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Malacological indicators of anthropogenic and natural environmental changes of the Podhale Basin during the last 2000 years. Studies in the Rogoźnik Stream valley (the Carpathian Mountains, Southern Poland)

Witold Paweł Alexandrowicz[1], Sylwia Skoczylas-Śniaz[2], Paulina Laskowska[3]

[1] *AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Department of General Geology and Geotourism, Krakow, Poland, e-mail: wpalex@agh.edu.pl, ORCID: 0000-0002-5403-6696*

[2] *Polish Academy of Sciences, W. Szafer Institute of Botany, Krakow, Poland, e-mail: s.skoczylas@botany.pl, ORCID: 0009-0001-0437-3926*

[3] *AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, Krakow, Poland, e-mail: laskoska@student.agh.edu.pl*

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Abstract: The lithological and malacological studies covered sediments forming the low terrace of the Rogoźnik Stream in the northwest part of the Podhale Basin. This terrace is characterised by a uniform structure within a significant part of the valley. Three layers of gravel and four layers of sandy and silty muds were found there. A rich and diversified malacofauna was discovered in fine-grained sediments. Its analysis allowed us to characterise environmental conditions during sediment deposition. The age of the individual components of the sedimentary sequence was determined by radiocarbon dating. A distinct change was found in the upper intervals of the sequence, corresponding to the warm phase of the Medieval Climate Optimum. This period is associated with the robust development of agriculture, and processes related to human activities became the main factor shaping the environment, influencing the course of geological processes, and changing the taxonomical and ecological structure of the fauna and flora assemblages found in this area.

Keywords: fluvial deposits, molluscs, environmental changes, human impact, Podhale Basin, Southern Poland

INTRODUCTION

Anthropopressure is understood as all types of human activities influencing natural processes. The role of humans as an important environmental factor in Central Europe has been marked since the origins of agricultural societies and covers the last several thousand years. Previously, mainly hunter-gatherer groups arrived here, and their influence on the course of natural processes was very limited. The introduction of agriculture resulted in significant changes, manifested in particular as a reduction of forest areas and changes in hydrological conditions. Settlement in southern Poland underwent various levels of intensity. First, the upland areas were taken, distinguished by the favourable shape of the terrain and the presence of fertile soils. Settlement in the mountain areas occurred much later as a result of the more difficult terrain conditions, less favourable climate, and low-quality of soils. Demographics are another very important factor decisive for the anthropopressure intensity. The more numerous the human population settles in a given area, the stronger its environmental impact is.

The Podhale Basin is a depression, the bottom of which lies several hundred meters lower than the surrounding mountain ranges (the Tatra Mts. in the south and the Beskidy Mts. in the north) surrounding it. This area is characterised by a diverse morphology. The southern part is characterised by more variable relief. Hills of a height of up to 1000 m a.s.l., with steep slopes (the Gubałówka Highlands), are found here. This range is cut by numerous streams flowing in narrow, steep valleys. The northern part (the Orawa-Nowy Targ Basin) is a flat plain divided by flat-bottomed, wide valleys of a small slope.

The history of environmental changes in the Podhale area during the Holocene is well known, especially due to numerous palynological (Obidowicz 1990, Rybníček & Rybníčková 2002, Krąpiec et al. 2016) and malacological (e.g. Alexandrowicz 1997, 2019a, 2022, 2023, Alexandrowicz et al. 2014) analyses. Following this data, the discussed area was covered by dense forest for nearly all that time. The settlements started to develop only in the Middle Ages (since the 12th century) (Czepiel 1999, Alexandrowicz 2013, 2020, Kłapyta 2021). At that time, human activities became an important factor impacting the environment. The most visible manifestation of human activities was the rapid progress of deforestation, leading to the replacement of forests with arable fields and pastures, changes in the intensity of geological processes and redevelopment of taxonomical composition and the structure of fauna and flora assemblages (Rączkowska et al. 2012, Alexandrowicz 2019a, 2023, Święchowicz et al. 2022).

Molluscs are a group of organisms sensitive to fast and rapid changes in the environment. Anthropopressure, and deforestation in particular, result in the replacement of the taxonomically diverse forest malacocenoses by assemblages poor in species with a predominating share of taxa characteristic for open areas. The disappearance of forests and the appearance of open habitats (arable fields and pastures) significantly influence erosion and sediment deposition processes, especially those accumulated in river valleys (e.g. Starkel 1987, 2005, Kukulak 2003, Gębica 2013, Kijowska-Strugała et al. 2018, Łajczak 2021). A decrease in retention on valley slopes and runoff processes leads to the deposition of sediments of significant thickness, at the same time representing short periods of time (e.g. Gębica 2013a, 2013b, Łajczak et al. 2014, Alexandrowicz 2019b, Łajczak 2021). These formations, sometimes called agricultural alluvial soils, are frequently found in river and stream valleys in Polish Carpathians (e.g. Starkel 2005, Święchowicz 2010, Alexandrowicz 2013a, Łajczak et al. 2014).

This article presents the possibilities of the application of malacological analyses to reconstruct phases of anthropopressure and changes in the intensity of fluvial processes generated, on the one hand, by human activities, and on the other, by short-term climate fluctuations over the last 2000 years.

SITE DESCRIPTION

The area covered by the studies is located in the northwest part of the Podhale Basin (Fig. 1). The geological substrate is formed by Paleogene flysch sediments (so-called Podhale flysch) and Mesozoic limestones forming a narrow, strongly tectonically distorted zone included in the Pieniny Klippen Belt. The sediments mentioned above are covered by sandy formations of the Neogene and the Quaternary sediments. In terms of morphology, it is a flat area of a poorly diversified relief. The Rogoźnik Stream is the largest water course. It is about 20 km long and has a slight drop (about 50 m along its entire length). Its valley is wide and flat-bottomed. Currently, nearly the entire basin of that stream is completely deforested and covered by arable fields and pastures. A distinct terrace slope stretches along the stream channel, showing a profile of fluvial sediments represented by gravels and silts forming continuous and well-distinguished layers. The malacological studies were conducted in the lower part of the Rogoźnik Stream valley, at a ca. 7 km section (Fig. 2).

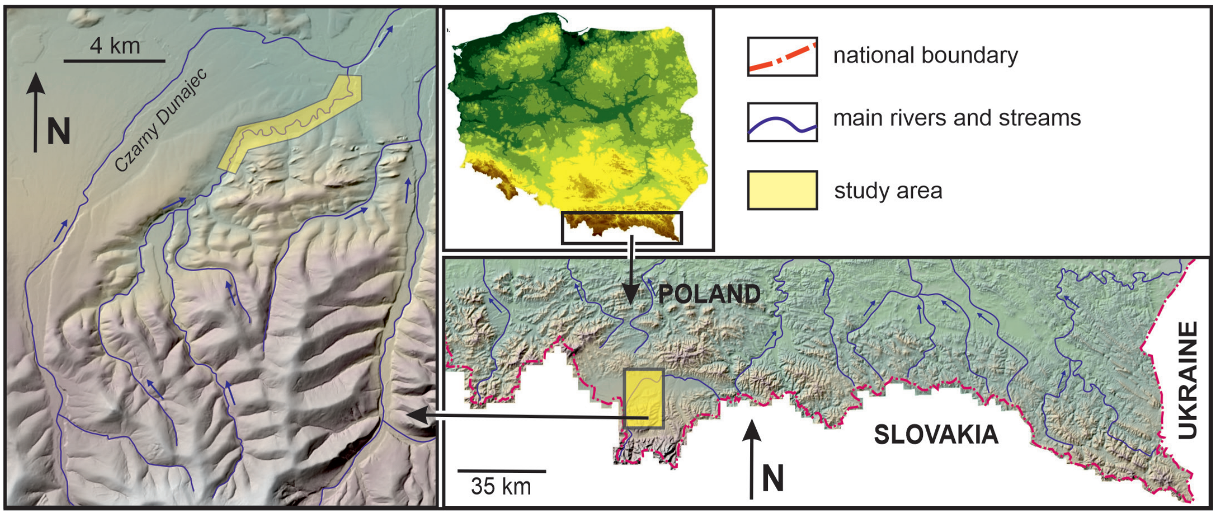

Fig. 1. *General location of the Rogoźnik Stream valley (map base: www. polska.e-mapa.net)*

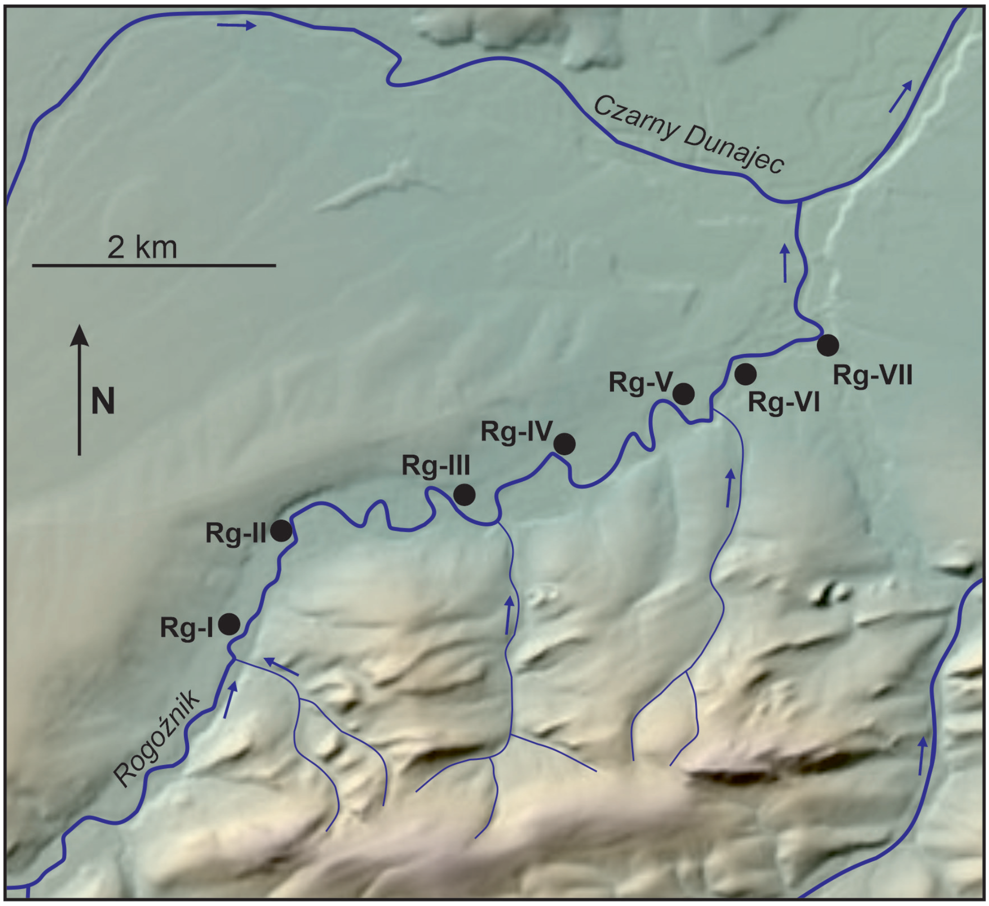

Fig. 2. *Location of profiles of fluvial deposits in the Rogoźnik Stream valley (map base: www. polska.e-mapa.net)*

MATERIALS AND METHOD

The malacological analyses covered the material obtained from sediments forming a low terrace of the Rogoźnik Stream. Seven profiles were analysed in total (Rg-I – Rg-VII; Fig. 2). All samples were collected directly from natural exposures. They were sectional and covered intervals 10–15 cm thick, associated with the lithology of the sediments and their mass was approx. 2–3 kg. The well-preserved shell material was found in samples collected only from fine-grained sediments. Samples representing gravels did not contain shells or only included their scarce and poorly preserved fragments, making their identification impossible. For this reason, they were not used in the presented analyses. A total of 86 samples were taken (55 of which had shell material present). The laboratory processes included slurrying on a 0.5 mm sieve and selecting the shells (whole specimens, juvenile forms, and shell fragments possible to identify). Then, the taxa were identified using the keys (Wiktor 2004, Welter-Schultes 2012, Horsák et al. 2013) and the comparative collection. Individual species were classified into ecological groups (according to the scheme developed by Ložek (1964) with subsequent modifications by Alexandrowicz & Alexandrowicz (2011) and Juřičková et al. (2014a)). The analysed fauna included taxa belonging to the following ecological groups: forest species (F_F), shadow-loving species of rare forests and shrub zones (F_B), shadow-loving moist forest species (F_H), xerophilous and underground species (O_X), open-country species (O_O), mesophilous species of dry environments (M_D), mesophilous species of medium humid environments (M_I), mesophilous species of humid environments (M_H), hygrophilous taxa (H) and aquatic species (W). Using calculations of percentage shares of particular ecological groups and individual taxa in each sample, malacological diagrams were developed, forming a basis for paleoenvironmental analyses. The conducted statistical analyses – an analysis of a dendrogram of similarities (the unweighted pair group method with arithmetic mean (UPGMA) and the Morisita index (Morisita 1959) were used) and the principal component analysis (PCA), enabled the determination of fauna assemblages and the specification of their most important components. Statistical analysis was carried out using the statistical program PAST (Hammer at al. 2001). The stratigraphic position of the sediments was determined by five radiocarbon dating. The isotope analyses were based on organic remains (plant detritus and charcoal) found in the sediments. The results of age determination were calibrated using the OxCal software (Bronk Ramsey 2017) and an IntCal20 calibration data (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).

RESULTS

Low terrace of the Rogoźnik Stream – lithology of sediments

The analysed terrace stretches along the entire stream valley, and its height above the level of the contemporary bed rises from ca. 0.5 m in its upper course to 2.5 m at its ostium. Its structure is uniform nearly this entire stretch. Three layers of gravel can be distinguished here, of thickness varying from several to 30 cm. All mentioned layers contain fine or/and medium grained gravels, formed mainly of well-rounded, discoidal sandstone pebbles. No sedimentary structures were noted in the gravel series, apart from locally visible, poorly marked imbrication. The matrix is formed by sands and silts and is relatively abundant. Finely broken mollusc shells are rarely found in the discussed gravels. The second type of sediments consists of dark grey lime muds with a significant admixture of fine and medium grained sands and single small sandstone pebbles. Locally, accumulations of small plant detritus and sometimes larger pieces of plants (twigs) can be found. The discussed sediments contain numerous and well-preserved mollusc shells. In the described terrace, these muds form two layers of a varying thickness, from several to several dozen centimetres. In all analysed profiles, a characteristic insert off dark grey muds, several centimetres thick and containing quite numerous fragments of charcoal, is found above the sandy muds discussed above. No mollusc shells were found in it. Yellow and light brown silty muds form the roof of the discussed terrace and are arranged in two layers separated by a layer of gravel several cm thick. These sediments contain mollusc shells and local accumulation of plant detritus. In the upper part, one (in the upstream part of the valley) or two (in the downstream part) layers clearly enriched with small sandstone pebbles appear. The thickness of the discussed mud layers ranges from about a dozen to a maximum of 75 cm, while the top of the terrace is made of a thin layer of recent soil. The lithology of the individual analysed profiles is shown in Figures 3 and 4.

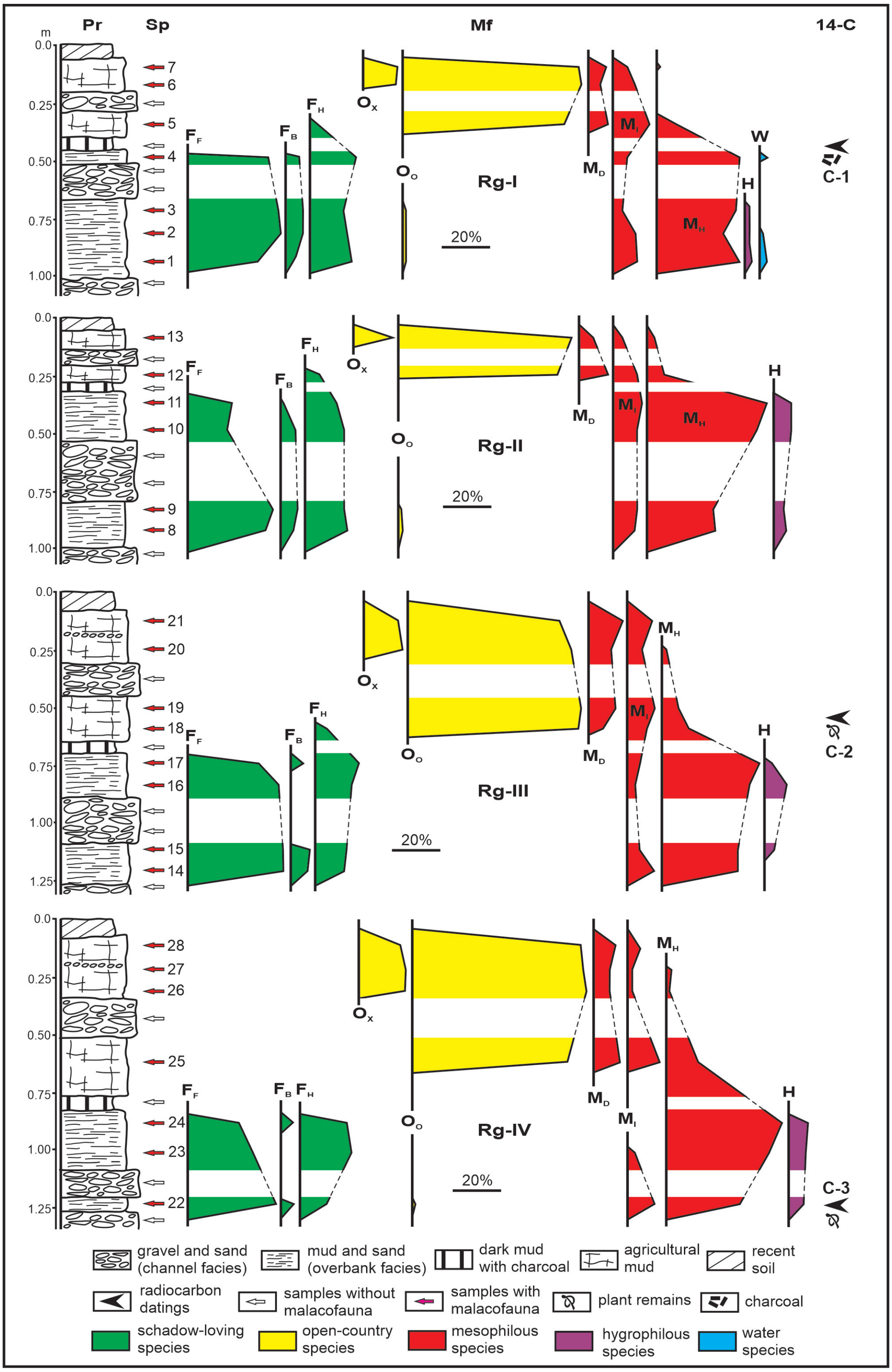

Fig. 3. *Lithology of fluvial sediments and mollusc fauna in the Rogoźnik Stream valley (profiles Rg-I – Rg-IV): Pr – lithological profiles, Sp – samples, Mf – malacofauna. Ecological groups of molluscs (after: Ložek 1964, Alexandrowicz & Alexandrowicz 2011, Juřičková et al. 2014a); F_F – forest species, F_B – shadow-loving species of rare forests and shrub zones, F_H – shadow-loving, moist forest species, O_X – xerophilous and underground species, O_O – open-country species, M_D – mesophilous species of dry environments, M_I – mesophilous species of medium humid habitats, M_H – mesophilous species of humid habitats, H – hygrophilous species, W – aquatic species, ^{14}C – radiocarbon dating*

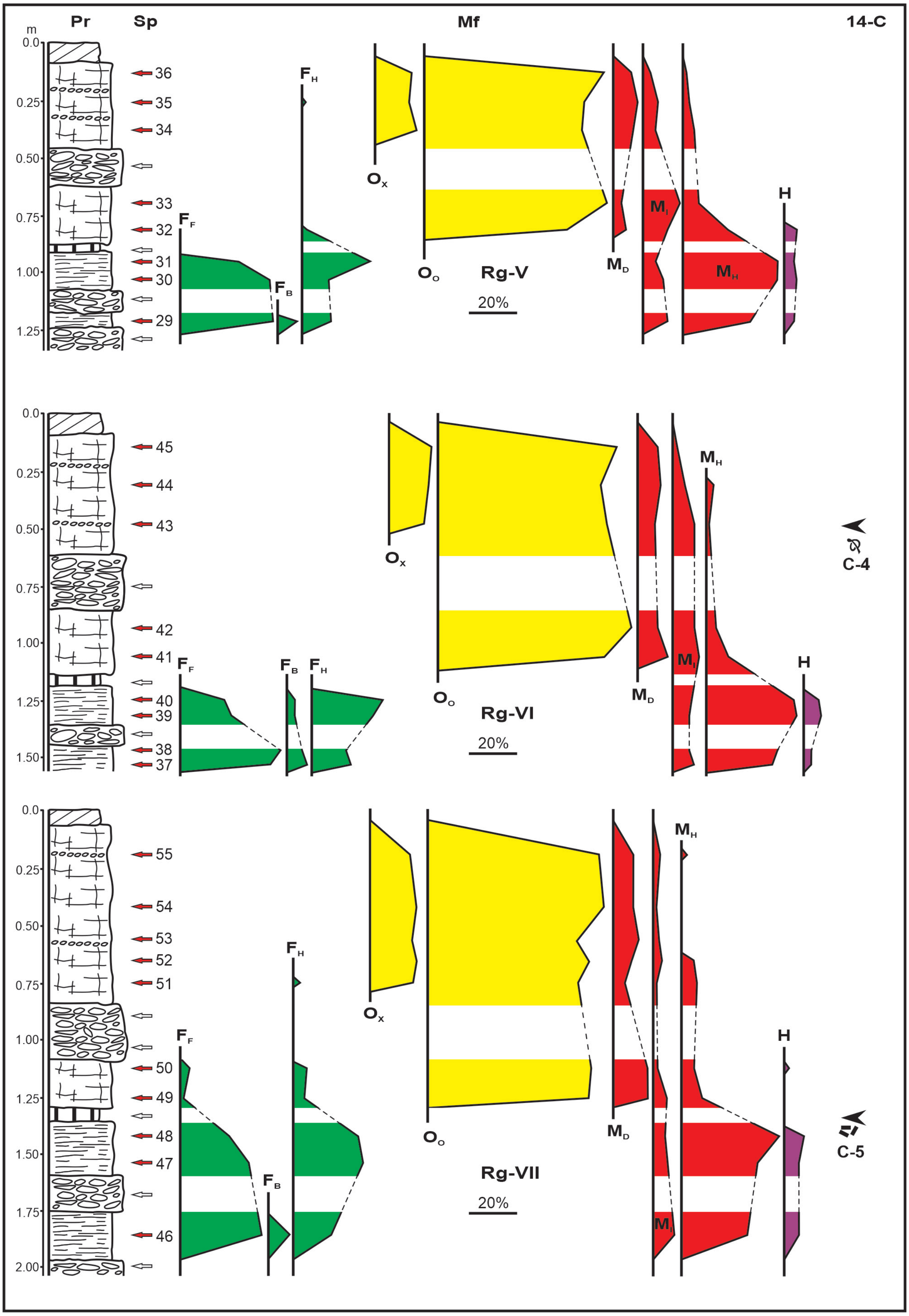

Fig. 4. Lithology of fluvial sediments and mollusc fauna in the Rogoźnik Stream valley (profiles Rg-V – Rg-VII). For explanations see Figure 3

Malacofauna

The entire identified shell material contained 52 species of land snails and one species of a water snail, represented by over 12,000 specimens. Additionally, vestigial plates of slugs were found (Table 1). The identified malacofauna includes taxa of various ecological preferences. Species typical for forests (group F_F) are represented by 18 taxa. Among them, *Aegopinella pura*, *Discus ruderatus* and *Platyla polita* were the most numerous. The forest species are found solely in sandy muds in the lower part of the profiles. The discussed group is the most important fauna component here, representing up to 40% of the assemblage (Figs. 3, 4; Table 1). Shadow-lowing species, living in bright forests and bushes (group F_B), are represented by five taxa. They are scarce and found only in lower intervals, representing an auxiliary component of the assemblage (Figs. 3, 4, Table 1). Shadow-loving species, typical for wet biotopes (group F_H), represent an important component of malacocenoses found in the upper layer of sandy muds. *Vitrea crystallina* and *Monachoides vicinus* are particularly numerous (Figs. 3, 4, Table 1). Open-country snails (groups O_X and O_O) are found mainly in silty muds in the upper part of the profiles. Their share in malacocenoses frequently exceeds 90%. *Vallonia pulchella* and *Vallonia costata*, species living in open grassy biotopes of variable humidity, are very numerous. The presence of *Cecilioides acicula* should also be noted. It is a species living underground, particularly characteristic for arable fields (e.g. Alexandrowicz et al. 1997, 2019a, Alexandrowicz 2004, Wiktor 2004, Welter-Schultes 2012, Čiliak et al. 2015). *Cecilioides acicula* shells were found in the top layer of silty muds forming top parts of the described profiles (Figs. 3, 4, Table 1). Mesophilous species (groups M_D, M_I and M_H) live in environments of varying humidity and shading. Taxa preferring dryer and more open habitats (group M_D) are represented only by *Cochlicopa lubricella*, quite numerous in the roof parts of profiles. The remaining groups (M_I and M_H) prefer more humid and more shady biotopes. They represent an important component of malacocenoses identified in lower sections of the profiles. *Carychium tridentatum*, *Arianta arbustorum* and *Perforatella bidentata* are numerous. The listed taxa form a characteristic component of malacofauna living on humid and shady terraces near water courses (Figs. 3, 4, Table 1). Higrophilous species (group H) are a less important component of the discussed fauna. Aquatic snails (group W) are only represented by *Galba truncatula*. Both higrophilous and aquatic species are mainly found in bottom parts of the profiles (Figs. 3, 4, Table 1).

Table 1

List of species recognized in profiles of fluvial deposits in the Rogoźnik Stream valley. For explanations see Figures 3 and 6

E	Taxon	Assemblages of molluscs			
		SL-Fo	SL-Hg	OC-Md	OC-Ag
F_F	*Platyla polita* (Hartm.)	228	204	1	
	Acanthinula aculeata (Müll.)	21			
	Vertigo pusilla Müll.	80	57		
	Ena montana (Drap.)	166	58		
	Discus ruderatus (Hartm.)	245	50		
	Cochlodina laminata (Mont.)	20	4		
	Cochlodina orthostoma (Menke)	8			
	Macrogastra plicatula (Drap.)	10			
	Clausilia cruciata (Stud.)	25	4		
	Vitrea diaphana (Stud.)	81	17		
	Vitrea transsylvanica (Cless.)	69	4		
	Mediterranea depressa (Sterki)	14	1		
	Aegopinella pura (Ald.)	350	255	8	

Table 1 *cont.*

E	Taxon	Assemblages of molluscs			
		SL-Fo	SL-Hg	OC-Md	OC-Ag
F_F	*Semilimax semilimax* (Fér.)	25	2		
	Eucobresia nivalis (Dum. & Mort.)	13	3		
	Petasina unidentata (Drap.)	95	26		
	Faustina faustina (Rossm.)	95	20		
	Isognomostoma isognomostomos (Schröt.)	147	93		
F_B	*Vertigo alpestris* Ald.	5			
	Alinda biplicata (Mont.)	26			
	Aegopinella minor (Stab.)	101	19		
	Fruticicola fruticum (Müll.)	100	24		
	Monachoides incarnatus (Müll.)	86	27		
F_H	*Columella edentula* (Drap.)	59	55		
	Macrogastra tumida (Rossm.)	3	5		
	Vestia turgida (Rossm.)	42	34		
	Vestia gulo (Bielz)	6	6		
	Vitrea crystallina (Müll.)	452	398	38	9
	Monachoides vicinus (Rossm.)	135	84		
	Urticicola umbrosus (Pfeif.)		57		
O_X	*Cecilioides acicula* (Müll.)				504
O_O	*Vallonia costata* (Müll.)	20	2	321	750
	Vallonia pulchella (Müll.)	14		407	892
	Pupilla muscorum (L.)			151	262
	Vertigo pygmaea (Drap.)			120	206
M_D	*Cochlicopa lubricella* (Rossm.)			137	244
M_I	*Cochlicopa lubrica* (Müll.)	127	57	79	107
	Clausilia dubia Drap.	25	1		
	Punctum pygmaeum (Drap.)	63	24	21	10
	Euconulus fulvus (Müll.)	49	16	16	14
	Nesovitrea hammonis (Ström)	105	87	30	7
	Vitrina pellucida (Müll.)	5	4	1	
M_H	*Carychium tridentatum* (Risso)	483	401	33	5
	Succinella oblonga (Drap.)	141	120	39	47
	Vertigo substriata (Jeffr.)	36	8		
	Vertigo angustior Jeffr.	69	23		
	Nesovitrea petronella (Pfeif.)	67	45	1	
	Trochulus villosulus (Rossm.)	25	32	2	
	Perforatella bidentata (Gmel.)	304	315	24	
	Arianta arbustorum (L.)	239	261	28	
H	*Carychium minimum* Müll.	158	159	7	
	Zonitoides nitidus (Müll.)	11	24		
W	*Galba truncatula* (Müll.)	16	5		
Plates of slugs		45	22	8	30
Total species		49	44	21	14
Total individuals		4664	3091	1467	3057

DISCUSSION

The sediment sequence of the low terrace of the Rogoźnik Stream

The analysed terrace stretches along the stream bed. It is well uncovered on nearly its entire length. Therefore, it is possible to observe its lithological variability. The horizons of sandy or silty muds are separated by series of gravels. Although the thickness of individual distinguished layers changes, their sequence in the vertical layout of the profiles is constant (Fig. 5). The oldest part are gravels visible in all profiles (excluding the Rg-VI profile). Their bottom part is not visible anywhere. Consequently, it is impossible to determine whether that layer is deposited on older alluvial sediments or directly on the rocky basement (G1; Fig. 5). Sandy muds located above them (M1 layer; Fig. 5) are of a varying thickness of maximum 30 cm (the Rg-I profile). In the middle part of the analysed section of the valley, this layer is poorly visible, and its thickness drops to 5–7 cm (Fig. 5). The second gravel insert (G2; Fig. 5) is the best formed in the upstream part of the valley, and its thickness reaches up to 25 cm (Rg-II profile). Moving downstream, the discussed layer becomes thinner (10–12 cm). The layer of sandy muds located above it (M2; Fig. 5) maintains a constant thickness (20–25 cm) at nearly the entire analysed section, and only in the Rg-I profile, it is poorly visible (up to 5 cm). Its characteristic feature are the numerous accumulations of fine plant detritus. Another element of the sediment sequence is a characteristic layer of dark muds containing numerous plant residues and charcoal fragments (Dm; Fig. 5). Contrary to the previously described M1 and M2 layers, no mollusc shells are found here. The discussed level is well visible in all profiles and has a constant thickness of about 5 cm. The top part of the terrace is formed by light silty muds, possibly being agricultural deposits (Am1 and Am2; Fig. 5). They contain numerous mollusc shells and plant detritus. The thickness of these sediments clearly increases downstream in the valley from ca. 25–30 cm to over 1 m. Am1 and Am2 layers are separated by an insert of the gravel, of thickness ranging from 5 cm in the upstream part of the valley to over 20 cm in its downstream part (G3; Fig. 5). In the upper part of the silty muds (the Am2 layer), there are visible horizons enriched with small pebbles (G3a and G3b). One such layer is found in the Rg-III and Rg-IV profiles, and two are visible in the Rg-V and Rg-VII profiles. The sediment sequence of the terrace is topped with a layer of recent soil (RS; Fig. 5).

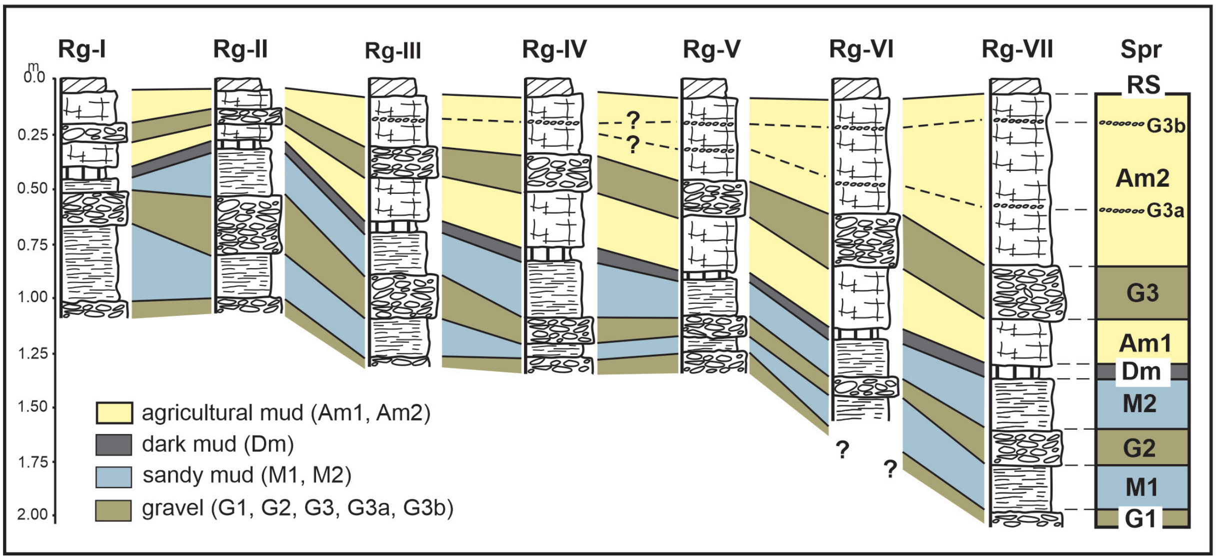

Fig. 5. *Longitudinal section of the low terrace of the Rogoźnik Stream valley (see also Figs. 2, 3 and 4): Spr – synthetic lithological profile, M1, M2 – sandy-mud horizons (described in text), G1–G3 – gravel horizons (described in text), G3a, G3b – gravel inserts (described in text), Am1, Am2 – silty-mud horizons (agricultural mud) (described in text), Dm – dark mud horizon (described in text), RS – recent soil, Rg-I – Rg-VII – profiles of fluvial deposits*

Mollusc assemblages

Numerous mollusc shells were found in muddy sediments representing M1, M2, Am1 and Am2 layers. Based on the dendrogram of similarities analysis, four types of fauna could be defined, differing from each other in their taxonomical composition and ecological structure (Fig. 6).

The conducted analysis of the principal components identified the most important components of each assemblage (Fig. 7).

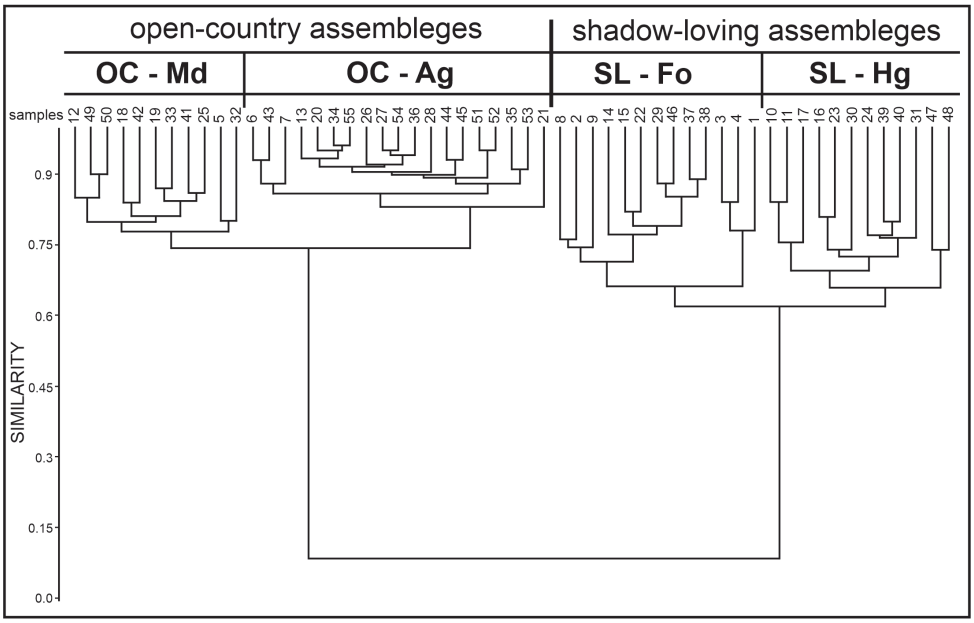

Fig. 6. *Cluster analysis (dendrogram of similarites) of malacofauna of fluvial deposits from the Rogoźnik Stream valley; OC-Md, OC-Ag, SL-Fo, SL-Hg – molluscan assemblages (described in text)*

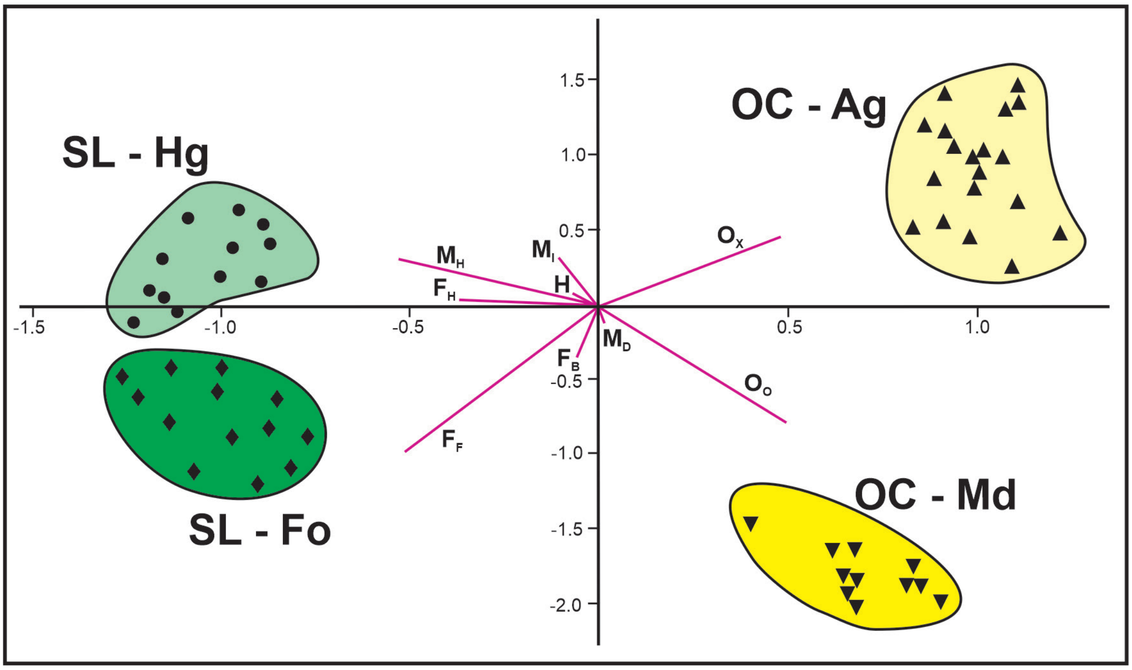

Fig. 7. *Principal component analysis (PCA) of malacofauna of fluvial deposits from the Rogoźnik Stream valley; OC-Md, OC-Ag, SL-Fo, SL-Hg – molluscan assemblages (described in text), F_F, F_B, F_H, O_X, O_O, M_D, M_I, M_H, H, W – ecological group of molluscs (for explanation see Figure 3)*

The SL-Fo assemblage (Fig. 6) was found in samples collected from sandy muds layers in the bottom part of the sediments sequence of the Rogoźnik Stream terrace (M1; Fig. 5). The discussed fauna is characterised by a significant taxonomic diversity, with snails typical for shady habitats, especially forests with the relatively humid substrate, *Discus ruderatus*, *Aegopinella pura*, and *Platyla polita*, being its main component. The share of shadow-loving taxa is very high (usually, they represent ca. 60% of the assemblage) (Fig. 8). Another important component of the discussed fauna are mesophilous species (*Arianta arbustorum*, *Perforatella bidentata*, and *Carychium tridentatum*), particularly characteristic for humid habitats. Their share in the assemblage amounts to ca. 30% (Fig. 8). The role of the remaining ecological groups is of low significance, especially in the case of taxa preferring open environments, with their share in the assemblage not exceeding several per cent at the most (Fig. 8). An analysis of the principal components indicates that for the discussed fauna, a large presence of shadow-loving taxa is characteristic, especially of forest species included in the F_F ecological group (Fig. 7). The discussed malacocenose contains mainly species of a relatively extensive thermal tolerance. It does not include cold-tolerant taxa (e.g., *Semilimax kotulae*) or thermophilic species (e.g., *Discus perspectivus*). In ecological terms, the discussed assemblage is characteristic of coniferous or mixed forests growing on a relatively humid substrate, probably at the bottom of the valley.

The SL-Hg assemblage (Fig. 6) is found in sandy muds distinguished as the M2 layer (Fig. 5). It is characterised by the domination of taxa preferring shady habitats. When compared to the fauna described above (the SL-Fo) assemblage is, however, characterised by a different taxonomical composition and the ecological structure. The most important component of this malacocenose are mesophilous species typical for humid habitats (*Arianta arbustorum*, *Perforatella bidentata*, and *Carychium tridentatum*) representing the M_H ecological group. The mesophilous snails preferring dryer habitats (*Cochlicopa lubrica*, *Euconulus fulvus*) are less numerous. In total, the taxa of a significant ecological tolerance represent ca. 50% of the assemblage (Fig. 8).

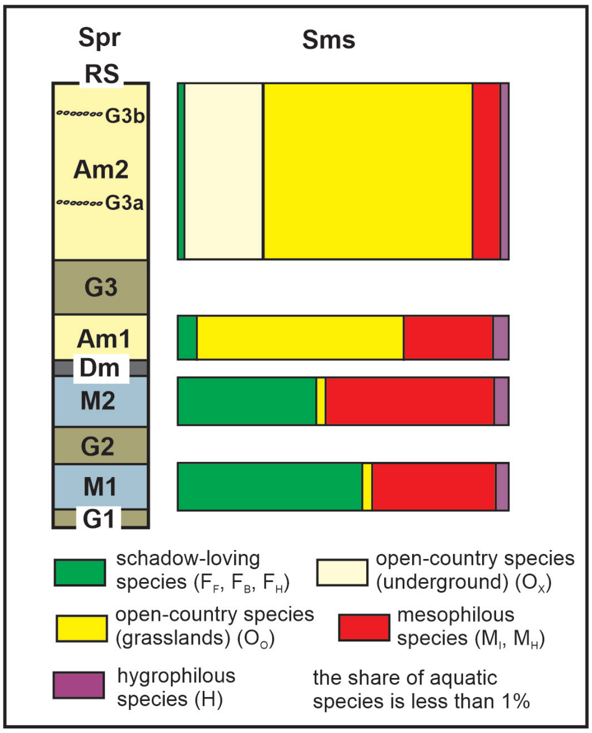

Fig. 8. *Diversity of molluscan assemblages in fluvial deposits from the Rogoźnik Stream valley; Spr – synthetic lithological profile, M1, M2, G1–G3, G3a, G3b, Am1, Am2, Dm, RS – lithological sequence of low terrace of the Rogoźnik Stream valley (for explanation see Figure 5), MSI – malacological spectrum of individuals*

The shadow-loving species are another important component of the discussed fauna. In this group, forms living in humid habitats (*Vitrea crystallina*, *Monachoides vicinus*, and *Discus ruderatus*) are the most numerous. The summary share of the shadow-loving component reaches up to 35–40% (Fig. 8). The hygrophilous species appear rarely and are insignificant. Their share in the assemblage does not exceed 5% (Fig. 8). Open-country snails are even rarer. Only a few specimens were found here. An analysis of the principal components indicates that mesophilous snails of humid environments (ecological group M_H) are an indicator for the discussed assemblage (Fig. 7). The SL-Hg assemblage represents the environment of the humid valley bottom covered by dense bushes. The numerous presence of *Perforalella bidentata* indicates a significant spreading of alder forests.

The OC-Md assemblage (Fig. 6) was determined in the lower layer of silty muds (agricultural muds; Am1; Fig. 5). When compared to previously described assemblages, it is characterised by a completely different taxonomical composition and an ecological structure. Open-country species, living in dry or slightly humid biotopes represent the most important component of this fauna, with the most important and most numerous taxa being *Vallonia pulchella* and *Vallonia costata*, accompanied by *Pupilla muscorum* and *Vertigo pygmaea*. The share of that ecological group in the assemblage is very high and exceeds 70% (Fig. 8). The mesophilous species are mainly represented by the xerophylous taxon *Cochlicopa lubricella*. Forms living on a more humid substrate, *Punctum pygmaeum* and *Cochlicopa lubrica* are much rarer. Taxa representing humid habitats are very scarce. The mesophilous snails represent up to 20% of the discussed fauna. Shadow-loving and hygrophilous species are represented only by single specimens and their importance in the assemblage is marginal (Fig. 8). An analysis of the principal components indicates that open-country species (O_O ecological group), especially typical for grassy biotopes, are an indicator of this fauna (Fig. 7). The assemblage in question is typical of open meadow biotopes of various humidity, both natural and anthropogenic.

The OC-Ag assemblage (Fig. 6) was identified in samples from the top layer of the silty muds (Am2; Fig. 5). It is a fauna poor in terms of its taxonomic properties. Taxa typical for open habitats, included in the O_O and O_X groups, play the most important role here. The first of the mentioned taxa is the dominant group (representing even up to 70% of the assemblage), with its typical representatives being *Vallonia pulchella* and *Vallonia costata*. The second group (O_X) is represented solely by *Cecilioides acicula*. This underground snail is characteristic of agricultural areas, especially arable fields, and its presence can be considered an indicator of human agricultural activities (e.g. Alexandrowicz et al. 1997, 2019a, Alexandrowicz 2004, Wiktor 2004, Welter-Schultes 2012, Čiliak et al. 2015). In the discussed fauna, the share of *Cecilioides acicula* reaches up to 20%. In total, the taxa of open environments represent over 90% of the assemblage. The remaining ecological groups are of marginal importance, and their share does not exceed 10% (Fig. 8). An indicator characterising the OC-Ag assemblage is the presence of the O_X group (Fig. 7). The discussed assemblage has typical features of malacocenoses of open biotopes, especially the zone of arable fields.

Natural and anthropogenic changes in the environment

The sequences of alluvial sediments formed as a series of gravel alternating with mud layers were frequently described for many valleys, especially in mountain areas. The gravel series are usually interpreted as channel sediments accumulated during periods of intense fluvial activity of rivers and streams, and in consequence, correlated with cold and humid climate fluctuations. The fine-grained deposits (muds) represent environments of low energy (overbank sediments) accumulated during periods of decreased fluvial activity (e.g. Starkel et al. 2006, 2013, Hoffmann et al. 2008, Gębica 2011, 2013a, 2013b, Wirth et al. 2013, Benito et al. 2015, Gębica et al. 2016, Perşoiu & Perşoiu 2019, Rădoane et al. 2019). In the low terrace of the Rogoźnik Stream, three gravel series (G1–G3) and four mud layers (M1, M2, Am1 and Am2) can be distinguished. Additionally, in the roof layer of muds (Am2), one or two intercalations enriched with pebbles (G3a and G3b) are visible (Fig. 9). This sequence enables reconstruction of changes in the environment, and especially, distinguishing the period of increased fluvial activity of the stream. The presence of rich and diversified mollusc assemblages in the mud levels offers an opportunity to recreate the character of environmental habitats during the sediment deposition and to assess the impact of human activities. Studies of this type were conducted in several stream valleys in the Polish part of the Carpathian Mountains (e.g. Alexandrowicz & Wyżga 1992, Alexandrowicz & Łanczont 1995, Alexandrowicz 2019b, Alexandrowicz et al. 2019), including the Podhale Basin (Alexandrowicz 2019a, 2020, 2023). The fragments of plants and charcoal found in the sediments allowed the sediment age to be determined by radiocarbon dating. Thus, it was possible to characterise the changes in the environment and relate them to periods of climate fluctuations and phases of settlement in the Podhale Basin.

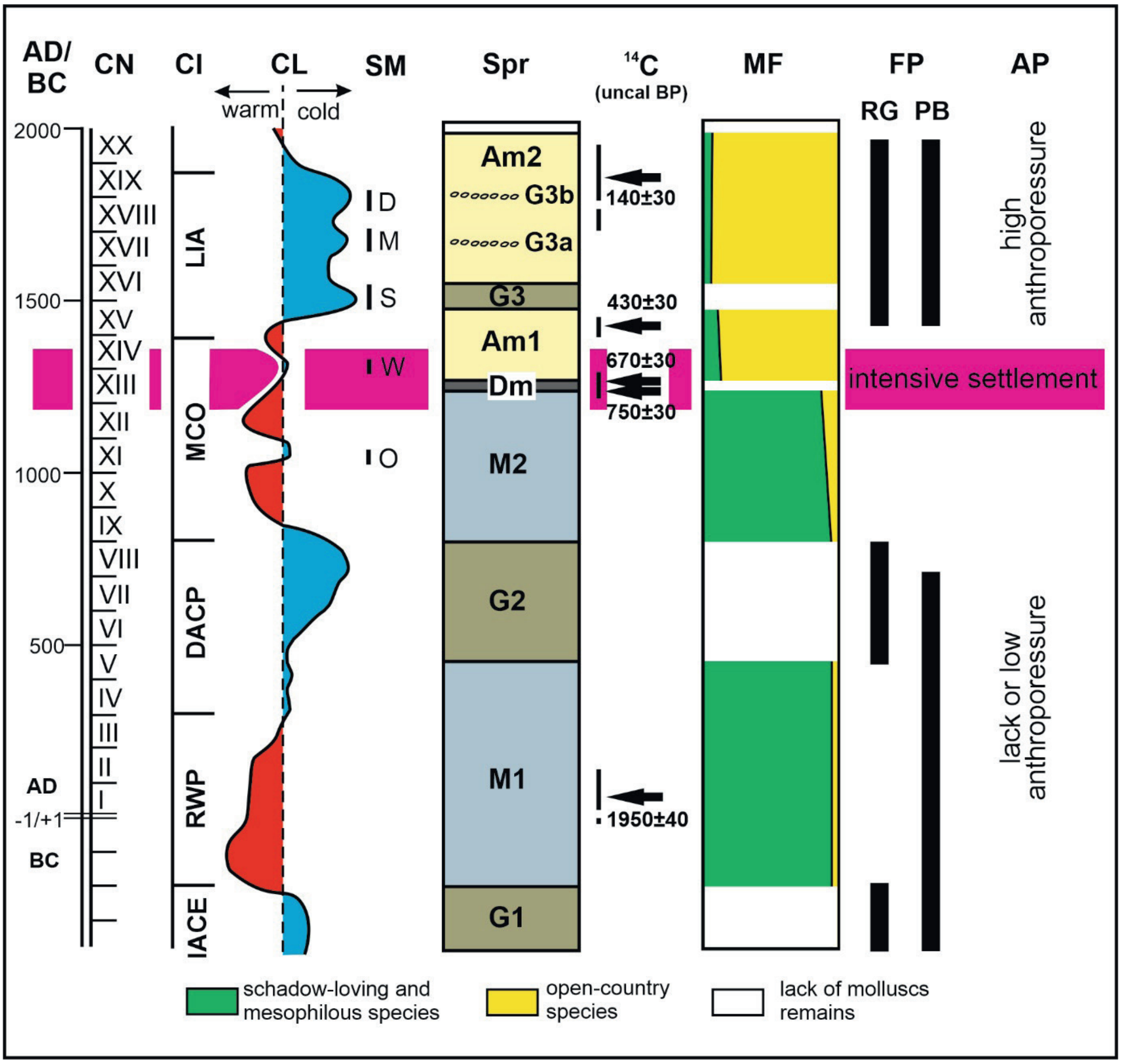

Fig. 9. *Chronology of sequence of fluvial deposits in Rogoźnik Stream valley against the background of climate changes, malacological and lithological data and the development of settlement; AD – time scale (in BC/AD calendar years), CN – centuries, CI – climatic events (after: Mayewski et al. 2004, Plunkett & Swindles 2008, Mauri et al. 2015); IACE – Iron Age Cold Epoch, RWP – Roman Warm Period, DACP – Dark Ages Cold Period, MCO – Medieval Climatic Optimum, LIA – Little Ice Age, CL – climate, SM – solar minima (after: Mayewski et al. 2004, Kudsk et al. 2022); O – Oort, W – Wolf, S – Spörer, M – Maunder, D – Dalton, Spr – synthetic lithological profile (for explanations of lithological units see Figure 5), ^{14}C – radiocarbon dating, MF – malacofauna, FP – fluvial phases, RG – Rogoźnik Stream valley, PB – Podhale Basin (after: Alexandrowicz 2013a, 2019a, 2020, 2023), AP – anthropopressure*

The oldest part of the discussed terrace is formed by gravels (G1) visible in the bottom layer of all profiles (excluding the Rg-VI profile). No mollusc shells were found in it, and the age of this layer can be determined only indirectly. Probably, it can be correlated with a phase of an intensified fluvial activity of rivers corresponding to the Iron Age Cold Epoch (Mayewski et al. 2004, Plunkett & Swindles 2008, Mauri et al. 2015) (Fig. 9). The discussed period is associated with the intensification of fluvial activity of rivers both in Podhale Basin (Alexandrowicz 2019a, 2020, 2023) and in other areas of the Carpathians (Starkel et al. 2006, 2013; Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Gębica et al. 2016, Rădoane et al. 2019). There is also phase of intensification of mass movements (e.g. Alexandrowicz 1996, 2013b, Starkel 1997, Margielewski 1998, 2006, 2018, Dapples et al. 2002, Soldati et al. 2004 Pánek et al. 2013), and period of development of Alpine glaciers correlated with the Löbben and Göschenen I phases (Joerin et al. 2006, Ivy-Ochs et al. 2009, Nussbaumer et al. 2011).

The sandy muds located above it (M1) contain numerous and rich malacofauna, with the forest species predominating (the SL-Fo assemblage). The radiocarbon dating of plant fragments from the described layer gave a result of 1950 y BP ±40 y BP (39–12 cal BC and 2–204 cal AD) (C-3; Figs. 3, 9, Table 2). The provided date indicates that silts were deposited during a warm climate phase noted in Europe between 250 BC and ca. 300 AD (the Roman Warm Period) (Mayewski et al. 2004, Plunkett & Swindles 2008, Mauri et al. 2015). At that time, the Podhale region was covered with dense mixed forests, providing favourable conditions for the development of taxonomically diversified snail assemblages. Similar faunas of analogous age were also described at other sites in the Podhale region (Alexandrowicz 1997, 2019a, 2020, 2023, Alexandrowicz et al. 2014), as well as in many profiles identified in other parts of the Carpathian Mountains (Alexandrowicz 1997, 2004, 2019b, Alexandrowicz et al. 2014, 2016, Juřičková et al. 2014b, 2020, Horáčková et al. 2015, Frodlová & Horsák 2021). Also, the results of palynological analyses of Podhale peatbogs confirm the presence of extensive forest complexes at that time (phases: *Picea-Carpinus-Abies* and *Fagus-Abies*; Obidowicz 1990, Rybniček & Rybničková 2002, Krąpiec et al. 2016). On the other hand, no signs of human activities are visible in that period. Probably, the human groups living in the Podhale region at that time were very small and scattered, and the environmental impact of their activities was practically unnoticeable (Fig. 9).

The gravels located above the M1 layer (G2) imply a significant change in conditions of the sediment deposition. They do not contain mollusc remains or plant fragments, and thus their age can be determined only indirectly. Possibly, the G2 layer represents the period of increased fluvial activity and can be correlated with the colder climate in the early Middle Ages – the Dark Ages Cold Period (Mayewski et al. 2004, Helama et al. 2017). That phase is associated with the deposition of gravels described for other valleys in the Podhale Basin (Alexandrowicz 2013a, 2019a, 2020, 2023), and numerous sites of river sediments in the entire Carpathians (Starkel et al. 2006, 2013, Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Gębica et al. 2016, Rădoane et al. 2019). In this period, the increase in the mass movements (e.g. Alexandrowicz 1996, 2013b, Starkel 1997, Margielewski 1998, 2006, 2018, Dapples et al. 2002, Soldati et al. 2004, Pánek et al. 2013) and development of Alpine glaciers (Göschenen II phase; Joerin et al. 2006, Ivy-Ochs et al. 2009, Nussbaumer et al. 2011) are observed (Fig. 9).

The next element in the described sequence are sandy muds (M2) containing numerous mollusc shells. Hydrophilous taxa typical for shady habitats (the SL-Hg assemblage) play a significant role in the malacocenoses.

Table 2
Results of radiocarbon dating

Date	Profile	Layer	Age [y BP]	Age [cal BC/AD]	Material
C-1	Rg-I	Dm	750 ± 30	1262–1310 cal AD (80.1%) 1362–1387 cal AD (15.3%)	charcoal
C-2	Rg-III	Am1	430 ± 30	1423–1500 cal AD (91.6%) 1600–1615 cal AD (3.8%)	plant detritus
C-3	Rg-IV	M1	1950 ± 40	39–12 cal BC (6.7%) 2–204 cal AD (88.7%)	wood (branch)
C-4	Rg-VI	Am2	140 ± 30	1672–1778 cal AD (37.2%) 1798–1944 cal AD (58.3%)	plant detritus
C-5	Rg-VII	Dm	670 ± 30	1277–1323 cal AD (53.1%) 1357–1392 cal AD (42.3%)	charcoal

Their presence indicates that the Rogoźnik Stream basin was thickly forested. Similar silty sequences are also found in other valleys in the Podhale region (Alexandrowicz 2013a, 2019a, 2020, 2023). The described layer is probably associated with a phase of progressing climate warming in the Middle Ages. The palynological profiles representing that period also indicate the domination of forest environments (Obidowicz 1990, Rybniček & Rybničková 2002, Krąpiec et al. 2016). The anthropopresure is very poorly marked in this period. However, the historical data indicates the progressing inflow of settlers to the Podhale region (Czepiel 1999, Alexandrowicz 2020, Kłapyta 2021) (Fig. 9).

Dark muds (Dm) are located above the M2 layer. They contain numerous fragments of charcoal but are free of mollusc shells. The described layer is found in all profiles and always has a very small thickness (a few centimetres). Two cases of dating within it gave similar results: 710 ± 30 (1262–1310 cal AD and 1362–1387 cal AD) (C-1) and 670 ± 30 (1277–1323 cal AD and 1357–1392 cal AD) (C-5); Figs. 3, 4, 9, Table 2). The dating results indicate that the discussed layer was associated with the warm period of the Medieval Climate Optimum (Grove & Switsur 1994, Bradley 2000, Briffa 2000). In the Podhale region, this period is associated with a fast inflow of settlers. The demographic increase became the main cause of extensive deforestation, initially in flat areas of the northern Podhale (the Orawa-Nowy Targ Basin), favourable for agricultural activities. At that time, numerous villages are built here (location of settlements: Nowy Targ – 1346, Rogoźnik – 1237, Ludźmierz – 1234). Due to human activities, forest assemblages were quickly replaced by open areas. Clear manifestations of these changes are recorded in the palynological (Obidowicz 1990, Rybniček & Rybničková 2002, Krąpiec et al. 2016) and malacological (Alexandrowicz 2013a, 2019a, 2020, 2023) sequences described for the Podhale region. It should also be noted here that the rapid increase in the number of human groups and associated intensified anthropopressure in the Middle Ages is noted throughout almost the whole of the Carpathian Mountains (Starkel et al. 2006, 2013, Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Gębica et al. 2016, Alexandrowicz et al. 2019).

The light silty muds above the Dm layer (Am1) and their malacological content clearly indicate significant changes in the nature of the habitats and the rapid intensification in the anthropopressure. The rich and diversified assemblages with a large share of sciophilous species (SL-Fo and SL-Hg assemblages), initially found in this area, are replaced by a poor fauna, in which the taxa of open environments, particularly, typical for grasslands (the OC-Md assemblage) play the most important role (Fig. 9). Its presence indicates that forests in the Rogoźnik Stream valley were scarce. The forests were probably replaced by pastures. Similar changes in the habitat characteristics are commonly observed both in the Podhale and in other regions of the Carpathian Mountains (Starkel et al. 2006, 2013, Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Alexandrowicz 2013a, 2019a, 2019b, 2020, 2023, Gębica et al. 2016, Alexandrowicz et al. 2019, Perşoiu & Perşoiu 2019, Rădoane et al. 2019). The discussed phase can probably be associated with the end of the Middle Ages.

The roof of the sediment sequence forming the low terrace of the Rogoźnik Stream includes a clearly distinguished layer of gravel (the G3 layer) and a layer of silty muds (the Am2 layer) covering it. In this last part, levels can be noticed (either one or two, enriched with pebbles – G3a and G3b) (Fig. 9). This entire sequence possibly corresponds to the cold phase of the Little Ice Age (e.g. Grove 1988, Bradley 2000, Briffa 2000, Mayewski et al. 2004, Matthews & Briffa 2005). The deteriorated climate conditions possibly led to depopulation and reduced anthropopressure intensity. However, this phenomenon was mainly visible in areas of more diversified relief and land conditions less favourable for agricultural activities. Traces of those changes are recorded in profiles of river sediments and in malacocenoses described for the southern, more mountainous part of the Podhale (Alexandrowicz 2013a, 2019a, 2020, 2023). However, they are not visible in flat areas of the Orava-Nowy Targ Basin, where the anthropopressure intensity was still strong. Gravel levels can be correlated with periods of colder climate fluctuations. At least three such fluctuations were noted during the Little Ice Age. They correspond to the periods of the decreased solar activity – the Spörer, Maunder and Dalton minima (Mayewski et al. 2004, Kudsk et al. 2022). It is highly probable that gravel layers G3, G3a, and G3b observed in the studied valley correspond to those minima (Fig. 9). The presence of gravel sequences in the sediments corresponding to the Little Ice Age is commonly noted in the valleys of the Carpathian rivers (Starkel et al. 2006, 2013, Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Alexandrowicz 2013a, 2019a, 2019b, 2020, 2023, Gębica et al. 2016, Alexandrowicz et al. 2019, Perşoiu & Perşoiu 2019, Rădoane et al. 2019). This period is also associated with an increase in mass movements (e.g. Alexandrowicz 1996, 2013b, Starkel 1997, Margielewski 1998, 2006, 2018, Dapples et al. 2002, Soldati et al. 2004, Pánek et al. 2013) and a phase of the advance of the Alpine glaciers (Joerin et al. 2006, Ivy-Ochs et al. 2009, Nussbaumer et al. 2011). The time frame for deposition of sediments forming the roof of the sediment sequence of the Rogoźnik Stream terrace is determined by two radiocarbon dates: 430 ± 30 (1423–1500 cal AD and 1600–1615 cal AD; C-2) and 140 ± 30 (1672–1778 cal AD and 1798–1944 cal AD; C-4) (Figs. 3, 4, 9, Table 2). In dust silts (Am2), a numerous though poorly diversified malacofauna was found. Its characteristic feature is the presence of *Cecilioides acicula* specific for the agricultural area. Here, it should be noted that the Am2 layer, characterised by a significant thickness, was formed in a relatively short time. This implies a high rate of the sediment deposition. Such sequences are frequently noted in the Carpathian river valleys (Starkel et al. 2006, 2013, Gębica & Krąpiec 2009, Gębica 2011, 2013a, 2013b, Alexandrowicz 2013a, 2019a, 2019b, 2020, 2023, Gębica et al. 2016, Alexandrowicz et al. 2019, Perşoiu & Perşoiu 2019, Rădoane et al. 2019). Three factors are decisive here. The first one is the climate conditions. The period of the Little Ice Age was characterised by a moist climate with large amounts of precipitation. The second one is the replacement of forests (of high retention) by agricultural areas (of low retention), which contributes to the intensification of the soil degradation processes by ablation (Święchowicz 2010, Święchowicz et al. 2022). The third one, finally, is the introduction of mass-scale root crop cultivation, especially the potato, in the whole the Carpathians in the 19th century. The ownership structure at that time frequently led to the presence of narrow fields arranged along the slope incline. The coincidence of these three factors resulted in the increase in the supply of small grain material from slopes to river valleys, and in consequence, to deposition of thick silt sequences, frequently containing numerous plant remains. This situation is also found in the Rogoźnik Stream valley (Fig. 9).

CONCLUSIONS

1. The sediment sequence forming the Rogoźnik Stream terrace represents a period of the last 2000 years. It is a record of changes in the environment generated by natural, mainly climate fluctuations and anthropogenic, related to intensified human settlement and agricultural activities and processes.
2. The layers of gravel are visible in the profiles correspond to periods of the increased fluvial activity of the stream and are correlated with colder climate phases: Dark Ages Cold Period (the G2 layer) and the Little Ice Age (the G3 layer and the G3a and G3b levels). The gravels found in the bottom part of the sequence can possibly be correlated with the Iron Age Cold Epoch, colder climate older than 300 BC.
3. In the roof part of the sequence, of the age corresponding to the period of the Little Ice Age, three layers of gravel can be distinguished (the G3 layer and the G3a and G3b levels). They may correspond to periods of the intensified activity of the stream during colder climate fluctuations associated with phases of the minimum Sun activity. In this respect, the G3 layer corresponds to the Spörer minimum, and the G3a and G3b levels represent and Maunder/Dalton minima, respectively.
4. In the sandy (M1 and M2) and silty (Am1 and Am2) mud layers, numerous mollusc shells are found. Shadow-loving species, preferring moderately humid and humid habitats, predominate in the bottom part (the M1 and M2 layers). The ecological composition of the fauna indicates that forests covered the stream basin to a large extent. In the roof part (Am1 and Am2 layers), snails typical of open environments

prevail, indicating a rapid disappearance of forests in the Rogoźnik Stream valley.

5. A significant change of the habitat nature is marked in the layer of dark muds (the Dm layer). Its formation was associated with a period of intense anthropogenic deforestation of the valley during the Middle Ages (probably in the 13th and 14th centuries).
6. The role of humans as an important or even a decisive factor leading to environmental changes has been noticeable since the period of the Medieval Climate Optimum. At that time, numerous groups of people arrived in the Podhale region and intense agricultural use of this area began. An indicator of these changes is the numerous occurrence of *Cecilioides acicula* in the top part of the sedimentary sequence (Am-2 layer).
7. The fast rate of the alluvial sediments increase has been visible since the 18th and 19th centuries, and was probably associated with the introduced large-scale cultivation of root crops, especially the potato.
8. The observed phases in the changes of the environment of the Rogoźnik Stream valley are very consistent with results of lithological and malacological studies conducted in valleys of other streams in the Podhale region, conclusions drawn from analyses of pollen profiles of the Podhale peatbogs, and historical data on settlements in this area.

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REFERENCES

Alexandrowicz S.W., 1996. Holoceńskie fazy intensyfikacji procesów osuwiskowych w Karpatach. *Geologia: kwartalnik Akademii Górniczo-Hutniczej im. Stanisława Staszica w Krakowie*, 22(3), 223–262.

Alexandrowicz S.W. & Alexandrowicz W.P., 2011. Analiza malakologiczna. Metody badań i interpretacji. *Rozprawy Wydziału Przyrodniczego PAU*, 3, 5–302.

Alexandrowicz S.W. & Łanczont M., 1995. Loesses and alluvia in the Krzeczkowski Stream valley in Przemyśl environs (SE Poland). *Annales Universitatis Mariae Curie-Sklodowska, sectio B*, 50(2), 29–50.

Alexandrowicz S.W. & Wyżga B., 1992. Late Glacial and Holocene evolution of the Raba River Valley floor in the vicinity of the Carpathian Border, Southern Poland. *Quaternary Studies in Poland*, 11, 17–42.

Alexandrowicz S.W., Alexandrowicz W.P., Krąpiec M. & Szychowska-Krąpiec E., 1997. Zmiany środowiska południowej Polski w okresie historycznym. *Geologia: kwartalnik Akademii Górniczo-Hutniczej im. Stanisława Staszica w Krakowie*, 23(4), 339–387.

Alexandrowicz W.P., 1997. Malakofauna osadów czwartorzędowych i zmiany środowiska naturalnego Podhala w młodszym vistulianie i holocenie. *Folia Quaternaria*, 68, 7–132.

Alexandrowicz W.P., 2004. Molluscan assemblages of Late Vistulian and Holocene calcareous tufa in Southern Poland. *Folia Quaternaria*, 75, 3–309.

Alexandrowicz W.P., 2013a. Molluscan communities in Late Holocene fluvial deposits as an indicator of human activity: a study in Podhale Basin in Southern Poland. *Ekologia Bratislava*, 32, 111–125.

Alexandrowicz W.P., 2013b. Molluscan assemblages in the deposits of landslide dammed lakes as indicators of late Holocene mass movements in the Polish Carpathians. *Geomorphology*, 180–181, 10–23. https://doi.org/10.1016/j.geomorph.2012.09.001.

Alexandrowicz W.P., 2019a. Record of environmental changes and fluvial phases in the Late Holocene within the area of Podhale (the Carpathians, southern Poland): studies in the Falsztyński valley. *Geological Quarterly*, 63(4), 629–642. https://doi.org/10.7306/gq.1466.

Alexandrowicz W.P., 2019b. Malacological evidence of the natural and anthropogenic changes of the environment in the eastern part of the Carpathian Foreland: the studies in the Glinne stream valley near Rzeszów (southern Poland). *Carpathian Journal of Earth and Environmental Sciences*, 14(2), 367–384. https://doi.org/10.26471/cjees/2019/014/087.

Alexandrowicz W.P., 2020. Development of settlements in Podhale Basin and Pieniny Mts. (western Carpathians, southern Poland) in light of malacological research. *Carpathian Journal of Earth and Environmental Sciences*, 15(1), 247–259. https://doi.org/10.26471/cjees/2020/015/126.

Alexandrowicz W.P., 2022. Molluscan assemblages in sediments of a landslide on Majerz Hill near Niedzica (Inner Carpathians, Southern Poland) – phases of development and environmental changes. *Geology, Geophysics and Environment*, 48(1), 51–68. https://doi.org/10.7494/geol.2022.48.1.51.

Alexandrowicz W.P., 2023. 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). *Acta Geologica Polonica*, 73(1), 85–102. https://doi.org/10.24425/agp.2022.142643.

Alexandrowicz W.P., Szymanek M. & Rybska E., 2014. Changes to the environment of intramontane basins in the light of malacological research of calcareous tufa: Podhale Basin (Carpathians, Southern Poland). *Quaternary International*, 353, 250–265. https://doi.org/10.1016/j.quaint.2014.10.055.

Alexandrowicz W.P., Szymanek M. & Rybska E., 2016. Molluscan assemblages from Holocene calcareous tufa and their significance for palaeoenvironmental reconstructions. A study in the Pieniny Moutains (Carpathians, southern Poland). *Carpathian Journal of Earth and Environmental Sciences*, 11(1), 37–54.

Alexandrowicz Z., Alexandrowicz W.P. & Buczek K., 2019. Conservation of the Natura 2000 areas in the context of environmental changes in past and present: A case from the Polish Carpathians geoheritage. *Geoheritage*, 11, 517–529. https://doi.org/10.1007/s12371-018-0302-3.

Benito G., Macklin M., Panin A., Rossato S., Fontana A., Jones A.F., Machado M.J., Matlakhova E., Mozzi P. & Zielhofer C., 2015. Recurring flood distribution patterns related to short-term Holocene climatic variability. *Scientific Reports*, 5, 16398. https://doi.org/10.1038/srep16398.

Bradley K.R., 2000. Past global changes and their significance for the future. *Quaternary Science Reviews*, 19, 391–402. https://doi.org/10.1016/S0277-3791(99)00071-2.

Briffa K.R., 2000. Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quaternary Science Reviews*, 19, 87–105. https://doi.org/10.1016/S0277-3791(99)00056-6.

Bronk Ramsey C., 2017. Methods for summarizing radiocarbon datasets. *Radiocarbon*, 59, 1809–1833. https://doi.org/10.1017/RDC.2017.108.

Čiliak M., Čejka T. & Šteffek J., 2015. Molluscan diversity in stream driftwood: relation to land use and river section. *Polish Journal of Ecology*, 63(1), 124–134. https://doi.org/10.3161/15052249PJE2015.63.1.011.

Czepiel J., 1999. *Z dziejów osadnictwa na Podhalu*. Abrys, Kraków.

Dapples F., Lotter A.F., van Leeuven J.F.N., van der Knapp W.O., Dimitriadis S. & Oswald D., 2002. Palaeolimnological evidence for increased landslide activity due to forest clearing and land-use since 3600 cal BP in the western Swiss Alps. *Journal of Paleolimnology*, 27, 239–248. https://doi.org/10.1023/A:1014215501407.

Frodlová J. & Horsák M., 2021. High-resolution mollusc record from the Mituchovci tufa (western Slovakia): A reference for the Holocene succession of Western Carpathian mid-elevation forests. *Boreas*, 50, 709–722. https://doi.org/10.1111/bor.12503.

Gębica P., 2011. Stratigraphy of alluvial fills and phases of the Holocene floods in the lower Wisłok river. *Geographia Polonica*, 84(spec. iss. 1), 39–60.

Gębica P., 2013a. Chronostratigraphy of alluvia and age of fluvial landforms in the Carpathians foreland during the Vistulian. *Studia Quaternaria*, 30(1), 19–27. https://doi.org/10.2478/squa-2013-0002.

Gębica P., 2013b. Geomorphological records of human activity reflected in fluvial sediments in the Carpathians and their foreland. *Landform Analysis*, 22, 21–31. https://doi.org/10.12657/landfana.022.003.

Gębica P. & Krąpiec M., 2009. Young Holocene alluvia and dendrochronology of subfossil trunks in the San river valley. *Studia Geomorphologica Carpatho-Balcanica*, 43, 63–75.

Gębica P., Jacyszyn A., Krąpiec M., Budek A., Czumak N., Starkel L., Andrejczuk W. & Ridush B., 2016. Stratigraphy of alluvia and phases of the Holocene floods in the valleys of the Eastern Carpathians foreland. *Quaternary International*, 415, 55–66. https://doi.org/10.1016/j.quaint.2015.11.088.

Grove J., 1988. *The Little Ice Age*. Methuen, London – New York.

Grove J.M. & Switsur R., 1994. Glacial geological evidence for the Medieval Warm Period. *Climatic Change*, 26, 143–169. https://doi.org/10.1007/BF01092411.

Hammer Ø., Harper D.A.T. & Ryan P.D., 2001. PAST: paleontological statistics software package for education and data analysis. *Palaeontologica Electronica*, 4(1), 1–9. http://palaeo-electronica.org/2001_1/past/issue1_01.htm.

Helama S., Jones P.D. & Briffa K.R., 2007. Dark Ages Cold Period: A literature review and directions for future research. *The Holocene*, 27(10), 1600–1606. https://doi.org/10.1177/0959683617693898.

Hoffmann T., Lang A. & Dikau R., 2008. Holocene river activity: analysing 14C-dated fluvial and colluvial sediments from Germany. *Quaternary Science Reviews*, 27(21–22), 2031–2040. https://doi.org/10.1016/j.quascirev.2008.06.014.

Horáčková J., Ložek V. & Juřičková L., 2015. List of malacologically treated Holocene sites with brief review of palaeomalacological research in the Czech and Slovak Republics. *Quaternary International*, 357, 207–211. https://doi.org/10.1016/j.quaint.2014.03.007.

Horsák M., Juřičková L. & Picka J., 2013. *Molluscs of the Czech and Slovak Republics*. Kabourek, Zlín.

Ivy-Ochs S., Kerschner H., Maisch M., Christl M., Kubik P.W. & Schlüchter Ch., 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews*, 28(21–22), 2137–2149. https://doi.org/10.1016/j.quascirev.2009.03.009.

Joerin U.E., Stocker T.F. & Schlüchter Ch., 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene*, 16(5), 697–904. https://doi.org/10.1191/0959683606hl964rp.

Juřičkova L., Horsák M., Horáčková J. & Ložek V., 2014a. Ecological groups of snails – use and perspectives. [in:] *7th Congress of the European Malacological Societies, 7–11 September, 2014, Cambridge, UK* [poster]. https://mollusca.sav.sk/malacology/Jurickova/2014-ecological-groups-poster.pdf.

Juřičková L., Horsák M., Horáčková J., Abraham V. & Ložek, V., 2014b. Pattern of land-snail succession in Central Europe over the 15,000 years: Man changes along environmental, spatial and temporal gradients. *Quaternary Science Reviews*, 93, 155–166. https://doi.org/10.1016/j.quascirev.2014.03.019.

Juřičková L., Šída P., Horáčková H., Ložek V. & Pokorný P., 2020. The lost paradise of snails: Transformation of the middle-Holocene forest ecosystems in Bohemia, Czech Republic, as revealed by declining land snail diversity. *The Holocene*, 30(9), 1254–1265. https://doi.org/10.1177/0959683620919985.

Kijowska-Strugała M., Bucała-Hrabia A. & Demczuk P., 2018. Long-term impact of land use changes on soil erosion in an agricultural catchment (the Western Polish Carpathians). *Land Degradation & Development*, 29(6), 1871–1884. https://doi.org/10.1002/ldr.2936.

Kłapyta P., 2021. Klimatyczne uwarunkowania rozwoju osadnictwa na prawie wołoskim w Karpatach Zachodnich na przełomie XV i XVI wieku na przykładzie Podtatrza. *Balcanica Posnaniensia. Acta et Studia*, 28(1), 133–148. https://doi.org/10.14746/bp.2021.28.6.

Krąpiec M., Margielewski W., Korzeń K., Szychowska-Krąpiec E., Nalepka D. & Łajczak A., 2016. Late Holocene palaeoclimate variability: The significance of bog pine dendrochronology related to peat stratigraphy. The Puścizna Wielka raised bog case study (Orawa-Nowy Targ Basin, Polish Inner Carpathians). *Quaternary Science Reviews*, 148, 192–208. https://doi.org/10.1016/j.quascirev.2016.07.022.

Kudsk S.G.K, Knudsen M.F, Karoff Ch., Baittinger C., Misios S. & Olsen J., 2022. Solar variability between 650 CE and 1900 – Novel insights from a global compilation of new and existing high-resolution ^{14}C records. *Quaternary Science Reviews*, 292, 107617. https://doi.org/10.1016/j.quascirev.2022.107617.

Kukulak J., 2003. Impact of medival agriculture on the alluvium in the San River headwaters (Polish Eastern Carpathians). *Catena*, 51(3–4), 255–266. https://doi.org/10.1016/S0341-8162(02)00165-0.

Ložek V., 1964. *Quartärmollusken der Tschechoslovakei*. Rozpravy Ustředniho Ustavu Geologického, 31, Herausgegeben von der Geologischen Zentralanstalt im Verlag der Tschechoslowakischen Akademie der Wissenschaften, Praha.

Łajczak A., 2021. Changes of the Vistula river channel pattern and overbank accumulation rate in the Carpathian Foreland (South Poland) under human impact. *Studia Geomorphologica Carpatho-Balcanica*, 55, 153–184.

Łajczak A., Margielewski W., Rączkowska Z. & Święchowicz J., 2014. Contemporary geomorphic processes in the Polish Carpathians under changing human impact. *Episodes*, 37(1), 21–32. https://doi.org/10.18814/epiiugs/2014/v37i1/003.

Margielewski W., 1998. Landslide phases in the Polish Outer Carpathians and their relation to the climatic changes in the Late Glacial and Holocene. *Quaternary Studies in Poland*, 15, 37–53.

Margielewski W., 2006. Record of the Late Glacial-Holocene climatic changes in landslide forms and deposits of the Beskid Makowski and Beskid Wyspowy Mts. area (Polish Outer Carpathians). *Folia Quaternaria*, 76, 1–149.

Margielewski W., 2018. Landslide fens as a sensitive indicator of paleoenvironmental changes since the Late Glacial: a case study of the Polish Western Carpathians. *Radiocarbon*, 60(4), 1199–1213. https://doi.org/10.1017/RDC.2018.68.

Matthews J.A. & Briffa K.R. 2005. The 'Little Ice Age': re-evaluation of an evolving concept. *Geografiska Annaler*, 87A, 17–36.

Mauri A., Davis B.A.S., Kaplan J.O. & Collins P., 2015. The climate of Europe during the Holocene: A gridded pollen-based reconstruction and its multi-proxy evaluation. *Quaternary Science Reviews*, 112, 109–127. https://doi.org/10.1016/j.quascirev.2015.01.013.

Mayewski P.A., Rohling E.E., Stager J.C., Karlen W., Maasch K.A., Meeker L.D., Meyerson E.A., Gasse F., van Kreveld S., Holmgren K., Lee-Thorp J., Rosqvist G., Rack F., Staubwasser M., Schneider R.R. & Steig E.J., 2004. Holocene climate variability. *Quaternary Research*, 62(3), 243–255. https://doi.org/10.1016/j.yqres.2004.07.001.

Morisita M., 1959. Measuring of interspecific association and similarity between communities. *Memories of the Faculty of Sciences, Kyushu University*, E, 3, 65–80.

Nussbaumer S.U., Steinhilber F., Trachsel M., Breitenmoser P., Beer J., Blass A., Grosjean M., Hafner A., Holzhauser H., Wanner H. & Zumbühl H.J., 2011. Alpine climate during the Holocene: A comparison between records of glaciers, lake sediments and solar activity. *Journal of Quaternary Science*, 26, 703–713. https://doi.org/10.1002/jqs.1495.

Obidowicz A., 1990. Eine Polleanalytische und Moorkundliche Studie zur Vegetationsgeschichte des Podhale-Gebietes (West-Karpaten). *Acta Palaeobotanica*, 30, 147–219.

Pánek T., Smolková V., Hradecký J., Baroò I. & Šilhán K., 2013. Holocene reactivations of catastrophic complex flow-like landslides in the Flysch Carpathians (Czech Republic/Slovakia). *Quaternary Research*, 80, 33–46. https://doi.org/10.1016/j.yqres.2013.03.009

Perşoiu I. & Perşoiu A., 2019. Flood events in Transylvania during the Medieval Warm Period and the Little Ice Age. *The Holocene*, 29(1), 85–96. https://doi.org/10.1177/0959683618804632

Plunkett G. & Swindles G.T. 2008. Determining the Sun's influence on Lateglacial and Holocene climates: a focus on climate response to centennial-scale solar forcing at 2800 cal. BP. *Quaternary Science Reviews*, 27, 175–184. https://doi.org/10.1016/j.quascirev.2007.01.015

Rączkowska Z., Łajczak A., Margielewski W. & Święchowicz J., 2012. Recent landform evolution in the Polish Carpathians. [in:] Loczý D., Stankoviansky M. & Kotarba A., (eds) *Recent Landform Evolution. The Carpatho-Balcan-Dynaric Region*. Springer Geography, Springer Dordrecht Heidelberg, London, New York, 47–101. https://doi.org/10.1007/978-94-007-2448-8.

Rădoane M., Chiriloaei F., Sava T., Nechita C., Rădoane N. & Gâza O., 2019. Holocene fluvial history of Romanian Carpathian rivers. *Quaternary International*, 527, 113–129. https://doi.org/10.1016/j.quaint.2018.11.014.

Reimer P., Austin W., Bard E., Bayliss A., Blackwell P., Bronk Ramsey C., Butzin M., Cheng M.H., Edwards R., Friedrich M., Grootes P., Guilderson T., Hajdas I., Heaton T., Hogg A., Hughen K., Kromer B., Manning S., Muscheler R. & Talamo S., 2020. The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). *Radocarbon*, 62(4), 725–757. https://doi.org/10.1017/RDC.2020.41.

Rybníček K. & Rybníčková E., 2002. Vegetation of the Upper Orava region (NW Slovakia) in the last 11000 years. *Acta Palaeobotanica*, 42, 153–170.

Soldati M., Corsini A. & Pasuto A., 2004. Landslides and climate change in the Italian Dolomites since the Lateglacial. *Catena*, 55(2), 141–161. https://doi.org/10.1016/S0341-8162(03)00113-9.

Starkel L., 1987. Man as a cause of sedimentologic changes in the Holocene. *Striae*, 26, 5–12.

Starkel L., 1997. Mass movement during the Holocene: Carpathian example and the European perspective. [in:] Frenzel B. et al. (Hrsg.), Rapid mass movement as a source of climatic evidence for the Holocene, European Palaeoclimate and Man, 12, Paläoklimaforschung, 19, Gustav Fischer Verlag, Stuttgart – Jena – Lübeck – Ulm, 385–400.

Starkel L., 2005. Role of climatic and anthropogenic factors accelerating soil erosion and fluvial activity in Central Europe. *Studia Quaternaria*, 22, 27–33.

Starkel L., Soja R. & Michczyńska D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. *Catena*, 66(1–2), 24–33. https://doi.org/10.1016/j.catena.2005.07.008.

Starkel L., Michczyńska D.J., Krąpiec M., Margielewski W., Nalepka D. & Pazdur A., 2013. Progress in the Holocene chrono-climatostratigraphy of Polish territory. *Geochronometria*, 40(1), 1–21. https://doi.org/10.2478/s13386-012-0024-2.

Święchowicz J., 2010. Ekstremalne spłukiwanie i erozja linijna na stokach użytkowanych rolniczo w Karpatach fliszowych. *Prace i Studia Geograficzne*, 45, 29–48.

Święchowicz J., Margielewski W., Starkel L, Łajczak A., Pietrzak M., Krzemień K., Gorczyca E. & Bucała-Hrabia A., 2021. Współczesna ewolucja rzeźby Karpat Zewnętrznych i Podhala. [in:] Kostrzewski A., Krzemień K., Migoń P., Starkel L., Winowski M. & Zwoliński Z. (eds.), *Współczesne przemiany rzeźby Polski*, Bogucki Wydawnictwo Naukowe, Poznań, 95–222. https://doi.org/10.12657/9788379863822-04.

Welter-Schultes F., 2012. *European non-marine molluscs, a guide for species identification*. Planet Poster Editions, Göttingen.

Wiktor A., 2004. *Ślimaki lądowe Polski*. Mantis, Olsztyn.

Wirth S.B., Glur L., Gilli A. & Anselmetti F.S., 2013. Holocene flood frequency across the Central Alps – Solar forcing and evidence for variations in North Atlantic atmospheric circulation. *Quaternary Science Reviews*, 80, 112–128. https://doi.org/10.1016/j.quascirev.2013.09.002.