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The sedimentary sequence recovered from the Voka outcrops, northeastern Estonia: implications for late Pleistocene stratigraphy

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Abstract. New palaeoenvironmental and geological data, which may be integrated with the results from the neighbouring regions, were collected from two well-exposed continuous outcrops in the vicinity of Voka village, northeastern Estonia. These outcrops, situated in a klint depression – klint bay –, show an about 22 m thick stacked sequence of sandy to clayey subaqueous deposits. This succession of water-lain sediments documents the response to climate change during the late Pleistocene. On the basis of grain size characteristics, sedimentological structures, and luminescence chronostratigraphical data, the sequence is subdivided into two main units – A and B. Optical dating of 18 samples from the upper unit A shows that the unit is of middle Järva (= middle Weichselian) age (marine isotope stage (MIS) 3). Representative pollen spectra derived from 45 samples from the pollen-bearing part of unit A provide convincing evidence of noticeable changes in vegetation and climate in NE Estonia during the time period from 39 to 33 kyr BP, within which two intervals of severe climate and two relatively milder ones have been recognized. Preliminary data from the underlying unit B indicate that deposits of the last interglacial *sensu lato* and those of early pleniglacial age correlating with MIS 5 and MIS 4, respectively, occur here as well. Thus, the data obtained during the present study show unambiguously that in contrast with the expectations, the greater part of the late Pleistocene sequence is represented in the Voka section. No evidence was found for glacial activity during the late Pleistocene period predating the last glacial maximum. The use of the Voka event stratigraphy as a template facilitates search for correlative horizons in the neighbouring regions.

Key words: last ice age, chrono- and palynostratigraphy, northeastern Estonia, Voka site, palaeoenvironmental changes.

INTRODUCTION

The greater part of the modern southern coastline of the Gulf of Finland is bordered by the steep northern margin of the Harju–Viru limestone plateau, widely known as the North Estonian Klint. The klint makes up approximately a quarter of the up to 1200 km long Baltic Klint, which extends from the western coast of the Island of Öland in Sweden to the southern shore of Lake Ladoga (Fig. 1a). It is more continuous and its relative height is greater east of Lahemaa within the Viru plateau, culminating at Ontika at 55.6 m a.s.l. East of Toila, remarkable cliffs occur at Voka (43 m) (see Fig. 1a) and Päite (41 m) (Tammekann 1940).

The klint and adjoining limestone plateau are intersected by canyon- or ravine-like palaeoincisions at various depths. Different reasons have been set forth for the formation of these palaeoincisions: (1) preglacial or interglacial river erosion, (2) glacial erosion of the Pleistocene glaciers, (3) glacial and glaciofluvial erosion during repeated advances and retreats of the Pleistocene glaciers. Besides, as it was recently pointed out, the palaeoincisions could also be carved by subglacial meltwaters or formed by catastrophic outbursts of subglacial meltwater from the marginal parts of the ice sheet.

The location of the palaeoincisions in the northern part of the limestone plateau, their sinuosity and gradual deepening downstream (i.e. towards the klint) testify more likely to their pre-glacial fluvial genesis (Tavast & Raukas 1982). It is believed that later the palaeoincisions were transformed by the plucking of the subsequent glaciers and eroded by glacier meltwaters and/or interglacial rivers (*ibid*). Erosion played the greatest role in northeastern Estonia, where the palaeoincisions are aligned along the movement of the Pleistocene glaciers (from the north and northwest to the south and southeast, Raukas 1978; Tavast & Raukas 1982; Karukäpp 1996).

No great variation has been recorded in the distribution of fillings of the palaeoincisions of northern Estonia (Raukas 1978; Tavast & Raukas 1982). Late Pleistocene deposits, mostly glaciofluvial and glaciolacustrine in origin, prevail, sometimes being interstratified by thin layers of different-aged tills. The incisions may also be completely filled with till. The

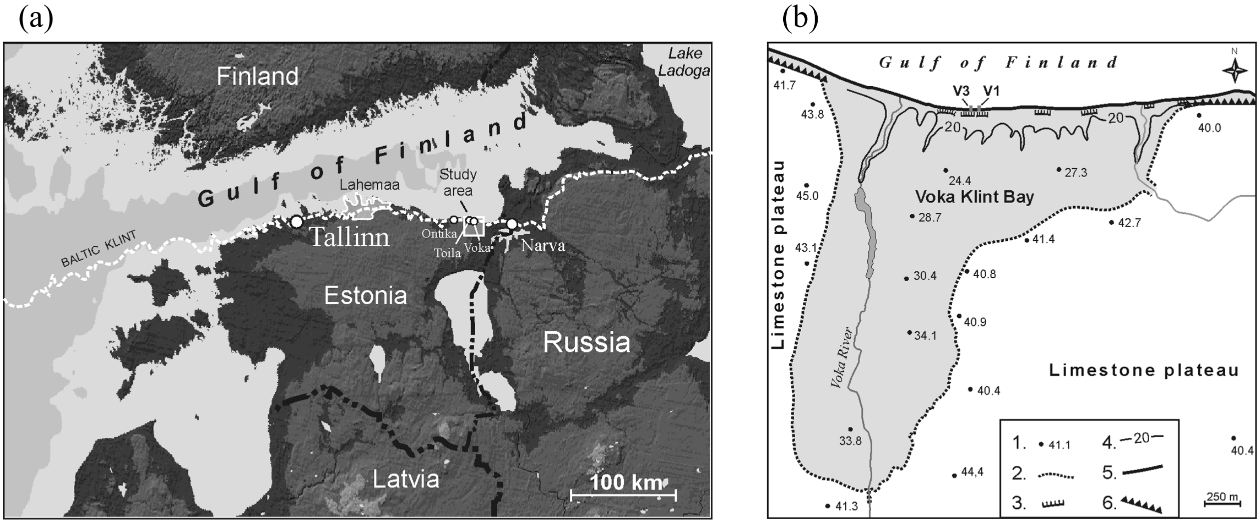


Fig. 1. (a) Location map of the study area with the sites mentioned in the text and (b) scheme of the Voka Klint Bay with locations of the sections V1 and V3; 1, altitudes above sea level indicated in metres; 2, klint bay boundary; 3, outcrop; 4, 20 m contour line; 5, coastline; 6, klint.

thickness of the glaciofluvial deposits in such buried palaeoincisions of the Viru plateau only rarely reaches 40 m (Tavast & Raukas 1982) but is much greater in the one cutting the klint near Voka village some 34 km west of Narva (Fig. 1a,b).

Considering the bedding, stratification, grain size of sediments, and other geological indications, it was widely assumed that the upper visible part of the Voka palaeoincision was filled mainly with subaqueous deposits during the Pandivere phase of the last glaciation (i.e. in subglacial environment) (Raukas & Stankowski 2005) or with the deposits of an ice lake at the end of the late Pleistocene, when the ice margin had reached either the Gulf of Finland or already South Finland (Miidel 2003). The characteristics of the deposits exposed at the Voka site are associated also with low-amplitude deformations, possibly load casts, slumps, etc.

Since no absolute dates are available for ice-dammed lake deposits on the territory of Estonia and the ages of the deformations occurring therein are unknown, a chronostratigraphical investigation was undertaken to obtain new facts for elucidating these aspects of the late-postglacial sedimentary history of the ice lake. Such work proved possible during the fieldwork in the summer of 2001.

As the deposits are devoid of macroscopic organic remains, the optically-stimulated luminescence (OSL) technique, introduced more than 20 years ago by Huntley et al. (1985), and its feldspar-based infra-red version, IR-OSL, first introduced by D. I. Godfrey-Smith, D. J. Huntley, and W.-H. Chen in an unpublished report at the 5th International Specialist Seminar on TL and ESR Dating, Cambridge, in 1987 (see also Godfrey-Smith et al. 1988), seemed most suitable for their dating. The latest developments of the IR-OSL technique by the Research Laboratory for Quaternary Geochronology, Institute of Geology, Tallinn University of Technology (for details see, e.g., Vasilchenko et al. 2005; Molodkov & Bitinas 2006; Molodkov et al. 2007) were applied to produce an absolute chronology of the events that are assumed to have occurred during a relatively short period: between about 12 400 conventional ^{14}C yr BP – that is the radiocarbon age of the Pandivere ice-marginal zone (see, e.g., Raukas & Stankowski 2005) – or about 14 370 cal (i.e. calendar or calibrated) yr BP, calculated using the calibration program by Stuiver et al. (1998), and 10 200–10 500 ^{14}C yr BP (or about 12 200 cal yr BP) – the time of the drop from the Baltic Ice Lake level to the Yoldia Sea level as a consequence of the opening of an outflow channel through central Sweden in the Mount Billingen region (Donner 1978; Stromberg 1992).

However, contrary to expectations, the first results of the IR-OSL analysis of the Voka outcrop deposits obtained in 2002 indicated a much older age than earlier supposed. As the preliminary absolute ages of these deposits fully contradict the existing viewpoint on the geological history of the region, the problem is of principal importance, necessitating further comprehensive investigation of the site. As the deposits of the palaeoincisions in northern Estonia are still insufficiently studied, and the deposits predating the last glacial maximum (LGM) are very rarely well preserved in situ, this can potentially provide a unique opportunity to study the Järva sedimentary environment and to reconstruct the palaeoenvironmental history of the region in a greater detail.

This paper reports some initial findings from a pilot and subsequent study, aimed at elucidating the sedimentary history and age of the deposits revealed in the Voka outcrops and preliminary examination of the essential palaeoenvironmental information documented at that site.

GEOLOGICAL SETTING

The Voka site is located on the rather flat Viru limestone plateau where its edge, the North Estonian Klint, is broken by a depression – the Voka Klint Bay (Figs 1a,b, 2a). It is supposed that the Voka Klint Bay actually represents a mouth segment of a deep Voka (Vasavere) ancient valley that comes into being about 25 km southwards (Fig. 2b). In the west, the klint bay is presently occupied by a young 25–30 m deep V-shaped river valley. However, together with the structural terraces on the western slope of the bay, the depth of the young valley reaches 44 m (Fig. 2a). On the western slope of the bay, at least three terraces can be distinguished at absolute heights of 21–25, 28–30, and 33–35 m. The river valley was formed in the Holocene. The foreklint lowland represents a glaciolacustrine plain.

The bedrock in the Voka Klint Bay and in the surrounding area is composed of Ediacaran (Vendian), Lower and Upper Cambrian, and Lower and Middle Ordovician sedimentary rocks, overlying the crystalline basement at a depth of 191.4 m b.s.l. at Türsamäe (borehole F7) and 189.7 m b.s.l. at Voka (F9) (Fig. 3). The thickness of the sedimentary cover is 226 and 228 m, respectively.

The sedimentary rocks from the Lontova Formation (Lower Cambrian) up to the Lasnamägi Stage (Middle Ordovician) are represented by clay-, silt-, and sandstones, argillites, and dolo- and limestones, outcropping at the steep escarpment of the klint and on the slopes of the Voka Klint Bay (Fig. 2a). The beds are dipping to the south with a gradient of 3.75 m/km. It is a bit more than the average (2.10 m/km) in northeastern Estonia (Vaher 1972). The northernmost part of the valley deepens very abruptly – the bottom gradient reaches 12 m/km, the slope gradient more than 500 m/km (Fig. 2a,b).

The Quaternary cover in the area adjacent to the Voka Klint Bay does not usually exceed 0.5 m, and only occasionally is 2–3 m thick. It is much thicker in lowlands and buried palaeoincisions, which can be filled with deposits of different origin – glacial (e.g. tills), glaciofluvial, glaciolacustrine, etc. Such is, for example, the buried Voka palaeoincision passing through Voka village. The lithology of the Quaternary deposits filling the Voka Klint Bay and the palaeoincision is summarized in Fig. 2a,b. Judging from drilling data, most of the section is composed of fine-grained sands, silts and till with a total thickness of at least 160.9 m in borehole 8618 (Fig. 2b), containing also layers of gravelly sand, coarse- to medium-grained sand and clays.

The surficial part of the klint bay is composed of at least 15 m thick yellowish-brown fine-grained sands, silty sands, and silts. Miidel (2003) believed that this part represents the post-LGM glaciolacustrine and deltaic deposits. Some boreholes revealed a 0.3–1.0 m thick layer of gravel, embedded either in silty sand or in fine sand.

The plateau, bordering the klint and the Voka Klint Bay, is covered by yellowish or brownish sandy clay till of the last glaciation. The till usually lies upon the bedrock and includes gravel and boulders up to 30 cm in diameter. The coarse material is mainly represented by poorly rounded local carbonate rocks and Cambrian sandstones, but magmatic and metamorphic rocks from Finland can also be found.

In some boreholes (see Fig. 2a,b) two relatively thin layers were recorded throughout the Voka Klint Bay, interpreted in the drilling report as diamicton layers. However, these can also be treated as tills. In the eastern part of the klint bay, the till lying on the bedrock is rather thin – usually 0.4–1.5 m, rarely more than 2 m (Fig. 2a). The age of the tills is unclear.

Gravel ridges occur at various levels on the inland of the klint bay (Tammekann 1926, 1940). These have been treated as beach ridges of the Baltic Ice Lake, with its water level at 45 m (BI) and 40 m (BIII) a.s.l. The subsequent deposits of the Baltic Sea are missing within the sediment sequence of the Voka buried palaeoincision, because the waters of the Yoldia Sea, Ancylus Lake or Litorina Sea did not reach the edge of the klint and the bay. According to Kessel & Raukas (1979), the height of the Ancylus Lake was 16–18 m and of the Litorina Sea 10–12 m at the Voka site.

VOKA OUTCROPS AND DEPOSITS

The deposits studied are exposed along the coast of the Gulf of Finland, about 500 m to the east from the mouth of the Voka (Vasavere) River (see Fig. 1b) in two neighbouring outcrops – V1 (59°24.86′ N, 27°35.94′ E; Fig. 4) and V3 (59°24.86′ N, 27°35.88′ E; Fig. 5). The outcrops are located approximately 60 m from each other, and separated by a ravine (Fig. 6). Immediately on the shore the tops of the outcrops are at about 22 m a.s.l.

The sandy to clayey sedimentary sequence comprises at least two lithostratigraphic units – A and B. Topwards

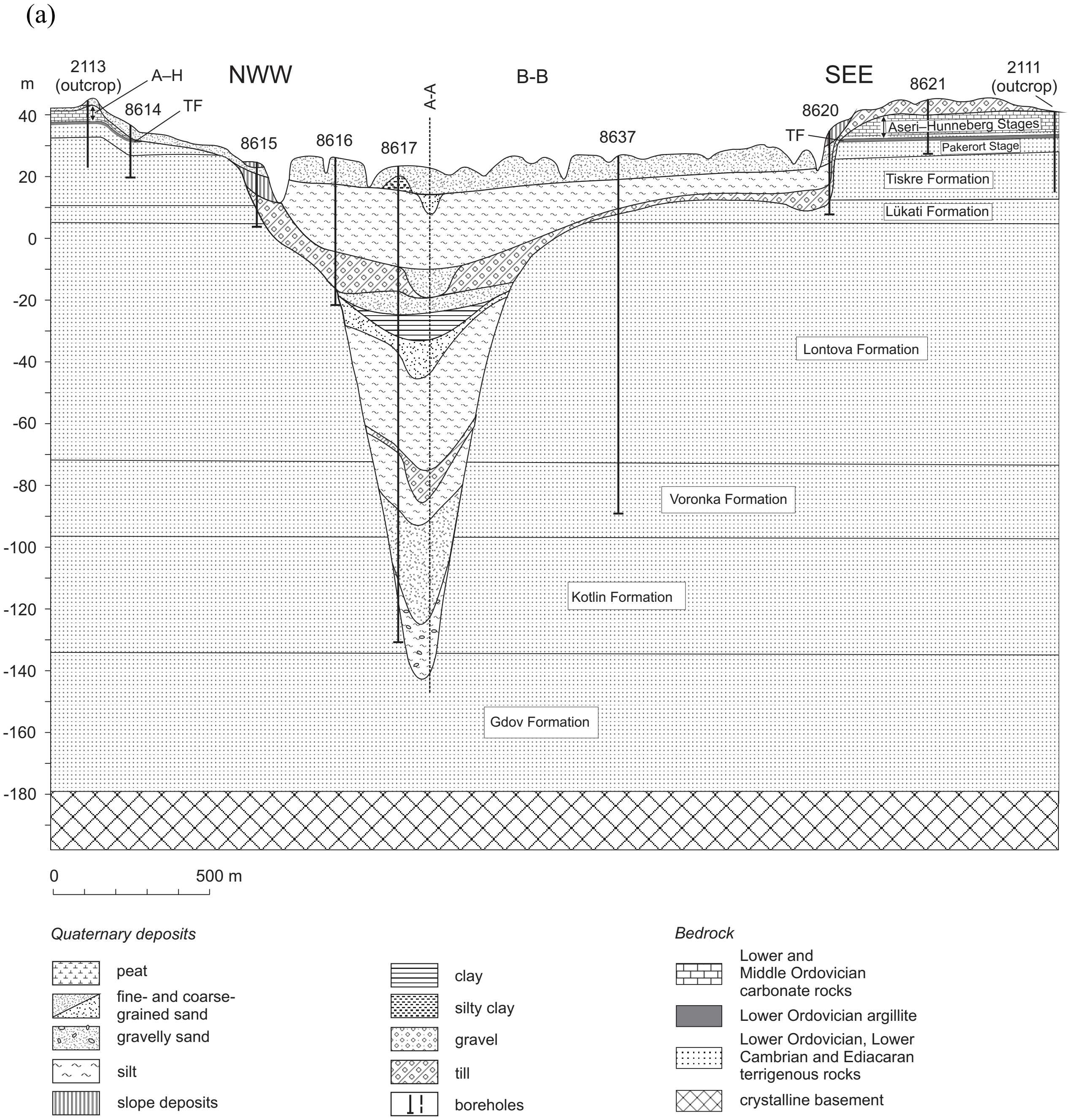


Fig. 2. (a) Transversal geological cross-section of the Voka palaeoincision. TF, Türisalu Formation; A–H, Aseri–Hunneberg stages. (b) Longitudinal geological cross-section of the Voka palaeoincision. Refer to Fig. 3 for borehole positions.

in the exposure V3 unit A is overlain by about 1.1 m thick brownish-grey to light-brown soil resting upon a ca 0.7 m thick layer of light-brown silt-like deposits, which show signs of soil formation, are densely penetrated by roots, and contain filled krotovina-like irregular tunnels made probably by burrowing animals. Similar deposits occur also on the top of the V1 section (Fig. 7). The boundary between units A and B is marked by a relatively thin (up to about 10–15 cm) gravel bed (Fig. 8) The thickness of unit A is about 4 m in the eastern (VI) and about 10 m in the western (V3) section. The altitude of the marker bed varies from about 16 m a.s.l. in the V1 section to about 10 m a.s.l. in the V3 section.

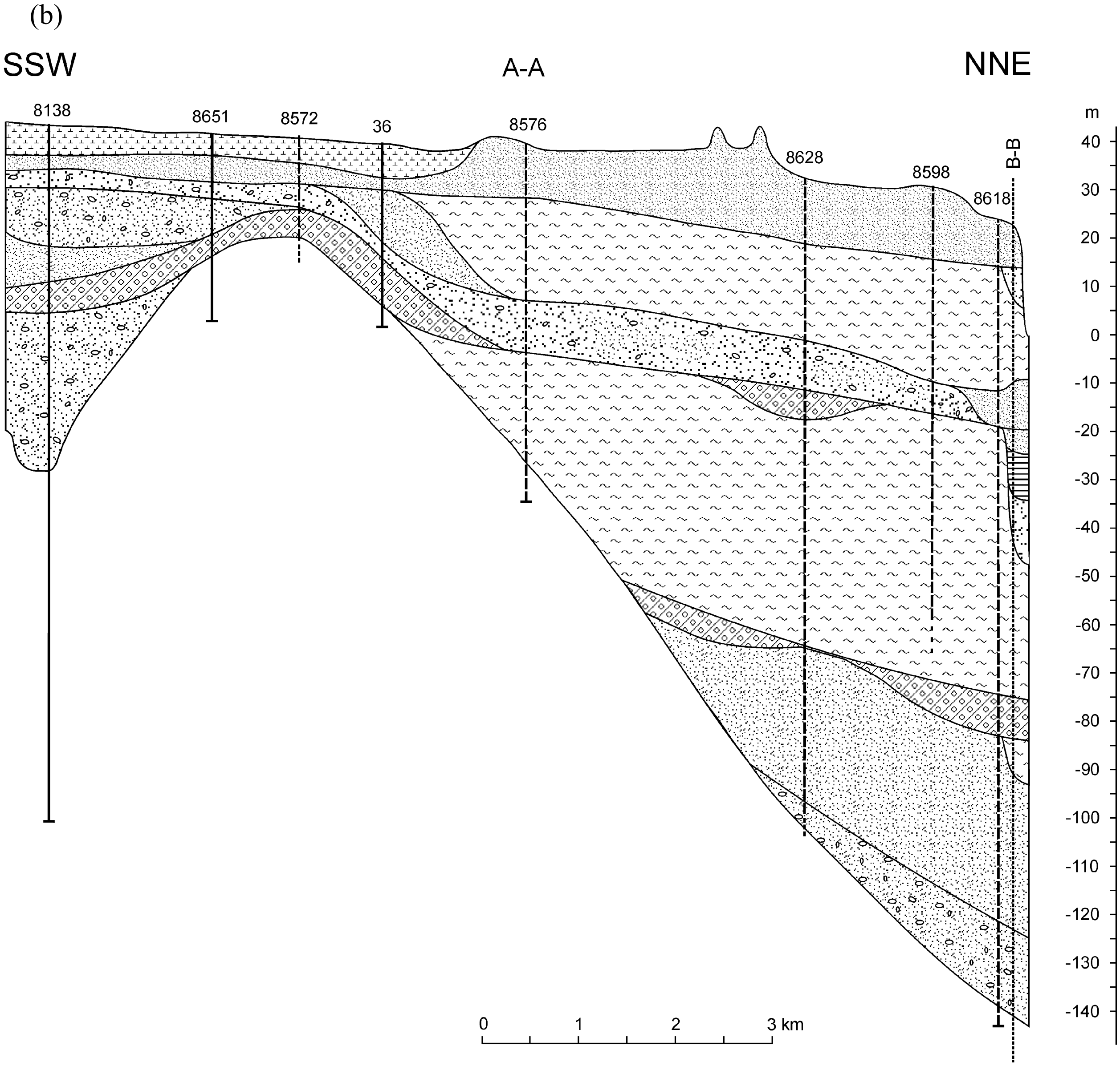


Fig. 2. *Continued.*

Unit A is characterized by alternating laminated fine sand and clay with dispersed particles of lower Ordovician *Dictyonema* argillite (Türisalu Formation; Fig. 9). This composition presumably indicates the main source of the sediments: incision slopes and reworked deposits from the south of the study site. The further subdivision of this unit can be based on smaller-scale lithologic, compositional and palaeo-environmental changes and variations in other parameters, including granulometry, micromorphology, petrography, and mineralogy. It is believed that this unit, characterized by parallel, mostly horizontal lamination, was laid down in a freshwater basin (Molodkov & Bolikhovskaya 2005).

Unit B is represented by fine- to medium-grained sands with clayey interlayers in the eastern, and coarse-grained cross-bedded sands in the western part of the outcrop (Fig. 10). The maximum visible thickness of the unit is about 15 m. Most likely, the deposits of this unit were also laid down in a freshwater basin (*ibid*).

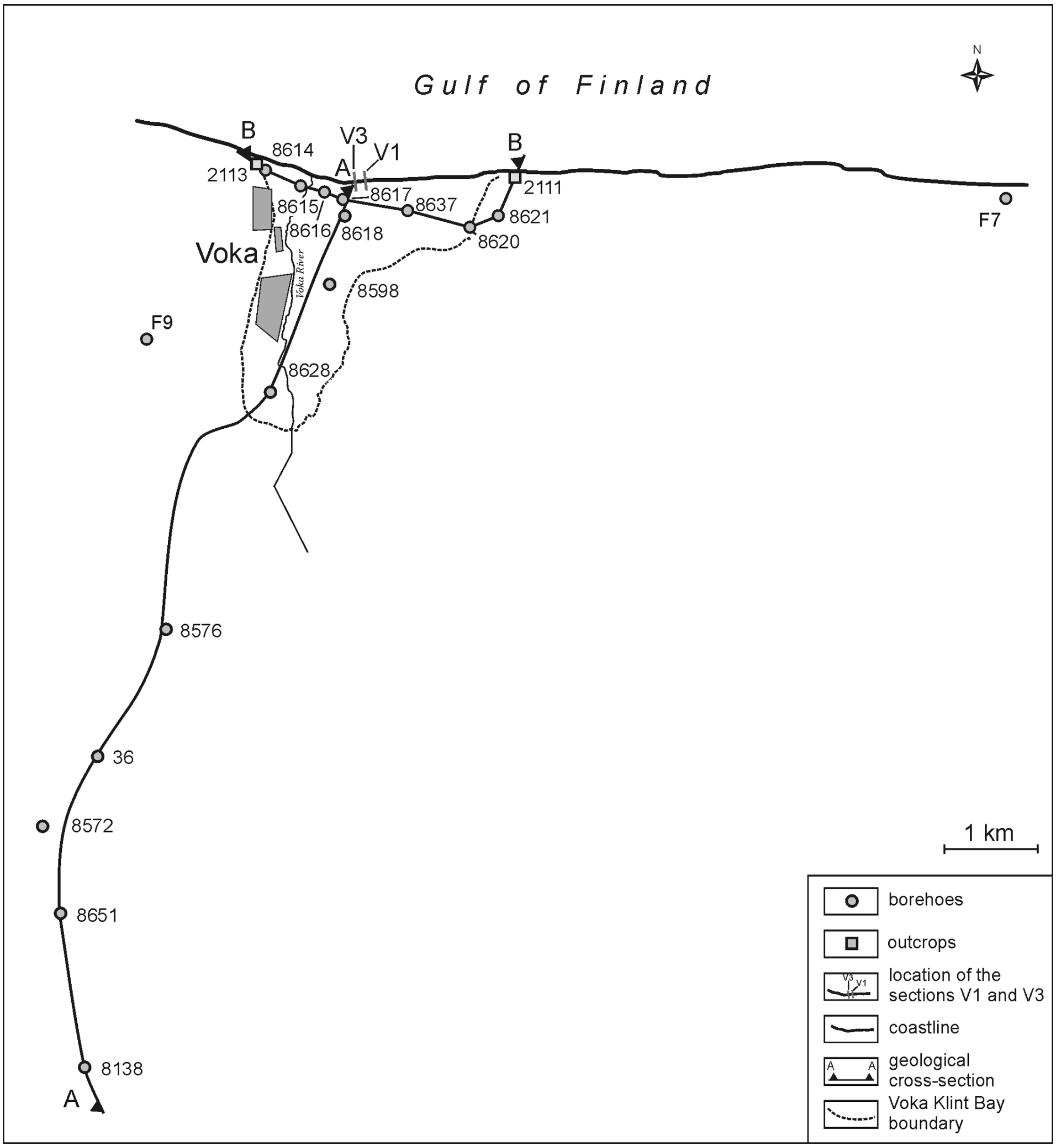


Fig. 3. The positions of the boreholes, outcrops, and geological cross-sections mentioned in the present paper. Boreholes and their numbers are according to Radik et al. (1983).

MATERIAL AND METHODS

At the Voka site, we first visited the best accessible outcrops exposed along the Gulf of Finland coast, described and measured coastal sections using laser level, hand level, and tape-measure, and collected samples for IR-OSL dating, palynological and diatom analyses, and samples for granulometry. The first chronological investigations performed in 2002 on V1 clearly revealed contradictions with the existing conceptions of the sedimentary history of the site, and the potential of the site for further and more detailed investigations. During the follow-up studies, conducted in the frames of the pilot project (in 2003–2004) and the current full-scale research project (in 2005–2008), sampling for IR-OSL dating was undertaken in the V1 and V3 sections. Samples for pollen and diatom analysis were taken from V3 and a few ones from V1. Besides, we also studied the stratigraphy of the deposits exposed in situ.

All IR-OSL ages reported in this paper were obtained in the Research Laboratory for Quaternary Geochronology, Institute of Geology, Tallinn University of Technology, according to the technique developed in the laboratory since 2000. The IR-OSL ages given here are in calendar years before present (BP). The details of the dating results obtained for unit A from the exposures V1 and V3 are available in Molodkov (2007).

Some of the analytical data are reported in Molodkov & Bolikhovskaya (2005), Bolikhovskaya & Molodkov (2007), and Molodkov (2007). The complete integrated palyno- and chronostratigraphic results on unit A of the V3 section will be published soon.

Fig. 4. The V1 outcrop at the Voka site. Talus covers most of the slope. The top of the outcrop is about 22 m a.s.l. (photo by K. Ploom).

Fig. 5. The V3 outcrop. The lower half of unit A characterized by parallel, mostly horizontal lamination, is clearly seen. Unit B is not visible due to thick talus at the base of the outcrop. The top of the outcrop is about 22 m a.s.l. (photo by A. Miidel).

RESULTS AND INTERPRETATION

Eighteen samples from unit A of the V1 and V3 sections were measured with IR-OSL and an age model was developed (Molodkov 2007) to provide a timescale for the upper part (unit A) of the Voka section and the temporal base for further palaeoenvironmental reconstructions. Ninety samples were taken from unit A of the V3 section and from the overlying soil deposits for detailed palynological analysis. Forty-five samples from unit A contained enough pollen to provide representative spectra. Besides, two samples were taken from the lower part of the V1 section at depths of 15.55 and 16.00 m for preliminary estimation of palaeoenvironmental conditions during the formation of the deposits in the lowest available part of the section.

Plotted against depth, palynological analysis and luminescence datings of the samples from the V3 section (see Fig. 7) produced a dated sequence within the whole unit A, ranging from ca 39 kyr BP to ca 31 kyr BP (Molodkov 2007), which revealed the specific features of pre-LGM palaeoenvironmental variations during the time span of about 8 kyr. The deposits overlying unit A are most likely post-LGM in age, as indicated by an IR-OSL date of 8.1 ± 0.8 kyr for the sample taken from the V3 section at a depth of 1.6 m (Molodkov 2007).

According to several preliminary age determinations (*ibid*), the deposits of unit B with a visible thickness of about 8 m (V1) span the period from about 110 to 70 kyr and those about 3.5 m thick (V3) – the period from about 115 to 90 kyr (Fig. 6). The presence of older deposits (> 115 kyr) is suggested in the lower part of the sections currently not accessible due to thick talus at the base of the outcrops. Taking into account the estimated sedimentation rate of about 0.27 mm/yr within unit B of the V1 section, it can be assumed that the deposits immediately beneath the marker bed are about 60 kyr in age. It means that the upper part of unit B in the V1 section may hold a critical border between interglacial marine isotope stage (MIS) 5 and glacial MIS 4.

Pollen data on the middle Järva (= Weichselian) deposits are rather scarce in northern Estonia. No distinct interstadial warmings have been identified there up to now. Pollen assemblages recovered from periglacial middle Järva layers of the Tõravere, Valguta, Savala, and other sections were interpreted by Liivrand (1991, 1999) as evidence of cold environments with widespread tundra and xerophytic communities dominated by *Betula nana*, *Artemisia*, Chenopodiaceae, Poaceae (Gramineae), and Cyperaceae. This palaeoenvironmental

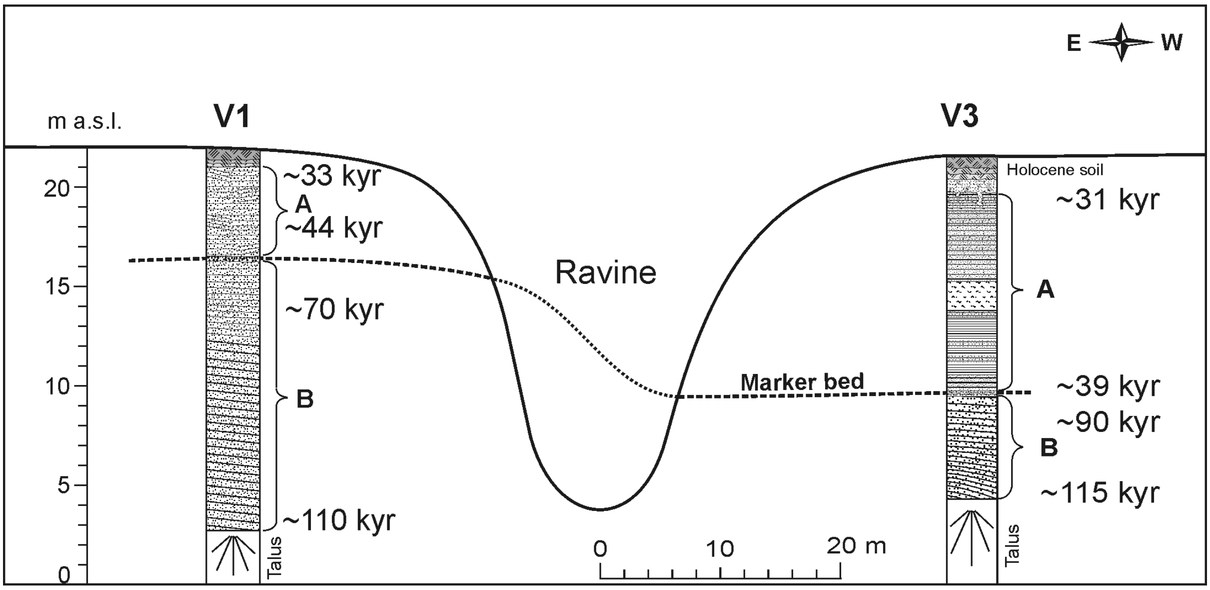


Fig. 6. Scheme of the Voka outcrops with the age assessment of the main sedimentary units. For explanation of the symbols see Fig. 7.

gap may now be filled with new data from the deposits exposed in unit A of the V3 section at depths between 5.0 and 12.2 m (Figs 7, 11), IR-OSL-dated at about 39–33 kyr BP (Bolikhovskaya & Molodkov 2007; Molodkov 2007).

Representative pollen spectra derived at these depths from 45 samples provide a convincing evidence of noticeable changes in vegetation and climate in NE Estonia: two intervals of severe climate and two relatively milder ones have been recognized (Figs 11, 12). The first period of relative warming (38.6–37.6 kyr BP; 12.2–11.2 m) was marked by the dominance of periglacial forest-tundra, locally with open forests of spruce and pine (with *Larix* and *Pinus sibirica*). It was followed by a relatively short (37.6–36.8 kyr BP; 11.2–10.4 m) interval of colder and drier climate. Prevailing landscapes were tundra-steppe and tundra-forest-steppes, where *Betula nana*, *Alnaster fruticosus*, *Artemisia* (including *A.* subgen. *Seriphidium*, *A.* subgen. *Dracunculus*), and Chenopodiaceae were dominating, with a smaller proportion of *Ephedra*, *Lycopodium dubium*, *Diphazium alpinum*, and *Selaginella selaginoides*.

The next interstadial (36.8–35.3 kyr BP; 10.40–8.75 m), much warmer than the previous one, was marked by a new expansion of boreal forest species onto the area under study. Repeated changes in plant communities took place in this interval. At least twice – during wetter and warmer climatic phases – periglacial forest-tundra (locally with open spruce and pine forests) was replaced by northern taiga coniferous forests of *Pinus sibirica*, spruce, and common pine.

During the last interval (35.3–32.6 kyr BP; 8.75–4.95 m) periglacial tundra stayed the dominant landscape in the region. The considerably colder climate and expansion of permafrost resulted in the appearance of wetlands of moss and grass types. The pollen assemblages are dominated by *Betula nana*, Poaceae, and Cyperaceae, together with spores of *Sphagnum*, Bryales, *Selaginella selaginoides*, *Lycopodium dubium*, *Diphazium alpinum*, and other tundra species. This suggests that the considered interval was close to the final part of the middle Järva peniglacial (= middle Weichselian, middle Valdai), preceding the late Järva ice sheet expansion into the region.

Two minor warmings were recognized within this cold event at the depths corresponding to the ages of about 34.2 and 33.7 kyr BP. During these short-term warmings the dominating periglacial tundras were replaced by periglacial forest-tundras with small patches of pine light forests (of *Pinus sylvestris*). Only single pollen grains were found in the deposits exposed in unit A of the V3 section at the depths from 4.95 to 2.00 m, corresponding to the ages between 32.5 and 31.1 kyr BP (see Fig. 7).

The spore and pollen data have shown that the deposits underlying the Holocene soil accumulated in a freshwater basin. It is clearly indicated by the abundance of algae (*Pediastrum* sp.) and constant presence of the pollen of littoral aquatic plants

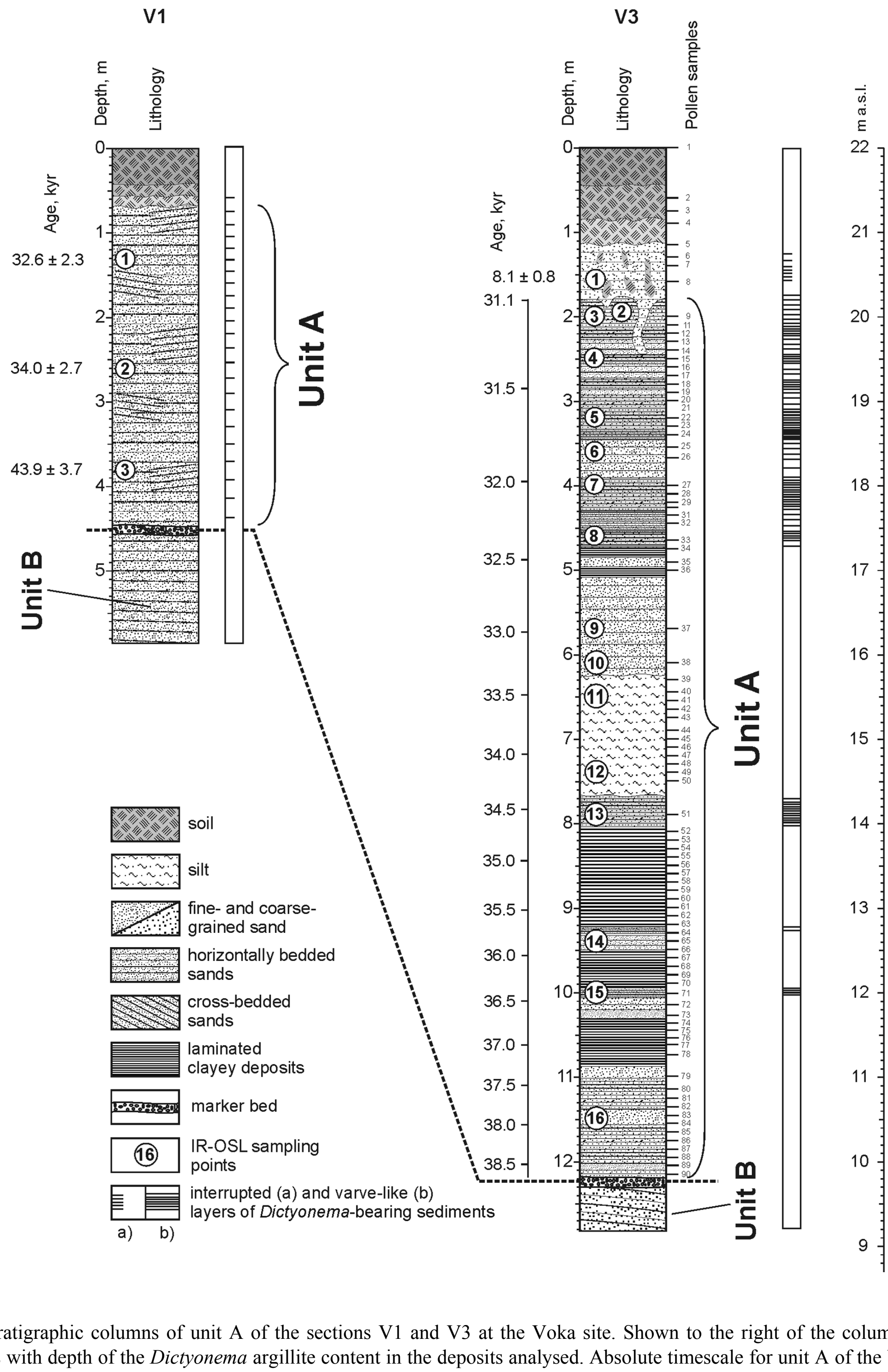


Fig. 7. Stratigraphic columns of unit A of the sections V1 and V3 at the Voka site. Shown to the right of the columns are the variations with depth of the *Dictyonema* argillite content in the deposits analysed. Absolute timescale for unit A of the V3 section is indicated on the left (redrawn and modified from Molodkov 2007).

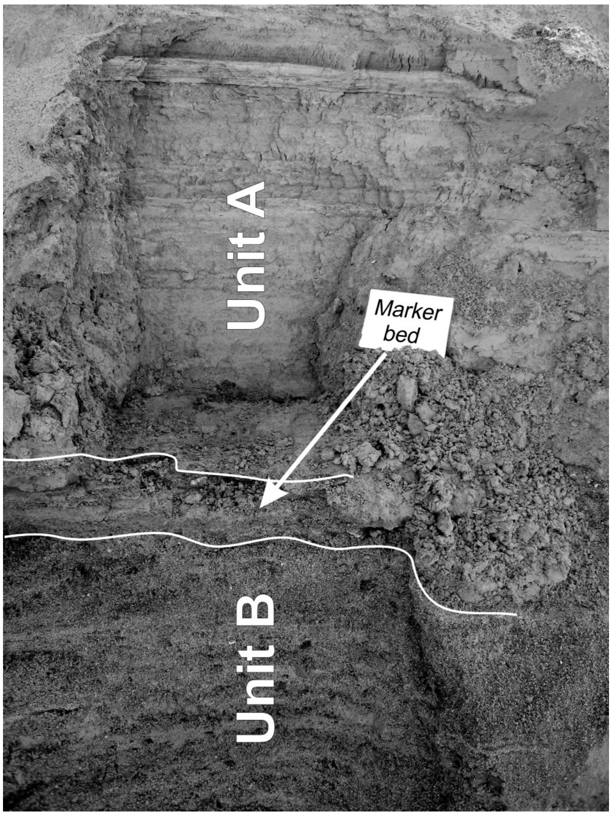


Fig. 8. The boundary between units A and B is marked by a gravelly bed. This part of the V3 outcrop is located 7.5 m westward from the V3 section in Fig. 6. The white sheet in the middle is about 210 mm × 150 mm (photo by A. Molodkov).

occupying freshwater basins today. In some samples analysed typical species of freshwater diatoms were also encountered (V. S. Gunova, pers. comm. 2005). The estimated sedimentation rate was relatively low in this basin, about 1.2 mm/yr.

The preliminary pollen and IR-OSL data indicate that the sands of the lower part of the V1 section, dated at about 110 ka (see Fig. 6), were deposited during some of the optimal climatic-phytocenotic phases within the second half of the last interglacial *sensu lato* (MIS 5). This time was characterized by the domination of coniferous-broadleaved forests, with the prevalence of hornbeam (*Carpinus betulus*), pine (*Pinus sylvestris*), spruce (*Picea abies*) and the presence of birch (*Betula pendula*, *B. pubescens*), linden (*Tilia cordata*, *T. platyphyllos*), alder (*Alnus glutinosa*, *A. incana*) and several other species. The finds of the spores of *Salvinia natans* are a significant indicator of the interglacial origin of the studied flora. Grasses (Poaceae = Gramineae), sedges (Cyperaceae), and wormwood (Artemisia) predominated among herbs and dwarf shrubs.

DISCUSSION

Our first results for the Voka sections help evaluate hypotheses about the timing and duration of sedimentation in the palaeoenvironments represented by units A and B, and the genesis of the respective deposits. These deposits were originally considered to have accumulated in a subaqueous (glaciofluvial or glaciolacustrine) environment during late-glacial (the Pandivere stadial) or post-glacial time. However, our data set, obtained by completely different methods (IR-OSL and palynological analyses) applied to different samples (lithogenic and biogenic material), indicates that the sedimentation in the Voka basin lasted much longer (for at least 85 000 years) than the assumed relatively brief final deglaciation event falling in northern Estonia in the time period from approximately 14 370 to 12 200 cal yr BP, i.e. in a period spanning only about 2200 years. The palyno-chronostratigraphical record, derived from the numerous Voka samples taken between about 3 and 20 m a.s.l., suggests the second half of the middle Järva pleniglacial for the uppermost unit A and at least the second half of the last interglacial *sensu lato* (MIS 5) for the lower unit B. The IR-OSL ages obtained on the V1 and V3 sections fall within time periods of about 44–31 kyr for unit A and at least 115–70 kyr for unit B. Considering the estimated sedimentation rate in the basin represented by unit A deposits (about 1.2 mm/yr), it can hardly be assumed that the upper part of the sections was formed in a glaciofluvial environment.

A relatively thin gravel bed at the base of unit A marks the boundary between units A and B. Probably, this bed was formed due to erosion or a rather long sedimentation break.

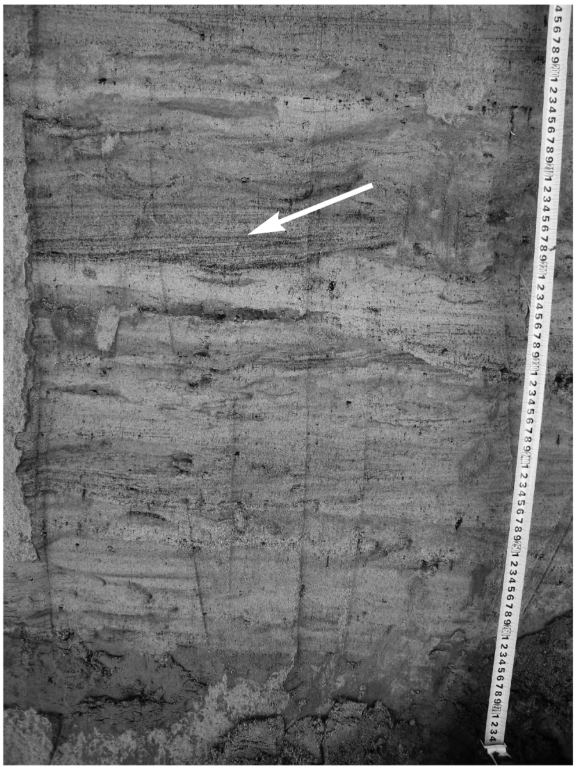
Our palynological investigations of unit A deposits also indicate that the climatic conditions during the period under consideration, i.e. prior to the LGM, substantially differed from those recorded in northern Estonia and neighbouring areas for the late- or post-glacial period, or for the Holocene. Our data and geological observations allow us to interpret these deposits as evidence for the existence here of a freshwater basin within the Järva pleniglacial. If this interpretation is correct, then the IR-OSL ages and palynological features will mark the time of relatively complex and changeable environmental conditions during the middle Järva (=Weichselian, Valdai) period as it was also revealed by our latest palyno-chronostratigraphic study of the materials from complete late Pleistocene sequences on the Central East European Plain and climate-controlled marine deposits along the continental margin of the Eurasian North (Bolikhovskaya & Molodkov 2005; Molodkov & Bolikhovskaya 2007; Fig. 12). According to our results reported in the present paper and elsewhere (see, e.g., Bolikhovskaya & Molodkov 2007), the middle Järva pleniglacial was characterized at Voka by rapid, short-term climatic variations, sharply defined also in the representative ice-core climate archives (see, e.g., Shackleton et al. 2004).

It is also noteworthy that we found no evidence in the array of our analytical results (Molodkov & Bolikhovskaya 2005; Bolikhovskaya & Molodkov 2007; Molodkov 2007) to infer the presence of glacigenic deposits in the Voka sections, which could be attributed to the glacial advance during MIS 4. And this is in spite of the fact that the reconstructions of the Eurasian ice sheet extent during the middle Weichselian glacial maximum (60–50 kyr) by Svendsen et al. (2004) demonstrate that during the maximum advance of the ice sheet its margin passed just over our study area during MIS 4. That is, our field observations and data obtained by IR-OSL, as well as the results of the palynological study, imply that during MIS 4 the ice sheet did not cover the Voka site. The only candidate for this possible glacial advance is the period corresponding to interruption of sedimentation observable between units A and B. However, we have not yet found any sign of glacigenic deposits in this part of the sections either.

The deposits studied could more securely be attributed to late- or post-glacial time, as suggested by Raukas (1978), Tavast & Raukas (1982), and many others, if the till of the LGM was found beneath these deposits. However, our attempts to find such a till in the Voka outcrops failed. It is not possible to assert with confidence that such an unequivocal LGM till exists even along the whole depth profile of the Voka palaeoincision (see Fig. 2a,b).

According to the literature, buried palaeoincisions were subjected to strong glacial erosion in northern Estonia (see, e.g., Raukas 1978), where they are aligned along the movement of the Pleistocene glaciers (from the north and northwest to the south and southeast). It was, accordingly, assumed that some of these buried palaeoincisions could be of great stratigraphical interest, because as a result of numerous glacier passages many tills and intertill deposits were developed and preserved in them (*ibid*). However, our data show that, contrary to expectations, at least the last glacier's passage over

(a)



(b)

Fig. 9. Typical deposits of unit A in the V1 (a) and V3 (b) sections at depths of 3.0–3.7 m and 9.7–10.8 m, respectively. Black layers of the dispersed particles of lower Ordovician *Dictyonema* argillite are indicated by arrows. The notebook shown in the right lower corner of (b) measures 140 mm × 205 mm (upper photo by A. Molodkov, lower photo by A. Miidel).

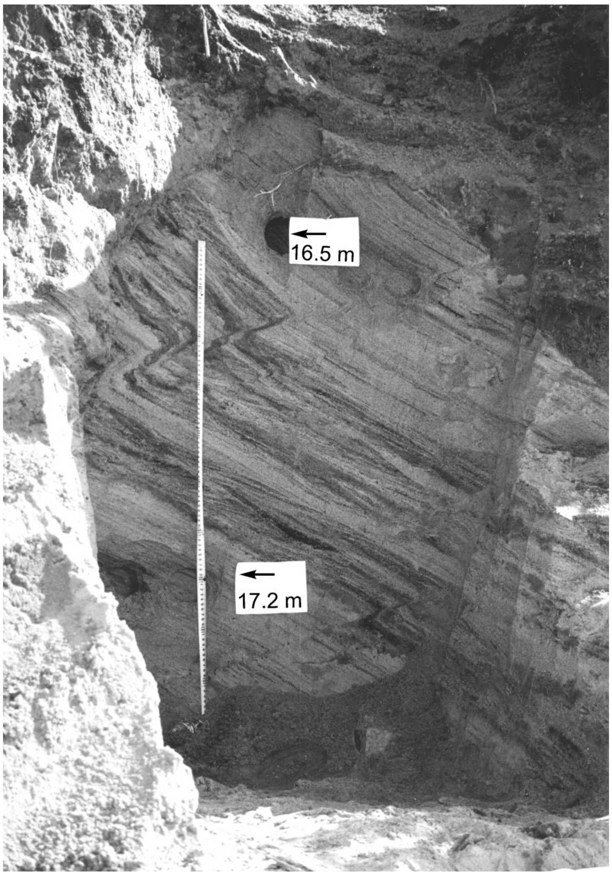


Fig. 10. Typical coarse-grained cross-bedded sands representing unit B in the V3 outcrop. Low-amplitude deformations are also represented in this picture. This part of the V3 outcrop is located about 15 m eastward from the V3 section in Fig. 6 (photo by A. Molodkov).

northern Estonia left no glacigenic deposits in the studied part of the Voka palaeoincision. Moreover, it did not disturb pre-LGM deposits here, which is incomprehensible from the geological point of view and needs further investigations. The late Pleistocene deposits seem to have preserved in the Voka palaeoincision. Most probably, they can be found here in the initial deposition, providing a unique basis for creating a detailed chrono- and pollen stratigraphic framework.

CONCLUSIONS

Contrary to expectations, the Voka outcrops displayed no late-glacial and early Holocene deposits but contained subaqueous sedimentary deposits covering most of the late Pleistocene period. The upper part of the Voka sections (unit A) spans the time period from about 44 to 31 kyr, and the lower part (unit B) the period from at least 115 to 70 kyr. This proves that part of the last interglacial *sensu lato* (MIS 5, see, e.g., Bolikhovskaya & Molodkov 2002, Molodkov & Bolikhovskaya 2002, 2006, 2007; Molodkov & Yevzerov 2004) deposits correlating with the marine isotope substages 5d to 5a occur here as well. The presence of older deposits correlating at least with the first climatic optimum (MIS 5e) of the last interglacial is expected in the deeper part of the section currently not yet available for investigations.

No evidence was found in the Voka outcrops, suggesting the presence of glacigenic sediments deposited during the period between about 115 and 31 kyr. If this is correct, it will mean that no ice sheet covered the Voka site between MIS 5 and MIS 2, i.e., during the early to late Weichselian, according to NW European chronostratigraphy (Mangerud 1989).

The use of the integrated palyno- and chronostratigraphic method is the best possible approach, which provides the most significant estimates for the dynamics of the last ice age and the preceding interglacial palaeoenvironmental changes. This approach can help decipher the palaeoenvironmental changes in different areas and enable correlation between different records. The use of the Voka event stratigraphy as a template can help also searching for correlative horizons in the neighbouring outcrops or regions (Molodkov & Bolikhovskaya 2006).

On the other hand, the data obtained show unambiguously that, in spite of the expectations to find and study the late-glacial and early Holocene deposits, the greater part of the late Pleistocene sequence is represented in the Voka section. The upper part of the section (unit A) covers at least the last 8 kyr, closely predating the late Järva glacier advance. It offers a unique opportunity to investigate this time period in the greatest detail, which was realized during the first pilot study and the current project. The first comprehensive palynological study conducted on unit A has already given convincing evidence of noticeable changes in the vegetation and climate in NE Estonia (Bolikhovskaya & Molodkov 2007): two intervals of severe climate and two relatively milder periods have been recognized between about 39 and 33 kyr BP. The constructed palyno- and chronostratigraphic framework states the chronostratigraphic position of unit A at the very end of the middle Järva pleniglacial and provides for the first time the timescale for North Estonian middle Järva palaeoenvironmental events.

According to preliminary age determinations, the lower unit B falls within the second half of MIS 5 and is estimated to have been deposited between ca 115 and 70 kyr BP. These data, together with palynological results, indicate the presence of the deposits of the last interglacial *sensu lato* (MIS 5) in the Voka outcrops. It also

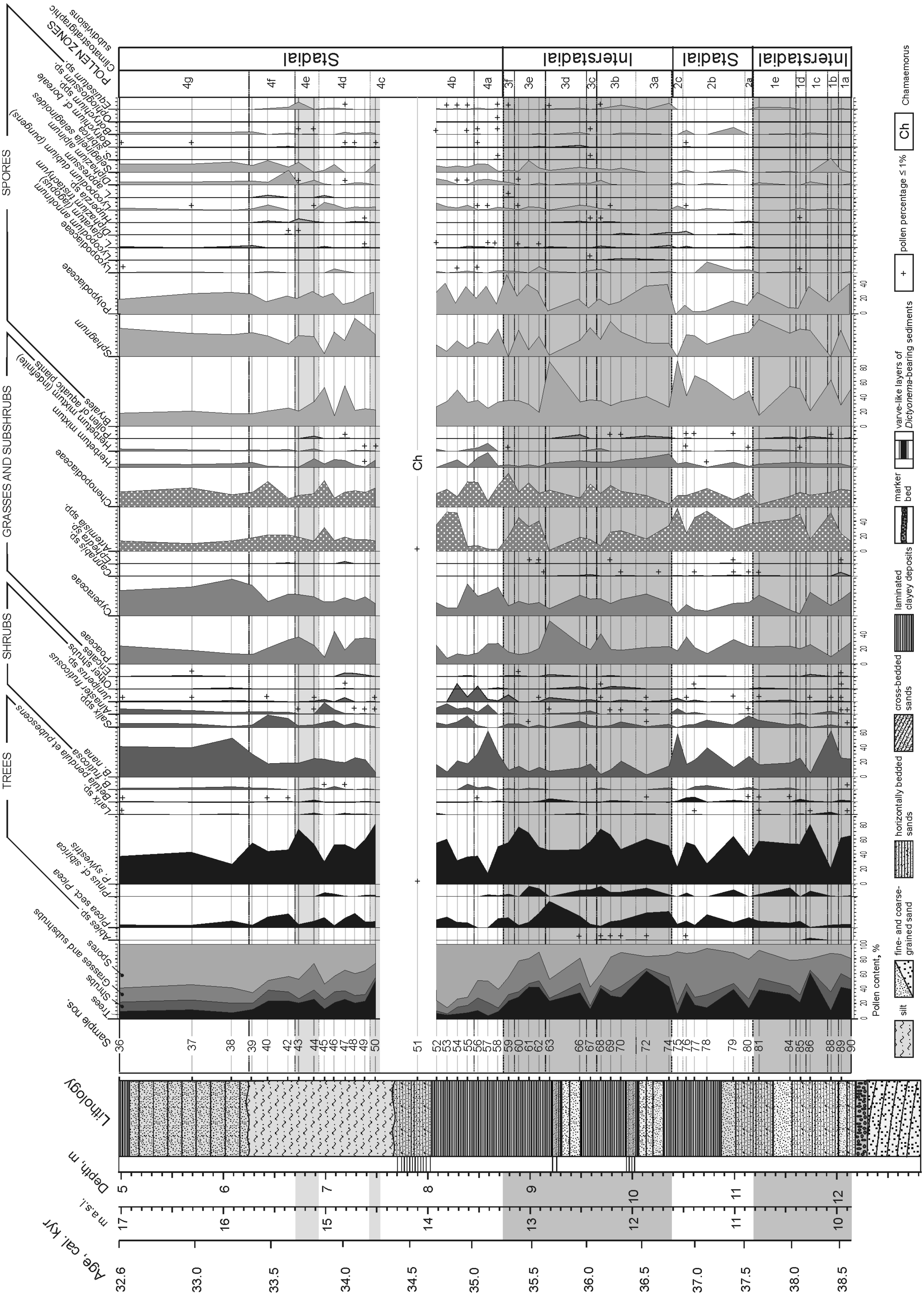


Fig. 11. Pollen and spore percentage diagram from unit A of the V3 section (5.00–12.15 m).

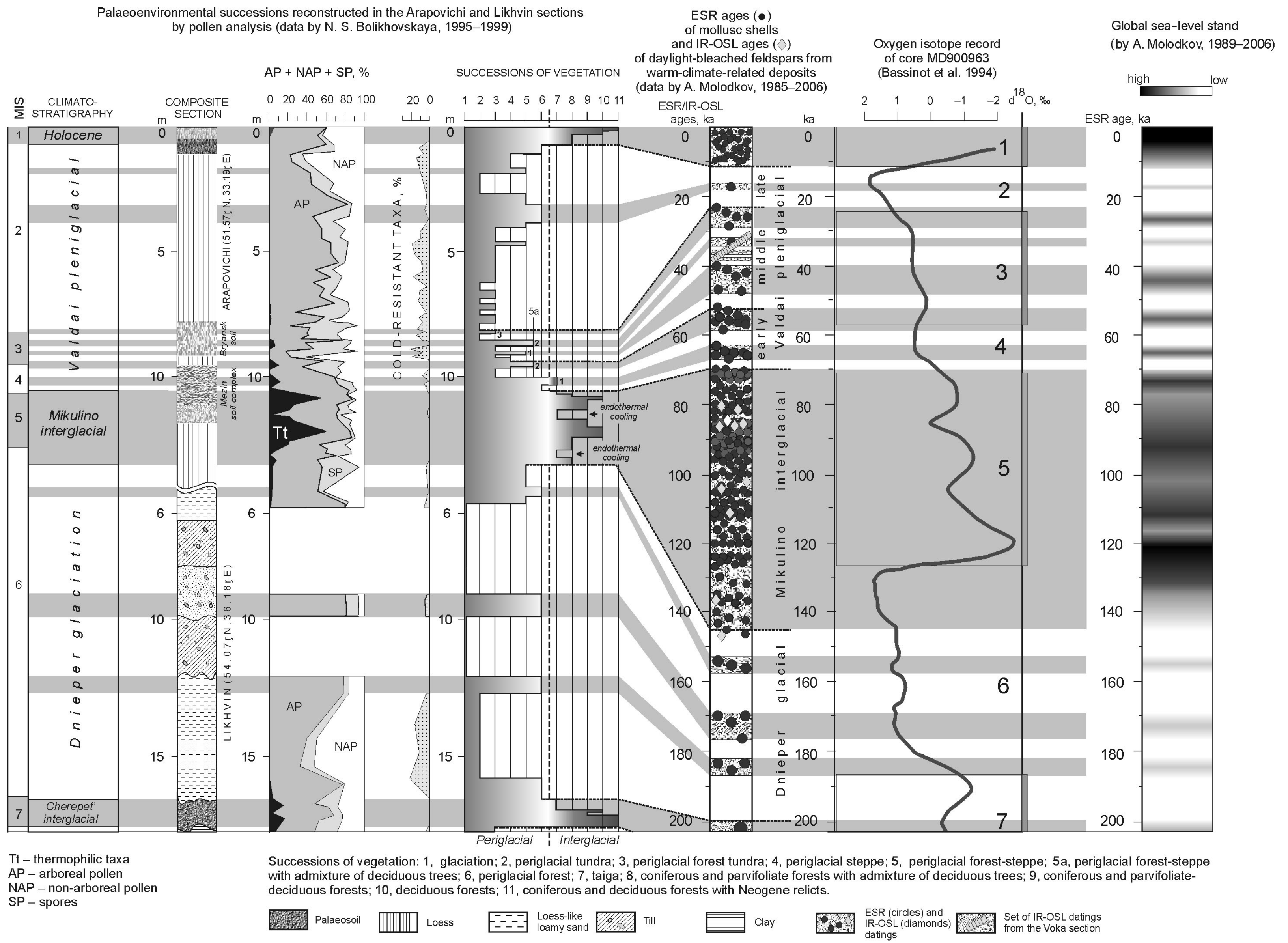


Fig. 12. Palaeoenvironmental changes over the last 200 ka reconstructed from pollen evidence, feldspar-based IR-OSL, and mollusc-based ESR chronostratigraphy in Northern Eurasia (modified and updated from Bolikhovskaya & Molodkov 2005; Molodkov & Bolikhovskaya 2007). Oxygen isotope record from Bassinot et al. (1994).

seems that the upper part of unit B in the V1 section holds a critical border marking the transition between the final phase of the last interglacial (MIS 5a) and the last ice age (MIS 4–2) (see Fig. 12). This is extremely important in the context of large-scale chronostratigraphical correlation and palaeoenvironmental reconstruction, especially because deposits of this kind are known to be very rare in the Baltic region.

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Voka läbilõige ja selle asend Hilis-Pleistotseeni stratigraafias

Anatoli Molodkov, Natalija Bolihhovskaja, Avo Miidel ja Kuldev Ploom

Voka aleviku põhjaservas on Balti klindi jaoks ebatüüpiliselt Voka klindilahte täitvatesse liivakas-savikatesse pinnakatte setetesse murrutatud kuni 22 m kõrgused astangud. Kahest vahetult Voka (Vasavere) ürgoru suudmes paiknevast esinduslikust paljandist on saadud üllatavaid andmeid selle piirkonna geoloogilise ajaloo kohta.

Väliuuringute andmete ja luminestsentsanalüüsi põhjal on läbilõige jagatud kaheks suureks osaks. Ülemine osa (A) on 18 optilise vanusemäärangu järgi osutunud Kesk-Järva keskosa ealiseks (kolmas mereline isotoopstaadium – MIS 3). Ülemise osa setetest võetud 45 suiraproovi alusel koostatud õietolmuspekter esitab veenvaid tõendeid Kirde-Eesti kliima ja taimkatte märgatavate muutuste kohta. Ajavahemikus 39 000–33 000 kalendriaastat tagasi on eristatud kaks suhteliselt mõõduka ja kaks suhteliselt karmima kliimaga intervalli. Autorite esialgsetel andmetel kuhjus lamav osa (B) ajavahemikus vähemalt 115 000–70 000 aastat tagasi, st Prangli (Eemi) jäävaheajal *sensu lato* ja Kesk-Järva algul (MIS 5 ja 4).

Seega on Voka läbilõikes vastu ootusi esindatud suurem osa Hilis-Pleistotseenist. Samas pole seal leitud viimase jäätumise maksimumile vastavaid ja eelnenud Hilis-Pleistotseeni liustikulisi setteid.