountain and lowland lakes.

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