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3. Late Quaternary History and Palaeoclimatic Implications of Danubian Flat Based on Dating, Geochemistry, Lithology, Isotope Analyses and Land Snail Assemblages

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Abstract: The paper presents the results of geological research of the Podunajská rovina Flat (hereinafter Danubian Flat) in terms of stratigraphy of near-surface and surface sediments and palaeo-environmental changes in the period from the last interglacial period (Eemian, about 127,000 years BP) to the present. The period of Late Glacial to Holocene was studied in more detail because the climatic transition of the Last Glacial to postglacial had the greatest influence on the formation of the present natural environment, fauna and flora. In this context, the possibility of using isotopic analyses of oxygen and carbon from gastropods shells was also investigated in the reconstruction of palaeoclimatic changes and the natural environment in the past.

Using the AMS ^{14}C method, 24 samples from 16 localities dating from the Late Glacial to Holocene succession were dated. The observed age of dated samples by this method ranged from 135 ± 30 years BP to 14,410 ± 90 years BP. The OSL method of the studied profiles of 15 localities of the Danubian Flat territory dated 22 samples. The age of these dated samples ranged from 127,000 to 314 years BP. The time period from the Eemian Interglacial (i.e. the penultimate glacial period) to the present has been recorded. Both methods specified the stratigraphic position of fluvial and aeolian sediments in the area studied.

Research shows that the climate has never been stable in the past. The alternation of climate cycles during the last (Weichselian) glacial was reflected in the formation of sediments, to which flora, fauna and naturally also human society responded.

The article also highlights the importance and merits of the study of climate change by various scientific disciplines. Without an interdisciplinary approach to the study of climate change, it is not possible to detect, record and accurately interpret minor climate oscillations in the past. Knowledge of climate history and its impact on the natural environment and human civilization is therefore essential for the forecast of future climate change.

Key words: Late Pleistocene, climate, environment, dating, land snails, oxygen isotopes, carbon isotopes

3.1 Introduction

The article presents a synthesis and interpretation of the results of research and laboratory analyses obtained in the framework of the project "Geological map of the region Danube Lowland – Danubian Flat – in scale 1: 50,000".

Thanks to its sedimentary records in fluvial, aeolian and organogenic deposits as well as soils (including fossil soils) the area of the Danubian Flat provided the possibility of detailed study and evaluation of samples from the above mentioned genetic types of the Quaternary sediments and weathering scree not only from stratigraphic, but also palaeoecological point of view.

The article characterizes climate change from the last interglacial (Eemian) to the present (MIS 5 to MIS 1). This is a period of time that had a great influence on the formation of the current natural environment not only in the area under investigation (Fig. 3.1). The article also deals with the possibilities of using isotopic analyses of oxygen and carbon in land snail shells for reconstructions of climate changes and natural environment in the past.

Fig. 3.1 The area of the Podunajská rovina Flat

3.2 Geological and climate setting

From the geological point of view, the surveyed area is a part of the northwest depocentre of the Neogene Danube Basin termed as the "Slovak part of the Danube Basin". This basin in the area under investigation is represented by Gabčíkovo Basin.

The sedimentary fill of the Gabčíkovo Basin consists of sub-horizontally deposited, marine, towards the surface brackish to freshwater deposits, generally overlying the pre-Mesozoic bedrock, built mainly of the crystalline rocks. The assumed local Palaeogene part of the basin fill consists of sandstone and claystone. The substantial Neogene sequence consists of sand to sandstone, clay, gravel and locally also volcaniclastics, Miocene to Pliocene in age. The Neogene sequences overlie relatively coarse deposits of the Quaternary fluvial gravel and sand. Fluvial accumulations represent a unique inland delta of the Danube, laterally limited by a smaller delta of the Váh, or Nitra and Žitava rivers. The character of the deposition is superpositional and transitional (Šujan et al., 2018) only at the edges of the flat and along the mountain range foothills there is a terrace development of accumulation. The Holocene fluvial accumulation, aeolian sediments are deposited on the Pleistocene fluvial sediments, and occurrences of organogenic sediments are also common. (Maglay et al., in press).

The total sedimentary fill of the basin reaches a maximum of 8,000 to 9,000 m according to seismic sections (sensu Hrušecký, 1999). The basin was formed by active arc extension and subsequent thermal subsidence in the post-rift stage of development (Hók et al., 2001; Horvath et al., 2006; Kováč et al., 2011; Kováč et al., 2017).

The area of the Gabčíkovo Basin roughly corresponds to the on the surface geomorphologically delimited area of the Danubian Flat (Mazúr & Lukniš, 1986; Fig. 3.2). Its fluvial relief is morphotectonically undifferentiated, planar, slightly undulated with an average slope of 1.5° (max. to 2°). According to Mazúr (in Mazúr & Jakál – eds., l.c.), the horizontal structure of the relief is in the range of 0 – 0.5 km/km^2. It is a fluvial plain, sometimes even fluvial and peat wetland with recent, locally erosive, mostly laterally acting processes.

The low height segmentation of the Danubian Flat is reflected in the small climatic differences among its individual parts. Most of the territory under study belongs to a warm, slightly dry to dry climate area with a warm, slightly dry to dry lowland climate with temperature inversion (Konček, in Mazúr & Jakál – eds., 1980; Lapin et al., in Atlas of the Slovak Republic, 2002). It is characterized by a mild winter (up to 90 days) with an average temperature in January of -3 °C and higher; a warm summer with a number of summer days (above 25 °C) of more than 50 per year. The mean annual temperature (MAT) in the lowland ranges from 8 to 10 °C (Šťastný et al., in Atlas in the Slovak Republic, 2002). A characteristic feature of the Danubian Flat is its aridity. Average annual rainfall totals range between 530 – 700 mm/year, which is the lowest in Slovakia, only at the edge of the Malé Karpaty Mts. the values reach between 600 – 900 mm/year. In January, average totals range from 30 to 50 mm. The July totals for the whole territory reach values in the range of 60 – 80 mm (Faško & Šťastný in Atlas of the

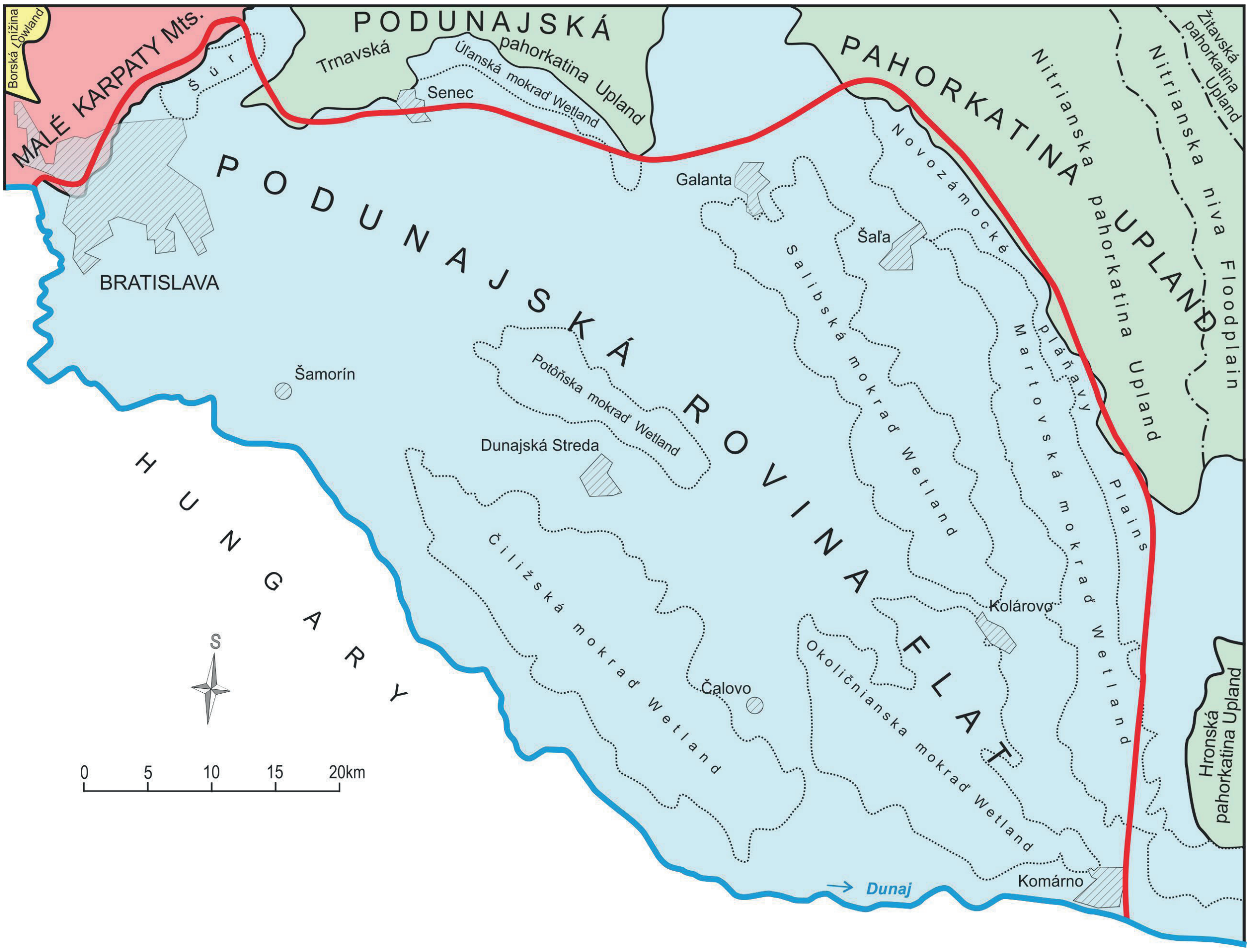


Fig. 3.2 Schematic outline of the geomorphological division of the Danube Flat (According to Mazúr & Lukniš, 1980, revised by Maglay, 2017). The red line indicates the studied area of the Danube Flat.

Slovak Republic, 2002). The average dry period lasts 30 – 50 days a year (Tarábek in Mazúr & Jakál – eds., 1980). The whole area is dominated by NW winds; less frequent are N and S winds. Their average speed ranges from 2 to 4 m.s^{-1}.

3.3. Materials and methods

Field research

Within geological mapping and field research, 13 sites with fluvial sands, 3 sites with aeolian sands, 13 sites with well-preserved fossil soils and 1 site with humoliths in oxbows fills. From 2 sites the gastropods were dated and studied and from 1 site the wood fragment.

Detailed field research included the preparation and cleaning of sampling profiles, macroscopic sedimentological analysis, GPS positioning with photodocumentation, sediment colour determination according to the Munsell scale, precise and systematic sampling – sampling for malacofauna analyses, geochemical analyses and dating by OSL and ^{14}C AMS dating methods (Fig. 3.3). Samples for analyses were also taken in some cases from hand drilled probes with a depth of up to 1.2 m.

^{14}C dating with the AMS technique

^{14}C AMS dating was performed in the AMS ^{14}C laboratory of the a Mickiewicz Unoversity in Poznań, Poland. Procedure of ^{14}C dating with the AMS technique, consists of a few stages:

a) chemical pre-treatment
b) production of CO_2 and graphitisation
c) AMS ^{14}C measurement
d) calculation of ^{14}C age and calibration of ^{14}C age

a) Methods of chemical pre-treatment generally follow those used in the Oxford Radiocarbon Accelerator Unit, as described by Brock et al. (2010). Samples of charcoal, wood, or other plant remains (after mechanical removal of macroscopic contamination visible under binocular) are treated with 1M (UW, ZR) HCl (80 °C, 20+ min), 0.025-0.1M NaOHand – if needed – 80 °C for wood and charcoal (UW, ZR) and then 0.25M HCl (80 °C, 1 hour). After treatment with each reagent, the samples are rinsed with deionised water (Millipore) until pH=7. For the first HCl treatment, longer time (20+ min) is applied, if emanation of gas bubbles from sample is still visible. The step of NaOH treatment is repeated a few times, generally until no more coloration of the NaOH solution appears (coloration of solution is caused by humic acids dissolved in NaOH), but the NaOH treatment is interrupted if there is a danger of complete dissolution of the sample.
In case of wood samples (UW), additional treatment with 5% $NaClO_2$ (room temperature, 30 min) is applied.
Samples of sediments (and soils) are usually treated with 1M HCl (80 °C, 1+ hour), 0.1M NaOH (80 °C,

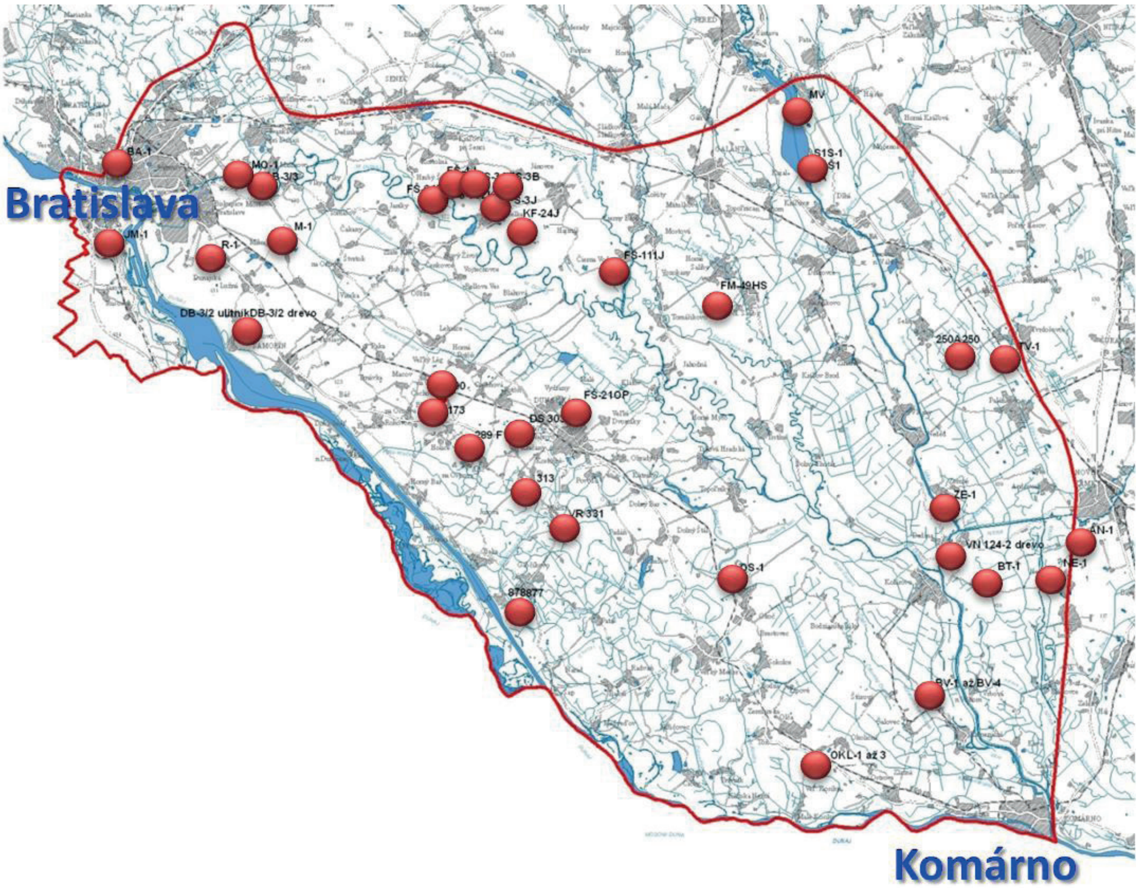


Fig. 3.3 Sites with ^{14}C AMS and OSL methods dating

10+ min) and then 0.25M HCl (80 °C, 1 hour) (SRa). After treatment with each reagent, the samples are rinsed with deionised water (Millipore) until pH=7. For the first HCl treatment, longer time (1+) is applied, if emanation of gas bubbles from a sample is still visible. The step of NaOH treatment is repeated a few times, generally until no more coloration of the NaOH solution appears (coloration of solution is caused by humic acids dissolved in NaOH).

Samples of shells (and other carbonate features) are checked and mechanically cleaned under binocular. The organic coating, if visible, is removed with H_2O_2 (15 – 30%) in an ultrasonic bath. Then the outer carbonate layer (ca. 30%) is removed in 0.5M HCl (if the sample is large enough), the remaining material is treated in 15% H_2O_2 again (for 10 min in a ultrasonic bath) and the remaining carbonate is leached with concentrated H_3PO_4 in a vacuum line.

b) In case of organic samples, CO_2 is produced by combusting the sample. Combustion of organic samples is performed in closed (sealed under vacuum) quartz tubes, together with CuO and Ag wool, in 900 °C over 10 hours. CO_2 from carbonate samples is leached by treating with concentrated orto-phosphoric acid (H_3PO_4) in a vacuum line.

The obtained gas (CO_2 + water vapour) is then dried in a vacuum line, and reduced with hydrogen (H_2), using 2 mg of Fe powder as a catalyst. The obtained mixture of carbon and iron is then pressed into special aluminium holder, according to the description provided by Czernik & Goslar (2001).

In the same way were prepared the standard samples, i.e. samples not containing ^{14}C (coal or IAEA C1 Carrara Marble) and samples international modern ^{14}C standard (Oxalic Acid II).

c) Measurements described in this point, are performed in the AMS ^{14}C Laboratory of the A. Mickiewicz University in Poznań. Cooperation between the Poznań Radiocarbon Laboratory and the AMS ^{14}C Laboratory is regulated by the Agreement between Foundation of the A. Mickiewicz University and the A. Mickiewicz University.

Content of ^{14}C in a sample of carbon is measured using the spectrometer "Compact Carbon AMS" (produced by: National Electrostatics Corporation, USA) described in the paper: Goslar & Czernik (2001), Goslar (2004). The measurement is performed by comparing intensities of ionic beams of ^{14}C, ^{13}C and ^{12}C measured for each sample and for standard samples (modern standard: "Oxalic Acid II" and standard of ^{14}C-free carbon: "background"). In each AMS run, 30 – 33 samples of unknown age are measured, alternated with measurements of 3 – 4 samples of modern standard and 1 – 2 samples of background. In case, where organic samples are dated, the background is represented by coal, while in case of carbonate samples, the background is represented by the sample IAEA C1.

d) Conventional ^{14}C age is calculated using correction for isotopic fractionation (according to Stuiver&Polach, 1977), basing on ratio $^{13}C/^{12}C$ measured in the AMS spectrometer simultaneously with the ratio $^{14}C/^{12}C$ (note: the measured values of $\delta^{13}C$ depend on isotopic fractionation during CO_2 reduction and isotopic fractionation inside the AMS spectrometer, and as such, they cannot be compared with values of $\delta^{13}C$ determined with conventional mass spectrometers on gas samples). Uncertainty of calculated ^{14}C age is determined using uncertainty implied from counting statistics, and also spread (standard deviation) of partial $^{14}C/^{12}C$ results, whichever is bigger. Uncertainties of $^{14}C/^{12}C$ ratios measured on standard samples are additionally taken into account. The 1-sigma uncertainty of conventional ^{14}C age given in Poznań Laboratory reports is the best estimate of the total uncertainty of measurement.

Calibration of ^{14}C age is performed using the program OxCal ver. 4.2 (2014), the ground of which is described by Bronk Ramsey (2001), while the recent version – by Bronk Ramsey (2009), and Bronk Ramsey and Lee (2013). Calibration is performed against the newest version of ^{14}C calibration curve, i.e. INTCAL13 (Reimer et al. 2013).

Optically stimulated luminescence (OSL)

OSL dating was performed in Silesian University of Technology, Institute of Physics, Gadam Centre, Gliwice, Poland. The annual dose was calculated using Canberra spectrometer equipped with HPGe detector. Typical mass of dry sample was about 800 g, which was measured at least 24 hours. Dose rates were calculated using the conversion factors devised by Guerin et al. (2011). For beta dose rates, the cosmic ray dose-rate at the site was determined as described by Prescott & Stephan (1982). We assumed that the average water content was no higher than 20% and consequently used a value of (15±5) %.

For standard OSL measurements, medium sized grains (45 – 63 µm) of quartz were extracted from the sediment samples. Laboratory protocol includes few steps of chemical treatment such as 20% hydrochloric acid (HCl), 20% hydrogen peroxide (H_2O_2) and finally concentrated hydrofluoric acid (HF). The quartz grains were also separated using density separation with the application of sodium polytungstate solutions leaving grains of densities between 2.62 $g.cm^{-3}$ and 2.75 $g.cm^{-3}$. The quartz fraction discs were prepared by spraying silicone oil on to 10-mm-diameter stainless steel discs through a mask with holes of a diameter of ca. 6 mm allowing for ca. 1 mg of grains be stuck on them.

All OSL measurements were made using an automated Daybreak 2200 TL/OSL reader (Bortolot, 2000). This reader uses blue diodes (470±4 nm) delivering about 60 $mW.cm^{-2}$ at the sample position and is equipped with 6 mm Hoya U-340 filter for the OSL measurements. Laboratory irradiations were made using a calibrated $^{90}Sr/^{90}Y$ beta source mounted onto the reader with a dose rate of 3.0 $Gy.min^{-1}$.

For the medium grain quartz fraction, equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle, 2000). Ages calculated using the Central Age Model (CAM) (Galbraith et al., 1999).

Stable isotopes

Stable isotope analyses were preformed in the laboratory of isotope geology, State Geological Institute of Dionýz Štúr, Bratislava, Slovakia.

Measurement principle for carbon

Isotope ratio mass spectrometry (IRMS) represents the preferred method for analyses of the bulk $^{13}C/^{12}C$ carbon isotope ratio at natural abundance, because of the relative high accuracy (0.1‰) and sensitivity (up to 0.01‰). The element of interest must be isolated from the sample matrix and converted to a gas that is stable and unreactive at room temperature. In the case of carbon, samples are analyzed as CO_2 (Fry, 1991). In the EA/IRMS technique, the sample is instantaneously melted and cracked by thermal treatment, oxidized (in the presence of O_2) and converted into homogenous combustion gases (CO_2, N_2 and H_2O) in amounts stoichiometrically equivalent to its elemental components in the sample. These effluent gases (A water removal trap filled with anhydrous magnesium perchlorate [$Mg(ClO_4)_2$] removes H_2O present in the mixture) are carried in a stream of He and introduced into the IRMS as transient peaks. Unlike the GB technique, which allows determination of $\delta^{13}C$ and $\delta^{18}O$ of sample CO_2 gas during a single run, the EA technique only allows determination of $\delta^{13}C$ of sample CO_2 during a single run. The analytical circuit of the EA comprises of a combustion reactor (Cr_2O_3 catalyst and Co_3O_4 coated with silver), a reduction reactor (reduced copper wire, 0.7 mm diameter) and a GC column (Paul & Skrzypek, 2006).

All carbon isotopic compositions of samples are reported in the standard δ -notation in the $^{13}C_{V\text{-}PDB}$ scale:

$$\delta_e = \left(\frac{R_{sample}}{R_{reference}} - 1 \right) \text{ x } 1000$$

δ_e is defined as the relative difference, in parts per mille (‰), between the isotope ratio of the sample and the VPDB carbonate standard (established by the International Atomic Energy Authority, IAEA, Vienna) (Werner & Brand, 2001).

Measurement procedure

For sample combustion, the peripheral EA unit (Flash HT 2000, Thermo Fisher) was connected to IRMS spectrometer (Delta V Advantage, Thermo Fisher). A small amount of the sample (about 350 µg) was wrapped into a silver capsule, which was dropped through the autosampler (AS2000, Thermo Fisher) to the furnace tube heated to 1,020 °C. The sample was flash-combusted with the assistance of oxygen pulse and the resulting gases were flown through a silica column packed with chromium oxide, reduced copper and silver cobaltous-cobaltic oxide, which served as further oxygen donors to ensure complete sample combustion. By this way, all carbon was fully oxidised to CO_2 and $\delta^{13}C$ was measured by the mass spectrometer (Grolmusová et al., 2012). The ion currents of mass/proton number 44–46 were registered and the results were calculated relative to a CO reference gas. The duration of one sample run was 500 s.

Samples and standardization

The calibration samples were internationally distributed reference materials and standards. 350 µg of $CaCO_3$ samples and standards were weighed into silver capsules (3.3 x 5 mm, Säntis Analytical. Standards used were IA-R022 (Iso-Analytical, $\delta^{13}C_{V\text{-}PDB}$ = -28.63‰), NBS 19 (IAEA, $\delta^{13}C_{V\text{-}PDB}$ = 1.95‰) and IAEA KST (IAEA, $\delta^{13}C_{V\text{-}PDB}$ = -5.76‰). Used laboratory standards are intended to provide a samples of known isotope composition with $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotope ratios stated in parts per thousand difference (‰) from the V-PDB (Pee Dee Belemnite) isotope ratio standard.

Measurement principle for oxygen

Precise $\delta^{18}O$ analyses of carbonate samples can be performed with the high-temperature pyrolysis method in an Elemental Analyzer (using CO as the analyte gas) (Gehre et al., 2003) coupled with isotope ratio mass spectrometer (IRMS). A prerequisite for an on-line technique for $\delta^{18}O$ measurement is a fast and quantitative conversion of the sample oxygen to a single gaseous product (Kornexl et al., 1999). The precision of TC/EA-IRMS is in general close to or slightly lower than other methods, but it has the combined advantages of minimal sample amount requirement, easy operation, high throughput, and most importantly, the capability to measure the $\delta^{18}O$ value of different types of substances (Yin & Chen, 2014). The apparatus consists of a thermal conversion — elemental analyzer (TC/EA) unit, which is a graphite crucible (composed of an outer reaction tube made of Al_2O_3 ceramic and an inner glassy carbon tube) inserted in the hottest zone of the reaction furnace, and heated to 1,450 °C. At these temperatures, carbon from the inner tube and glassy carbon grit, which partially fill the reactor, primes the reduction of the analyzed compounds following the reaction

$$\text{O compound}_{(s)} + C_{(s)} = CO_{(g)} + [\text{residuals}]_{(s,g,l)}$$

For such measurements on inorganic compounds it is necessary to have a reactive carbon source near the sample (Boschetti & Iacumin, 2005). The mass spectrometer software calculates their isotope ratio and the final result for the sample in the δ notation, given in ‰ deviation from the reference :

$$\delta_e = \left(\frac{R_{sample}}{R_{reference}} - 1 \right) \text{ x } 1000$$

In practice, a series of standardization runs are performed to calibrate the reference CO gas, which will subsequently be used as a standard during the measurement (Koziet, 1997).

Measurement procedure

The reaction furnace is heated to maximum temperature of 1,450 °C. With command given by software (ISODAT3.0, Thermo Fisher), the autosampler (AS2000, Thermo Fisher) dropped the samples into the reaction tube, flushed with the constant flow (140 mL/min) of carrier gas (He, 99.999%). Carrier gas transported the main gaseous products of pyrolysis through $MgClO_4$ trap (for retention of H_2O) and GC column held at 90 °C, where CO was separated from other gases. Consequently, CO was transferred via a ConFlo IV open split interface to the Delta V Advantage isotope ratio mass spectrometer (both Thermo Fisher). The ion currents of mass/proton number 28–30 were registered and the results were calculated relative to a CO reference gas (Fig. 3.4). The duration of one sample run was 360 s.

Samples and standardization

The calibration samples were internationally distributed reference materials and standards. 150 µg of $CaCO_3$ samples and standards were weighed into silver capsules (3.3 x 5 mm, Säntis Analytical) with addition of 200 µg of carbon (internal laboratory grade) for better thermal conversion. Standards used were IA-R022 (Iso-Analytical, $\delta^{18}O_{V\text{-}PDB}$ = -22.69‰) and NBS 19 (IAEA, $\delta^{18}O_{V\text{-}PDB}$ = -2.2‰). Used laboratory standards are intended to provide a samples of known isotope composition with $^{13}C/^{12}C$ and $^{18}O/^{16}O$ isotope ratios stated in parts per thousand difference (‰) from the V-PDB (Pee Dee Belemnite) isotope ratio standard.

3.4 Results and discussion

3.4.1 Sites dating using ^{14}C AMS and OSL dating methods

To determine the age of fossil soils, gastropods and woods we used mass spectrometry of the ^{14}C AMS dating method. Altogether 24 samples from 16 localities were dated by this method (Tab. 3.1).

The age of the dated samples ranged from 135 ± 30 years BP to 14,410 ± 90 years BP. One sample was outside the ^{14}C AMS dating method range. It came from the well VN 124-2 (Kolárovo). Its age was more than 50,000 years BP (Tab. 3.1).

The samples were dated in AMS ^{14}C Laboratory of A. Mickiewicz University in Poznań, Poland.

Optically stimulated luminescence (OSL dating) was used to determine the age of aeolian and fluvial sands. Altogether 22 samples from 17 sites were dated by this method.

The age of the dated samples ranged from 314 to 127,000 years BP (Tab. 3.1).

The age of all dated samples by ^{14}C AMS and OSL ranged from 135 ± 30 years BP to 127,000 ± 1000 years BP. The dated samples captured the time period from the Eemian Interglacial (i.e. the last interglacial period) to the present (Tab. 3.1).

A description of the sedimentary development of dated sites is discussed in more detail in the summary work Maglay et al. (in press).

We used time data according to Musil (2014) to classify them into timescale.

3.4.2 The character of climate in the period of origin of dated soils and organic residues

For better understanding and orientation in the timelines presented in this article, we compare $\delta^{18}O$ records of the NGRIP and GRIP glacier core for the last 123,000 years in 20 year resolution (Fig. 3.5), the last 30,000 years in 50 year resolution (Fig 3.6) and the last 19 000 years in 20 year resolution (Fig. 3.7; according to Lowe et al., 2008). Fig. 3.5 displays a detailed comparison of Greenlandic Glacier Chronology (GICC05) records at 20 years (blue curve) and ^{14}C AMS dating samples from the Danubian Flat.

In Fig. 3.7 a detailed comparison of Greenland Glacier Chronology (GICC05) records at 20 years (blue curve)

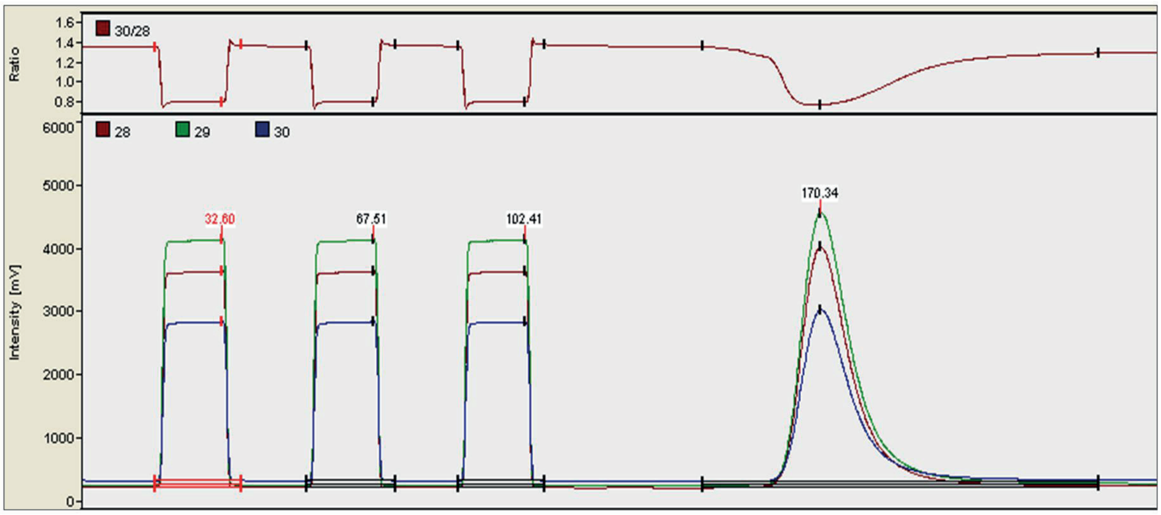


Fig. 3.4 Mass traces 28, 29 and 30 and the ratio 30/28 of CO produced from 150 µg of $CaCO_3$; First three broad peaks are zero enrichment tests with standardized gas, fourth sharp peak represents sample; the time programming of the sample run is indicated at the top of peaks

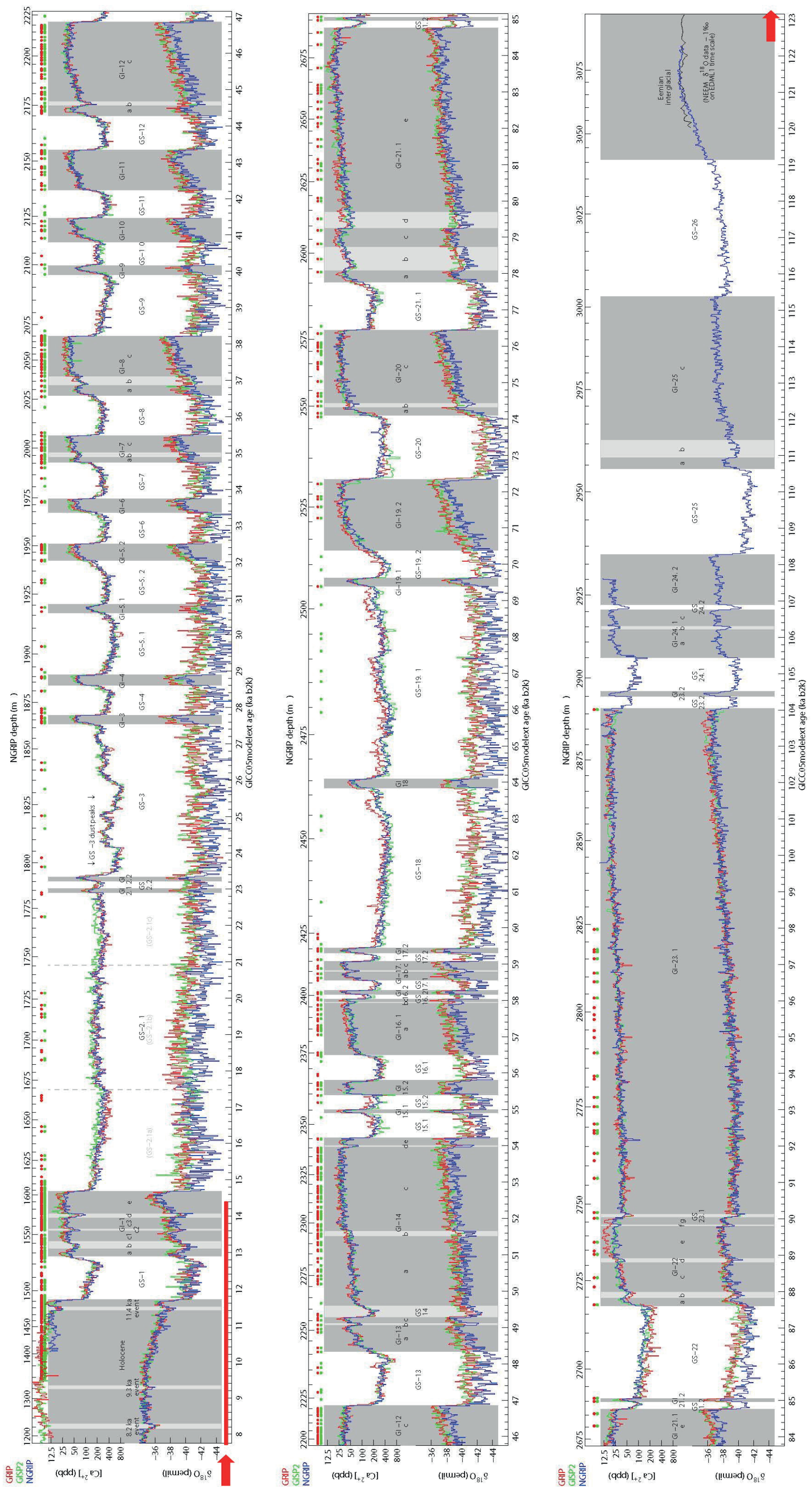


Fig. 3.5. 20-year average values of $\delta^{18}O$ and $[Ca^{2+}]$ (note the reversed logarithmic $[Ca^{2+}]$ scale) from GRIP (red), GISP2 (green), and NGRIP (blue) on the GICC05modelext time scale. The dots just below the upper NGRIP depth axis show the position of the match points used to transfer the GICC05 modelext time scale from NGRIP to the GRIP (red dots) and GISP2 (green dots) records. The proposed extension of the INTIMATE event stratigraphy scheme is shown with interstadials illustrated by grey shading (light grey indicates cold sub-events). In the Eemian Interglacial, NGRIP data are extended by NEEM $\delta^{18}O$ data offset by 2‰ (NEEM community members, 2013). Note the small time overlap between the three panels introduced to ease interpretation (see above for a detailed description.) (Rassmussen, et al., 2014). The red bars with the red arrow indicate the periods in which dated fluvial sands, aeolian sands, fossil soils, timber, and gastropod shells from the Danubian Flat study area fall.

Tab. 3.1 Results of dating fluvial sands, aeolian sands, fossil soils, woods and gastropod shells from the studied area using OSL and ^{14}C AMS methods

lab. code	designation	localisation	depth (m)	coordinates		age (years BP)	deviation (years BP)	age (years cal. BP)	sediment type	dating method	chronozone (BP, cal BP)	Holocene stages	series
				N	E								
Poz-74252	DB-3/2	Most	1.5	48° 03′ 10.5′′	17° 15′ 44.1′′	**135**	± 30 BP	240 – 38	wood	^{14}C AMS	Younger Subatlantic (920 BP – present)	Meghalayan	HOLOCENE
GdTL-2542	FS-3B	Jelka	0.6	48°09′54′′	17°30′58′′	**314**	± 28 BP	-	aeolian sand	OSL			
Poz-74920	FS-3j	Jelka	1.05 – 1.1	48° 09′ 23.99′′	17° 30′ 58.0′′	**835**	± 30 BP	777 – 717	soil	^{14}C AMS			
Poz-74922	FS-4j	Jelka	0.45 – 0.58	48° 09′ 58.99′′	17° 28′ 31.0′′	**960**	± 30 BP	918 – 824	soil	^{14}C AMS	Older Subatlantic (2,750 – 920 BP)		
GdTL-2544	MO-1	Most pri Bratislave	2.3	48° 09′ 21.0′′	17° 14′ 56.8′	**1,230**	± 120 BP	-	fluvial sand	OSL			
GdTL-2543	R-1	Rovinka	1.5	48° 05′ 53.4′′	17° 13′ 33.0′	**1,690**	± 120 BP	-	fluvial sand	OSL			
GdTL-2670	ZE-1	Zemné	2.1	47° 58′ 22.99′′	18° 0′ 23.35′′	**1,690**	± 210 BP	-	fluvial sand	OSL			
Poz-73939	DB-3/2	Most pri Bratislave	0.8	48° 03′ 10.5′′	17° 15′ 44.1′′	**1,835**	± 30 BP	1,794 – 1,716	gastropod shell *Arianta arbustorum*	^{14}C AMS			
Poz-75138	KF-24j	Jelka	0.35-0.70	48° 08′ 25.99′′	17° 32′ 05.0′′	**2,340**	± 30 BP	2,646 – 2,346	soil	^{14}C AMS			
Poz-75133	878	Gabčíkovo	0.6 – 0.8	47° 52′ 39.99′′	17° 34′ 32.0′′	**2,595**	± 30 BP	2,755 – 2,729	soil	^{14}C AMS			
Poz-85102	250	Jánošíkovo	0.65 – 0.75	48° 04′ 52.18′′	18° 0′ 05.06′′	**2,790**	± 30 BP	2,934 – 2,862	soil	^{14}C AMS	Subboreal (4,950 – 2,750 BP)		
Poz-75137	FS-64zk	Hurbanova Ves	0.6-0.9	48° 09′ 06.99′′	17°27′ 08.0′′	**2,830**	± 30 BP	2,977 – 2,895	soil	^{14}C AMS			
Poz-75135	FS-21op	Malé Blahovo	0.75 – 1.1	48° 09′ 06.99′′	17°27′ 08.0′′	**2,862**	± 30 BP	3,044 – 2,946	oxbow fill	^{14}C AMS			
Poz-78072	MV-20	Šoporňa	2.45	48° 01′ 06.2′′	17° 36′ 58.2′′	**2,935**	± 35 BP	3,162 – 3,032	soil	^{14}C AMS			
Poz-78071	S1	Štrkovec	1.5 – 1.6	48° 14′ 29.0′′	17° 49′ 11,66′	**3,750**	± 30 BP	4,155 – 4,035	humoliths	^{14}C AMS			
Poz-75132	877	Gabčíkovo	0.4 – 0.6	48° 12′ 06.87′′	17° 50′ 37.89′′	**3,780**	± 35 BP	4,222 – 4,106	soil	^{14}C AMS			
Poz-78079	173	Čechová	0.6 – 0.7	47° 52′ 38.99′′	17° 34′ 33.0′′	**4,010**	± 30 BP	4,515 – 4,445	soil	^{14}C AMS			
Poz-78073	FM-49C	Horné Saliby	0.6-0.85	48°00′32′′	17°28′29′′	**4,250**	± 40 BP	4,852 – 4,730	soil	^{14}C AMS		Northgrippian	
Poz-75131	DB-3/3	Most	1.15	48° 06′ 11.7′′	17° 44′ 48.2′′	**4,760**	± 35 BP	5,568 – 5,472	soil	^{14}C AMS			
Poz-78078	313	Okrúhle Jazero-Moravské Kračany	2-2.3	48° 03′ 10.5′′	17°15′44.1′′	**4,890**	± 40 BP	5,658 – 5,606	soil	^{14}C AMS			
Poz-74923	JM-1	Bratislava Petržalka	0.8 – 0.9	47°57′28′′	17° 34′ 30′′	**4,970**	± 35 BP	5,736 – 5,660	soil	^{14}C AMS	Late Atlantic (7,050 – 4,950 BP)		
Poz-85103	250A	Jánošíkovo	0.85 – 1	48° 04′ 52.18′′	18° 0′ 05.06′′	**5,155**	± 35 BP	4,011 – 3,941	soil	^{14}C AMS			
Poz-75134	FS-53zk	Nový Život-Šalamúnove polia	0.5 – 1	48° 7’ 2,1”	17° 28’ 30,7”	**5,600**	± 40 BP	6,420 – 6,334	soil	^{14}C AMS			
GdTL-2674	BV-4	Balvany	1.8	47° 50′ 27.47′′	18° 0′ 18.23′′	**5,660**	± 460 BP	-	aeolian sand	OSL			
GdTL-2677	BT-1	Batoňa	1.6	47° 55′ 33.27′′	18° 03′ 30.84′′	**5,870**	± 400 BP	-	fluvial sand	OSL			
GdTL-2666	OKL-1	Okoličná na Ostrove	3.9	47° 47′ 03.8′′	17° 54′ 14.1′′	**6,240**	± 460 BP	-	fluvial sand	OSL			
Poz-78076	190 F	Čechová	1.1 – 1.2	48° 00′ 57′′	17°28′29′′	**7,110**	± 50 BP	7,980 – 7,884	soil	^{14}C AMS	Early Atlantic (7,900 – 7,050 BP)		
GdTL-2669	OS-1	Opatovský Sokolec	0.9	47° 54′ 32.7′′	17° 47′ 32.58′′	**7,170**	± 530 BP	-	fluvial sand	OSL			
GdTL-2678	NE-1	Nesvady	3.8	47° 55′ 56.53′′	18° 07′ 35.06′′	**7,170**	± 420 BP	-	aeolian sand	OSL			
GdTL-2668	OKL-3	Okoličná na Ostrove	2.55	47° 47′ 03.8′′	17° 54′ 14.1′′	**7,880**	± 580 BP	-	fluvial sand	OSL			
GdTL-2541	FS-3A	Jelka	2.45	48° 09′ 54′′	17°30′58′′	**8,040**	± 520 BP	-	aeolian sand	OSL	Boreal (9,000 – 8,000 BP; 10,203 – 8,900 cal. BP)		
GdTL-2667	OKL-2	Okoličná na Ostrove	3.1	47° 47′ 03.8′′	17° 54′ 14.1′′	**8,460**	± 470 BP	-	fluvial sand	OSL		Greenlandian	
GdTL-2533	M-1	Miloslavov	2.5	48° 06′ 57.9′′	17° 17′ 58.11′′	**8,470**	± 680 BP	-	fluvial sand	OSL			
GdTL-2530	DS 303	Dunajská Streda	1.7	47° 59′ 55′′	17°33′43′′	**8,520**	± 470 BP	-	fluvial sand	OSL			
GdTL-2673	BV-3	Balvany	1.7	47° 50′ 27.47′′	18° 0′ 18. 23′′	**9,540**	± 770 BP	-	aeolian sand	OSL	Preboreal 10,000 – 9,000 BP; 11,734 – 10,203 cal. BP)		
GdTL-2671	BV-1	Balvany	5.4	47° 50′ 27.47′′	18° 0′ 18.23′′	**9,610**	± 930 BP	-	aeolian sand	OSL			
GdTL-2545	O-1	Oldza	0.85	48° 04′ 21.0″	17° 25′ 12.8″	**9,840**	± 470 BP		fluvial sand	OSL			
GdTL-2672	BV-2	Balvany	0.55	47° 50′ 27.47′′	18° 0′ 18. 23′′	**10,320**	± 970 BP	-	fluvial sand	OSL			
GdTL-2531	VR 331	Vrakúň	0.7	47°56′06′′	17°36′41′′	**11,530**	± 840 BP	-	fluvial sand	OSL			

Tab. 3.1 – Continue

lab. code	design ation	localisation	depth (m)	coordinates		age (years BP)	deviation (years BP)	age (years cal. BP)	sediment type	dating method	chronozone (BP, cal BP)	Holocene stages	series
				N	E								
GdTL-2532	S-1	Štrkovec	4.2	48° 12′ 06.87′′	17° 50′ 37.89′′	**11,850**	± 920 BP	-	fluvial sand	OSL	Late Glacial 15,000 – 11,700 years BP (18,252 – 11,734 cal. BP)		PLEISTOCENE
GdTL-2675	TV-1	Tvrdošovce	1.7	48° 04′ 46.82′′	18° 03′ 34.66′′	**12,630**	± 930 BP	-	fluvial sand	OSL			
GdTL-2676	AN-1	Aňala	1.6	47° 57′ 23.7′′	18° 08′ 58.37′′	**12,700**	± 1,100 BP	-	fluvial sand	OSL			
Poz-78074	FŠ-111$_J$	Čierna Voda	0.65-1.1	47° 07′ 04.7′′	17° 38′ 36.6′′	**13,020**	± 800 BP	16,303 – 15,483	soil	^{14}C AMS			
Poz-78131	Š-1	Štrkovec	1	48° 12′ 06.87′′	17° 50′ 37.89′′	**13,370**	± 900 BP	16,730 – 15,874	gastropod	^{14}C AMS			
Poz-78132	Š-2	Štrkovec	3.5	48° 12′ 06.87′′	17° 50′ 37.89′′	**13,410**	± 700 BP	16,722 – 15,938	gastropod	^{14}C AMS			
Poz-78075	289F	Lúč na Ostrove	0.8-1.2	47° 59’ 0,1”	17° 30’ 24,5”	**14,410**	± 900 BP	17,814 – 17,300	soil	^{14}C AMS			
Poz-74329	VN 124-2	Kolárovo	30.0-30.2	47° 56′ 21.09′′	18° 01′ 23.26′′	**>50,000 BP**		-	wood	^{14}C AMS			
GdTL-2529	BA-1	Bratislava		48° 09′ 21.5′′	17° 07′ 05.7′	**127,000**	± 1,000	-	fluvial sand	OSL	EemianIntergla-cial(Riss-Würmint-erglacial) (130,000 – 115,000 years BP)		

and ^{14}C AMS dating of samples (red lines) and OSL dating (blue lines) from the Danubian Flat region is shown.

3.4.2.1 Pleistocene

Dated sediments and organic residues from the Danube Lowland study area cover the period from the last interglacial (Eemian or Riss/Würm), the Last Glacial (Weichselian Glacial, Würm) (delimited in the marine isotopic MIS 5-2 stages) untill the Holocene period (MIS 1). The period of the Last Glacial is traditionally divided into Early Glacial (Eoglacial, ~ 100–70 ka BP, MIS 5d-5a), Pleniglacial (~ 70–15 ka BP, MIS 4-2) and Late Glacial (~ 15–11.7 ka BP).

Eemian Interglacial (Riss-Würm Interglacial) (130,000 – 115,000 years BP)

The onset of the Eemian Interglacial (MIS 5e, 130,000 years BP) was very sudden and pronounced compared to Holocene. In less than 2,000 years, fully involved, highly diversified forest communities had probably originated. A characteristic difference from Holocene Interglacial is the high proportion of Atlanto-Mediterranean elements (e.g. holly, hackberry, yew, ivy) in traditional European stands (oak, ash, elm, linden, hazel, etc.), while some of the leading vegetation elements of the Holocene hardly ever appeared here (e.g. beech). The climate of the Eemian Interglacial was probably a little warmer and significantly wetter than the Holocene climate. This is also reflected in higher ocean levels (Eemian transgression). The Eemian Interglacial itself (sensu stricto), i.e. the section of the stable climate optimum regime (MIS 5e), ends approximately 116,000 years BP with a distinct global cooling (MIS 5d). This is clearly recorded in Antarctic drillings (Vostok), and there are significant changes in Europe with some time lag. The sudden loosening of the vegetation cover and the disintegration of the contiguous forest communities are still documented only at the end of MIS 5d (107,000 years BP). During the MIS 5c-5a sections (105,000 – 75,000 years BP) several phases of significant warming and cold sections with massive retreat of woody vegetation were alternating. This is a period of considerable climatic instability, when both the climate regime and the vegetation structure have changed significantly over several years or decades (Kukla et al., 2002).

One of the OSL datings of fluvial sand dates back to the period of the Eemian Interglacial from the Danube Lowland: BA-1 Bratislava: 127,000 ± 10 BP (Maglay et al., in press).

Based on this dating, the age of the Danube terrace fluvial sediments was included in the younger part of the Middle Pleistocene (Maglay et al., in press).

Late Glacial 15,000 – 11,700 years/10,200 BP (18,252 – 11,734 cal. BP)

The Late Glacial represents the end of the Weichselian Glacial. Three cooler climate episodes (Older, Middle and Younger Dryas) are divided by relatively warmer climatic fluctuations (Bølling = Dansgaard-Oeschger event 1 and Allerød = Dansgaard-Oeschger event A; Mangerud et al.,

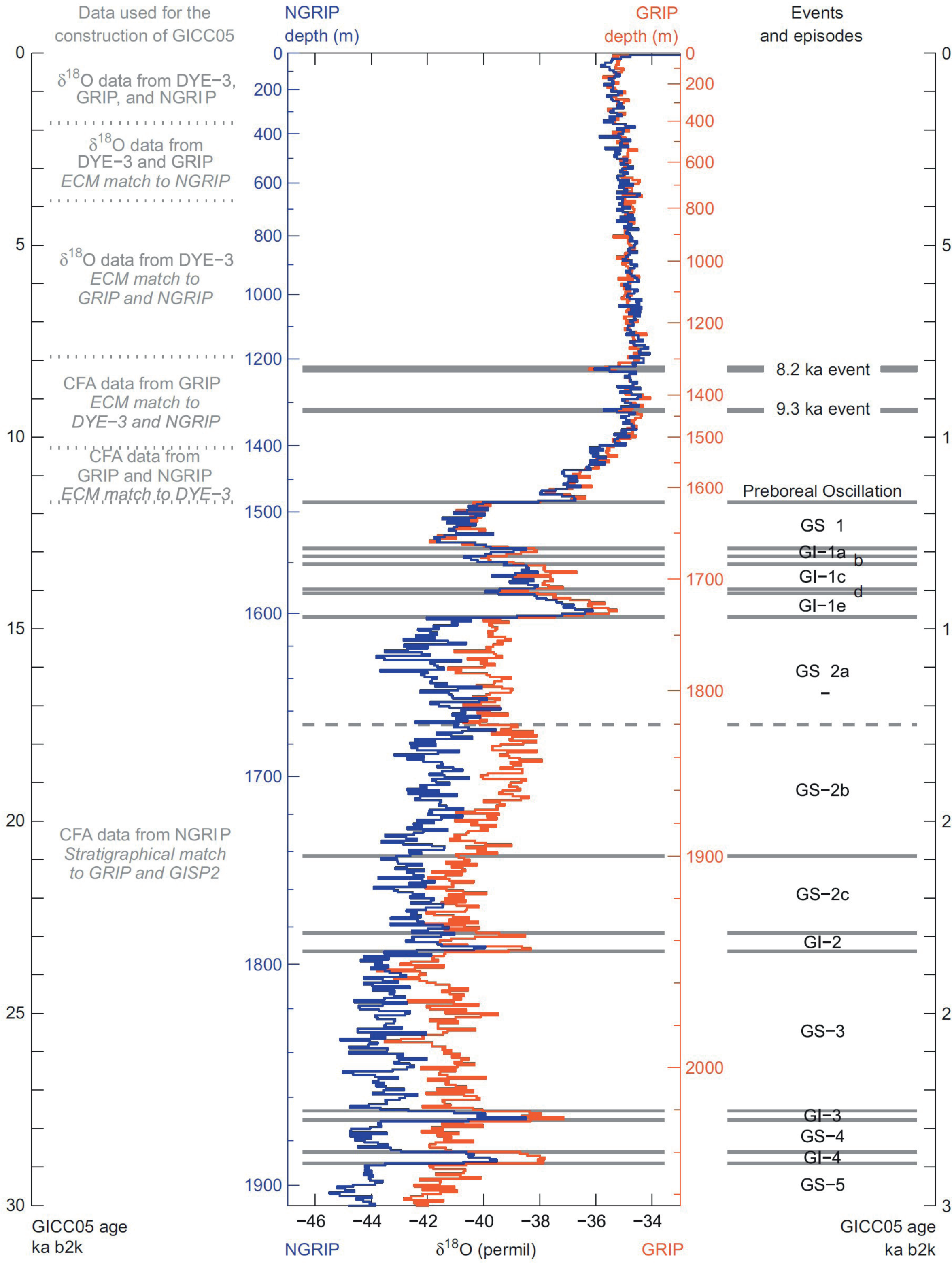
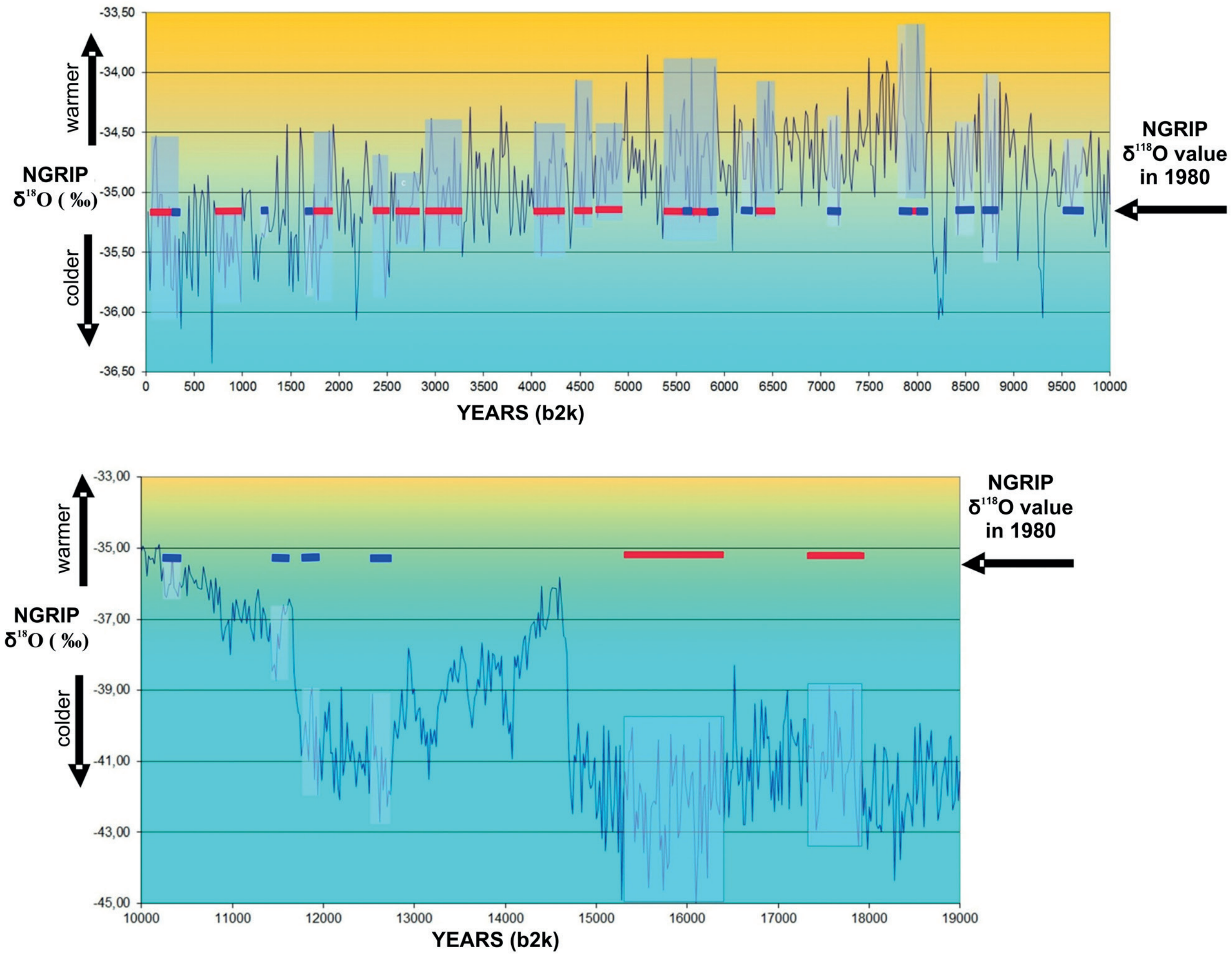


Fig. 3.6 Comparison of $\delta^{18}O$ records of glacier core NGRIP and GRIP for the last 30,000 years in 50 year resolution. Microtephra allows correlation of archaeological events with climatic cycles (according to Lowe et al., 2008). GS – Greenlandic stadials, GI – Greenlandic interstadials.

1974). This is the period of transition from Pleniglacial to Holocene. There were recorded many cold oscillations with sudden warm events. From 15,000 years BP, temperature began to rise, but between 14,000 – 13,000 years BP, this temperature rise was interrupted by a cold episode. Between 16,000 and 15,000 years BP loess accumulated in Normandy (France), England, Belgium, the Netherlands and throughout the Central Europe. This period between 16,000 and 15,000 years of BP has not yet received as much attention in our country and is underinvestigated so far. This is a time period that is important not only in terms of flora and fauna, but also in terms of humans. At



Note: the red bars represent the extent of the AMS dating in the Podunajská rovina Flat, the blue bars represent the extent of the OSL dating in the Podunajská rovina Flat.

Fig. 3.7 Detailed comparison of Greenlandic Glacier Chronology (GICC05) records at 20 years (blue curve) and ^{14}C AMS dating of samples (red lines) and OSL dating (blue lines) from the Danubian Flat. The red bars show the extent of ^{14}C AMS dating in b2k years (years before A.D. 2000). Red and blue lines showing the range of ^{14}C AMS and OSL dating are located at δ^{18}O from 1980 (-35.16‰). Pale blue translucent rectangles represent the theoretical range of δ^{18}O at the time the samples were dated. It can thus be clearly seen that e.g. soils from 10,000 years ago had to be formed at much lower temperatures than at present (chronology of the glacier core: http://www.iceandclimate.nbi.ku.dk/research/strat_dating/annual_layer_count/gicc05_time_scale/).

this time, the lasting ecosystem of the Last Glacial, which was replaced by the present ecosystem at the beginning of the Holocene, disappeared. Even in this period, climatic fluctuations were evident. Palaeoclimatic records e.g. from the Central and Western European stalagmites, witness for warmer periods between 20,000 – 17,000 years BP and then around 14,000 BP (e.g. Alley et al., 1993; Musil, 2005; Severinghaus & Brook, 1999; Taylor et al., 1993). In north-western Europe, the January palaeo-temperature increased by more than 20 °C from values between -25 °C and -15 °C in Older Dryas (12,700 BP; about 14,700 cal. BP) and Younger Dryas (around 10,000 BP; 11,500 cal. BP) to temperatures between -5 °C and 5 °C (in Bølling and Preboreal). The changes were minor during July. The July temperature rose in North-West Europe by 3 – 5 °C, from 10 °C to 15 °C (in Older Dryas and Younger Dryas) to values from 13 °C to 17 °C (in Bølling and Preboreal). In southern Europe, the rise in July's temperature was less intense. The precipitation remained the same at the turn of the Older Dryas and Bølling (around 14,700 cal. BP). However, in some areas, there is a small increase in precipitation during the transition of the Younger Dryasto the Preboreal (11,500 cal. BP) (Renssen & Isarin, 2001).

In the **Late Glacial** period, the following datings were gained from the Danube Lowland area (Fig. 3.8):

- BV-2 Balvany – fluvial sand (10,320 ± 970 BP), OSL dating (Fig. 3.14)
- VR 331 Vrakúň – fluvial sand (11,530 ± 840), OSL dating (Fig. 3.12)
- S-1 Štrkovec – fluvial sand (11,850 ± 920), OSL dating
- TV-1 Tvrdošovce – fluvial sand (12,630 ± 930), OSL dating
- AN-1 Aňala – fluvial sand (12,700 ± 11), OSL dating
- FŠ-111 FS-111 Čierna Voda (Poz-78074) (13,020 ± 80 BP), 15,483 – 16,303 cal. BP ^{14}C AMS dating

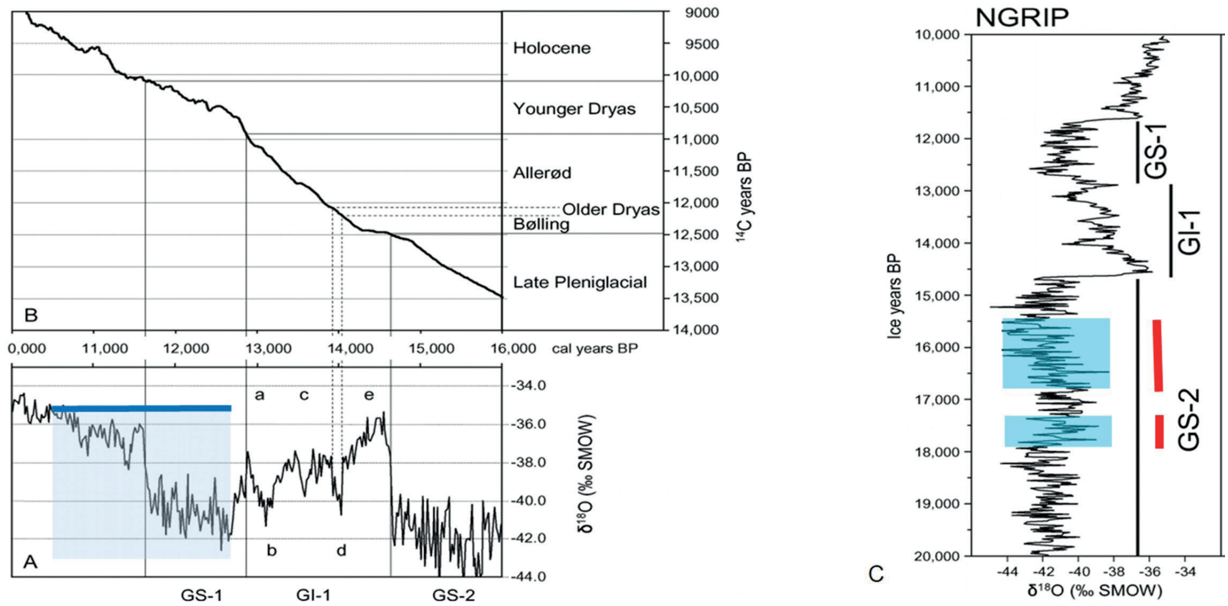


*Fig. 3.8 The correlation between event stratigraphy of the transition of the Last Glacial to the Holocene after Lowe et al. (2008) depicted on the time scale of glacial layers calculated in BP (= 1,950 AD) (**A**) and the classical late-glacial stratigraphy of NW Europe (**B**) depicted in the ^{14}C time scale. Correlation is generated using the INTCAL04 calibration curve (Reimer et al., 2004). A: NGRIP oxygen isotopes and INTIMATE event stratigraphy (Lowe et al., 2008), B: INTCAL09 calibration curve (Reimer et al., 2010). (**C**) Oxygen isotope record from the Greenland Glacier Core NGRIP (according to Rasmussen et al., 2006 and Lowe et al., 2008). Shown events are: Greenland GS-1, Greenland Interstadial GI-1, and Greenland GS-2.*

The red bars with blue rectangles show the span to which fall the dated gastropods Štrkovec – gastropod – 1 m (Poz-78131) (13,370 ± 90 BP) and Štrkovec – gastropod – 3.5 m (Poz-78132) (13,410 ± 70 BP), dated soil F-111, Čierna Voda (Poz-78074) (13,020 ± 80 BP) and 289 F Lúč na Ostrove (Pos-78075) (14,410 ± 90 BP). The figure shows calibrated data from dated gastropods and soils.

The blue line with the blue rectangle shows the range to which the dated aeolian and fluvial sands fall: BV-2 Balvany– aeolian sand (10,320 ± 97 BP), VR 331 Vrakúň – fluvial sand (11,530 ± 84 BP), TV-1 Tvrdošovce – fluvial sand (12,630 ± 93 BP), S-1 Štrkovec – fluvial sand (11,850 ± 92 BP), AN-1 Aňala – fluvial sand (12,700 ± 11 BP).

The blue and red bars showing the extent of OSL and ^{14}C AMS dating are placed at δ^{18}O from 1980 (-35.16‰) to better compare the climatic conditions at present and in the period of dated sands, soils and organic residues.

- Štrkovec – gastropod – 1 m (Poz-78131) (13,370 ± 90 BP), 16,730 – 15,874 cal. BP, ^{14}C AMS dating
- Štrkovec – gastropod– 3.5 m (Poz-78132), (13,410 ± 70 BP), 16,722 – 15,938 cal. BP, ^{14}C AMS dating
- 289 F Lúč na Ostrove (Poz-78075), (14,410 ± 90 BP), 17,814 – 17,300 cal. BP, ^{14}C AMS dating

The studied gastropods from the locality Štrkovec – from a depth of 1 m (Poz-78131) (13,370 ± 90 BP) and from a depth of 3.5 m (Poz-78132) (13,410 ± 70 BP) as well as dated soils FŠ-111 Čierna Voda (Poz-78074) (13,020 ± 80 BP) and 289 F Lúč na Ostrove (Poz-78075) (14,410 ± 90 BP) (Fig. 3.9), fluvial sand BV-2 Balvany (10,320 ± 970 BP; (Fig. 3.14) and fluvial sands VR 331 Vrakúň (11,530 ± 840 BP), S-1 Štrkovec (11,850 ± 920 BP) (Fig. 3.11), TV-1 Tvrdošovce (12,630 ± 93 BP) and AN-1 Aňala (12,700 ± 1100 BP) originate from the Late Glacial period, namely the Greenlandic GS-2 (Older Dryas/Oldest Dryas), namely GS-2.1b and GS-2.1a (Fig. 3.13).

At the locality of Lúč na Ostrove there were developed sediments of moor and transitional type of mire peats (Fig. 3.9). They represent the fill of the old fossilized oxbow of the Danube. Organogeneous deposits are located in the longitudinal up to 700 m long and 100 m wide zone tracking the course of the old sunken river bed. The thickness of this accumulation of humus-rich, very porous peat loams containing both decomposed and semi-decomposed plant matter reaches a value of about 2.5 – 3 m. The sediments were formed and developed above impermeable grey-blue plastic clayey-silty fluvial sediments of the bottom layers of the oxbow fill and are mostly wetted with infiltrated water from the surroundings. On the basis of ^{14}C AMS dating they were deposited in the Late Glacial period (^{14}C AMS dating 14,410 ± 90 BP).

In the Štrkovec gravel pit, which is located on the left bank of the river Váh in the cadastre of the village of Šoporňa, species of Pleistocene fauna *Mammuthus primigenius* – wolly mammoth and bos/bison sp. – aurochs or wisent (Fig. 3.10) were found. The palaeontological material originates from the upper part of the Váh bottom accumulation, consisting of sandy gravel and gravel sand. The material is extracted partly from the western edge of the Late Pleistocene low terrace of Váh, where the fluvial sands of the point bar are located on the sandy gravel, with local occurrence over a short distance wind-blown aeolian sands. Using the OSL and ^{14}C AMS methods, a layer of fluvial sands at the Štrkovec site was dated 11,000 to 13,000 years BP, i.e. the end of the Last Glacial. Thus, the fossil findings of Pleistocene mammals originate from underlying gravel of either approximately the same or slightly older age. According to Vlačiky (2017), the redeposited fluvial material containing fauna was washed out of its own lower middle terraces of the younger part of the Middle Pleistocene (Younger Riss) by lateral erosion eroded, along with the washed-out loamy material of the overlying loess series of the Upper and Middle Pleistocene as it had occurred on the higher downstream of the river

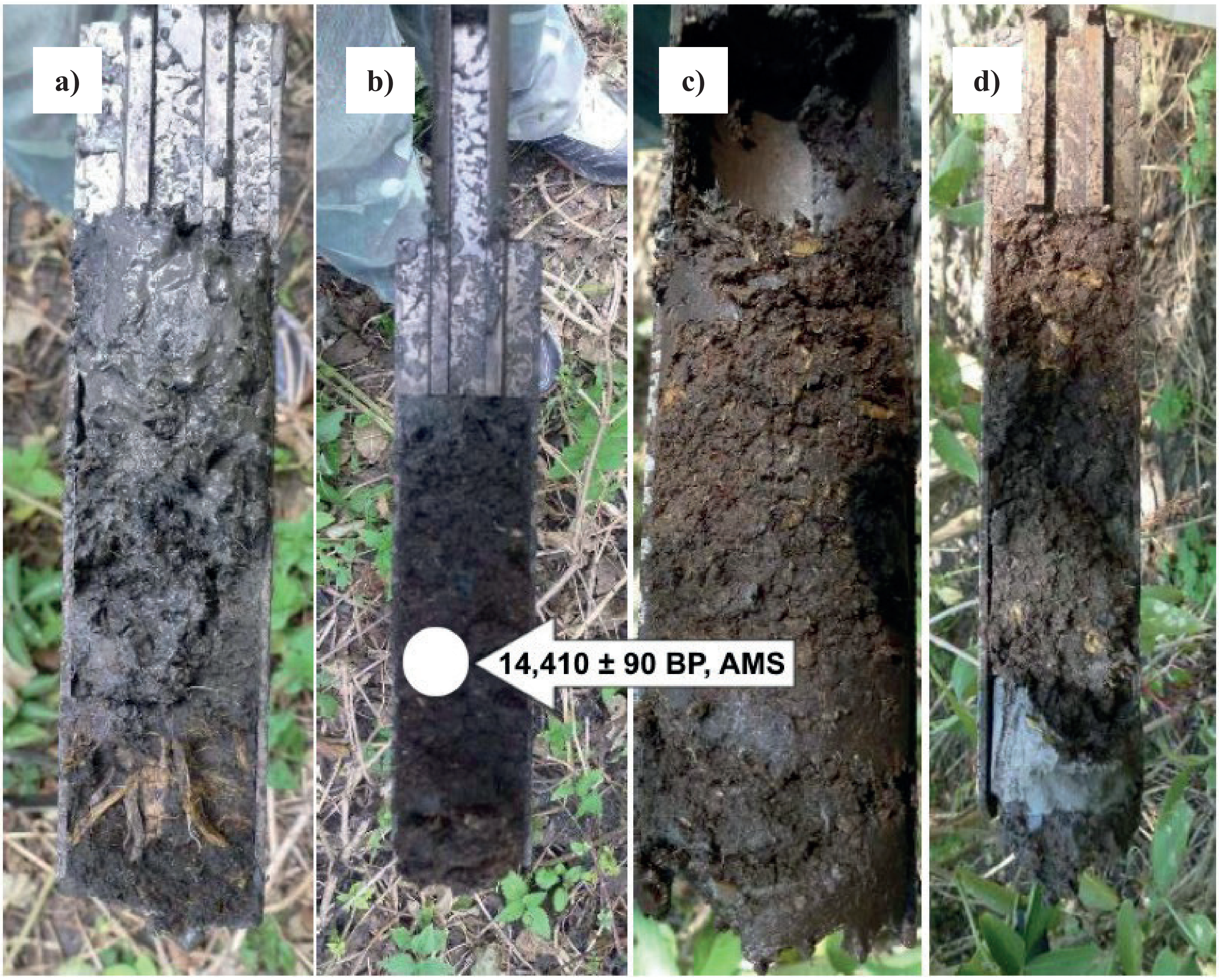


Fig. 3.9 Location Lúč na Ostrove. Plant humoliths and humus-enriched peat clays in the core of a hand drilled probe from an oxbow filling near the village of Lúč na Ostrove (width of the core is 5 cm).
a) – a surface layer of water-saturated sand-clay sediments with a rich content of recent organic matter (root systems) in thickness up to 20 cm; (b) – in the direction of the subsoil, a layer of very porous brown-black peat loams with H_2S released in pores with a total thickness of 1.8 – 2 m from which samples were taken for AMS dating. (c) – in the direction of the subsoil, more compact, sand, brown, dark brown to light brown humoliths containing a semi-decomposed plant matter with a total thickness of 30 – 40 cm; (d) – the passage of the abovementioned sediments into a subsoil consisting of medium-grained dark grey sand with organic matter, which passes into grey-blue strongly plastic clays.

Váh situated in Šoporňa until the realization of the Kráľová Waterworks.

The relatively warm period of the Late Pleniglacial optimum (GS-2b) was again followed by a period of cooler conditions, the so-called "cold" period, i.e. Old Dryas or Greenland Stadial GS-2a. This period lasted nearly 2,000 years, from about 16,900 to 14,700 cal. BP (Björck et al., 1998; Rasmussen et al., 2006). It is clear that the Central Europe at the time of the Old Dryas was already an environmentally diverse area.

Sedimentary evolution of the Late Glacial

During cold climatic conditions with lack of rainfall, loess deposition had taken place in some places of the Danube Lowland. The very frequently present sediments of the studied territory are the wind-blown sands.The youngest ones are deposited on the surface of the Late Pleistocene gravel terrace of the Danube and its tributaries. They originated from the sediments of the above-mentioned terraces at the end of the Late Glacial or in the Holocene (Pelíšek, 1963). In some wet areas and in the area above the river terraces, sapropels were formed on the basis of peat or silty alms (e.g. Jur pri Bratislave, Pusté Úľany, old Danube oxbows and Ostrov, Hrabušice; Kovanda, 1971).

Climate changes of the Late Glacial reflected in vegetation

Studying the evolution of vegetation during the Last Ice Age has an important place in order to understand the interrelationships between climate change and changes in the species assemblages of our forests and their areal representation. Moreover the course of these changes provides a comparative basis for estimating future forest community changes due to the effects of climate change in the near future (Škvarenina et al., 2013).

Since 15,000 cal. BP reforesting of the Central European region has began by expanding broad-leaved boreal forests to low mountains and foothills. The loess formation terminated in the Pannonian Basin around 13,000 cal. BP (Sümegi & Krolopp, 2002). Even in the northern part of

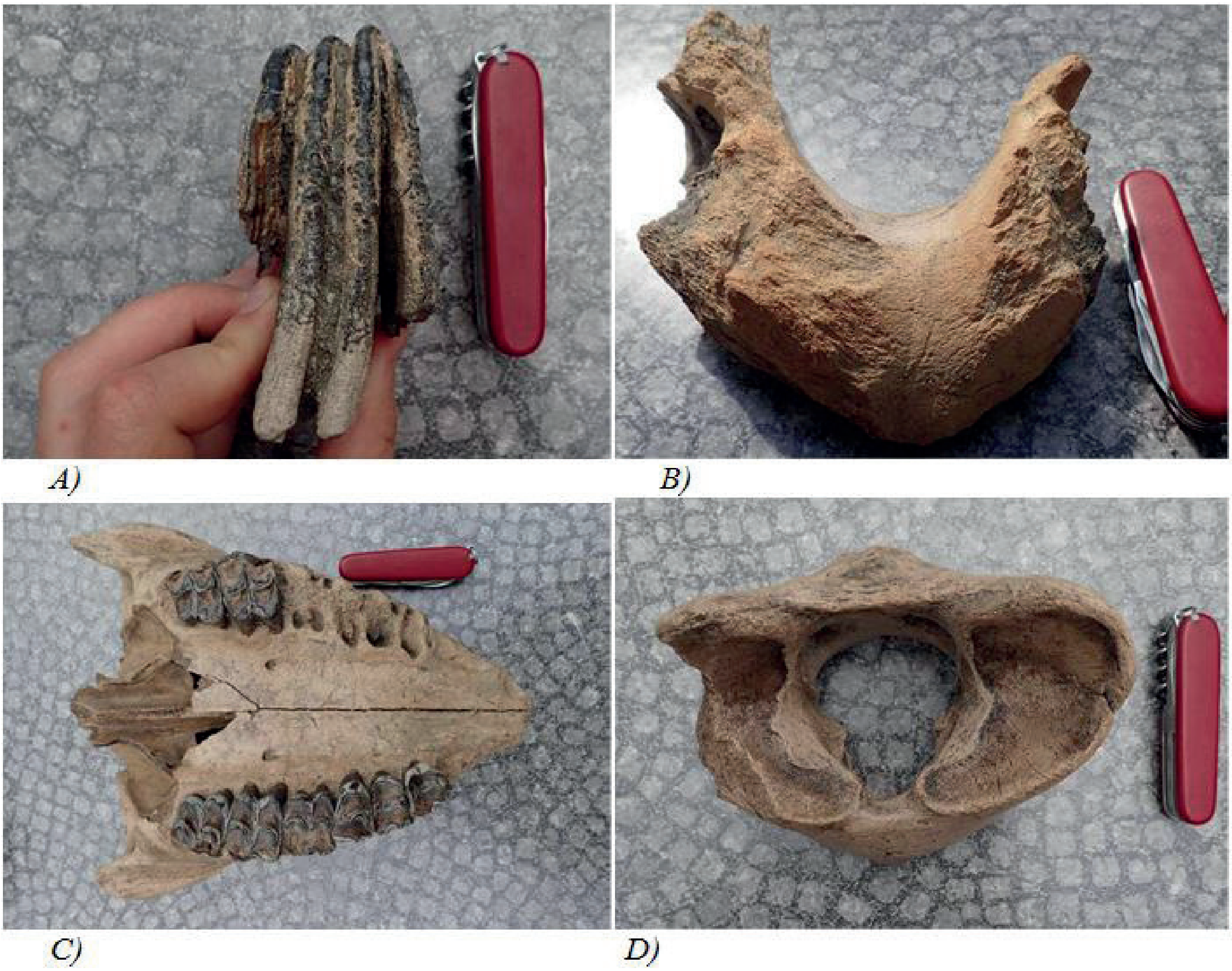


Fig. 3.10 Locality Štrkovec. Late Pleistocene fauna: A) Mammuthus primigenius – tooth fragment, B) Mammuthus primigenius – jawbone symphysis. C) Bos/Bison sp. – skull fragment, D) Bos/Bison sp. – atlas.

Hungary in the Late Glacial period, in the sediments of Lake Nagy-Mohos there were pollen-analytically found woody species such as *Larix* sp., *Pinus cembra, Picea* sp., etc. (Magyari et al., 1999). Such elements of vegetation (and fauna as well) have been mixed here with steppe elements (see also Bennet et al., 1991; Willis et al., 2000; Stewart & Lister, 2001).

13,000 years BP ago (15,854 cal. BP) across Europe significant warming and humidification of the climate occurred. Insect communities in NW Europe indicate conditions that were as warm or even warmer than today (Atkinson et al., 1987). Across the majority of Europe, changes in plant communities have begun: from dry and cold steppe-tundra to steppe, with the slow emergence of forest stands. In the European part of Russia, forests consisting of birch trees and boreal conifers very quickly followed by a warm event (Velichko, 1993), although the Western Europe and the Iberian Peninsula remained a more open steppe for several hundred years thereafter. The NW Europe remained poorly forested in the period 14,000 – 13,000 BP (17,245 – 15,854 cal. BP), with open tundra with dwarf bushes (*Juniperus* sp., *Salix* sp.; Anderson, 1977).

The NW Europe remained essentially tree-free till about 12,000 BP (13,971 cal. BP) towards the end of this period with only a very mosaic birch cover. Even dwarf bushes, which were initially present 12,000 BP, began to decline during a brief cooling of Older Dryas (around 12,000 – 11,800 BP; 13,971 – 13,697 cal. BP; Huntley & Birks, 1983; Turner & Hannon, 1988; Velichko, 1993; Anderson, 1997). Following colder conditions, tundra vegetation had been restored (Guiot & Pons, 1986).

The cold and dry period of the Younger Dryas meant the temporary disappearance of the forest cover, which had previously spread throughout Europe (northern and southern) and replacement by dry steppe and steppe tundra vegetation (Velichko, 1993; Laval et al., 1991; Starkel, 1991). According to some authors (e.g. Adams & Faure, 1997), the conditions during the Younger Dryas may not have been so harsh in the Northwest Europe. Based on their research, most of Poland and Germany were forest tundra mixed with steppe elements. The northernmost region of Poland and Germany, near the Scandinavian glacier cover, was a shrubby tundra. The conditions during most of the Younger Dryas were drier than at present, but nowhere as dry as during the Late Glacial peak.

At the end of the Younger Dryas 10,000 BP (11,482 cal. BP), forest stands returned to most of Europe. Even 9,000 years ago (10,203 cal. BP), forest cover in many parts of Europe had a rather open character comparing to present (Starkel, 1991; Huntley & Prentice, 1993; Roberts & Wright, 1993).

Over the past 15,000 years, the formability of floodplains has changed a lot. The floodplains of mainly large rivers have become refugees of climatically demanding vegetation in warmer areas in the Late Glacial. They differed significantly from their surroundings and these alluvial communities were considerably richer than the communities of the foothills (Břízová et al., 2007).

Climate change of the Late Glacial based on fauna records

The Late Glacial was formed by numerous climatic oscillations, which was also reflected in the nature of mammal fauna. During cold fluctuations (Oldest, Older and Younger Dryas), the steppe species dominated the communities. In interstadial periods (Bølling and Allerød) the species were more thermophilic, inhabiting forest and meadow environments. In many places lakes and marshes were formed, which was reflected in the continuously growing number of hygrophilous animals. Palaeontological research suggests that the communities of this period were substantially richer than during the Holocene (Musil, 1956; Klíma, 1959; Valoch, 1989; Musil, 2000; 2002a; Horáček et al., 2002; Svoboda et al., 2002).

New faunistic elements that characterize climate change began to penetrate in the territory of Slovakia. In addition to the species living on the studied area throughout the last Würm stage, animals typical of the following Holocene (e.g. *Bos primigenius, Cervus elaphus, Bison bonasus*, etc.) appeared sporadically. Similar development is evidenced by the findings of malacofauna (Svoboda et al., 2000). They are a sign of the climate change that had taken place at this time (Musil, 2002). The predominant animals were steppe species (Ložek, 1985; Horáček et al., 2002).

However, there occurred local fauna developments. Therefore, it is necessary to create and use local stratigraphic scales. Communities of this period were basically richer than those during the Holocene. Species requiring a warm climate are essentially absent. At that time, the region of Slovakia can be classified as a cold climate. Characteristic species of this period: *Rangifer tarandus, Ochotona pusilla, Lepus timidus, Lemmus lemmus, Equus* sp., *Coelodonta antiquitatis, Mammuthus primigenius, Gulo gulo, Alopex lagopus, Dicrostonyx torquatus, Alces alces, Citellus citellus, Saiga tatarica, Cricetus cricetus, Vulpes vulpes, Martes martes, Panthera leo, Bos primigenius, Cervus elaphus, Ursus arctos, Lynx lynx, Castor fiber, Canis lupus, Rupicapra rupicapra, Talpa europaea, Mustela nivalis, Sorex araneus* (Musil, 1985, 2000). In addition to this fauna, there are rare species that had diminished up in this area: mammoths, rhinos, hyenas and possibly cave bears. The composition of the findings points to their survival up to this time or, more likely, to possible sporadic migrations from the northern area than to the origin from older sediments (Musil, 2002). The findings of malacofauna, where some typical loess forms survived, show the same scenario (Ložek, 2000).

Although the structure of the communities is broadly consistent with the period of the Pleniglacial, it has been enriched by a greater number of more demanding species specialized in various open habitats, from warm steppe slopes or debris fields to marsh meadows and floodplains. So the nature of the country was obviously different from the homogeneous cold steppe with the tundra islands,which are supposed for the Pleniglacial. It apparently included not only wet habitats, but also islets of taiga and seasonal meadows (Horáček et al., 2002).

Climate change of the Late Glacial based on malacofauna records

Overall, the cold-loving elements of open formations such as *Pupilla loessica* and *Vertigo parcedentata* retreated, and the onset of thermophilic species started, particularly at warm and dry intervals (*Fruticicola fruticum* (Müll.), *Carychium tridentatum (Riss.), Discus ruderatus* (Fér.), *Pupilla triplicata. (Stud.), Helicopsis striata* (Müll.) (Kernátsová, 2001). The northern parts of the Danube Lowland could be characterized as a steppe landscape with park taiga islands based on habitats and species composition. The climate was cold with striking warmer and more humid fluctuations (Kernátsová, 1997).

First, a cold and drier climate predominated, then the climate gradually humidified. In these areas, the southern parts differed from the northern parts, which took on a steppe character with islets of park taiga.

In the Late Glacial period, changes in malacofauna communities confirm the specific position of the Pannonian region in the formation of the present Central European fauna. They demonstrate the early onset of thermophilic elements and the very late occurrence of forms of glacial fauna. During the Allerød and Younger Dryas, the climate warmed up and more demanding elements of malacofauna began to appear.

True cryophilic molluscs disappeared gradually since 15,000 cal. BP, retreating to the cold relict sites that developed in the higher altitudes of the Carpathians. It was a period of dominance of cold resistant species, followed by the boom of mesophilic species in shellfish fauna (Sümegi & Krolopp, 2002).

Climatic conditions and temperature values show a well identifiable trend in the SW and NE directions. Towards SW, higher average July palaeo-temperatures were recorded in both warm and cold seasons. Lower July palaeo-temperatures were measured in the north and south. The differences between the July palaeo-temperatures measured in the northern and southern regions were between 2 °C and 4 °C. These temperatures are consistent with the July temperatures observed today between the northern and southern regions (Sümegi & Krolopp, 2002). Modern snail species inhabiting higher Central European mountain ranges (beech and pine zones) occupied the N and E part during the Late Würm. They were either dominant species or expanded into this area along the main rivers flowing from the Carpathians during this period (Deli & Sümegi, 1999; Sümegi & Krolopp, 2000).

There is a big difference between the Late Glacial models proposed by the different approaches. According to the climate simulation model, gradual warming occurred

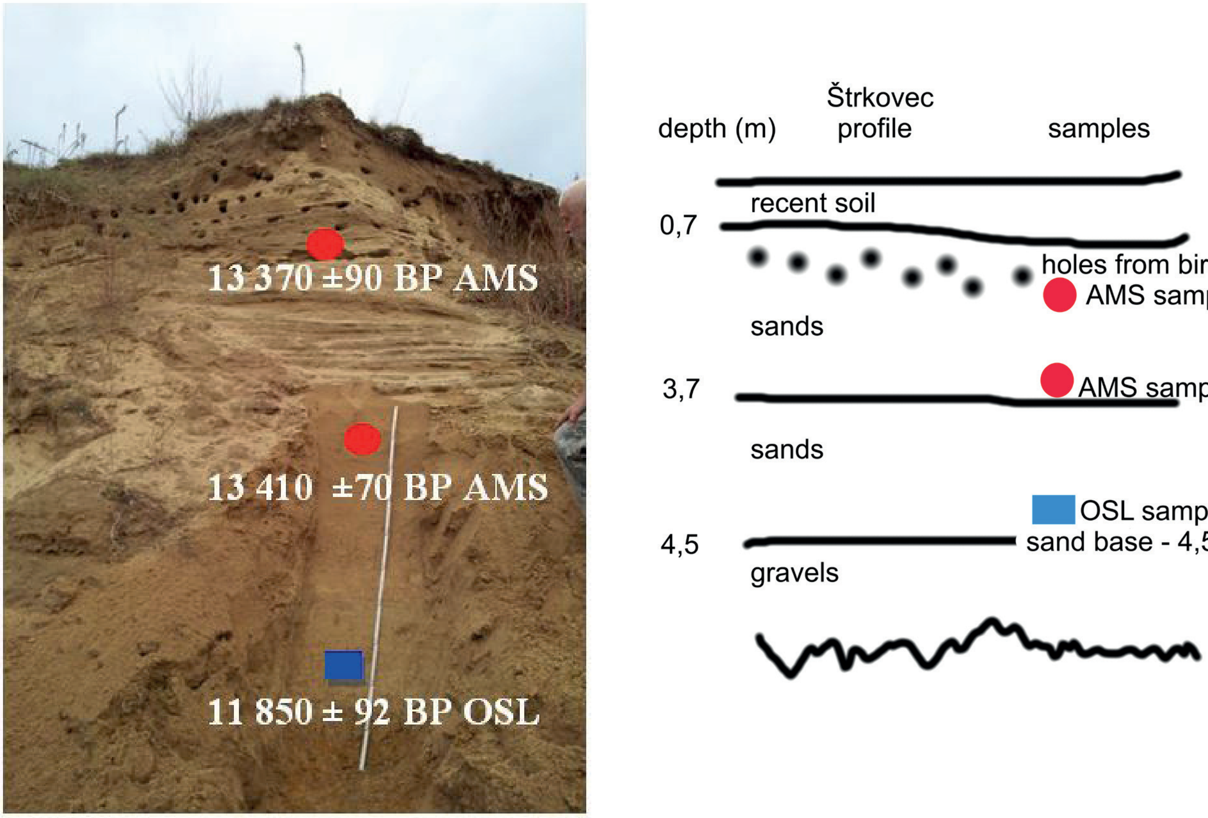


Fig. 3.11 Locality Štrkovec. Sampling sites from the thin-rhythmic-graded sands of the point bar of the Váh low terrace for dating by the ^{14}C AMS (red dots) and OSL (blue square) methods, the evaluation of which assigned the terrace to the Pleistocene period (Vlačiky, Maglay, Moravcová & Fordinál, 2017).

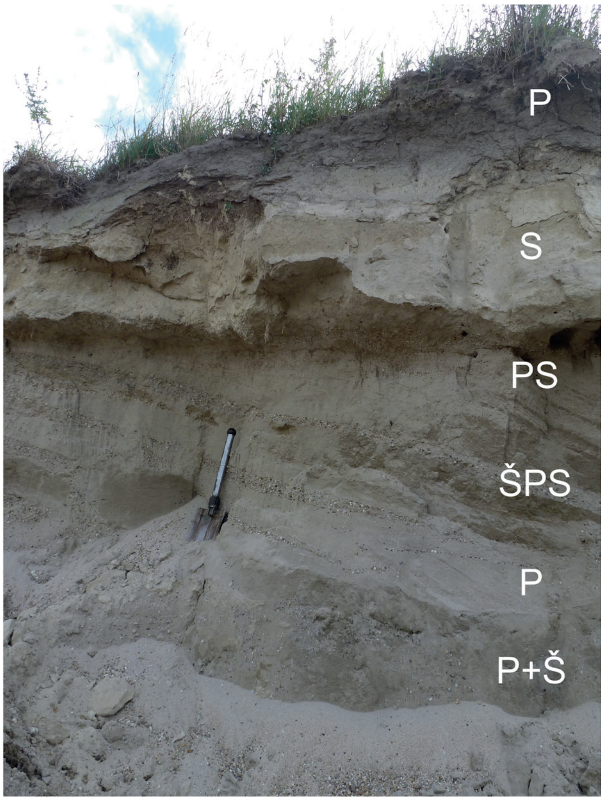


Fig. 3.12 Locality Vrakúň. Example of lithofacies: undivided silts (S), sandy silts (PS), gravel-sand silts (ŠPS), sands (P) and sand with occasional small gravel (P + Š) in the interval of 0 – 2 m in the profile at the locality Vrakúň. OSL dating of fluvial sands is 11,530 ± 84 BP.

at this time. However, changes in the composition of the malacofauna, as well as data from the dated GISP2 core recovery annual layers, indicate the presence of alternating warmer and cooler periods even during the Late Glacial. Changes in radiocarbon-dated mollusc fauna, along with palaeogeographic interpretations suggested by them, confirm the latest results obtained from radiocarbon dating and pollen analyses (Magyari et al., 1999; Sümegi et al., 1999). The results of the pollen analyses partially overlap with the malacological data confirming the expansion of the trees and vegetation during mild, humid periods and the expansion of the steppe vegetation during colder, drier periods as suggested by the composite data from malacofauna.

The Pannonian Basin can be considered as a wide fluctuation zone in the biogeographic sense, allowing expansion of the Palaeo-Illyricum, Palaeo-Carpathian, Palaeo-Balkanian, Palaeo-continental and Boreo-Alpine elements during periods with appropriate climatic conditions. However, due to the mosaic nature of environmental factors, they could occupy only a small part of this highly heterogeneous region (Sümegi & Krolopp, 2002). The Late Glacial malacofauna community is characterized by a significant change in fauna caused by higher habitat diversity, which caused an increase in the number of species and differentiation of malacocoenosis. In addition to the steppe communities, which still contained a number of loess elements, there were more frequent mesic communities, rather corresponding to meadows as well as a wide range of marshes and small aquatic environments. However, characteristic forest and thermophilic species were absent (Ložek, 1988; Ložek & Cílek, 1995).

Man and the natural environment in the Late Glacial period

In the Late Glacial (Palaeolithic) period people made their living by fishing, hunting and harvesting plants. At that time hunting was mainly focused on species such as *Rangifer tarandus*, *Equus* sp. and smaller animals (*Lepus* sp., *Aves*). *Mammuthus primigenius* had already lost its importance as a food ingredient.

The Late Glacial period is divided into three stages – Oldest, Older and Younger Dryas. Among them are shorter interstadials – Bølling and Allerød.

The INTIMATE group (INtegration of Ice-core, MArine and TErrestrial records) has proposed to standardize the terminology of Pleistocene along with a methodological guideline for Late Pleistocene proxy data (Björk et al., 1998; Walker et al, 1999).

The INTIMATE group has recognized the GRIP ss08c ice core recovery isotope record as the finest indicator of the Late Glacial climate change. As such, this Greenland iceberg record was identified as a reference stratotype. Several short-term climatic episodes are recognized in the GRIP stratotype and collectively represent the event stratigraphy. The event stratigraphy follows the isotopic nomenclature of the GRIP glacier core using the GS prefix, indicating Greenland Stadials (cold periods) versus the GI prefix, indicating Greenland Interstadials (warm periods). Denominations such as GS-2 and GS-1 further subdivide these prefixes to identify unique modes of the same kind over time. Thus, within the Stadials (GS) or Interstadials (GI), subtle events such as GS-2a and GS2c (cold episodes) versus GS-2b (warmer episodes) can be distinguished (Tab.3.2 and Fig. 3.13).

Tab. 3.2 Event stratigraphy for Last Glacial to Holocene transition based on NGRIP oxygen isotope stratigraphy presented on the GICC05 time scale (Rasmussen et al., 2006): age b2k is 2,000 AD, with maximum error (MCE) and conversion to cal. BP (before 1,950). It should be noted that the difference between the time scale given in years b2k and cal. BP is 50 years. This time difference should be taken into account when comparing results between ice core recovery and ^{14}C dated events.

	age b2k	**MCE**	**cal BP**
Holocene			
	11,703	99	11,653
GS-1			
	12,896	138	12,846
GI-1a			
	13,099	143	13,049
GI-1b			
	13,311	149	13,261
GI-1c			
	13,954	165	13,904
GI-1d			
	14,075	169	14,025
GI-1e			
	14,692	186	14,642
GS-2 .1a			
	17,480	**330**	**17,430**
GS-2.1b			
	20,900	**482**	**20,850**

3.4.2.2 Holocene (11,500 BP – present)

In the period of transition of Glacial to Interglacial, the climate changed from coldest to warmest over a few millennia (Horáček & Ložek, 1988). This transition period corresponds to the second part of the first phase of the climate cycle in the sense of Ložek (1973). After the transitional period of Late Glacial to Holocene, there was a peak and late warm period, characterized mainly by the continuous development of the forests as a consequence of high temperature and humidity. It corresponds to the second phase of the climate cycle in the sense of Ložek (1973). In the peak section, the temperature could be up to 2 – 4 °C above today's average and the precipitation could reach very high values, which in certain sections could amount to more than double the current precipitation at a given location (Smolíková, 1982; Ložek, 2002).

At this time it is necessary to begin to distinguish natural phenomena and their laws from anthropogenic interventions. The beginning of increased human activity is manifested only in the Neolithic period (in the wider area of the Central Europe, the Neolithic period is approximately the 6th-5th millennium BC) by housing development, agriculture and cattle breeding. This is the first major human intervention in the natural environment (Musil, 2014).

However, the Holocene climate was not stable in the long term. Relatively long-lasting cold periods were repeated several times (in ages of 9,200, 8,600, 5,800 cal. BP.). Rapid warming occurs at about 11,590 cal. BP, further between 8,000 to 5,800 – 4,000 cal. BP. There were also changes in the amount of rainfall. At the time of 11,160 to 10,800 cal. BP due to the severe drought, the level of European lakes was reduced on up to 5 – 7 m. Further reductions are known only from the years 9,250 to 9,340 cal. BP. Unlike the previous period, which lasted 360 years, this lasted only 90 years. Another minor reduction in precipitation was between 8,800 to 7,850, 7,000 to 6,750 cal. BP. Dry season in the years 6,200 to 5,950 cal. BP closed this period of fluctuations (Kalis et al., 2003; Litt, 2003; Zolitschka et al., 2003).

The Holocene period includes the following dating of sands, soils and organic residues:

Preboreal 10,000 – 9,000 BP; 11,734 – 10,203 cal. BP):

- O-1 Oldza – fluvial sand (9,840 ± 470 BP) OSL dating)
- BV-1 Balvany – aeolian sand (9,610 ± 470 BP), OSL dating, (Fig. 3.14)
- BV-3 Balvany – aeolian sand (9,540 ± 470 BP), OSL dating, (Fig. 3.14)

Boreal (9,000 – 8,000 BP; 10,203 – 8,900 cal. BP)

- M-1 Miloslavov – fluvial sand (8,740 ± 680 BP), OSL dating
- DS 303 Dunajská Streda – fluvial sand (8,520 ± 470 BP), OSL dating
- OKL-2 Okoličná na Ostrove – fluvial sand (8,460 ± 470 BP), OSL dating
- FS-3A Jelka – aeolian sand (8,040 ± 520 BP), OSL dating, (Fig. 3.23)

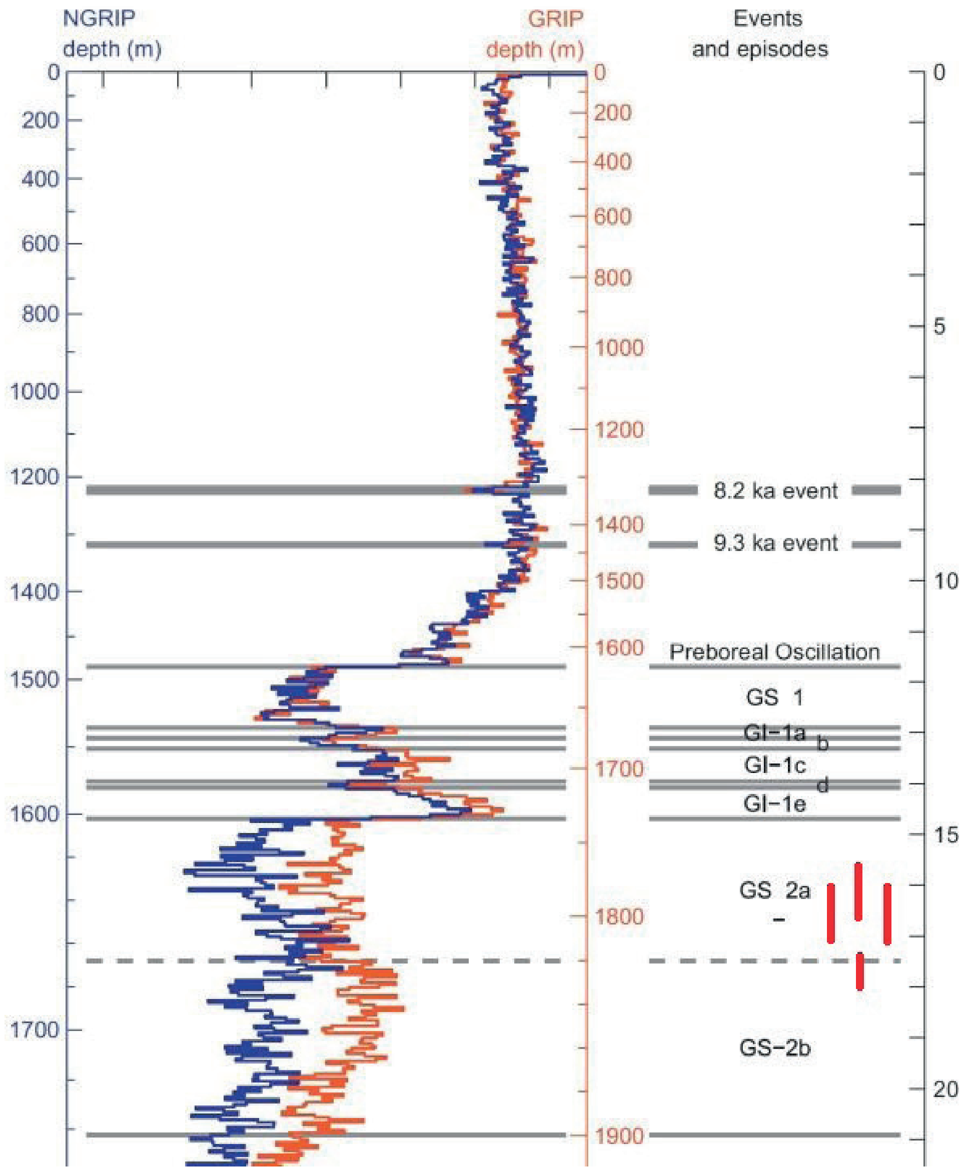


Fig. 3.13 Event stratigraphy according to INTIMATE group. The time is given in years for 2000 (b2k). NGRIP and GRIP ^{18}O profiles with determined depth, with data placed on the GICC05 time scale (Rasmussen et al., 2006; Svensson et al., 2008) and NGRIP-GRIP matches with to Rasmussen et al. (2008).
The red bars (on the left timeline) with blue rectangles show the time span in which fall the dated soils FŠ-111 Čierna Voda (Poz-78074) (13,020 ± 80 BP); 15,483 – 16,303 cal. BP and 289 F Lúč na Ostrove (Poz-78075) (14,410 ± 90 BP); 17,814 – 17,300 cal. BP and gastropods Štrkovec – shellfish – 1 m (Poz-78131) (13,370 ± 90 BP); 16,730 – 15,874 cal. BP and Štrkovec – gastropod – 3.5 m (Poz-78132) (13,410 ± 70 BP); 16,722 – 15,938 cal. BP.

Early Atlantic (7,900 – 7,050 BP)

- OKL-3 Okoličná na Ostrove – fluvial sand (7,880 ± 580), OSL dating
- NE-1 Nesvady – aeolian sand (7,170 ± 420), OSL dating
- OS-1 Opatovský Sokolec – fluvial sand (7,140 ± 530 BP), OSL dating
- 190 F Čechová – soil (Poz-78076) (7,110 ± 50 BP) 7,932 ± 48 cal. BP, ^{14}C AMS dating

Late Atlantic (7,050 – 4,950 BP)

- OKL-1 Okoličná na Ostrove – fluvial sand (6,240 ± 460 BP, OSL dating
- BT-1 Batoňa – fluvial sand (5,870 ± 400 BP), OSL dating
- BV-4 Balvany – aeolian sand (5,660 ± 460 BP), OSL dating, (Fig. 3.14)
- FS-53zk Nový Život – Šalamúnove polia – Palaeosoil (Poz-75134) (5,600 ± 40 BP), 6,377 ± 43 cal. BP, ^{14}C AMS dating
- 250A Jánošíkovo (5,155 ± 35 BP), 5,926 ± 35 cal. BP, ^{14}C AMS dating
- JM-1 Bratislava Petržalka (Poz-74923) (4,970 ± 35 BP), 5,698 ± 38 cal. BP, ^{14}C AMS dating

Subboreal (4,950 – 2,750 BP)

- 250 Jánošíkovo (2,790 ± 30 BP), 2,898 ± 36 cal. BP, ^{14}C AMS dating
- 313 Okrúhle Jazero – Moravské Kračany (Poz-78078) (4,890 ± 40 BP), 5,632 ± 26 cal. BP, ^{14}C AMS dating
- DB-3/3 soil Most pri Bratislave (Poz-75131) (4,760 ± 35 BP), 5,520 ± 48 cal. BP, ^{14}C AMS dating
- FM-49C Horné Saliby – palaeosoil (Poz-78073) (4,250 ± 40 BP), 4,791 ± 61 cal. BP, ^{14}C AMS dating
- 173 Čechová (Poz-78079) (4,010 ± 30 BP), 4,480 ± 35 cal. BP, ^{14}C AMS dating
- 877 Gabčíkovo (Poz-75132) (3,780 ± 35 BP), 4,164 ± 58 cal. BP, ^{14}C AMS dating
- S1 Štrkovec (Poz-78071) (3,750 ± 30 BP), 4,095 ± 60 cal. BP, ^{14}C AMS dating

- MV-20 Šoporňa (Poz-78072) (2,935 ± 35 BP), 3,097 ± 65 cal. BP, ^{14}C AMS dating
- FS-21op Malé Blahovo – oxbow fill (Poz-75135) (2,865 ± 30 BP), 2,995 ± 49 cal. BP, ^{14}C AMS dating
- FS-64zk Hurbanova Ves – palaeosoil (Poz-75137) (2,830 ± 30 BP), 2,936 ± 41 cal. BP, 1,083 – 906 BC, ^{14}C AMS dating

Older Subatlantic (2,750 – 920 BP)

- 250 Jánošíkovo (2,790 ± 30 BP), 2,898 ± 36 cal. BP, ^{14}C AMS dating
- 878 Gabčíkovo (Poz-75133) (2,595 ± 30 BP), 2,742 ± 13 cal. BP, ^{14}C AMS dating
- KF-24j Jelka – palaeosoil (Poz-75138) (2,340 ± 30 BP), 2,361 ± 15 cal. BP, ^{14}C AMS dating
- DB-3/2 gastropod Most (Poz-73939) (1,835 ± 30 BP), 1,775 ± 39 cal. BP, ^{14}C AMS dating
- ZE-1 Zemné – fluvial sand (1,690 ± 210 BP), OSL dating
- R-1 Rovinka – fluvial sand (1,690 ± 120 BP), OSL dating
- MO-1 Most pri Bratislave – fluvial sand (1,230 ± 120 BP) OSL dating
- FS-4j Jelka – soil (Poz-74922) (960 ± 30 BP,), 871 ± 47 cal. BP, ^{14}C AMS dating

Younger Subatlantic (920 BP – present)

- FS-3j Jelka – soil (Poz-74920) (835 ± 30 BP), 747 ± 30 cal. BP, ^{14}C AMS dating, (Fig. 3.23)
- FS-3B Jelka – aeolian sand (314 ± 28 BP), OSL dating
- DB-3/2 Most – wood (Poz-74252) (135 ± 30 BP), 139 ± 101 cal. BP, ^{14}C AMS dating

Sedimentary evolution in Holocene

Geological development in the Danubian Flat was relatively uniform during the Holocene. Climate change and hydrodynamic conditions of all major rivers have influenced the landscape structure, sedimentary and plant cover. In later periods, human activity was also associated with the impact on the natural environment. The whole territory is strongly influenced by hydromorphism. The Preboreal period in the studied area is characterized by a rather sudden and definite rise in temperatures and a decrease in precipitation. The erosive activity of the wind has been substantially reduced. The activity of the Danube also decreased. The Danube often translated its main and side channels, eroded its own deposits and resedimented them. The flood waters spilled on a wide area and also affected the higher stage of the Danube River floodplain. Fine-grained particles carried by the Danube stream settled on the riparian plain. The areas, which were not regularly flooded with water, overgrew with trees and grassland. Preboreal and Boreal periods were characterized by the greatest afforestation, followed by steppe. During the Atlantic period, the climate warmed and gradually humidified. This period was characterized by pronounced soil formation in those parts of the territory where floods did not occur frequently. In higher places, chernozems (e.g. Kuraľany, Bíňa; Šajgalík & Modlitba, 1983) and gley soils were formed. During this period, some fens began to form in abandoned meanders and oxbows. In many places aeolian sands were blown over (Pelíšek, 1963).

Holocene climate change based on vegetation records

The onset of Holocene initially shows similar conditions to the warmer phases of the Late Glacial, but the rapid rise in temperature and the consequent increase in humidity conditioned the permanent immigration of climatically more demanding species. However, the biggest changes are in living nature, especially in vegetation. Loess steppes and stony areas, or tundra formations gradually passed into the pine-birch stands of light taiga, which later penetrated more demanding deciduous trees, especially *Corylus* sp. and *Quercus* sp. In the older phase, the open formations of mesophilic meadows also played an important role. In dry and warm areas, the continental steppe on black and warm calcareous hillsides as well as the formation of hornbeams with *Cornus* sp., *Betula* sp. and *Pinus* sp. have been gradually pushed to extreme sites, such as rocky edges, sand, etc. During the Atlantic period, natural conditions (warming and humidification) prompted the emergence of enclosed damp forests (Ložek, 2002).

Holocene climate change based on malacofauna records

The elements of the glacial steppe gradually disappeared and were replaced mainly by forest species. The malacofauna community was similar to the Late Glacial in the Early Holocene. Later, thermophilic species appear more and more. There were also xerothermal species, typical of communities living in karst steppes and rocks. The occurrence of xerophilous species is also remarkable. Many species also survived from the Late Glacial. This malacofauna documents the dynamic changes in biota, which was reflected in a significant increase in the number of species and habitat diversity. The full development of forest communities occurred only in the Atlantic period (Ložek, 2002), when wet closed forests expanded. Forest species recorded in the previous period were also becoming important. Elements of continental steppe fauna and loess steppe relics were also present, but gradually diminished or moved into extreme relict environments. Due to the warming climate, the number of xerothermal populations has increased in suitable places, especially sun-exposed limestone rocks (Ložek, 1985; Ložek & Cílek, 1995).

Postglacial (Holocene) is generally a period of warmer and humid climatic development, when the July palaeo-temperature reached 18 to 20 °C. At the beginning of the Holocene there were colder climatic conditions (Kernátsová, 2001). Mollusc communities species corresponded to the recent fauna of the studied sites (Ambrož et al., 1952).

In terms of refuge theory, the relics of the Bratislava floodplain forests are among the so-called palaeo-refuges (Nekola, 1999), i.e. the fragments of the former more or less continuous and large area of historical floodplain forests,

Fig. 3.14 Location Balvany. A) The torso of the dune after the extraction of most of the aeolian sands north of the settlement Balvany near Kameničná. B) White dots with arrows indicate sampling sites for OSL dating..

which occupied the territory of Bratislava at the beginning of the 19th century. Unlike today's floodplain forests, there was a much more varied mosaic of different forest types, or their successive stages. The results of the faunistic survey show that the relics of the Bratislava floodplain forests, despite their considerable fragmentation, serve as a quality refuge of the original Danube malacofauna. There are only a few species known from the Danube Lowland in the Bratislava riparian meadows, which are otherwise predominantly rare in the Danube floodplain out of Bratislava. The floodplain forest fragments provide refuge for populations of 45 terrestrial gastropods; 68% of all terrestrial species known from the Danube Lowland by 2012. Xenocene species do not penetrate into the relics of floodplain forests, the structure of most communities is semi-natural (Čejka et al., 2012).

Man and the natural environment in the Holocene period

In the Preboreal, Boreal and Early Atlantic (Mesolithic) periods, human influence on the country was not yet significant. People continued to make their living by

Fig. 3.15 Location Oldza. Layers of medium-grained sand (in places also gravel sand) in thicker layers of sand gravel in the accumulation of the core of Žitný ostrov. The white dot represents site for the OSL dating.

Fig. 3.16 Location Miloslavov. Sandy gravel at the bottom of the upper complex of fluvial accumulation of the core of Žitný ostrov without covering of sands and silts, cropping out directly to the surface. Artificial exposure with direct contact of sandy gravel and recent soil in an abandoned gravel pit north of Miloslavov. White rectangle – OSL dating.

Fig. 3.17 Location Nesvady. A) Preserved aeolian dune of loaf shape. B) Thin-rhythmic stratification of medium-grained aeolian sands in the dune. The age of the OSL (white dot) is 7,170 ± 420 BP. The sampling position is located about 6 m above the dune base, which assumes that the sands in the lower positions were deposited during the Late Pleistocene period.

fishing, their settlements were found mainly on the coasts of lakes and rivers. The settlement was still relatively scattered (Ložek, 1973). At the end of the Mesolithic period the hunters and gatherers period had terminated.

During the Neolithic period (the Late Stone Age; the end of the Atlantic and the first half of the Epiatlantic), man shifted from hunting and harvesting to agriculture. This period can be described as the beginning of anthropogenic transformation of nature (Zeman & Demek, 1984). Farmers have started to build relatively permanent settlements by cutting and burning in forest areas, preparing the land for cereal cultivation and cattle grazing.

At first they founded their settlements in the most fertile xerothermal areas, but later advanced to higher areas. They introduced new cereal crops with weed communities, but in particular they also inadvertently fostered a new secondary development of xerothermal vegetation in the area. This significantly influenced the development of vegetation and flora. In the subsequent periods of the Eneolithic, virtually nothing has changed. Farmers had increasingly sophisticated tools and advanced to higher altitudes. During the Bronze Age (including the end of Epiatlantic and Subboreal) there was an even greater development of agriculture, both ploughing and grazing. With the use of bronze (nickel-copper alloy) for the production of various tools, field machining was significantly improved and accelerated. Human settlements have expanded and interfered with ever higher altitudes (Zeman & Demek, 1984).

Preboreal (10,000 – 9,000 BP; 11,734 – 10,203 cal. BP)

This period represents the entry period of the Holocene after the last cold fluctuation of the Late Glacial. There was a continuous improvement of the climate – temperature, soil and air humidity. The climate was warming and humidifying. Temperatures rose by 4 – 8 °C. The climate was still very continental. Permafrost disappeared. The thin taiga thickened and cold steppes began to afforest due to the warming and humidification of the climate (*Pinus* sp., *Betula* sp., Svobodová et al., 2001). The landscape was gradually gaining forest character, although forests could be described only as birch-pine and birch-birch taiga with limited species diversity – pine, birch and white birch, aspen, juniper, willow, spring-tree with accompanying vegetation, which is preserved today on wetlands and peat bogs. The area of the Carpathian basins has already acquired the character of spruce taiga, unlike the light taiga. However, the steppe and tundra elements have retained a large representation of them. In dry and warm

Fig. 3.18 Location Okoličná na Ostrove. Floodplain sands. White dots represent OSL dating.

steppe areas, chernozems began to form. Archaeology recorded a breakthrough of the Late Palaeolithic and Mesolithic (Svobodová et al., 2001).

After the end of the Ice Age, the climate changed and along with it the natural conditions (Krippel, 1986; Ložek, 1980). With warming and increasing humidity, especially since the Boreal, deciduous forests began to spread and cold seasons had either extinct (mammoths) or moved north (reindeers). Instead, species of forest animals similar to today's have appeared (deer, roe deer, aurochs, bison, pig; Kaminská et al., 2014).

Reconstruction of the natural environment clearly shows that the Danube Lowland was characterized by a varied macro-, meso- and micro-level mosaic during the Pre-Prehistoric to Atlantic period (Kertész & Sümegi, 1999; 2001; Sümegi & Kertész, 1998; 2001; Sümegi et al. 2002; Sümegi, 1996). At the macro-level, this mosaic was formed by the intersection of the main climatic zones: the impact of continentality dwindling from east to west, oceanity from west to east, sub-Mediterranean from south to north, and sub-Carpathian climate in mountain areas. The mosaic pattern of climatic zones and vegetation zones resulted in a mosaic of soil types that were further influenced by the strong subsoil diversity.

In many localities of the central zone (central mound) of the "core" of Žitný ostrov, sandy gravels are exposed, where they become a significant component of recent soil cover. This is also the case at the dated Oldza site (Fig. 3.15).

Boreal (9,000 – 8,000 BP; 10,203 – 8,900 cal. BP)

Boreal is the first significant climatic period of Holocene, evolving from Early Holocene-Preboreal. The trend of climate development continues until the average temperature and ultimately the humidity slightly exceeded the present state. Mean annual temperature (MAT) was up to 2 °C higher than today. The summers were dry and the climate had a continental character. Plants with *Pinus* sp. and *Betula* sp. gave way to mixed oaks, where beside *Quercus* sp. other deciduous trees – *Ulmus* sp., *Tilia* sp., *Fraxinus* sp., *Corylus* sp. spread in the forest crossings, *Picea* sp. in mountainous locations. Man did not influence the country yet (Svobodová et al., 2001).

The precipitation conditions are less well-known, a more continental character can be assumed. However, the corresponding vegetation (e.g. Northern Italy, the Balkans) has not yet been able to penetrate into the Central Europe, as the region of its refuge was too remote. Nevertheless, fundamental changes in the forest vegetation took place. The genera were oak, elm, linden, maple and locally hazel. This is sometimes referred to as a characteristic tree, but its dominance is only regional. Foundations of floodplain forests began to form in the river valleys. In Slovakia, spruce was the dominant woody species so far; in lower areas there were more warm demanding trees, which could rise to higher elevations than today. The vegetation of the tundra, the woodland, and the cold steppes withdrew quickly, the forest dominated the whole country. This vegetation retreated to extreme sites and altitudes, allowing their refugees to rise. Significant was also the occurrence of larger lakes persisting from the Late Glacial period. It was lakes that were a significant food base of man in an otherwise forested country during the Mesolithic period.

Atlantic (7,900 – 4,920 BP)

The Atlantic period is consistent with the Holocene climate optimum. The MATs of the whole Europe at this time were 2 – 3 °C higher than today. The warming occurred very quickly and was almost stable throughout the Atlantic. Period from 9,800 to 8,500 cal. BP. represents a dry and warmer period with a peak around 9,200 cal. BP. Between 8,000 to 7,500 and between 6,000 and 5,800 cal. BP colder periods follow (Musil, 2014). The amount of precipitation also increased – up to 60 – 70% compared to the previous Boreal. The climate was humid, yet warm, with an oceanic character, which facilitated the development of forests. Soils (chernozem) formed on the surface of loess. In the lowlands, mixed forests (*Quercus* sp., *Ulmus* sp., *Tilia* sp.) were combined into continuous forests. The spread of *Fagus* sp. and *Abies* sp. began, at the same time agricultural deforestation. In cave sediments, the humid, unfavorable Atlantic climate, was expressed in sinter formation. This period was characterized by the development of Middle to Late Neolithic cultures and inhomogeneous climate (Velichko, 1989).

Since the 8,000 (8,900 cal. BP) years, the forest stands became coherent, but with more conifers than in the Eastern Europe today. Based on vegetation and lake evidence, it can be concluded that during this period more rainy conditions dominated in most of Central and Southern Europe compared to today (Harrison et al., 1996).

During the Atlantic, air temperatures culminated and, with sufficient rainfall, very favourable conditions were created for the development of forest communities. Vertical differentiation of vegetation has significantly advanced, where beeches and firs have started to become more prominent (Krippel, 1986). The fauna was typically forestry: deer, bison, aurochs, bear, marten, squirrel, fox, badger.

This climate optimum can be divided into three parts (Kalis et al., 2003):

- Early Atlantic (9,200 to 7,000 cal. BP) with low human impact and stable climatic (temperature) conditions,
- Middle Atlantic (7,000 to 6,300 cal. BP). A period of Early and Mid-Neolithic, a culture that brought increased tillage, livestock and grazing. There were noticeable changes in the vegetation cover, but the impact of human activity was still small,
- Late Atlantic (after 6,300 cal. BP). Younger Neolithic. Traces of human activity are already clearly visible on the landscape.

The accumulation of aeolian sand at the Nesvady site (NE-1 Nesvady 7,170 ± 420 BP, Fig. 3.17) was dated to the Atlantic period. These aeolian sediments represent an important genetic element of the final stage of the transitional Late Pleistocene-Holocene aeolian sedimentation, continuing into the Holocene and in many cases until recent. The aeolian sands are also a significant relief-forming element, which enriches the overall planar landscape character of the Danubian Flat. They create various irregular forms of deposition from isolated islet-like small loaves of loaf-like shape, through continuous line formations of connected loaves, to spatially more distinctive dunes of various, particularly elongated, parabolic, arched and loaf shapes. The inter-dune depressions in this area are filled with humous sandy loams and peat humoliths.

In the locality Okoličná na Ostrove, the floodplain sands were dated. They are predominantly fine-grained to silty, but in places very silty with the transition to sandy and silty loam. The age based on OSL method confirms their deposition in the Boreal to Atlantic period (Fig. 3.18).

Epiatlantic (6,000 – 3,200 BP; 6,837 – 3,423 cal. BP)

In this period, the wet and dry periods were often alternating, the summers were on average warmer than at present. MAT was 1 to 2 °C higher than today. Over time, the moisture content decreased (http://lfskripta.webpark.cz/fyto/fyto12.htm).

The term Epiatlantic was introduced by Jäger (1969) for a section corresponding to Firbas's section VII (Firbas, 1949; 1952) (Younger Atlantic) and partly also VIII (Older Subboreal section) to express periods with rapid and significant alternation of wet and dry periods. This period represents a breakthrough in the development of vegetation and the whole Central European nature, because at the beginning of the Atlantic there is a man – a farmer, who initially established settlements in the most fertile forest steppe and steppe areas. He introduces not only cereal crops with accompanying weed communities, but also inadvertently encourages the new development of xerothermal vegetation, which would otherwise have to give way to the spreading forest.

Subboreal (4,950 – 2,750 BP)

In the Subboreal period, the MAT was on average 1 to 2 °C warmer than today, but the climate was dry, rather subcontinental. At the beginning of this period there was an agricultural ecumen, i.e. continuous, populated and agriculturally exploited areas were emerging (forest grubbing – later oak in lower altitudes and later beech in middle altitudes – and ploughing of land). As a result of the permanent plowing of the soil, the removal of the continuous plant cover and the increase in the amount of rainfall, there began a strong erosion of the soil, especially in the sloping relief. This created thick layers of colluviums and in the valleys of the streams at this time large flood plains were formed. Our fluvisoils are therefore only 3,000 years old. In the lower altitudes, the hornbeam-oak forests were already spread. However, these receded in open areas, where xerothermal steppe vegetation was spreading again (http://lfskripta.webpark.cz/fyto/fyto12.htm).

Rainfall was decreasing during the Subboreal, the temperatures kept approximately the same regine. During this period, the mixed oaks gradually retreated as a result of the development of fir-beech forests, which gradually formed a separate vegetation stage, which formed between mixed oak stands and mountain coniferous forests (Krippel, 1986).

The climatic period in which the soils BD-3/3 from Most pri Bratislava (Fig. 3.19) and 313 Okrúhle Jazero – Moravské Kračany were formed represents the Subboreal period (but can be included sensu Jäger /1969/ in Epiatlantic, 6,000 – 3,200 BP). This period is characterized by a relatively rapid alternation of wetter and drier fluctuations. Local environmental problems (heavy rains, reduced water absorption, floods) should be taken into account. The whole period of the previous Atlantic and Epiatlantic was relatively calm in terms of sedimentation, but the fundamental changes in the country, which at times becomes park-like, begin to manifest themselves.

The whole stretch from 4,000 to 3,500 BC was entirely marked by a long and relatively deep precipitation minimum (3,870 to 3,640 BC), designated m-c, which undoubtedly had to have a very strong impact on the climate in a large area of Eurasia. In the whole section from 4,000 BC up to 3,500 BC there were very few noticeable increases in precipitation. Rather, it is possible to speak of a long dry period, which was probably quite cold (Svoboda, 2009). Between 3,485 and 3,400 BC it is possible to detect a marked increase in the precipitation activity, which was manifested in the maximum M-d1. This was followed by a significant precipitation minimum of m-d (Diagram 3.1).

Between 3,000 BC and 2,860 BC there was a gradual decrease in precipitation activity. The period from 2,860 – 2,833 BC represents a longer dry section of the precipitation minimum m-1 with a slight oscillation of the increase in precipitation between 2,830 – 2,820 BC. In the years 2,815 – 2,770 BC, the rapid onset of precipitation activity began to peak at M-1. During the onset of precipitation, there was a slight decrease in precipitation to sub-lows in approximately 2,815 – 2,793 BC. In the period 2,770 – 2,750 BC there was a very rapid decrease in precipitation to a minimum of m-2. Years 2,725 – 2,350 BC represent more or less normal rainfall with minor fluctuations (Svoboda, 2009).

Generally, it is possible to characterize the 3,000 – 2,500 BC section as a rather humid one. Between 2,830 and 2,730 BC, there were a few less pronounced oscillations, after which the precipitation began to decrease significantly (Svoboda, 2009).

In the period from 2,500 to 2,400 BC there was a gradual decrease of precipitation with slight fluctuations. In the years 2,400 – 2,375 BC there was a very small increase in cloudiness and precipitation, which did not even reach normal. The drought was long-lasting. Very moderate precipitation maximum M-3 is characteristic for the period from 2,375 to 2,350 BC. Its parameters correspond to rather minor oscillations (Diagram 3.2).

The beginning of the period from about 2,350 to 2,300 BC is characterized by a faster decrease in precipitation, leading to a lower m-3 minimum. This was followed by a smaller precipitation maximum of M-4 (2,245 to 2,220 BC) followed by a very long precipitation minimum of m-4 with slight fluctuations towards the increase in precipitation, but the increased values did not even reach the normal limit (2,220 to 1,935 BC; Svoboda, 2009).

Half a millennium since 1,500 BC up to 1,000 BC can be evaluated as dry, but with very significant peaks M-7 and M-8, which were quite rich in rainfall. The oscillatory period in the years of about 1,290 to 1,130 BC, which is characterized by extremely large fluctuations in precipitation activity, is significant. It is this period that can be considered one of the most powerful climatic oscillations of antiquity, during which several massive migration waves occurred throughout the Eurasian continent (Diagram 3.3).

In general, the period from 1,000 BC to 500 BC can be assessed as normal with one significant minimum of m-10 peaking around 770 BC. It can be said that in this period of time, Europe had to be extremely dry. The milder drought dominated during the next low of m-11, around 650 – 520 BC. These precipitation anomalies can be linked to the possible migration of European and non-European populations. The following oscillations were low and ranged around average values. After a very long and intensive precipitation minimum m-9 (1,235 – 1,125 BC)

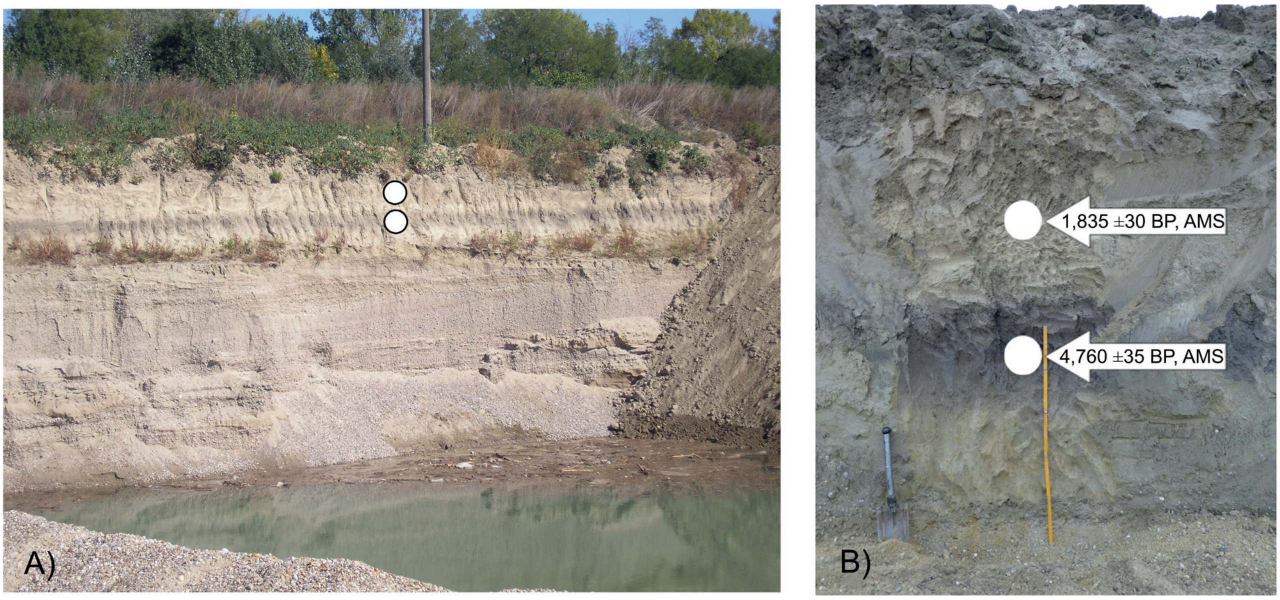


Fig. 3.19 Gravel pit Most pri Bratislave – Zelená voda

- A) *Panoramic view of transient Pleistocene-Holocene accumulation of the so-called "core" of Žitný ostrov in the Zelená voda gravel pit between Ivanka pri Dunaji and Most pri Bratislave. Up to 6 m thick layer of sandy gravel with apparent lateral accretion and herringbone bedding in the right part of the picture is covered by 2 m thick layer of Pleistocene-Holocene silts and Holocene loams forming a stripped overburden.*
- B) *Fluvial fine-sand silts of the Danube alluvium in the fossil soil overburden in the gravel pitwall profile. Numerical ^{14}C AMS dating from gastropod shells taken from silts above the fossil soil (upper white point) documented the Subatlantic age of the layer and the dating of the fossil soil (lower white point) documented the Subboreal age.*

with less oscillation in the years 1,205 – 1,180 followed in the years 1,125 – 1,035 BC a rapid onset of precipitation activity especially in the years 1,125 to 1,086. Then the rainfall remained at the maximum M-8 until 1,035. In the period from 1,015 to 972 BC, after a slight and minor minimum in the years 1,036 – 1,015, precipitation started to increase intensively up to the maximum of M-9. This was followed by a slight precipitation decrease between 972 and 883 (see Diagram 3.4). Dated soil from the profile FS-64zk Hurbanova Ves (1,083 – 906 BC) originated at the onset of the Late Bronze Age. All cultures in Slovakia during this period belonged to the cultures of ash fields (Diagram 3.3).

The climate during the Subboreal (1,250 – 700 BC) was supposed to be very dry and warm with heavy, storm rainfalls. The cultural steppe began to spread very quickly at the expense of the forest – especially oak and beech woods. The forest retreated by several hundred meters to higher altitudes. Exposure of large surfaces, torrential rains, and the inability to absorb water in the landscape led to repeated floods and considerable soil erosion. Slopes debris were formed. Human activities related to logging for construction, consumer and manufacturing purposes contributed to further devastation. Further destruction of the forest stand by grazing reached its peak and caused the first major changes in the composition of forest stands. Further social development takes place roughly up to the Slavic settlement of our countries in the Subatlantic climate period (700 BC – 600 BC). According to natural scientists, the climate should be less favourable than in the Subboreal. The result of the change should be soil erosion in exposed locations and their secondary sedimentation in depressions. Around amidst of this period, there was a partial decline of open areas and gradual afforestation began. This process stopped only at the end of the Subatlantic. In terms of human cultures, however, the situation seems to be slightly different. The settlement in the Early Iron Age – Hallstatt period to Early La Tène (750 – 370 BC) continuously followed the extent and forms of the previous settlement with its spatial diversification and developed further (Cílek & Kubíková, 2003; Diagram 3.3).

Subatlantic (2,750 – present)

In the Subatlantic period, the climate was humid and slightly cooler than today. However, there were fluctuations in the wet and dry phases. This is also suggested by the research of malacofauna from the pebbles in Most pri Bratislave – Zelená voda. The profile reveals Holocene flood sediments lying in the overburden of the Late Pleistocene fluvial gravel of the Danube. In floodplain sediments – calcareous silts, fossil soil was developed (age 4,760 ± 35 BP; 5,520 ± 48 cal. BP (Subboreal; Fig. 3.19). In the overburden of the humus horizon there was a rich but diversified gastropods community (Fig. 3.20). In the malacofauna community, the dominant species was *Arianta arbustorum.* The species *Fruticola fruticum* and *Trochulus striolatus* were also abundant in the community. Small amounts of *Cepaea hortensis, Ena montana, Petasina unidentata, Succinea putris* and *Oxychilus cellarius* were found.

The age of this malacofauna was dated on the basis of ^{14}C AMS dating of the snail shell *Arianta arbustorum* (from a depth of 0.75 m) to 1,835 ± 30 BP (1,775 ± 39 cal. BP, Fig. 3.19). The character of the landscape based on the analysis of this fossil community of malacofauna can be characterized as a floodplain forest. Based on isotopic oxygen analysis from shellfish shells the palaeotemperature was lower than today's temperature.

Overall, however, the climate was more oceanic in the Subatlantic period than it is at present. The upper limit of the forest descended and it can be assumed that it reached the present climatic limit of the forest by the end of this period. The Subatlantic is generally ranked in the Iron Age. At its end, nations moved in the Central Europe and our country was populated by Slavs (http://lfskripta.webpark.cz/fyto/fyto12.htm).

During this period, air temperatures gradually dropped to current levels. Differentiation of forest communities has reached its almost present form. The forests of our territory were in the middle of the Subatlantic period in terms of their composition ideal representative of today's groups of forest types sensu Zlatník (1959). During this period, human activity was already applied to the formation of forest communities (in some territories to a dominant extent) mainly in relation to deforestation of the area for agricultural production.

In the period of the Younger Subatlantic, the anthropogenic influence in the whole territory began to prevail. This represents a determining impact on the forest communities, with the exception of the most remote and extreme sites. Degradation and devastation occurred on ever larger areas, and the proportion of pioneer species (aspen, birch, pine) was growing again.Until the middle of the last century, the overall biodiversity of habitats and animal and plant species increased thanks to the introduction of new crops, animals, weed invasion, expansion of steppe and forest steppe elements. On the contrary, it was only with the beginning of industrialization that its decline have taken place due to large-scale agriculture and new trends in forestry. The overall development of forests in Central Europe and the Czech lands in particular was very short-lived and it can be assumed that it has not been fully completed. This should also have consequences in the formulation of the so-called natural composition of forests and management of protected areas, where the protection of nature and indigenous communities prevails. Frequent famines, crop failures and population fluctuations should warn us of over-romanticism in understanding human relationships and environments in recent centuries (Remeš, 2008).

Years 843 to 775 BC represent a very pronounced and deep m-10 minimum, which is most likely a dry period. The m-10 deep minimum was followed by a very rapid onset of precipitation (775 to 750 BC), but reached only normal values, so it cannot be considered a maximum (Diagram 3.4; Svoboda, 2009).

The dated soil KF-24j from Jelka (Diagram 3.5, Fig. 3.23) was formed in the period of the Early Iron Age (Hallstatt) until the beginning of the Early Iron Age (La

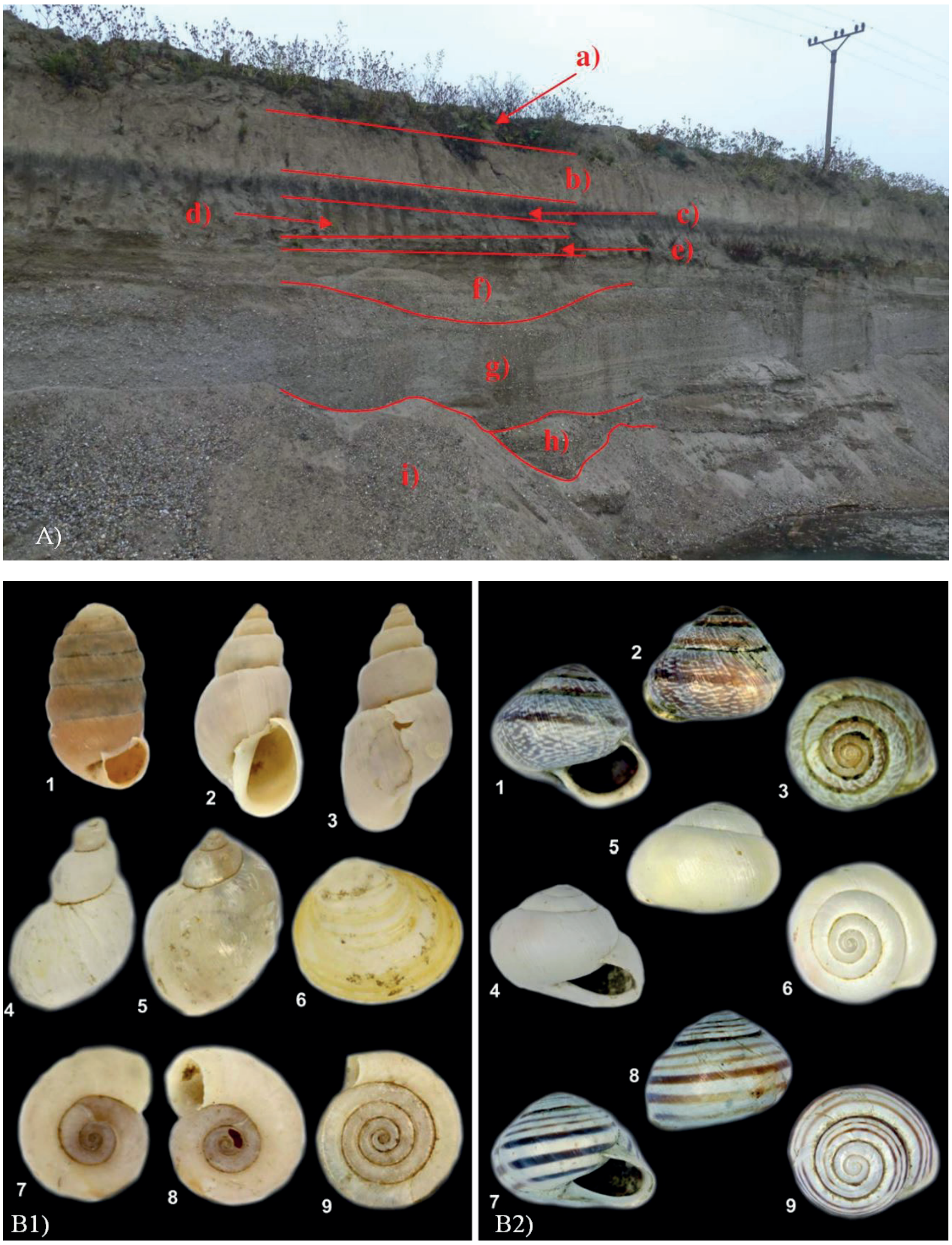


Fig. 3.20 Location Most pri Bratislave – Gravel pit Zelená voda.

A)
Fine-rhythmic stratification of the transient accumulation of the “core” of Žitný ostrov in Most pri Bratislave. (a) – recent overburden; b – Holocene fluvial flood silts (loams); (c) Holocene fossil soil (Atlantic); d – silts of Early Holocene to transition period; e) – carbonate layer (calcrete); (f) – the zone of alternation of thin layers of silt, sands, sandy silts and silty fine gravels; (g) – fine-rhythmic alternation of layers, gravel, sand, sandy gravel and gravelly sands of the transitional complex; (h) – coarse layers of coarse-grained sandy gravels of the Late Pleistocene with calcrete (upper part of the Middle Complex); (i) – talus piles;

B)
Shells of gastropods from the Štrkovec and Most pri Bratislave B1) Štrkovec locality – 1 Pupilla muscorum (Linné); 2, 3 Galba truncatula (O. F. Müller); 4 Succinella oblonga (Draparnaud); 5 Radix sp.; 6 Pisidium amnicum (O. F. Müller); 7, 8 Gyraulus laevis (Alder); 9 Anisus vortex (Linné); B2) Most pri Bratislave locality – 1 – 3 Arianta arbustorum (Linné); 4 – 6 Fruticola fruticum (O. F. Müller); 7 – 9 Cepaea hortensis (O. F. Müller).

Tène – Celts). This sand dune N of Jelka demonstrates the stadial development of the aeolian sediment in dependence on palaeo-climatic changes during the Holocene. The results show the stage development of the bodies, while the location of the fossil soil in the body of the dune demonstrates the interruption of the body development in the warm and humid period of the climatic optimum of the Middle Holocene, favourable for the development of soils. On the surface of fossil soil there were found fragments of ceramics, proving the settlement of such places in terms of strategy and flood defence.

The precipitation between 528 and 491 years BC was characterized by a minor low m-12. From 491 BC to 435 BC there was a gradual increase in precipitation to a very small and minor maximum. Then, in the years 435 to 400 BC, there was a decrease in precipitation, leading to a marginal minimum of m-13. This was followed by a fairly long stretch of rainfall normal with a few mild oscillations reaching the minimums (400 – 250 BC). The dry years were probably between 380 – 360, 338 – 316 and 250 – 225; Svoboda, 2009).

Generally, an interval from 1,000 BC up to 500 BC can be evaluated as normal with one significant minimum of m-10 culminating around 770 BC. It can be said that in this period of time, Europe had to be extremely dry. The milder drought dominated during the next low of m-11, around 650 – 520 BC. These precipitation anomalies can be linked to the possible migration of prehistoric European and non-European populations. The following oscillations were low and ranged around average values.

Period from 500 BC to 0 can be characterized comparable to recent conditions. Although the rainfall curve was oscillating, it was surprisingly low. Significant were two precipitation lows, m-14 and m-15, which were extremely poor in precipitation (Svoboda, 2009).

Dated gastropod from Most pri Bratislave (DB-3/2 gastropod Most (Poz-73939): (1,835 ± 30 BP) 86 AD – 246 AD) lived in a period that falls within the **Roman**

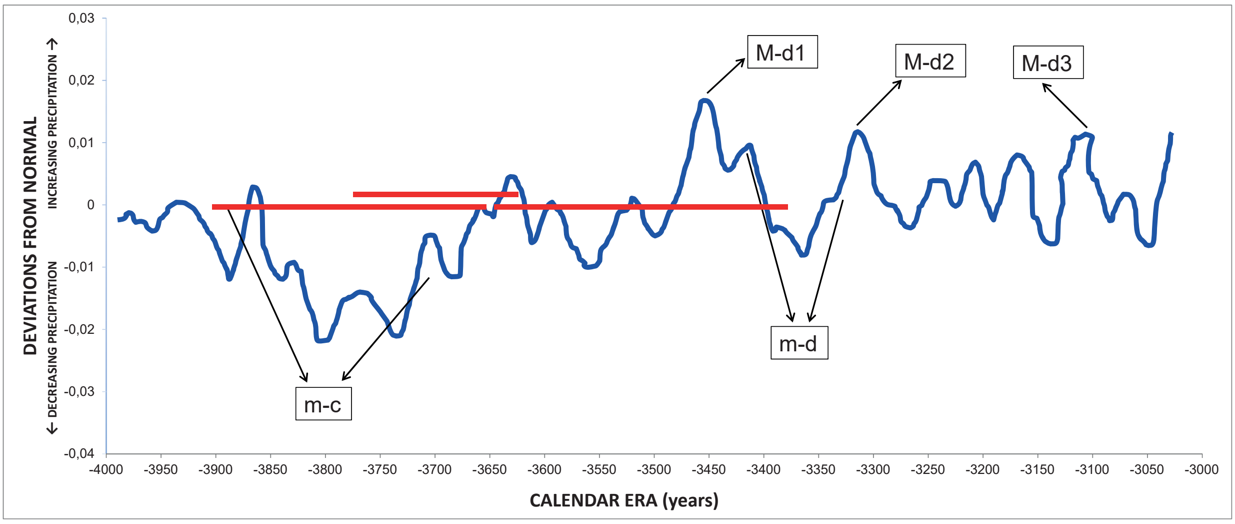


Diagram 3.1 GISP-2 Greenland – annual increases in snow in the period 4,000 – 3,000 BC (Svoboda, 2009). The red bars show the range of dated soil formation JM-1 Bratislava Petržalka (3,909 – 3,657 BC), DB-3/3 from Most pri Bratislava (3,640 BC – 3,381 BC) and 313 Okrúhle Jazero – Moravské Kračany (3,767 – 3,635 BC).

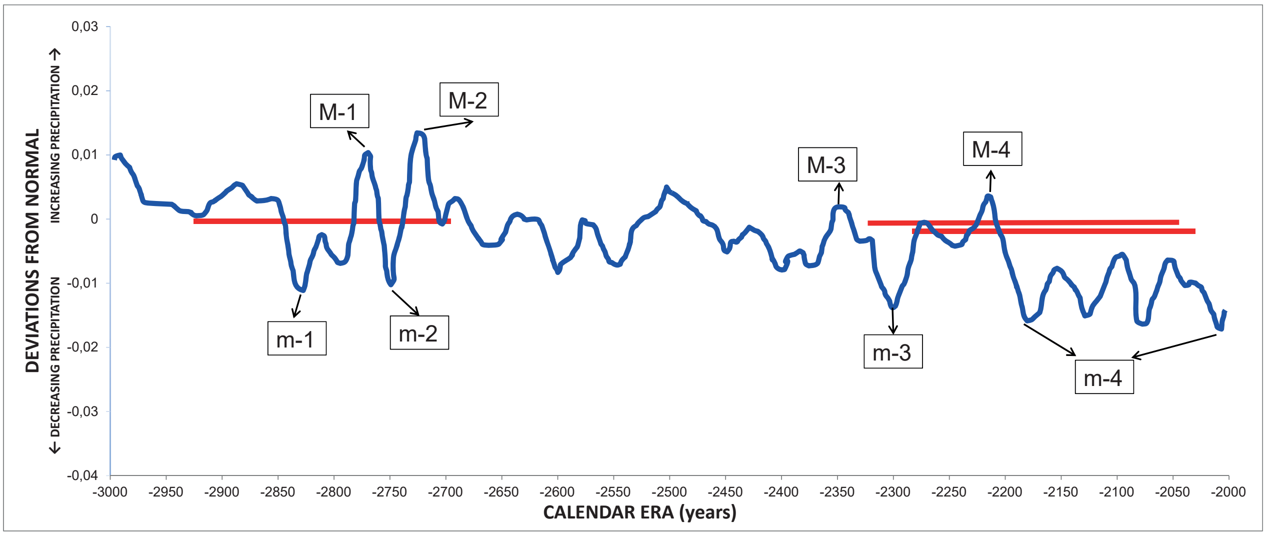


Diagram 3.2 GISP-2 Greenland – annual snow increments of 3,000 – 2,000 years BC (Svoboda, 2009). The red bars show the span of the dated soils 77 Gabčíkovo (2,336 BC – 2,047 BC), S1 Štrkovec (2,281 BC – 2,038 BC) and FM-49C Horné Saliby (Poz-78073) 2,926 – 2,680 BC.

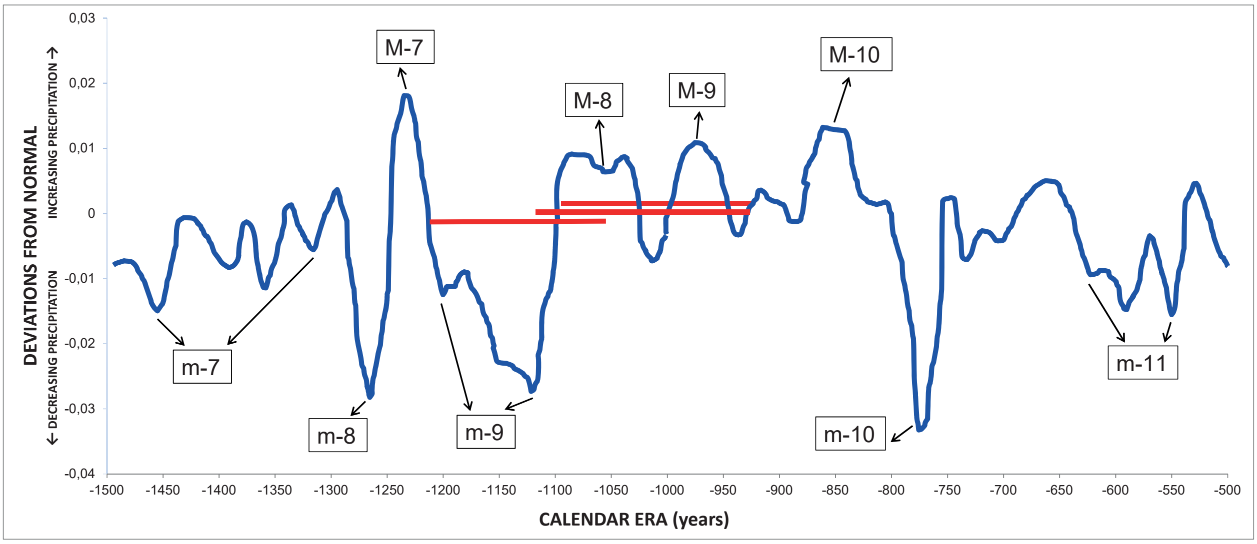


Diagram 3.3 GISP-2 Greenland – annual snow increments between 1,500 and 500 years BC (Svoboda, 2009). The red bars show the span of the dated soils FS-64zk Hurbanova Ves (Poz-75137) 1,083 – 906 BC, FS-21op Malé Blahovo (Poz-75135) 1,123 – 930 BC and MV-20 Šoporňa (Poz-78072) 1,210 – 1,060 BC.

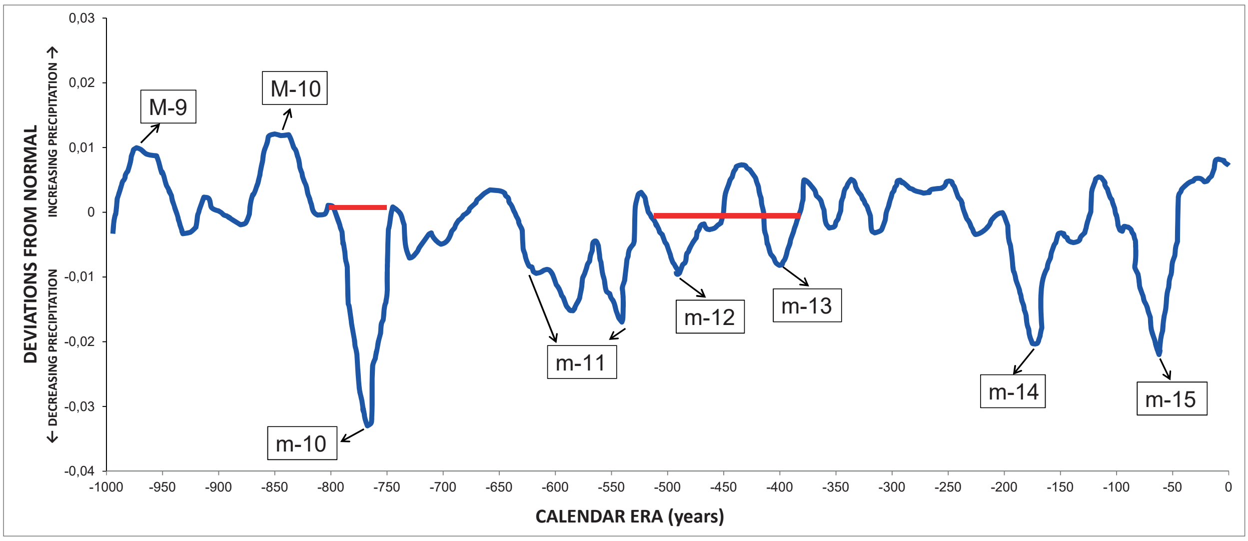


Diagram 3.4 GISP-2 Greenland – annual snow increments of 1,000 y BC – 0 years (Svoboda, 2009). The red line shows the span to which the dated KF-24j Jelka 507 – 366 BC and 878 Gabčíkovo (825 – 757 BC) fall.

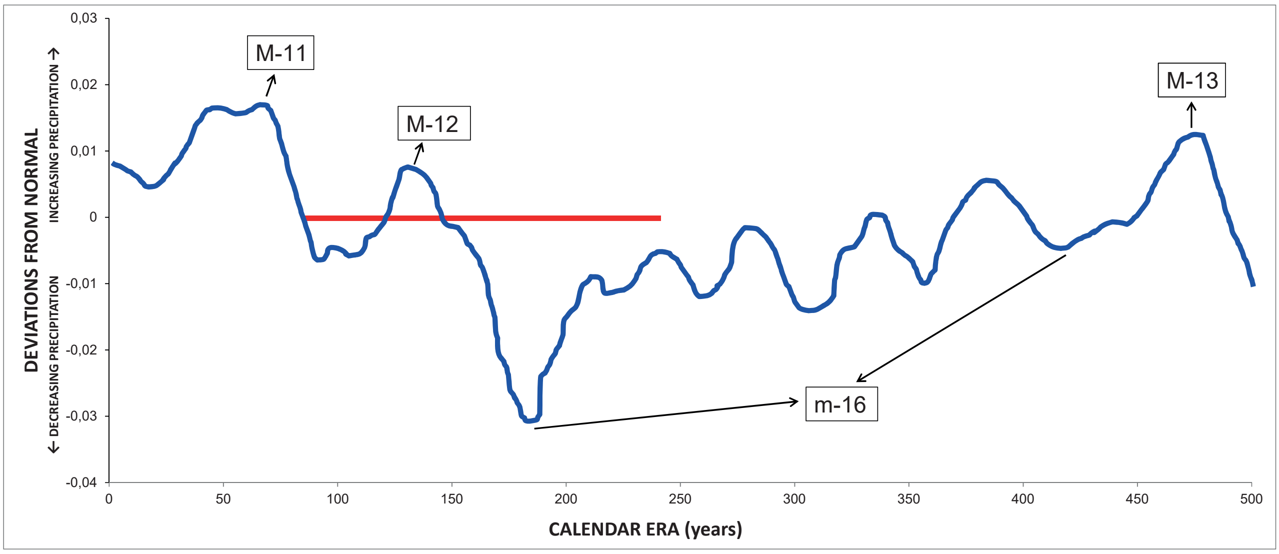


Diagram 3.5 GISP-2 Greenland – annual snow increments from 0 to 500 years AD (Svoboda, 2009). The red line shows the span of DB-3/2 from Most pri Bratislave (86 AD – 246 AD) and the blue line OSL dating of fluvial sands from ZE-1 Zemné (1,690 ± 21 BP) (= 260 AD) and R-1 Rovinka (1,690 ± 12 BP) (= 260 AD).

Climatic Optimum (about 100 BC to 200 – 250 AD). This was a relatively warm and rainfall-rich episode. At this time, the Roman Empire reached the limits of its greatest expansion (Fig. 3.24; Svoboda, 2009). Temporary warming in Central Europe is evidenced by several archaeological and palaeo-botanical findings. In the first century BC the Carpathian basin was dominated by a drier and warmer climate, similar to the one in northern Italy today. This is evidenced by densified annual rings of oak remains, findings of Mediterranean plants such as figs, apricots, peaches, plums and pears, proven by grapes growing on high cordons (Svoboda, 2009).

This is evidenced both by archaeological findings and by depictions on mosaics and paintings from that time. At the end of this period, the first signs of the impending climate catastrophe began to appear. Even in summer, strong cold inbreaks occurred (Svoboda, 2009).

Between 16 and 60 AD, there was a very sharp increase up to year 38, when the peak of M-11 was reached and remained at the same intensity until 65. Thereafter, between 60 and 100 AD, rainfall decreased with a sub-minimum of around year 100 AD. However, it can be assumed that in this case it was the start of an extraordinarily long section of a noticeable decrease in precipitation activity. Around the years 100 – 128 AD there was a slightly milder increase in precipitation to a smaller maximum of M-12. Years 130 – 418 AD are characterized by very significant and extreme precipitation minimum m-16. Generally, however, we can characterize the onset of a very long significantly rainfall-poor section. In this long period, several minor fluctuations leading to increased rainfall can be registered in the years 184 to 208, 225 to 235, 255 to 278, 310 to 333, 356 to 383 (Diagram 3.5). It was a very long period of permanently low cloudiness and probably lower temperatures. It was at this time that there had been extremely strong migratory movements throughout Europe, for which the concept of ‘migration of nations’ had become established. It was a time so chaotic that it

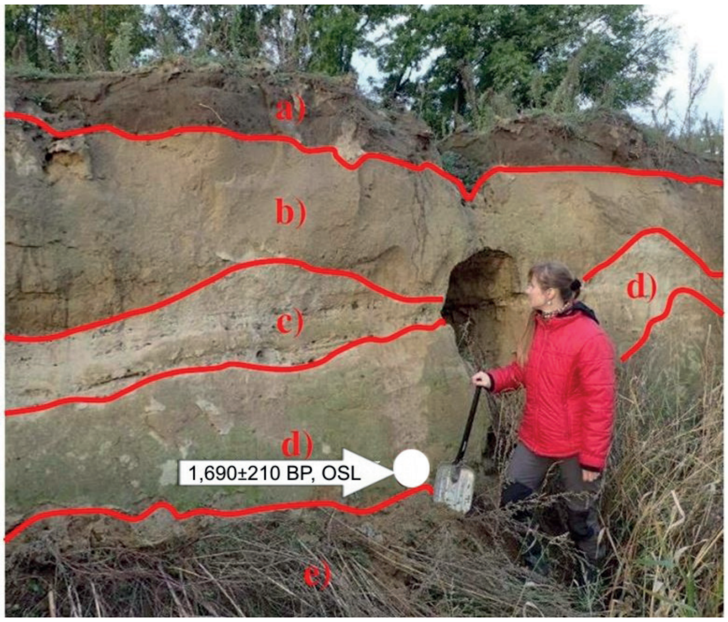


Fig. 3.21 Location Zemné. Fluvial loams (silts) of the flood facies on the fluvial sands of the riverbed facies
(a) – recent soil with anthropogenic interference; (b) – fine-sand flooding silts; (c) – calcareous silts with fine gravel; (d) – weakly calcareous fluvial sands; (e) – loamy outwash. The white point indicates the sampling point from which the sediment age was determined by the OSL method to 1,690 ± 210 BP.

Fig. 3.22 Location Rovinka. Fluvial sands. The white dot indicates the sampling point from which the sediment age was determined by the OSL method at 1,690 ± 12 BP.

Fig. 3.23 Location Jelka. White points – sampling sites and ages of individual layers of aeolian sands based on a fossil soil in the ditch of Jelka.

was enough for everything that was reached in ancient education to be completely forgotten and destroyed. A large number of people of various nationalities were moving through Europe and were constantly fighting with each other (Svoboda, 2009).

Younger Subatlantic

(920 BP – present)

Dated soil and aeolian sand (FS-3j Jelka soil (Poz-74920) (835 ± 30 BP), 747 ± 30 cal. BP, ^{14}C AMS dating and FS-3B Jelka – Aeolian sand (314 ± 28 BP), (= 1,635 AD), OSL dating, as well as wood (DB-3/2 wood Most (135 ± 30) BP), 139 ± 101 cal. BP, ^{14}C AMS dating) come from a period of Younger Subatlantic (Fig. 3.25). The soil FS-4j Jelka (Poz-74922) temporarily falls into the uppermost part of the Older Subatlantic (depending on the stratigraphy used). At this time, the climate development was optimized (from the 11th to the 13th Century). It is the period of the High Middle Ages (the High Middle Ages falls in the period from the beginning of the 11th to the 13th or 14th centuries). The climate was favourable for a long time, had warmed-up considerably and winters were mild. This climatically mild interval, so-called **Medieval Climatic Optimum** (950 – 1250 AD) ended in a generally colder so-called Little Ice Age (between the 14th and 19th centuries, with a peak in the 17th Century; Mann et al.

Fig. 3.24 The Roman Empire during the reign of Emperor Traian (117 AD). Area 6,500,000 km²(Bennet, 1997).

2009). However, as far as the Medieval Climatic Optimum and the Little Ice Age are concerned, this is not a worldwide synchronous period of heat and cold (IPCC, 2001).

Despite considerable uncertainties, especially for the period before 1,600, for which we do not have enough data, the period between 950 and 1,100 AD was the hottest period in the 2,000 years before the beginning of the 20th Century. At that time, however, temperatures were around 0.1 °C and 0.2 °C below the average of 1961 – 1990 and well below the 1980s. Proxy data records from different regions show that the hottest period of different regions took place in different years (Solomon, 2007). These regional warm periods did not occur as coherently in all areas as the warming of the late 20th Century. In some parts of the world, this period was characterized, for example, by population explosions and population expansion into previously uninhabitable areas (Mann et al., 2009).

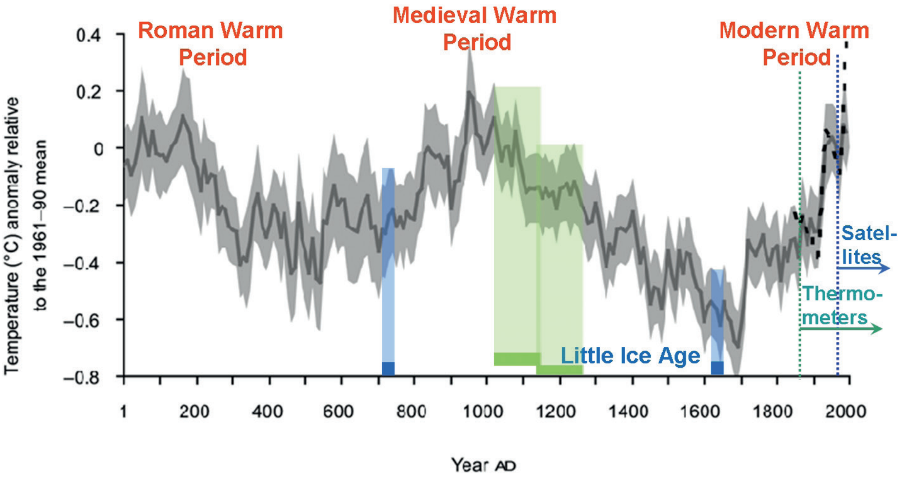


Fig. 3.25 Reconstruction of the temperature for the Northern Hemisphere in the period 1 – 2,000 AD (Ljungqvist, 2010). The green bars show the span to which the dated soils FS-3j Jelka (1,157 – 1,264 AD) and FS-4j Jelka (1,020 – 1,155 AD) fall. The blue bars show the range of OSL dating of fluvial sands from MO-1 Most pri Bratislave (1,230 ± 12 BP) (= 720 AD) and the aeolian sands from FS-3B Jelka (314 ± 28 BP) (= 1,635 AD).

Subrecent (600 BP – present)

This is the youngest period of Subatlantic, but it is strongly influenced by human settlements penetrating into previously unpopulated areas. During the subrecent, there was a clear drying-out of the landscape and the continentality increased.

The moisture difference between wooded highlands and deforested lowlands has increased. Accompanying phenomenon is again the rise of light-loving trees such as oak, hazel, alder and sometimes even pine. Spruce spreads and the pastures are occupied by juniper and a number of herbs bound to open areas. Medieval logging also affects the up-to-date forested mountain areas, leading to the drying-up of large areas and the gradual lack of water in lowland areas. The continuous forest cover is broken up into smaller units by mutually separated pastures (Wallachian colonization in the Carpathians and other types of mountain settlements). Thus, the forest stands lose their internal climate and many of the more moisture-demanding elements disappear. Recent times are characterized by the boom of artificial forest cultures of pine and spruce. In some warm areas, acacia is artificially spread. A new revival of agriculture begins with the arrival of the Slavs and continues smoothly until now (Zeidler & Banaš, 2013).

During this period, there is a large-scale deforestation of the landscape due to agriculture, a decrease in the amount of not only tree species, but also the bush floor (reduction in the amount of pine, oak, linden, elm, hazel and spruce). Wetlands with herbaceous cover are spreading. Owing to farming, nitrophilic communities (elder, nettle, marsh dock, carrot), anthropogenic indicators (juniper, heather), weeds (cornflower, knotgrass).

Later stages have witnessed retreat of the alluvial forests (beech, fir, hornbeam, shrubs) and greater development of pine forests (Remeš, 2008).

Agriculture has intensified **over the last 250 years**. There are plantings of spruce and pine monocultures, deterioration of forest soils due to clearcut logging, forest calamities (drying, frost, calamities due to pests), deterioration of water management in the country. The overall development of the Central European forests was very short-lived and it can be assumed that it has not been fully completed. This should also have consequences in the formulation of the so-called natural composition of forests and management of protected areas, where aspects of nature protection and indigenous communities prevail (Remeš, 2008).

2.4.3 Results of isotope research

As a part of the research of climate change and palaeo-environment, the shell of *Arianta arbustorum* (Linnaeus) from the locality Most pri Bratislave was studied in the Danube Lowland. We used isotopes of oxygen $\delta^{18}O$ and carbon $\delta^{13}C$. This gastropod research is a model example of an isotopic study that was measured to detect changes in the palaeo-environment based on isotopes.

Gastropod *Arianta arbustorum* inhabits damp forests in the lowlands and extends high into the mountains. It avoids only forest-free areas and steppes. Its distribution is in the Central and Northern Europe – the Carpathians, the Alps, north of the Alps, Finland, Poland, Ukraine, eastern France (Buchar et al., 1995; Juřičková et al., 2001; Ložek, 1956).

Holocene flood deposits located in the overburden of the Late Pleistocene fluvial gravel of the Danube are uncovered in the gravel pile near Most pri Bratislave, from where the analyzed gastropod originate. In flood sediments – calcareous silts, fossil soil was developed (age 4,760 ± 35 BP, Subboreal). Its overburden contained a rich but diversified malacofauna community.

In the association of gastropods, the dominant species was *Arianta arbustorum* (Linnaeus). The species *Fruticola fruticum* (O.F. Müller) and *Trochulus striolatus* (C. Pfeiffer) were also abundant in the community. Small amounts of *Cepaea hortensis* (O.F. Müller), *Ena montana* (Draparnaud), *Petasina unidentata* (Draparnaud), *Succinea putris* (Linnaeus) and *Oxychilus cellarius* (O.F. Müller) were identified, as well (Fordinál et al., 2016).

On the basis of the abovementioned malacofauna community, it can be concluded that during the Subatlantic the floodplain forest was located near Most pri Bratislave (Fordinál et al., 2016). The age of this malacofauna was dated on the basis of ^{14}C AMS dating of the snail *Arianta arbustorum* (from a depth of 0.75 m) to 1,835 ± 30 uncal. years BP (Poz-73939: 86 AD – 246 AD /95.4% probability/; Fig.3.26).

$\delta^{18}O$ and $\delta^{13}C$ have been analyzed so far from the fossil shell of land snail *Arianta arbustorum* (Linnaeus) from probe DB3/2, shell sample number DB 3/2-1 (Tab.3.3). Isotope analyses were performed in laboratories of the State Geological Institute of Dionýz Štúr in Bratislava.

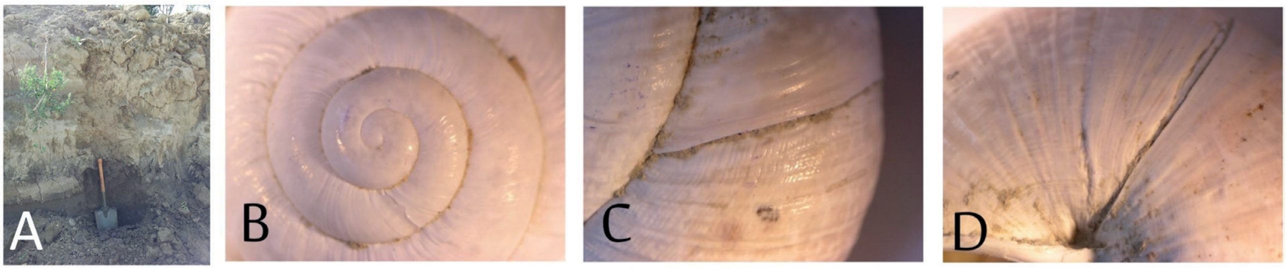
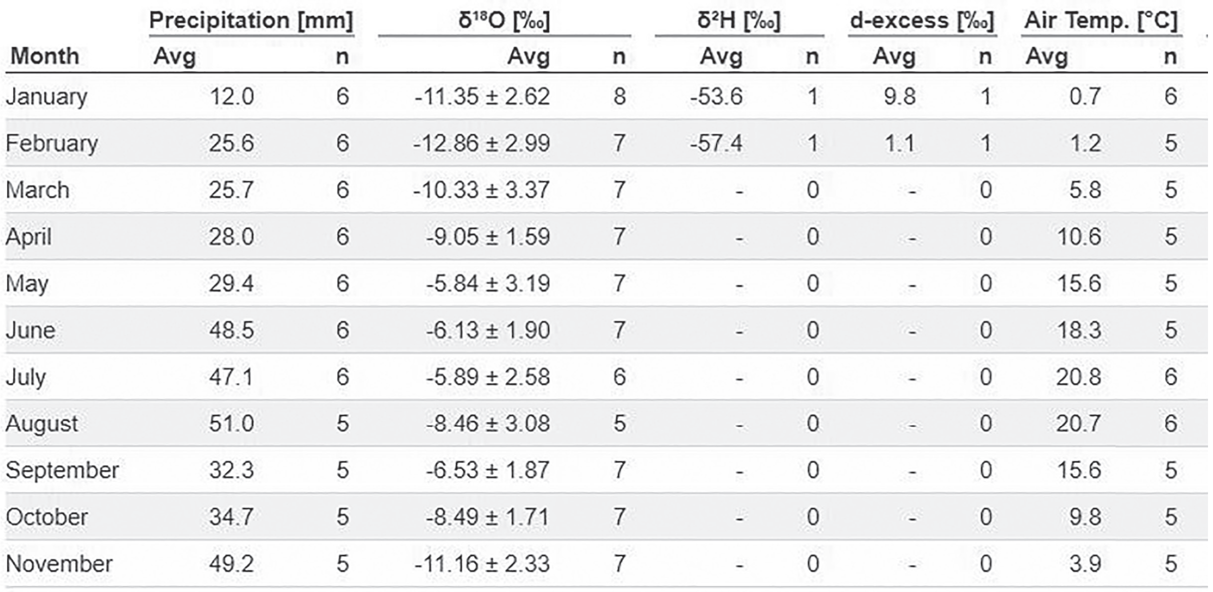


Fig. 3.26 A – location Most pri Bratislave, probe DB-3/2. B-D – gastropod sample number DB 3/2-1, which was used for isotopic analysis of carbon and oxygen. B – protoconch, the initial chamber, C – winter growth arrest line, followed by the last increment on the shell, D – winter growth arrest line and umbilicus.

Tab. 3.3 Results of isotopic ratio of carbon and oxygen from the shell of *Arianta arbustorum* from locality Most pri Bratislave, probe DB-3/2, snail sample number DB 3/2-1. The gastropod shell was divided into 5 so-called years – yearly increments, separated from each other by winter growth arrest line. 1 represents protoconch and 5 represents the last increment on the shell (stdev – standard deviation).

shell increments "years"	**δ $^{13}C/^{12}C$**	**stdev**	**δ $^{18}O/^{16}O$ vs V-PDB**	**stdev**	**corr δ $^{18}O/^{16}O$ vs V-PDB**	**stdev**	**δ $^{18}O/^{16}O$ vs VSMOW**
1 – protoconch	**-8.77**	xx	**-3.22**	0.36	-3.22	0.36	27.57
2	**-8.70**	0.04	**-3.07**	0.20	-3.07	0.20	27.73
3	**-9.27**	0.06	**-2.40**	1.13	-1.78	0.45	28.42
4	**-9.18**	0.06	**-3.68**	0.87	-3.28	0.56	27.10
5 – last increment	**-9.54**	0.06	**-2.88**	0.08	-2.88	0.08	27.93



	Precipitation [mm]		δ¹⁸O [‰]		δ²H [‰]		d-excess [‰]		Air Temp. [°C]	
Month	Avg	n	Avg	n	Avg	n	Avg	n	Avg	n
January	12.0	6	-11.35 ± 2.62	8	-53.6	1	9.8	1	0.7	6
February	25.6	6	-12.86 ± 2.99	7	-57.4	1	1.1	1	1.2	5
March	25.7	6	-10.33 ± 3.37	7	-	0	-	0	5.8	5
April	28.0	6	-9.05 ± 1.59	7	-	0	-	0	10.6	5
May	29.4	6	-5.84 ± 3.19	7	-	0	-	0	15.6	5
June	48.5	6	-6.13 ± 1.90	7	-	0	-	0	18.3	5
July	47.1	6	-5.89 ± 2.58	6	-	0	-	0	20.8	6
August	51.0	5	-8.46 ± 3.08	5	-	0	-	0	20.7	6
September	32.3	5	-6.53 ± 1.87	7	-	0	-	0	15.6	5
October	34.7	5	-8.49 ± 1.71	7	-	0	-	0	9.8	5
November	49.2	5	-11.16 ± 2.33	7	-	0	-	0	3.9	5

Fig. 3.27 Location Topoľníky, 133 m a.s.l.: average amount of precipitation in mm, average monthly air temperature, average δ^{18}O precipitation in ‰, average δ^{2}H precipitation in ‰, average air temperature in °C for 1988 – 1993 (IAEA/WMO, 2018).

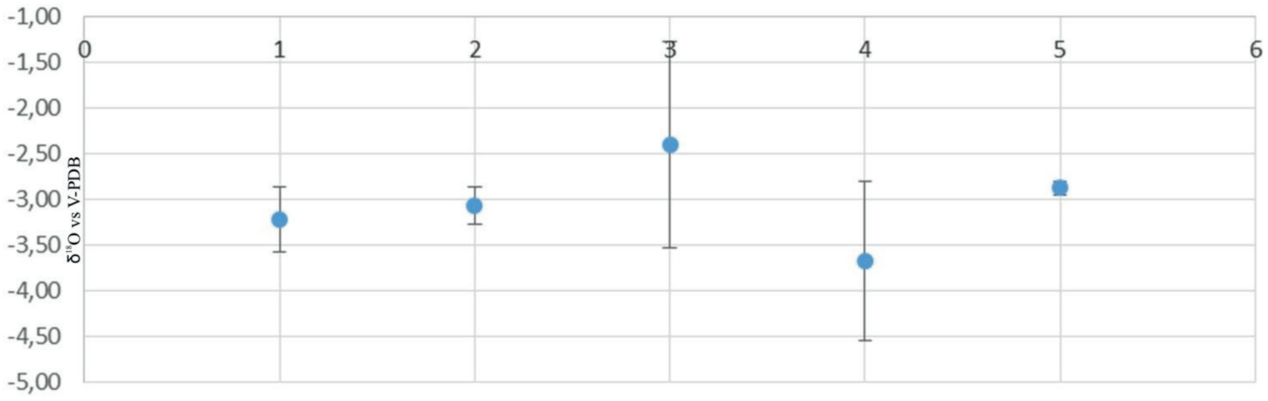


Diagram 3.6 Isotope ratio δ^{18}O from shell of Arianta arbustorum, locality Most pri Bratislave, probe DB-3/2, snail sample number DB 3/2-1. 1 represents protoconch and 5 represents the last increment on the shell (error bars represent standard deviation).

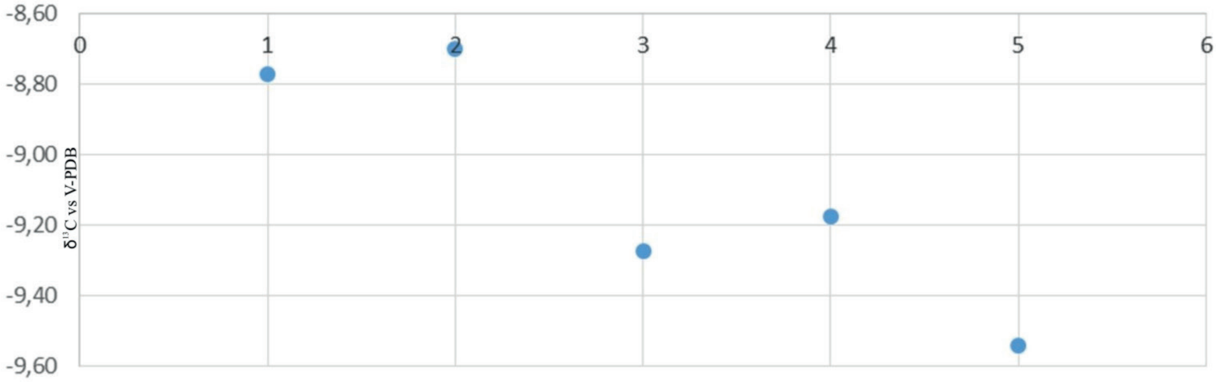


Diagram 3.7 Isotope ratio $\delta^{13}C$ from shell of Arianta arbustorum, locality Most pri Bratislave, probe DB-3/2, snail sample number DB 3/2-1. 1 represents protoconch and 5 represents the last increment on the shell (error bars represent standard deviation).

The gastropod shell was divided into individual years – increments – of winter growth arrest lines. These increments represent the period in which the individual lived actively and his shell grew (Fig. 3.26). The studied individual DB 3/2-1 survived 5 years. Each increment was isotopically analysed. The values δ $^{13}C/^{12}C$ a δ $^{18}O/^{16}O$ were determined. $\delta^{13}C$ values of *Arianta arbustorum* shellfish range from -8.77‰ to -9.25‰, $\delta^{18}O$ values from - 2.40‰ to -3.22‰ (Tab. 3.3, Diagrams 3.5, 3.6). The average value for $\delta^{13}C$ is 9.092‰, for $\delta^{18}O$ the average value is 3.05‰ (Diagram 3.7).

3.4.3.1 Palaeo-temperature derived from isotope analyses

Oxygen isotope values indicate changes in the palaeo-temperature during the life of the studied gastropod.

The $\delta^{18}O$ value of meteoric water in the study age (1,775 ± 39 cal. BP) received by the studied gastropod ranged from -7.4‰ to -8.68‰ (average -8.06‰) (assuming enrichment of $\delta^{18}O$ shells by 5‰ due to palaeo-rainwater). If we compare the average of palaeo-meteoric water values in the study period ($\delta^{18}O$ = -8.06‰) with the values of $\delta^{18}O$ rainwater from the period from 1988 to 1993 (average $\delta^{18}O_{\text{April-September}}$= -6,98‰) from Topoľníky (113 m a.s.l., southern Slovakia, approx. 46 km from Most pri Bratislave; based on data from IAEA/WMO (2018), we find that $\delta^{18}O$ palaeo-precipitation was on average -1.08‰ lower/negative than in 1988 – 1993. The average temperature in the years 1988 – 1993 in the months April-September was 17 °C (IAEA/WMO, 2018). Based on the $\delta^{18}O$ values of *the Arianta arbustorum* shell and calculations according to Goodfriend's equation (1999) (Eq. 1). we can conclude that palaeo-temperature changes during the lifetime of the subject (during the growth period of the shell) were about 5.12 °C.

$$´\Omega\ (°C) = (\delta^{18}O_{\text{max.}} – \delta^{18}O_{\text{min.}}/0{,}5‰) \times 2°C \qquad \text{(Eq. 1)}$$

Where: Ω (°C) – relative palaeo-temperature change, $\delta^{18}O_{\text{max.}}$ – maximum value of $\delta^{18}O$ shell, $\delta^{18}O_{\text{min.}}$ – minimum value of $\delta^{18}O$ shell.

Using the recalculation according to Balakrishnan et al. (2005; Eq. 2) palaeo-temperature changes will be about 3.6 °C:

$$´\Omega\ (°C) = (\delta^{18}O_{\text{max.}} – \delta^{18}O_{\text{min.}}/0{,}35‰) \times 1°C \qquad \text{(Eq. 2)}$$

3.4.3.2 Palaeo-environment deduced from isotope analyses

Climate change during glacial and interglacial periods is a major cause of vegetation changes that are reflected in $\delta^{13}C$ plant values (Huang et al., 2001; Hall & Penner, 2013). If the $\delta^{13}C$ values are more negative, this is an indication that the molluscs consumed C3 plants and that the climate was cooler and humid (Goodfriend & Ellis, 2002, Yanes et al., 2008).

If the $\delta^{13}C$ values are more positive, this is an indication that molluscs consumed C4 plants, indicating a drier environment (Galy et al., 2008; Yanes et al., 2008). Variation of $\delta^{13}C$ values measured in the shell of the specimen of *Arianta arbustorum* from Most pri Bratislave ranges from **-9.54‰** to **-8.7‰** (Diagram 3.7).

C4 vegetation as a dietary source for the studied gastropod from Most pri Bratislave can be ruled out because these plants show very different $\delta^{13}C$ values ranging from **-8‰** to **-19‰** (Ambrose & Sikes, 1991), which contradicts our results, because $\delta^{13}C$ values measured in shells of fossil gastropods are enriched by 8 – 19‰ due to isotopic fractionation compared to the values of the plants they consumed (McConnaughey & Gilikin, 2008). This means that the $\delta^{13}C$ values of the molluscs from Most pri Bratislave were approximately in the range of **-17.54‰** to **16.7‰** when using at least 8‰ enrichment. This is very close to the most negative border of $\delta^{13}C$ for C4 plants. If we use the 19‰ enrichment, the plant food values consumed by the studied gastropod from Most pri Bratislave range from **-28.54‰** to **27.7‰.**

Based on these results, we can conclude that C3 plants were the main food type of vegetation for the studied gastropod. As could be observed from the variables, the gastropod's food fluctuated throughout his life. In the first years, the $\delta^{13}C$ was less negative towards the last increment on the shell, and the $\delta^{13}C$ values moved to less negative values. This provides evidence for changing food of the studied gastropod throughout his life. However, these changes in palaeo-food are not very significant.

3.5 Conclusions

The article presents the reconstruction of the palaeoenvironmental development of the Danubian Flat in the period from 127,000 years BP to the present day and solving the chronostratigraphic affiliation of selected sites on the basis of dating organic material and sediments using AMS ^{14}C (radiocarbon dating) and OSL (optically stimulated luminescence).The period studied is the section of time that includes deposition of dated soils, aeolian and fluvial sands, and organic residues from the study area. The period of the Late Glacial to Holocene is discussed in more detail, because the transition of the Last Ice Age to postglacial had the greatest influence on the formation of the present natural environment, fauna and flora.

During the research, the extent of a wide spectrum of fluvial accumulations subtypes of the transient "core" of Žitný ostrov was mapped in detail, their non-coherent occurrence and precise delineations were confirmed.

There have been mapped in detail the extent and exact delimitation of sites and zones of aeolian sand (sand dunes). The post-glacial (Holocene) genesis has been assigned to majority of the aeolian deposits; to a less extent the older Late Pleistocene facies have been confirmed. The Holocene age of the vast majority of organogenic sediments (humoliths) was found, only in some cases of the fills of open oxbows within Žitný ostrov the older age has been found.

The formation of sediments in the period of the Roman Climate Optimum, the Medieval Climate Optimum and the "Little Ice Age" in our territory in the Danubian Flat area has been confirmed.

Sedimentary evolution

During the overall cold climatic conditions with a lack of air precipitation, loess formation took place in some places. However, the most widespread sediments in the Danube region and the lower reaches of the Váh, Nitra and Žitava rivers were the sands. In some humid places and in the area above the river terraces, sapropels were formed overlying peat or silty alms.

Geological development during the Holocene had a relatively uniform character in the Danube Lowland. Climate change and hydrodynamic conditions of larger rivers influenced the landscape structure, sedimentary and plant cover. In later periods, human activity was also associated with the impact on the natural environment. The whole territory was strongly influenced by hydromorphism. The Danube often shifted its main and side channels, eroded its own deposits and resedimented them. The flood waters spilled on a wide area and also affected the higher degree of the Danube River floodplain. Preboreal and Boreal periods were characterized by the greatest afforestation, followed by steppe intrusion. During the Atlantic period, the climate warmed and gradually humidified. This period was characterized by more pronounced soil formation in those parts of the territory where flood water was not frequently used. Chernozems and gley soils were formed at higher places (Šajgalík & Modlitba, 1983). During this period, some fens began to form in abandoned meanders and oxbows. Aeolian sands were blown over many places (Pelíšek, 1963).

Holocene climate change based on vegetation

The onset of Holocene initially shows similar proportions to the warmer phases of the Late Glacial, but the rapid rise in temperature and the consequent increase in humidity conditioned the permanent immigration of more climatically demanding species. However, the greatest changes occur in living nature, especially in vegetation. The loess steppes and stony areas, or tundra formations gradually passed into the pine-birch stands of light taiga, which later penetrated deciduous trees, especially *Corylus* sp. and *Quercus* sp. In the older phase, the open formations of mesophilic meadows also played an important role. In dry and warm areas, the continental steppe developed on the chernozems, and on the warm calcareous hillsides, the forest formation was gradually pushed to extreme habitats, such as rocky edges, sand, etc. In the Atlantic, natural conditions (warming and humidification) triggered the formation of enclosed damp forests (Ložek, 2002).

Dating

Using the AMS ^{14}C method, 24 samples were dated from 16 localities (Bratislava – Petržalka, Čechová, Čierna Voda, Gabčíkovo, Horné Saliby, Hurbanova Ves, Jánošíkovo, Jelka, Kolárovo, Lúč na Ostrove, Malé Blahovo, Most pri Bratislave, Nový Život – Šalamúnove polia, Okrúhle jzero – Moravské Kračany, Šoporňa, Štrkovec) from the period of the Late Glacial to the Holocene. The age of the dated samples by AMS ^{14}C ranged from 135 ± 30 years BP to 14,410 ± 90 years BP. One sample was outside the ^{14}C AMS dating method range. It came from the well VN 124-2 Kolárovo. Its age was more than 50,000 years BP.

By the OSL method in the studied profiles of the western part of the Danubian Flat 22 samples from 17 localities were dated (Aňala, Balvany, Batoňa, Bratislava, Dunajská Streda, Jelka, Miloslavov, Most pri Bratislave, Nesvady, Okoličná na Ostrove, Oldza, Opatovský Sokolec, Rovinka, Štrkovec, Tvrdošovce, Vrakúň, Zemné) from the period of the penultimate interglacial (Eemian) to Holocene. The age of the dated samples ranged from 127,000 to 314 years BP.

The age of all dated samples (both ^{14}C AMS and OSL) ranged from 127,000 ± 1000 years BP to 135 ± 30 years BP. In the dated samples, the time period from the Eemian Interglacial (i.e. the penultimate glacial period) up to the present day has been captured, thus specifying the chronostratigraphic situation in the study area.

Isotope analyses of malacofauna

The article discusses the possibilities of using isotopic analyses of oxygen and carbon in terrestrial malacofauna shells for reconstructions of climate change and natural environment in the past. Calculated relative palaeotemperature change during the life of the studied gastropod *Arianta arbustorum* from the locality Most pri Bratislave (1,835 ± 30 years BP (86 AD – 246 AD)) was 5.12 °C, or 3.6 °C, depending on which conversion formula we used.

The $\delta^{18}O$ values of the detected palaeo-precipitation were on average -1.08‰ lower/more negative than in 1988 – 1993. This suggests that the palaeo-temperature (in the months in which the gastropod was active) during the period 1,835 ± 30 uncal. BP was slightly lower than in 1988 – 1993.

Based on the analysis of $\delta^{13}C$ results from the gastropod shell. The gastropod's food fluctuated throughout his life. In the first years, the $\delta^{13}C$ was less negative towards the last increment on the shell, and the $\delta^{13}C$ values shifted to less negative values. This testifies for the changing food of the studied gastropod throughout his life. However, these changes in palaeo-food do not indicate significant differences.

Based on the results obtained by a comprehensive review from the Danube region, it can be concluded that the climate has never been stable for a long time. The alternation of climatic cycles during the Quaternary was reflected in the development of sediments, to which flora, fauna and, of course, human societies responded.

The above results show the importance of exploring climate change based on several scientific approaches. Without an interdisciplinary approach to the study of climate change, it is not possible to detect, record and explain minor climate oscillations in the past. To predict future climate change, it is necessary to know climate history and its impact on nature and human civilization.

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