Chronology of Late Saalian and Middle Weichselian episodes of ice-free lacustrine sedimentation recorded in the Arumetsa section, southwestern Estonia

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Abstract. The information obtained from a 21 m thick open-pit section of silty-clayey sediments in the Arumetsa bedrock valley, southwestern Estonia, revealed that lacustrine to glaciolacustrine sedimentation at the site started prior to 151 ka ago and lasted to about the end of marine isotope stage 6 (MIS6) at 130 ka. Further down from the 151 ka age-level to the bottom of the buried valley there are ca 60 m of lacustrine fine-grained sediments, the age of which remains still unclear. The Late Saalian sediments at Arumetsa are discordantly overlain by Middle Weichselian clay, silt and sand, deposited between ca 44 and 37 ka ago. As testified by optically stimulated luminescence (OSL) ages, and pollen and diatom record, the Middle Weichselian fine-grained sediments contain redeposited Holsteinian but no Eemian pollen, and have not been fully bleached during deposition. Chronological, microfossil and sedimentological data show two hiatuses in the Arumetsa section. The first hiatus has left no sedimentary evidence for the period between ca 130 ka and 44 ka ago (MIS5 to older half of MIS3). The younger hiatus from ca 37 to 22 ka occurs between the Middle Weichselian lacustrine silt and the Late Weichselian till layer on top of the section.

Key words: Late Saalian, Middle Weichselian, OSL dates, ^{14}C dates, pollen, ostracods, diatoms, Estonia.

INTRODUCTION

Deposits of the Late Saalian–Eemian transition (MIS6–MIS5e) have been described from many sites in northern Europe (see Fig. 1 and references therein). Several marine and terrestrial records indicate a rapid Late Saalian (Saalian II, Warthe) deglaciation with gradual warming conditions (Mamakowa 1989; Bińka & Nitychoruk 2001; Funder et al. 2002), others reflect a two-step event (called Zeifen-Kattegat oscillation), where warm conditions were interrupted by a cold dry oscillation preceding the Eemian Interglacial (Seidenkrantz 1993; Seidenkrantz et al. 1996, 2000; Beets et al. 2006). In the northeastern Baltic region there are a number of sediment sequences (Peski, Põhja-Uhtju, Juminda, Prangli, Kihnu, Core 21 in the Gulf of Riga, Satiki, Plašumi, Grini) where, according to current knowledge (Cheremisinova 1961; Kajak 1961; Liivrand 1991, 2007; Kalniņa 2001; Miettinen et al. 2002; Kadastik et al. 2003), the end of the Late Saalian (MIS6) cold stage is represented by lacustrine sediments. The Late Saalian age of these, usually laminated silty-clayey deposits has been derived from their position under the Eemian strata. The latter were recognized from the characteristic succession of pollen assemblage zones and occasionally from diatom analyses results (e.g. Kajak 1961; Liivrand 1987, 1991, 2007; Kalniņa 1997, 2001; Miettinen et al. 2002; Kadastik et al. 2003; Kalniņa et al. 2007).

The most complete Late Saalian to Eemian pollen succession in Estonia is known from the Prangli core section, indicating a gradual change from the Late Saalian limnic and brackish phase to ‘normal marine’ conditions in the early Eemian (Cheremisinova 1961; Kajak 1961; Liivrand 1987, 1991). Late Saalian sediments and respective pollen assemblage zones were also distinguished in the sections on Põhja-Uhtju Island (Miettinen et al. 2002) and the Juminda Peninsula (Kadastik et al. 2003) in northern Estonia, both indicating open late glacial

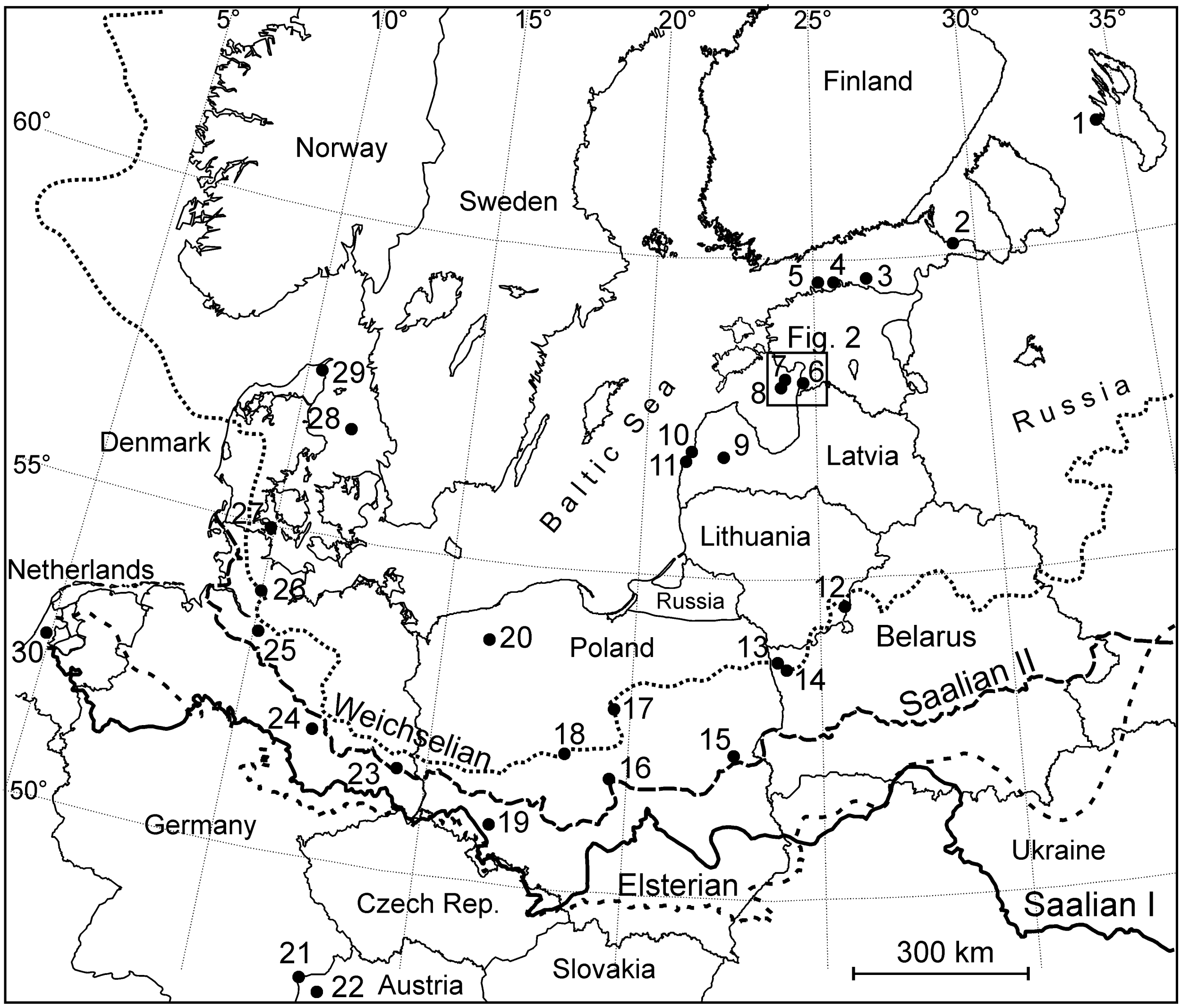

Fig. 1. Location of Late Saalian (Saalian II, Warthe) sites with lacustrine and marine deposits: 1, Petrozavodsk (Funder et al. 2002); 2, Peski (Miettinen et al. 2002); 3, Põhja-Uhtju (Miettinen et al. 2002); 4, Juminda (Kadastik et al. 2003); 5, Prangli (Cheremisinova 1961; Kajak 1961; Liivrand 1987, 1991); 6, Arumetsa (this paper); 7, Kihnu, Core 526 (Liivrand 1976, 1991, 2007); 8, Gulf of Riga, Cores 21 and 25 (Kalniņa 1997, 2001); 9, Satiki (Kalniņa et al. 2007); 10, Plašumi (Kalniņa 2001); 11, Grini (Kalniņa 2001); 12, Medininkai (Satkunas & Kondratienė 1998); 13, Pyshki (Shalaboda 2001; Litviniuk et al. 2002); 14, Zhukevichi (Sanko et al. 2002); 15, Dziewule (Bińka & Nitychoruk 2001); 16, Besiekierz (Mirosław-Grabowska 2009); 17, Studzieniec (Mirosław-Grabowska 2009); 18, Ruszkowek (Mirosław-Grabowska 2009); 19, Imbramowice (Mamakowa 1989; Mirosław-Grabowska 2009); 20, Rzecino (Mirosław-Grabowska 2009); 21, Zeifen (Beug 1973); 22, Mondsee (Drescher-Schneider & Papesch 1998); 23, Klinge (Velichko et al. 2005; Novenko et al. 2008); 24, Gröbern (Wansa & Wimmer 1990; Litt 1994); 25, Lüneburger Heide (Behre 1962); 26, Brokenlande (Menke & Ross 1967); 27, Mommark (Kristensen & Knudsen 2006); 28, Anholt (Seidenkrantz 1993; Knudsen 1994; Seidenkrantz & Knudsen 1997); 29, North Jylland (Apholm, Skærumhede, Skagen) (Knudsen & Lykke-Andersen 1982; Knudsen 1984, 1985, 1994; Seidenkrantz & Knudsen 1997; Sejrup & Knudsen 1999; Knudsen et al. 2009); 30, Amsterdam and Amersfoot basins (Zagwijn 1996; De Gans et al. 2000; Beets et al. 2006; van Leeuwen et al. 2000). Glacial limits are shown according to Ehlers & Gibbard (2004).

cold and dry conditions (derived from the presence of herbs *Artemisia* and Chenopodiaceae). Late Saalian silty-clayey deposits are found also on Kihnu Island (Liivrand 1976, 1991, 2007) in the Gulf of Riga, and in the coastal areas of Latvia (Kalniņa 1997, 2001). On Kihnu Island brown silty-clayey deposits were described beneath the Eemian marine sediments at a depth of 34–40 m (–32 to –38 m relative to sea level) (Liivrand 1976; Raukas 1978; Kajak 1996). The sediment sequence in Core 21 in the Gulf of Riga (~17 km SSE from Kihnu Island) shows a

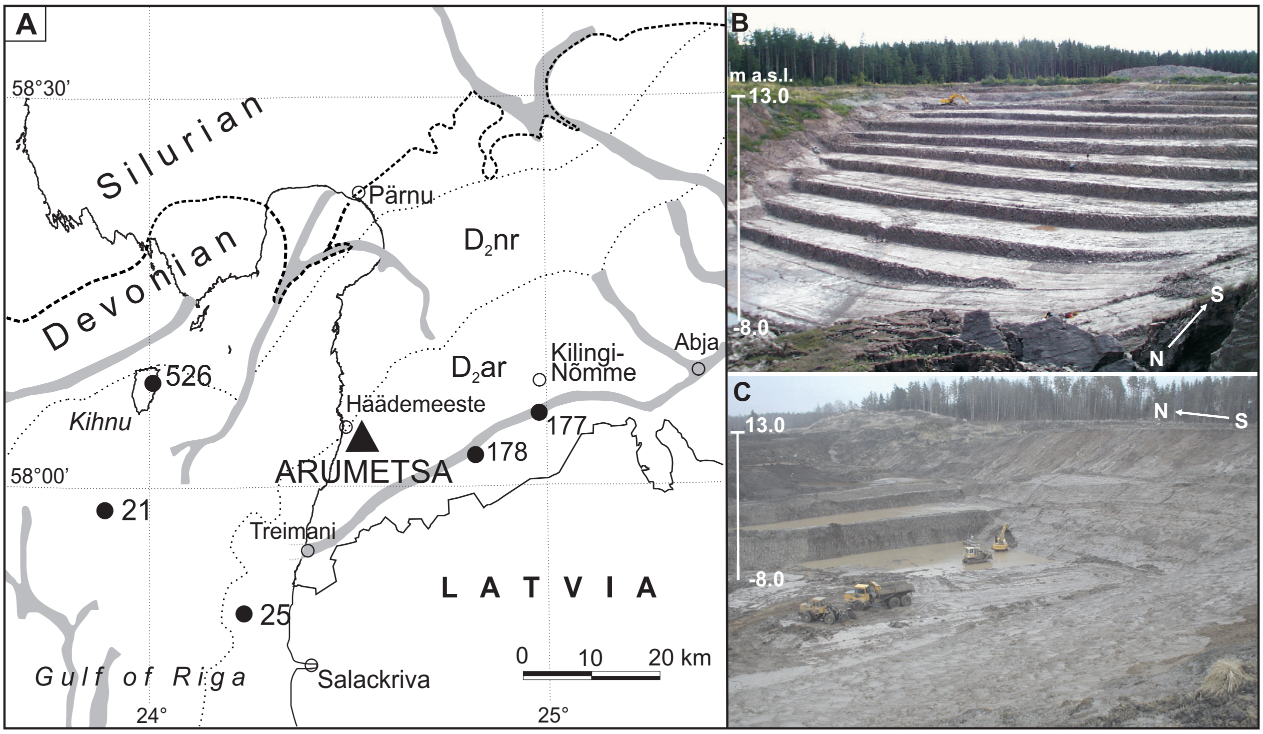

Fig. 2. (A) Location of the Arumetsa site (▲) and the other core sections (●) discussed in the text. Dotted lines mark the distribution of Devonian bedrock formations (D_2ar, Aruküla Fm.; D_2nr, Narva Fm.). Thick grey lines denote continuous buried bedrock valleys. Photos of the Arumetsa quarry taken in 2001 (B) and in 2005 (C).

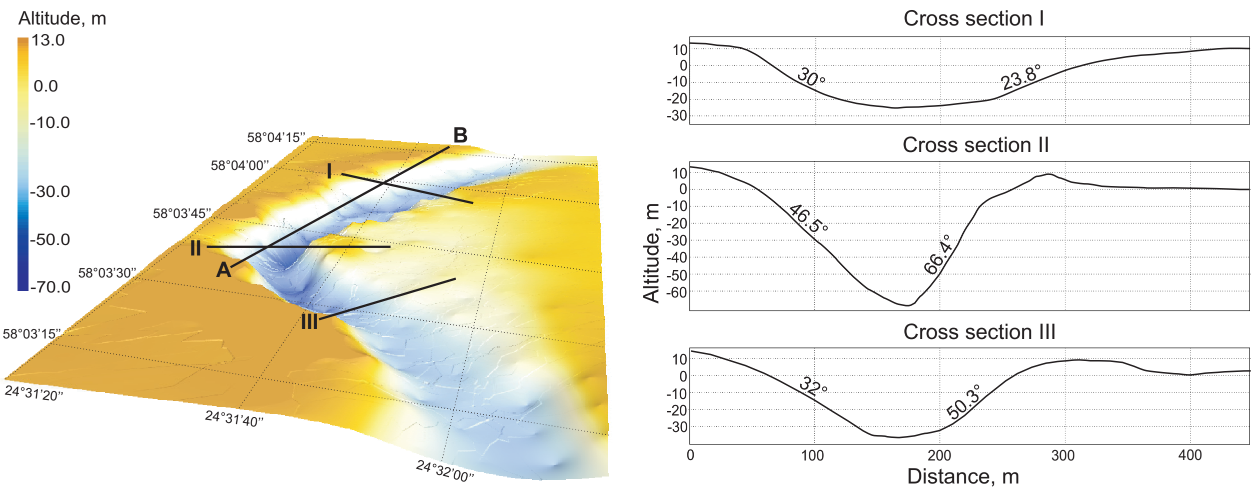

Fig. 3. 3D model and selected bottom profiles (I, II, III) of the bedrock valley at Arumetsa. A–B marks the line of the cross section presented in Fig. 4.

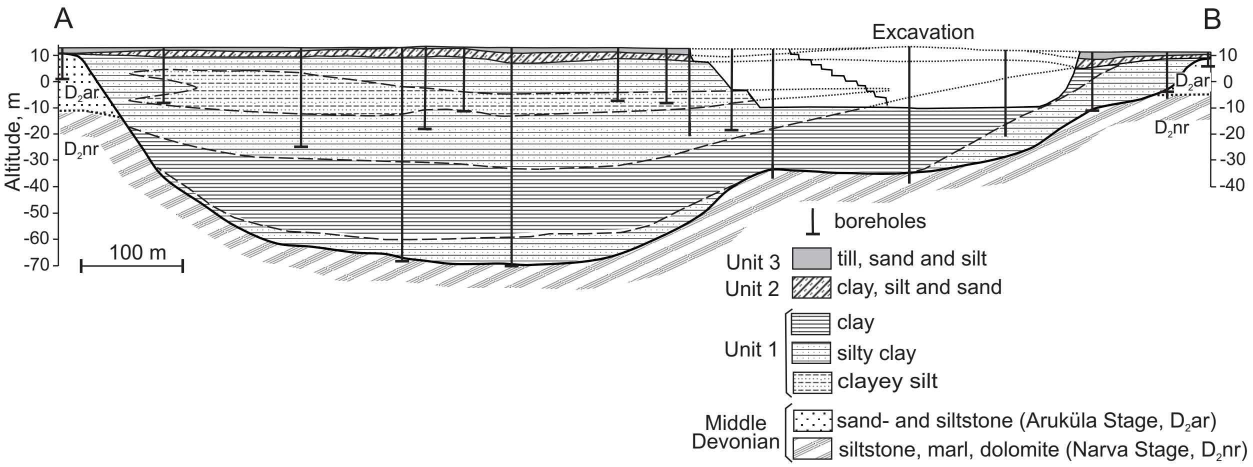

Fig. 4. Generalized cross section through the infill of lacustrine sediments in the Arumetsa valley. For location of the cross section see Fig. 3.

Fig. 5. Pieces of wood (*Pinus sylvesteris*; pers. comm. A. Läänelaid 2009) discovered at the base of SU2 and dated by means of conventional and AMS ^{14}C methods (see Table 3). Note the flat compressed cross section of the log fragments.

long continuous vegetation development (Kalniņa 1997, 2001) starting with the Saalian late glacial, continuing through the Eemian Interglaciation and ending in the Weichselian Glaciation.

However, regardless of the number of the studied sections, the Eemian strata as well as the underlying supposed Late Saalian non-glacial sediments have not been previously directly dated in this region. The absence of chronological data from the respective sequences may partly be due to the fact that most of the presumably Late Saalian and Eemian sediments were described and studied from core sections, which complicates the sampling for datings. The age control of the Late Saalian to Eemian sediment sequences has until now been based on the correlation of pollen and other micropalaeontological evidence with the NW European bio- and climate stratigraphies (Liivrand 1991, 2007; Kalniņa 2001; Miettinen et al. 2002).

The Arumetsa site is the northernmost one among the few open-cast sections with Saalian sediments in the eastern Baltic region. The site has been explored by the Geological Survey of Estonia since the 1950s as a clay resource. A total of 135 boreholes have been drilled in the area, 70 of which penetrate the clay complex, reaching the underlying Devonian bedrock. The 21 m thick section of the fine-grained sediment sequence, which was opened in the course of clay mining, provided an opportunity for detailed investigation of the sedimentological, compositional and chrono- and biostratigraphical characteristics of the sediments exposed.

The main objective of the current study is to report chronological data and determine the stratigraphical position of the Late Saalian (MIS6) and Middle Weichselian (MIS3) lacustrine sediments in the northeastern Baltic region. Chrono-, bio- and lithostratigraphical data are used to assess the duration of the episodes of lacustrine sedimentation at the Arumetsa site in southwestern Estonia. Microfossil and pollen data provide information on environmental conditions at the time of formation of different palaeolacustrine sedimentary units. The interpretation of detailed sedimentological data, sediment composition and provenance, and depositional environments is the topic of a forthcoming publication.

REGIONAL GEOLOGICAL BACKGROUND

The Arumetsa site (58°04′00″N, 24°31′40″E) is located in southwestern Estonia, about 40 km south of the town of Pärnu and 3 km east from the coast of the Gulf of Riga (Fig. 2). The bedrock surface in the area is gently rising from –50 m relative to sea level on Kihnu Island in the Gulf of Riga to about the current sea level near the coastline at Häädemeeste (Tavast & Raukas 1982) and up to 50 m a.s.l. on the slope of the Sakala Upland in the east (near the town of Kilingi-Nõmme). The upper sequence of the bedrock is composed of Devonian sedimentary rocks (sand- and siltstone, dolomitic marl and clay) ca 108 m thick at Häädemeeste and Arumetsa. The Quaternary cover is generally rather thin in the region, normally varying from <1 to 50 m. Most of it is composed of Late Weichselian till and glaciolacustrine sand, silt and varved clays of the Baltic Ice Lake, and the Holocene marine and aeolian deposits. The upper surface of the Arumetsa site lies at an elevation of 11–13 m a.s.l., that is well below the water level of the late glacial Baltic Ice Lake (>40 m; Rosentau et al. 2009). The greatest thickness of the Quaternary deposits occurs in buried valleys, reaching ca 200 m in the Abja–Treimani valley (boreholes Nos 177 and 178 in Fig. 2). The cores from the valleys revealed a sequence of Saalian and Elsterian tills and related aquatic deposits, but no interglacial sediments (Väärsi & Kajak 1969; Raukas 1978). On Kihnu Island and in its surroundings the up to 60 m thick Pleistocene sequence contains an up to 20 m thick inter-till layer of dark brown to grey clay. Liivrand (1991, 2007) identified Late Saalian and Early Weichselian pollen zones in this clay complex in core No. 526 from Kihnu Island. However, in the neighbouring core section (No. 21) in the Gulf of Riga Kalniņa (1997, 2001) determined an almost complete succession of pollen zones from the Late Saalian through the Eemian to the Early Weichselian. In core No. 25 in the Gulf of Riga Early Weichselian sediments lie directly on the Devonian bedrock and no Eemian or older deposits were found (Kalniņa 1997).

The valley that hosts lacustrine deposits at Arumetsa is a N–S oriented ca 2 km long and 300 m wide arc-shaped channel (Fig. 3). The 80 m deep valley is incised into the reddish-brown weakly cemented sand- and siltstone and dolomitic marl of the Middle Devonian Aruküla (D_2ar) and Narva (D_2nr) formations. The cross section of the valley has normally U-shaped morphology, with slopes of 20–30° or even ≥50° in some segments. The longitudinal profile of the valley shows an undulating bottom profile with hollows, thresholds and varying gradients, which is presumed to be the result of an irregular erosional cut. The irregularities in the valley bottom gradients indicate that the water flow may have been under substantial glacio-static pressure under the overlying ice sheet (ÓCofaigh 1996), thus confirming the conclusion on subglacial formation of the valley.

MATERIAL AND METHODS

Detailed sedimentological studies and sampling were carried out to the extent (ca 21 m) of the open-pit section

(Fig. 4) in the central part of the Arumetsa bedrock valley. Information on the deeper sediments, including their thickness and some grain-size data, is available from reports of earlier exploration works, conducted by the Geological Survey of Estonia. Borehole data were also used in reconstructing the morphology of the bedrock valley. Main sedimentary units and lithofacies were distinguished on the basis of their characteristic textures, structures, bedding conditions and post-depositional deformations. The lithofacies classification is modified from Eyles et al. (1983) and Krüger & Kjær (1999).

For ostracod separation and identification clayey sediments were first suspended and separated by wet sieving into two size-fractions (>0.25 mm and 0.1–0.25 mm). The material was dried at 105 °C, and ostracod carapaces and their fragments were picked out by hand and studied under a binocular microscope. Ostracod species were identified and their ecological preferences were determined using the Meisch (2000) monograph.

Samples for diatom analyses were prepared after the methods described in Battarbee (1986) and Miller & Florin (1989). Naphrax (refraction index RI = 1.7) was used as the slide mounting medium. Diatom frustules were counted on traverses across the slide at 1000× magnification under oil immersion. It was attempted to count a minimum of 300 diatom valves per slide where possible, and the abundance of each taxon was calculated as a percentage of total count. The diatom floras of Krammer and Lange-Bertalot (1986–1991) and Mölder and Tynni (1967–1973) were used for identification and as sources of ecological information.

Samples for pollen analyses were prepared following standard techniques (Berglund & Ralska-Jasiewiczowa 1986; Faegri & Iversen 1989), with additional flotation treatment with a heavy liquid (CdI_2 and KI solution with specific gravity of 2.2 g/cm^3) according to Grichuk's method (Pokrovskaya 1950). If possible, a minimum of 500 terrestrial pollen grains were counted. The basis for the percentage calculations was the sum of terrestrial pollen, i.e. the sum of arboreal pollen (AP) and non-arboreal pollen (NAP) as 100%. The percentages of the other identified microfossils were calculated from the basic pollen sum plus the actual value of the microfossil as 100%. The pollen diagram was compiled using the Tilia and Tilia-Graph software (Grimm 1992). Samples which contained less than 100 pollen grains are not shown in the diagram and the results are presented in the table instead.

Radiocarbon (^{14}C) and optically stimulated luminescence (OSL) dating methods were applied in order to establish the chronological framework for the studied sediment sequence. Six ^{14}C age estimations from wood (Fig. 5) and ten OSL datings of silty sediments were performed from the materials available in the outcrop section. Two conventional ^{14}C datings of wood were done at the Radiocarbon Laboratory at the Department of Geology, University of Tartu. Four ^{14}C accelerator mass spectrometry (AMS) datings from the same collection of wood pieces were performed at the Dating Laboratory of the University of Helsinki, Finland. The OSL ages were obtained at the Nordic Laboratory for Luminescence Dating at Risø, Denmark. Quartz equivalent doses were estimated using a Single Aliquot Regenerated (SAR) dose protocol (Murray & Wintle 2003). The dose rates were derived from a high-resolution gamma spectrometry (Murray et al. 1987), assuming that the samples were saturated with water during their burial time.

RESULTS AND INTERPRETATIONS

Lithostratigraphy

The Aruküla section displays three major sedimentary units (SU1, SU2 and SU3) (Figs 4 and 6). Each unit consists of several sediment facies.

Sedimentary unit 1 (SU1) forms the lower and the major part of the section (up to 72 m). It consists of two laterally discontinuous facies – laminated silty clay and homogeneous massive clay. Sediments of this unit fill in most of the bedrock valley and represent a long period of relatively steady para-pelagic sedimentation (Fig. 4). However, few dropstones (≤6 cm in diameter) of crystalline rocks were found in these sediments. Deformation structures occur in a large variety of morphologies (Fig. 6) and represent complex structures from deformations of different events at different times. The upper surface of the unit is an erosional plane of discontinuity. According to the information from old core sections, at the very bottom of the valley there is a 2 m thick, well-sorted, unconsolidated layer of bright brown silty sand with a sharp (erosional?) contact with the overlying brown clay (SU1).

Sedimentary unit 2 (SU2) of grey fine-grained sediments (fine sand to clay) has an undulating basal contact with SU1 and represents a continuous depositional sequence consisting of two low-energy lacustrine facies. Grey, massive clay is conformably overlain by laminated fine sand and silt facies, thus exhibiting coarsening-upward sediment succession. The thickness of SU2 varies between 1 and 8 m, being greater in the central part of the valley. At the base of SU2, just above the erosional contact with SU1, wood pieces (Fig. 5) were discovered.

The topmost unit (SU3) consists of two different facies. The first facies includes a discontinuous layer of a brownish, massive, medium-grained, matrix-supported (poor of clasts) diamicton with a maximum thickness

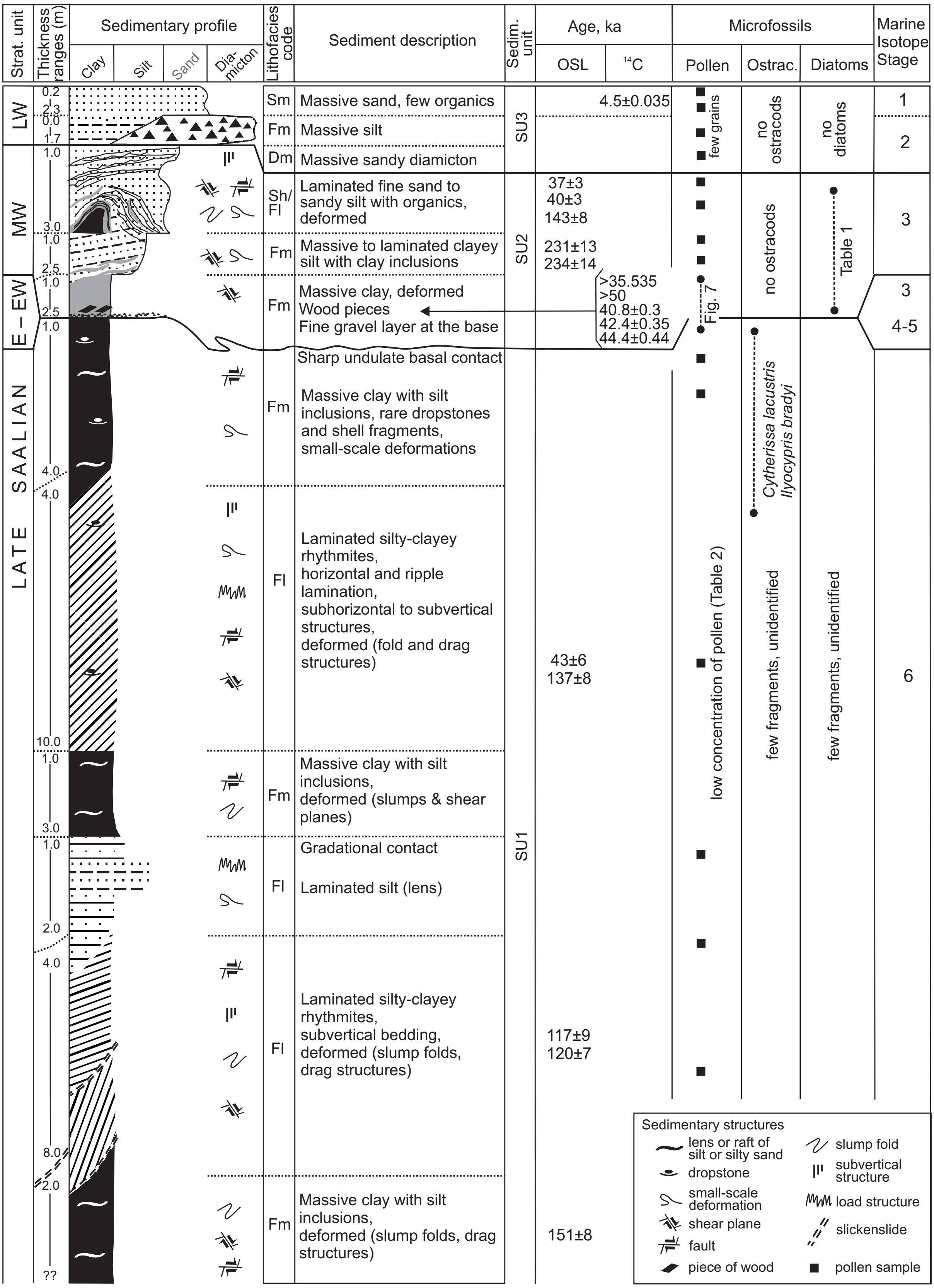

Fig. 6. Late Saalian to Holocene sedimentary sequence in the Arumetsa section shown on an age scale. Ages of MIS follow Martinson et al. (1987). LW, Late Weichselian; MW, Middle Weichselian; E–EW, Eemian and Early Weichselian.

of 2 m. The diamicton has a sharp conformable lower contact with the silty clay (SU2) underneath. Beyond the bedrock valley the diamicton lies directly on the Devonian sandstone. The diamicton is interpreted as the lodgement till of the last (Late Weichselian) glaciation, which is widely distributed in Estonia as the surficial till layer. Waters of local ice lakes and the Baltic Ice Lake have rewashed its upper portion. The till is mantled by a thin (±1 m), continuous, subhorizontal sheet of massive to vaguely laminated beige sand and sandy silt with occasional diffuse layers and pieces of redeposited organics (peat?). The sand and silt are interpreted as Late Weichselian and Holocene lacustrine sediments that deposited in a near-shore shallow zone during the Baltic Ice Lake and successive stages of the development of the Baltic Sea.

In general, the entire open section of clay and silt under the diamicton (SU3) shows many soft-sediment deformation structures at different levels. They occur in a large variety of morphologies and older deformations are overprinted by the younger ones. Slump, rolling-, folded-, fault- and compaction structures (Fig. 6) are common in the laminated lacustrine deposits at Arumetsa.

Microfossil and pollen record

The studied sequence of Arumetsa lacustrine sediments contains rare poorly preserved ostracods. The diatom and pollen material is also limited.

Ostracod carapaces and their fragments were found in four samples (out of 24 between the depths of 0.45 and 19.8 m) from the upper part of the massive brown clay of SU1 (Fig. 6). Identification of ostracod species was complicated because the majority of the carapaces were broken. Only two species were identified: the dominant *Cytherissa lacustris* and very few *Ilyocypris bradyi* individuals. The dominance of *C. lacustris* refers to cold and well-oxygenated water in a freshwater lake. However, the species is tolerant to salinities up to 1.5‰ and to great thermal fluctuation (Meisch 2000), referring to possible occurrence of slightly brackish-water conditions. Late Saalian marine sediments have been deposited in brackish-water conditions at the Prangli site in northern Estonia (Liivrand 1991) and in the coastal areas of western Latvia (Kalniņa 2001). *Ilyocypris bradyi* inhabits muddy and sandy bottom sediments of springs, ponds and lakes fed by springs. Thus, it indicates also cold-water aquatic environment, but low water level. Usually *I. bradyi* is associated with very low salinities, but it tolerates oligohaline waters of up to 4.4‰ salinity (Meisch 2000).

Diatoms were found only in the massive grey clay facies of SU2 (Fig. 6). Within the facies the abundance and diversity of the diatom assemblage are increasing upwards. The diatom flora is a typical freshwater (oligohalobes) assemblage, dominated by planktonic species of the genera *Aulacoseira*, *Stephanodiscus*, *Cyclosyephanos* and *Cyclotella*. The species *A. islandica*, *A. granulata* and *S. astraea* make up about 70% of the diatom flora (Table 1).

The brown clay and silty clay of SU1 are virtually barren of diatoms, containing only occasional unidentifiable fragments. Probably the environment during clay sedimentation was not suitable for the diatoms who possibly need more sunlight and clear water for their normal life than may have been available in the suspension-rich body of water.

Pollen data from the Arumetsa section are rather limited. Sedimentary unit 1 is characterized by a very low concentration (Table 2) of poorly preserved pollen grains, which suggest redeposition. Although occurring in low quantities, the pollen of trees (85%) dominates over the herbs (15%). *Betula*, *Pinus* and *Alnus* pollen were dominant, other trees (*Picea*, *Tilia* and *Quercus*) and herbs (*Artemisia*, Chenopodiaceae, *Eurotia ceratoides* and *Hippophae rhamnoides*) were represented by only few grains. Contrary to pollen, sediments of SU1 are rich in microscopic charcoal particles (Fig. 7) and in pre-Quaternary (Mesozoic to Silurian) palynomorphs (Table 2).

Table 1. Distribution of diatom taxa (number of identified valves) in samples from sedimentary unit 2 in the depth interval from ca 0.9 to 1.4 m, and their ecological preference. Analysed by M. Sakson

Diatom taxa	Sample depth, m		Ecology
	0.9	1.4	
Aulacoseira islandica (O. Müller) Simon.	226	230	p
A. islandica spp. *helvetica* Grun.	61	10	p
Aulacoseira sp. resting spores	78	24	p
Stephanodiscus astraea (Ehr.) Grun.	92	20	p
Fragilaria brevistriata Grun.	54	2	p
F. inflata var. *istvantfyi* (Pantocsek) Hust.	20	1	e
F. pinnata Ehr.	10	3	e
Opephora martyi Heribaud	10	8	e
Achnanthes clevei Grun.	3	1	e
Achnanthes spp. frag.	4	2	e
Diploneis ovalis (Hilse) Cleve	3	–	b
Navicula scutelloides W. Smith	4	1	b
Gyrosigma attenuatum (Kütz.) Rabenh.	2	1	b
Cyclotella cf. *iris* Brun.	1	–	p
Pinnularia sp. frag.	2	2	b
Total diatom valves counted (per sample)	570	305	
Relative abundance per traverse	57	10	

Ecology: p, planktonic; e, epiphytic; b, benthic.

Table 2. Redeposited Quaternary pollen and spores, and pre-Quaternary palynomorphs in the brown clay complex (SU3) at Arumetsa. Analysed by E. Liivrand

	Number of findings					
	Depth, m					
	3.6	4.8	9.8	13.0	14.8	16.8
Quaternary pollen						
Picea	–	–	–	1	1	–
Pinus	1	–	11	10	3	–
Betula	–	–	–	15	2	–
Alnus	–	–	–	6	–	–
Quercus	–	–	–	–	2	–
Tilia	–	–	–	1	–	–
Salix	–	–	–	2	–	–
Chenopodiaceae	–	–	1	–	6	1
Artemisia	–	–	–	3	1	–
Eurotia ceratoides	–	–	–	–	1	–
Hippophae rhamnoides	–	–	–	–	1	–
Polygonaceae	–	–	–	–	1	–
Sphagnum	1	1	1	4	2	–
Polypodiaceae	–	1	–	–	–	–
Bryales	–	–	–	–	1	–
Unidentified	–	–	–	5	2	–
Pre-Quaternary polynomorphs						
Mesozoic						
Gleichenia	–	–	–	1	3	–
Mohria	–	–	–	–	–	2
Carboniferous						
Eupicea	–	–	–	–	1	2
Trilobozonotriletes	–	1	–	1	–	–
Trematozonotriletes	–	–	–	2	1	–
Euryzonotriletes	–	–	–	–	2	2
Devonian						
Veryachium	–	–	–	2	–	–
Hymenozonotriletes perpusillus	–	–	–	2	2	–
Pre-Cambrian to Silurian						
Acritarchs	–	–	–	3	1	–
Unidentified	3	2	1	6	13	–

Pollen of trees, mainly of conifers *Pinus* and *Picea*, is prevailing (96%) in the clay and silty clay facies of SU2 (Fig. 7). Among deciduous trees *Alnus* and *Betula* dominate and only few pollen grains of broad-leaved trees – *Quercus*, *Ulmus*, *Tilia* and *Carpinus* – were found. Laminated silt and fine sand above clay contain lesser amounts of pollen but the proportion of trees is still high (80–85%), with *Pinus* and *Betula* the main taxa. The sum of herbs and grasses, mainly Poaceae and Cyperaceae, reaches 20%. The pollen in SU2, being overwhelmingly derived from trees, refers to their interglacial origin, but not any typical forest succession or pollen-zonal record of known interglacials was observed (Fig. 7). Similarly to the lacustrine sediments below the Late Weichselian till in the Kihnu section (Liivrand 2007), the pollen record from Arumetsa refers to possible redeposition from older interglacial sediments. Holsteinian and Eemian sediments are the only possible source for the tree pollen of interglacial origin in the region. The Holsteinian sediments are characterized mainly by the pollen of conifers, with high amounts of *Alnus* and very modest *Corylus* pollen. In the Eemian strata the pollen of deciduous trees dominates, with both *Alnus* and *Corylus* occurring in large amounts (Liivrand 1991, 2007). On the basis of this evidence we may draw a conclusion that Holsteinian and not Eemian sediments have served at least partly as a source for fine sand and silt in the current SU2.

Age of the deposits

Altogether six ^{14}C and ten OSL age estimations (Tables 3 and 4) from eight different depth levels were applied in reconstructing the time frame for the sedimentary profile at Arumetsa and for respective geological development of the region. In SU1 the five OSL ages vary from 151 ± 8 to 43 ± 6 ka (Fig. 6). However, one of the two parallel samples from a depth of 10 m yielded a ca 100 ka younger age (43 ± 6 ka) than the other (137 ± 8 ka, see Table 3) and the whole cohort of ages from this sedimentary unit. The OSL measurements from the same sample (43 ± 6 ka) were poorly reproducible and the dating was disregarded in further interpretations. Although not ideally correlated with depth, the rest of the OSL ages from SU1 refer to Late Saalian to Eemian age (151 ± 8 to 117 ± 9 ka) of the sediments. However, the pollen and diatom data from the Arumetsa section, if compared with their records from the Eemian sediments in the region (Liivrand 1991; Kalniņa 2001; Miettinen et al. 2002), unequivocally rule out the Eemian age of the sediments in SU1. Indeed, the very low abundance of poorly preserved pollen and diatoms with no typical successions of flora and fauna assemblages demonstrate that the sediments under discussion should not be correlated with the Eemian strata. Considering the OSL ages and the pollen and diatom record from SU1, we presume its Late Saalian (MIS6) age.

Wood pieces immediately above the erosional contact between SU1 and SU2 (Figs 5 and 6) were dated using conventional and AMS radiocarbon methods (Table 3). The conventional method yielded infinite ages (≥ 35.5 and ≥ 50 ka), but the four AMS datings (between 44.5 and 40.8 ka) proved the MIS3 (Middle Weichselian) age of the wood and thus the base of SU2. Five OSL ages from the upper fine sand and silt facies in SU2 follow the stratigraphic order with the oldest (234 ± 14 ka) at

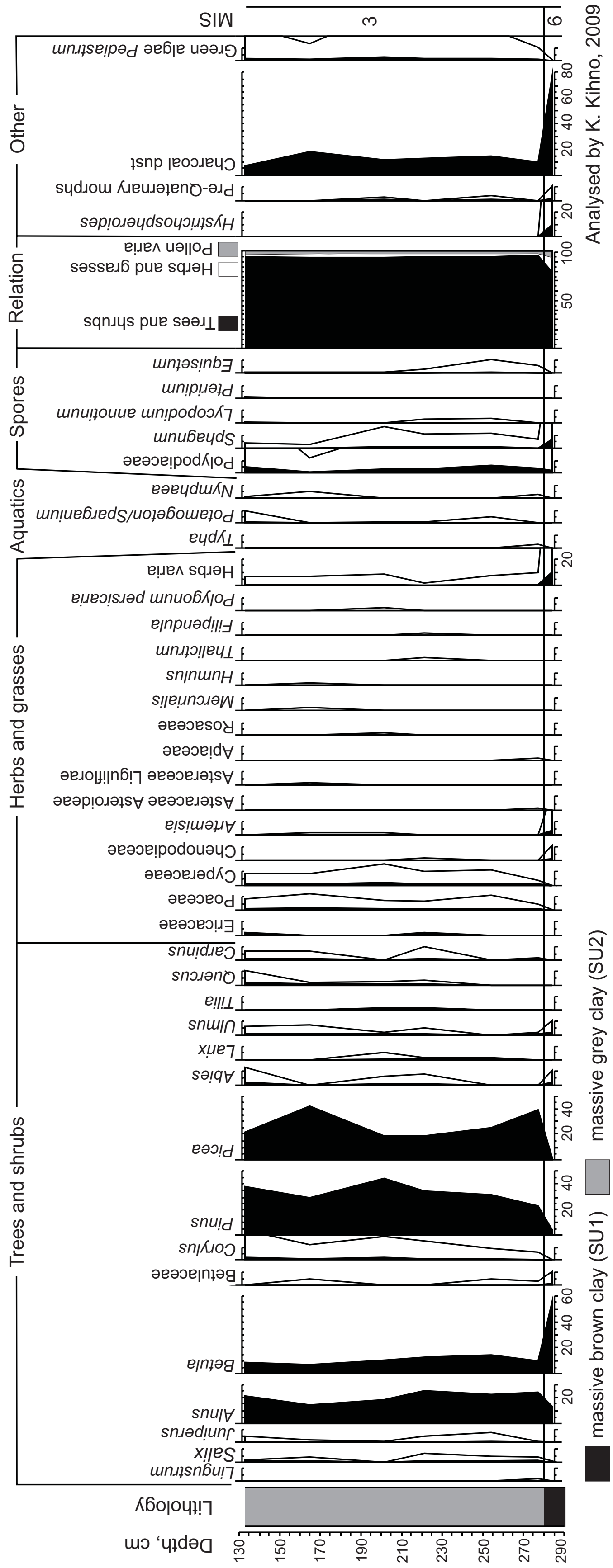

Fig. 7. Pollen diagram from SU2 with the transition from SU1 to SU2 at the bottom. The black areas on the diagram show the actual pollen abundance in per cent, while the white areas show the actual percentages with an exaggeration of 10×.

Table 3. ^{14}C ages of wood and organics (peat) from the Arumetsa section by conventional (Ta) and AMS (Hela) methods

Laboratory No.	Dated material	$\delta^{13}C$, ‰	Abs. pMC, %	Age, ^{14}C yr BP
Ta-2845*	Wood	–	–	≥35 535
Ta-2846	Wood	–	–	≥50 000
Hela-1600	Organics (peat)	–28.5	57.08 ± 0.25	4 450 ± 35
Hela-1599*	Wood	–23.7	0.62 ± 0.02	40 840 ± 300
Hela-1601	Wood	–25.9	0.39 ± 0.02	44 410 ± 440
Hela-1602	Wood	–28.4	0.51 ± 0.02	42 350 ± 350

* Samples are taken from the same piece of wood. pMC = per cent modern carbon.

Table 4. OSL age determinations from the Arumetsa section

Risø No.	Depth, m	Dated material	Age, ka	Dose, Gy	*n*	Dose rate, Gy ka^{-1}	Water content, %
052901	0.6	Fine sand	37 ± 3	89 ± 7	24	2.39 ± 0.08	33
052902	1.08	Fine sand	40 ± 3	104 ± 7	24	2.56 ± 0.09	31
052903	1.1	Fine sand	143 ± 8	355 ± 13	32	2.48 ± 0.10	24
052904	1.68	Fine sand	231 ± 13	372 ± 13	32	1.61 ± 0.06	29
052905	2.08	Grey silt	234 ± 14	374 ± 16	31	1.60 ± 0.06	35
052906*	10.0	Silt in brown clay	43 ± 6	146 ± 19	23	3.35 ± 0.12	31
052907	10.0	Silt in brown clay	137 ± 8	373 ± 14	33	2.73 ± 0.10	32
052908	16.5	Silt in brown clay	120 ± 7	413 ± 17	22	3.45 ± 0.13	30
052909	16.5	Silt in brown clay	117 ± 9	368 ± 23	23	3.14 ± 0.12	32
052910	20.0	Silt in brown clay	151 ± 8	502 ± 18	21	3.32 ± 0.11	49

* Sample was very weak and poorly reproducible. All water contents are laboratory saturation values.
n, the number of individual measurements used to derive the dose.

the bottom and successively younger with lesser depth (Fig. 6). However, the three oldest OSL ages (234 ± 14, 231 ± 13 and 143 ± 8 ka) above the 44.5–41 ka old base of the unit, although in a logical age-depth order, may equally represent incomplete bleaching of sediments, redeposition from the older strata without complete bleaching or combination of the two possibilities. Pollen evidence from SU2 suggests the redeposition from the Holsteinian sediments which ought to have a much greater age (MIS9, ca 330–310 ka; Litt 2007) than the referred OSL ages. Consequently, SU2, particularly its sandy-silty facies, is a mixture of the older sediments from different sources, whereas the sediments did not completely bleach during the final sedimentation. The two youngest OSL dates (37 ± 3 and 40 ± 3 ka) from the uppermost part of SU2 confirm the MIS3 (Middle Weichselian) age of the unit, derived from the ^{14}C ages of the wood at its base.

The till above SU2 obviously belongs to the Late Weichselian glaciation, although not directly dated at Arumetsa. The till and the whole section are capped by a layer of lacustrine sand. An occasional piece of redeposited organics (peat) in the cover sand from a depth of 0.6 m was dated back to 4450 ± 35 ^{14}C yr BP.

GEOLOGICAL DEVELOPMENT RECORDED AT ARUMETSA

Lacustrine environment at the Arumetsa site existed at least during Late Saalian time (MIS6), which is documented by the OSL age (151 ± 8 ka) and microfossil data from the clayey sediments at the bottom of the open-pit section. In the Late Saalian sequence of the section (SU1, Fig. 6) rhythmite packages alter with layers of massive clay, indicating variable water depth and sediment influx conditions.

With the exception of ostracods in the uppermost massive clay facies, the sediments in SU1 are practically barren of diatoms and ostracods and contain only few poorly preserved grains of redeposited pollen. From this circumstance we derive a conclusion that the majority of SU1 represents periglacial glaciolacustrine deposition in close proximity to the seasonally melting glacier and there are no Eemian sediments in this unit. In addition, we presume that the Late Saalian sediments at Arumetsa have been deposited earlier, in more severe climatic conditions than the known pre-Eemian deposits of the region (Kihnu Island, Core 21, Satiki, Prangli, Põhja-Uhtju), which are relatively rich in pollen and diatoms (Liivrand 1991, 2007; Kalniņa 2001; Miettinen et al. 2002; Kadastik et al. 2003; Kalniņa et al. 2007). The 151 ± 8 ka age from the Arumetsa silty clay correlates well with the mid-MIS6 discharge event at 155 ka ago, interpreted (Toucanne et al. 2009) as reflecting the retreat of the ice sheet between the Early Saalian (Drenthe, Saalian I) and Late Saalian (Warthe, Saalian II) advances (see Fig. 1). The Late Saalian (Warthe) maximum occurred between 143 and 140 ka BP (Lambeck et al. 2006) and was more extensive than the Weichselian one (Miettinen et al. 2005). However, in the Arumetsa sediments there is no other direct evidence of a glaciation than the Late Weichselian till at the top of the sequence. Nevertheless, occasional dropstones in the clay rhythmites of SU1 indicate that deposition from the bottom of the glacier which ran over or floated above the deep valley at Arumetsa may have taken place during Late Saalian time.

In the uppermost facies of SU1 (brownish massive clay) *Cytherissa lacustris*-dominated ostracod fauna appears, referring to a cold, well-oxygenated freshwater body of water. The occurrence of the ostracod *I. bradyi* in this clay indicates a change to shallower water, which may be due to valley fill with sediments and an isostatic uplift following the Late Saalian glaciation. From the borehole data it is evident that the lacustrine sedimentation and respective environment at Arumetsa appeared well before the dated age-level of 151 ± 8 ka BP at the depth level of ca 20 m from the ground.

From the southern fringe of the Baltic Sea basin Knudsen et al. (2009) reported the ≥140 ka old Late Saalian Skærumhede Till in Denmark. Head et al. (2005) recorded an only 4.5 m thick varved clay layer between the Warthanian (Late Saalian) till and the Eemian sediments in the Licze core in northern Poland. As no till layers were recorded in the core sections further down to the bedrock, at Arumetsa the Late Saalian lacustrine sedimentation has lasted considerably longer than in the southern Baltic region. However, the true age of the sediments in the lower portion of the Arumetsa buried valley remains unclear.

An erosional plane of discontinuity occurs on top of SU1, separating the Late Saalian sediments below from the Middle Weichselian sediments (SU2) above. The base of SU2 is firmly dated (Fig. 6) to the middle (44.5–41 ka) of the Middle Weichselian interstadial (MIS3, 60–25 ka; Martinson et al. 1987), indicating a long-lasting hiatus or/and a period of erosion prior to 44.5 ka BP. However, 40 km southwest of the Arumetsa site, in the core section (Core 21) from the Gulf of Riga, Kalniņa (2001) has estimated an almost complete sediment record from the Late Saalian through the Eemian to the Weichselian Glaciation. In the current topographic setting the known Eemian sediments in the Gulf of Riga region (Core 21, Kihnu Island) are located at a depth of –32 to –41 m relative to the present sea level (Kalniņa 2001), while at Arumetsa the hiatus between Late Saalian and Middle Weichselian sediments lies at 5–8 m a.s.l. This would imply that the possibility of having terrestrial (and erosional?) conditions with no sedimentation at Arumetsa during the Eemian and Early Weichselian, when the bedrock valley was already filled in with Late Saalian sediments (see Fig. 4), cannot be ruled out. The pollen and OSL ages evidently suggest a redeposition of SU2 at least partially from the Holsteinian but not from the Eemian sediments. Contrary to the Eemian strata, the known Holsteinian sediments in the region (at Karuküla, 32 km east of Arumetsa, see Fig. 2) are located between 60 and 62 m a.s.l., that is well above the SU2 level at Arumetsa, and in principle may have served as some source for the sediments in SU2.

The uppermost sandy-silty layers of SU2 just underneath the Late Weichselian till yielded OSL ages of 40 and 37 ka and thus the whole SU2 provides a record covering a time period from about 44.5 to 37 ka. Other directly dated Middle Weichselian sections in Estonia exhibiting continuous lacustrine sedimentation are Voka (between 44 and 31 ka; Molodkov 2007) in northern Estonia, and Peedu (ca 40–31 ka; Punning 1970), Rõngu (40–32 ka; Kalm 2005) and Kammeri (43–41 ka; Kalm 2005) in southern Estonia. Evidently the onset of lacustrine environments around 44–41 ka had to be extensive in this region. Further south in the eastern Baltic a number of Middle Weichselian lacustrine sediment sequences have been dated: Lejasciems (36–32 ka; Zelčs & Markots 2004) in Latvia, and Purviai (34–33 ka; Satkunas et al. 2009), Netiesos (48–34 ka; Gaigalas et al. 2005) and Rokai (55–45 ka; Gaigalas & Hütt 1995) in Lithuania. The presented chronological evidence suggests that terrestrial lacustrine environments were widely spread almost throughout MIS3 (60–25 ka) in the eastern Baltic region.

As the onset of the Late Weichselian glaciation in Estonia occurred at ca 22 ka BP (Kalm 2006), another hiatus exists between the Middle Weichselian lacustrine and Late Weichselian glacigenic sediments in the Arumetsa section or, alternatively, the youngest layers of the Middle Weichselian sediments have been eroded away in the course of the last glaciation. The age of the ^{14}C-dated fragment of peat (4.5 ka) from the sand above the till layer confirms the notion on postglacial formation of the cover sands in the Arumetsa region.

CONCLUSIONS

The Late Saalian sediments at Arumetsa are represented by periglacial freshwater massive to varved clay and silt which yielded OSL ages between 151 and 117 ka, while pollen and diatom record (i.e. absence in the sediments) rules out the Eemian age of the deposits. These are the first datings of the Late Saalian (MIS6) sediments in the northeastern Baltic region. Borehole data show the presence of 60 m of fine-grained lacustrine sediments with no till layers below the 151 ka age-level. Consequently, the lacustrine sedimentation at Arumetsa started much ahead of this date, although the true age of the sediments below the open section remains unclear.

The Middle Weichselian complex of lacustrine clayey-silty sediments at Arumetsa overlie discordantly the Late Saalian strata and provide a record for the time period between 44 and 37 ka ago. However, combined chronological evidence from different sections suggests that in the eastern Baltic area terrestrial lacustrine environments were widely spread almost throughout MIS3 (60–25 ka).

The chronological, microfossil and sedimentological data prove two hiatuses in the Arumetsa section. These hiatuses have left no sedimentary evidence for the periods from ca 130 to 44 ka and from 37 to 22 ka.

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Hilis-Saale ja Kesk-Weichseli järvelise settimise episoodide kronoloogia Arumetsa läbilõikes Edela-Eestis

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Arumetsa karjääri 21 m paksuse aleuriidi ja savi läbilõike komplekse uuringu (OSL- ning ^{14}C-dateeringud, sedimentoloogilised, õietolmu-, diatomeede ja ostrakoodide analüüsid) tulemusel selgus, et järvelised tingimused Arumetsa aluspõhjalises orus eksisteerisid Saale (Ugandi) külmaperioodi lõpul vähemalt alates ajast 151 000 aastat tagasi ning kestsid kuni Eemi (Prangli) jäävaheaja alguseni (umbes 130 000 aastat tagasi). Puursüdamike andmeil on Arumetsas 151 000 aasta vanuse taseme all veel 60 m järvelise või jääjärvelise tekkega peeneteralisi setteid, mille vanus on praegu ebaselge. Hilis-Saale setete peal lasuvad põikselt Kesk-Weichseli (Kesk-Järva) savi, aleuriit ja liiv, mis ladestusid ajavahemikul 44 000–37 000 aastat tagasi. Nimetatud Kesk-Weichseli (Kesk-Järva) setted sisaldavad ümbersettinud puude õietolmu, mis on pärit Holsteini (Karuküla), aga mitte Eemi (Prangli) jäävaheaja setteist. Arumetsa läbilõikes on kaks ajaliselt pikka katkestust: vahemikus ligikaudu 130 000–44 000 ja 37 000–22 000 aastat tagasi.