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New insight into the palaeoenvironmental dynamics as a background of the human history in the Nemunas River delta region, W Lithuania, throughout the Lateglacial and Early Holocene

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Abstract. A new reconstruction of the Lateglacial – Early Holocene paleoenvironmental dynamics as a background of the habitation history in the territory of the Nemunas River Delta (NRD) was based on the geological-geomorphological, grain-size, isotope (^{14}C), pollen and diatom data supplemented by archaeological information obtained within the framework of the project „*Man and Baltic Sea in the Meso-Neolithic: Relict Coasts and Settlements Below and Above Present Sea Level. ReCoasts&People*". The existence of extended proglacial lakes formed during the onset of the Lateglacial was succeeded by a period of low water estuaries or freshwater lagoons as early as 13.8 cal kyr BP. Simultaneously, groups of the Final Palaeolithic population, representing the classic Swiderian culture, inhabited the area. As shores of the Yoldia Sea and Ancylus Lake were situated further westwards (-11 to -24 – -29 m NN), wetlands and lake systems alongside with shallow boggy basins and fluvial streams predominated in the local landscape throughout the Early Holocene. Archaeological data suggest an episodic human activity in the territory while part of the archaeological sites might have been covered by sediments during the further intervals of the Holocene. Since the Early Holocene an extended peat bogs have become an important part of the landscape here.

Keywords*: lithology; grain-size; pollen; palaeoenvironmental dynamics; Final Palaeolithic; Eastern Baltic*

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INTRODUCTION

Lagoonal systems, river mouths and estuaries are typical for the coastal regions of the Baltic Sea. The territory of western Lithuania is bordered by the Curonian Lagoon (Kuršių Marios), one of the largest lagoons in this part of the Baltic. Also, the River Nemunas flows into the lagoon forming an extensive delta, and that is why the territory was influenced by both the lagoonal and deltaic processes throughout the postglacial. It is generally acknowledged that bays and lagoons have high time-resolution sedimentary sequences, thus being suitable for multi-proxy investigations justifying the subsequent reconstruction of the palaeoenvironmental dynamics. Moreover, such areas have attracted humans since prehistoric times, providing the necessary resources and habitats. Thus, the above-mentioned region of the Lithuanian territory is of particular importance for the reconstruction of nature and human dynamics in this part of the Eastern Baltic.

The development of the Curonian Lagoon and Nemunas River Delta (NRD) has been of interest to numerous researchers doing research in the postglacial development of the Baltic Sea and the Curonian Lagoon emphasising the geological and geomorphological structure of the coastal territory (Gudelis 1959, 1979; Gudelis, Klimavičienė 1990, 1993; Gelumbauskaitė 2002; Gelumbauskaitė, Šečkus 2005; Kabailienė *et al.* 2009; Bitinas *et al.* 2000, 2001, 2002), the pattern of the vegetation dynamics (Stančikaitė, Kabailienė 1998; Kabailienė 2006), the hydrological and sedimentological regime of the NRD and its tributaries (Červinskas, Kunskas 1982; Žaromskis 1999), and the history of the population of the territory (Girininkas, Žulkus 2017).

It should be noted that a wide range of questions about the evolution of the Baltic Sea are of particular importance in discussing the postglacial history of the NRD. Traditionally, the area has been interpreted as being influenced by different lake and sea stages of the Baltic Sea and its postglacial history has been constructed in accordance with the changes noted in the sea formation (Gelumbauskaitė, Šečkus 2005; Bitinas *et al.* 2002). However, the spatial and temporal resolution of the different stages of the Baltic Sea as well as the ecological regime of the basins is often difficult to describe despite the long-lasting discussions and investigations conducted in the circum-Baltic area. Nevertheless, an increasing number of well-dated detailed multi-proxy investigations have been conducted during the recent decades providing new insights into the history of the basin. The eastern sector of the Baltic Sea is not an exception here (Saarse *et al.* 2009; Miotk-Szpiganowicz *et al.* 2010, 2016; Uścinowicz *et al.* 2011; Vassiljev, Saarse 2013; Vassiljev *et al.* 2015; Napreenko-Dorokhova 2015; Rosentau *et al.* 2017, 2021). These publications suggested some fresh ideas for the interpretation of the earlier findings, prompting revision of the Baltic Sea history in the area. It should be emphasised that in discussing the shore-level displacement history, an increasing importance of the underwater landscape studies, including those in submerged archaeological layers, has been demonstrated as well (Veski *et al.* 2005; Žulkus *et al.* 2015; Girininkas, Žulkus 2012, 2017; Žulkus, Girininkas 2020; Berzins *et al.* 2016; Muru *et al.* 2017; Hansson *et al.* 2018; Nirgi *et al.* 2020; Rosentau *et al.* 2013, 2020). Correlation between geological-geomorphological and archaeological data is of particular importance analysing the Lateglacial – Early Holocene environmental dynamics in the area and we follow the trend in our study as well.

The aim of the conducted study is to provide novel insights into the palaeoenvironmental dynamics and the human history in the NRD in the context of the new data describing the development of the Baltic Sea basin and the Final Palaeolithic of the region (Grigaliūnas 2013; Rimkus 2019; Rimkus, Girininkas 2021a). The results of the archaeological investigations and the extended geological-geomorphological, lithological and sedimentological (grain-size determination) and palaeobotanical (pollen and diatom) survey along with the results of the isotopic measurements (^{14}C dating) were used for refined Lateglacial – Early Holocene environmental-archaeological interpretations.

REGIONAL SETTING

Geological-geographical situation and site description

The investigated territory (Fig. 1; 55.532099, 21.180591; NE 55.541012, 21.457945; SE 55.273423, 21.475074; SW 55.266484, 21.171253, Cord. system WGS) is situated on the western outskirts of the territory of Lithuania and includes the northern part of the NRD and the northern part of the Curonian Lagoon, a freshwater shallow (up to 6–8 m depth) basin, the largest lagoon of such type in the Baltic. The region is predominated by Quaternary formations covering the bedrock that consists of Lower – Upper Cretaceous rocks (Bitinas *et al.* 2002). The Quaternary stratigraphy is characterised by the predominance of biogenic, limnic and terrigenous beds of the postglacial age overlying morainic and glaciolacustrine formations deposited during the Middle – Late Pleistocene and reaching up to 60–70 m thickness on average (Bitinas *et al.* 2000, 2002). The prominent set of the palaeoincisions cutting into the pre-Quaternary surface and reaching few hundred metres is typical for the Earth interiors in this region (Bitinas *et al.* 2002). Situated between the higher topography in the east (20 m NN) and the lower terrain in the west, the surface of the NRD and the surrounding territories is dominated by a range of end moraines, glaciofluvial, glaciolacustrine and alluvial plains of different altitudes, extended boggy lowlands and raised bogs, small limnic basins and water streams (Atmata, Skirvytė, and etc.). A few huge raised bogs, Svencelė (13.33 km^2) and Aukštumala (25 km^2) with peat deposits of up to 9–7 m thickness dominate the territory. Also, the northern part of the investigated territory comprises the confluence of the River Minija and the River Atmata, the northern branch of the River Nemunas in the deltaic area. It should be noted that Nemunas is the largest river in Lithuania's territory with a mean annual streamflow of about 536 $m^3 s^{-1}$. The river drains a catchment area of about 98 × 10^3 km^2, flowing through the territories of the present Lithuania and Belarus. Cutting into the Quaternary beds, it forms a prominent valley reaching up to 35 m depth in the midstream, while river terraces are absent in the downstream part of the valley including the investigated territory.

Archaeological context

Earlier archaeological data suggest that the first human communities settled in the territory of Lithuania as early as in the Allerød Interstadial (Rimkus, Girininkas 2021b). However, new evidence of dated remains of reindeer (*Rangifer tarandus*) skeletons', as well as the discovery of large tanged points suggest that the settling process could have started at the end of Bølling oscillation (Ukkonen *et al.* 2006; Šatavičius 2016) already. In this paper, the Final Palaeolithic refers to the period characterised by Ahrensburgian and Swiderian tanged point technocomplexes, dated to the Younger Dryas and the beginning of the Preboreal ca. 10 500–9 200 cal BC (ca. 12 500–11 200 cal yr BP) (Płonka *et al.* 2020).

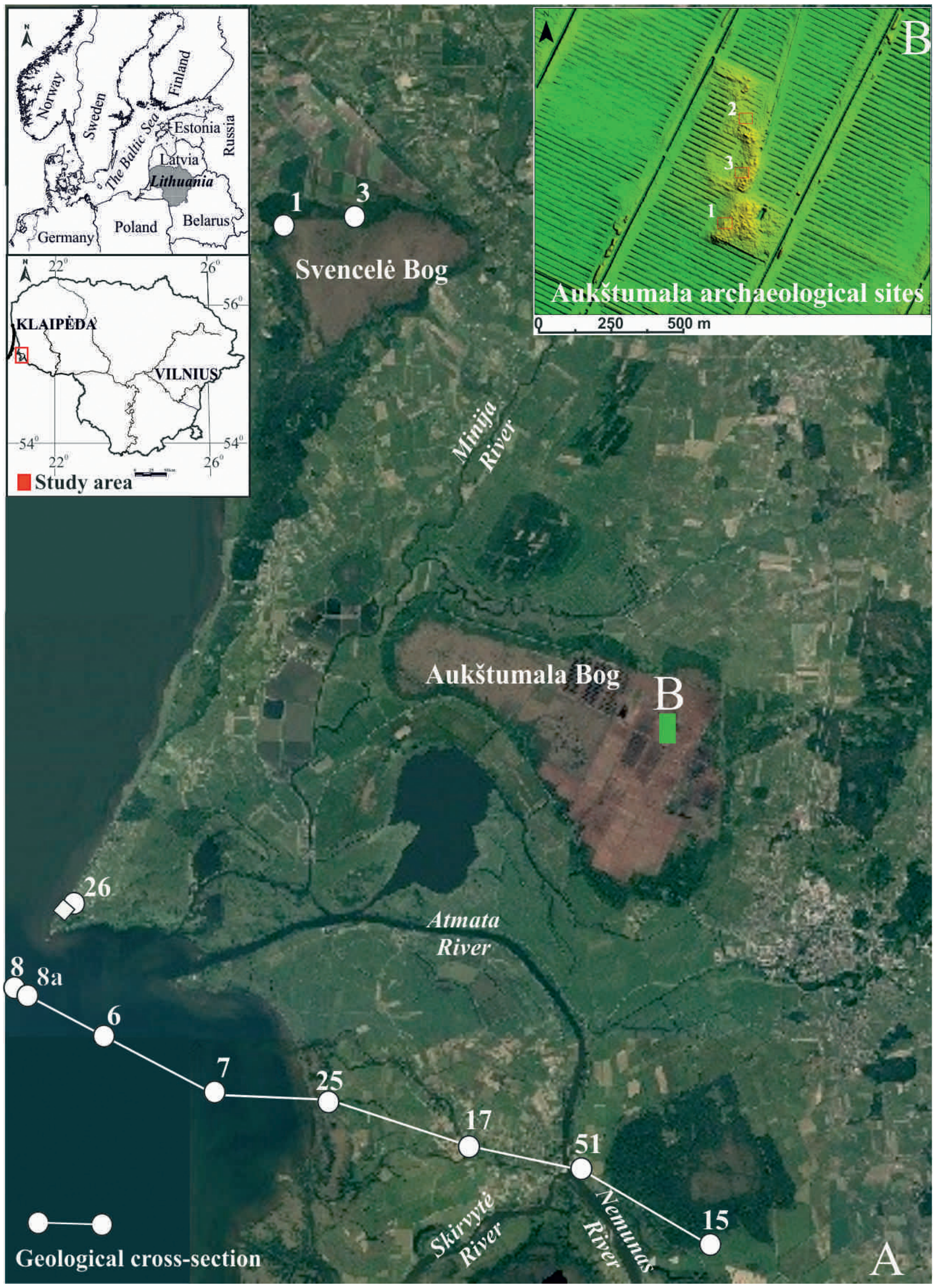

Fig. 1 Study area (A) and location of Aukštumala Stone Age sites (B, 1–3). Cores (with numbers) are marked with circles, the Ventės Ragas Outcrop – with a diamond

However, in the coastal part of Lithuania's territory, the situation is different. Here, the archaeological material evidencing immigration of the earliest human groups is sparse and can only be attributed to the Final Palaeolithic. Although skeletal remains of reindeer and osseous implements were discovered and ascribed to the Final Palaeolithic (Groß 1939; Rimantienė 1971) during the second half of the 19th c. and the 20th c. already, no modern research methods have been applied to confirm these chronological conclusions so far. Those include well-known bone and antler points from Kalniškiai (former Bachmann manor, east of Klaipėda), described as implements made of reindeer bone and antlers and attributed to the Swiderian Culture (Daugnora, Girininkas 2005).

Due to the dynamic development of the Baltic Sea during particular periods of the past, the survey of the Final Palaeolithic and Mesolithic communities in the coastal part of Lithuania is rather complicated. Obviously, part of the archaeological heritage of the Lateglacial and the Early Holocene is submerged now (Žulkus *et al.* 2015) and the extent of such sites is unknown. Furthermore, the remarkable dynamics of the water table has led to the formation of prominent sediment beds covering archaeological sites including the submerged ones, thus new discoveries providing valuable data (Žulkus, Girininkas 2020) are rather scarce in the area. Due to the lack of reliable data, former synthetic studies devoted to the Lateglacial archaeology in this part of Lithuania were based on the data available from the inland territories (Rimantienė 1996; Girininkas 2009; Šatavičius 2016). However, it must be noted that in separate regions, including the coastal one, community subsistence practices, choices and preferences of raw materials as well as taxonomy and advance of technology differed.

The first reliable archaeological record of the Final Palaeolithic on the Lithuanian coast became available from the eastern part of Aukštumala raised bog (Fig. 1B) only in 2004. This area is situated in the southern part of the Lithuanian Maritime region within the territory of the NRD. Two sites situated on the glaciofluvial hill were excavated delivering a fragment of an arrowhead along with other diagnostic Final Palaeolithic lithic implements (Grigaliūnas 2013). In 2020, a stray tanged point was discovered in Pūzraviečiai village (55°47'59''N, 21°68'37''E), the second location where Final Palaeolithic technology is evident along the coastal region of the country. Situated outside the area covered by the presented map, the site is not specified in the provided graphic material. Today, only these two locations represent the Final Palaeolithic human communities in the coastal Lithuania. In order to obtain more information and fill in the existing gap, a field survey at Aukštumala Stone Age sites was extended for the period 2018–2019 providing novel insights into the understanding of the Final Palaeolithic life in the area.

MATERIAL AND METHODS

Archaeological survey

Three Stone Age sites ascribed to the Final Palaeolithic are located on the glaciolacustrine hill, situated in the eastern part of the Aukštumala raised bog (Fig. 1B). In 2004, more than 100 m^2 area was excavated along the glaciofluvial hill and two archaeological sites (Site 1 and Site 2) were discovered (Grigaliūnas 2013). In 2018 and 2019, an area of 84 m^2 and a few test-pits were excavated in the territory of the glaciolacustrine hill (Rimkus, Girininkas 2019, 2020a). The excavated trenches were situated within the territory of the previously discovered archaeological sites and covered plots of 40 m^2 and 10 m^2 of Site 1 and Site 2 respectively. To discover new archaeological sites, additional test-pits were made in the most perspective locations of the sandy hill. As a result, a new Stone Age site, named Site 3, was discovered in between Sites 1 and 2 (Fig. 1B) and an area of 20 m^2 was excavated at this location. All excavated plots are located along the edge of the hill, in proximity to the peat fields. All the discovered settlements are considered sandy type open-air Stone Age sites.

A collection of 311 lithic finds were discovered during the 2018–2019 fieldwork seasons at Aukštumala Sites 1–3. The discovered artefacts, i.e., tools and tool fragments made of flint and various metamorphic rocks, were accompanied by knapping waste and debris of the tool manufacturing process. Although the typological and technological features of the lithic items discovered at Aukštumala Sites 1 and 2 in 2004 had been discussed by Grigaliūnas (2013), the technological and taxonomical interpretations were revised on re-investigation of the lithics and acquisition of new data in 2018–2019.

Apart from the systematic archaeological investigations conducted in the Aukštumala raised bog, the territories situated along the wetlands and riverbanks' were researched in 2018 and 2019 in expectation to get more information about the Stone Age habitation of the coastal region. Several patinated flint items were found on the sandy terrace of the Svencelė raised bog (Rimkus, Girininkas 2020b). Unfortunately, these items lack diagnostic technological features. The aforementioned tanged point accidentally discovered in Pūzraviečiai village was collected from the local landowner.

Geological-geomorphological survey

For the initial geological-geomorphological analysis of the surface structure, lithology, hydrology and etc., the analysis of the former data was supplemented by the interpretation of the black-white stereoscopic aerial photos (scale 1:17 000; 1952). The results of the aerial photo interpretation were checked in the field and both geological and geomorphological maps, scale 1:50000, were compiled to distinguish the main structural components of the landscape, estimate the preliminary origin of the particular forms and complexes and describe the lithological composition of the surface sediments. These data provided geologists with the information necessary for planning and subsequent realisation of drilling works, being the next step of the geological-geomorphological investigations. The results of these investigations were of particular importance in characterising the lithological composition and structure of the earth interiors. Also, a considerable number of samples for laboratory analysis were collected to this end. Finally, based on the compilation of various data sources, the final version of the geological-geomorphological maps describing the structure and composition of the sediments, the age of the identified lithological units and the postglacial history of the territory was compiled.

Coring and sampling

Eight cores situated along the west-east orientated gradient were retrieved from the region of the NRD (Fig. 1A) in order to get information revealing the structure and composition of the Quaternary strata. Four sedimentary sequencies representing the key-sites of the regional importance (huge peat bogs, outcrops and etc.) have been included in this discussion as well. Sediments deposited above the uppermost layer of the till were recovered using mechanical drillers. The description of the sediment strata was based on visual inspection with the focus on the thickness of the bed, the character of the boundaries, the colour and etc. (Table 1). At the same time, the sediment material for further analysis was collected. The number of the analyses applied and the intervals analysed are shown in Table 2. The cited depths are calculated with reference to the sea level and the further discussion is based on the altitude of the interval or the particular sample.

Table 1 Lithological description of the investigated cores

Core	Latitude N Longitude E	Altitude, cm NN	Unit	Lithological description
1	55.492804 21.271114	160 – -60	U3	Light brown peat, greyish brown sandy peat
		-60 – -70		Fine-grained yellow sand
		-70 – -130		Black compact peat
		-130 – -350		Fine-grained yellow sand
		-350 – -680	U2	Greenish silty gyttja
		-680 – -1270		Middle and fine-grained greyish sand
		-1270 – -1320	U1	Fine-grained silty-clayey grey sand
		-1320 – -1490		Till
3	55.495002 21.292497	70–25	U3	Brownish soil
		25 – -260		Light brown peat
		-260 – -360		Fine-grained sand with organic and wood remains
		-360 – -510		Fine-grained greyish sand
6	55.318108 21.214963	-390 – -450	U3	Sandy black mud with mollusc shells
		-450 – -790		Fine-grained silty sand with organic and mollusc shells
		-790 – -1640	U2	Sandy silt with mollusc shells and organic
		-1640 – -1680		Fine-grained silty sand with organic matter
		-1680 – -1970	U1	Clay with interbeds of silt and sand
		-1970 – -2140		Till, sandy loam
7	55.311443 21.258314	-295 – -335	U3	Sandy mud
		-335 – -445		Very fine-grained greenish grey sand with admixture of brown peat
		-445 – -645		Fine-grained yellowish grey sand
		-645 – -845		Very fine-grained greenish grey sand
		-845 – -905	U2	Sandy silt, greenish grey – dark grey, with organic
		-905 – -955		Silty sand yellowish grey very fine-grained
		-955 – -1135	U1	Clayey silt yellowish dark grey
		-1135 – -1485		Silty grey-brown clay
		-1485 – -1725		Till, sandy loam greenish grey
8	55.325088 21.173621	-355 – -535	U3	Fine-grained silty dark grey sand with organic and mollusc shells
		-535 – -715	U2	Fine-grained greenish grey sand
		-715 – -895		Very fine-grained silty brown-grey sand
		-895 – -1045		Sandy-clayey yellowish grey silt
		-1045 – -1435		Till brown-grey and greenish-grey

Core	Latitude N Longitude E	Altitude, cm NN	Unit	Lithological description
8a	55.322853 21.180828	-430 – -470	U3	Various-grained greenish-grey sand with organic and mollusc shells
		-470 – -520		Peat brown
		-520 – -660		Very fine-fine-grained greenish grey sand with organic
		-660 – -720		Silty fine-grained greenish grey sand, at the bottom – gravelly sand
		-720 – -760	U2	Sandy silt greenish grey with organic
		-760 – -850		Very fine-fine-grained silty-clayey greenish grey sand with organic
		-850 – -870		Silt brown grey
		-870 – -1100		Till from greenish grey to greyish-brown
15	55.279195 21.429172	60–0	U3	Gyttja dark grey brown
		0 – -60		Peat dark brown
		-60 – -240		Fine-grained brown yellow sand with admixture of brown peat
		-240 – -410		Medium-grained greenish grey sand
		-410 – -680	U2	Medium-grained grey sand, at the bottom – sand with gravel
		-680 – -780		Fine-grained light grey sand
		-780 – -930	U1	Gravelly sand grey
		-930 – -1260		Fine-grained greenish grey sand with organic
		-1260 – -1360		Till greenish grey
17	55.299459 21.349722	100 – -120	U3	Fine-grained black sand with peat
		-120 – -230		Medium-fine-grained dark grey sand
		-230 – -370		Medium-grained dark greenish-grey sand with mollusc shells
		-370 – -420	U2	Medium-grained dark greenish-grey sand with mollusc shells
		-420 – -720		Fine-medium-grained light grey sand
		-720 – -800		Clayey-sandy silt brown grey
		-800 – -880	U1	Sandy silt grey
		-880 – -1030		Till dark grey
25	55.312238 21.295291	20 – -220	U3	Fine grained dark grey sand with mollusc shells
		-220 – -350		Very fine-fine grained greenish grey sand with organic and mollusc shells
		-350 – -430		Very fine-grained yellowish grey sand with organic and brown peat interlayers
		-430 – -470		Peat dark brown
		-470 – -510	U2	Fine-grained dark brown sand with peat
		-510 – -560		Peat with gyttja from dark brown to greenish brown
		-560 – -630		Sandy silt yellowish grey with gyttja and dark brown peat interlayers
		-630 – -640		Peat with gyttja dark brown
		-640 – -830		Very fine-grained yellowish grey sand with brown peat
		-830 – -920		Fine-grained greyish yellow sand
		-920 – -990	U1	Clayey silt light grey
		-990 – -1260		Clay grey with silt interlayers
		-1260 – -2280		Till grey-brown, grey
		-2280 – -2620		Clayey glauconitic silt grey green
26	55.35058 21.035063	260–190	U3	Sand, fine-grained with remains of organic
		190–0	U2	Sand, fine-grained
		0 – -50		Silty sand, greyish, with remains of organic
		-50 – -100	U1	Sandy silt, dark greyish, with remains of organic
		-100 – -220		Till brownish, compact
Ventės Ragas Outcrop	55.351427 21.201397	580–520	U3	Sand, very fine-grained, yellowish, with soil interlayers
		520–505		Technogenic deposits
		505–395		Sand, very fine-grained, yellowish, with soil interlayers
		395–325		Sand, fine-grained, brownish with gyttja interlayers
		325–315	U2	Peat, black, compact
		315–305		Gyttja, greenish, compact
		305–210		Till brownish, compact
51	55.294475 21.389451	100 – -130	U3	Silty very fine-fine grained sand greenish grey with organic and peat
		-130 – -220		Gyttja dark green – brown grey
		-220 – -390		Peat brown-grey brown
		-390 – -480		Very fine-fine grained yellowish grey sand with organic
		-480 – -800		Fine-medium grained grey sand with organic and shells detritus
		-800 – -850	U2	Sandy silt greenish grey sand with organic
		-850 – -1010		Silty very fine-grained light grey sand with organic
		-1010 – -1290	U1	Silt light grey
		-1290 – -2050		Till grey green
		-2050 – -2080		Glauconitic siltstone grey green

Grain-size measurements

Separated samples representing individual lithological units or contiguous intervals were analysed in the context of grain-size measurements (Table 2). The grain-size measurements were performed by dry-sieving of the clastic material. Twenty-one sediment fractions (>10–<0.05 mm) were determined by a Fritsch Laser Particle Sizer "Analysette 22" in boreholes No. 15 and No. 25; twenty-six fractions (>10–<0.001 mm) – in sequences No. 17 and No. 26; thirteen fractions (>10–<0.001) – in sequences No. 7, No. 8 and No. 8[a] and twelve fractions (>10–<0.001 mm) – in sequence No. 6. To finalise the obtained information, some of the fractions were merged and subdivided according to the applicable grain size grades: >20 mm (pebble); 20–2 mm (gravel); 2–0.5 mm (coarse-grained sand); 0.5–0.25 mm (middle-grained sand); 0.25–0.1 mm (fine-rained sand); 0.1–0.05 mm (very fine-grained sand); <0.05–0.001 mm (silt-clay) and <0.001 mm (clay). Coarse-grained compounds, larger than 20 mm, were extracted prior to the analysis. The grain-size data are expressed in percentages.

Palaeobotanical investigations

Pollen analysis. The master cores 6, 8a, 25, 26, Svencelė 1 (S1) and Svencelė 3 (S3) were analysed for pollen. The sampled intervals are shown in Table 2. Sediment samples covering 10 cm intervals each were taken from the sandy beds, while 2–5 cm intervals were collected from the biogenic or limnic part of the sequency. Sample sizes varied depending on the lithological composition of the strata as well: subsamples of about 10 cm^3 were taken from the sandy bed and subsamples of 3–5 cm^3 were taken from the organic or limnic deposits. Totally, about 250 samples were prepared in accordance with the methodology suggested by Berglund, Ralska-Jasiewiczowa (1986) and analysed in accordance with Moore *et al.* (1991), Fægri, Iversen (1989) and Moe (1974). The number of counted terrestrial pollen grains varied between 500, in sandy intervals, and 1200 in peat or gyttja. The sum of arboreal (ΣAP) and non-arboreal (ΣNAP) pollen grains based the percentage calculation of the spectra.

Diatom analysis. Sediment cores 6, 8a and 25 were subsampled for diatom analysis (Table 2). 32 sediment samples (30–50 g of dry weight) represent core 6 and 31 sample represent core 8a. The sediment samples were prepared in accordance with Battarbee (1986). Sediments were treated with 10% HCL to remove carbonates and with 30% hydrogen peroxide to destroy organic matter. A heavy liquid was used for the concentration of diatom valves. The slides for

Table 2 Sampled intervals and methods applied

Core	Cored interval (cm)	Methods applied (with the altitude (cm, NN) of investigated interval)			
		Grain-size	^{14}C	Pollen	Diatoms
1	1790		176–174 156–154 96–94	275–85 -335 – -860	
3	580		-57 – -59 -112 – -114 -217 – -219 -245 – -247	-23 – -325	
6	1750	-480 – -2090	-690 – -740 -1010 – -1015	-630 – -1670	-690 – -1970
7	1430	-375 – -1625			
8	1080	-435 – -1345			
8a	670	-460 – -1060		-460 – -570 -470 – -870	-455 – -870
15	1420	-70 – -1015			
17	1130	-50 – -860			
25	2640	0 – -910		-20 – -510	-90 – -1010
26	480	220–200 140–120 40–20 -20 – -30		240 – -40	180 – -40
Ventės Ragas Outcrop	370		325–313 324–320 318–314 312–309 325–324 316–315 310–205		
51	2180		-130 – -150 -160 – -170 -260 – -280 -310 – -330 -350 – -370		

microscopic analysis were prepared using 'Naphrax" mounting medium. The diatom species were identified using a light microscope 'Leica' (magnification ×1000). Diatom valves were counted in the central part of the slide (at least 300). The diatoms were ascribed to the species level by means of primary European sources (Krammer, Lange-Bertalot 1986, 1988, 1991a, b). The species names were updated according to the *AlgaeBase* database taxonomic nomenclature (Guiry, Guiry 2021). The diatom checklists of Denys (1991), van Dam *et al.* (1994) and Barinova *et al.* (2006) were mainly applied to analyse the ecological requirements of the particular diatom taxa while ecological grouping according to salinity was performed in accordance with van Dam *et al*. (1994). The total sum of the counted valves per sample based the calculation of the relative abundance of the species.

^{14}C investigations

Both the conventional ^{14}C dating method with the application of liquid scintillation counting (LSC) and the Accelerator Mass Spectrometry (AMS) radiocarbon analyses were applied to identify the age of bulk sediment samples. Totally, twenty one^{14}C measurements were made in the following three laboratories: the Laboratory of Nuclear Geophysics and Radioecology at the Nature Research Centre in Vilnius (Lithuania), the National Laboratory for ^{14}C Dating at the Norwegian University of Science and Technology (NTNU) in Trondheim (Norway) in cooperation with the Ångström Laboratory of Uppsala University in Uppsala (Sweden) and the Laboratory of Chronology (former Dating Laboratory) of the University of Helsinki, Helsinki (Finland).

The radiocarbon calibration program OxCal v.4.4 (Ramsey, B 2009) and the calibration IntCal20 curve (Reimer *et al.* 2020) were used for the calibration of radiocarbon dates. All dates are reported with the confidence level of 1δ (68.27%) and 2δ (95.45%) and expressed in calibrated years before 1950 AD (cal yr BP).

Statistical evaluation of the data

Ordination analysis. The detrended correspondence analysis (DCA) of the pollen data resulted in a compositional gradient length of 2.1 SD units, implying that the data set has mainly a linear structure and suggesting that a principal components analysis (PCA) is a suitable ordination method to summarize the general vegetation dynamics and relations. Ordination by PCA was performed using the log transformed percentage pollen data of 6 cores including 198 samples and 154 taxa. Samples without any pollen data were excluded from the analysis.

The grain-size data set was analysed using the same algorithm as in the case of the pollen data analysis. The DCA yielded that the compositional gradient length of the grain-size data set is 2 SD units suggesting that a liner ordination method should be used instead of the unimodal method. The PCA was accomplished using the grain-size data of eight cores and eight grain-size classes. To summarize the general and specific features of the cores, a grain-size data matrix containing 103 samples and eight grain-size classes has been compiled.

Ordinations by PCA and DCA were done by means of Canoco 5.04 (Ter Braak, Šmilauer 2012). TILIA, TILIA GRAPH (Grimm 2011) and CorelDraw 5 software packages were applied to construct all the diagrams presented.

RESULTS

Human history

The majority of the discovered flint artefacts represent Aukštumala 1 Site, whereas Sites 2 and 3 contain a lesser number of items. Flakes constitute the major part of the entire inventory, testifying the local tool production. Light grey Cretaceous flint was used for the production of various hunting and domestic tools. It should be pointed out that this type of flint is uncommon in the coastal part of Lithuania. The closest location where this material is available is situated in the upper- and mid-regions of the River Nemunas (Baltrūnas *et al.* 2006).

A total of 14 lithic finds can be attributed to the category of tools, where the group of arrowheads (Fig. 2) is the most important, supporting the chronological and cultural attribution of the sites. Points were discovered only in Sites 1 and 3. Two points were almost fully preserved, whereas the rest were recreated from the scattered fragments. However, both the fully preserved finds and the discovered fragments demonstrate an important technological aspect – flat retouch on the ventral surface of the tangs. Based on the identified technological features, these items were attributed to the Final Palaeolithic Swiderian culture. All arrowheads found at the Aukštumala Stone Age sites were made by means of the classical Swiderian willow leaf-shaped point (Serwatka 2018) technology. The finds include a backed piece, a perforator, some scrapers, some burins and a core axe (Fig. 3). Made of massive flint blades and flakes, the discovered burins represent the classical Final Palaeolithic technology, most evident in the examples of the angle and dihedral burins.

Toolkits made of metamorphic rocks are rare and only several characteristic items were discovered (Fig. 4). One of the most interesting tools discovered

Fig. 2 Willow leaf-shape points found at Aukštumala Stone Age sites 1 and 2 (No. 1–5) and Pūzraviečiai village (No. 6)

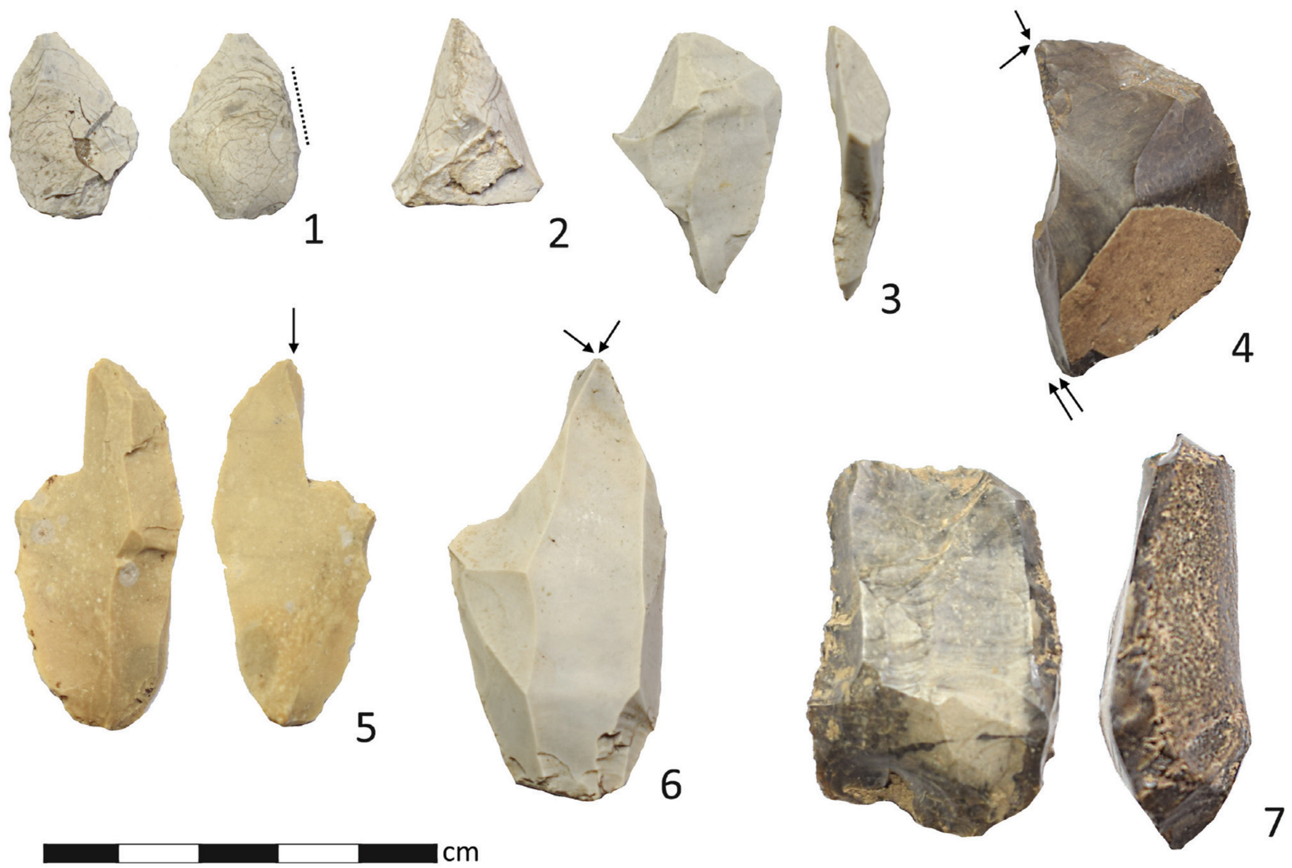

Fig. 3 Household tools found at Aukštumala Stone Age sites: 1) a backed piece; 2) a perforator; 3) a scraper; 4–6) burins; 7) a core axe

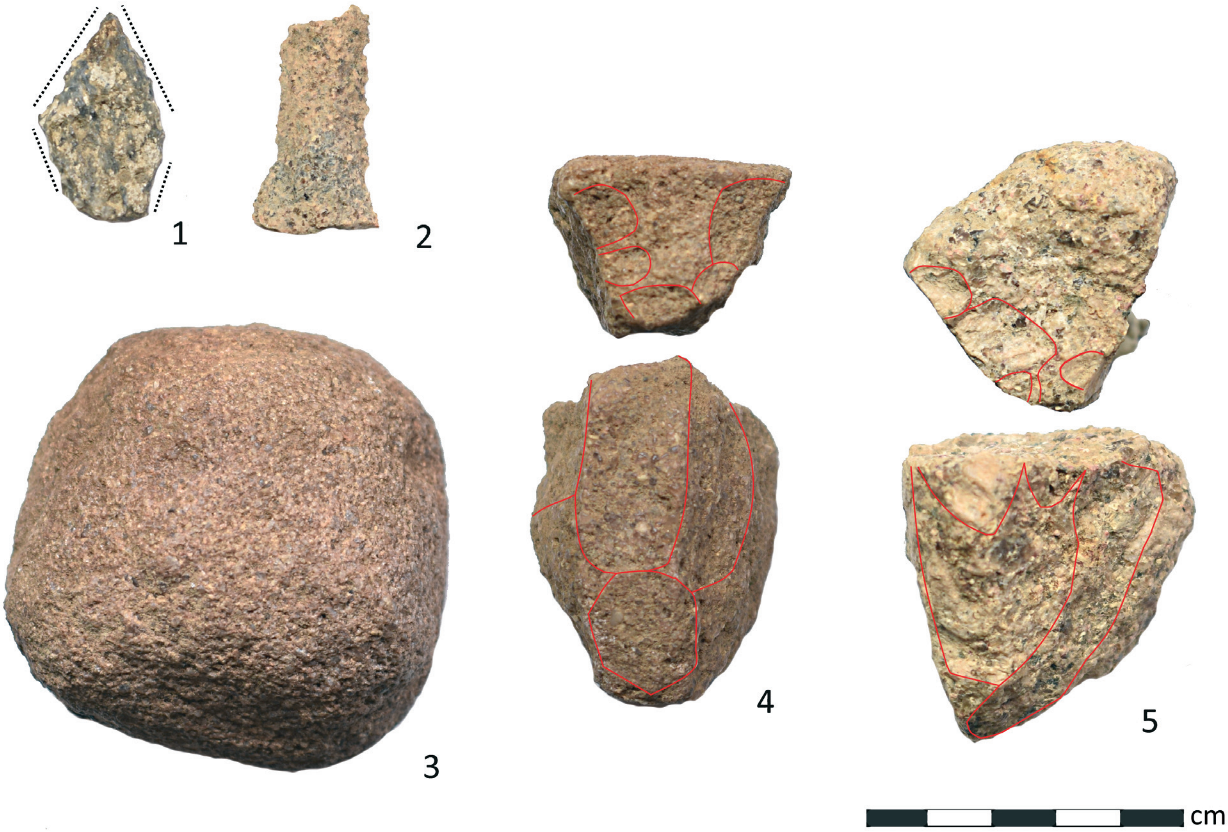

Fig. 4 Non-flint tools found at Aukštumala Stone Age sites: 1) a fragment of an arrowhead (site 3); 2) a blade fragment (site 2); 3) a hammerstone (site 3); 4–5) cores (site 3)

was a point made from a granite flake. Its tip is retouched on both sides in the distal part and contains no retouch on the ventral part. The technology of this point differs from that typical for the classic Swiderian arrowheads made of flint. Unfortunately, the proximal part of this find is missing. On the other hand, there are still very little data on the manufacturing technology of non-flint hunting tools of the Swiderian culture in the eastern Baltic (Šatavičius 2016). Several non-flint items represent knapping techniques were also discovered in Aukštumala. These include a granite hammerstone and some single platform granite cores. The hammerstone is rounded and heavily worn at both ends whereas the cores have unfaceted platforms. Most of the non-flint finds, i.e., the cores, the hammerstone, the arrowhead and the blade fragment, were found at Site 3. The majority of the artefacts found at Sites 1 and 2 were made of flint, items made of other rocks being less common here. Therefore, we presume that Site 3 might have been used for processing of various metamorphic rocks.

The Pūzraviečiai village is one more location in the Lithuanian Maritime region where artefacts of the Final Palaeolithic period were discovered. A classic Swiderian culture tanged point was found accidentally in a cultivated field. According to the typologically based periodization of the classical Swiderian culture (Rimantienė 1996; Zaliznyak 1999), hunting implements of this type could be dated back to the Younger Dryas, whereas willow leaf-shape points characteristic for Aukštumala Stone Age sites are typical of the Preboreal. Obviously, dating of the discovered artefacts is still problematic due to the broad chronological framework of the Swiderian arrowheads. Moreover, the chronology of the human presence should be based on the relative chronology of lithic implements as no reliable chronological data suggesting the age of the Aukštumala Stone Age sites (Rimkus, Girininkas 2021b) have been obtained from the sites so far. Obviously, a further survey is necessary for clarification of this issue.

It should be noted that information describing the character of the subsistence economy of the Aukštumala population during the Final Palaeolithic is absent. There have been no organic sediments or animal bones discovered so far. However, according to archaeological data, resources of various locally available metamorphic rocks were intensively exploited at all the sites investigated, and various rock types, such as granite, sandstone, gaize, mica, quartz and quartzite, were used for tool manufacturing. Flint constituted 51% of the collected lithic material while the rest 49% were metamorphic rocks. Obviously, local lithic raw material along with Cretaceous flint was widely used during the Final Palaeolithic by local human groups.

The latter, however, must be considered an exotic raw material in the region. We assume that non-flint was not used to merely compensate the lack of high-quality raw materials such as flint. As it is demonstrated from the Final Palaeolithic sites situated more inland, Swiderian culture technology relied on non-flint material for the processing of various lithic tools (Šatavičius 2012). Unfortunately, this technological aspect of resources management has been studied insufficiently to date and requires scholarly attention.

Age control of the sediments

The number of the dated samples varied from five (core 51) to two (core 6). The results of ^{14}C dating were calibrated (Fig. 5) and summarised in Table 3. To increase the reliability of the chronological framework, pollen-based stratigraphical comparisons were applied as well. In the majority of the sequences, ^{14}C measurements resulted in concordant ages with respect to the sediment depth confirming a relatively stable

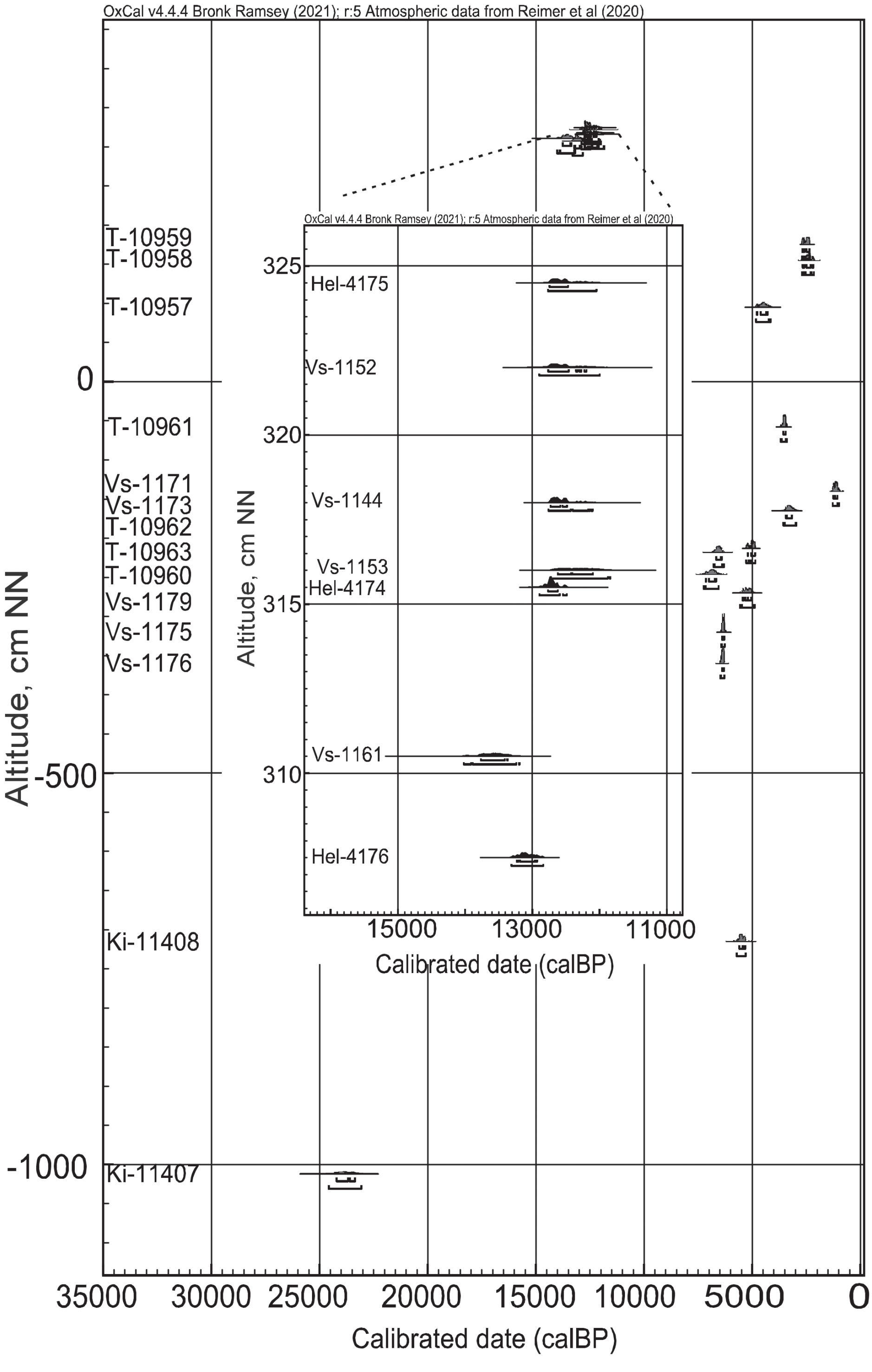

Fig. 5 Calibrated ^{14}C dates *versus* the altitude of the dated sediment samples

Table 3 Results of ^{14}C measurements

Site	Latitude N; Longitude E	Uncalibrated ^{14}C years BP	Age, cal yr BP		Examined interval	Altitude, (cm, NN)	Dated material	Lab. code	References
			1σ (68.3%)	2σ (95.4%)					
1	52°29'34" 21°16'16"	2430 ± 45	2495–2360 (51.6%)	2545–2350 (62.4%)	124–126	176–174	Peat	T-10959	Bitinas *et al.* 2002
		2345 ± 70	2495–2305 (60.5%)	2545–2295 (66.1%)	144–146	156–154	Peat	T-10958	
		4005 ± 105	4620–4350 (57.9%)	4830–4230 (93.5%)	204–206	96–94	Peat	T-10957	
3	55°29'42" 21°17'33"	3295 ± 50	3565–3455 (68.3%)	3640–3440 (89.1%)	127–129	-57 – -59	Peat	T-10961	
		4415 ± 45	5050–4870 (64.8%)	5075–4860 (70.4%)	182–184	-112 – -114	Peat	T-10962	
		5755 ± 100	6670–6440 (66.9%)	6750–6380 (89.2%)	287–289	-217 – -219	Peat	T-10963	
		6010 ± 125	7000–6720 (61.1%)	7170–6555 (94.8%)	315–317	-245 – -247	Peat	T-10960	
6	55°19'05" 21°12'54"	4780 ± 100	5600–5440 (53.0%)	5730–5300 (95.4%)	300–350	-690 – -740	Sand with organic	Ki-11408	This study
		19800 ± 300	24210–23380 (49.3%)	24580–23060 (95.4%)	620–625	-1010 – -1015	Sandy gyttja	Ki-11407	
51	55°17'40" 21°23'22"	1220 ± 55	1180–1065(54.2%)	1285–1050 (89.9%)	230–250	-130 – -150	Gyttja	Vs-1171	Bitinas *et al.* 2002
		3090 ± 110	3410–3160 (64.3%)	3490–2990 (93.0%)	260–270	-160 – -170	Gyttja	Vs-1173	
		4570 ± 90	5200–5050 (33.4%)	5480–4960 (93.6%)	360–380	-260 – -280	Peat	Vs-1179	
		5545 ± 45	6355–6295 (46.1%)	6410–6275 (93.5%)	410–430	-310 – -330	Peat	Vs-1175	
		5590 ± 45	6400–6310 (68.3%)	6450–6290 (94.6%)	450–470	-350 – -370	Peat	Vs-1176	
Ventės Ragas Outcrop	55°21'05" 21°12'05"	10610 ± 110	12730–12580 (48.8%)	12770–12420 (82.2%)	255–267	325–313	Peat	Vs-1144	Bitinas *et al.* 2002
		10640 ± 160	12770–12450 (60.8%)	12900–11990 (95.4%)	256–260	324–320	Sandy peat	Vs-1152	
		10460 ± 150	12410–12090 (40.5%)	12730–11870 (95.0%)	262–266	318–314	Peat	Vs-1153	
		11700 ± 180	13770–13400 (66.6%)	13890–13230 (89.7%)	268–271	312–309	Gyttja	Vs-1161	
		10610 ± 130	12750–12470 (68.3%)	12770–12040 (68.3%)	256–255	325–324	Peat	Hel-4175	This study
		10740 ± 100	12770–12620 (68.3%)	12900–12590 (89.1%)	264–265	316–315	Peat	Hel-4174	
		11190 ± 120	13190–12960 (61.2%)	13320–12830 (68.3%)	270–275	310–305	Gyttja	Hel-4176	

sediment deposition, i.e., minor erosion or contamination of the bed. According to the radiocarbon data, the oldest sediments, sandy gyttja, were deposited at about 24 000 cal yr BP (core 6, -1010 – -1015 cm NN), i.e., even before the beginning of ice retreat from the region (Rinterknecht *et al.* 2006; 2008; Bitinas 2011; Guobytė, Satkūnas 2011). No similar age has been obtained in the area by means of ^{14}C method so far. For this reason, the data must be interpreted with some caution. Both radiometric and biostratigraphic (palynostratigraphy) information suggests the onset of sediment formation in the investigated sequences during the Bølling warming (~ 13 800 cal yr BP). Peat and gyttja with a remarkable input of terrigenous matter were deposited in small lakes or peat bogs while terrigenous beds with remarkable participation of silt and clay particles occurred in larger and deeper basins at the time. According to the radiometric data and pollen records, sedimentation in the analysed cores lasted until the final stages of the Younger Dryas (~11 870 cal yr BP) chronozone. The biostratigraphic data suggest an episodic presence of the Early Holocene sediments in the investigated sequences. However, no ^{14}C dates were obtained to confirm that the age of the strata is similar. Moreover, the number of pollen samples of the Preboreal – Boreal age is very low, making the chronological attribution of the analysed layers rather disputable. The beds of limnic and alluvial origin were deposited in the territory of the present-day delta at that time. At about 7 500–7 000 cal yr BP, formation of extensive peat bogs started in the area, including the Russian part of the NRD (Napreenko-Dorokhova 2015).

Grain-size data

The grain-size information of the master cores (6, 8, 15, 25) expressed in percentages is presented in Fig. 6. The data obtained show that the examined sections are different in specific features of the grain size distribution. In general, sand fractions of various sizes (2–0.05 mm) are of critical importance in the material analysed. However, in some intervals, representation of silt and clay particles (0.05–<0.001 mm) increases suggesting different sedimentation regime. The general lithostratigraphical characteristic and palaeoenvironmental interpretation are as follows:

Unit 1 (-1970 – -1700 cm NN (core 6); -1485 – -950 cm NN (core 7); -880 – -800 cm NN (core 17)

Unit 1 is characterized by the abundance of silt-clay particles, varying between 40–60% and peaking at up to 90% (core 7) in some intervals. Coarse fractions are less visible in the sediments, implying a calm sedimentation environment and rewashing or reworking of the underlying till beds with limited transportation of the coarse material into the basin.

Unit 2 (-1700 – -790 cm NN (core 6); -950 – -845 cm NN (core 7); -1045 – -700 cm NN (core 8); -870 – -825 cm NN (core 8a); -1015 – -410 cm NN (core 15); -800 – -370 cm NN (core 17); -920 – -480 cm NN (core 25); 30–190 cm NN (core 26)

Unit 2 demonstrates a shift towards coarser grain size material, i.e., very fine or fine-grained sand dominate in the beds reaching up to 50–60% in separate intervals. Apart from this, very coarse or coarse-grained sand is present in bigger proportions (up to 50%) in individual samples, suggesting short lasting transportation of unsorted material into the basin (-830 – -800 cm core 15; -920 – -890 cm core 25). Also, silt and clay particles are present, demonstrating lower curves at the level of 30–40%. Obviously, sorting of the material is lower in comparison with that of the previous unit. The decreasing proportion of fine particles was presumably determined by the changing hydrodynamic conditions of the basin or the palaeoenvironmental regime.

Unit 3 (-790 – -500 cm NN (core 6); -700 – -485 cm NN (core 8); -410 – -70 cm NN (core 15); -370 – 100 cm NN (core 17); -480 – -0 cm NN (core 25); 190–260 cm NN (core 26)

Different fractions of sand, including very coarse-grained sand, played the key role in the formation of the sediment beds attributed to Unit 3. The proportion of clay particles is negligible or very small, hardly reaching 5% in separate intervals, while silt percentage is slightly higher, reaching up to 10%. It should be pointed out that the recorded sedimentary changes manifest to a different extent within the investigated cross-section, most probably depending on differences in sedimentary environment of the investigated sites.

Pollen stratigraphy

A total of seven pollen records were used in the study (Table 2). In each pollen diagram, pollen spectra were subdivided into local pollen assemblage zones (LPAZ) applying visual inspection and statistical approaches. As the number of available ^{14}C measurements was limited, for assessing the age of the investigated beds, the authors referred to the regional biostratigraphical information supported by ^{14}C data (Stančikaitė, Kabailienė 1998; Bitinas *et al.* 2002; Kabailienė 2006; Stančikaitė *et al.* 2008):

before 12 900 cal yr BP (-1005 – - 630 cm NN (core 1); -1670 – -1110 cm NN (core 6); -870 – -725 cm NN (core 8a); -880 – -645 cm NN (core 25); -40–160 cm NN (core 26))

Pinus predominates throughout the zone and reaches up to 80% in particular intervals (Fig. 7) while represen-

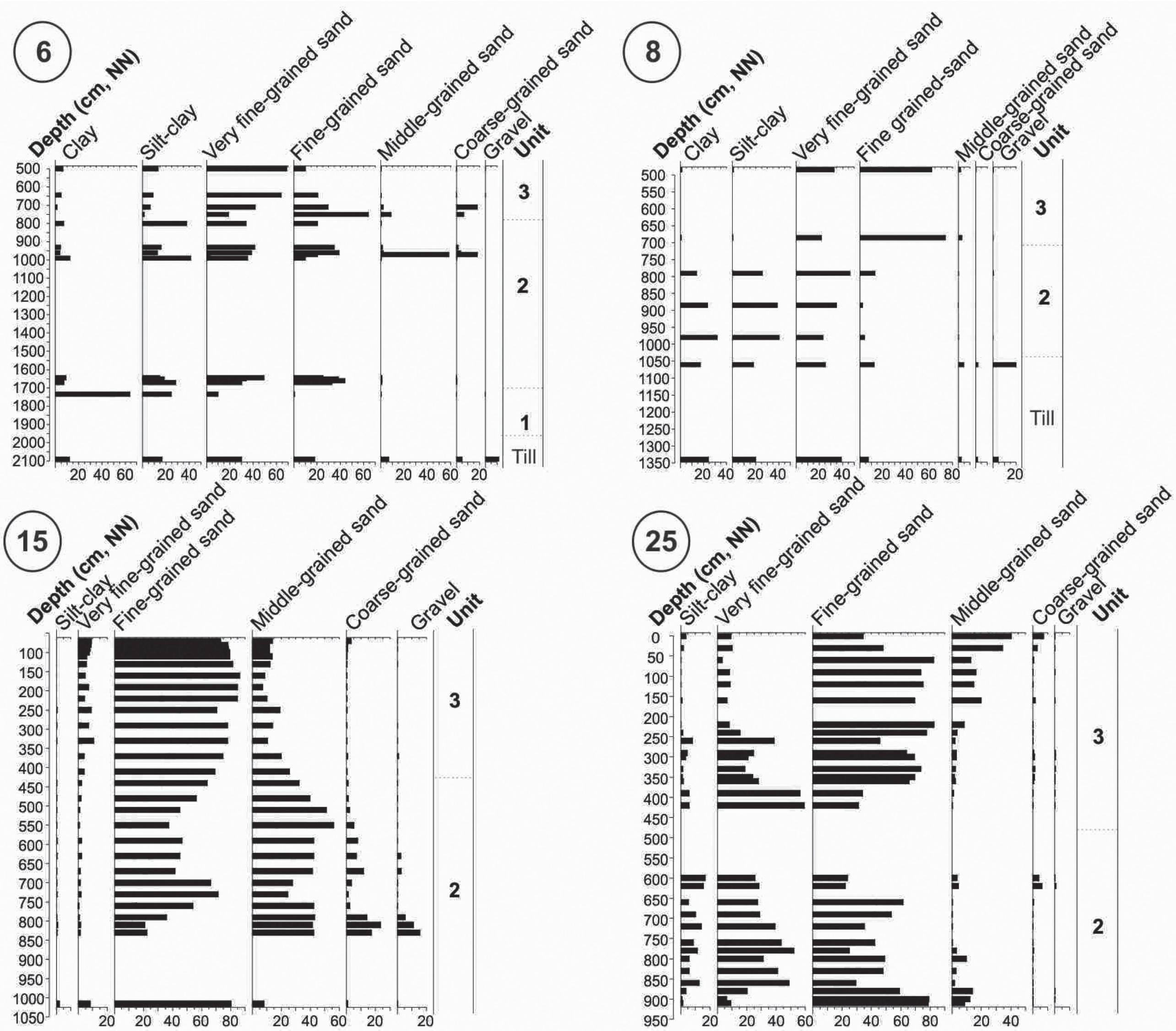

Fig. 6 Variations of grain size fractions (cores 6, 8, 15, 25)

tation of *Betula* is lower, varying from 10 to 40% only. *Alnus* and *Picea* appear in most sequencies reaching up to 13.3% and 12.4% respectively. Pollen grains of the broad-leaved trees (*Tilia, Ulmus, Quercus*) are also recorded in the sediments, but their values are distinctly lower. NAP species are well represented in most of the spectra analysed and Cyperaceae exhibit the highest values reaching up to 50%. Ericaceae, *Artemisia* and Poaceae show continuous curves in the zone as well. Aquatic taxa is represented only by Typhaceae. *Selaginella selaginoides*, *Sphagnum* and Polypodiaceae are found in all investigated samples and their spores exhibit peak values close to the limits of the zone.

12 900–11 600 cal yr BP (-630 – - 475 cm NN (core 1); -1110 – -1005 cm NN (core 6); -725 – -685 cm NN (core 8a); 160–240 cm NN (core 26))

Betula values reach up to 87.6% in particular sections although in the majority of the sequencies, the number of the taxon fluctuates between 20% and 40%. It should be pointed out that the representation of *Betula nana* improves within particular intervals as well. *Picea* record varies from 1% to 5% whereas the representation of *Pinus* deteriorates simultaneously (Fig. 7). The representation of deciduous taxa is low with *Alnus* and *Corylus* being the most common. Single grains of *Tilia, Ulmus, Quercus* pollen were also noted in the spectra. The number of NAP (non-arboreal taxa) increases throughout the zone with the continuously represented Cyperaceae reaching up to 60% in separate diagrams. *Artemisia* and Poaceae are recorded alongside with Chenopodiaceae and *Thalictrum*. The representation and diversity of aquatic species in this zone improves meanwhile Polypodiaceae and *Sphagnum* show lower values. At the same time *Botrychium* and *S. selaginoides* are registered.

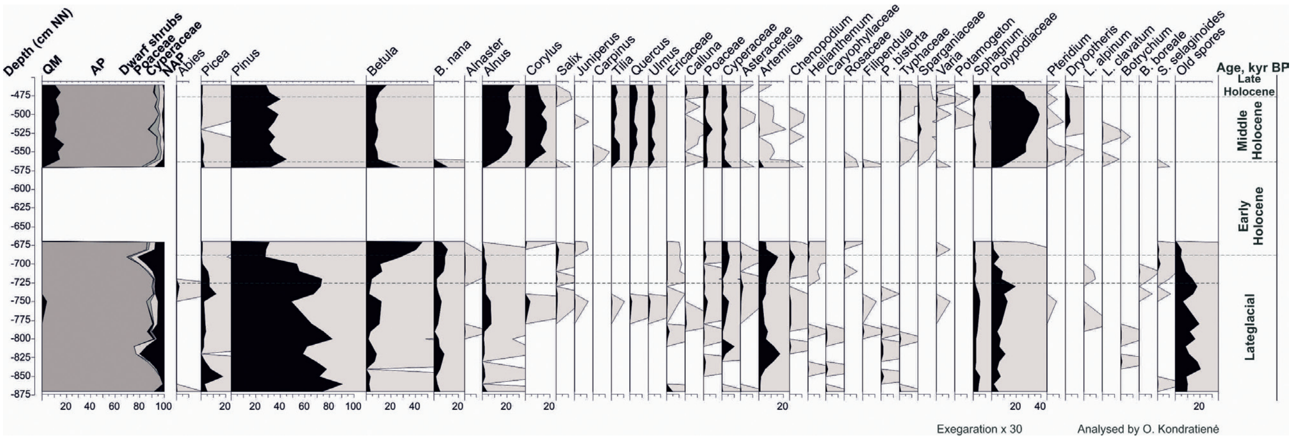

Fig. 7 Percentage pollen diagram of core 8a

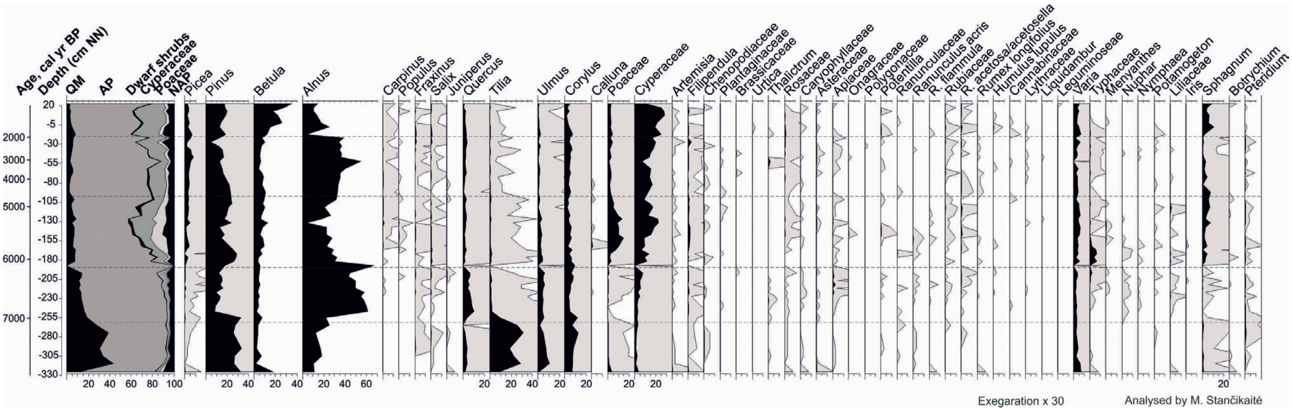

Fig. 8 Percentage pollen diagram of Svencelė core 3

11 600–8 200 cal yr BP (-1005 – -790 cm NN (core 6); -685 – -670 cm NN and -565 cm NN (core 8a); -645 – -545 cm NN (core 25); 180–215 cm NN (core 26))

Pinus (up to 60%) and Betula (up to 40%) are predominat in this zone while the number of *Picea* pollen grains is insignificant. The number of deciduous trees is very low with *Alnus* and *Corylus* playing the major role although the number of the taxa is still low. The diversity of NAP is still high with *Artemisia*, Cyperaceae, Poaceae and Chenopodiaceae predominating, but the representation of these plants deteriorates as they approach the upper limit of the zone. Polypodiaceae and *Sphagnum* still show continuous curves and *S. selaginoides* is also recorded within this zone.

8 200–7 100 cal yr BP (-325 – -251 cm NN (core 3))

This zone is characterised by the dominance of AP pollen over that of NAP. A particularly high value of *Tilia* pollen is observed in core 1 (Fig. 8) while the curves of *Quercus* and *Ulmus* are less prominent. *Pinus* reaches the maximum of about 33.6% while the curve of *Betula* in this zone is rather low. *Corylus* exhibits a continuous curve and scattered pollen grains of *Viburnum* and *Juniperus* occur. Cyperaceae, Rosaceae and Poaceae are represented continuously while *Artemisia*, Chenopodiaceae and *Rumex acetosa/acetosella* occur sporadically. The number of aquatic taxa in the spectra is low and the representation of *Sphagnum* is the best among the spores.

7 100–6 100 cal yr BP (-251 – -192 cm NN (core 3); -565 – -475 cm NN (core 8a))

The number of *QM* taxa shows a dramatic decrease at the beginning of the zone. At the same time, the representation of *Alnus* increases and *Quercus* culminates in the lower part of the zone (10.3 %) while the rest of AP taxa show lower percentages. For example, the number of *Pinus* pollen shows a dramatic decrease at the onset of the zone but at its upper limit, *Pinus* pollen percentage slightly recovers reaching 17.7%. The curves of *Picea* and *Betula* in this zone are also low. Scattered grains of *Juniperus*, *Rhamnus* and *Viburnum* pollen are observed. The amount and diversity of NAP improve in comparison with the previous zone. The number of Cyperaceae as well as those of Apiaceae, *R. acetosa/acetosella, Filipendula*, *Calluna* and etc. increases simultaneously. The number of aquatic taxa also rises throughout the zone with *Nuphar* and Typhaceae being prevalent. The representation of Polypodiaceae spores is especially high in the spectra.

6 100–4 200 cal yr BP (-192 – -82 cm NN (core 3))

The downward curve of *Alnus* reaches a low point in the middle of the zone whereas the number of *Betula* and *Pinus* pollen show a gradual rise. The representation of QM declines even more throughout the zone. At the same time, *Carpinus* forms a continuous curve with the maximum representation of 1.6%. *Calluna* shows a distinct increase and Poaceae (17%) along with Cyperaceae (23%) have the highest representation among NAP. NAP culminates reaching 41.7% at about 5 000 cal yr BP. *Artemisia* is represented continuously and *R. acetosa/acetosella* has a maximum of 1.1%. Single pollen grains of Chenopodiaceae, Plantaginaceae, *Ranunculus flammula* were also noted. Typhaceae culminates at the beginning of the zone rising up to 6.5%. The increase in *Sphagnum* curve is clear and it reaches the maximum value of 7.5% in the vicinity of the upper boundary of the zone.

4 200–2 500 cal yr BP (-55 – 0 cm NN (core 1); -82 – -25 cm NN (core 3); -430 – -215 cm NN (core 25))

This zone is characterised by the high value of *Alnus* with the maximum of 40% (Figs 7 and 8) and the culmination of *Picea* at 40%. The representation of *Pinus* varies from 20% to 40% and drops approaching the upper limit of the zone. *Betula* shows a steady curve varying around 20%. The number of QM pollen as well as that of *Corylus* is rather low throughout the zone. Scattered pollen grains of *Fagus*, *Populus* and *Sorbus* may be also observed while *Carpinus* demonstrates a continuous record. The diversity of NAP is high in this zone, but most of the taxa are represented only by individual pollen grains except for Cyperaceae, the value of which rises reaching 18.9%. Continuous curves of *Filipendula*, Rosaceae, Caryophyllaceae are accompanied by scattered grains of *Artemisia*, *Rumex longifolius* and Chenopodiaceae. Typhaceae plays a leading role among aquatics while *Pteridium* predominates among spores.

2 500 cal yr BP – present (0–135 cm NN (core 1); -25 – 23 cm NN (core 3); -790 – -630 cm NN (core 6); -475 – -460 cm NN (core 8a); -215 – 10 cm NN (core 25); 240–215 cm NN (core 26))

This zone is characterised by the increasing representation of AP pollen, including the culmination of *Betula* and the high number of *Pinus* and *Picea* pollen while the representation of the rest of the tree taxa is steadily low or even negligible. Meanwhile, the over-representation of Cyperaceae and *Calluna* is noted in several cores. In general, the NAP curve increases at the beginning of the zone whereas *R.acetosa/acetosella* and Caryophyllaceae have continuous curves. The *Artemisia* curve rises in the middle part of the pollen zone where Chenopodiaceae and *Urtica* occur. Pollen grains of Cerealia accompanied by ruderals have also been recorded. The number and variety of aquatic taxa are miniscule and *Sphagnum* predominates among spores.

Diatom data

Only single diatom valves were found in the lower part of core 6 (-970 − -1970 cm NN) and very few valves were identified in core 8a (−455 − -870 cm NN). Meanwhile, almost a continuous diatom record was obtained by M. Kabailienė (1999), who was analysing core 25 (Fig. 9).

before 11 600 cal yr BP (-1010 – -470 cm NN (core 25))

Freshwater benthic and fresh-brackish diatoms prevail (95–100%) in the spectra and in some sam-

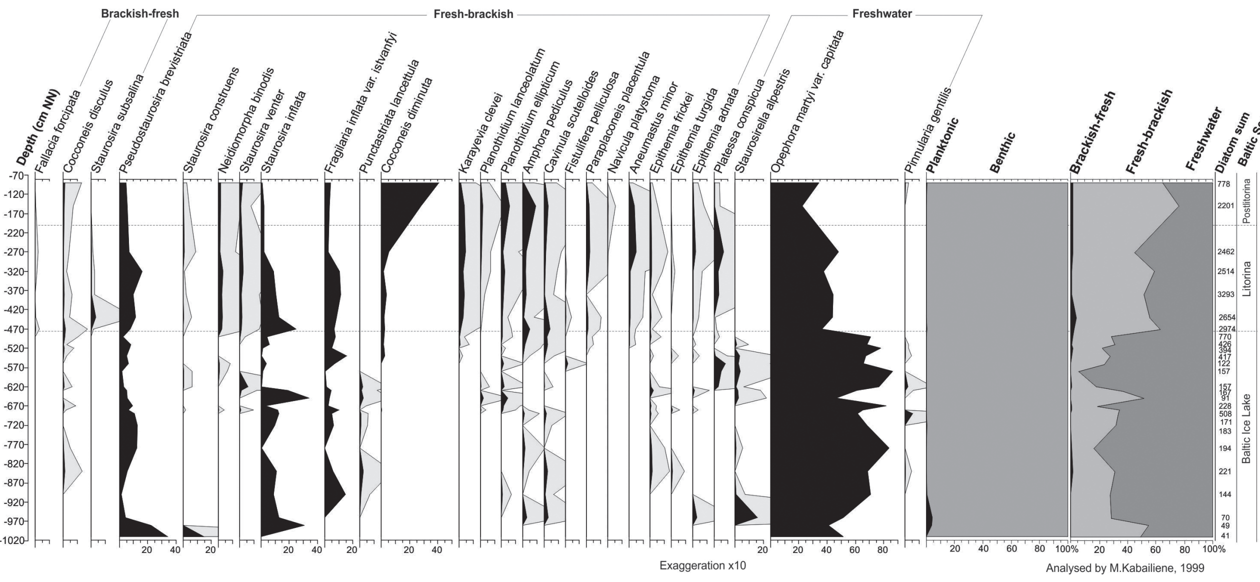

Fig. 9 Percentage diatom diagram of core 25

ples, *Opephora martyi* var. *capitata* Héribaud constitutes up to 86%. Meanwhile, representatives of the fresh-brackish benthic group, i.e., *Pseudostaurosira brevistriata* (Grunow) D.M. Williams & Round, *Staurosira inflata* (Heiden) A. Rusanov, Ács, E. Morales & Ector, *Fragilaria inflata* var. *istvanffyi* (Pantoscek) Hustedt, *Amphora pediculus* (Kützing) Grunow, *Cavinula scutelloides* (W. Smith) Lange-Bertalot as well as freshwater diatoms *Staurosirella alpestris* (Krasske) Le Cohu and *Platessa conspicua* (Ant. Mayer) Lange-Bertalot are less numerous.

11 600 – 8 200 cal yr BP (-790 − -970 cm NN (core 6))

In core 6, at the depth of -790 − -970 cm NN, the diatom number varies from 165 to 580 diatom valves per sample. Freshwater benthic diatoms prevail and account for up to 90%. The most common species *Staurosirella martyi* (Héribaud) E.A. Morales & K.M. Manoylov constitutes up to 80% in some samples. Less numerous freshwater benthic species are *Navicula radiosa* Kützing, *Amphora ovalis* (Kützing) Kützing, *Amphora pediculus (*Kützing) Grunow, *Epithemia adnata* (Kützing) Brébisson, *Epithemia gibba* (Ehrenberg) Kützing, *Cymbella cymbiformis* C.Agardh, *Encyonema elginense* (Krammer) D.G.Mann, *Gomphonema angustatum* (Kützing)Rabenhorst and *Mastogloia lacustis* (Grunow) Grunow. Planktonic freshwater *Aulacoseira granulata* (Ehrenberg) Simonsen and brackish *Actinocyclus normanii* (W. Gregory ex Greville) Hustedt are scarce and make up only a few percent of the total amount.

4200 – 2 500 cal yr BP (-470 – -200 cm NN (core 25))

The spectra is totally dominated by benthic diatoms (99-100%). Meantime, the content (25–60%) of fresh-brackish diatoms (*Pseudostaurosira brevistriata*, *Staurosira inflata*, *Fragilaria inflata* var. *istvanffyi*, *Karayevia clevei* (Grunow) Bukhtiyarova, *Amphora pediculus* has been noted to rise. The representation of freshwater taxa slightly decreases but the freshwater *Opephora martyi* var. *capitata* is still dominant. The content of brackish-fresh diatoms is low constituting only up to 3%. The dominant taxa are *Fallacia forcipata* (Greville) Stickle & D.G.Mann, *Cocconeis disculus* (Schumann) Cleve and *Staurosira subsalina* (Hustedt) Lange-Bertalot.

2 500 cal yr BP – present (-690 – -790 cm NN (core 6); -455 – -470 cm NN (core 8a); 200 – -90 cm NN (core 25))

The diatom number decreases and varies from 10 to 309 diatom valves per sample in the topmost part -690 – -790 cm NN of core 6. The percentage of planktonic species increases up to 60–75%. The most common planktonic species are freshwater *Aulacoseira islandica* (O. Müller) Simonsen, *Aulacoseira granulata*, *Stephanodiscus rotula* (Kützing) Hendey and *Stephanodiscus hantzschii* Grunow. Brackish diatoms make up about 45% of the total content and are mainly represented by brackish *Actinocyslus normanii*. The variety of benthic species decreases and is mainly dominated by freshwater *Staurosirella martyi*, *Cavinula scutelloides* (W. Smith) Lange-Bertalot, *Amphora ovalis* and *Cocconeis placentula* Ehrenberg. The topmost (-455 – -470 cm NN) two sandy samples (core 8a) yield very low diatom data (74–126 diatom valves). The most common species are freshwater planktonic *Aulacoseira granulata*, *Stephanodiscus rotula* and benthic *Staurosirella martyi*, *Cavinula scutelloides*. Planktonic brackish *Actinocyclus normani* accounts for about 15%. In core 25, sediments of this time period are characterized by the prevalence (99%) of benthic fresh-brackish and freshwater diatoms. At the same time the representation of freshwater diatoms decreases as well. The fresh-brackish taxa *Cocconeis diminuta* Pantocsek, *Planothidium ellipticum* (Cleve) M.B. Edlund, *Amphora pediculus*, *Pseudostaurosira brevistriata*, *Cavinula scutelloides* and *Aneumastus minor* Lange-Bertalot are prevalent.

Statistical data processing

Two PCA axes are shown in the ordination diagrams (Fig. 10A, B) that allow interpretation of the results of the statistical evaluation of the pollen and grain-size data. In the case of pollen records (Fig. 10A), the first and the second axes represent more than 44% of the total variation (PCA1–30.16%, PCA2–14.31%). At the same time, 20 taxa with the strongest positive (more than 0.4) and the strongest negative (less than -0.3) correlation were plotted on the ordination diagram. In the case of the grain-size analysis (Fig. 10B), the first and second axes represent more than 88% of the total variation (PCA1 –66.91%, PCA2–21.64%). Also, 8 classes of grain-size were plotted on the ordination diagram. The correlations between grain-size classes and axes are different and vary from strong positive (in the case of grain-size ø < 0.05 mm the correlation with the first axis is r = 0.97) to strong negative (in the case of grain-size ø 0.25–0.1 mm the correlation with the first axis is r = -0.87).

Pollen records. The highest of PC1 axis values (Fig. 10A) are characteristic of the taxa of poor soils and unstable habitats. It seems that this factor, i.e., the habitat type is of critical in the formation for the formation of the analysed pollen spectra as both AP (*Pinus, Betula*) and NAP (*Artemisia*, Chenopodiaceae, *S. selaginoides*) are rather common at similar sites. On the contrary, the taxa that are sensitive to soil fertility, including broad-leaved and thermophilous species, occur on the negative side of this axis. The PC2 axis, reflects the importance of the climatic factor for the distribution of the taxa. According to the data available, this factor was less important in the formation of the pollen spectra. Here, the taxa typical of moderate or severe climatic regime (*B. nana*, *Helianthemum*, Asteraceae) show higher PC2 values. In order to improve the reliability of the pollen zonation, clustering of the samples was referred to. It should be noted that in some cases, cores 3 and 25 for example, the clustering of the spectra was miniscule suggesting a rather stable vegetation pattern and slow changes in the vegetation composition despite the broad chronological range of the sediments. This fact also confirms the predominance of the habitation factor over the climatic one.

Grain-size data. The results of the PAC analysis (Fig. 10B) point to the high importance of silt-clay and very fine-grained sand particles (ø < 0.05, ø 0.1–0.05 mm) in the sediments. As predominance of similar particles is typical of the well-sorted material deposited in deep sedimentary basins, mentioned factor suggests the deposition in large size glaciolimnic/proglacial lakes. The basin type or the sedimentation regime can be distinguished as a critical factor in formation of sediment sequencies. On the other hand, PCA2 reveals the importance of external factors to the composition of sediment beds. Very coarse-grained and coarse-grained sand, gravel and pebble show higher PC2 values suggesting the impact of water streams, erosion and similar factors. It seems that the second axis reflects the transformation of the glaciolimnic or limnic environment into the fluvial one.

Geological-geomorphological structure of the territory

Thickness of the Quaternary strata, underlined by the Upper and Lower Cretaceous formations, varies from 20 to 40 m in the NRD territory and reaches up to 100 m within palaeoincisions extending into pre-Quaternary formations. Morainic till deposits predominate in the sequences. Meanwhile, formations of the Upper Nemunas (Late Weichselian) Glaciation, Lateglacial and Holocene age, consisting of glacial, glaciolacustrine, glaciofluvial, limnic, biogenic, alluvial and deluvial sediments predominate in the surface (Fig. 11).

The ice-marginal ridge, which was formed during the Last (Weichselian) Glaciation and is stretching from the N–NE to SE, is of particular importance for the surface structure of the investigated territory. (Fig. 11). Covered by a thin layer of glaciolacustrine deposits, it reaches from 5 m NN in SW up to 15 m NN in NE. East of the ridge, in the northern part of the investigated territory, basic moraine (till) covered by aquaglacial deposits predominates (+10 – +12 m NN) whereas glaciofluvial deposits predominate in the NE part of the territory (+20 m NN). Meanwhile, the territories situated east of the ridge are covered by deposits of the glaciolacustrine origin (+12 – +17 m NN) and fragments of these formations are stretching along the ridge (+3 m NN).

Analysing the postglacial relief, deposits of the proglacial lakes are of particular importance. Identified in the eastern part of the investigated territory and noticeable along the marginal ridge, these ter-

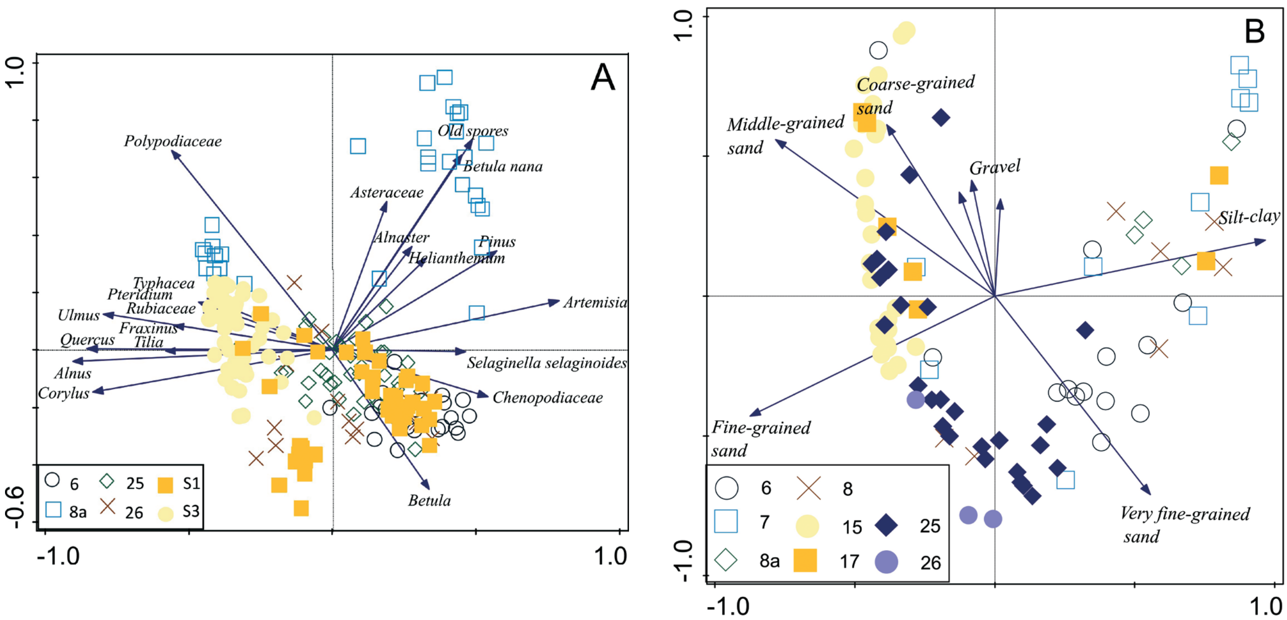

Fig. 10 Principal components analysis (PCA) of pollen data (A) and results of grain-size measurements (B) and the sequencies investigated (6, 7, 8, 8a, 15, 17, 25, 26, S1, S3)

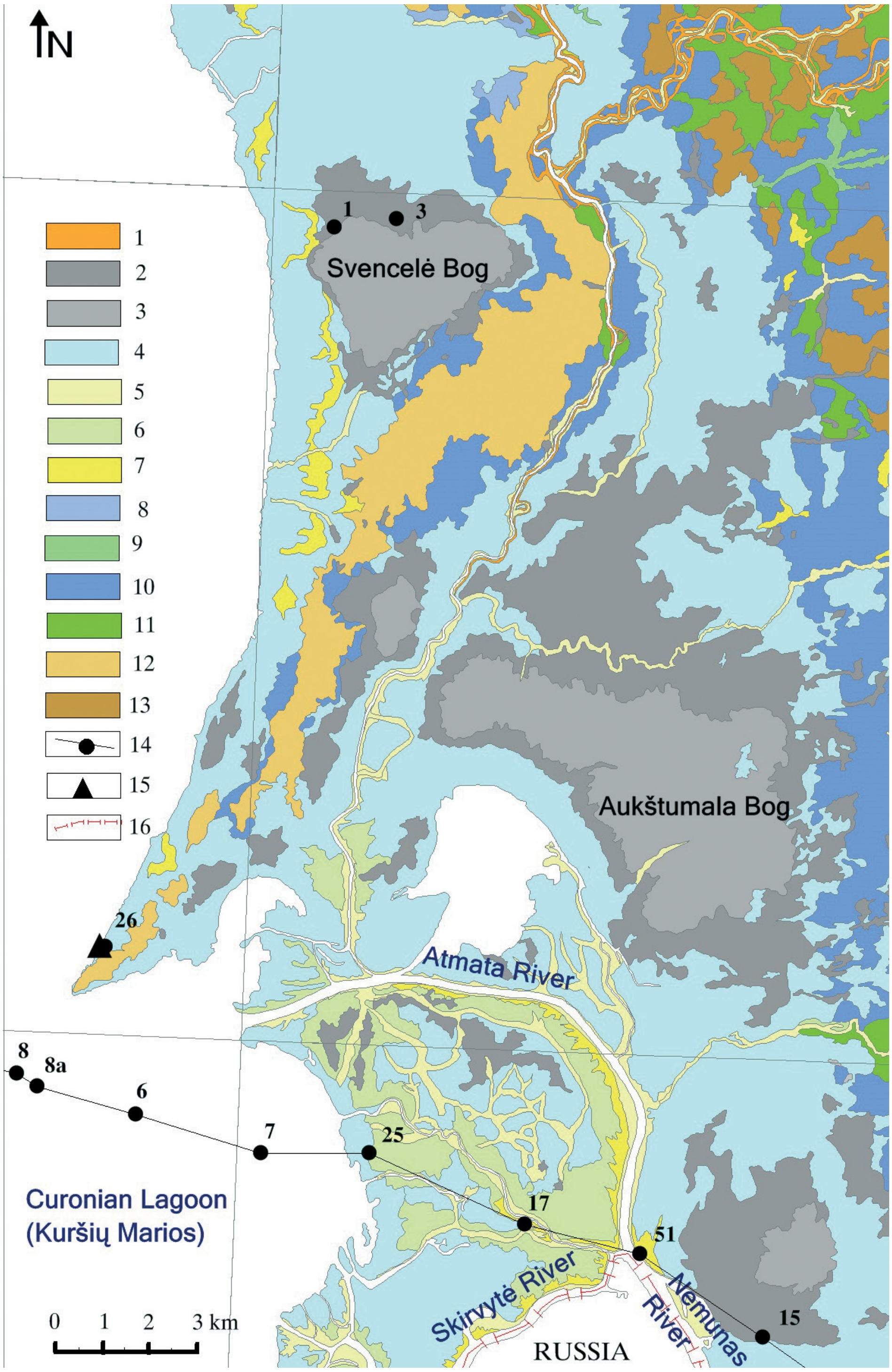

Fig. 11 Geological-geomorphological map of the study area

Age and genesis of sediments:

Holocene: 1 – deluvial (various – clayey sand with gravel); biogenic: 2 – low-moor bog peat; 3 – high-moor bog peat; 4 – lacustrine (various sand, fine-grained sand, very fine-grained sand, silty sand, clayey sand, silt, sandy silt, clayey-sandy silt, clay, silty clay, sandy clay, sand with peat, sand with gyttja, gyttja); 6 – flood plain alluvium (various sand, fine-grained sand, very-grained fine sand, sand with peat); 7 – deltaic alluvium (fine-grained sand, very fine-grained sand, silty sand, sand with gyttja).

Lateglacial: 8 – Baltic Ice Lake (fine-grained sand, sandy silt, silty clay, silty-sandy clay); 9 – alluvium (very fine-grained sand, peaty sand).

Upper Nemunas Formation: 10 – glaciolacustrine (fine-grained sand, very fine-grained sand, silty sand, clayey sand, silty-clayey sand, silt, sandy silt, clayey silt, clay, silty clay, sandy clay, sandy-silty clay); 11 – glaciofluvial (various sand, fine-grained sand, very fine-grained sand, clayey sand, sand with gravel). Glacial (till): 12 – marginal, 13 – basal.

Other signs: 14 – core, line of geological cross-section; 15 – Ventės Ragas Outcrop; 16 – State border. Compiled (2000) and modified (2021) by A. Damušytė ritories mark the extension of the above-mentioned basins. Obviously, the altitude of these basins was rather high as glaciolacustrine sediments are lying at about +16 – +20 m NN. Meanwhile, the deposits of the Lateglacial age attributable to the Baltic Ice Lake (BIL) are present in the northern part of the territory where a small fragment of the glaciolacustrine terrace (+5 m NN) has been discovered. Deposits of the Holocene age, consisting of biogenic and limnic beds, are widely distributed all over the territory where large low water estuaries or freshwater lagoons have existed. Also, forms of aeolian origin are situated in the western part of the territory and along the Nemunas, Atmata and Skirvytė Rivers (+2 – +5 m NN). Alluvial deposits are widely distributed along valleys of numerous rivers and deltaic sediments are common in the territory between the Atmata and Skirvytė Rivers. Extended raised bogs, including the Aukštumala and the Svencelė, are common in the territory reaching up to +6 m NN.

Lithostratigraphic structure of the strata

The basic description of sediment lithology suggests the predominance of mineral matter in the sequencies investigated (Fig. 12). In some intervals of the particular sequences, i.e., 8, 25, 51, 15, 1, an increasing value of limnic or biogenic constituent was noted while core 3 was found to predominantly consist of organic matter.

Analysis of the lithological composition, grain-size distribution of the sediments as well as biostratigraphical and chronostratigraphical data was followed by the stratigraphical subdivision of the beds, which revealed the existence of three distinct units (Fig. 12). Three intervals in the development of the investigated sediments overlying the till deposits of the Middle Pleistocene (gIIžm and gdIImd) or the Late Pleistocene (gIIInm3) age were distinguished. The lowermost part of the deposits consists of terrigenous particles, which are quite well sorted, and clay or silt particles, which are more or less indiscriminately mixed with material of sand grade and very fine-grained sand predominantly. The bedding of these layers is plane. The general character of these deposits thus points to their glaciolacustrine origin, i.e., deposition in a large water body at a certain distance from the edge of the ice-sheet. Based on the data obtained, these layers, indicated as Unit 1 in Table 1, were described as having originated from proglacial basins that existed alongside the Scandinavian Ice Sheet during the initial stages of the ice retreat.

The further phase of sediment formation points to the deposition of coarse terrigenous material, including coarse-grained sand or gravel (Unit 2, Table 1). The stratification of the deposits is either blurred or absent and the increased presence of organic matter in the sediments was recorded. It should be pointed out that presence of non-terrigenous material is rather episodic displaying the horizontally bedded layers of peat or peat enriched terrigenous sediments The described character of the sediment formation is consistent with formation of the beds in a lacustrine setting, with initial deposition of fine-middle grained sand and silts in a low energy environment along with deposition of the coarse material, including gravel in a prograding high energy delta setting. The latter is especially evident in the eastern part of the area where an inflow of unsorted material is evident. Age determination suggests the formation of the above-described sediments during the Lateglacial-Early Holocene, pointing to the deposition in the BIL.

The upper-most interval of the three-part sediment structure (Unit 3, Table 1) is characterised by the predominance of sand grade particles. The recorded different admixture of silt and gravel or pebble most probably points to a different sedimentation environment. The unsorted sandy deposits with the admixture of coarse particles or silt most likely have been deposited in separate basins. Thin interlayers of organic matter-enriched strata as well as a layers enriched with calcium carbon. The pronounced layers of biogenic deposits were also recorded. Both biostratigraphical and chronostratigraphical records suggest the deposition of sediments during various periods of the Holocene.

DISCUSSION

Being situated in the area repeatedly influenced by advances of the Quaternary glaciations, the territory of the present Baltic Sea basin was covered by a massive amount of ice during the global Last Glacial Maximum (LGM, 26.5-20 kyr BP; Clark *et al.* 2009). Since then, the area of the basin and surrounding territories, including the present territory of the NRD, has undergone numerous transformations in response to the changing climatic regime, isostatic uplift, water discharges and etc.

The deglaciation of the Baltic Basin started at about 16.5 cal kyr BP and took about 4 000 years until it reached the Younger Dryas position (Stroeven *et al.* 2016). When analysing the earliest intervals of the ice retreat, the ice-marginal and subglacial landforms are considered as the key factors. Therefore, the Pajūris ridge, which is represented by a subdued, low, slightly east sloping formation (Guobytė, Satkūnas 2011) stretching along the coast of the Baltic Sea and the Curonian Lagoon, is of particular importance (Fig. 1). Results of ^{10}Be dating show that ice sheet retreated from this area at about 13.3 ± 0.7 ka (Rinterknecht *et al.* 2006, 2008). Retreat of the ice sheet was accompanied by the emergence of numerous progla-

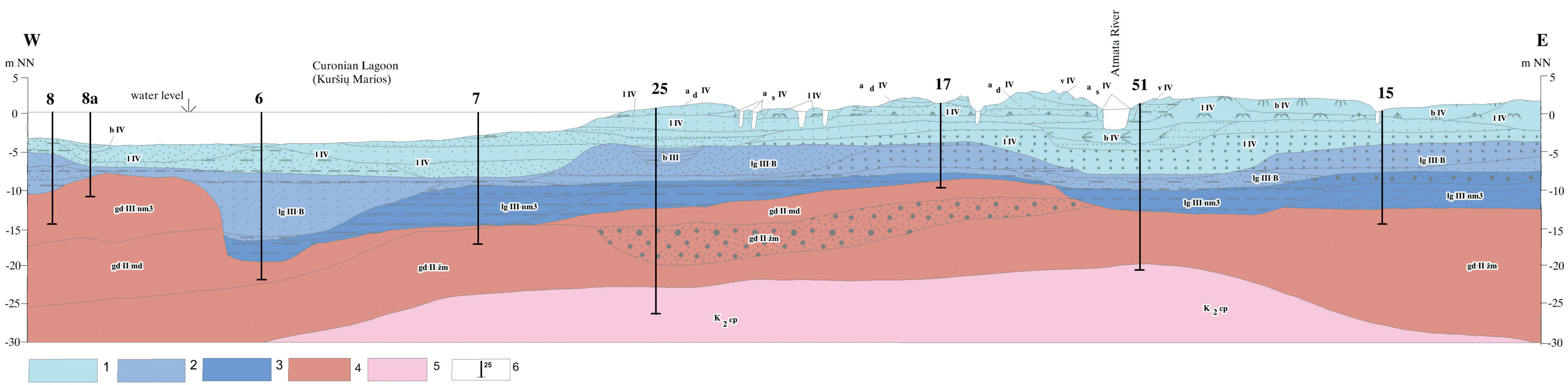

Fig. 12 Geological cross-section. Compiled by A. Bitinas (2000), modified by A. Damušytė (2021)

Age and genesis of sediments:

1 – **Holocene** (unit U3): b IV– biogenic, low-moor (peat); l IV – limnic (various sand, fine-grained sand, very fine-grained sand, silty sand, silt); a_s IV – flood plain alluvium (very fine-grained sand); a_d IV – deltaic alluvium (fine-grained sand); v IV – aeolian (fine-grained sand).

2 – **Lateglacial** (unit U2): b III – biogenic, low-moor (peat); lg III B – Baltic Ice Lake (middle-grained sand, fine-grained sand, silt, sandy silt, clayey-sandy silt).

3 – **Upper Nemunas Formation** (unit – U1): lg III nm_3 – glaciolacustrine (sand with gravel, fine-grained sand, silt, sandy silt, clayey silt, clay, silty clay).

4 – **Glacial sediments of different age** (deformational till: morainic sandy and clayey loam, sand with gravel): gd III nm3 – Upper Pleistocene, Upper Nemunas Formation; gd II md – Middle Pleistocene, Medininkai Formation; gd II žm – Middle Pleistocene, Žemaitija Formation.

5 – **pre-Quaternary sediments:** K_2cp – Upper Cretaceous.

6 – core and its number

cial lake basins, which were impounded between an ice body and a higher terrain, in different parts of the Scandinavian Glacial (Lundqvist 1972; Stroeven *et al.* 2016; Patton *et al.* 2017), including the coastal area of Lithuania (Bitinas *et al.* 2002; Damušytė 2011). Shorelines, both erosional or depositional, are of particular importance in reconstructing the extent and the retreat stages of such basins. In the eastern part of the present-day NRD territory, the highest terraces of proglacial basins are found at the elevation of +40 m NN (Bitinas *et al.* 2002). A few terraces of the same origin being visible at lower altitudes, i.e., +16 – +20 m NN and +6 – +8 m NN, have been identified here (Fig. 11) as well (Damušytė 2011). Sediment deposition took place in deep calm basins where well-sorted terrigenous particles predominated *sensu* PCA record (Fig. 10B). Layers of sediments deposited in proglacial lakes were discovered in the bottom part of the sedimentary sequencies analysed, at the altitude of about -8.10 m NN (lithological unit 1, Fig. 12). Fine and very fine-grained sand with high proportion of silt and clay particles was deposited on the surface inherited from the Middle Pleistocene, consisting of till, glaciolacustrine and glaciofluvial deposits. The chronological attribution of the noted sediments, reflecting the initial intervals of the ice recession, is very complicated due to the limited availability of material suitable for dating, uncertainty of the dating methods and etc. No biostratigraphical or chronostratigraphical evidence confirming the chronological attribution of the aforementioned sediments is available from the NRD area so far. Regional records suggest the development of open-ground vegetation with *B. nana* and *Betula* sect. *Albae* on the unstable low fertility soil of the coastal region pre-14 300 cal (Stančikaitė *et al.* 2008). Later, gradual formation of the forest cover with increasing participation of pine and birch is supposed to have taken place all over the region throughout the Allerød.

The further development of the investigated area was directly related with the history of the BIL, a freshwater body which existed until about 11.7 cal kyr BP (Björck 1995; Andrén *et al.* 2011). The spatial and temporal distribution of this water body in the coastal region of Lithuania has been discussed by various authors in different contexts (Gudelis 1979; Kabailienė 1999; Bitinas *et al.* 2000, 2001, 2002; Gelumbauskaitė, Šečkus 2005; Gelumbauskaitė 2002, 2009; Kabailienė *et al.* 2009). However, the maximum extent of this basin in the NRD is still debatable. The coastal formations of the BIL stretching at about +12 – +16 m NN were noted in the northern part of the Lithuanian coast (Gudelis 1979) and further north (Rosentau *et al.* 2009). However, no clear evidences of similar geomorphological features have been discovered in the NRD so far. Earlier, fragments of the terraces discovered in the northern part of the NRD area were attributed to the BIL based on the results of OSL dating (Bitinas *et al.* 2002). However, these dates show great uncertainties in practices and, thus, should be taken with precaution as they are "insufficient for a detailed shore displacement reconstruction" (Linden *et al.* 2006). Thus, based on the data available, we think that the coastal BIL formations are absent or have not survived because they were eventually destroyed in the NRD. This conclusion is also supported by regional reconstructions, suggesting variations of the water table at about 0 m NN altitude in the southern part of the Lithuanian coast at the time in question (Vassiljev, Saarse 2013). At the same time, pollen, mollusc and diatom assemblages indicate intensive sedimentation processes having taken place in the area (Figs 7–9). The lithological composition and the altitudes of the analysed beds differ considerably, which makes it possible to infer that the sedimentation pattern was rather complicated and that even isolated basins might have existed there (Fig. 12). In favour of this interpretation is the presence of the organically enriched gyttja of the early Allerød age (13.8–13.2 cal kyr BP) discovered in the Ventės Ragas Outcrop (Rinterknecht *et al.* 2008; Stančikaitė *et al.* 2008) suggesting the existence of a small, shallow oligotrophic basin as diatoms, e.g., *Staurosirella martyi*, *Cavinula scutelloides*, *Fragilaria inflata* et var. *istvanfyi*, which have been discovered here (Stančikaitė, Kabailienė 1998), are typical for such habitats. To confirm the age of these sediments, new isotopic measurements of organic remains, outcropping on the proximal slope of the Pajūris ridge (+305 – +312 cm NN) were carried out (Table 3). The basin must have been surrounded by an open *Betula-Pinus* wood as forestation of the terrain was noted on the regional scale (Stančikaitė *et al.* 2008). Nevertheless, presence of *S. selaginoides, B. nana, Juniperus* and other light-demanding or pioneer taxa (Fig. 7) implies flourishing of open vegetation in the area during the final stage of the BIL existence, which generally coincides with the end of the Younger Dryas cooling. However, the occurrence of macro-remains of *Alnus incana* (L.) Moench, *Picea* sp. and *Alnus glutinosa* (L.) Gaertn. in regional records (Latałowa, Borówka 2006; Stančikaitė *et al.* 2008) points to the predominance of a milder climatic regime, which, possibly, triggered formation of sparse forest throughout the coastal region (Saarse *et al.* 2009). As the territory of the Northern Europe is supposed to have been inhabited since about 14 700 cal yr BP (Wygal, Heidenreich 2014), the presence of human groups in Aukštumala during the Bølling-Allerød is highly probable. The favourable climatic situation and the changeable landscape provided rich coastal resources that may have encouraged migration of human groups to the territory. Moreover, a great number of herbivores lived in the region at that time (Ukkonen *et al.* 2006, 2011; Sommer *et al.* 2011) reaching the highest density at about 13 400–13 000 cal yr BP according to reconstructions from dung fungal spores (Stivrins *et al.* 2019).

At the same time, sandy formations typical of deeper basins (lithological unit 2, Fig. 12), were deposited in the territory of the present-day Curonian Lagoon (core 6). Moreover, flourishing of mollusc species, i.e., *Pisidium supinum* infer the existence of water streams and flows in the basin. Should be pointed out that the lithological transgression from gyttja to peat, which occurred in the Ventės Ragas outcrop (12.8–12.7 cal kyr BP), is of particular importance analysing development of the palaeogeographical situation. In general, it coincides with the first drainage of the BIL, dated back to 12.87 ka BP (Muschitiello *et al.* 2016). Approximately at the same time, strait systems were closed and separate basins were isolated from the main water body in the northern part of the eastern Baltic (Rosentau *et al.* 2009). Shortly after, at about 12.3 cal kyr BP, the deposition of peat layers started at Slupsk Bank in Poland at -25 m NN (Uścinowicz 2006). Recent investigations conducted in the Lithuanian sector of the Baltic Sea prove formation of peat deposits at -29 m NN at about 12.1–10.5 cal kyr BP (Lab. code Vs-2634; 9860 ± 250^{14}C years BP) (Žulkus *et al.* 2015; Girininkas, Žulkus 2017) suggesting regression in this part of the basin even before the final drainage of the BIL.

Based on the data described above, the territory of the NRD might be described as the broken landscape of low water estuaries or freshwater lagoons directly connected with the BIL during the later stages of the Lateglacial. These territories have also been affected by water discharge from the inland, which is evidenced by shallow buried valleys that were discovered therein (Bitinas *et al.* 2002). The suggested palaeogeographical interpretation is in accordance with the regional records as GIS-based palaeogeographical reconstructions (Vassiljev *et al.* 2011; Vassiljev, Saarse 2013) indicate minimum water level elevations in this part of the BIL, i.e., the water table fluctuated around the zero point before 13 300 cal yr BP, and significantly lowered already before the final drainage of the BIL.

Following the final regression of the BIL, which took place shortly before 11.7 cal kyr BP, the next stage in history of the Baltic Sea started with the transgression of the saline Atlantic water to the basin (Björck 1995). Formation of the Yoldia Sea, which existed for about 800 years (Björck 1995), was coincident with the base/start of the Holocene Series/Epoch (Walker *et al.* 2009). However, the data available indicate that the history of the Yoldia Sea was highly variable in different parts of the circum-Baltic (Andren *et al.* 2002; 2011; Rosentau *et al.* 2009, 2021). Due to the rapid recession of the Scandinavian ice sheet, a huge outflow of meltwater from the northern regions replenished the basin while vast areas in the southern part shallowed up (Björck 1995; Andrén *et al.* 2000; Uścinowicz 2006; Vassiljev, Saarse 2009; Miotk-Szpiganowicz *et al.* 2010; Miotk-Szpiganowicz 2016; Andrén *et al.* 2011). The continuous transgression of the saline water to the basin lasted for about 300 years (Andrén *et al.* 2011).

A rather complicated situation occurred while the palaeogeographical and palaeoecological situation along the present-day Lithuanian coast was being analysed. According to the earlier shore displacement curves, the BIL regression resulted in a decrease of the water column by about 30–33 m (Gudelis 1979; Kabailienė 1999). Some authors indicated that near the Lithuanian coast the water level altitude lowered to -55.5 – -57.6 m NN (Gelumbauskaitė 2009). According to data newly obtained from the Lithuanian zone of the Baltic Sea basin, remains of up to 500 m wide terrace were detected at -37 – -39 m NN and -44 – -47m NN about 15. –15.5 km westwards from the Curonian Spit (Žulkus, Girininkas 2020). Moreover, numerous pine tree trunks, dated back to about 11.4–10.1 cal kyr BP, were discovered at about -24 – -25 m NN (Bitinas *et al.* 2003; Žulkus *et al.* 2015). A similar situation was may be observed all over the territory of the southern Baltic coast where no sediments of simultaneous basins were found above -15 m NN (Björck 1995; Berglund 2005; Uścinowicz 2006).

Obviously, the coast of the Yoldia Sea was situated further westwards from the NRD where the palaeogeographical situation was shaped by local factors. Hence, the water retreated resulting in a remarkable lowering of the water table in the basins that existed in the delta region at that time. The biostratigraphical records of cores 6, 8a, 25 and, 26 point to the episodic occurrence of the Early Holocene deposits in the basins investigated. The prevailing freshwater benthic diatoms indicate the existence of a very shallow freshwater environment between 11 600 cal BP and 8 200 cal BP (core 6). The habitat and life forms of some benthic species are described as epipelic (e.g., *Cavinula scutelloides*) and epipsamic (e.g., *Staurosirella martyi*) (Snoeijs, Vilbaste 1994; Snoeijs, Kasperovičienė 1996). The abundantly found epipsamic *Staurosirella martyi* suggest that the bottom of the shallow freshwater basin was sandy and not overgrown by water plants. The decreasing representation of fine-grained terrigenous material, i.e., silt and clay, which is typical of these sediments (Fig. 10B), and points to the instability of the sedimentary environment. Most probably, the rising inflow of the unsorted particles transported by water streams, i.e., rivers or streams discharging from the inland, was the real reason. The deepening of the valleys of such rivers as River Minija, cannot be ignored when discussing the palaeogeography of the area as lowering of the erosion base was pronounced at that time. Also, interbedding of terrigenous and organic layers, which was noted in some sequencies (core 8a), suggesting periodic inundations of the area where biogenic sedimentation had already started. At the same time, gradual establishment of deciduous taxa started all over the territory of Lithuania (Kabailienė 2006) and the NRD in particular (Stančikaitė *et al.* 2008; Napreenko-Dorokhova 2015). The noted increase in *Alnus*, *Corylus* and *Ulmus* pollen (Figs 7 and 8) suggests the formation of a shadow forest. The discovered archaeological artefacts (Figs 2–4) evidence the presence of scattered groups of the Final Palaeolithic population in the NRD region in the Early Holocene. The rising productivity of the environment led to the increased density of the herbivorous population (Stivrins *et al.* 2019), which in turn attracted human groups. Actually, the limited occurrence of the archaeological heritage of the Early Holocene in the region might have been predetermined by the palaeogeographical situation, i.e., the archaeological sites in westward located territories are submerged by the Baltic Sea at present and those situated within the present-day delta territory were possibly covered by the biogenic or limnic strata deposited during different stages of the Holocene.

The final degradation of the above-mentioned pine forest (-24 – -25 m NN, Fig. 13) dated back to about 10 100 –10 200 cal BP according to the results of ^{14}C measurements (Žulkus *et al.* 2015), generally marks the maximum transgression of Ancylus Lake, which was one of the lake stages in the Baltic Sea history (Björck 1995; Andrén *et al.* 2011; Rosentau *et al.* 2021). Submerged pine trees and biogenic deposits of the same age evidencing the transgression of the basin have been noted all over the southern Baltic (Andrén *et al.* 2007; Uścinowicz *et al.* 2011). The onset of the Ancylus Lake coincides with the water transgression, which started in the southern Baltic basin (Björck 1987) at about 10.7 cal kyr BP (Andrén *et al.* 1999). However, the exact outlet of the lake is still a matter of debates (Björck 1995; Lemke *et al.* 1998; Andrén *et al.* 2011; Rosentau *et al.* 2009; 2021). In any case, the pronounced recession of the basin followed after 10 200 cal BP (Björck 2008), and in the eastern Estonia the water level lowered by 11 m (Rosentau *et al.* 2013); in the Haväng area by 10 m (Hansson *et al.* 2018); and in Blekinge (Berglund 2005) and Poland (Uścinowicz 2006) by 5 m.

Though regional reconstructions suggest varying shore-level imprints in the southern part of the Baltic basin during the maximum transgression of the Ancylus Lake (Andrén *et al.* 2011; Rosentau *et al.* 2021), so far there have been no direct traces of coastal formations found in the territory of the Lithuanian coast, including the NRD (Damušytė 2011). Nonetheless, the palaeoecological and chronostratigraphical situation of the Ancylus Lake has been described on the basis of both offshore (Vaikutienė 2003) and terrestrial records (Kabailienė 1999; Kabailienė *et al.* 2009) in Lithuania. Sediments of the early Holocene age deposited in fresh shallow eutrophic water basins with high presence of benthic and epiphytic diatoms (*Amphora pediculus*, *Staurosirella martyi*, *Cavinula scutelloides*, *Pseudostaurosira brevistriata*) have been discovered in sediment sequencies distributed all over the territory of the Curonian Spit and the northern part of the Curonian Lagoon (Bitinas *et al.* 2000, 2002; Vaikutienė 2003; Kabailienė *et al.* 2009). However, according to the palaeobotanical data, i.e., cores 6, 8a and 25 (Fig. 7), sediments of the early

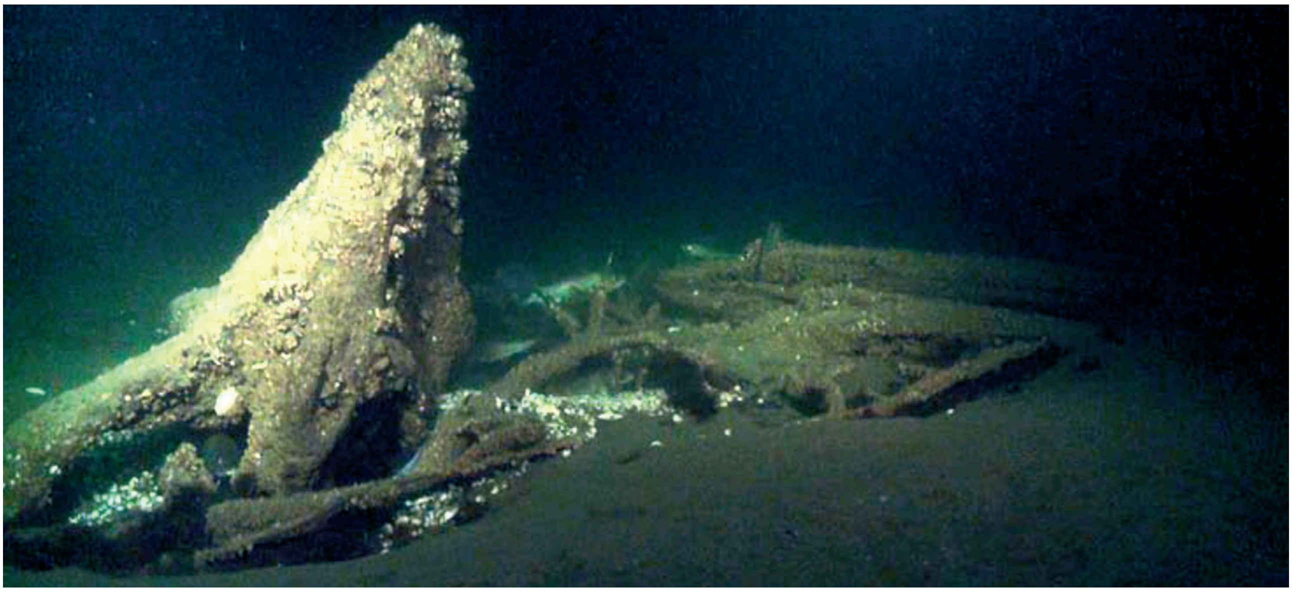

Fig. 13 *In-situ* rooted pine stump dated back to 10 706–10 247 cal yr BP (RF-I-C-3, -25 m NN, photo by V. Žulkus)

Holocene age are very scarce in the NRD. Meanwhile, regional records indicate a sudden culmination of the hazel and flourishing of *Ulmus* or *Alnus* (Napreenko-Dorokhova 2015; Stančikaitė *et al.* 2008). In addition, *Quercus* and *Tilia* gradually immigrated into the area. The early immigration of broad leave taxa into the coastal zone was also mentioned in the neighbouring Poland (Ralska-Jasiewiczowa, Latałowa 1996).

The terrestrial sedimentation predominated in the area of NRD *sensu* lithological and grain-size records (Table 1, Fig. 6). Apart from that, the representation of unsorted material in the beds was observed to increase (Fig. 10B). The lithological composition of the investigated sequencies suggests the predominance of the destabilized depositional environment in the NRD during the period under consideration. Likewise, the area developed as a wet, periodically inundated territory with inflows and streams transporting rich unsorted material from the inland. In general, this interpretation of the palaeogeographical situation corresponds well with the former reconstructions indicating a low water table varying at about -4 m NN in this part of the South Baltic basin during the maximum transgression of the Ancylus Lake (Gelumbauskaitė 2000, 2002, 2003; Bitinas *et al.* 2002). Negative water level tendencies of that basin were proved by the new data, which were collected from the Lithuanian offshore sector of the Baltic Sea during the resent decade (Bitinas *et al.* 2003; Žulkus *et al.* 2015). Numerous limiting points of the terrestrial origin, i.e., peat deposits or *in situ* pine stumps, were discovered and dated off the Baltic Sea coast, indicating the water table variations from -11 m NN to -32 m NN (Žulkus, Girininkas 2020) or even lower (Žulkus, Girininkas *in press*) during the final part of the Ancylus Lake stage and throughout the Initial Litorina Sea stage (9.8–8.5 cal BP *sensu* Andrén *et al.* 2000) in this part of the SE Baltic (Žulkus *et al.* 2015).

The onset of the Holocene was concomitant with the establishment of vast boggy areas in the region. Uninterrupted development of peat layers in Svencelė and Aukštumala (Stančikaitė, Kabailienė, 1998; Stančikaitė *pers. info*) started more than seven thousand years ago and in the Kozje peat bog, the Russian part of the NRD (Napreenko-Dorokhova 2015), even earlier, at about 9 600–9 300 cal yr BP, suggesting remarkable changes in the palaeogeographical situation in the territory.

CONCLUSIONS

The collected data outlining the major chronological and spatial limits of the NRD during the Lateglacial and Early Holocene (14 700–8 200 cal yr BP), reveal the existence of extended proglacial lakes, forming erosional terraces laying at about +40 m NN, during the initial stages of the Lateglacial. Later, in about 13.8 cal kyr BP, the broken landscape of low water estuaries or freshwater lagoons was formed following the regression of the above-mentioned proglacial basins. The freshwater body of the BIL existed westwards from the territory of the present-day NRD. The results of the archaeological excavations evidence the immigration of the Final Palaeolithic population into this territory during the favourable intervals of the Lateglacial when open-forest vegetation was flourishing in the region. Based on the new data, low water level elevations persisted in this part of the south Baltic basin until the end of the Early Holocene as shores of both the Yoldia Sea and Ancylus Lake were situated further westwards laying at about -11 to -24 – -29 m NN. The newly obtained data, including chronological one, evidences the existence of shallow boggy basins in the presently submerged offshore areas of the Baltic Sea until 10 200–10 100 cal yr BP. Archaeological finds evidence modest human presence within the delta region during the Early Holocene, However, it cannot be ruled out that the majority of the archaeological sites might have been covered by the biogenic or limnic strata or submerged by the sea during the further stages of the Holocene. The Early Holocene marks the onset of the next stage in the history of the territory as the development of extended peat bogs started therein.

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