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Depositional environment and climate changes during the late Pleistocene as recorded by the Netiesos section in southern Lithuania

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ABSTRACT

The Netiesos section in southern Lithuania exposes a late Pleistocene sedimentary sequence at a depth of between 17 and 4 m. An interdisciplinary study of the section investigated the environmental changes that occurred in the study area during the greater part of Marine Isotope Stage (MIS) 5. Geochemical, thermoluminescence, palaeontological (plant macro-remain, diatoms, fishbones) and magnetic susceptibility analyses were performed on numerous sediment samples. Chronological control of the sequence was provided by electron spin resonance (ESR), infrared optically stimulated luminescence (IR-OSL) and conventional radiocarbon dating methods. This interdisciplinary approach enabled the subdivision of the section into stratigraphic units reflecting environmental changes. According to chronological data, the development of the Netiesos palaeolake began at the end of the Medininkai (Saalian) glaciation, which is thought to correlate with MIS 6, and continued up to the thermophilous deciduous forests phase of the subsequent last interglacial of MIS 5. Sediments of the final phase of the interglacial are missing, as are the initial and final phases of the following early Nemunas (Weichselian) cooling (MIS 4). The palaeomagnetic Blake Event was recorded in the interglacial sediments. One of the richest palaeofloras in the East Baltic region was observed representing the second half of MIS 5. The implications of the results for the regional late Pleistocene climato-chronostratigraphy are discussed.

1. Introduction

Sediments representing the last interglacial and the following Weichselian cold period exposed in one section are rare, and so they are of great significance for investigations of environment and climate changes during the late Pleistocene. The aim of the present work is to provide a detailed reconstruction of the sedimentary environment and the climate conditions using multidisciplinary investigations of the late Pleistocene sedimentary sequence of the Netiesos section. To achieve this objective, geochemical, palaeontological (plant macro-remains, diatom, fishbones), chronological and magnetic susceptibility investigations were performed.

The area surrounding Merkinė in southern Lithuania is of special interest for Quaternary studies, because several outcrops contain interglacial sedimentary sequences. Interglacial peat lenses in the outcrop of the right bank of the Nemunas River near the village of Netiesos were noted in the work of Sobolev (1910). Later, the sections were studied by a number of scientists (Dalinkevičius, 1944; Halicki, 1948; Bremówna and Sobolewska, 1950; Pachucki, 1952; Borówko-Dłużakowa and Halicki, 1957; Čepulytė, 1957; Gaigalas, 1959; Klimašauskas, 1962; Vaitiekūnas and Špokauskas, 1966; Vaitiekūnas, 1969; Vonsavičius, 1975; Pevzner and Gaigalas, 1976; Gaigalas, 1979; Riškienė, 1979; Baltrūnas, 1995, 2002; Kondratienė, 1996; Gaigalas and Molodkov, 2002; Gaigalas et al., 2002, 2005a, 2005b; Satkūnas et al., 2003; and others).

Former sedimentological investigations (Gaigalas et al., 2005a) ascertained that during the most part of Merkinė (Eemian)

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interglacial, lake littoral and deep sedimentation existed, and only in its second part did bog formation start under dry and warm conditions. During the early Nemunas (Weichselian) time, periglacial conditions existed and deposition took place in stagnant water. Hereinafter, discussion refers to the units described by Gaigalas et al. (2005a). The results of the previous palaeontological studies of the Netiesos section are summarised by Kondratienė (1996). Spore and pollen analyses have shown the development of typical Merkinė (Eemian) interglacial vegetation characterised by the spectra of pollen zones M1–M4. The rodent faunal remains were found only in the lowermost part of the Netiesos section (Kalinovskiy, 1981). The species composition of the rodent fauna is indicative of a cold environment. The malacological investigations of the lower part of the section between lower sand and upper peat (Sanko and Gaigalas, 2007, Fig. 2) revealed a transition from the periglacial mollusc fauna, corresponding to the late glacial stage of the penultimate Medininkai (MIS 6) glaciation, to the faunal composition characteristic of the optimum of the following Merkinė interglacial. Age determination of the freshwater mollusc shells collected from the interglacial gyttja and peat was performed by electron spin resonance (ESR) (Gaigalas and Molodkov, 2002). Past palaeomagnetic studies of Netiesos outcrop were inconclusive, and no significant geomagnetic excursions were recognized (Gaigalas et al., 2002).

2. Regional setting

The Netiesos outcrop is situated on the right bank of the Nemunas River approximately 6 km downstream from the town of Merkinė (Fig. 1). Quaternary sediments of Saalian, Eemian and Weichselian age are represented in the outcrop and reach more than 20 m thick (Fig. 2).

Quaternary deposits at Netiesos at 20–40 m a.s.l. lie on Upper Cretaceous chalk. The thickness of the Quaternary cover reaches as much as 60–70 m. The structure of the late Pleistocene deposits in the vicinity of Netiesos has been investigated by drilling, which was carried out during recent studies in order to reconstruct a bed of the Merkinė interglacial palaeolake observed in the Netiesos outcrop (Figs. 3 and 4).

The interglacial palaeolake sediments were found in the palaeoincision filled by glaciolacustrine sediments from the depression in the middle Pleistocene Medininkai till. Sediments are rich in organic matter and form a lens with thickness reaching 6 m (Fig. 4). The distribution of the investigated sediments indicates formation in the bay of a large lake. The interglacial sediments are covered by layers of very fine sands, which preliminarily could be subdivided into three parts according to the nature of the genesis and age: lower and middle Nemunas (Weichselian) glaciolacustrine, and upper Nemunas (Weichselian) glaciofluvial (Fig. 4).

3. Methods

Twenty-one samples for plant macro-remain analysis were taken from organic rich layers every 25 cm at the depths of 12.0–17.6 m (Fig. 2). Plant macro-remains were extracted by wet sieving and were analysed using a NICON SMZ 1500 microscope at a magnification of 20–100×. The identification of taxa was performed using the atlases of Berggren (1969, 1981), Grigas (1986), Cappers et al. (2006) and a reference collection at the Institute of Geology and Geography, Nature Research Centre (IGGNRC), Vilnius (Lithuania). The local plant macro-remain zones were distinguished using cluster analysis. Botanical nomenclature follows Gudžinskas (1999).

Forty-six samples were taken for diatom analysis from all lithological complexes. Diatom frustules were extracted from the sediments in the conventional manner as described by Battarbee (1986) and Miller and Florin (1989).

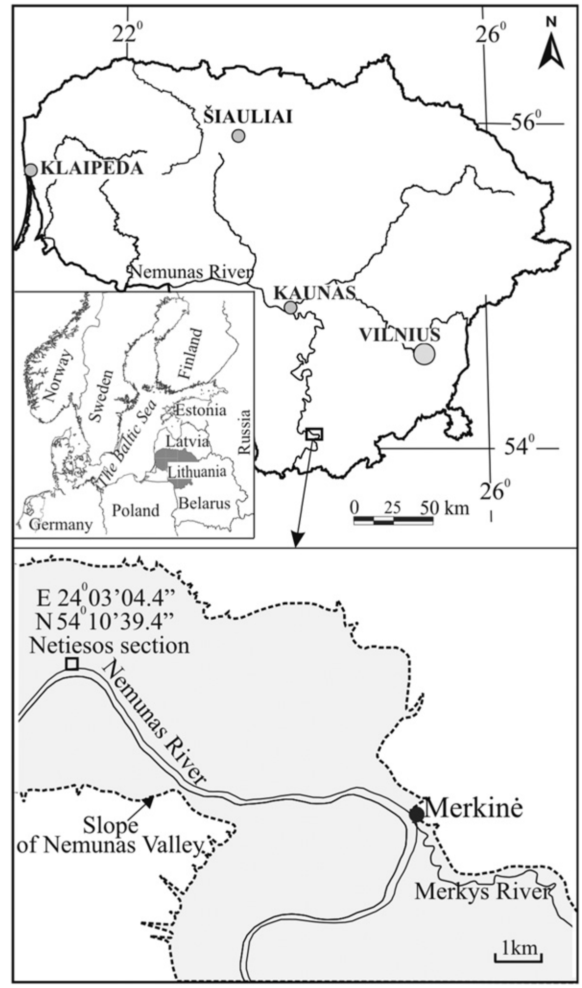

Fig. 1. Location of the investigated site.

The fishbones collected from the gyttja were identified using the reference collections of modern skeletons from the Centre for Baltic and Scandinavian Archaeology in Schleswig (Germany) and the Zoological Institute of the University of Kiel (Germany). The palaeoecological interpretation of the fish species community is based on the modern ecological requirements of the recorded species. The main reference for the Holocene distribution and the ecological requirements is the report by Kottelat and Freyhof (2007).

The potassium feldspar-based IR-OSL dating method was applied to 8 samples of sandy deposits collected in 2010 from the outcrop in the depth range between 12.2 and 3.9 m (Fig. 2). The samples were taken from about 0.5 m below the slope surface avoiding the light and wrapped into a black bag (several layers) and taped tightly to prevent disintegration (Fig. 2). Glow curves of thermoluminescence (TL) for the IR-OSL analysed feldspar samples were used for subdivision of the sedimentary sequence.

The ESR method was applied to date freshwater mollusc shells taken directly from the gyttja and peat situated in the lower part of the section. Thin-walled, small-sized shell fragments of different mollusc species were used for dating. All ESR and IR-OSL ages reported in this paper were obtained at the Research Laboratory for Quaternary Geochronology (RLQG) Institute of Geology, Tallinn

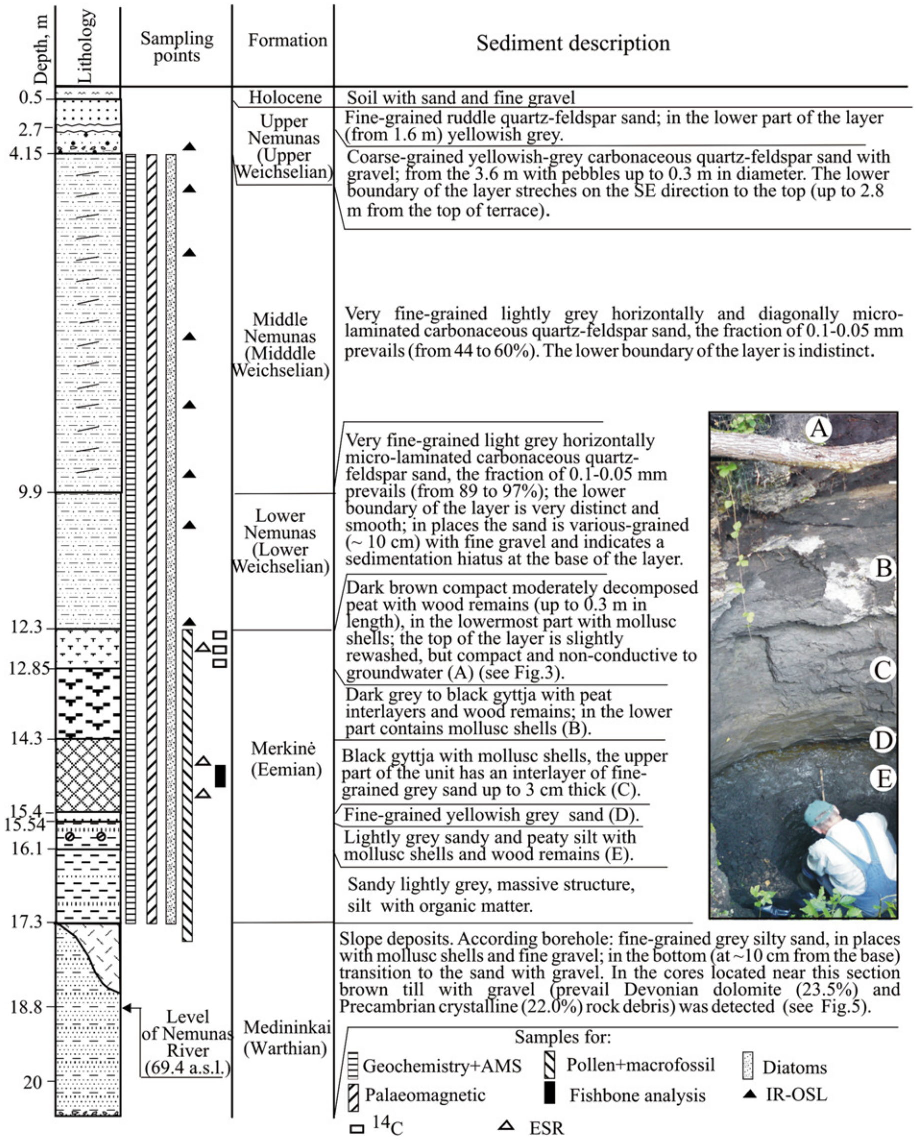

Fig. 2. Lithological description of the Netiesos section.

University of Technology. Overviews of the ESR and IR-OSL dating procedures used in RLQG are presented in Molodkov et al. (1998) and Molodkov and Bitinas (2006), respectively.

Three samples, one bulk sample of peat and two pieces of wood, taken from the compact peat layer at the depth of 12.85–12.3 m (Fig. 2) were dated at the Radioisotope Laboratory of the IGGNRC by the conventional radiocarbon method. The specific ^{14}C activity of the samples was defined using the liquid-scintillation analyser TriCarb 3170 TR/SL. The measurement of 2.6 g sample of benzene was performed in low-volume glass phials. From the specific ^{14}C activity of the investigated sample, the radiocarbon age was calculated using the law of radioactive decay. Additionally, dendrochronological calibration to calendar years using OxCal 3.10 (Bronk Ramsey, 2001) was applied.

Sampling for geochemical investigations was performed from all lithological complexes (Fig. 2). Samples of approximately 5 g were air-dried and milled for 10 min at 27 Hz using an MM 400 mixer mill (Retsch). Afterwards, the sub-sample for geochemical analysis was homogenised with Licowax and pressed with a PP15 press into 32 mm pellets.

Major and trace element contents were determined by energy-dispersive X-ray fluorescence (EDXRF) using SPECTRO XEPOS equipment and the TURBOQUANT calibration method. As the number of geological variables is great (10 major and 19 trace elements) and many of them might be correlated, one of the factor analysis methods (principal component analysis with varimax rotation) was applied for geochemical data reduction. In heterogeneous data sets, this method distinguishes the subsets by analysing the scores of the latent factors (Iberla, 1980). The interpretation of each latent factor is based on chemical elements with significant positive and significant negative loadings on this factor. Variation of factor scores in the core profile adds information about the main sedimentary units distinguished by other methods (Barros de Oliveira et al., 2009). The approach of this research was slightly different: the scores of the first 3 factors (taking into account their magnitude) were used for subdivision of the section into geochemical units presuming that the factor with the highest score has the greatest influence.

A total of 183 samples were collected for the analyses of magnetic susceptibility from the depth range between 17.3 and

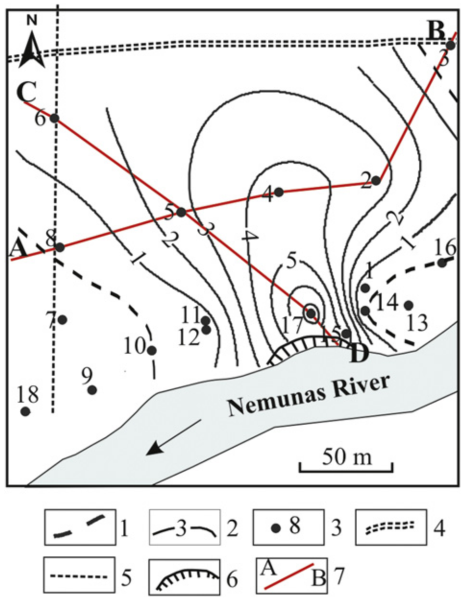

Fig. 3. Distribution of the Merkinė (Eemian) interglacial sediments in the Netiesos environs. 1 – limit of the Merkinė interglacial sediments distribution; 2 – isoline of sediment thickness (m); 3 – borehole and its number; 4 – road; 5 – clearing; 6 – outcrop; 7 – cross-section.

4.1 m of the Netiesos section. A total of 55 oriented samples from the lower 5 m of the outcrop were taken at every 10 cm for determination of the anisotropy of magnetic susceptibility (AMS) (Tarling and Hrouda, 1993). AMS was measured with an MFKI-B kappa bridge (AGICO) in the palaeomagnetic laboratory of the IGGNRC. The AMS measurements were made along fifteen different directions (Jelinek, 1977). The analysis of the AMS data was performed using Anisoft 4.2 software.

In addition, a palaeomagnetic study of 56 samples was carried out. The natural remanent magnetization was measured using JR-6 spinner magnetometer from AGICO in paleomagnetic laboratory of IGGNRC. All samples were subjected to stepwise alternating field (AF) demonetarization with a demagnetizer from Molspin. All specimens were AF-demagnetized in small steps to 40 or 60 mT. Magnetic susceptibility was monitored using a MFK-1B susceptibility bridge from AGICO. Demagnetization experiments and the NRM measurements were performed inside Helmholz coils that reduced the geomagnetic field by 95%. Characteristic directions were calculated using principal component analysis (Kirschvink, 1980) using Remasoft 30.

Drilling of the boreholes was performed as part of the project No. T-04/09 (Piličiauskas et al., 2011). The material from this research was used to construct the cross-sections in the current study. Cone penetration testing, auger drilling and vibracoring were conducted on the slope and terrace of the Nemunas River. A total of 18 research points were distributed within an area of 3.5 ha.

4. Results

4.1. Plant macro-remains and pollen investigation

The examination of sediments revealed the presence of plant macro-remains (fruits, seeds, oospores and needles) belonging to 114 taxa. The identified plant macro-remains were grouped according to their habitats: woodland (trees and shrubs), aquatic plants, wetland, and xeromesophytes. According to palaeoflora compositional changes throughout the section, five plant macro-remain zones (PMZ) were distinguished (Fig. 5).

The lower part of the section (16.89–17.55 m PMZ Md) is dominated by aquatic plants, primarily different *Potamogeton* species among which the temperate and cold-resistant species (*Potamogeton filiformis*, *Potamogeton vaginatus*, *Potamogeton perfoliatus*) predominate quantitatively. These species are accompanied by *Hippuris vulgaris*, *Sparganium emersum* and *Sparganium minimum*, which could easily adapt to different environmental conditions. The conifers (*Picea obovata*, *Picea* sect. *Picea*, *Pinus*) prevail in the group of arboreal species. At the same time, the presence of heliophilous plants (*Arctostapylos uva-ursi*, *Selaginella selaginoides*) indicates open environmental conditions. *S. selaginoides* is a poor competitor that does not grow in areas with tall, dense vegetation.

Pollen composition of this interval (PZ Md) is dominantly herbs. Among trees, coniferous species, mostly *Pinus*, and *Betula* are dominant (Kondratienė, 1996; Velichkevich et al., 1999).

In the sediment interval from 16.19 to 16.89 m (PMZ N1), the presence of new slightly thermophilic aquatic (*Nuphar lutea*, *Najas marina*, *Ceratophyllum demersum*) as well as arboreal (*Alnus glutinosa*, *Fraxinus excelsior*) plants is recorded. Water plants, together with different species of sedge and celery-leaved buttercup predominate, characterising the palaeobasin as eutrophic lake with well-developed shore vegetation.

A pollen spectrum of this interval (end of the PZ Md; M1) is more diverse in species composition. At the end of zone Md, *Picea* trees prevail among conifers. In zone M1, *Picea* is replaced by *Pinus* and *Betula*, where *Pinus* constitute up to 70%. *Betula nana* vanished from the territory (Kondratienė, 1996).

The next zone (15.61–16.19 m, PMZ N2) is characterised by a reduction in the abundance of aquatic and wetland plants. The exception is the increase in the number of *N. marina* and *Nympaea alba*, which could be related to lake-level change, because these species occur most commonly in water depths of approximately 2 m or less. The terrestrial vegetation also indicates environmental changes (PZ M2). Mixed forests, prevalently *Pinus* and *Betula*, occupied the territory. Herb vegetation markedly decreased (Kondratienė, 1996).

The palaeoflora becomes most thermophilic in the upper part of the outcrop (interval 12.90–15.61 m) where vegetation of the optimum phase of the interglacial is recorded. This interval is divided into three subzones. The first subzone (PMZ N3a, depth 14.97–15.61 m) is characterised by the occurrence of *Tilia tomentosa* and *Vitis vinifera*. The finds of *Tilia platyphyllos*, *Carpinus betulus* and *Cornus sanguinea* characterise the second subzone (13.91–14.97 PMZ N3b). In the third subzone (PMZ N3c, depth 12.90–13.91 m), dramatically increased quantities of thermophilic plants, especially broad-leaved trees and aquatic ferns (*Salvinia natans*), are present.

According to pollen composition, three subzones of the climatic optimum of the interglacial are identified (Kondratienė, 1996). The first one (PZ M3a) is characterised by spread of *Quercus* (58%) and *Ulmus* forests. At the beginning of the zone, *Pinus* was numerous and represents approximately 30% of the tree pollen. In the second half of the zone, *Corylus* and *Alnus* understory was common. Deciduous forests with *Tilia* up to 33% occupied the territory during the second subzone (PZ M3b). *Alnus*, *Corylus*, *Quercus* and *Acer* are also represented. The third subzone (PZ M3c) shows *Carpinus* up to 50% and *Picea* forests. *Alnus* was abundant as well. Similar flora composition for this period was recorded in adjacent areas (Savchenko and Pavlovskaya, 1999; Kalnina, 2001; Granoszewski, 2003; Kupryjanowicz, 2008).

Zone PMZ N4 (depth 12.0–12.9 m) is dominated by xeromesophytes (*Urtica*, *Polygonu*, *Mentha*) and wetland plants

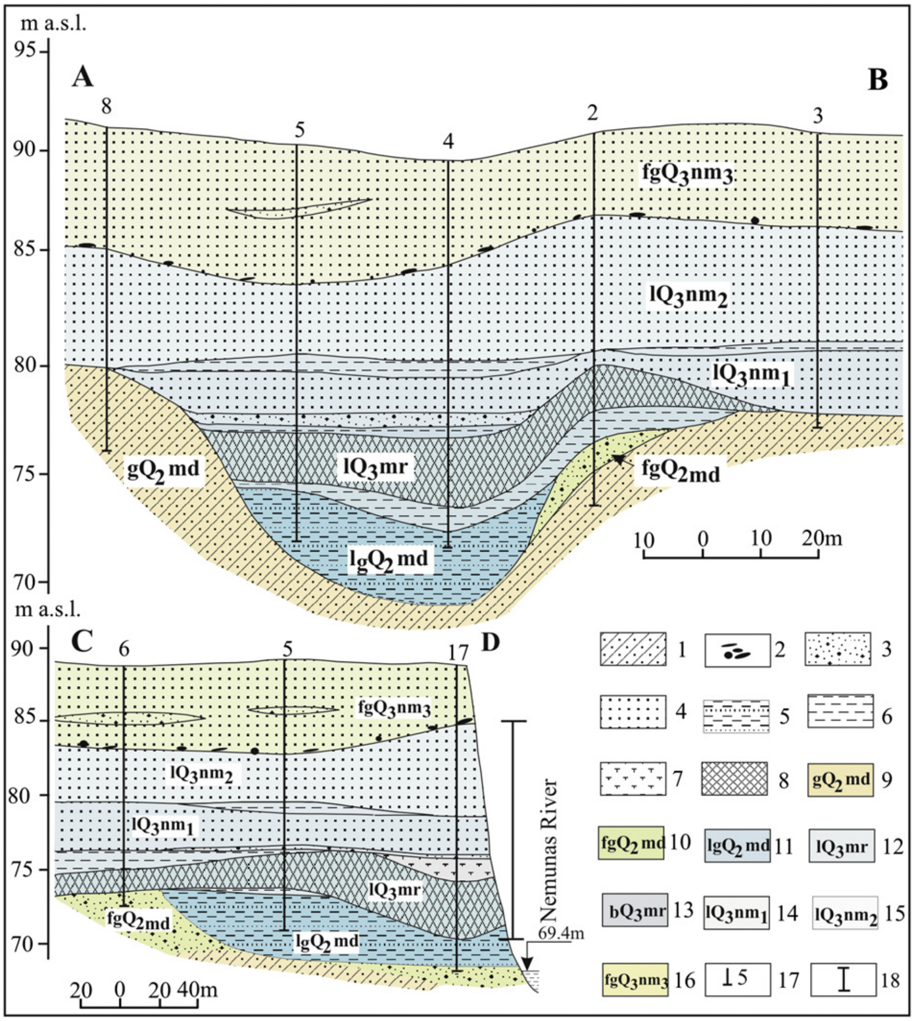

Fig. 4. Cross-section of the upper part of the late Pleistocene thickness in the Netiesos environs. 1 – till; 2 – gravel and pebble; 3 –various sand; 4 – very fine-grained sand; 5 – sandy silt; 6 – silt; 7 – peat; 8 – gyttja; 9 – Medininkai till; 10 – glaciofluvial sediments of Medininkai age; 11 – glaciolacustrine sediments of Medininkai age; 12 – Merkinė interglacial lacustrine sediments; 13 – Merkinė interglacial bog sediments; 14 – Lower Nemunas lacustrine sediments; 15 – Middle Nemunas lacustrine sediments; 16 – glaciofluvial sediments of Upper Nemunas age; 17 – borehole; 18 – investigated part of Netiesos section.

(*Ranunculus*, *Lysimachia*, *Lycopus*). The remains of aquatic species are presented in reduced numbers. Pollen composition shows the occurrence of *Picea* forests with an admixture of *Carpinus* and *Alnus* in the first half of the zone, replaced by *Pinus* in the second half of the zone (PZ M4). These changes in the composition of the flora are related to the degradation of the water basin and the formation of bog. This zone is attributed to the optimal phase of the interglacial, because the presence of *Quercus*, *Corylus*, *Acer*, *Tilia*, *Frangula*, *Brasenia*, *Stratiotes*, although in low frequency, represent thermophilic flora.

4.2. Diatom investigation

Diatoms were investigated in the depth interval between 17.3 and 4.0 m. Notably poor diatom flora was observed. Solitary samples contained from 1 to 20 frustules, and in the greatest number of samples, diatoms are absent. All diatoms identified are freshwater species that are often found in lake sediments. The most numerous planktonic species are *Cyclotella meneghiniana*, *Aulacoseira granulata* and *Stephanodiscus rotula*, and the prevailing epiphytic species are *Epithemia adnata*, *Epithemia turgida*, *Fragilaria pinnata*, and *Synedra ulna.* Benthic species are represented mainly by *Navicullа scutelloides* and fragments of *Amphora* genus species and *Cymbella ehrenbergii*. *Cyclotella meneghiana* is characteristic of large, deep lakes, whereas *A. granulata* and *S. rotula* indicate an eutrophic environment. Epiphytic *Epithemia* genus species do not require very specific environmental conditions, but are often found in slightly acid environments in shallow water bodies, such as bogs and mires.

Unfortunately, scanty diatom findings do not allow confident reconstruction of the environmental changes throughout the section. Deposition occurred in a lake, at the beginning oligotrophic and later eutrophic, probably in its littoral zone.

4.3. Fishbone investigation

In total, 106 bone fragments (see, e.g., Fig. 6, Table 1) were retrieved, and 88 fragments, originating from 85 bones, could be determined to a higher taxonomic level. The minimum number of individuals (MNI) is 12. Five different species of fish are identified. Bones of two taxa, cyprinids (Cyprinidae) and perch (*Perca fluviatilis* Linnaeus, 1758), clearly predominate, comprising, respectively, $n = 48$ (56%) and $n = 32$ (38%) of the total number of identified specimens, or $n = 5$ in each case (42%) of the MNI. Three species of

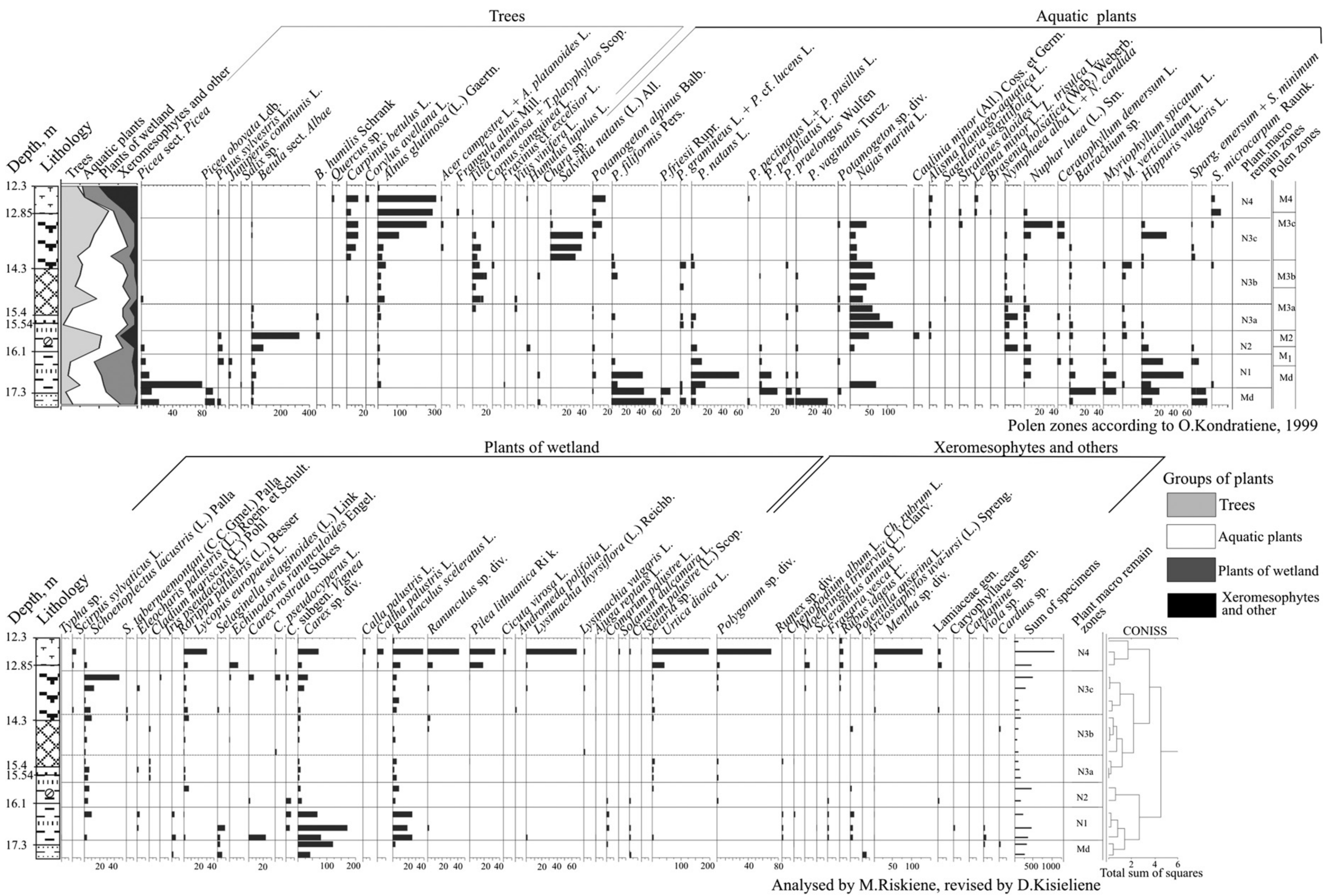

Fig. 5. Plant macro-remains for the Netiesos section. For lithological description, see Fig. 8.

Fig. 6. The fish remains of the Netiesos outcrop. 1–4 – *Esox lucius*, tooth, 5 – *Esox lucius*, Vertebra praecaudales, 6 – *Cyrinidae*, Vertebra praecaudales, 7 – *Perca fluviatilis*, Suboperculare, 8 – *Perca fluviatilis*, Keratohyale, 9 – *Perca fluviatilis*, Operculare, 10 – *Perca fluviatilis*, Spina pinnae ventr.

Cyprinidae have been identified: bream (*Abramis brama* Linnaeus, 1758), roach (*Rutilus rutilus* Linnaeus, 1758), and tench (*Tinca tinca* Linnaeus, 1758). In addition, pike (*Esox lucius* Linnaeus, 1758) is recorded.

broken into two parts, indicates another perch of approximately 30 cm. A larger perch of approximately 35 cm is identified by its teeth. All of the bones of the cyprinids record small individuals with lengths of 15 cm at most. The three roaches, detected by three left

Table 1
The fish remains from Netiesos outcrop in systematic and anatomical order; sin: left, med: medium, dext: right.

Skeletal region Skeletal element	*Perca fluviatilis* sin/med/dext	Cyprinidae indet. sin/med/dext	*Rutilus rutilus* sin/med/dext	*Abramis brama* sin/med/dext	*Tinca tinca* sin/med/dext	*Esox lucius* sin/med/dext
Cranium						
Paraspenoideum	1					
Exoccipitale	1/–/1					
Dentale	–/–/2		1/–/–			
Dentes	1/–/1					4
Pharyngeum inferior		3				
Articulare		–/–/1				
Quadratum		–/–/1				
Maxillare	–/–/1		1/–/–			
Hyomandibulare	–/–/1	–/–/1	1/–/–			
Keratohyale	1/–/2	1/–/–				
Epihyale		–/–/1				
Frontale	2/–/2	1/–/–				
Parietale		1/–/–		1/–/–		
Prooticum	–/–/1					
Operculare	1/–/3		4/–/1			
Praeoperculare	1/–/2	2/–/1		–/–/1		
Suboperculare	1/–/–	2				
Interoperculare		1/–/2				
Branchiostegale	2/–/1					
Branchiale	–/–/2					
Remaining skeleton						
Cleithrum	–/–/1	3/–/2				
Supracleithrale		1/–/–			–/–/1	
Basipterygium		–/–/1				
Vertebra praecaudales		6				1
Vertebra caudales		6		1		
Spina pinna	1					

The perch bone assemblage includes predominantly skeletal elements of the skull. The MNI are based on differences in size. Whereas a single fragment of a Parasphenoideum is derived from a specimen of less than 10 cm in length, two fragmented Praeopercularia represent specimens of 10–15 cm, and a Maxillare,

Opercularia, were even smaller, with a size of only approximately 10 cm.

The five recorded fish species were not very valuable for the late Pleistocene palaeoecological environmental reconstruction. In the Holocene, all of them are common in all types of lowland lakes and rivers throughout most parts of Europe. When young, *Perca* lives in small schools near the shore. Its oxygen demand is relatively high. *Rutilus* is characterised by the ability to survive in poor water conditions; however, it prefers water rich in macrophytes. *Tinca* lives often in the same environment; it needs a water temperature of 18–20 °C for spawning (Müller, 1987). Finally, *Esox* uses a variety of freshwater habitats. It waits amongst marginal vegetation for prey, and such vegetation bordered the Eemian lake.

Esox, *Perca* and *Rutilus* are present in many Central European Eemian assemblages and also in the beds from the transitional glacial periods. At the important and well-investigated Eemian site of Schönfeld, Germany, *Esox*, *Perca*, and *Abramis* have been identified throughout the whole interglacial period (Böhme, 1996). The Quaternary distribution of these species was not strongly influenced by smaller climatic changes (Böhme, 2008), and it is not known if they occurred in this area during glacial stages (Lepiksaar, 2001). Evidence for this may be the record of these species in the late Weichselian sediments (Rosenlund, 1976; Heinrich, 2001). In contrast, the more thermophilic *Tinca* is an indicator of mid-Eemian climate because it has occurred in Eemian northern Central Europe contemporaneously with the thermophilic European pond turtle *Emys orbicularis* (Linnaeus, 1758; Böhme, 2008). Furthermore, there is evidence of a late immigration of *Tinca* into northern Central and Eastern Europe during the Holocene (Lepiksaar, 2001; Makowiecki, 2003).

4.4. Electron spin resonance

The analytical data and the results of ESR dating are reported in Table 2 and Fig. 10. In most cases, the ESR ages were determined on as many as three different samples of freshwater mollusc shells that were taken from the same sampling point. Two groups of shell samples were collected from gyttja, and the third was taken from above the peat layer. The ages of two groups of the shell samples from the gyttja (N-l and N-2) are notably similar, 112.5 ± 10.8 and 112.1 ± 25.9 ka, which is not surprising because the difference in the sampling depth is relatively small, 0.8 m. Shell samples from the peat layer (N-3) are dated at 101.5 ± 11.5 ka. This result coincides closely with the ages of 108.8 ± 8.7 and 105.7 ± 10.0 ka of the peat that were obtained by U–Th (Gaigalas et al., 2005a).

Table 2
ESR/IR-OSL results and radioactivity data for the samples from the Netiesos site.

Lab no.	Field no.	Depth (m)	ESR age (ka)	IR-OSL age (ka)	U (ppm)	Th (ppm)	K (%)
RLQG 2059-111	N-11	3.9	–	20.4 ± 1.6	0.85	3.26	1.47
RLQG 2058-111	N-10	4.6	–	64.4 ± 5.0	1.58	5.96	1.62
RLQG 2057-111	N-9	5.9	–	65.6 ± 5.1	0.99	2.78	1.43
RLQG 2056-111	N-8	7.3	–	65.0 ± 7.5	0.86	2.64	1.52
RLQG 2055-111	N-7	8.7	–	66.5 ± 5.2	0.93	2.86	1.70
RLQG 2054-111	N-6	9.8	–	66.2 ± 5.1	1.24	3.21	1.71
RLQG 2053-111	N-5	10.8	–	89.8 ± 6.8	0.73	2.28	1.03
RLQG 2052-111	N-4	12.2	–	93.1 ± 8.4	0.44	1.58	1.09
RLQG 2215-095	N-3	12.7	101.5 ± 11.5	–	0.64	0.93	0.30
RLQG 2200-095	N-2	14.4	112.5 ± 10.8	–	1.32	3.62	0.97
RLQG 2224-095	N-l	15.2	112.1 ± 25.9	–	1.32	3.15	1.02

Notes: U, Th, K are the uranium, thorium and potassium content in sediments. Uncertainties: U determination, ±2–3%; Th determination, ±3–4%; K determination, ±1–2%.

4.5. Infrared optically stimulated luminescence

Two samples (N-4 and N-5) taken from the sands overlying the peat at depths 12.2 to 10.8 m were dated by IR-OSL at 93.1 ± 8.4 and 89.8 ± 6.8 ka, respectively. Samples N-6–N-10 collected from the fine-grained sands at depths of 9.8–4.6 m are dated between approximately 66 and 64 ka. A sample of coarse-grained sands with gravel and pebbles (N-11) taken at a depth of 3.9 m was dated at 20.4 ± 1.6 ka (Table 2, Fig. 10).

4.6. Radiocarbon

The maximum age limit of radiocarbon dating is generally approximately 40–45 ka, depending on the initial volume of the investigated sample and especially on the accuracy of ^{14}C background value determination. Radiocarbon analysis of three samples (Vs-2122, Vs-2124 and Vs-2125) taken from the compact peat layer of the Netiesos section yielded infinite radiocarbon ages (>62.6, >63.6 and >66.6 ka BP). Therefore, these results indicate that the true age of the peat layer cannot be determined as it exceeds the age limit of this dating method.

4.7. Geochemical investigation

Samples for geochemical analysis were taken from the Netiesos outcrop at depths of between 17.5 and 4.0 m (see Fig. 2). The study interval consists of 4 main lithological units: silt (17.3–15.5 m) from which 36 samples were taken, gyttja (15.5–14.3 m, 24 samples), peat (14.3–12.3 m, 41 samples) and sand (12.3–4.0 m, 83 samples). The studied sediments have different elemental compositions, and therefore, transitions between these units serve as natural geochemical boundaries. An attempt was made to identify as many geochemical boundaries as possible and to subdivide the units into smaller ones using factor analysis. The following 29 chemical elements were used in this research: a) 10 major elements (Si, Al, K, Fe, Ti, P, Ca, Mg, Na, S); and b) 19 trace elements (Mn, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, Pb, Th, Hf, V, Cr, As, Mo, Br).

Factor analysis performed for these 29 chemical elements yielded 3 resumptive factors (Table 3, see Fig. 10). The first factor Fl(m) helps to distinguish the minerogenic (allogenic) chemical elements (Nb, Ti, Ba, Mg, Pb. Y, Rb, Hf, K, Zr, Al, Th, Ga, P, Na, Cr), which have positive factor loadings, from the elements that are related to organic matter (S, Mo, As, Br) or carbonates (Ca), which have negative loadings. This factor may be called the minerogenic factor, and an increase in its scores indicates an increase in the supply of allogenic material.

Table 3
Characterisation of geochemical units according to changes of factor scores.

Unit	Interval, m	Description	Magnitude of factor scores
U14	<5.90	Sharp increase of F1(m), partly F2(a)	F1(m) > F2(a) > F3(b)
U13	5.90–9.90	Sharp increase of F1(m), F2(a), then gradual decrease	F1(m) > F2(a) > F3(b)
U12	9.90–12.30	Decrease of F3 and F2, fluctuations of all factors	F1(m) > F3(b) > F2(a)
U11	12.30–12.60	Decrease of F1, F3	F3(b) > F2(a) > F1(m)
U10	12.60–12.85	Increase of F1, F3, decrease of F2	F3(b) > F2(a) > F1(m)
U9	12.85–13.15	Increase of F1, F2, decrease of F3	F3(b) > F1(m) > F2(a)
U8	13.15–13.60	Increase of F3, fall and rise of F1, F2	F3(b) > F1(m) > F2(a)
U7	13.60–14.15	Decrease of F2, F3, fall and rise of F1	F3(b) > F1(m) > F2(a)
U6	14.15–14.30	Increase of F1, F3, decrease of F2	F3(b) = F1(m) > F2(a)
U5	14.30–14.55	Decrease of F3, F1, rise of F2	F3(b) > F2(a) > F1(m)
U4	14.55–15.05	Decrease of F1, F2, increase of F3	F3(b) > F2(a) > F1(m)
U3	15.05–15.40	Decrease of F1, F2, F3	F2(a) > F3(b) > F1(m)
U2	15.40–16.10	Increase of F1, F3, rise and fall of F2	F2(a) > F3(b) > F1(m)
U1	>16.10	Decrease of F1(m), F2(a), F3(b)	F2(a) > F3(b) = F1(m)

The second factor F2(a) can be considered authigenic because it helps to distinguish elements related to carbonates (Sr, Ca), hydroxides (Mn, Fe), and organic-matter (Br, Mo), which have positive loadings, from the minerogenic chemical elements, which have negative loadings. The third factor F3(b) can be considered biogenic because it helps to distinguish sediments rich in organic matter and elements enriched in organic matter (Cu, Zn, Ni, V, S), which have positive loadings, from elements indicating allogenic sand (Si, Na, Zr), which have negative loadings. However, this factor does not discriminate between biogenic elements and allogenic elements that are more related to the fine fraction of terrigenous material because the latter elements have positive loadings on F3(b).

4.8. Investigation of magnetic susceptibility and its anisotropy

According to the results of magnetic susceptibility, the sedimentary sequence could be subdivided into three clear and large-scale cycles of deposition change that are related to the lithology. The noticeable changes in magnetic susceptibility are fixed at depths of 16.10, 15.05, 14.30, 12.30 and 5.90 m. The sandy silt sediments in the lower part of the section have the highest magnetic susceptibility. In the overlying gyttja, the magnetic susceptibility decreases, and in the peat, it reaches the lowest readings. In the sands (depth of 12.3 m), the magnetic susceptibility gradually and steadily increases (Fig. 7).

Analysis of the anisotropy of magnetic susceptibility (AMS) has been applied to rock fabric investigation at a depth of 17.3–12.3 m for Merkinė interglacial sediments. To interpret the AMS data

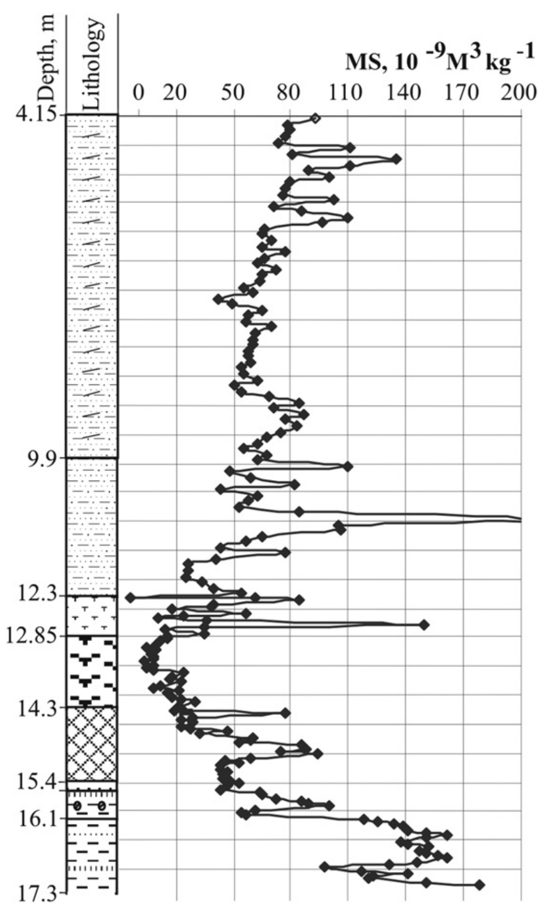

Fig. 7. Distribution of magnetic susceptibility in Netiesos section (magnetic susceptibility, $\times 10^{-9}$ m^3 kg^{-1}/depth of samples, m). For lithological description, see Fig. 8.

of sedimentary flow directions, the general orientation for the lower part of the outcrop (5 m thickness) had declination and inclination of 328°/5°. During the accumulation of silt, the sedimentary flow in the column was 353°/15° and changed by 180° to become 119°/9° during the formation of gyttja. During the formation of the peat, the sedimentary direction was as for the silt.

4.9. Results of the palaeomagnetic study

The results of the study indicate that all of the samples, except three at the depths of 15.15 and 15.45 m, have a normal-polarity direction, and that three samples have a reversed polarity direction. According to ESR chronology, this interval of reversed inclination can be related to the Blake Event (Fig. 8) first defined by Smith and Foster (1969) from a palaeomagnetic study of four deep-sea cores recovered from the Blake Outer Ridge. Later, observations from the highest resolution marine cores and from loess sections demonstrated that the Blake excursion is a global geomagnetic feature, with a characteristic structure comprising two short periods of almost reverse polarity separated by a short period of almost normal polarity. In this study, only one short period of reversed polarity was fixed. This can serve as grounds for a more detailed investigation.

4.10. TL-based sedimentary subdivision

The results of TL analysis of the feldspar grains extracted from 7 samples of enclosing sediments (N-4–N-11) taken at the depths between 12.9 and 3.9 m show that based on the shapes of TL glow curves (Fig. 9), the studied sedimentary sequence can be subdivided into at least two main units. Sediments of these units probably were supplied from two different source areas and/or transported to the site of deposition under different environmental conditions. The first distinct sedimentary unit corresponds to seven samples (N-4–N-10) taken between 12.9 m and 4.6 m and dated from 93.1 to 64.4 ka. These samples have identical TL glow curve shapes and therefore can be clustered under this criterion into a separate sedimentary unit. The last sample that has different TL glow curve is the uppermost sample N-1 dated to 20.4 ± 1.6 ka. This finding is to be expected because this distinct sedimentary unit is clearly associated with the period of the last glaciation in Northern Europe (MIS 2) and is composed primarily of coarse-grained sands with gravels and pebbles.

5. Discussion and interpretation

Geochemical, thermoluminescence, and magnetic susceptibility and its anisotropy data show that many specific boundaries (layers) were distinguished in the Netiesos section (Fig. 10). These boundaries often coincide with the lithological variations (subdivisions), plant macro-remain and pollen zones. This finding suggests the close relation of climate changes not only to vegetation development but also to changes in the deposition environment, the hydrodynamic regime and the derivation of incoming material.

Three factors determined from the geochemical data correspond to three major fractions of lake sediments, namely, the authigenic, biogenic and allogenic components: they were described, and a stepwise procedure for isolating them was devised by Engstrom and Wright (1984). Considering all of the evidence, the geochemical differences between the units can be predetermined by environmental conditions. The main period of the deposition of authigenic elements was during U1–U3 formation, decreasing to the middle of U8 (Table 3). This could be related to the feeding of palaeolake by hydrocarbonate groundwater, which decreased as

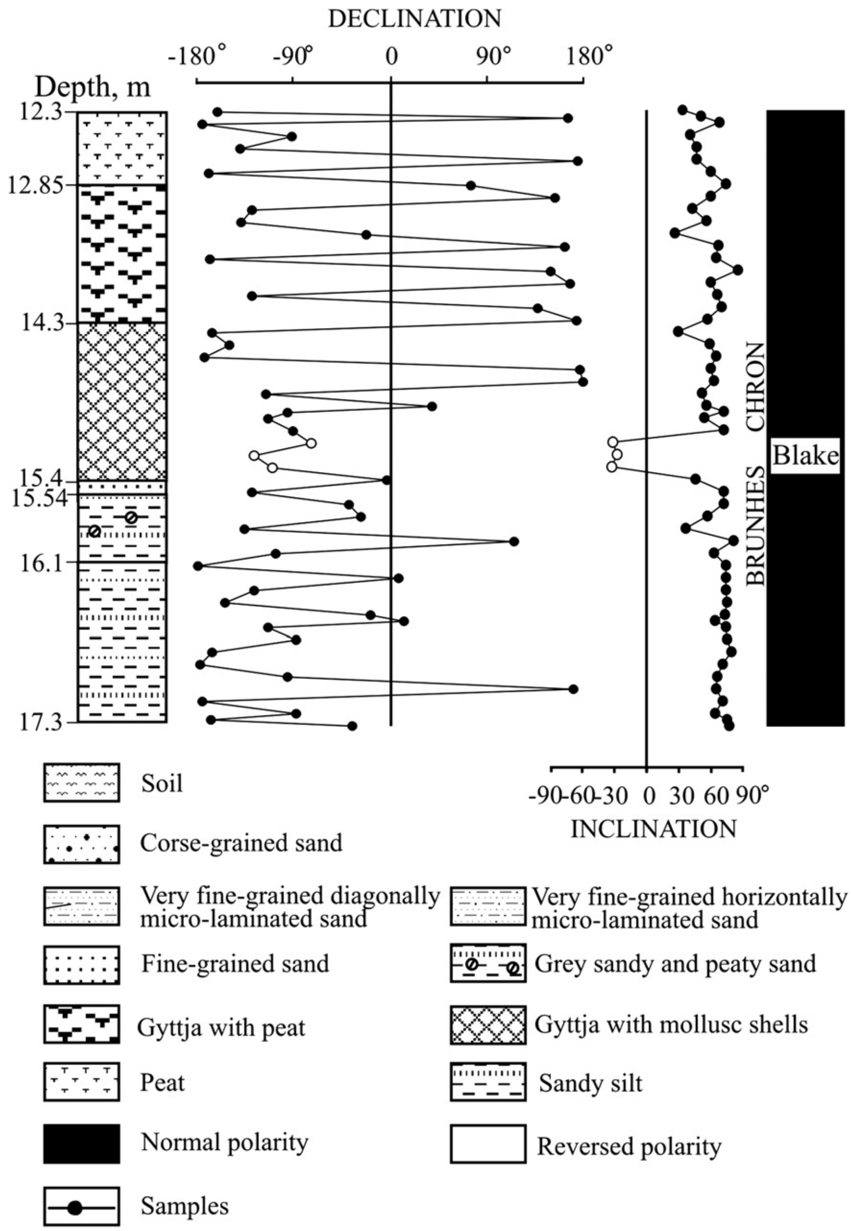

Fig. 8. Magnetic polarity scale from Netiesos section including inclination and declination data.

well (Bajkiewicz-Grabowska, 2004). Highly fluctuating during U2–U11 formation, the biogenic elements reached their highest values during U5–U9 formation. Meanwhile, for the minerogenic elements the main period was during the units UI3–U14 formation (Fig. 10). During U12, the decrease of biogenic sedimentation and sharp increase of palaeolake water level, considerably increased the allogenic (minerogenic) sedimentation. During U13, the amount of authigenic material fractionally increased. The primary source of allogenic (minerogenic) and authigenic material could be caused by the rise of the weathering from the Eemian weathering crust because of the cooling of the climate and degradation of the vegetation cover. Mineralogical investigations of the 2–3 m thick siallitic weathering crust formed from till during the Merkinė interglacial in Netiesos revealed a decrease in the carbonates, pyrite, potassium feldspars and other weathering less-resistant minerals (Baltrūnas, 1995). The analysis of rock debris in the gravel fraction indicated decreases in the limestone, marl, chalk, gneisses components and increases in the amounts of crystalline rocks, quartz and flint. The chemical analysis of the weathering crust showed an upward increase in SiO_2 and a decrease in Al_2O_3 and CaO, indicating that there was intensive leaching of Ca and Al from the crust (Baltrūnas, 1995, 2002). Those processes intensified since the beginning of U14.

According to the palaeobotanical investigations, development of the lake began in the late glacial phase and continued up to the end of the optimal phase of the Merkinė interglacial. Most likely, the sedimentation occurred in the sublittoral zone of the lake.

During the accumulation of the silt at the lowermost part of the section (plant macro-remain zone (PMZ) and pollen zone (PZ) Md) (Fig. 10), terrestrial vegetation was a mosaic, with forest islands in the tundra environment. This floristic complex is typical of the late glacial time that preceded the Merkinė (Eemian) interglacial. Similar types of vegetation during this period could be traced in neighbouring countries (Kalnina, 2001; Granoszewski, 2003;

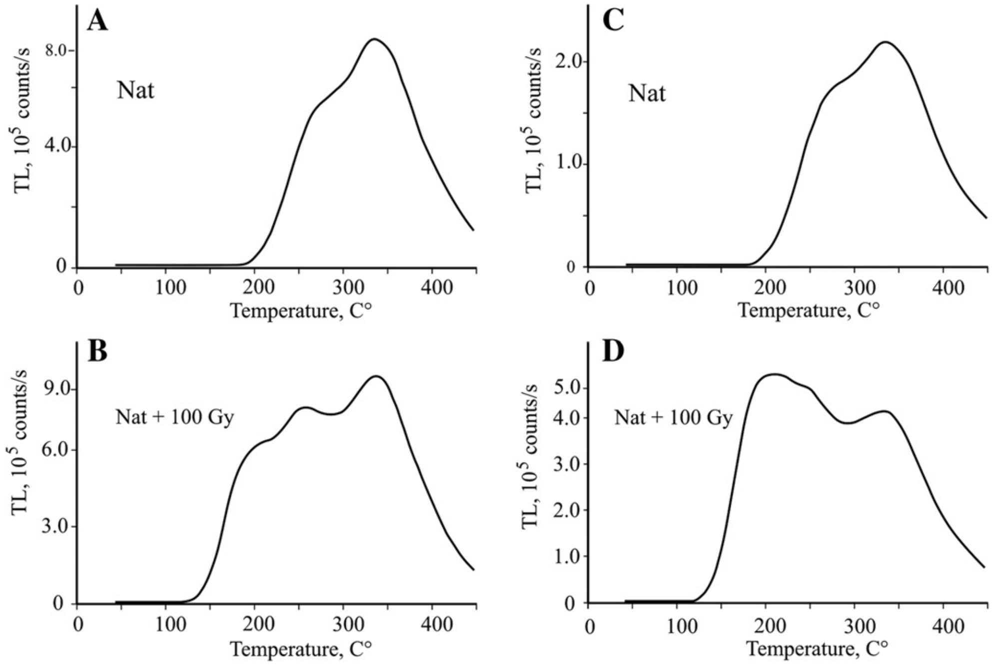

Fig. 9. Typical TL glow curve shapes for natural (A) and irradiated to 100 Gy (B) potassium feldspar extracted from the sediment samples N-4–N-10 taken from the depths between 12.9 and 4.6 m (91.1–64.4 ka). TL glow curve shape for natural (C) and irradiated feldspar (D) from the sediment sample N-11 taken at a depth of 3.9 m (20.4 ka) is considerably different.

Kupryjanowicz, 2008). Composition of macro-remains of water plant species as well as finds of small epiphytic cold-resistant *Fragilaria* diatom species indicates an oligotrophic character.

The transition from the late glacial complex to the interglacial is clearly fixed, as recorded by the change in the flora composition at the (PMZ Nl; PZ M1). The presence of thermophilic plants indicates the starting process of the eutrophication of palaeobasin and well-developed shore vegetation.

The most favourable conditions for vegetation evolution appear during the accumulation of gyttja and peat layers (interval 12.90–15.61 m; PMZ N3a–c–N4 and PZ M3a–c). At this time, the territory was covered by deciduous forests and numerous thermophilic water and terrestrial plant species were present. The existence of optimum conditions is proved by flourishing warm water eutrophic diatom species such as *A. granulata*, *S. rotula*, *C. ehrenbergii* and others. Temporal position of the PMZ N3a–N4 and PZ M3a–M4 zones in the second half of MIS 5 coincides with the ESR/IR-OSL palaeoclimatic records derived between 145 and 70 ka on directly ESR- and IR-OSL-dated warm climate-related deposits along the climate-sensitive arctic and subarctic regions of Northern Eurasia (Molodkov and Bolikhovskaya, 2009; Molodkov, 2012) and in Estonia (Bolikhovskaya and Molodkov, 2012). The time-dependent frequency distribution of ESR and IR-OSL dates (ca 245) obtained within MIS 5 on transgressive marine and inter-till palynologically characterized terrestrial sediments also demonstrates that the overwhelming majority of dates (ca 82%) are concentrated in the second half of MIS 5 in the time range between 110 and 70 ka, which may be correlated with periods of a relatively warm climate and flooding of the Arctic coastal areas due to global sea level rise.

Compositional changes of the flora during final stages of the palaeobasin development indicated the lowering of water level and transformation of the eutrophic lake into the bog. This is confirmed by changes in the lithology of the sediment. Deposits from the end of the interglacial may have been destroyed.

The palaeomagnetic Blake Event was recorded in the interglacial gyttja sediments at a depth from 15.45 to 15.15 m where three samples of reversed polarity were obtained. Although this geomagnetic inversion was studied by many researchers, the position and duration of this event has different interpretations (Tucholka et al., 1987; Zhu et al., 1994; Fang et al., 1997; Sier et al., 2011). The record of reversed polarity in the Netiesos section has great potential for more detailed study. The data obtained from the fish fauna that were collected from the gyttja of the Netiesos section clearly imply non-glacial conditions during MIS 5d, i.e., approximately 112 ka according to the ESR dates on freshwater mollusc shells from the same gyttja.

The peat layer of the PMZ N4 and PZ M4 zones is ESR dated at approximately 102 ka (MIS 5c). The peat layer is followed by the fine-grained sands, the lower part of which was dated to 93.1 $\pm$ 8.4 ka, and the middle part of which was dated to 89.8 $\pm$ 6.8 ka. Extrapolation of the data to the upper limit of the sand layer at a depth of 10.2 m indicates that the temporal limit of the layer is equal to 86.7 ka. Therefore, this layer may represent the transition between MIS 5c and MIS 5b (Bassinot et al., 1994; Cohen and Gibbard, 2011). The deposits from the final phase of MIS 5 have been destroyed in the studied section.

According to IR-OSL data, the fine-grained sands between the depths of 10.1 and 4.2 m were deposited in the cold period from approximately 66 to 64 ka. This period meets the middle part of MIS 4, which is associated with the first post-Eemian glaciation, during which glaciers reached as far south as approximately 53–52°N in the study region (Zarrina, 1991). However, no signs of glacigenic deposition were observed during this severe glacial event, neither in the Voka section on the south-eastern coast of the Gulf of Finland (59.4°N) (Molodkov and Bolikhovskaya, 2011) nor in the Netiesos section (~54°N). In addition, data indicate that deposits corresponding to the initial and final phases of this cold stage (MIS 4), as well as to the whole MIS 3 (~59–24 ka), are missing in the Netiesos section.

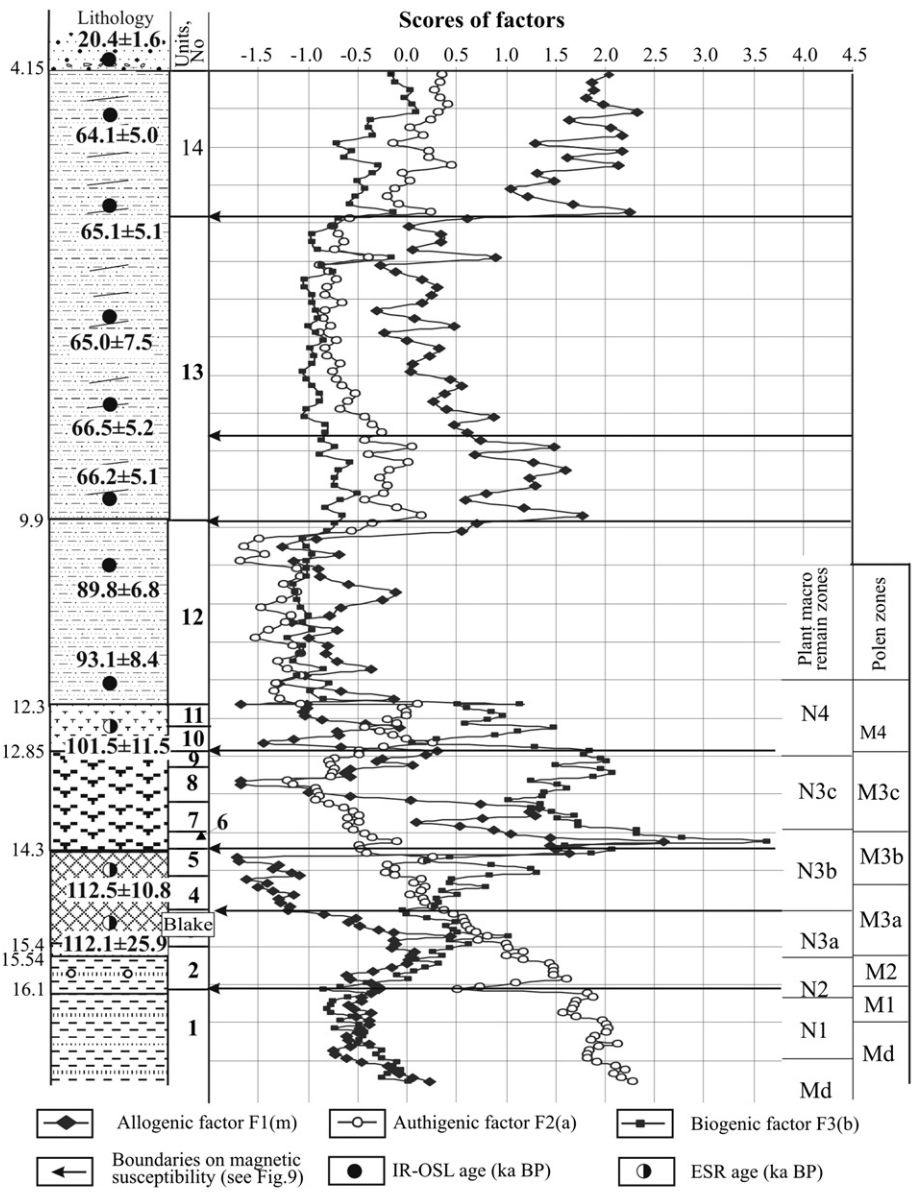

Fig. 10. Summary chart of palaeoenvironmental changes, based on complex data. For lithological description, see Fig. 8.

A sample of the coarse-grained sands with gravel and pebbles (N-11) taken at a depth of 3.9 m is dated at 20.4 ± 1.6 ka. It implies that the deposition occurred during the earlier part of MIS 2.

6. Conclusions

1. Comparison of the magnitudes and distribution pattern of the scores of minerogenic (allogenic), authigenic and biogenic factors determined according to geochemical data from 29 chemical elements distinguished 14 depth-related geochemical units (U1–U14), reflecting changes of sedimentation environment from the inherited glaciolacustrine to eutrophic lake with considerable water level changes.
2. Geochemical units fit well with depositional episodes revealed by investigation of magnetic susceptibility and its anisotropy. The boundaries between these units and episodes often coincided with the lithological and palaeobotanical zone boundaries.
3. Parallel geomagnetic and ESR geochronological research identified the palaeomagnetic Blake Event in the gyttja at a depth from 15.15 to 15.45 m ESR, dated at about 112 ka. This could be correlated with the beginning of the thermophilous deciduous forest phase of the last interglacial period (spread of *Quercus*, *Ulmus*, *Corylus*, *Pinus*).
4. Development of the Netiesos palaeolake began in the late Medininkai glacial (~MIS 6) and continued until the end of the deciduous forest phase of the Merkinė interglacial. Sedimentation in this period occurred in the sublittoral zone of the eutrophic lake, which gradually overgrew. Plant macro-remain data demonstrate the development of the terrestrial vegetation from open tundra with coniferous islands typical of the late glacial to broadleaved forests of interglacial times. The palaeoflora of the studied part of the Netiesos section is one of the richest floras of the last interglacial period in the East Baltic region, and it contains a high amount of thermophilic species with such unique elements as *Pilea lithuanica* and *Vitis vinifera.*
5. The temporal position of the thermophilous deciduous forests phase in the second half of MIS 5 coincides with ESR/IR-OSL palaeoclimatic records derived between 145 and 70 ka mostly

on directly ESR- and IR-OSL-dated warm climate-related deposits in the climatically highly sensitive Eurasian Arctic palaeo-shelf area.
6. The five fish species distinguished in the gyttja horizon of the Netiesos section are common in all types of the Holocene lowland lakes and rivers throughout most of Europe. Therefore, it can be concluded with a high degree of confidence that the data obtained from the fish fauna clearly imply non-glacial conditions in the vicinity of Netiesos during MIS 5d, i.e., approximately 112 ka, as derived from the ESR dating on freshwater mollusc shells from the same horizon. The overlying peat was ESR dated at approximately 102 ka.
7. The layer of fine-grained sands overlying the peat is sequentially dated by IR-OSL from 93.1 ± 8.4 ka to 89.8 ± 6.8 ka. The upper limit of the sand layer at a depth of 10.2 m is estimated to be 86.7 ka. This implies that the layer was formed mainly during the MIS 5c and MIS 5b transition. The deposits from the final phase of MIS 5 are most likely destroyed in the Netiesos section.
8. According to IR-OSL data, the overlying horizon of fine-grained sands was deposited in the period from approximately 66 to 64 ka, during the cold MIS 4. No signs of glacigenic deposition were observed within this period in the Netiesos section. Deposits corresponding to initial and final phases of the MIS 4, as well as to the entire MIS 3, are missing in the Netiesos section.
9. A sample of coarse-grained sands with gravel and pebbles taken in the upper part of the section is IR-OSL dated at 20.4 ± 1.6 ka and implies deposition during the earlier part of MIS 2.

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Appendix A. Supplementary material

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.quaint.2012.11.038.

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