Applied Quaternary research in the central part of glaciated terrain,
edited by *Peter Johansson and Pertti Sarala*.
Geological Survey of Finland, Special Paper 46, 103–112, 2007.

POLLEN AND IR-OSL EVIDENCE FOR PALAEOENVIRONMENTAL CHANGES BETWEEN CA 39 KYR TO CA 33 KYR BP RECORDED IN THE VOKA KEY SECTION, NE ESTONIA

by
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Bolikhovskaya, N. S. & Molodkov, A. N. 2007. Pollen and IR-OSL evidence for palaeoenvironmental changes between ca 39 kyr to ca 33 kyr BP recorded in the Voka key section, NE Estonia. Applied Quaternary research in the central part of glaciated terrain. *Geological Survey of Finland, Special Paper 46*, 103–112, 4 figures.

The sediment sequences of the Voka site situated on the south-eastern coast of the Gulf of Finland were analysed to reconstruct the environmental evolution of northern Estonia over the last Ice Age. Our reconstruction is based on an optically-dated record of pollen-induced palaeoclimate (palaeoenvironmental) proxies. Plotted against depth, palynological analysis and luminescence datings of the samples produced a dated sequence ranging from ca 39 to ca 33 kyr BP, which reveal the specific features of the palaeoenvironmental variations before the last glacial maximum (LGM). Representative pollen spectra from 45 samples provided convincing evidence of noticeable changes in vegetation and climate in northeastern Estonia. Two intervals of severe climate and two considerably milder ones were recognised. Matching of the Voka chronoclimatic pattern to the Greenland ice core variations shows a good fit with the palaeoclimatic signals recorded in Greenland ice cores between Greenland Interstadials 8 and 5.

Key words (GeoRef Thesaurus, AGI): palaeoenvironment, palaeoclimatology, palaeobotany, sediments, pollen analysis, geochronology, optically stimulated luminescence, Pleistocene, Weichselian, Voka, Estonia.

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INTRODUCTION

The last Ice Age is generally assumed to have been characterised by pronounced climatic variations, recorded in many geological archives around the Baltic sphere (Mangerud 1981, Grichuk 1982, Lagerback & Robertsson 1988, Behre 1989, Mamakowa 1989, Liivrand 1991, Donner 1995, Kondratienė 1996, Helmens et al. 2000, Kalnina 2001). However, the timing and reconstruction of palaeoenvironmental evolution on the basis of available fragments of geological record remains a problem in Quaternary geology. There are often gaps in the geological record, and the absolute age of its constituents is frequently unknown. Local stratigraphic schemes are often difficult to correlate with interregional time divisions and with the global palaeoclimatic levels of the ice-core and deep-sea oxygen isotope records. This especially holds true in the Baltic countries where the late Pleistocene glacial erosion over this area could have been very intensive and, therefore, palaeoenvironmental records here may consist of a number of hiatuses. As a result, even the number of Järva (=Weichselian) glaciations or big stadials in Estonia, the northernmost of the three Baltic states, is not yet precisely known (Raukas 2003). In the Estonian Weichselian, two till beds (Valgjärv and Võrtsjärv subformations) are distinguished. The till beds correspond to two Järva glaciation cycles, each of which lasted some 50–55,000 years (Raukas et al. 2004); however, this arouses doubts, see, for example, Kalm (2006). As well, it is not yet clear whether the oldest Valgjärv till belongs to the lower or middle Weichselian (Raukas 2003). The till is widely distributed in central and southern Estonia but is absent from the bedrock areas and other regions of intense glacial erosion in the northern and north western parts of the country (Raukas et al. 2004). For the corresponding early Weichselian glaciation, Kalm (2006) leaves only some 25 kyr (68–43 kyr BP). Therefore, it becomes understandable why different, often contradicting schemes of stratigraphic subdivision and palaeoenvironmental interpretations of past climates and sedimentary history of the region during the last Ice Age have been proposed in the last decades (Kajak et al. 1976, Raukas & Kajak 1995, Gaigalas 1995, Satkūnas 1997).

The survival of well-preserved, in situ pre-LGM deposits is very rare in northern Estonia. In this area, glacial erosion prevailed and the thickness of the Quaternary deposits is usually less than 5 m. Therefore, interdisciplinary study of those sections that do exist, such as Voka site, can potentially provide a unique opportunity to reconstruct the palaeoenvironmental history of the region in greater detail.

The aim of this study was to identify the main palaeoenvironmental stages in northern Estonia using palaeoclimate proxies based on detailed palynological analysis of the deposits from the new late Pleistocene section at the Voka site, north eastern Estonia. A depth-age model in this study was constructed using regression analysis of the infrared optically stimulated luminescence (IR-OSL) dating results obtained on the samples collected from this section (Molodkov 2007).

STUDY SITE AND RESEARCH METHODS

The Voka site is located on the south eastern coast of the Gulf of Finland where the Estonian part of the Baltic Clint is interrupted by an about 2.2-km-wide depression – the Voka Clint Bay (Figs. 1A, B). The latter, in its turn, is intersected by a deep canyon-like palaeoincision. According to drilling data, most of the incision is filled with fine-grained sand and silt with a total thickness of at least 147 m. Layers of gravely sand, coarse- to medium-grained sand and clays also occur. The northernmost part of the valley deepens very abruptly, with the bottom gradient reaching 12 m per km and the slope gradient is more than 500 m per km (Molodkov et al. 2007).

The deposits studied are exposed along the Gulf coast in the V3 outcrop (59°24.86´N, 27°35.88´E) situated about 500 m to the east from the mouth of the Voka (Vasavere) River (see Fig. 1B). Immediately on the shore, the height of the outcrop is about 22 m a.s.l. The sandy to clayey sedimentary sequence comprises at least two lithostratigraphic units – A and B (Fig. 2). Topwards unit A in the V3 outcrop is overlain by about 1.1-m-thick brownish-grey to light-brown soil resting upon ca 0.7-m-thick layer of light-brown silt-like deposits showing signs

exposure V3 are available in Molodkov (2007) on Quaternary Geochronology Online).

Such an integrated approach based on two independent methods applied to one and the same source of climate-stratigraphic information gives a unique opportunity to reveal specific features of pre-LGM palaeoenvironmental variations.

RESULTS OF PALAEOENVIRONMENTAL RECONSTRUCTIONS

Plotted against depth, palynological analysis and luminescence datings of the samples taken from the section produced a dated sedimentary sequence within the whole unit A (between the depths of 12.15 m and 1.80 m) covering the period from ca 39 to 31 kyr BP (Fig. 2). Deposits from the depths between 12.15 m and 5.00 m reveal specific features of pre-LGM palaeoenvironmental variations during the time span of ca 6 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 these deposits at a depth of 1.60 m (Molodkov 2007). According to several preliminary age determinations (ibid), the dated deposits of unit B span the period from at least 115 kyr to at least 70 kyr. The presence of older deposits (>115 kyr) is expected in the lower part of the sections currently unavailable due to the thick talus at the base of the outcrops. Representative pollen spectra derived from 45 samples taken at depths between 12.15 m and 5.00 m provide convincing evidence of noticeable changes in vegetation and climate in northern Estonia during the period from ca 39 to 33 kyr BP.

The results of palynological analysis of the studied sediments are presented on the spore-pollen diagram (Fig. 3). Most of the taxa of the studied palynoflora are grouped by genera and families to

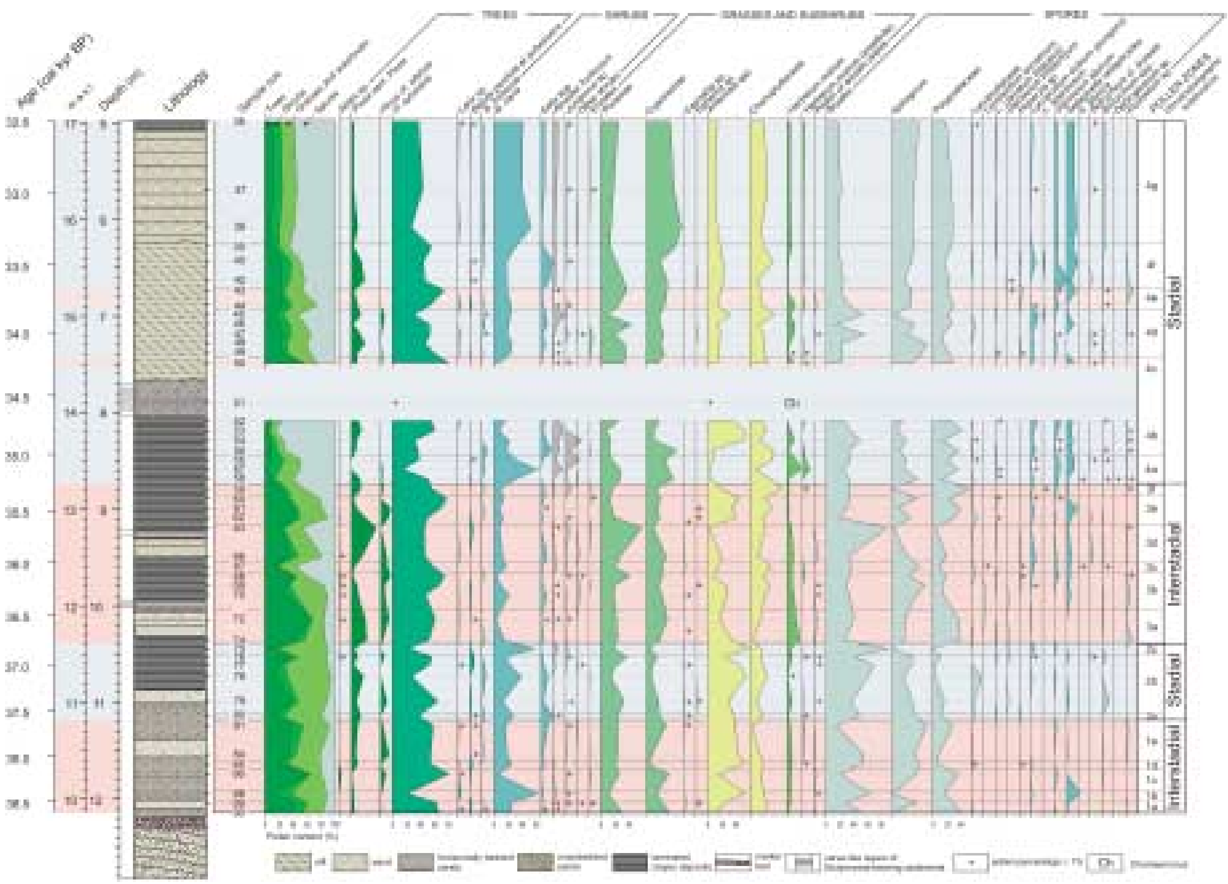

Fig. 3. Pollen and spore percentage diagram from unit A of the V3 section (5.00–12.15 m).

make the diagram more compact. The palynological data obtained testify that the period of accumulation of the middle Weichselian (=middle Valdai, middle Järva) sediments under consideration corresponds to four climatostratigraphic subdivisions – two intervals of severe climate and two interstadials with remarkably milder climatic conditions.

The pollen data from the middle Weichselian deposits are rather scarce in Estonia. Pollen assemblages recovered from the periglacial middle Weichselian deposits in Tõravere, Valguta, Savala and other sections were interpreted by E. Liivrand (1991, 1999) as evidence of cold stadial environments with widely spread tundra and xerophytic communities (with dominance of dwarf birch *Betula nana*, wormwood *Artemisia*, wormseed *Chenopodiaceae, Poaceae/Gramineae* and *Cyperaceae*). No middle Weichselian interstadial warmings have been identified up to now. In this connection, we shall consider in more detail the climatostratigraphic subdivision of the investigated deposits as well as the changes that took place in vegetation and climate during the period of sedimentation.

The 1st Voka interstadial (VIS-1A, 38.6 – 37.6 kyr BP)

The first period of relative warming (38.6–37.6 kyr BP) is revealed by pollen assemblages between 11.20–12.20 m (Fig. 3). At the Voka site, this interstadial was marked by the dominance of mainly periglacial forest-tundra, locally with open forest patches of spruce (*Picea sect. Picea*) and common pine (*Pinus sylvestris*), with a mixture of larch *Larix* and Siberian cedar pine *Pinus sibirica*.

Five pollen zones (1a–1e) corresponding to five phases of vegetation and climate evolution reflect dynamics of palaeoenvironmental changes during this interval. Periglacial forest-tundra comprising patches of pine forests (with an admixture of *Larix sp.*) prevailed during the first phase (pollen zone 1a; 12.0–12.2 m). Later, in the second phase (pollen zone 1b; 11.9–12.0 m), the climate became colder and dryer. This resulted in an increased abundance of cryophytes and xerophytes in the vegetation – *Betula sect. Nanae, Alnaster fruticosus, Selaginella selaginoides, Artemisia* (including *Artemisia subgenus Seriphidium*), *Chenopodiaceae*, etc. Patches of larch open forests occasionally occurred. Open tundra-steppe landscapes dominated.

The most significant warming within this interstadial and expansion of coniferous trees over the study area took place during the third phase (pollen zone 1c; 11.7–11.9 m). *Pinus sylvestris* accounted for more than 90% in the relevant palynospectra. Pine forests and open forests of common pine (*Pinus sylvestris*) dominated. The fourth phase (pollen zone 1d; 11.6–11.7 m) is characterised by the dominance of periglacial forest-tundra with spruce-pine forests, in combination with yernik (formed by the *Betula nana* and *Alnaster fruticosus*), and *Chenopodiaceae-Artemisia* communities.

During the fifth phase (pollen zone 1e; 11.2–11.6 m), the studied area was occupied by periglacial forest-tundra with Siberian cedar pine-spruce-common pine forests with a mixture of larch, along with steppe and shrubby (*Betula nana* and *Salix sp., Alnaster fruticosus*) communities. The steppe biotopes were prevailed *(Poaceae, Asteraceae, Primulaceae, Onagraceae, Primulaceae, Polygonaceae, Rumex sp., Urtica sp., Plantago media, Ranunculus sp.*, etc.) and wormwood (*Artemisia subgenus Euartemisia, A. subgenus Seriphidium*) associations.

The 1st Voka stadial (VS-1A, 37.6 – 36.8 kyr BP)

The first period of warming (VIS-1A) was followed by a relatively short interval of a colder and dryer climate, which lasted some 800 years (37.6–36.8 kyr BP; 10.4–11.2 m). According to palynological data (see Fig. 3), the prevailing landscapes were tundra-steppe and tundra-forest-steppes.

The herb-dwarf shrub pollen (mainly *Artemisia, Chenopodiaceae, Poaceae, Cyperaceae*) and spores (*Bryales, Sphagnum*) predominate in all pollen assemblages (NAP – 41 to 70%; Spores – 6 to 20%). Besides, the pollen spectra are characterized by high percentages of cryophytes and xerophytes, such as *Betula nana, Alnaster fruticosus, Artemisia (including A. subgen. Seriphidium, A. subgen. Dracunculus), Chenopodiaceae, Ephedra, Lycopodium dubium, Diphazium alpinum, Selaginella selaginoides*.

Pollen zones 2a, 2b and 2c correspond to three phases of environmental evolution and reveal transformations of vegetation during this stadial episode.

In the first phase (pollen zone 2a; 11.1–11.2 m) open tundra-steppe environments predominated.

In the second phase (pollen zone 2b; 10.5–11.1 m) humidity increased, and the tundra-forest-steppes with patches of Siberian cedar pine-spruce-common pine light forests became dominant.

In the third phase (pollen zone 2c; 10.4–10.5 m), the climate turned drier and tundra-steppes prevailed again.

During the first and third phases, tundra-steppe vegetation was most widespread in the surroundings of Voka. The distinctive features of the long-term second phase were the more humid climate, expansion of patches of coniferous (Siberian cedar pine–spruce–common pine) light forests and predominance of tundra-forest-steppes.

The 2nd Voka interstadial (VIS-2A; 36.8 – 35.3 kyr BP)

The next interstadial (36.8–35.3 kyr BP; 8.75–10.40 m), much warmer than the previous one, was characterised by a new expansion of boreal forest species onto the area under study. Six climatic-phytocoenotic phases were reconstructed, reflecting changes in the plant communities during this interval. These successions show that at least twice – during wetter and warmer climatic phases – periglacial forest-tundra (locally with open spruce and pine forests) was replaced by more humid landscapes with prevailing northern taiga communities.

During the first phase, the Siberian cedar pine–spruce–common pine (*Pinus sylvestris*) forests and parkland forests dominated, corresponding to pollen zone 3a (10.1–10.4 m). In the evolution of vegetation, this was the warmest interval of the whole interstadial. In the dendroflora, the total boreal pollen accounted for about 70–90%. The second phase (pollen zone 3b; 9.65–10.1 m) was prevailed by periglacial forest-tundra with patches of Siberian cedar pine–pine open forests. In approximately the middle of this interstadial – in the third phase (pollen zone 3c; 9.55–9.65 m) – a short interval with a significantly colder climate and domination of periglacial tundra is recorded.

During the forth phase (pollen zone 3d; 9.15–9.55 m) periglacial forest-tundras with patches of pine-spruce and Siberian pine-spruce-pine light forests dominated.

Periglacial light forests of Siberian cedar pine (*Pinus sibirica*), spruce (*Picea sect. Picea*) and common pine (*Pinus sylvestris*) prevailed in the Voka area during the fifth phase characterized by pollen zone 3e (8.85–9.15 m), reflecting a new warming within VIS-2A. During the latest sixth phase (pollen zone 3f; 8.75–8.85 m), periglacial forest-tundras with small patches of spruce–pine open woodlands predominated in the studied area.

The 2nd Voka stadial (VS-2A; 35.3 – 32.6 kyr BP)

During the last interval (VS-2A; 35.3–32.6 kyr BP), periglacial tundra remained 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 were dominated by *Betula nana*, *Poaceae* and *Cyperaceae*, together with the spores of *Sphagnum, Bryales, Selaginella selaginoides, Lycopodium dubium, Diphazium alpinum* and other typical tundra species. This suggests that the interval was close to the final part of the middle Weichselian preceding the late Weichselian ice sheet expansion into the region.

Pollen-and-spore spectra recovered from the deposits at the depths between 8.75 and 4.95 m allowed for reconstruction below the presented seven successive phases in the evolution of vegetation and climate during this second cold episode.

In the first phase (pollen zone 4a; 8.45–8.75 m), periglacial tundra dominated with a prevalence of yernik bushes (from dwarfish birch *Betula nana*) and shrubby communities (from juniper *Juniperus sp*., willow *Salix sp., Alnaster fruticosus*, etc.) and grass-moss bogs.

In the second phase (pollen zone 4b; 8.05–8.45 m), a distinctive feature of vegetation was the almost ubiquitous expansion of periglacial tundra with the domination of moss bogs and the presence of small patches of tundra shrubs.

Sands in the depth interval 7.55–8.05 m contained only single pollen grains.

In the third phase (pollen zone 4c; 7.45–7.55 m), periglacial forest-tundra with small patches of pine light forests (of *Pinus sylvestris*) occupied the Voka area under warmer climate conditions.

In the fourth phase (pollen zone 4d; 6.95–7.45 m), the forested areas were considerably reduced due to the cooling of the climate. The role of microthermic tundra plants (*Betula nana, Alnaster fruticosus, Selaginella selaginoides, Lycopodium dubium, L.appressum, Diphazium alpinum*, etc.) increased. Periglacial tundras dominated. *Pinus sylvestris* and *Larix sp*. were edificators in forest stands of rare forest-tundra communities.

A new short warming led to reduction of tundra shrubby coenoses in the fifth phase (pollen zone 4e; 6.70–6.95 m). The significance of periglacial forest-tundras and boreal tree species (*Pinus sylvestris*, *Larix*, etc.) increased.

In the sixth phase (pollen zone 4f; 6.25–6.70 m), the incipient climate cooling triggered a new expansion of grassy cryophytes (*Selaginella selaginoides, Diphazium alpinum, Lycopodium dubium, L. appressum*, etc.) and domination of periglacial tundras.

In the final seventh phase of this stadial (pollen zone 4g; 4.95–6.25 m), periglacial tundra predominated in the Voka area with a prevalence of yernik bushes (from dwarf birch *Betula nana*) and grass-moss bogs.

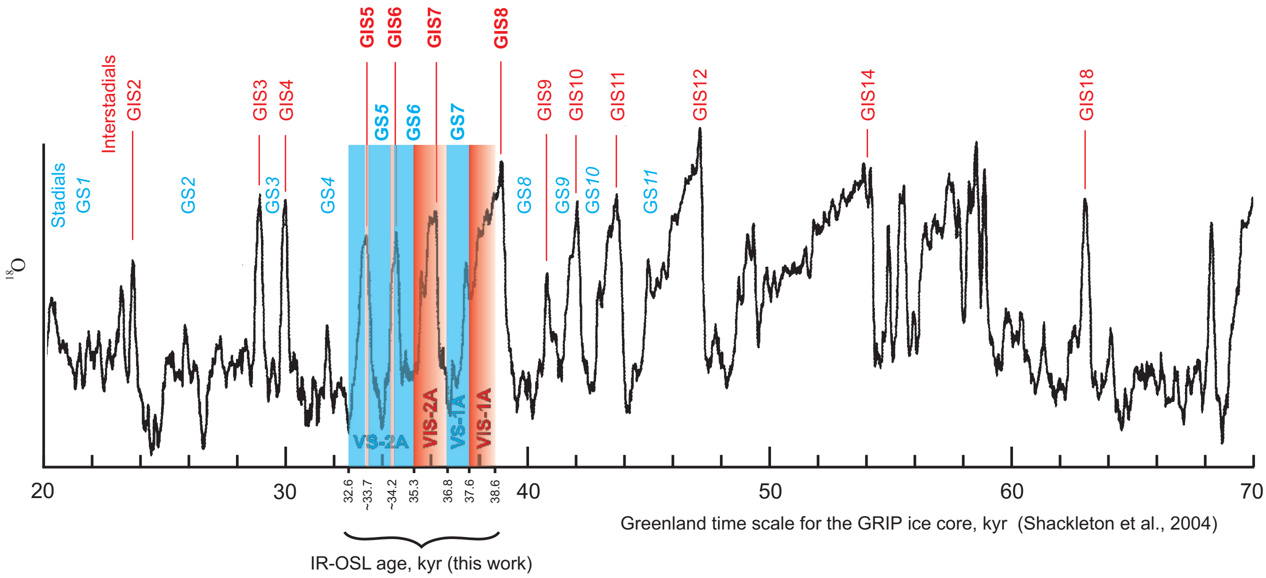

Fig. 4. Matching Voka chronoclimatic pattern (this work) to the Greenland ice-core variations (Shackleton et al. 2004). The best fit lies between Greenland Interstadial 8 (GIS8) and GIS5.

Thus, two minor warmings are recognised within the second cold event (VS-2A) at depths of about 7.50 m and 6.70–6.95 m corresponding to the ages of 34.2 kyr and between 33.7 and 33.8 kyr BP, respectively. During these short-term warmings, the dominating periglacial tundras were replaced by periglacial forest-tundras with small patches of light forests, in which Pinus sylvestris served as an edificator.

DISCUSSION

The reconstructed paleoenvironmental changes give evidence for specific individual features of the mid-Weichselian palaeoclimatic stages.

The obtained pollen data show that the share of dark coniferous trees – spruce and Siberian cedar pine – was considerable in the forest communities during the interstadial between ca 38.6 – 37.6 kyr BP, whereas during the younger interstadial ca 36.8 – 35.3 kyr BP spruce (*Picea sect. Picea*) and *Pinus sibirica* were far less abundant. Forest biotopes of this warmer interstadial were rather dominated by larch (*Larix sp.*).

Palaeoenvironments of each cold interval also had their own characteristic features. This primarily concerns the dominant zonal types of vegetation. Climatic conditions of the oldest interval were more arid, and the study territory was covered by tundra-steppe and tundra-forest-steppe. The open grass-low bush biotopes were dominated by *Chenopodiaceae-Artemisia* associations. During a long cold epoch that lasted for about 2500 years from ca 35.3 kyr BP till at least 32.6 kyr BP, the Voka area was characterized by periglacial tundra with grasses and sedges dominating the open landscapes. Also, such arctic alpine and hypoarctic tundra grass species as *Selaginella selaginoides*, *Diphazium alpinum, Lycopodium dubium, L. appressum, Botrychium boreale* were abundant.

The data on the duration of the reconstructed interstadials and stadials during the Weichselian glacial epoch are of critical importance for detailed chrono- and climatostratigraphy. Based on the obtained IR-OSL data, the duration of the established interstadials is estimated at approximately 1000 and 1500 years. Due to the incompleteness of the geological record of the most ancient of the interstadials, caused by a relatively long break in sedimentation, its duration was not less than 1500 years. The duration of the reconstructed mid-Weichselian cold stadials is even more different. The first cooling lasted for about 800 years (ca 37.6 – 36.8 kyr BP), but the next one was at least 2700 years long (ca 35.3 – 32.6 kyr BP). These data together with the obtained floristic, phytocoenotic, and climatostratigraphic characteristics of the investigated interstadials and stadials should be considered when identifying and correlating palaeogeographical events of the Weichselian (Valdai, Järva) glacial epoch. Our data unambiguously demonstrate that the studied sediment sequence in the Voka section is by no means a late glacial formation. This is substantiated by comparison of the climatophytocoenotic features and chronological extent of the studied intervals with analogous data on the late glacial events in Estonia and adjacent regions.

Firstly, the late glacial warm and cold intervals had a shorter duration than the stratigraphical units investigated in the Voka section. Secondly, the Voka interstadials strongly differ from the Allerød, which is well represented in the Baltic countries, also in the dominant type of palaeovegetation. Forests of the reconstructed warm epochs were lacking birch stands and were dominated by coniferous communities. In southern and northern Estonia, birch was predominate among arboreal species during the first half of the Allerød, and only during its second half was replaced by pine (*Pinus sylvestris*) (Pirrus 1969, Pirrus & Raukas 1996, Kabailienė & Raukas 1987). During the Allerød, forests composed of *Betula sect. Albae* and alder (*Alnus sp.*) were widespread to the east from Estonia, in the vicinity of the Lake Il'men' (Razina & Savel'eva 2001). Further north, in the southern Karelia, the birch Betula sect. Albae, including *Betula pubescens*, was also a dominant species (Elina et al. 1995, Wohlfarth et al. 2002).

Matching our Voka chronoclimatic pattern to the Greenland ice-core variations shows that there is only one good fit with the palaeoclimatic signals recorded in Greenland ice cores, which exists between Greenland Interstadial 8 (GIS8) and GIS5 (Fig. 4). The first Voka interstadial VIS-1A identified within unit A corresponds to GIS8. The second Voka warm event VIS-2A is clearly comparable with GIS7. It is highly probable that two warm spells identified in the Voka section during the second Voka stadial VS-2A can be correlated with GIS6 and GIS5. As well, this Voka stadial VS-2A can be correlated with Greenland Stadial 6 (GS6), GS5 and with the initial part of GS4.

As in the Greenland ice core record, the second interstadial in the Voka section is warmer than the previous one. It also seems that the initial part of the interstadial correlative to GIS8 is absent in the Voka section because the corresponding part of the sediments is interrupted by a gravel bed at the bottom of unit A. As well, like in the ice core, the second Voka stadial VS-2A is also somewhat colder than the previous one. Thus, it seems that there are quite a few coincidences between features in the ice core and the Voka records. In view of this, there is a possibility that these coincidences are not accidental.

CONCLUSIONS

It was established in the present study that optical ages and palynological features derived from unit A of the V3 section mark the time of the existence of relatively complex and changeable environmental conditions during the middle Weichselian pleniglacial.

Representative palynological data obtained at the Voka site have provided convincing evidence of the occurrence of two severe and two considerably milder climate intervals in the time span ca 39–33 kyr.

The first interstadial at the Voka site (38.6–37.6 kyr) was marked by the dominance of mainly periglacial forest-tundra, locally with open forest patches of spruce and common pine with a mixture of larch and Siberian cedar pine. During the following relatively short (37.6–36.8 kyr) interval with a colder and dryer climate, landscapes of tundra-steppe and tundra-forest-steppes prevailed. The next interstadial (36.8–35.3 kyr), much warmer than the previous one, was characterised by a new expansion of boreal forest species into the study area. The last interval (35.3–32.6 kyr) was characterised by landscapes where a periglacial tundra type of vegetation dominated. The considerably colder climate at that time and expansion of permafrost resulted in the appearance of wetlands of moss and grass types. This suggests that this interval was close to the final part of the middle Weichselian preceding the late Weichselian ice sheet expansion into the region.

The Voka outcrops studied do not display the assumed late-glacial deposits. Instead, it was established that the deposits exposed in the Voka outcrops demonstrate a general similarity between the Voka and Greenland ice-core records. Matching the Voka chronoclimatic pattern to the Greenland ice-core variations shows a good fit with the palaeoclimatic signals recorded in Greenland ice cores between Greenland Interstadials 8 and 5.

ACKNOWLEDGEMENTS

We are grateful to A. Miidel, A. Nikonov and K. Ploom for valuable discussions. We also thank T. Balakhnichova, T. Metslang, V. Nikonov and T. Tubli for their helpful support during fieldworks, T. Balakhnichova and M. Osipova for their contribution to the laboratory work, and H. Kukk for revision of the English text. Special thanks go to the referees Dr. Antti E.K. Ojala and Dr. Heikki Hirvas for their valuable comments on the paper. This research was supported through grants nos. 5440 and 6112 from the Estonian Science Foundation and by Estonian State Target Funding Projects nos. 0331759s01 and 0332089s02.

REFERENCES

Behre, K.-E. 1989. Biostratigraphy of the last glacial period in Europe. Quaternary Science Reviews 8, 25–44.

Donner, J. 1995. The Quaternary history of Scandinavia. Cambridge: Cambridge University Press. 200 p.

Elina, G. A., Filimonova, L. V. & Klimanov. V. A. 1995. Late glacial and Holocene paleogeography of East Fennoscandia. In: Velichko, A. A. (ed.) Climate and environment changes of East Europe during Holocene and Late-Middle Pleistocene. Materials of IGU conference: Global changes and geography, Moscow, August 14–18, 1995. Moscow: Institute of Geography of Russian Academy of Sciences, 20–27.

Gaigalas, A. 1995. Glacial history of Lithuania. In: Ehlers, J., Kozarski, S. & Gibbard, Ph. (eds.) Glacial deposits in North-East Europe. Rotterdam: Balkema, 127–135.

Grichuk, V. P. 1982. Rastitel'nost' Evropy v pozdnem plejstotsene (Vegetation of Europe During Late Pleistocene). In: Gerasimov, V. P. & Velichko, A. A. (eds.) Palaeogeography of Europe during the last 100,000 years (Atlas-monograph). Moscow: Nauka, 92–109. (in Russian)

Grichuk, V. P. & Zaklinskaya, E. D. 1948. Analiz iskopaemykh pyltsy i spor i ego primenenie v paleogeografii (Pollen-and-spores analysis and its application in palaeogeoraphy). Moscow: Moscow Lomonosov State University, Geography Press. 223 p. (in Russian)

Helmens, K. F, Räsänen, M. E, Johansson, P. W, Jungner, H. & Korjonen, K. 2000. The Last Interglacial-Glacial cycle in NE Fennoscandia: a nearly continuous record from Sokli (Finnish Lapland). Quaternary Science Reviews 19, 1605–1623.

Kabailienė, M. & Raukas, A. 1987. Stratigraphy of lake and bog deposits and climatic changes in the late-glacial and Holocene in the Soviet Baltic Republics: review. Boreas 16, 125–131.

Kajak, K., Kessel, H., Liivrand, E., Pirrus, R., Raukas, A. & Sarv, A. 1976. Mestnaya rabochaya stratigraficheskaya skhema chetvertichnykh otlozhenij Estonii (Local Estonian version of the stratigraphical scheme of Quaternary deposits). Vilnius: Stratigrafiya chetvertichnykh otlozhenij Pribaltiki, 4–52. (in Russian)

Kalm, V. 2006. Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. Quaternary Science Reviews 8, 960–975.

Kalnina, L. 2001. Middle and Late Pleistocene environmental changes recorded in the Latvian part of the Baltic Sea basin. Stockholm: Stockholm University, Department of Physical Geography and Quaternary Geology. 173 p. (Ph.D Thesis)

Kondratienė, O. 1996. Quaternary stratigraphy and paleogeography of Lithuania based on palaeobotanical studies. Vilnius: Academia. 213 p. (in Russian with English summary)

Lagerback, R. & Robertsson, A.-M. 1988. Kettle holes – stratigraphical archives for Weichselian geology and palaeoenvironment in northermost Sweden. Boreas 17, 439–468.

Liivrand, E. 1991. Biostratigraphy of the Pleistocene deposits in Estonia and correlations in the Baltic region. Stockholm: Stockholm University, Department of Quaternary Research. 114 p. (Ph.D Thesis)

Liivrand, E. 1999. Palynological investigations of the early and middleValdaian periglacial deposits in Estonia. In: Bolikhovskaya, N. S. & Rovnina, L. V. (eds.) Urgent problems of palynology on the boundary of the third millennium. Abstracts of IX Palynological Conference, Moscow, September 13–17, 1999. Moscow: IGiRGI, 162–163. (in Russian)

Mamakowa, K. 1989. Late Middle Polish Glaciation Eemian and Early Vistulian vegetation at Imbramowice near Wrocław and the pollen stratigraphy of this part of the Pleistocene in Poland. Acta Palaeobotanica 29 (1), 11–176.

Mangerud, J. 1981. The Early and Middle Weichselian in Norway: a review. Boreas 10, 381–393.

Molodkov, A. 2007. IR-OSL dating of uranium-rich deposits from the new late Pleistocene section at the Voka site, North-Eastern Estonia. Quaternary Geochronology 2, 208-215.

Molodkov, A., Bolikhovskaya, N., Miidel, A. & Ploom, K. 2007. The sedimentary sequence recovered from the Voka outcrops, North-Eastern Estonia: Implications for late Pleistocene stratigraphy. Estonian Journal of Earth Sciences 56 (1), 47–62.

Pirrus, R. 1969. Stratigraficheskoe raschlenenie pozdnelednikovykh otlozhenij yuzhnoj Éstonii po dannym sporovo-pyl'tcevogo analiza (Stratigraphic division of South Estonian late glacial deposits by means of pollen analysis). Proceedings of the Estonian Academy of Sciences. Chemistry, Geology 18, 181–190. (in Russian)

Pirrus, R. & Raukas, A. 1996. Late-glacial stratigraphy in Estonia. Proceedings of the Estonian Academy of Sciences. Geology 45, 34–45.

Raukas, A. 2003. Progress in Estonian Quarternary stratigraphy during the last decade. Geologija 41, 36–43.

Raukas, A. & Kajak, K. 1995. Quaternary stratigraphy in Estonia. Proceedings of the Estonian Academy of Sciences. Geology 44, 149–162.

Raukas, A., Kalm, V., Karukäpp, R. & Rattas, M. 2004. Pleistocene glaciations in Estonia. In: Ehlers, J. & Gibbard, P. L. (eds) Quaternary Glaciations – Extent and Chronology, Part I: Europe. Amsterdam: Elsevier, 83–91.

Razina, V. & Savel'eva, L. 2001. Palynological results of the late glacial and Holocene sediments of Lake Il'men. In: Climate and environment during the last deglaciation and Holocene in NW Russia and around the Baltic. International Workshop, March 28–April 2, 2001, St. Petersburg–Znamenka. Abstract volume, 36.

Satkūnas, J. 1997. Outline of Quaternary stratigraphy of Lithuania. INQUA-SEQS Symp. In: Satkūnas, J. (ed.) The Late Pleistocene in eastern Europe: stratigraphy, palaeoenvironment and climate. Abstract volume and excursion guide of the INQUA-SEQS Symposium, September 14–19, 1997, Lithuania, 65–68.

Shackleton, N. J., Fairbanks, R. G., Chiu, T.-C. & Parrenin, F. 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for Δ14C. Quaternary Science Reviews 23, 1513–1522.

Wohlfarth, B., Filimonova, L., Bennike, O., Björkman, L., Brunnberg, L., Lavrova, N., Demidov, I. & Possnert, G. 2002. Late-Glacial and Early Holocene Environmental and Climatic Changes at Lake Tambichozero, Southeastern Russian Korelia. Quaternary Research 58, 261–272.