Acta Geologica Polonica, Vol. 65 (2015), No. 2, pp. 247–263
DOI: 10.1515/agp-2015-0010

DE GRUYTER OPEN

The application of malacological analysis in the study of slope deposits: late Pleistocene and Holocene of the Podhale Basin (Carpathians, Poland)

WITOLD PAWEŁ ALEXANDROWICZ

AGH University of Science and Technology, Faculty of Geology, Geophysics and Environment Protection, Chair of General Geology and Geotourism, Al Mickiewicza 30, PL-30-059 Kraków. E.mail: wpalex@geol.agh.edu.pl

ABSTRACT:

Alexandrowicz, W.P. 2015. The application of malacological analysis in the study of slope deposits: late Pleistocene and Holocene of the Podhale Basin (Carpathians, Poland). *Acta Geologica Polonica*, **65** (2), 247–263. Warszawa.

Slope deposits developed on calcareous sandstone and limestone formations in the eastern part of the Podhale Basin (Carpathians) were studied. In total, the analysis included fifteen profiles of such sediments, which revealed the presence of abundant malacofaunas comprising 39 mollusc species. Five faunistic assemblages differing in species composition and structure were defined in the material studied. Individual assemblages correspond to different climatic and environmental conditions, thereby making it possible to interpret the features of the sedimentary environments and specify the age of the deposits. Faunas with *Pupilla loessica* and *Pupilla sterri* containing species typical of loess formations are characteristic of deposits from the coldest phase of the last Glacial period (MIS 2). A fauna with *Vertigo genesii*, with a large proportion of cold-loving and moisture-loving taxa, is typical of the Younger Dryas. Associations that are dominated by shade-loving species, with *Discus ruderatus* and *Discus perspectivus*, correspond to the early and middle Holocene respectively. The investigations show that malacological analysis can be successfully applied to the research into slope deposits, enabling both the depositional conditions and the age of the sediments to be determined.

Key words: Molluscs; Molluscan assemblage; Slope deposits; Late Pleistocene; Holocene; Southern Poland.

INTRODUCTION

Slope deposits are the most widespread type of Quaternary sediments in the Carpathians. They form covers developed on slopes. The term ‘slope covers’ used in the present paper refers to deposits of various origins and lithological forms that can be found on slopes and which cover older underlying rocks. These sediments/covers are typically formed as a product of chemical or mechanical weathering of the underlying rocks. They can occur *in situ*; however, in most cases they are transported down the slope as a result of superficial mass movement. It should be stressed that such transport takes place only within a particular slope and is usually limited in distance.

The thickness of slope covers varies widely, ranging from a dozen centimetres to 4–5 metres and nearly always increases down the slope. The sediments are highly diverse and shaped by various factors. The first significant factor is the climate, which determines the dominant type of weathering processes affecting the lithological features of the deposits. The climate additionally determines the vegetation growing on the slopes, thus affecting the possibility of mass movements. The second essential factor is the structure of the underlying rocks on which the slope deposits are developed. In recent years, there has been significant development in the research into these deposits (e.g. Van Steijn *et al.* 1995; Bertran *et al.* 1997; Blikra and Nemec 1998; Matsuoka 2001; Pawelec 2006). There have been various other studies of slope sediments conducted in the Polish Carpathians (e.g. Zuchiewicz 1988; Butrym and Zuchiewicz 1990). Faunal remains are often found in slope deposits in the Polish Carpathians. They include both skeletal elements of large vertebrates, mainly mammoths (e.g. Kulczycki and Halicki 1950; Cieszkowski *et al*. 2010; Nadachowski *et al*. 2011), and molluscan shells (Alexandrowicz 1988a, 1997a; Alexandrowicz *et al*. 1991; Alexandrowicz and Rudzka 2006; Cieszkowski *et al*. 2010). This paper concerns the occurrence of the latter category. The main factors that enable the preservation of subfossil molluscan shells in slope deposits are: a relatively quiet process of sedimentation, and a high calcium carbonate level. The first of these factors minimizes the risk of destruction of shells during deposition while the second hinders the mechanical breaking and chemical dissolution of shells which are already present in the sediment. Such sediments usually cover gentle slopes formed in zones where the bedrock is represented by limestone or by calcareous sandstone. Approximately a dozen sites with malacofaunas have been described to date in the Polish Carpathians. Research into subfossil malacofaunas of slope deposits was also undertaken in other countries (e.g. Ložek 1976, 1982, 2000, 2006; Sümegi and Krolopp 2002; Sümegi 2005; Danukalova and Eremeev 2006; Yakovlev *et al*. 2013). These focused mainly on palaeoecological descriptions of malacocoenoses rather than being used as a tool to draw stratigraphic conclusions, and were applied in exceptional cases to determine the age of the host rock or to discriminate between deposits of different ages.

Molluscs are sensitive indicators of the characteristics of sedimentary environments. Therefore, the analysis of malacofaunas occurring in deposits allows one to reconstruct the conditions of sediment deposition, as well as the climate. As a consequence, malacological analysis is a tool for drawing stratigraphic conclusions. The age of slope covers is often difficult to determine with precision, given the specificity of the sedimentary environment in which they are formed. These difficulties are exacerbated by the relatively limited opportunity to use radiometric analyses in age determination. Therefore, the study of molluscs in slope deposits in many cases provides the main premise for stratigraphy. The aim of this paper is to present the possibilities of using the study of molluscs in palaeoenvironmental and stratigraphic interpretations of slope deposits of different ages and origins.

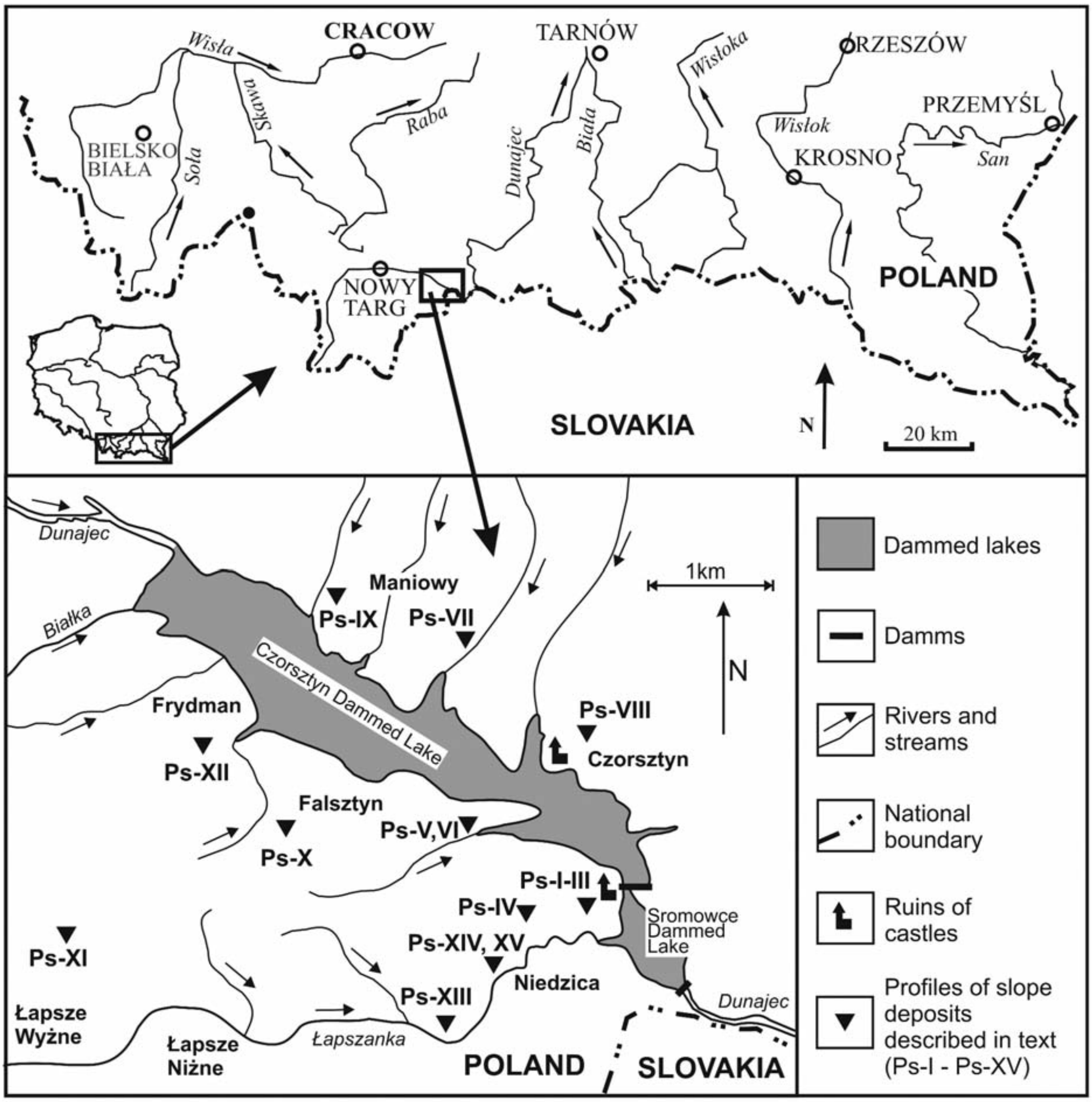
GEOLOGICAL SETTING

The Podhale Region is an intramontane basin forming a morphological depression encircled by mountain ranges, namely the Tatra Mountains to the south and the Flysch Carpathians to the west and north. The bottom of the basin is situated 500–1500 m below the surrounding mountain ranges. The basin is crossed by a strip, up to 900 m high, which is part of the Pieniny Klippen Belt. The geological substrate of the Podhale Basin is formed by weakly folded formations of Palaeogene flysch, represented chiefly by sandstone and shale with carbonate cement. The Pieniny Klippen Belt consists of strongly folded Jurassic and Cretaceous limestone. The abundance of carbonates in the underlying rocks causes the Quaternary deposits that have developed on them to contain increased levels of calcium carbonate, which creates favourable conditions for the preservation of molluscan shells. This rule also applies to slope covers.

The profiles studied are situated in the eastern part of the Podhale Basin, around the man-made reservoir in Niedzica (Text-fig. 1). They represent slope covers not exceeding 1 m in thickness located directly adjacent to slopes or forming the upper part of high terraces of the Dunajec and Łapszanka rivers.

MATERIAL AND METHODS

For the purpose of malacological studies, 61 samples (Ps-1–Ps-61) were collected from the fifteen profiles (Ps-I–Ps-XV) (Text-fig. 1). Individual samples weighed approximately 2.0 kg each and covered 10–20 cm intervals, depending on the lithological form of the deposits. The laboratory processing of the material involved maceration and flushing of the rocks, followed by collection of all complete molluscan shells and their identifiable fragments. The numbers of species and specimens were determined for each sample. The shell fragments were recalculated into whole specimens according to the formula proposed by Alexandrowicz (1987) and Alexandrowicz and Alexandrowicz (2011). The number of species per sample varied from 4 to 30, whereas the number of specimens ranged from 113 to



Text-fig. 1. Location of profiles of slope deposits in the eastern part of the Podhale Basin

508 respectively. The entire material studied comprised 14,679 specimens of 39 terrestrial snail taxa (including the calcareous plates of slugs under the collective name Limacidae) (Table 1).

Malacological analysis was performed using standard methods described by Ložek (1964), Alexandrowicz (1987) and Alexandrowicz and Alexandrowicz (2011). The ecological requirements of particular species were determined based on several studies (e.g. Ložek 1964, 2000, 2001; Kerney *et al*. 1983; Alexandrowicz 2004). Individual species were classified into ecological groups: F–shade-loving species, O–open-country species, M–mesophilous species, and H–hygrophilous species. Taxonomic analysis enabled the similarities between individual samples to be shown and the faunistic assemblages to be defined and described. To achieve this, correspondence analysis and the analysis of similarity dendrograms were conducted. The method described by Morisita (1959) was used for the construction of dendrograms, and PAST statistical software was used in statistical calculations (Hammer *et al.* 2001).

Stratigraphic conclusions were based on indirect indicators, i.e. the similarity of composition and structure of faunistic assemblages described in the analysed deposits to associations found in profiles that had been thoroughly studied and are located in the vicinity of the analysed sites. Due to its specific geological structure, the area covered in the study abounds in sites of late Pleistocene and Holocene deposits containing subfossil remains of molluscs. Up to now, 100 occurrences of such sites have been reported in the region (e.g. Alexandrowicz and Alexandrowicz 1995a, b; Alexandrowicz 1997a, 2001, 2004, 2013a, b, c; Alexandrowicz and Rybska 2013; Alexandrowicz *et al*. 2014a). Many of these sites contain malacofaunal assemblages that are highly similar to those presented below, whose age has been determined by radiocarbon dating. Direct determination of the age of the deposits was possible due to conventional radiocarbon dating of six samples. The dating was based either on shells of molluscs (mainly *Arianta arbustorum* and *Discus ruderatus*) or on plant remains. The radiocarbon analyses were conducted in the Radiocarbon Laboratory in Skała near Cracow (laboratory code: MKL) and at the Department of Radioisotopes of the Institute of Physics of the Silesian University of Technology in Gliwice (laboratory code: Gd). The results of the radiocarbon analyses were calibrated on the basis of the calibration curve (Stuiver *et al*. 1998), using the OxCal 3.9 software (Bronk Ramsey 2001).

Additionally, climatic and palaeoenvironmental changes during the Younger Dryas and the Holocene are well documented using palynological method from peatbogs developed in neighbouring regions, mainly from the Podhale Basin (Obidowicz 1990).

RESULTS

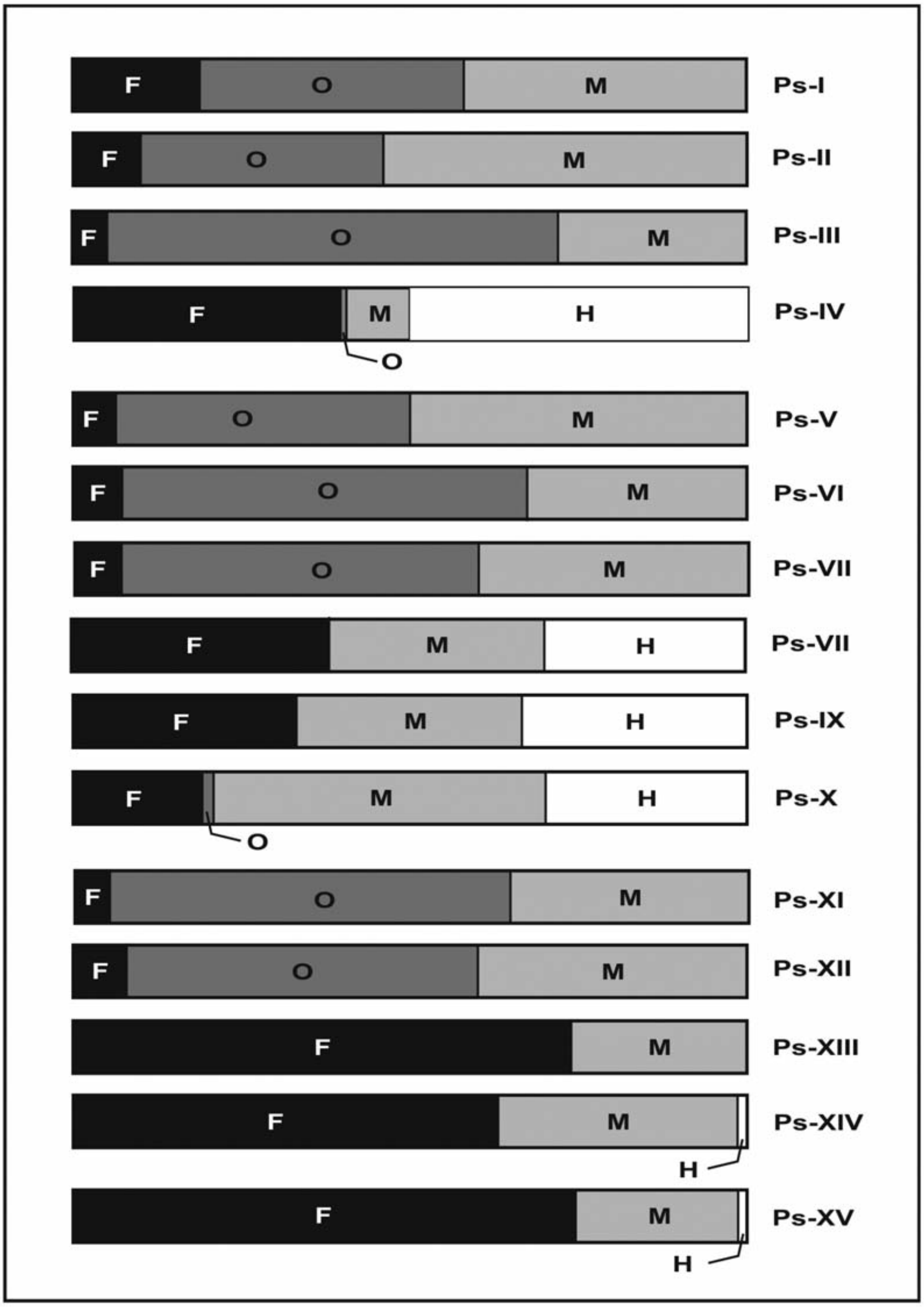
Profiles

Ps-I (samples Ps-1–Ps-4), Ps-II (samples Ps-5–Ps-7) and Ps-III (samples Ps-8–Ps-10) are located beneath Niedzica castle (GPS: 49˚25.18'N; 20˚19.11'E) (Text-fig. 1) and form the top part of the Dunajec River terrace rising 25 m above the current channel of the river. The bottom part of the terrace is composed of gravel. The actual slope cover is formed of yellow loam with numerous, sharp-edged limestone blocks that gradually decrease in number towards the top of the terrace. The lithological features of the terrace were described in detail by Kulczycki and Halicki (1950), and references to the occurrence of numerous molluscan shells in the slope deposits can be found in papers by Alexandrowicz (1988a, 1997a). The thickness of the exposed slope cover varies from 0.6 m (Ps-I) to 0.4 m (Ps-II and Ps-III). The malacofauna found in these profiles was marked by low diversity. Only loess species (*sensu* Ložek 1965, 2001) were found there: *Pupilla loessica*, *P. muscorum densegyrata* and *Succinella oblonga*. The assemblage was supplemented by cold- and shade-loving species: *Semilimax kotulai* and *Arianta arbustorum* (Text-fig. 2, Table 1).

Ps-IV (samples Ps-11–Ps-15) is located in the central part of the southern slope of the Majerz hill in Niedzica (GPS: 49˚25.11'N; 20˚19.7'E) (Text-fig. 1). Blueish loam with abundant rock clasts, devoid of malacofaunal remains, rests on strongly folded sandstone and is overlain by greyish and yellowish, 0.55 m thick, loam cover with an abundant malacofauna. The top of this cover is distinctly truncated by erosion and is overlain by dark peat mud with fragments of tree trunks. These formations fill a shallow depression that has remained after a small dammed lake. This small landslide form is much younger than the underlying slope cover and corresponds to the Subatlantic Phase of the Holocene (Alexandrowicz 1997a, 2013b). The malacofauna in the greyish and yellowish loam is characterised by the presence of cold-loving forms preferring moist or even waterlogged habitats: *Vertigo genesii* and *V. geyeri*. Another important component of the fauna consists of mesophilous species (*Columella columella*, *Euconulus fulvus* and *V. substriata*) as well as shade-loving taxa typical of a cool continental climate (*Discus ruderatus*, *Semilimax kotulai* and *Arianta arbustorum*) (Text-fig. 2, Table 1). Shells of *A. arbustorum* were radiocarbon dated to 11 250±250 BP (11 622–10 751 cal BC; Gd-4243) (Table 2).

Ps-V (samples Ps-16–Ps-19) and Ps-VI (samples Ps-20–Ps-24) are situated in the lower reaches of the Falsztyński stream valley in Kosarzyska (GPS: 49˚25.42'N; 20˚17.49'E) (Text-fig. 1). Ps-V is located at the foot of a rock formed of Jurassic limestone. An abundant malacofauna was found in reddish loam up to 0.5 m thick, with numerous limestone clasts. Ps-VI is located several dozen metres down the valley and represents a 0.45 m thick silty cover lying upon the top of the Dunajec River high terrace. The study material was collected in the 1990s (Alexandrowicz 1997a). Both profiles are currently submerged beneath the Niedzica dam lake and unavailable for direct observation. The malacofauna identified in these sites consists exclusively of forms typical of loess: *Pupilla loessica*, *P. muscorum densegyrata* and *Succinella oblonga*. Numerous shells of *P. sterri* occur in profile Ps-V (Text-fig. 2, Table 1). This is a xerophilous and petrophilous species, commonly found on exposed limestone rocks. Its abundant occurrence is undoubtedly related to local conditions. Shells of *Arianta arbustorum* from one sample from profile Ps-V were radiocarbon dated to 23 400±550 BP (26 756–24 576 cal BC; Gd-2800) (Table 2).

Ps-VII (samples Ps-25–Ps-28) is located on the left bank of the Dunajec River, in Mizerna (GPS: 49°26.53'N; 20°17.7'E) (Text-fig. 1). Yellow loam with angular sandstone and limestone fragments, situated at the top of a distinct high terrace, is exposed here (Birkenmajer and Środoń 1960). The thickness of the cover is 0.7 m. Numerous shells of molluscs typical of loess occur in the loam: *Pupilla loessica*, *P. muscorum densegyrata*, *Succinella oblonga* (Text-fig. 2, Table 1). Single bones of large vertebrates (*Equus* sp., *Mam-*



Text-fig. 2. Ecological structure of molluscan faunas in profiles of the slope deposits in the eastern part of Podhale Basin. Ps-I – Ps-XV – profiles described in text; ecological groups of molluscs (after: Ložek 1964, 2000; Alexandrowicz 1987; Alexandrowicz and Alexandrowicz 2011): F – shade-loving snails, O – open-country snails, M – mesophilous snails, H – hygrophilous snails *muthus primigenius* and *Rangifer tarandus*) identified by Professor Nadachowski (pers. comm.) were also found here, as well as plant detritus forming two distinctly marked dark layers. Plant remains were radiocarbon dated to 27 400±600 BP (31 106–28 580 cal BC; Gd-1917) (Alexandrowicz 1988a, 1997a) (Table 2).

Ps-VIII (samples Ps-29–Ps-31) is located on the northern slope of the castle hill in Czorsztyn (GPS:

E	TAXON	Profiles Ps-														
		I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**XIII**	**XIV**	**XV**
F	*Platyla polita* (Hartmann, 1840)													58	18	11
F	*Acanthinula aculeata* (Müller, 1774)													38	10	4
F	*Vertigo pusilla* Müller, 1774													42	4	9
F	*Ruthenica filograna* (Rossmässler, 1836)													61	12	4
F	*Macrogastra plicatula* (Draparnaud, 1801)													11	16	2
F	*Macrogastra borealis* (Boettger, 1878)													24	4	2
F	*Discus ruderatus* (Hartmann, 1821)	8			75				32	38	10			38	97	757
F	*Discus rotundatus* (Müller, 1774)													51	9	1
F	*Discus perspectivus* (Mühlfeld, 1816)													98	3	2
F	*Vitrea diaphana* (Studer, 1820)													89	53	72
F	*Vitrea transsylvanica* (Clessin, 1877)													51	54	32
F	*Vitrea crystallina* (Müller, 1774)	3							1					119	93	148
F	*Aegopinella pura* (Alder, 1830)													93	46	89
F	*Semilimax kotulai* (Westerlund, 1883)	62	32	21	95	30	27	17	86	63	27	22	56	11	36	66
F	*Petasina unidentata* (Draparnaud, 1805)													39	40	7
F	*Monachoides incarnatus* (Müller, 1774)													51	22	15
F	*Monachoides vicinus* (Rosssmässler, 1842)													22	14	15
F	*Arianta arbustorum* (Linnaeus, 1758)	161	87	36	108	26	40	35	71	46	30	28	58	82	50	123
F	*Faustina faustina* (Rossmässler, 1835)													72	12	2
F	*Isognomostoma isognomostomos* (Schröter, 1784)													78	24	25
O	*Pupilla muscorum* (Linnaeus, 1758)	150	136	214	7	21	93	94	3		9	128	114			
O	*Pupilla muscorum densegyrata* Ložek, 1954	59	49	149			91					90	142			
O	*Pupilla loessica* Ložek, 1954	316	217	386		161	323	240				331	394			
O	*Pupilla sterri* (Voith, 1840)					178										
O	*Vallonia tenuilabris* (Sandberger, 1875)	75	26	32		60	61	44				54	79			
M	*Succinella oblonga* (Draparnaud, 1801)	666	598	324	24	344	278	264				301	487	22	18	6
M	*Cochlicopa lubrica* (Müller, 1774)													48	63	68
M	*Columella columella* (Martens, 1830)				71				31	58	54	10	10	2	14	27
M	*Vertigo substriata* (Jeffreys, 1833)				57				39	21	10			40	117	176
M	*Vertigo modesta* (Wallenberg, 1858)				3				27	51	59				5	8
M	*Vertigo alpestris* Alder, 1837				2					1				3	3	
M	*Clausilia dubia* Draparnaud, 1805	58	48		9	56	23	20				44	63	29	3	7
M	*Punctum pygmaeum* (Draparnaud, 1801)				3				12	3	1			50	53	62
M	*Euconulus fulvus* (Müller, 1774)				16				37	10	31	6	15	70	40	48
M	*Perpolita hammonis* (Ström, 1765)				6				4	1	7			69	24	6
M	*Vitrina pellucida* (Müller, 1774)													30	2	7
M	Limacidae				7				4	3			4	35	18	4
H	*Vertigo genesii* (Gredler, 1856)				126				83	76	58				2	5
H	*Vertigo geyeri* Lindholm, 1925				85				63	68	46				1	4

Table 1. List of species recognized in profiles of slope deposits in the eastern part of the Podhale Basin. E. ecological groups of molluscs (after: Ložek 1964, 2000; Alexandrowicz 1987; Alexandrowicz and Alexandrowicz 2011): F – shade-loving snails, O – open-country snails, M – mesophilous snails, H – hygrophilous snails

49˚26.14'N; 20˚18.39'E) (Text-fig. 1). Here, a thin (0.3m thick) cover formed of grey loam with small rock clasts and abundant malacofauna lies upon folded Upper Jurassic limestone.

Very similar deposits were found in a roadworks pit in Maniowy (Ps-IX (samples Ps-32–Ps-34); GPS: 49˚27.15'N; 20˚15.39'E) (Text-fig. 1). In this case, the slope cover overlies sandstone and contains a

No	Selected Localities	Region	Datings (BP)		References
		ASSEMBLAGES WITH PUPILLA LOESSICA AND WITH PUPILLA STERRI			
1	Mizerna	Podhale Basin	27 400±600 (Gd-1917)	^{14}C	Alexandrowicz, 1988a; this paper
2	Kosarzyska	Podhale Basin	23 400±550 (Gd-2800)	^{14}C	this paper
3	Grodzisko	Carpathian Foredeep	18 000±2800 (GdTl-565) 22 200±2800 (GdTl-564)	TL	Alexandrowicz, 2014
4	Szklarka	Cracow Upland	24 000±3500 (Lub-534)	TL	Alexandrowicz, 1989, 1995
5	Niedźwiedź	Cracow Upland	20 600±2100 (Gd-4909)	^{14}C	Alexandrowicz, 1995
6	Maszków	Cracow Upland	23 900 ± 850 (Gd-4123)	^{14}C	Alexandrowicz, 1995
7	Spadzista	Cracow Upland	23 020±180 (Poz-242) 23 980±280 (Poz-225) 20 600±1050 (Ly-631)	^{14}C	Kalicki et al., 2007
8	Trawniki	Carpathian Foredeep	23 000±3000 (GdTl-253)	TL	Alexandrowicz and Gębica, 1997
9	Sienna	Flisch Carpathians	25 000±3000 (Lub-1041)	TL	Alexandrowicz et al., 1991
10	Roztoka	Flisch Carpathians	27 000±4000 (Lub-1171)	TL	Alexandrowicz et al., 1991
11	Olszanka	Carpathian Foothills	22 000±500 (Lub-1174)	TL	Alexandrowicz and Łanczont, 2001
12	Humniska	Carpathian Foothills	27100±900 (Gd-2695)	^{14}C	Gerlach et al., 1991
		ASSEMBLAGE WITH VERTIGO GENESII			
13	Maniowy	Podhale Basin	11 060±120 (Gd-5107)	^{14}C	this paper
14	Majerz	Podhale Basin	11 250±250 (Gd-4243)	^{14}C	this paper
15	Groń	Podhale Basin	10 670±110 (MKL-936)	^{14}C	Alexandrowicz, 1997a, 2013a
16	Gliczarów	Podhale Basin	10 850±1800 (Gl 1/83) 10 940±1830 (Gl 15/83)	^{14}C	Pazdur, 1987; Alexandrowicz, 1997a, 2003
17	Niedzica	Podhale Basin	9830±150 (MKL-1364)	^{14}C	Alexandrowicz, 1997a; Alexandrowicz and Rybska, 2013
18	Homole	Pieniny Mts.	9940±100 (Gd-5272)	^{14}C	Alexandrowicz, 1997c
19	Krynica	Flisch Carpathians	12 400±220 (Gd-6095)	^{14}C	Alexandrowicz and Alexandrowicz, 1999
20	Zabłocie	Flisch Carpathians	9680±90 (Gd-1930)	^{14}C	Alexandrowicz and Chmielowiec, 1992
21	Racławka	Cracow Upland	10 630±80 (Gd-1841) 9880±130 (Gd-4065) 9820±100 (Gd-5287)	^{14}C	Alexandrowicz, 1983, 2004; Pazdur, 1987
22	Szklarka	Cracow Upland	10 240±100 (Gd-5288) 9440±90 (Gd-5284)	^{14}C	Alexandrowicz, 1983, 1989, 2004
23	Kobylany	Cracow Upland	9870±170 (Gd-2941)	^{14}C	Alexandrowicz, 1983, 2004
		ASSEMBLAGE WITH DISCUS RUDERATUS			
24	Majerz hill	Podhale Basin	9040±90 (Gd-1778)	^{14}C	this paper
25	Groń	Podhale Basin	9060±90 (MKL-939)	^{14}C	Alexandrowicz, 1997a, 2013a
26	Niedzica	Podhale Basin	8660±130 (MKL-1344)	^{14}C	Alexandrowicz, 1997a; Alexandrowicz and Rybska, 2013
27	Łapsze Niżne	Podhale Basin	8800±100 (Gd-5109)	^{14}C	Alexandrowicz, 1997a
28	Łapsze	Podhale Basin	8150±110 (Gd-2792)	^{14}C	Alexandrowicz, 1997a
29	Krynica	Flisch Carpathians	8440±40 (Gd-5567) 8140±110 (Gd-5882)	^{14}C	Alexandrowicz and Alexandrowicz, 1999
30	Szymbark	Flisch Carpathians	8210±50 (Ly-661)	^{14}C	Alexandrowicz, 2004
31	Ojców	Cracow Upland	9040±90 (Gd-1778)	^{14}C	Alexandrowicz, 1988b , 1997b
32	Trzebienice	Cracow Upland	8760±100 (Gd-1664) 8620±90 (Gd-1843)	^{14}C	Pazdur, 1987; Alexandrowicz, 2004
		ASSEMBLAGE WITH DISCUS PERSPECTIVUS			
33	Łapsze Niżne	Podhale Basin	7410±130 (MKL-1393)	^{14}C	this paper
34	Falsztyński Potok	Podhale Basin	5610±130 (Gd-2316)	^{14}C	Alexandrowicz, 1997a
35	Zaskale	Pieniny Mts.	6500±270 (Gd-9977)	^{14}C	Alexandrowicz, 1997a
36	Harcygrunt	Pieniny Mts	7750±130 (Gd-953)	^{14}C	Alexandrowicz, 1997c
37	Niedzica	Podhale Basin	8010±110 (KML-1374)	^{14}C	Alexandrowicz and Rybska, 2013
38	Trzebienice	Cracow Upland	7380±180 (Gd-3021)	^{14}C	Pazdur, 1987; Alexandrowicz, 2004

Table 2. Stratigraphical value of molluscan assemblages described from Late Quaternary mollusc-bearing deposits in South Poland

significantly greater admixture of angular rock material.

Ps-X (samples Ps-35 and Ps-36) is located in Falsztyn (GPS: 49˚25.49'N; 20˚16.15'E) near the summit of a hill (Text-fig. 1). Jurassic limestone is overlain by a very thin (approx. 0.15 m) grey loam cover with numerous rock fragments.

A similar malacofauna was found at the three previously mentioned sites (Ps-VIII, Ps-IX, and Ps-X). It features the abundant occurrence of cold-loving taxa typical of moist habitats (*Vertigo genesii* and *V. geyeri*), accompanied by mesophilous forms (*Euconulus fulvus*, *V. substriata*, *Columella columella* and *V. modesta*), as well as shade-loving taxa (*Discus ruderatus*, *Semilimax kotulai* and *Arianta arbustorum*) (Text-fig. 2, Table 1). Shells of molluscs (*A. arbustorum*) from profile Ps-IX were radiocarbon dated to 11 060±120 BP (11 169–10 768 cal BC; Gd-5107) (Table 2).

Ps-XI (Ps-37–Ps-40) is located in Łapsze Wyżne (GPS: 49˚24.1'N; 20˚14.30'E) (Fig. 1). Here, a silty cover reaching 0.45 m in thickness and containing numerous rock clasts overlies the Łapszanka River terrace, 15–17 m above the current river channel. The top of this silty cover shows traces of vague lamination and layers enriched with sandy material.

Ps-XII (Ps-41–Ps-45) represents the top part of the Dunajec River terrace in Frydman (GPS: 49˚27.8'N; 20˚13.28'E) (Text-fig. 1). Here, a fluvial gravel layer is overlain by indistinctly laminated, yellow, strongly gritty loam with a small number of pebbles and angular rock fragments. The thickness of the cover is 0.80 m.

The abundant malacofauna in both profiles Ps-XI and Ps-XII shows poor species diversity and is dominated by the loess species *Pupilla loessica*, *P. muscorum densegyrata*, and *Succinella oblonga* (Text-fig. 2, Table 1).

The next profile (Ps-XIII; samples Ps-46–Ps-51) is located in Łapsze Niżne (GPS: 49˚23.48'N; 20˚11.48'E) (Text-fig. 1). In the lower part of a slope cut across by a small left-bank tributary of the Łapszanka River is exposed a 0.90 m thick sand and loam cover with numerous sandstone blocks, abundant malacofauna, and local aggregations of plant remains. These remains were radiocarbon dated to 7410±130 BP (6480–6010 cal BC; MKL-1393) (Table 2). The molluscan assemblage identified in this site is marked by a diverse species composition and by the abundant occurrence of shade-loving taxa with high ecological requirements, preferring a climate strongly influenced by maritime air masses: *Discus perspectivus*, *Ruthenica filograna* and *Monachoides vicinus*. Shade-loving taxa constitute over 70% of the assemblage. Mesophilous forms, including *Perpolita hammonis*, *Punctum pygmaeum* and *Vitrina pellucida*, also occur (Text-fig. 2, Table 1).

The last two profiles (Ps-XIV; samples Ps-52–Ps-55 and Ps-XV; samples Ps-56–Ps-61) are situated in the lower part of the western slope of Majerz hill in Niedzica (GPS: 49˚24.39'N; 20˚17.53'E) (Text-fig. 1). The slope cover found here is bisected by a small watercourse reaching up to 1.0 m in depth. Grey, strongly gritty loam with numerous sharp-edged sandstone fragments is exposed in the bluff. The size and proportion of rock clasts increase towards the bottom of the cover. Aggregations of plant detritus occur locally. The profiles are located approx. 100 m apart and probably represent a single cover. Both profiles yielded an abundant and diverse malacofauna. A particularly important role is played by shade-loving species, which comprise more than 50% of the assemblage. A characteristic feature is the occurrence of taxa considerably tolerant to temperature that prefer coniferous forests and a climate of continental character: *Discus ruderatus* and *Semilimax kotulai*. Forest species with higher ecological demands (*Aegopinella pura*, *D. rotundatus* and *Isognomostoma isognomostomos*), can also be found. Mesophilous forms are another important component of the fauna, the abundant occurrence of *Vertigo substriata* being of particular significance. An additional interesting feature of the fauna in question is the presence of single shells of the cold-loving taxa *V. modesta* and *Columella columella* (Text-fig. 2, Table 1). Shells of molluscs (*Discus ruderatus*) from profile Ps-XV were radiocarbon dated to 9040±90 BP (8493–7955 cal BC; Gd-1917) (Table 2).

Malacofauna

A total of 39 molluscan taxa were found in the analysed profiles of slope deposits in the eastern Podhale Region. Species typical of shaded habitats (ecological group F) are the most varied. They include forest forms, typical of warm, maritime climates (*Discus perspectivus*, *D. rotundatus* and *Ruthenica filograna*), taxa that inhabit taiga-type coniferous forests and prefer a continental climate (*D. ruderatus*), as well as cold-loving species associated with thin, light-penetrated forests or shrublands (*Arianta arbustorum* and *Semilimax kotulai*). Open-country snails (group O) are chiefly represented by cold-loving loess forms (*sensu*: Ložek 1965, 2001): *Pupilla loessica*, *P. muscorum densegyrata*, *Vallonia tenuilabris*. Taxa characteristic of very dry, xerothermic, and rock-based habitats (*P. sterri*) can also be found in this group. Mesophilous species (group M) include cold-loving forms (*Vertigo modesta* and *Columella columella*), and taxa of broad temperature tolerance, occurring during both the coldest glacial phases and significantly warmer periods: *Succinella* *oblonga*, *V. substriata*, *Euconulus fulvus*. Hygrophilous snails (group H) are represented by two taxa (*V. genesii* and *V. geyeri*) characteristic of a cold climate and tundra-type habitats (Table 1).

DISCUSSION

Molluscan assemblages

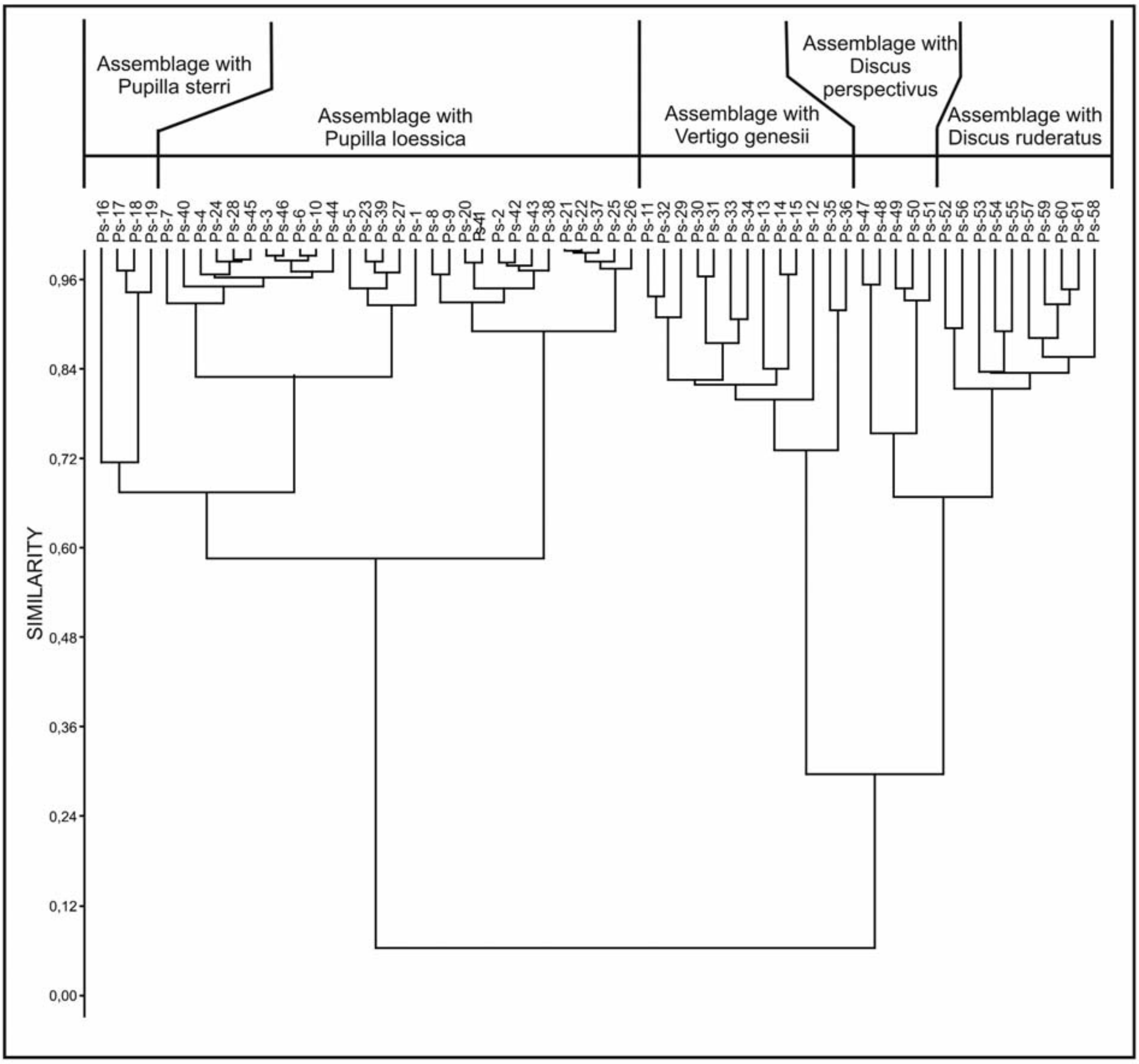
The above-described profiles of slope deposits are very thin. Within individual profiles, the malacofauna is of low diversity and represents a habitat of one type. It is therefore likely that the age of each of the analysed covers corresponds to the Late Pleistocene and Holocene. On the other hand, a considerable variability was noted between profiles. This indicates that different conditions prevailed during the formation of the slope covers, and enables definite differentiation of their ages. The malacological study makes it possible to identify specific groups of molluscan species that co-occur particularly often. This serves as a basis to distinguish faunistic assemblages strictly related to the environmental and climatic conditions under which the sedimentation of slope covers took place. Assemblages were distinguished based on a dendrogram analysis and correspondence analysis. As a result, it was possible to define four main types of assemblages

Assemblage with *Pupilla loessica* – it is a low diversity assemblage, dominated by “loess taxa” (*sensu*: Ložek 1965, 2001): *Pupilla loessica*, *P. muscorum*, *P. muscorum densegyrata*, *Vallonia tenuilabris*, and *Succinella oblonga*. Two cold-loving taxa, which prefer mildly shaded habitats (*Semilimax kotulai* and *Arianta arbustorum*), also occur. This assemblage was found in profiles Ps-I–Ps-III, Ps-VI, Ps-VII, Ps-XI and Ps-XII (Text-figs 1–3) and has been reported from numerous loess sites in Europe (e.g. Ložek 1965, 1969, 1991, 2001; Alexandrowicz 1995, 2014; Rousseau 1987; Alexandrowicz *et al.* 2002, 2013, 2014b; Sümegi 1995, 2005; Krolopp and Sümegi 1995; Rousseau *et al.* 2001, 2002; Sümegi and Krolopp 2002; Alexandrowicz and Dmytruk 2007; Moine 2008, 2014), as well as from many profiles of loess-like and slope deposits in the Carpathians (e.g. Alexandrowicz 1988a, 1997a; Cieszkowski *et al.* 2010).

Assemblage with *Pupilla sterri* – it is a variant of the assemblage described above, typified by the abundant occurrence of *Pupilla sterri*, accompanied by the “loess species” *P. loessica*, *P. muscorum*, *Vallonia tenuilabris* and *Succinella oblonga*. *P. sterri* commonly occurs on bare limestone rocks and is typical of xerothermic habitats. The presence of the assemblage with *Pupilla sterri* was noted in the Ps–V profile (Text-figs 1–3). A malacofauna with a similar composition has been reported from several loess profiles in the Cracow region (Cracow Upland) (Alexandrowicz 1995).

Assemblage with *Vertigo genesii* – it is an assemblage characterised by the abundant occurrence of two moist- and cold-loving species (*Vertigo genesii* and *V. geyeri*), accompanied by *V. modesta* and *Columella columella*. Another interesting feature of this fauna is the presence of *Semilimax kotulai* and *Arianta arbustorum*, both of which are categorised in traditional malacological classifications as shade-loving forms (Ložek 1964). However, both taxa are frequent components of loess faunas (Ložek 1965, 2001; Krolopp and Sümegi 1995; Alexandrowicz 1995, 2014; Alexandrowicz *et al*. 2002, 2013; Alexandrowicz *et al*. 2014b), and their current distribution, especially their occurrence in northern Europe and in high mountains, often above the timber line, proves their broad temperature tolerance. The assemblage also includes mesophilous taxa. This assemblage was identified at sites Ps-IV, and Ps-VIII–Ps-X (Text-figs 1, 2, 3). Assemblages with closely similar structure and composition were reported from numerous profiles of calcareous tufas (e.g. Alexandrowicz 1983, 1997a, 2001, 2003, 2004, 2013a; Limondin-Lozouet and Rousseau 1991; Limondin-Lozouet and Preece 1994; Alexandrowicz and Alexandrowicz 1995a, b; Meyrick 2001, 2002; Meyrick and Preece 2001; Gedda 2001, 2006, Alexandrowicz *et al.* 2014a), from fluvial deposits, and from lacustrine chalk and peat-filled palaeolakes (e.g. Alexandrowicz 1997a, 1999, 2013d).

Assemblage with *Discus ruderatus* – a characteristic feature of this association is the abundant occurrence of species typical of continental climates: *Discus ruderatus* and *Vertigo substriata*. They are accompanied by shade-loving taxa with low temperature requirements: *Semilimax kotulai*, *Arianta arbustorum* and *Vitrea crystallina*. Thermophilic forest taxa such as *D. rotundatus* and *D. perspectivus* are considerably less frequent. Mesophilous forms play a major role in the assemblage. The presence of single shells of cold-loving taxa, such as *V. modesta*, *Columella columella*, *V. genesii* and *V. geyeri*, is also characteristic. This assemblage corresponds to the “Ruderatus-fauna” (Dehm 1967) and was reported from numerous sites in the Podhale Basin (Alexandrowicz 1997a, 2001, 2003, 2004, 2013a; Alexandrowicz and Rybska 2013; Alexandrowicz *et al*. 2014a), the Pieniny Mountains (Alexandrowicz 2004), the Flysch Carpathians (Alexandrowicz and Alexandrowicz 1995a, b; Alexandrowicz 2004), and the environs of Cracow (Alexandrowicz 1983, 1997b, 2004). The assemblage with *Discus ruderatus* was found in profiles XIV and XV (Text-figs 1–3).

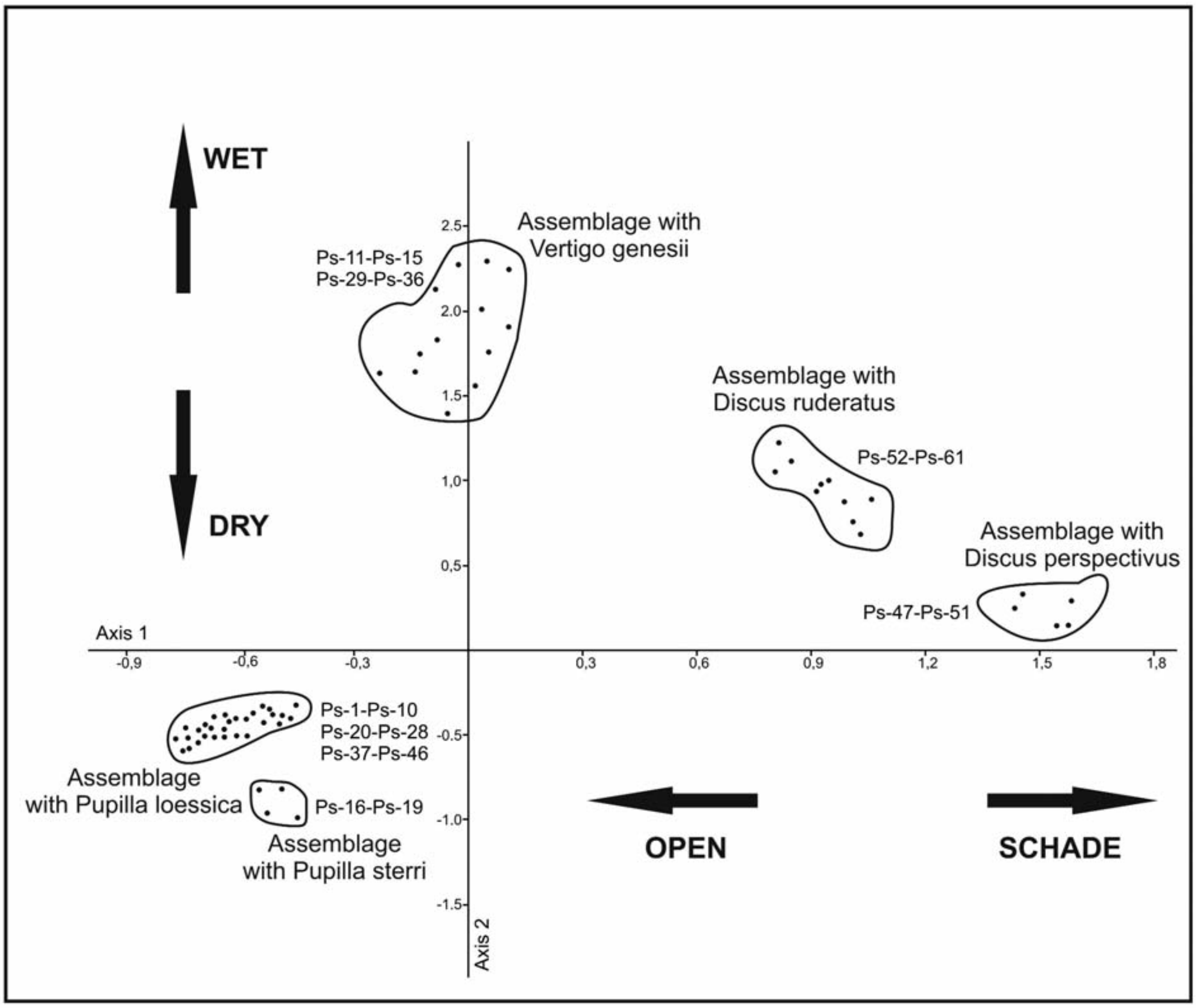


Text-fig. 3. Cluster analysis of malacofauna of slope deposit profiles in the eastern part of the Podhale Basin

Assemblage with *Discus perspectivus* – it is the most diverse and rich malacocoenosis occurring in slope deposits in the eastern Podhale Region. It is marked by a high proportion (exceeding 70%) of shade-loving species. The most essential role among them is played by forms preferring a warm climate strongly influenced by maritime air masses: *Discus rotundatus*, *D. perspectivus*, *Aegopinella pura* and *Ruthenica filograna*. In contrast, taxa typical of continental climates (*D. ruderatus* and *Vertigo substriata*) are much less numerous, while cold-loving species disappear almost entirely. Mesophilous taxa also occur. The fauna is equivalent to the "Perspectivus-fauna" distinguished by Dehm (1987) and was noted at numerous sites in the Polish Carpathians (Alexandrowicz and Alexandrowicz 1995a, b; Alexandrowicz 1997a, 2001, 2003, 2013a; Alexandrowicz and Rybska 2013; Alexandrowicz *et al*. 2014a) and the environs of Cracow (Alexandrowicz, 1983, 1997b, 2004). The assemblage with *Discus perspectivus* was identified only at site Ps-XIII (Text-figs 1, 2, 3).

Ecological and stratigraphic significance of the assemblages

The slope covers found in the eastern part of the Podhale Basin have small thicknesses. Within an individual cover, the molluscan assemblages do not display any significant variety in species composition or structure. These observations show that each cover represents



Text-fig. 4. Environmental diversity of molluscan assemblages from slope deposits in the eastern part of the Podhale Basin

a short time period limited to a single climatic phase. However, substantial dissimilarities are observed between malacocoenoses identified in separate covers. This clearly implies age differences between the covers. Such a situation not only creates the possibility to describe environmental conditions prevailing during the deposition of the sediments but also to draw stratigraphic conclusions and to use malacological analysis for the age determination of slope covers.

The assemblage with *Pupilla loessica*, dominated by open-country species typical of a cold climate, represents arctic steppe-type habitats (Text-fig. 4). The appearance of *Pupilla sterri* marks limestone rock outcrop zones (assemblage with *Pupilla sterri*) (Text-fig. 4). Both subassemblages are characteristic of loess formations in Europe (e.g. Ložek 1965, 1969, 1991, 2001; Alexandrowicz 1995, 2009, 2014; Rousseau 1987; Alexandrowicz *et al*. 2002, 2013, 2014b; Sümegi 1995, 2005; Krolopp and Sümegi 1995; Rousseau *et al*. 2001, 2002; Sümegi and Krolopp 2002; Alexandrowicz and Dmytruk 2007; Moine 2008, 2014) and loess-like formations in the Carpathians (e.g. Alexandrowicz 1988a, 1997a; Cieszkowski *et al*. 2010), and they are considered to be indicators of such habitats. The age range of the discussed assemblages is precisely specified based on the studies of loess and loess-like deposit profiles. Both types of fauna are set in the coldest phases of Glacials, particularly in the periods of intensive aeolian accumulation. Both the C-14 and TL dating methods (including the dating of the Kosarzyska profile (Ps-V) – 23 400±550 BP (26 756–24 756 cal BC; Gd-2800) and the Mizerna profile (Ps-VII) – 27 400±600 BP (31 106–28 580 cal BC; Gd-1917); Alexandrowicz 1988a) referred to in this paper reveal the correspondence of these malacocoenoses to MIS 2 (see Table 2). The upper occurrence boundary for assemblages with *Pupilla loessica* and *Pupilla sterri* is demarcated by the disappearance of particular species (*Pupilla loessica*, *P. mus-*

corum densegyrata and *Vallonia tenuilabris*) with the beginning of MIS 1.

The assemblage with *Vertigo genesii* represents open-country, grass habitats with small patches of trees or shrubs and a cold climate. Unlike the assemblages described above, it is characteristic of areas with a high substrate moisture level. It is therefore related to humid or even waterlogged tundra (Text-fig. 4). The malacocoenosis is an indicator of the Younger Dryas (e.g. Limondin-Lozouet 1992; Krolopp and Sümegi 1993; Alexandrowicz 2004, 2009). The correspondence of the fauna with *Vertigo genesii* to the Late Glacial, especially to the Younger Dryas, is documented both in this paper (radiocarbon datings at Majerz (Ps-IV) – 11 250±250 BP (11 622–10 751 cal BC; Gd-4243) and at Maniowy (Ps-IX) – 11 060±120 BP (11 163–10 768 cal BC; Gd-5107) and at numerous sites in south Poland (see Table 2).

The fauna with a major proportion of *Discus ruderatus* (assemblage with *Discus ruderatus*) is typical of forest zones dominated by coniferous trees that develop under a cool and moderate continental climate (Text-fig. 4). This malacocoenosis is commonly considered characteristic of the early Holocene and was reported from this stratigraphic position in a large number of sites in Europe (e.g. Ložek 1964, 2000; Dehm 1967; Preece and Day 1994; Preece 1998; Gedda 2001, 2006; Žak *et.al*. 2002; Meyrick 2002; Limondin-Lozouet and Preece 2004; Limondin-Lozouet 2011). The assemblage with *Discus ruderatus* was also described from numerous radiocarbon-dated profiles in southern Poland, including the profile on the Majerz hill in Niedzica (Ps-XV) – 9040±90 BP (8483–7955 cal BC; Gd-1917) (see Table 2).

The assemblage with *Discus perspectivus* is typical of strongly shaded forest habitats. It occurs mainly in mixed forests with major proportions of deciduous trees with high temperature demands. This fauna prefers a warm and fairly humid climate strongly affected by maritime air masses (Text-fig. 4). It is typical of deposits formed during the Holocene climatic optimum and has been reported at this stratigraphic position from numerous radiocarbon-dated sites both in Europe (e.g. Preece and Day 1994; Preece 1998; Gedda 2001, 2006; Žak *et.al*. 2002; Meyrick 2002; Limondin-Lozouet and Preece 2004; Limondin-Lozouet 2011) and southern Poland [Poland is in Europe! Presumably western Europe is intended] (see Table 2). The Łapsze Niżne (Ps-XIII) site described in this paper was dated to 7410±130 BP (6480–6010 cal BC; MKL-1393).

Age diversification of slope covers

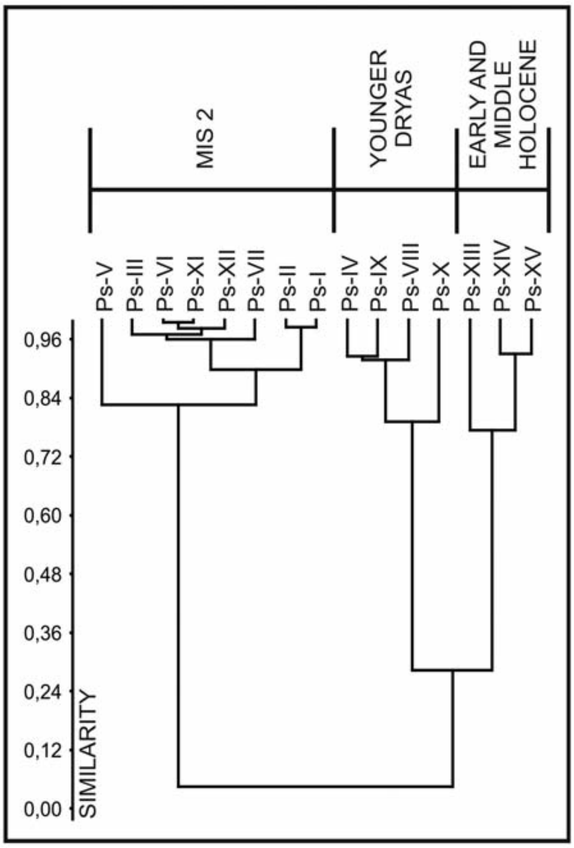
The profiles of the slope deposits studied in the eastern Podhale Region represent various climatic phases throughout the last 30 000 years. Each of these phases is reflected in different covers containing distinct malacofaunal assemblages. The slope deposits under discussion do not show major differences in lithology. It is thus very difficult, and often impossible, to derive their age solely from their lithological features and the geomorphological situation in which they occur. Malacofaunal assemblages, with their diversity and strict correlation to particular climatic phases,

	MIS 2	Younger Dryas	early Holocene	middle Holocene
Molluscan assemblage	*Pupilla loessica* *Pupilla sterri*	*Vertigo genesii*	*Discus ruderatus*	*Discus perspectivus*
Typical species	*Pupilla loessica* *Pupilla sterri* *Vallonia tenuilabris* *Pupilla muscorum densegyrata* *Succinella oblonga*	*Vertigo genesii* *Vertigo geyeri* *Vertigo modesta* *Columella columella*	*Discus ruderatus* *Vertigo substriata*	*Discus perspectivus* *Discus rotundatus* *Ruthenica filograna* *Aegopinella pura*
Species diversity	low	low	medium high	high
Dominant ecological group	cold-loving, open-country	cold-loving, hygrophilous	shade-loving (up to 50%)	shade-loving (up to 70%)
Environment	dry grasslands/ open rocky walls	wet grasslands, peatbogs, marshes	coniferous forests	mixed/deciduous forests
Plant formation	arctic steppe	tundra	taiga-type forests	mixed/deciduous forests
Climate	cold, dry, continental	cold, wet, continental	moderate cold, continental	moderate warm, oceanic
Marine isotope stages	MIS 2	MIS 1	MIS 1	MIS 1
Profiles (described in text)	Ps-I, Ps-II, Ps-III, Ps-V, Ps-VI, Ps-VII, Ps-XI, Ps-XII	Ps-IV, Ps-VIII, Ps-IX, Ps-X	Ps-XIV, Ps-XV	Ps-XIII

Table 3. Ecological and stratigraphical diversification of molluscan assemblages from slope deposits in the eastern part of the Podhale Basin

provide a convenient and accurate source of information concerning not only the conditions prevailing during the formation of the slope deposits but also their ages (Table 3).

The oldest slope covers described in the study region correspond to MIS 2. Slope covers of this age are formed as silty sediments, sometimes containing weakly rounded blocks of the underlying rock, usually sorted according to the slope inclination. They nearly always form the top part of the high terrace of the Dunajec River. These deposits contain an assemblage with *Pupilla loessica* indicative of loess formations that were formed during MIS 2 and an assemblage with *Pupilla sterri* typical of bare limestone rocks. Both these assemblages were repeatedly reported from the loess formations of Europe, particularly central and eastern (e.g. Ložek 1965, 1969, 1991, 2001; Alexandrowicz 1995, 2014; Alexandrowicz *et al*. 2002, 2013, 2014b; Sümegi 1995, 2005; Krolopp and Sümegi 1995; Sümegi and Krolopp 2002; Alexandrowicz and Dmytruk 2007; Moine 2008, 2014), as well as from the outcrops of loess-like deposits in the Carpathians (e.g. Alexandrowicz 1988a, 1997a; Cieszkowski *et al.* 2010). The above-mentioned assemblages represent entirely open, dry



Text-fig. 5. Stratigraphical range of profiles of slope deposits in the eastern part of the Podhale Basin

habitats and a cold, polar climate. They are distinguished by low diversity, with particular species usually occurring in large numbers, especially *Pupilla loessica* and *Succinella oblonga*. Slope covers associated with MIS 2 were identified in profiles Ps-I–Ps-III, Ps-VI, Ps-VII, Ps-XI and Ps-XII (Table 3, Text-fig. 5). The age of the deposits was additionally determined using radiocarbon dating to 23 400±550 BP (26 756–24 756 cal BC; Gd-2800) (profile Ps-V) and 27 400±600 BP (31 106–28 580 cal BC; Gd-1917) (profile Ps-VII) and derived from the bones of large vertebrates found in the Mizerna profile (profile Ps-VII) (Alexandrowicz 1988a, 1997a; Nadachowski *et al.* 2011).

The second group of profiles includes the outcrops of loam covers with sharp-edged blocks of the underlying rock, usually not showing any kind of sorting. These deposits rest directly on slopes, not coming into contact with the fluvial deposits that form terrace systems in valleys. The assemblage with *Vertigo genesii*, marked by a fairly diverse species composition and the domination of cold-loving forms (*Vertigo genesii*, *V. geyeri*, *V. modesta* and *Columella columella*), occurs in these covers. This fauna indicates a cold climate and humid or waterlogged habitats with small patches of tree or shrub vegetation (Table 3). The assemblage with *Vertigo genesii* is an indicator of the Younger Dryas (e.g. Limondin-Lozouet 1992; Krolopp and Sümegi 1993; Alexandrowicz 2004, 2009, 2013a; Alexandrowicz *et al.* 2014a), and was frequently noted at a very large number of sites with deposits of this age across Europe. Detailed palynological analysis of several peatbogs located in the vicinity of the sites under discussion show the domination of open, humid habitats with patches of trees and shrubs in the Podhale Region during the Younger Dryas (NAP phase; Obidowicz 1990). Slope covers corresponding to the Late Glacial were found in profiles Ps-IV (11 250±250 BP – 11 622–10 751 cal BC; Gd-4243), Ps-VIII, Ps-IX (11 060±120 BP – 11 163–10 768 cal BC; Gd-5107) and Ps-X (Text-fig. 5, Table 3).

Slope deposits associated with the early Holocene are marked by the occurrence of numerous blocks of the underlying rocks, randomly distributed within an abundant sand and loam matrix. The fauna found was the assemblage with *Discus ruderatus*, featuring a major species diversity and the abundant occurrence of shade-loving species typical of coniferous forests and a cool, moderate, continental climate (Table 3). Such a fauna is typical of the Preboreal and Boreal phases of the Holocene (Ložek 1964, 2000; Dehm 1967; Alexandrowicz and Alexandrowicz 1995a, b; Alexandrowicz 2004, 2009, 2013a; Alexandrowicz *et al*. 2014a). Its occurrence corresponds to the early Holocene *Pinus* phase distinguished in Podhale peatbogs (Obidowicz 1990). Slope covers dated at sites XIV and XV (9040±90 BP – 8483 –7955 cal BC; Gd-1917)) are related to the early Holocene (Text-fig. 5, Table 3)

The youngest of the slope covers described has a highly similar lithological form to the early Holocene deposits mentioned above. However, it contains an entirely different faunistic assemblage. Its characteristic feature is the exceptional abundance of shade-loving taxa typical of warm climates influenced by maritime air masses and of dense canopy forests with major proportions of deciduous trees. Another feature of the assemblage in question is the outstanding species diversity, a quality unseen in the older covers (Table3). This is the assemblage with *Discus perspectivus*, described from many sites as an indicator assemblage for the Atlantic Phase (e.g. Ložek 1964, 2000; Dehm 1987; Alexandrowicz and Alexandrowicz 1995a, b; Alexandrowicz 2004, 2009, 2013a; Alexandrowicz and Rybska 2013; Alexandrowicz *et al.* 2014a). Its presence in the analysed deposits can be correlated with the *Ulmus*, *Corylus* and *Ulmus-Tilia-Quercus-Fraxinus* phases reported in Podhale Region peatbogs (Obidowicz 1990). Profile XIII therefore represents the middle Holocene (Text-fig. 5, Table3). This stratigraphic position is additionally suggested by the result of radiocarbon dating performed on samples from this site: 7410±130 BP (6480–6010 cal BC; MKL-1393).

CONCLUSIONS

Progress in the research into slope covers over the last few years has resulted in numerous studies of these deposits being developed. Nevertheless, there are still many difficulties with drawing precise conclusions regarding the environmental conditions under which these sediments were deposited, and with determining the age of the covers. Traditional lithological and morphological indicators do not always provide answers to these questions. Moreover, slope deposits are not always suitable for precise radiometric dating (mainly radiocarbon dating). It is therefore necessary to constantly develop and improve research methods with respect to these deposits. The application of the malacological method allows more accurate studies and facilitates the creation of more precise reconstructions. Molluscan shells are frequent components of slope deposits, particularly in areas where carbonate rocks occur and especially where calcareous covers have formed. Malacological analysis may yield particularly satisfactory results in areas with the well-documented presence of molluscs in Quaternary deposits. The Podhale Basin is a model area that meets this requirement. In this region, the occurrence of thin covers representing distinct climatic phases, all containing malacofaunas, has allowed both the sedimentary environment features to be described and the age of deposition to be determined. The profiles representing MIS 2 were found to contain loess assemblages with *Pupilla loessica* and *Pupilla sterri*. In the Younger Dryas deposits, the assemblage with *Vertigo genesii*, typical of this period, is present. Holocene covers contain malacocoenoses with large proportions of shade-loving taxa: with *Discus ruderatus* (early Holocene) and *Discus perspectivus* (middle Holocene). The ecological and stratigraphic analyses show that the malacological method is promising in the context of slope deposit studies, and the results obtained from it may substantially supplement the data derived from other methods and provide more detail.

Acknowledgments

This study has been sponsored by AGH University of Science and Technology through the University grant no 11.11.140.173. The comments by journal referees, Pál Sümegi and Marcin Szymanek, as well as final corrections to the English by Christopher J. Wood, are acknowledged.

REFERENCES

Alexandrowicz, S.W. 1983. Malakofauna of the Holocene calcareous sediments of the Cracow Upland. *Acta Geologica Polonica*, **33**, 117–158.

Alexandrowicz, S.W. 1987. Malacological analysis in Quaternary research. *Kwartalnik AGH, Geologia*, **12**, 3–240. [In Polish with English summary]

Alexandrowicz, S.W. 1988a. Malacofauna of Late Quaternary loess-like deposits in the Polish Carpathians. *Acta Geologica Polonica*, **38**, 85–106.

Alexandrowicz, S.W. 1988b. The stratigraphy and malacofauna of the Holocene sediments of the Prądnik River Valley. *Bulletin of the Polish Academy of Sciences, Earth Sciences*, **36**, 109–120.

Alexandrowicz, S.W. 1989. Stratigraphy and malacofauna of the Upper Vistulian and Holocene deposits of the Szklarka River Valley, Cracow Upland. *Bulletin of the Polish Academy of Sciences, Earth Sciences*, **37**, 247–260.

Alexandrowicz, S.W. 1995. Malacofauna of the Vistulian loess in the Cracow Region (S Poland). *Annales Universitatis Mariae Curie Skłodowska*, **50**, 1–28.

Alexandrowicz, S.W. 1997b. Malakofauna of Holocene Sediments of the Prądnik and Rudawa River Valleys (Southern Poland). *Folia Quaternaria*, **68**, 133–188.

Alexandrowicz, S.W. 1997c. Holocene dated landslides in the Polish Carpathians. In: Frenzel, B. (Ed.), Rapid Mass Movement as a Source of Climatic Evidence for the Holocene. *Palaeoclimate Research*, **19**, 75–83.

Alexandrowicz, S.W. and Alexandrowicz, W.P. 1995a. Quaternary molluscan assemblages of the Polish Carpathians. *Studia Geomorphologica Carpatho-Balcanica*, **29**, 41–54.

Alexandrowicz, S.W. and Alexandrowicz, W.P. 1995b. Molluscan fauna of the Upper Vistulian and Early Holocene sediments of South Poland. *Biuletyn Peryglacjalny*, **34**, 5–19.

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

Alexandrowicz, S.W. and Alexandrowicz, Z. 1999. Recurrent Holocene landslides: a case study of the Krynica landslide in the Polish Carpathians. *The Holocene*, **9**, 91–99.

Alexandrowicz, S.W., Butrym, J., Krygowska-Iwaszkiewicz, M. and Zuchiewicz, W. 1991. On new sections of loess-like deposits of the Rożnów Foothills, West Carpathians, Poland. *Annales Universitatis Mariae Curie Skłodowska*, **46**, 1–19.

Alexandrowicz, S.W. and Chmielowiec, S. 1992. Late Vistulian and Holocene molluscan assemblages of the Bochnia Foothill near Gdów (Southern Poland). *Bulletin of the Polish Academy of Sciences, Earth Sciences*, **40**, 165–176.

Alexandrowicz, S.W. and Gębica, P. 1997. Malacofauna of less and Holocene sediments of middle terrace of Vistula river at Hebdów near Cracow. *Kwartalnik AGH, Geologia*, **23**, 9–28. [In Polish with English summary]

Alexandrowicz, S.W. and Łanczont, M. 2001. Deposits and malacofauna of the so-called low terrace in the valley of the Olszanka steram (Przemyśl Foothills). *Geneza, litologia i stratygrafia utworów czwartorzędowych*, **3**, 13–31. [In Polish with English summary].

Alexandrowicz, W.P. 1997a. Malacofauna of Quaternary deposits and environmental changes of the Podhale Basin during the Late Vistulian and Holocene. *Folia Quaternaria*, **68**, 7–132. [In Polish with English summary]

Alexandrowicz, W.P. 1999. Evolution of the malacological assemblages in North Poland during the Late Glacial and Early Holocene. *Folia Quaternaria*, **70**, 39–69.

Alexandrowicz, W.P. 2001. Late Vistulian and Holocene molluscan assemblages from calcareous tufa at Ostrysz Hill (Podhale Basin). *Folia Malacologica*, **9**, 159–169.

Alexandrowicz, W.P. 2003. The exposure of calcareous tufa in Gliczarów in the Podhale Basin. *Chrońmy Przyrodę Ojczystą*, **53**, 17–31. [In Polish with English summary]

Alexandrowicz, W.P. 2004. Molluscan assemblages of Late Glacial and Holocene calcareous tufas in Southern Poland. *Folia Ouaternaria*, **75**, 1–309.

Alexandrowicz, W.P. 2009. Malacostratigraphy of Vistulian and Holocene in Poland. *Studia Quaternaria*, **26**, 55–63.

Alexandrowicz, W.P. 2013a. Malacological sequence from profile of calcareous tufa in Groń (Podhale Basin, southern Poland) as an indicator of the Late Glacial/Holocene boundary. *Quaternary International*, **293**, 196–206.

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.

Alexandrowicz, W.P. 2013c. 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. 2013d. Late Glacial and Holocene molluscan assemblages in deposits filling palaeolakes in Northern Poland. *Studia Quaternaria*, **30**, 5–17.

Alexandrowicz, W.P. 2014. Malacological sequence of Weichselian (MIS 5-2) loess series from a profile in Grodzisko Dolne (southern Poland) and its palaeogeographic significance. *Quaternary International*, **319**, 109–118.

Alexandrowicz, W.P., Boguckyj, A., Dmytruk, R. and Łanczont, M. 2002. Molluscs of loess deposits in the Halyc Prydniestrov'ja region *Studia Geologica Polonica*, **119**, 253–290. [In Polish with English summary].

Alexandrowicz, W.P., Ciszek, D. and Gołas-Siarzewska, M. 2013. Malacological characteristic of the Weichselian Upper Pleniglacial loess profile in Tłumaczów (SW Poland). *Geological Quarterly*, **57**, 433–442.

Alexandrowicz, W.P. and Dmytruk, R. 2007. Molluscs in Eemian-Vistulian deposits of the Kolodiiv section, Ukraine (East Carpathian Foreland) and their palaeoecological interpretation. *Geological Quarterly*, **51**, 173–178.

Alexandrowicz, W.P., Łanczont, M., Boguckyj, A.B., Kulesza, P. and Dmytruk, R. 2014b. Molluscs and ostracods of the Pleistocene loess deposits in the Halych site (Western Ukraine) and their significance for palaeoenvironmental reconstructions. *Quaternary Science Reviews*, **105**, 162–180.

Alexandrowicz, W.P. and Rudzka, D. 2006. Molluscan communities from cave and slope deposits of the limestone rocky hills in the eastern part of Podhale Basin (Southern Polnd). *Folia Malacologica*, **14**, 191–201.

Alexandrowicz, W.P. and Rybska, E. 2013. Environmental changes of intermontane basins derived from malacological analysis of profile of calcareous tufa in Niedzica (Podhale Basin, Southern Poland). *Carpathian Journal of Earth and Environmental Sciences*, **8**, 4, 13–26.

Alexandrowicz, W.P., Szymanek, M. and Rybska, E. 2014a. Changes to the environment of intramontane Bains In the light of malacological research of calcareous tufa: Podhale Basin (Carpathias, Southern Poland). *Quaternary International*, **353**, 250–265.

Bertran, P., Hetu, B., Texier, J-P. and Van Steijn, H. 1997. Fabric characteristics of subaeral slope deposits. *Sedimentology*, **44**, 1–16.

Bronk Ramsey, C. 2001. OxCal Program 3.9. University of Oxford. Radiocarbon Accelerator Unit.

Birkenmajer, K. and Środoń, A. 1960. Aurignacian interstadial in the Carpathians. *Biuletyn Instytutu Geologicznego*, **150**, 9–54.

Blikra, L.H. and Nemec, W. 1998. Postglacial colluvium in western Norway: depositional processes, facies and palaeoclimatic record. *Sedimentology*, **45**, 909–959.

Butrym, J. and Zuchiewicz, W. 1990. On new sites of solifluction and deluvial (washout) deposits in the Rożnów Foothills, Outer West Carpathians. *Studia Geomorphologica Carpatho-Balcanica*, **24**, 87–99.

Cieszkowski, M., Zuchiewicz, W., Alexandrowicz, W.P. and Wojtal, P. 2010. A new find of mammoth tusk in loess-like sediments of the Zakliczyn Basin (Outer Western Carpathians, Poland). *Annales Societatis Geologorum Poloniae*, **80**, 89–99.

Danukalova, G. and Eremeev, A. 2006. Quaternary loess-like deposits of the southern Urals. *Quaternary International*, **152–153**, 31–36.

Dehm, R. 1967. Die Landschnecke *Discus ruderatus* im Postglazial Süddeutschlands. *Mitteilungen der Bayerische Staatssammlung für Paläontologie und Historische Geologie*, **7**, 135–155.

Dehm, R. 1987. Die Landschnecke *Discus perspectivus* im Postglazial Südbayerns. *Mitteilungen der Bayerische Staatssammlung für Paläontologie und Historische Geologie*, **27**, 21–30.

Gedda, B. 2001. Environmental and climatic aspects of the Early and Mid Holocene calcareous tufa and land mollusc fauna in southern Sweden. *Lundqua Thesis*, **45**, 1–50.

Gedda, B. 2006. Terrestrial mollusc succession and stratigraphy of a Holocene calcareous tufa deposit from the Fyledalen valley, southern Sweden. *The Holocene*, **16**, 137–147.

Gerlach, T., Krysowska-Iwaszkiewicz, M., Szczepanek, K. and Alexandrowicz, S.W. 1991. The Carpathian variety of loess at Humniska near Brzozów in the Dynów Foothills, Polish Flysch Carpathians. *Kwartalnik AGH, Geologia*, **17**, 193–219. [In Polish with English summary].

Hammer, Ø., Harper, D.A.T. and Ryan, P.D. 2001. Past: paleontological statistics software package for education and data analysis. *Palaeontologica Electronica*, **4**, 1–9.

Kalicki, T., Kozłowski, J.K., Krzemińska, A., Sobczyk, K. and Wojtal, P. 2007. The formation of mammoth bone accumulation at the Gravettian site Kraków-Spadzista B+B1. *Folia Quaternaria*, **73**, 5-30.

Kerney, M.P., Cameron, R.A.D and Jungbluth, J.H. 1983. Die Landschnecken Nord- und Mitteleuropas, 384 pp. Verlag P. Parey; Hamburg-Berlin.

Krolopp, E. and Sümegi P. 1993. *Vertigo modesta* (Say 1924), *Vertigo geyeri* Lindholm 1925 and *Vertigo genesii* (Gredler 1856) species in Pleistocene formations of Hungary. *Malacological Newsletter*, **12**, 9–14.

Krolopp, E. and Sümegi, P. 1995. Palaeoecological reconstruction of the Late Pleistocene, based on Loess Malacofauna in Hungary. *GeoJournal*, **36**, 213–222.

Kulczycki, J. and Halicki, B. 1950. Znalezisko mamuta w Pieninach. [La trouvaille d'un mammoth dans les Mts. Pieniny]. *Acta Geologica Polonica*, **1**, 330–334.

Limondin-Lozouet, N. 1992. Biogeographie Holocene de *Vertiginidae* (*Mollusca – Gastropoda*) Europeens: relations la derniere deglaciation. *Compest Rendus de l'Académie des Sciences Paris*, **315**, 1281–1287.

Limondin-Lozouet, N. 2011. Successions malacologiques à la charnière Glaciaire/Interglaciaire: du modèle Tardiglaciaire-Holocène aux transitions du Pleistocène. *Quaternaire*, **22**, 211–220.

Limondin-Lozouet, N. and Preece, R.C. 2004. Molluscan successions from the Holocene tufa of St Germain-le-Vasson, Normandy (France) and their biogeographical significance. *Journal of Quaternary Science*, **19**, 55–71.

Limondin-Lozouet, N. and Rousseau, D.D. 1991. Holocene climate as reflected by a malacological sequence at Verriers, France. *Boreas*, **20**, 207–229.

Ložek, V. 1964. Quartärmollusken der Tschechoslowakei. *Rozpravy Ustředniho Ustavu Geologického*, **31**, 1–374.

Ložek, V. 1965. Das Problem der Lössbildung und die Lössmollusken. *Eiszeitalter und Gegenwart*, **16**, 61–75.

Ložek, V. 1969. Paläontologische Charakteristik der Lösserien. Periglacial, Löss und Paläolith Tschechoslovakei, pp. 43–59. Brno.

Ložek, V. 1976. Klimaabhängige Zyklen der Sedimentation und Bodenbildung während Quartärs im Lichte malakozoologischer Untersuchungen. *Rozpravy Československé Akademie Věd,* **86**, 1–97.

Ložek, V. 1982. Faunengeschichtliche Grundlinien zur spät- und nacheiszeitlichen Entwicklung der Molluskenbestände in Mitteleuropa. *Rozpravy Československé Akademie Věd,* **92**, 1–106.

Ložek, V. 1991. Molluscs in loess, their paleoecological significance and role in geochronology – principles and methods. *Quaternary International*, **7–8**, 71–79.

Ložek, V. 2000. Palaeoecology of Quaternary Mollusca. *Antropozoikum*, **24**, 35–59.

Ložek, V. 2001. Molluscan fauna from the loess series of Bohemia and Moravia. *Quaternary International*, **76–77**, 141–156.

Ložek, V. 2006. Late Glacial palaeoenviromnents of the West Carpathians in the light of fossil malacofauna. *Antropozoikum*, **26**, 73–84.

Matsuoka, N. 2001. Solifluction rates, processess and land-forms: a global review. *Earth Science Reviews*, **55**, 107–134.

Meyrick, R.A. 2001. The development of terrestial mollusc faunas in the 'Rheinland region' (western Germany and Luxembourg) during the Lateglacial and Holocene. *Quaternary Science Reviews*, **20**, 1667–1675.

Meyrick, R.A. 2002. Holocene molluscan faunal history and environmental change at Kloster Mühle, Rheinland-Pfalz, western Germany. *Journal of Quaternary Science*, **18**, 121–132.

Meyrick, R.A and Preece, R.C. 2001. Molluscan succesions from two Holocene tufas near Northampton, English Midlands. *Journal of Biogeography*, **28**, 77–93.

Moine, O. 2008. West-European malacofauna from loess deposits of the Weichselian Upper Pleniglacial: compilation and preliminary analysis of the database. *Quaternarie*, **19**, 11–29.

Moine, O. 2014. Weichselian Upper Pleniglacial environmental variability in northwestern Europe reconstructed from terrestrial mollusc faunas and its relationship with the presence/absence of human settlements. *Quaternary International*, **337**, 90–113.

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

Nadachowski, A., Lipecki, G., Wojtal, P. and Miękina, B. 2011. Radiocarbon chronology of woolly mammoth (*Mammuthus primigenius*) from Poland. *Quaternary International*, **245**, 186–192.

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

Pawelec, H. 2006. Origin and palaeoclimatic significance of the Pleistocene slope covers in the Cracow Upland, southern Poland. *Geomorphology*, **74**, 50–69.

Pazdur, A. 1987. Isotopic composition of carbon and oxygen in Holocene calcareous tufa sediments. *Geochronometria*, **3**, 14–75.

Preece, R.C. 1998. Mollusca. In: Preece, R.C., Bridgland, D.R. (Eds), Late Quaternary environmental change in North-West Europe: excavations at Holywell Coombe, South-West England. Chapman & Hall, London, pp. 158–212.

Preece, R.C. and Day, S.P. 1994. Comparison of Post-glacial molluscan and vegetational successions from a radiocarbon-dated tufa sequence in Oxfordshire. *Journal of Biogeography*, **21**, 463–468.

Rousseau, D.D. 1987. Paleoclimatology of the Acenheim Series (Middle and Upper Pleistocene, Alsace, France). A Malacological Analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **59**, 293–314.

Rousseau, D.D., Gierasimenko, N., Matvischina, Z. and Kukla, G. 2001. Late Pleistocene Environments of the Central Ukraine. *Quaternary Research*, **56**, 349–356.

Rousseau, D.D., Antoine, P., Hatté, C., Lang, A., Zöller, L., Fontugne, M., Ben Othman, D., Luck, J.-M., Moine, O., Labonne, M., Bentaleb, I. and Jolly, D. 2002. Abrupt millennial climatic changes from Nussloch (Germany) Upper Weichselian aeolian records during the Last Glaciation. *Quaternary Science Reviews*, **21**, 1577–1582.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., van der Plicht, J. and Spurk, M. 1998. INTCAL98 Radiocarbon age calibration 24,000-0 cal BP. *Radiocarbon*, **40**, 1083–1127.

Sümegi, P. 1995. Quartermalacological analysis of Late Pleistocene Loess Sediments of the Great Hungarian Plain. *Malacological Newsletter Supplement*, **1**, 79–111.

Sümegi, P. 2005. Loess and Upper Paleolithic environment in Hungary, 312 pp. Aurea Press; Nagykovasci.

Sümegi, P. and Krolopp, E. 2002. Quartermalacological analysis for modeling of the Upper Weichselian palaeoenvironmental changes in the Carpathian Basin. *Quaternary International*, **91**, 53–63.

Van Steijn, H., Bertran, P., Francou, B, Hétu, B. and Texier, J-P. 1995. Models for the genetic and environmental interpretation of stratified deposits. *Permafrost and Periglacial Processes*, **6**, 125–146.

Yakovlev, A., Danukalova, G. and Osipova, E. 2013. Biostratigraphy of the Upper Pleistocene (Upper Neopleistocene) of the Southern Urals. *Quaternary International*, **292**, 150–167.

Zuchiewicz, W. 1988. Evolution of the eastern Beskid Niski Mts. and morphotectonics of the Polish Carpathians. *Kwartalnik AGH, Geologia*, **13**, 3–167.

Žak, K., Ložek, V., Kadlec, J., Hladikova, J. and Cilek, V. 2002. Climate-inducted changes in Holocene calcareous tufa formations, Bohemian Karst, Czech Republic. *Quaternary International*, **91**, 137–152.

Manuscript submitted: 7th December 2014
Revised version accepted: 20th April 2015