Geology, Geophysics & Environment 2022, vol. 48 (1): 51–68

Molluscan assemblages in sediments of a landslide on Majerz Hill near Niedzica (Inner Carpathians, Southern Poland) – phases of development and environmental changes

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Received: 24 January 2022; accepted: 11 April 2022; first published online: 20 April 2022

Abstract: A detailed malacological analysis was made of sediments associated with a small landslide which had developed on the north-eastern slope of Majerz Hill near Niedzica (Inner Carpathians, Southern Poland). The age of the development and environmental changes associated with particular phases of the landslide was determined by means of radiocarbon dating. The analyses made it possible to distinguish two periods of landslide activation falling on the turn of the Early/Middle Holocene and on the Late Holocene (probably on the Iron Age Cold Period). These phases are closely related to periods of increased mass movements, both of landslides and debris flows in other European mountains, stages of glacial advance in the Alps, periods of increased fluvial activity in rivers and elevated water levels in European lakes. The molluscan assemblages also enabled the reconstruction of environmental conditions before the landslide formation, during periods of dormancy, and after the end of its activity.

Kewords: landslide, molluscan assemblages, environmental changes, Holocene, Podhale Basin, Southern Poland

INTRODUCTION

The Carpathians are a favourable region for the development of mass movements. This is related to the presence of flysch formations, especially fine-grained sandstone and shale sequences. Slope gradient, density of river systems and the geological structure of the rocky basement also play an important role. The climatic conditions, characterized by high rainfall, especially in the spring and summer months, are another important element. A final factor influencing the intensity of mass movements is also human activity, which manifests itself in changes to both water relations and the mechanical disturbance of the slope balance. Approximately 23,000 landslides have been registered in the Polish Carpathians till now. In some parts, even several dozen percent of the slopes are covered by various types of mass movements (Rączkowski 2007, Bucała-Hrabia et al. 2022).

The geological structure of the rocky basement is one of the most important factors determining mass movements. Slopes made of flysch are very prone to the development of different types of mass movements (Margielewski 2009). A particular intensification of these phenomena falls on years characterized by intense precipitation concentrated in the summer months (Ziętara 1968, Gil & Starkel 1979). Analyses of numerous landslide forms have shown that there is a close relationship between phases of the activation of old forms and the formation of new ones and periods

https://doi.org/10.7494/geol.2022.48.1.51 ISSN 2299-8004 | e-ISSN 2353-0790 | Wydawnictwa AGH

of climate change (e.g., Starkel 1985, 1997, Margielewski 1998, 2006, 2018, Dapples et al. 2002, Soldati et al. 2004, Borgatti & Soldati 2010, Starkel et al. 2013, Pánek et al. 2013).

Studies on landslides range from traditional methods of describing their morphology to a broad spectrum of analyses of sediments associated with the forms in question. The age of landslides can be determined by various methods: from classical geomorphological observations, through analyses of sediments and organic remains to the use of historical accounts (Lang et al. 1999). The most effective methods of dating landslides are based on the analysis of organic remains (plant macrofossils, pollen and molluscs), dendrochronological analysis and radiocarbon dating (e.g., Braam et al. 1987, Krąpiec & Margielewski 1991, 2000, Alexandrowicz S.W. 1996, 1997, Alexandrowicz W.P. 2013a, Margielewski 2003, 2006, 2018, Michczyński et al. 2013, Stoffel et al. 2013, Pánek et al. 2013).

Malacological studies have rarely been conducted within landslide zones and have mainly focused on the Polish Carpathians (Alexandrowicz S.W. 1993, 1996, 1997, Alexandrowicz W.P. 2013a, Alexandrowicz S.W. & Alexandrowicz Z. 1999). Meanwhile, this method significantly complements the results of other analyses by adding a range of new data. The presented paper shows the interpretative possibilities of the malacological method in relation to environmental features and the age of landslide forms.

SITE DESCRIPTION

The presented form is located on Majerz Hill in the village of Niedzica (GPS: 49°25'08" N; 20°18'11" E). This hill is part of a small range known as the Pieniny Spiskie (Fig. 1). The landslide developed in the zone of outcrops of flysch sediments: thin-bedded, calcareous sandstones and grey shales.

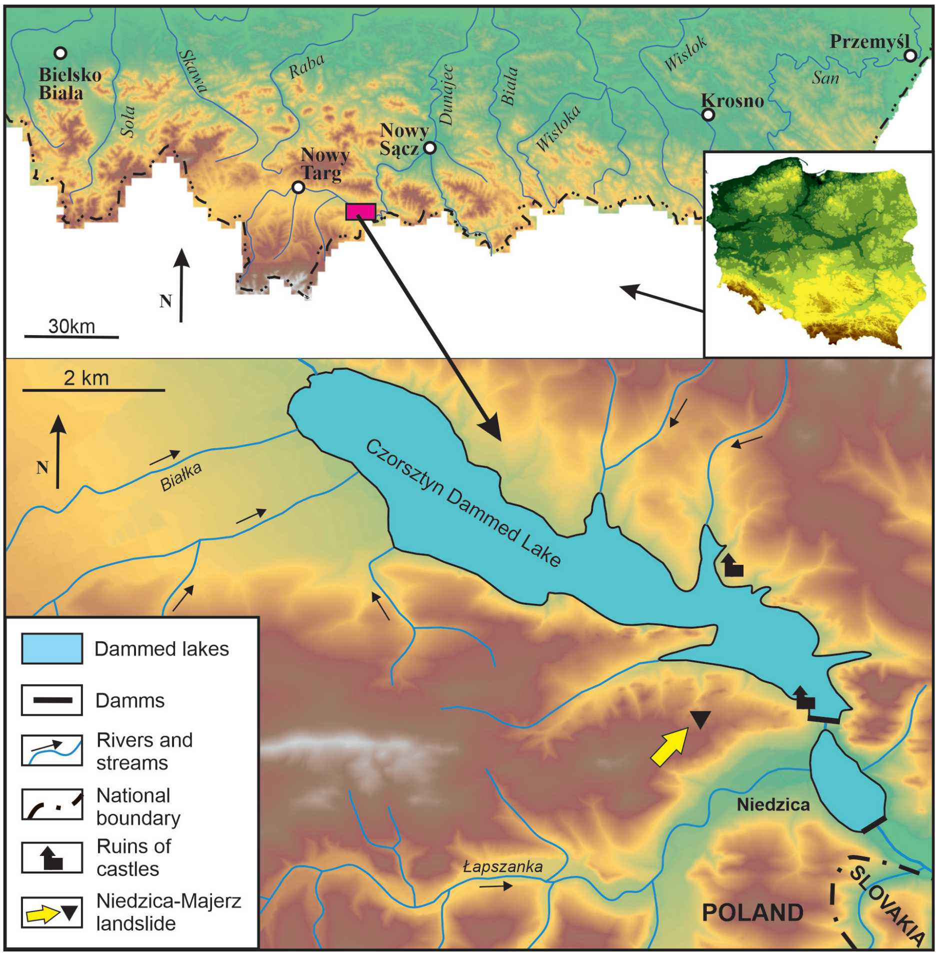

***Fig. 1.** Location of the Majerz landslide*

The proportion of shales in the sequence is slightly higher than that of sandstones and is approximately 60–70% (Kulka et al. 1985, Birkenmajer 1999, Golonka et al. 2018).

The landslide has developed on a consistent slope and the form in question is small (maximum length of the landslide tongue reaches 500 m and its width slightly exceeds 100 m) (Fig. 2). The head scarp is well visible and elevated about 2–3 m. Another scarp is located a dozen or so meters above it and is much less visible, reaching a height of 1–1.5 m. The condition of its preservation indicates that it represents an older phase of landslide development. The surface of the landslide body itself is undulating. Two flattenings are marked here: a higher one of about 25 acres and a lower one of about 5 acres. Both flattenings are remnants of landslide lakes (or mires) and are now filled with peat (Fig. 2). Preliminary data on its formation and on the molluscs occurring in the sediments filling the lakes (mires) are provided in several general studies on Carpathian landslides (Alexandrowicz S.W. 1996, 1997) and on Quaternary molluscs of the Podhale area (Alexandrowicz W.P. 1997).

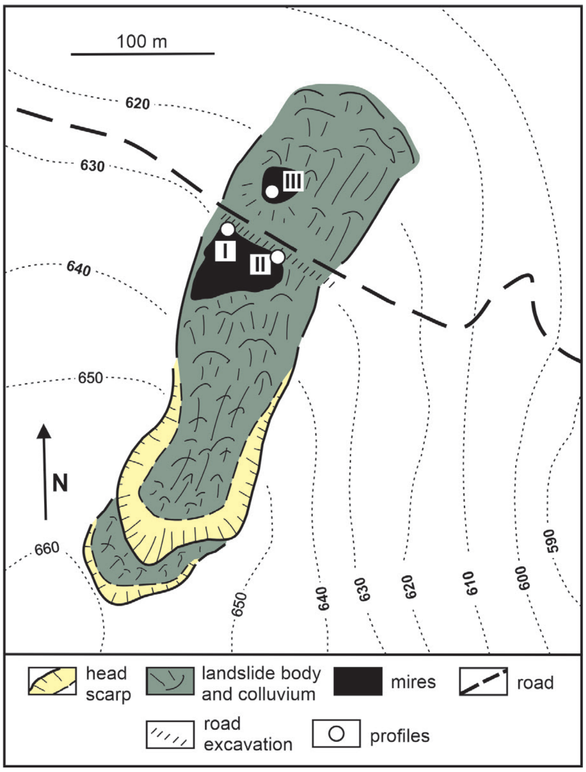

Fig. 2. Landslide of the Majerz Hill – morphology and analyzed profiles

Since then, the material has been significantly supplemented by the development of new exposures and the performance of radiocarbon dating.

MATERIALS AND METHODS

The malacological analysis was based on samples taken from the profiles described above. They had a mass of about 2 kg each and represented intervals of constant thickness (10 cm). The analysed samples represented all of the layers separated within the profiles, except the colluvial sediments. In the latter, the survey testing did not reveal the presence of mollusc shells. After sludging and drying, all mollusc shells were selected. The abundance of each taxon in the sample was determined using keys (Kerney et al. 1983, Wiktor 2004, Welter-Schultes 2012, Horsák et al. 2013) and the author's own comparative collection. A total of 41 samples (21 from profile Nm-I, 13 from profile Nm-II and 7 from profile Nm-III) formed the basis of the analysis.

Individual mollusc species were classified into ecological groups according to the scheme proposed by Ložek (1964) and modified by S.W. Alexandrowicz & W.P. Alexandrowicz (2011) and Juřičková et al. (2014a): F_F – forest species, F_B – shadow-loving species of sparse forests and shrubland zones, F_H – shadow-loving species of moist forests, O_O – open-country species, M_I – mesophilous species of medium-humid environments, M_H – mesophilous species of moist environments, H – hygrophilous taxa, and W – aquatic species. The percentages of each group and selected taxa were used to construct malacological diagrams as a starting point for paleoenvironmental reconstructions.

Statistical analysis, including dendrogram similarity analysis, was carried out using the PAST statistical program (Hammer at al. 2001). The UPGMA clustering method and Morisita's algorithm (Morisita 1959) were used to construct the dendrogram. This made it possible to distinguish faunistic assemblages characterized by a specific taxonomical composition and ecological structure. Radiocarbon dating made it possible to determine the age of the sediments. A total of 6 dates were made based on *Arianta arbustorum* shells (1 date), plant fragments (3 dates) and peat

(2 dates). Analyses were performed at the Absolute Dating Methods Centre, Institute of Physics, Silesian University of Technology in Gliwice (laboratory number: Gd) (4 samples) and in the Radiocarbon Laboratory in Skała (laboratory number: MKL) (2 samples). The results of these determinations were calibrated using OxCal software (Bronk Ramsey 2017) and the IntCal 20 calibration curve (Reimer et al. 2020).

RESULTS

Profile description

Three profiles (Nm-I – Nm-III) were analysed. Profiles Nm-I and Nm-II represent the filling of the larger lake (peat-bog). The sediments are exposed in a road excavation. The Nm-I profile represents the most complete sequence and is over 5.5 m thick. In the thill, the bedrock is exposed – shale and fine-grained sandstone flysch. Above, there are solifluction deposits developed as yellow silt with numerous sharp-edged sandstone blocks. The thickness of the solifluction deposits reaches 40 cm and decreases towards the NW. At a distance of about 60 m the layer in question disappears and is not present in the Nm-II profile (Figs. 2–4). Above it lie dark calcareous silts with isolated blocks of sandstone (thickness – about 30 cm) (profile Nm-I) decreasing towards the NW. Overlying this is a yellowish-brown silty sediment with very numerous sharp-edged sandstone blocks. The sediment is unsorted and shows no depositional structures. Fragments of branches and even small tree trunks are abundant, especially in the thill section. The sediments in question can be interpreted as a colluvial layer representing an older stage of landslide development. This layer appears in profiles Nm-I and Nm-II, reaching a thickness of up to 70 cm. A thin (up to 10 cm) layer of black peat is visible above the colluvial deposits in profiles Nm-I and Nm-II, above which lie dark grey calcareous silts (up to 40 cm thick) containing plant detritus. Above this lie brown silts containing very abundant sandstone crumbs. The sizes of the rock fragments vary over a wide range from 2 cm to 25 cm. The sediment in question is massive and shows no signs of ordering or segregation. There is an accumulation of branches and tree trunks mainly in the thill section. It is a colluvial deposit representing a younger stage of landslide development. The thickness of these sediments is the greatest in the Nm-I profile and reaches 3 m. It decreases to the NW and in the Nm-II profile is reduced to 2.2 m. The top part of both profiles is formed by black peat. The thickness of the peat in both profiles is similar, 80–90 cm (Figs. 2–4).

Profile Nm-III represents the filling of a smaller lake (peat-bog). The trench exposed the roof of the younger colluvial layer described above, covered by black poorly decomposed peat about 60 cm thick (Figs. 2, 4).

Mollusc shells have been found in the sediments described above. They occurred both under colluvial sediments and in the peat covering them. No mollusc remains were found in the colluvial deposits and in the thin peat layer in the middle part of the sequence. The analysis of this malacofauna supported by the results of age determination with the radiocarbon method enabled paleoenvironmental and stratigraphic reconstructions of the landslide on the Majerz Hill, as well as the reconstruction of the phases of its development.

Malacofauna

Mollusc shells were abundant in the samples analysed. Particualrly noteworthy is the good state of preservation of the shells (no traces of chemical dissolution, relatively small number of fragments indicating limited influence of physical destructive factors). The fauna included 55 terrestrial species and one aquatic species. Also, plates of slugs have been found. The number of taxa in each sample ranged from 8 to 36 and specimens from 103 to 713. In total, the shell material included over 8,500 specimens (Tabs. 1, 2).

The malacofauna found at the Majerz site is diverse in its ecological requirements. The most numerous groups are taxa typical of shaded habitats represented by a total of 30 species. Forest taxa (F_F group) include species inhabiting dense forests with varying substrate moisture. Present here are both taxa preferring coniferous forests and relatively cool climates with marked continental influences (*Discus ruderatus*) and forms associated with deciduous and mixed forests and warm, humid climates with greater importance of Atlantic air masses (*Discus perspectivus*, *Ruthenica filograna*) (Figs. 3, 4, Tabs. 1, 2).

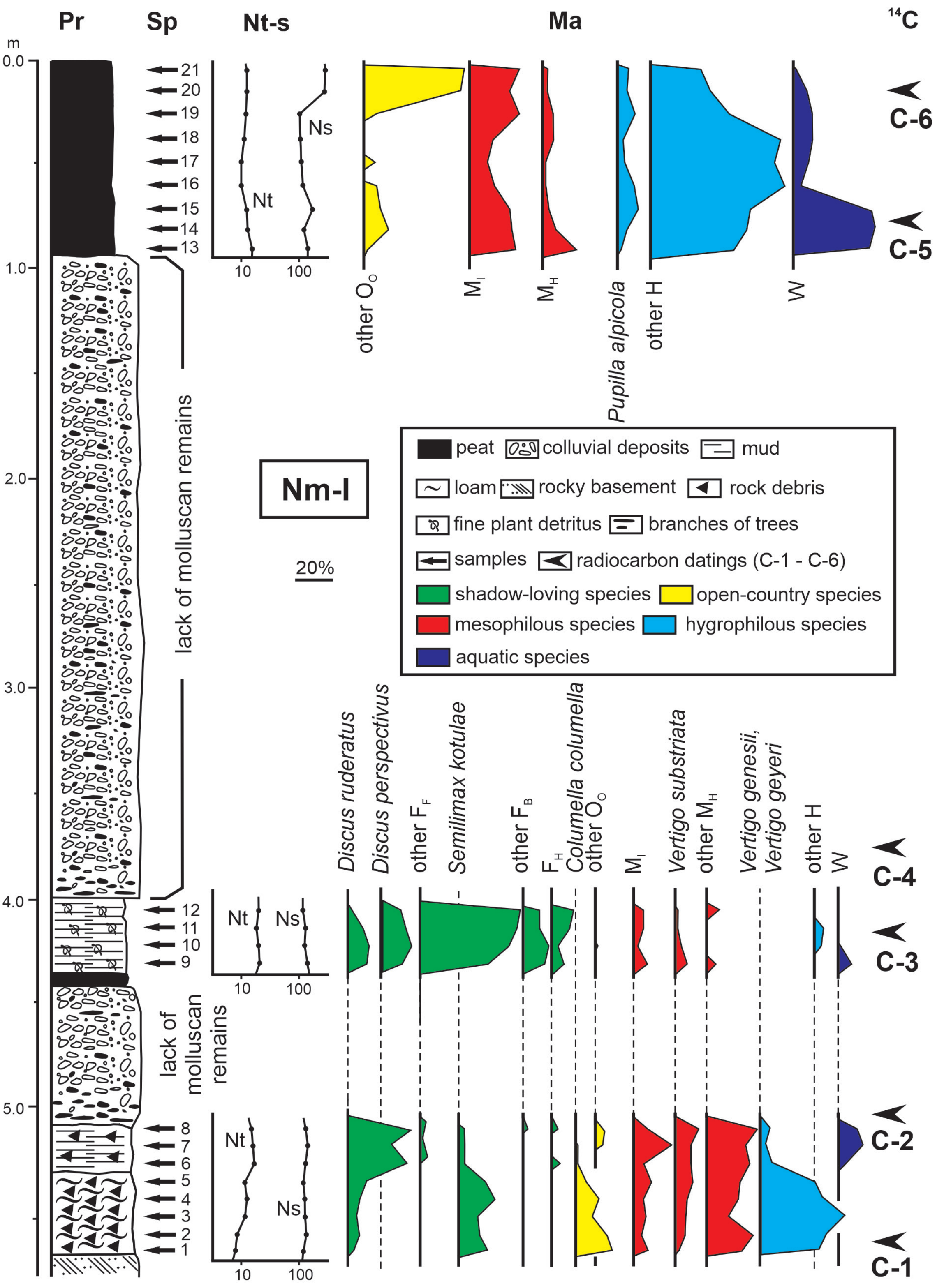

Fig. 3. *Lithology, sampling and malacological diagram of the profile Nm-I: Pr – lithological profile, Sp – samples, Nt-s – number of taxa (Nt) and specimens (Ns), Ma – malacological percentage diagram (ecological groups of molluscs [after Ložek 1964, Alexandrowicz S.W. & Alexandrowicz W.P. 2011, Juřičková et al. 2014a]: F_F – forest species, F_B – shade-loving species of sparse forests and shrubland zones, F_H – shade-loving species of moist forests, O_O – open-country species, M_I – mesophilous species of medium-humid environments, M_H – mesophilous species of moist environments, H – hygrophilous taxa, W – aquatic species), ^{14}C – radiocarbon dating (see Tab. 3)*

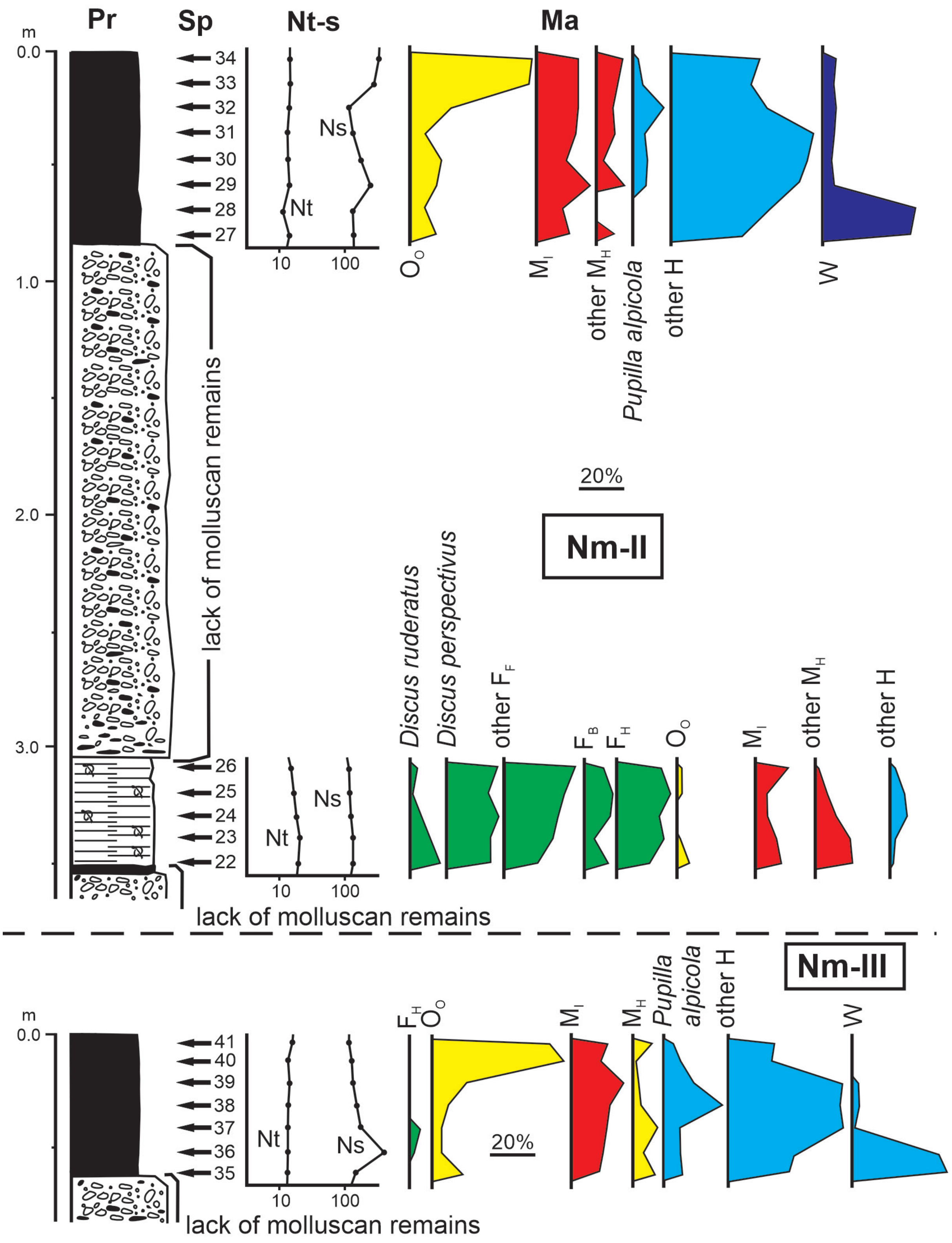

Fig. 4. *Lithology, sampling and malacological diagram of the profiles Nm-II and Nm-III. For explanations see Figure 3*

Table 1

Malacofauna of the profile Nm-I

E	Taxon	Samples (profile Nm-I)																				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
F_F	*Platyla polita*						S			R	S	R	R									
F_F	*Argna bielzi*									S			S									
F_F	*Ena montana*						S		S	S	S	S	S									
F_F	*Discus ruderatus*	S	S	S	S	R	C	C	C	F	F	F	S									
F_F	*Discus perspectivus*									F	F	F	F									
F_F	*Eucobresia nivalis*								S	S	S	S										
F_F	*Semilimax semilimax*										R	R	R									
F_F	*Aegopinella pura*									F	F	F	F									
F_F	*Mediterranea depressa*									S	R		S									
F_F	*Vitrea diaphana*									R	R	F	F									
F_F	*Vitrea transsylvanica*									S	S	R	R									
F_F	*Vitrea subrimata*									R	R	F	S									
F_F	*Clausilia cruciata*										S	S	S									
F_F	*Macrogastra plicatula*									R	S											
F_F	*Ruthenica filograna*									R	R	F	F									
F_F	*Monachoides incarnatus*										S	S										
F_F	*Petasina unidentata*						S	S		R	S		S									
F_F	*Chilostoma faustinum*									S	S	S										
F_F	*Isognomostoma isogn.*									R	R	R	S									
F_B	*Vertigo alpestris*				S					S	S											
F_B	*Discus rotundatus*								R	F	F	F	R									
F_B	*Semilimax kotulae*	F	F	F	C	F	R	S	R													
F_B	*Aegopinella minor*									R	R	R	S									
F_H	*Vitrea crystallina*						R		R	R	R	F	F									
F_H	*Monachoides vicinus*						S			S		S	S									
O_O	*Vallonia costata*						S	S						R	S	R		S			C	C
O_O	*Vallonia pulchella*						S	R	S	S			S	R	R	F		5		R	C	C
O_O	*Pupilla muscorum*						R	R						R							F	F
O_O	*Columella columella*	F	F	F	F	F	S	S	S													
O_O	*Vertigo pygmaea*							S						S	S	S	S	R			F	R
M_I	*Cochlicopa lubrica*							R		S			S	R	S	F	S	R	S	S	F	C
M_I	*Punctum pygmaeum*			S			S	F				S	S	S	S	R				S	R	S
M_I	*Vitrina pellucida*									S	S		S	R								S
M_I	*Perpolita hammonis*				S	S		R	S				S	S	S	R			S	S	R	F
M_I	*Vitrea contracta*								S	R		R		F	S	R	R		R	F	R	F
M_I	*Euconulus fulvus*	R		S	S	R	S	R						S								
M_I	*Clausilia dubia*		R			S		R						S	S							
M_H	*Carychiun tridentatum*						S		R	R				R								
M_H	*Vertigo substriata*	S	R	R	R	F	F	F	F	R	S	S	S									
M_H	*Vertigo angustior*												S	S	R	F	S	S	R	R	R	R
M_H	*Succinella oblonga*		F	S	S		F	F	F					R								
M_H	*Perforatella bidentata*						F	F					R	S					S	S		
M_H	*Arianta arbustorum*	F	F	F	F	F	F	F	F													
H	*Carychium minimum*										S	R		R		R				S	F	R
H	*Vertigo genesii*	F	C	C	F	F	S	S	S													
H	*Vertigo geyeri*	F	F	F	F	F	S	S	S													
H	*Vertigo antivertigo*													R	R	C	R	R	R	R	F	
H	*Pupilla alpicola*													S	R	F	F	R	R	F	F	F
H	*Succinea putris*										S	S		C	C	C	C	C	C	F	C	C
H	*Succinea elegans*													R	R	F	F	F	F	F	F	F
W	*Galba truncatula*						R	F	F	F	S			C	C	C	R	F	F	F	F	S
W	Plates of slugs			S	S	S	S		F			R		S	F	R	R	R	R	R	F	S
Stratigraphy		LG					EH			MH				LH								

Explanations: E – ecological groups of molluscs (after Ložek 1964, Alexandrowicz S.W. & Alexandrowicz W.P. 2011, Juřičková et al. 2014a): F_F – forest species, F_B – shade-loving species of sparse forests and shrubland zones, F_H – shade-loving species of moist forests, O_O – open-country species, M_I – mesophilous species of medium-humid environments, M_H – mesophilous species of moist environments, H – hygrophilous taxa, W – aquatic species. Number of specimens (after Alexandrowicz S.W. & Alexandrowicz W.P. 2011): S – single (1–3 specimens), R – rare (4–10 specimens), N – few (11–32 specimens), C – numerous (33–100 specimens), A – abundant (101–316 specimens). Stratigraphy: LG – Late Glacial, EH – Early Holocene, MH – Middle Holocene, LH – Late Holocene.

Table 2
Malacofauna of the profiles Nm-II and Nm-III

E	Taxon	Samples (profile Nm-II)													Samples (profile Nm-III)						
		22	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**
F_F	*Platyla polita*	R	S	R	S	S															
F_F	*Vertigo pusilla*	S	S	S	S	R															
F_F	*Ena montana*	R	R	S	R	S															
F_F	*Discus ruderatus*	F	R	R	S	R															
F_F	*Discus perspectivus*	C	R	C	C	R															
F_F	*Eucobresia nivalis*	S	S	S	S	S															
F_F	*Semilimax semilimax*	S	S	S	S	R															
F_F	*Aegopinella pura*	S	R	R	S	F															
F_F	*Meditterranea depressa*			S	S	S															
F_F	*Vitrea diaphana*		R		R	R															
F_F	*Vitrea transsylvanica*	S	S	R	S	R															
F_F	*Vitrea subrimata*		S	S	S	S															
F_F	*Cochlodina laminata*	R	S	R	S																
F_F	*Clausilia cruciata*	S	S	S																	
F_F	*Ruthenica filograna*	R	R	S	R	R															
F_F	*Monachoides incarnatus*		R	S																	
F_F	*Chilostoma faustinum*	S	S	S	S	S															
F_F	*Isognomostoma isognomostomos*	S	S	S	S	R															
F_B	*Discus rotundatus*	R	S	S	R																
F_B	*Aegopinella minor*	R	R	R	R	R															
F_B	*Fruticicola fruticum*	F	S	R	R	S															
F_H	*Vitrea crystallina*	F	F	F	F	F															
F_H	*Macrogastra tumida*		S		R																
F_H	*Monachoides vicinus*	R	R	R	R	R										F	F				
O_O	*Vallonia costata*	R	S		S		R	R	F	R	S	R	C	C	R	F	R	R	R	C	C
O_O	*Vallonia pulchella*	S				S	R	F	C	F	R	F	C	A	R	F	R	R	F	C	C
O_O	*Pupilla muscorum*					S						S	F	F	R					S	S
O_O	*Vertigo pygmaea*							R	F	F	R	S	R	R	R			R	R	F	R
M_I	*Cochlicopa lubrica*	S			S	S	S	S	F	F	R	R	F	F	F	C	F	S	F	R	R
M_I	*Punctum pygmaeum*	S	S				S		F			R	F	F		R			R	R	S
M_I	*Vitrina pellucida*		R	S			S		S				S			F	R				S
M_I	*Perpolita hammonis*	R	S	S		S			F		S	R	R	R	R	F	R	S	R	R	R
M_I	*Vitrea contracta*	S	S	S	S	F	F	F	R	R	F	R	F	F	R			R	R		
M_I	*Limacidae*	S	R	S	S	S	R	F	F	R	R	R	R	F	R		R	S	R	R	R
M_I	*Euconulus fulvus*	S	S		S	S	S									S					S
M_H	*Carychiun tridentatum*	F	R	R		R	R														R
M_H	*Vertigo substriata*	S	S	S																	
M_H	*Vertigo angustior*		S				R		F	R	S	R	F	F	S	C	R	R	R	S	R
M_H	*Succinella oblonga*	R	R	S	R										R						
M_H	*Perforatella bidentata*	F	F	S	S	S	S														
H	*Carychium minimum*	S	S	F	R	S	R		F	F	F	S	F	F	R		S	S	R	S	R
H	*Vertigo antivertigo*						F	F	C	C	R	S	F	F	F	F		F	F	R	R
H	*Pupilla alpicola*								F	F	F	F	F	R	F	C	F	C	F	F	R
H	*Succinea putris*						C	C	A	C	C	C	C	C	C	A	A	A	C	F	R
H	*Succinea elegans*						R	R	F	F	F	F	F	F	R	C	C	C	F	R	R
W	*Galba truncatula*						C	C	F	R	R	R	F	F	C	A	R	R	R		
W	Plates of slugs	S	R	S	S	S	R	F	F	R	R	R	R	F	R		R	S	R	R	R
Stratigraphy		MH					LH								LH						

For explanations see Table 1.

Shadow-loving species living in lit through forests and shrub thickets (group F_B) are less common. More noteworthy is the presence of *Semilimax kotulae*, a cold-loving taxon often found in Late Glacial and Early Holocene sediments. Today, it is a late glacial relict in the study area (e.g., Alexandrowicz W.P. 1997, 2013b, Wiktor 2004, Alexandrowicz W.P. et al. 2014). Ecological group F_H, which includes shadow-loving species preferring moist habitats, is represented only by three taxa (Figs. 3, 4, Tabs. 1, 2). Open-country taxa (group O_O) play an important role. *Vallonia pulchella* and *Vallonia costata*, species inhabiting open, grassy biotopes of varying humidity, are very abundant in the upper parts of all profiles. An important taxon for interpretation is *Columella columella*, a cold-loving species typical of moist grassy habitats. This form is one of the most characteristic of molluscan assemblages associated with periglacial zones or with high mountains where it usually lives in the alpine meadow zone. In Quaternary sediments this species is often found in loess formations and also in Late Glacial deposits. It is much less common in Early Holocene deposits. Since the Middle Holocene it has only been found in high mountain regions (Alps, Tatras) in Central Europe (Pokryszko 1990, Wiktor 2004, Welter-Schultes 2012). Mesophilous species include snails inhabiting moderately humid (group M_I) and humid (group M_H) biotopes in varying degrees of shading. Among the 14 taxa included in this group, the occurrence of *Vertigo substriata* and *Arianta arbustorum* is worthy of note. Both of these species have a high thermal tolerance and inhabit shady, moist biotopes. They are frequent components of assemblages associated with the Early Holocene. Another important species is *Vertigo angustior*, a moisture-loving form with relatively low thermal tolerance, preferring moderate warm climate (Figs. 3, 4, Tabs. 1, 2). An important component of the malacofauna identified at the Majerz site are hygrophilous taxa (group H). Notable among these is the presence of *Vertigo genesii* and *Vertigo geyeri* – species characteristic of cold climate and open wetland tundra-type habitats. Today they only occur in isolated localities in Central Europe and are glacial relicts (Pokryszko 1990, Horsák & Hájek 2005, Vavrová et al. 2009, Welter-Schultes 2012). The presence of a viable population of *Vertigo geyeri* was found several kilometres to the west of the discussed site (Schenková et al. 2012, Schenková & Horsák 2013). Another interesting example is *Pupilla alpicola*, a moist-loving taxon that prefers open habitats and is known in Europe from a small number of sites in the Alps and Carpathians (Horsák et al. 2011, Welter-Schultes 2012). Today it lives in the area of the presented site (Alexandrowicz S.W. 1994, Horsák et al. 2010) (the only site in Poland) (Figs. 3, 4, Tabs. 1, 2). This fauna is complemented by aquatic species (group W) represented by *Galba truncatula*, a desiccation-tolerant taxon characteristic for periodic water bodies (Figs. 3, 4, Tabs. 1, 2).

DISCUSSION

Molluscan assemblages

A similarity dendrogram was used to group fauna for the presence of assemblages characterizing specific environmental features. Using this method, six faunistic assemblages were distinguished, differing in both species composition and ecological preferences (Fig. 5).

Assemblage with *Vertigo genesii* (Vg). This is a relatively poor fauna, characterized by an abundance of cold-loving species: *Vertigo genesii, Vertigo geyeri, Columella columella* and forms with high thermal tolerance *Semilimax kotulae*, *Arianta arbustorum*. This assemblage is typical of cold and even polar climates and wet, open tundra-type habitats. The occurrence of taxa associated with lightly shaded habitats (*Semilimax kotulae*, *Arianta arbustorum*) indicates the presence of small patches of shrubby vegetation or sparse, overstory woodland. The fauna in question is characteristic of the Late Glacial, especially of its cold decline phase (Younger Dryas). It was identified within solifluction sediments in the thill part of the Nm-I profiles (Fig. 3). Its association with the Younger Dryas is indicated by the results of the radiocarbon dating of *Arianta arbustorum* shells (12 823–11 875 cal BP and 11 856–11 834 cal BP; C-1) (Fig. 3, Tab. 3). In a similar stratigraphic position, this assemblage has been found in many neighbouring sites (Alexandrowicz W.P. 1997, 2013b, 2015, Alexandrowicz W.P. et al. 2014, 2016) as well as in numerous profiles described from

Europe (e.g., Alexandrowicz S.W. 1983, Alexandrowicz W.P. 2004, 2019, 2021a, Limondin-Lozouet & Rousseau 1991, Limondin-Lozouet 1992, 2011, Krolopp & Sümegi 1993, Preece & Day 1994, Mania 1995, Preece 1998, Meyrick 2001, 2002, Meyrick & Preece 2001, Gedda 2001, 2006, Juřičková et al. 2014b, Horáčková et al. 2015).

Assemblage with *Discus ruderatus* (Dr). This is a fauna characterized by a high proportion of shadow-loving species, with *Discus ruderatus* being the dominant component. This taxon prefers coniferous forests with moist substrates and a relatively cool climate with continental characteristics. Cold-loving species, especially *Semilimax kotulae*, are an important component of the fauna in question. *Vertigo genesii*, *Vertigo geyeri* are slightly less common. The assemblage is complemented by mesophilous snails with high thermal tolerance (*Vertigo substriata*, *Euconulus fulvus*). This malacocenosis was found in the lower interval of the Nm-I profile (Figs. 3, 4). It is characteristic of the Early Holocene and corresponds to the *Ruderatus*-fauna (Dehm 1967). Similar assemblages have been described from the Carpathians (Alexandrowicz W.P. 1997, 2004, 2013b, 2015, 2019, Alexandrowicz W.P. et al. 2014, 2016, Juřičková et al. 2014b, Horáčková et al. 2015, Horsák et al. 2019, Frodlová & Horsák 2021), as well as from many other sites in Europe (Ložek 1964, 2000, Alexandrowicz S.W. 1983, Alexandrowicz W.P. 2004, 2021a, Preece & Day 1994, Preece 1998, Preece & Bridgland 1999, Gedda 2001, Meyrick 2002, Žak et al. 2002, Limondin-Lozouet & Preece 2004, 2014, Limondin-Lozouet 2011, Granai et al. 2020).

Assemblage with *Discus perspectivus* (Dp). It is a very rich malacocenosis, with a dominant proportion of shadow-loving species that make up to 70% of the assemblage. The fauna is complemented by mesophilous snails, while forms typical of open environments are rare. Among the shadow-loving taxa, the highest significance may be attributed to species with high thermal and ecological requirements such as: *Discus perspectivus*, *Discus rotundatus* and *Ruthenica filograna*. The fauna in question is typical of areas covered by deciduous forests (Figs. 3, 4). This assemblage represents the Middle Holocene and corresponds to the *Perspectivus*-fauna (Dehm 1987).

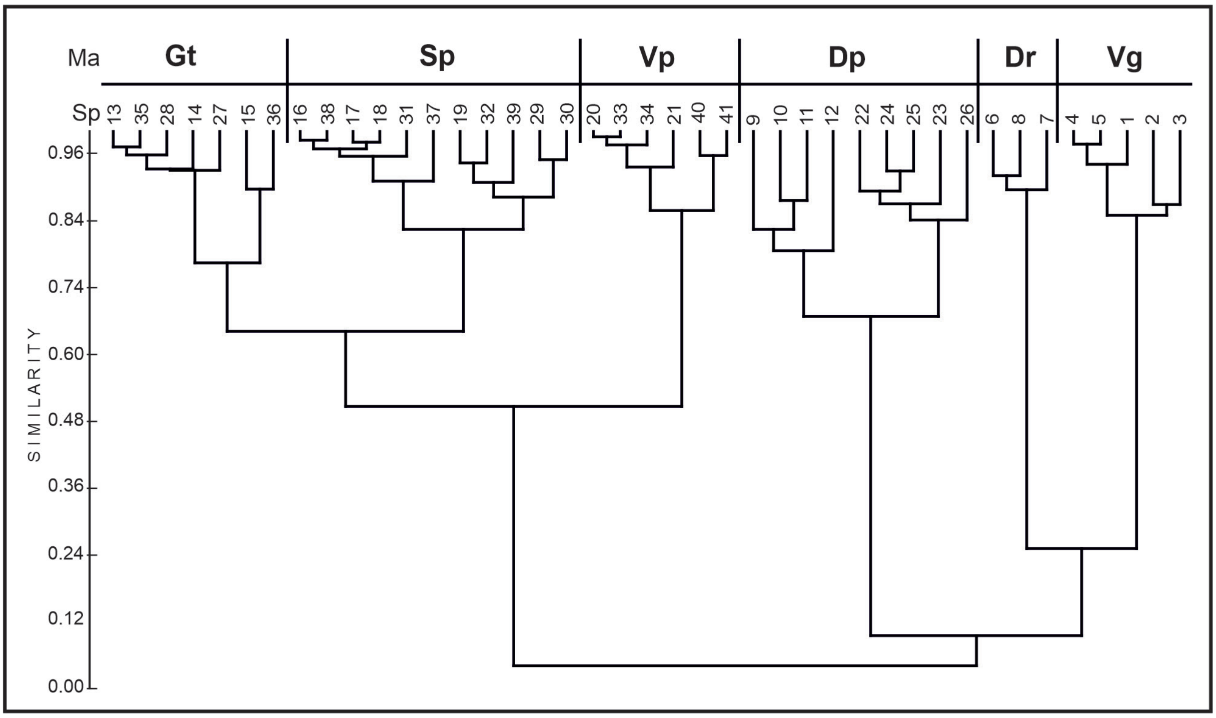

Fig. 5. *Cluster analysis of malacofauna of Holocene deposits from Majerz Hill: Sp – samples (1–41), Ma – molluscan assemblages (Vg, Dr, Dp, Gt, Sp, Vp) described in text*

Rich forest malacocenoses of a similar composition have been described several times, from both the Carpathians (Alexandrowicz W.P. 1997, 2004, 2013b, 2015, 2019, Alexandrowicz W.P. et al. 2014, 2016, Juřičková et al. 2014b, Horáčková et al. 2015, Frodlová & Horsák 2021), as well as from other sites in Central and Western Europe (e.g., Ložek 1964, 2000, Alexandrowicz S.W. 1983, Alexandrowicz W.P. 2004, 2021a, 2021b, Meyrick 2002, Limondin-Lozouet & Preece 2004, 2014, Granai et al. 2020). The Middle Holocene age of the fauna in question is indicated by the results of two radiocarbon age determinations. The older date (C-2: 8410–8192 cal BP) represents the floor part of the sediments lying below the zone of occurrence of the *Discus perspectivus* fauna. The earlier date (C-3: 6741–6450 cal BP) comes from the floor part of the layer containing the described assemblage (Fig. 3, Tab. 3). The fauna in question was found in the lower part of profile Nm-I and in the thill of profile Nm-II (Figs. 3, 4).

Assemblage with *Galba truncatula* (Gt). This assemblage is characterized by a high proportion of moisture-loving species. Other ecological groups appear infrequently and shadow-loving species are virtually absent. A characteristic feature is the abundance of *Galba truncatula* – an aquatic taxon commonly living in temporary water bodies. The assemblage in question indicates the presence of a small, shallow, and periodically disappearing water body. Its origin can be associated with the Late Holocene, and its time frame is determined by radiocarbon dates: 3003–2668 cal BP, 2658–2610 cal BP and 2603–2491 cal BP (C-4) and 2489–2302 cal BP, 2235–2177 cal BP and 2166–2161 cal BP (C-5) (Fig. 3, Tab. 3). The fauna in question occurs in the upper intervals of profiles Nm-I and Nm-II and in the thill part of profile Nm-III (Figs. 3, 4).

Assemblage with *Succinea putris* (Sp). This is a fauna dominated by hygrophilous snails. It is complemented by mesophilous taxa, particularly preferring moist habitats. Other ecological groups are of minor importance. Noteworthy is the complete absence of shade-loving snails. It is an assemblage characteristic of peatlands. It is also known for small peatlands developing in landslide zones (Alexandrowicz S.W. 1993, 1996, 1997, Alexandrowicz W.P. 2013a). At the Majerz site it appears in the upper sections of all profiles and represents the Late Holocene (Figs. 3, 4).

Assemblage with *Vallonia pulchella* (Vp). This is a fauna of low species diversity, in which the most abundant taxa are those of open grassland habitats, particularly *Vallonia pulchella* and *Vallonia costata* which can reach very high numbers. This is complemented by mesophilous and hygrophilous snails. Shadow-loving species are practically absent. The appearance of this assemblage indicates the development of grasslands with fairly high humidity. At the Majerz site this fauna appeared in the historic period, as indicated by the radiocarbon dating results – date C-6: 454–349 cal BP and 339–309 cal BP (Fig. 3, Tab. 3).

Table 3
Results of radiocarbon dating

Date	Age [y BP]	Age [cal BP]	Laboratory code	Material
C-6	320 ±20	454–349 (76.2%) 339–309 (19.2%)	MKL-1353	peat
C-5	2330 ±40	2489–2302 (84.3%) 2235–2177 (10.9%) 2166–2161 (0.3%)	Gd-5109	peat
C-4	2670 ±90	3003–2668 (83.6%) 2658–2610 (3.3%) 2603–2491 (8.5%)	Gd-4704	tree branches
C-3	5800 ±60	6741–6450 (95.4%)	Gd-10437	plant detritus
C-2	7520 ±60	8410–8192 (95.4%)	MKL-1394	tree branches
C-1	10 550 ±180	12 823–11 875 (94.9%) 11 856–11 834 (0.5%)	Gd-4243	shells of *Arianta arbustorum*

Phases of landslide evolution

The landslide on the Majerz Hill is a small form whose development took place in two stages. The malacological content allowed a detailed characteristic of the habitats, and the presence of organic remains (snail shells, plant detritus, branch fragments and peat) made it possible to establish the age and period of alteration on the basis of radiocarbon dating. According to these data, it is possible to distinguish several phases in the development of the form in question:

Phase I (Younger Dryas). The oldest sediments are exposed in the thill part of the Nm-I profile. In this horizon an assemblage with *Vertigo genesii*, characteristic for the Late Glacial decline (Younger Dryas) (12 823–11 875 cal BP and 11 856–11 834 cal BP; C-1; Fig. 6, Tab. 3) was recognized. It indicates a cold climate, the dominance of open, forestless habitats of the tundra type (in moister places) or steppe-tundra type (in drier places) (Fig. 6). Probably small patches of sparse, lit-through forests may have formed isolated enclaves (refugia) (Juřičková et al. 2014b, 2018, 2019, Mitka et al. 2014, Horáčková et al. 2015, Horsák et al. 2019). The similar character of habitats is also indicated by the results of palynological analyses carried out on peatlands in the eastern part of Podhale Basin (NAP phase; Obidowicz 1990, Rybníček & Rybníčková 2002) (Fig. 6).

Phase II (Early Holocene). The dark calcareous silts overlying the solifluction deposits have a different faunal assemblage. It is characterized by the presence of shadow-loving species with low ecological requirements. This is a typical Early Holocene fauna (assemblage with *Discus ruderatus*). Its composition indicates that the Majerz Hill was covered with dense coniferous forests during the Early Holocene. The dominance of such plant communities is also indicated by the results of palynological analyses of Podhale Basin peatlands (*Picea-Ulmus-Pinus* phase; Obidowicz 1990) (Fig. 6).

Phase III (Early/Middle Holocene). Above the silts in the Nm-I profile lies an older layer of colluvial sediments devoid of mollusc shells. The determination of the age of its thill part yielded a result of 8410–8192 cal BP (C-2, Fig. 6, Tab. 3). This period is clearly associated with strong cooling and an increase in climate humidity (8.2 ka event; Bond event 5) (Bond et al. 2001, Mayewski et al. 2004, Rohling & Pälike 2005, Mauri et al. 2015) setting the boundary between Early and Middle Holocene (Walker et al. 2019). It resulted in the formation (or activation) of numerous landslides in the Carpathians and the Alps (Alexandrowicz S.W. 1996, 1997, Starkel 1997, Margielewski 1998, 2006, 2018, Soldati et al. 2004, Pánek et al. 2013) (Fig. 6). There is also an increase in the activity of fluvial processes accentuated by erosion and the accumulation of gravel cover (e.g., Starkel et al. 2006, 2007, 2013) (Fig. 6). The lake sediment sequences show a rise in water level (Ralska-Jasiewiczowa & Starkel 1988, Magny 1993, 2004), and glacial advance is observed in the Alps (Joerin et al. 2006, Ivy-Ochs et al. 2009, Nussbaumer et al. 2011). The older phase of mass movements at Majerz Hill fits well into this trend (Fig. 6). The formation of the landslide and the erosion associated with its movement led to the destruction of part of the sediments representing the Early Holocene. Hence, a gap appears in the malacological sequence (Fig. 6).

Phase IV (Middle Holocene). On top of the colluvial sediments rests a thin layer of peat without mollusc shells. Its formation may be associated with the presence of small depressions, perhaps even short-lived lakes which developed on the landslide body. However, the lack of a malacological record in these sediments makes their interpretation difficult (Fig. 6).

Phase V (Middle Holocene). Above the peat and older colluvial cover lie dark calcareous silts with plant remains and abundant malacofauna. The complex is characterized by high species diversity and the presence of shadow-loving species with high ecological requirements. This is a typical Middle Holocene fauna with *Discus perspectivus*. Its presence is characteristic of dense mixed and deciduous forests and a warm climate with oceanic influences. Such conditions are also indicated by the results of palynological analyses of Podhale peatlands (*Ulmus-Tilia-Quercus-Fraxinus* phase; Obidowicz 1990, Rybníček & Rybníčková 2002). A radiocarbon date is associated with the occurrence of the assemblage with *Discus perspectivus* in the profile at Majerz Hill: 6741–6450 cal BP (C-3; Fig. 6, Tab. 3).

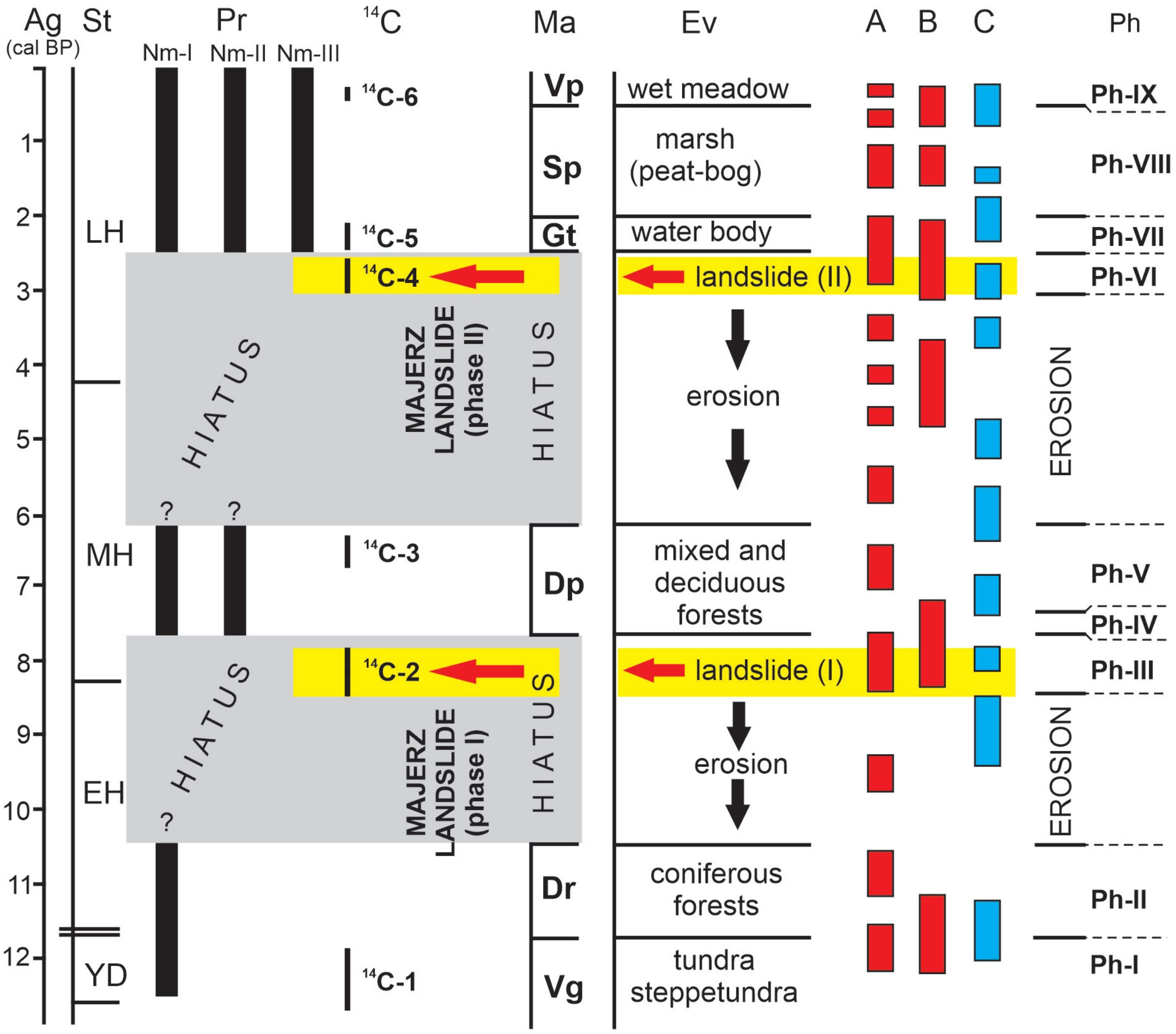

Fig. 6. Phases of development of the Majerz Hill landslide: Ag – age (ka cal BP), St – stratigraphy (after Walker et al. 2019): YD – Younger Dryas, EH – Early Holocene, MH – Middle Holocene, LH – Late Holocene, Pr – stratigraphical range of the profiles (Nm-I – Nm-III), ^{14}C – radiocarbon dating (see Tab. 3), Ma – molluscan assemblages (Vg, Dr, Dp, Gt, Sp, Vp) described in text, Ev – environmental changes, A – phases of increasing of mass movements in Polish Carpathians (after Margielewski 1998, 2006), B – phases of increasing of mass movements in Polish Carpathians (after Alexandrowicz S.W 1996, 1997, Alexandrowicz W.P. 2013a), C – phases of increasing of fluvial activity in Polish Carpathians (after Starkel 1985, Starkel et al. 2006, 2013), Ph – phases of development of the Majerz Hill landslide (Ph-I – Ph-IX) described in text

Phase VI (Late Holocene, Iron Age Cold Epoch?). Above the described silts lies a second layer of colluvial deposits. It represents a younger phase of the landslide's form development. The radiocarbon dating of C-4 – thill of colluvial layer: 3003–2668 cal BP, 2658–2610 cal BP and 2603–2491 cal BP, and C-5 – thill of peat covering colluvial layer: 2489–2302 cal BP, 2235–2177 cal BP and 2166–2161 cal BP (Fig. 6, Tab. 3) define the time interval when the form was activated. A number of climatic fluctuations occurred during this period (Mayewski et al. 2004, Mauri et al. 2015). It can be probably correlated with strong cooling corresponding to the Bond 2 event (Bond et al. 2001). An increase in the intensity of mass movements and fluvial activity of rivers were observed in both the Carpathians (Alexandrowicz S.W. 1996, 1997, Starkel 1997, Margielewski 1998, 2006, 2018, Starkel et al. 2006, 2007, 2013) and the Alps (Soldati et al. 2004, Bogratti & Soldati 2010). In the Alps, glacier advance is associated with this period (Joerin et al. 2006, Ivy-Ochs et al. 2009, Nussbaumer et al. 2011), and a rise in water levels is observed in lakes (Ralska-Jasiewiczowa & Starkel 1988, Magny

1993, 2004). The renewal of the landslide form on Majerz Hill obliterated most of the traces of the older form. Erosion associated with colluvium movement eroded the sediments of the younger part of the Middle Holocene and the older part of the Late Holocene. This is manifested by the gap observed in the malacological sequence (Fig. 6).

Phase VII (Late Holocene; Roman Warm Period?). Small depressions formed on the surface of the landslide body where peat had begun to accumulate. Their thill is dated to 2489–2302 cal BP, 2235–2177 cal BP and 2166–2161 cal BP (C-5; Fig. 6, Tab. 3). It is likely that these depressions were originally small, shallow, and probably periodically disappearing water bodies. This is evidenced by the occurrence of a fauna with *Galba truncatula* (Fig. 6).

Phase VIII (Late Holocene; Roman Warm Period? – the 13th century). Small bodies of water were soon transformed into marshy, swampy terrestrial habitats. This phase is associated with the occurrence of a fauna dominated by hygrophilous taxa (assemblage with *Succinea putris*). During this period, the landslide area was not covered by forest as evidenced by the lack of shadow-loving species. At the same time, palynological data indicate that the Podhale area was largely forested (phases *Picea-Carpinus-Abies* and *Fagus-Abies*; Obidowicz 1990, Rybníček & Rybníčková 2002). These differences are probably due to the specific local conditions, mainly the presence of wetland habitats, which are not conducive to forest development. The significant influence of local environmental factors, especially increased humidity of the substrate, was described on several sites located in the vicinity of the analysed profile (Alexandrowicz W.P. et al. 2018).

Phase IX (Late Holocene; after the 13th century). The final stage of development of this form was the transformation of marshy zones into open relatively wet meadow habitats. They are associated with an assemblage of *Vallonia pulchella*, which began to play a dominant role in the last few hundred years (radiocarbon date: 454–349 cal BP and 339–309 cal BP (C-6) (Fig. 6, Tab. 3). The malacological record lacks traces of human interference with natural processes. This is probably related to the unfavourable conditions for agricultural and pastoral activities and settlements (Alexandrowicz W.P. 2020).

CONCLUSION

A landslide developed on the slopes of Majerz Hill near Niedzica and the associated sediments provide the opportunity to reconstruct the changes in the environment in the period from the end of the Late Glacial (Younger Dryas) until modern times. These are marked both in the subfossil characteristics of the molluscan assemblages and in the nature, course, and intensity of the geological processes. The molluscan assemblages contained in the sediments play a significant role in these reconstructions.

The landslide in question developed in two stages. The former dates to the turn of the Early to Middle Holocene and the latter to the Late Holocene – probably the Iron Age. In both cases there is a clear correlation with climate change, manifested by cooling and wetting. Both phases of landslide development on Majerz Hill relate to periods of mass movement intensification in the Carpathians and higher fluvial activity of the rivers. In a broader context, these periods are associated with the advance of mountain glaciers recorded in the Alps as well as with the rise in the level of mountain and lowland lakes.

The molluscan assemblages occurring in the sediments associated with a landslide make it possible not only to determine the phases of its activity, but also to characterize the features of the environment during the time preceding its formation, as well as during dormant periods. There is a transition from treeless tundra-type habitats in the Younger Dryas through the coniferous forest phase in the Early Holocene to the period of dominance of deciduous and mixed forests in the Middle Holocene. This trend of environmental change has been described in a number of malacological profiles located in close proximity to the site under study. Similar conclusions are also supported by the results of palynological studies carried out in the peatlands of the Podhale region. Malacocoenoses present in the sediments accompanying the landslide on the Majerz Hill also show some specific features related to local conditions. They are most clearly visible in the Late Holocene sediments. Two aspects are worth noting here. Firstly, the presence of communities with a high proportion of moisture-loving and even aquatic species, which were rarely found in Podhale Basin at that time. Their presence can undoubtedly be associated with the appearance of small, probably periodic, water reservoirs formed in the drainless depressions. Secondly, the presence of communities indicating grassy, open biotopes with quite high humidity, while the neighbouring sites in this period were dominated by communities of shadow-loving species. These differences are generated by local conditions, and in particular by the increased soil moisture in the landslide zone. The observed lack of traces of human activity is typical for areas unfavourable for economic exploitation.

The analyses carried out indicate that the use of malacological analysis in landslide studies makes it possible to collect a considerable amount of paleoenvironmental data that are difficult or even impossible to obtain using other methods, especially with regard to the characterization of local microhabitats.

This study has been sponsored by AGH University of Science and Technology through the University subvention no 16.16.140.315.

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