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# Climate change dynamics in Northern Eurasia over the last 200 ka: Evidence from mollusc-based ESR-chronostratigraphy and vegetation successions of the loess–palaeosol records

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## ABSTRACT

The time span of the past 200 ka has been marked by many large-scale global and regional climate changes, between warmer and cooler conditions. As is usually the case when studying the past, palaeoenvironmental data become scarcer with increasing age. Therefore, every detailed palaeoenvironmental record may be of special interest to Quaternary geologists in terms of palaeoenvironmental reconstructions, correlations and general stratigraphy of the Quaternary.

In this paper we present a long palynological record of terrestrial flora and an ESR-dated marine record of global-scale climatic variation obtained from a loess–palaeosol sequence in the East European Plain and continental margin of Northern Eurasia for the time span starting from the penultimate glacial period correlating with Marine Isotope Stage (MIS) 6. These records show that in combination they have a potential of assigning warm/cold climate related deposits to the chronostratigraphically organised sequence of the late Pleistocene palaeoenvironmental events.

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## 1. Introduction

Long and continuous terrestrial proxy climate records throughout the time interval since the penultimate (Dnieper/Saale, MIS 6) glaciation are rare. A few most complete loess–palaeosol sections are situated in the glacial and extraglacial zones of the East European Plain. At present, these are among the longest and palynologically best studied sections (Bolikhovskaya, 1995). However, each of those is seriously limited in age control, especially beyond the limits of radiocarbon dating. Since our first joint paper (Bolikhovskaya and Molodkov, 1999), the palynostratigraphical record derived from long continuous loess–palaeosol sequences was calibrated for age by correlation to the mollusc-based ESR-chronostratigraphical record in which warm-climate-related events were dated by ESR on subfossil mollusc shells taken directly from the transgressive marine sediments. This integrated palynochronostratigraphic approach allowed us to constitute precious palaeoclimatic references helping to link at least the most prominent palaeoenvironmental events that had occurred in Northern

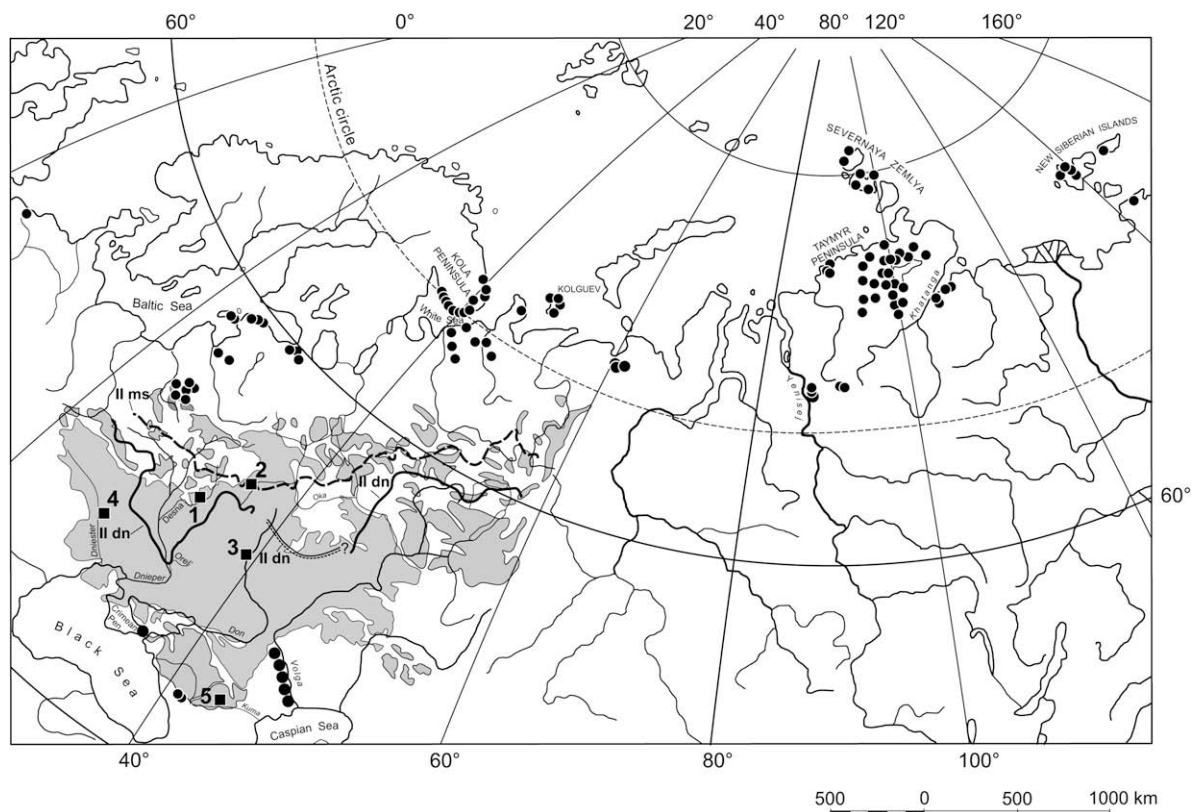
Eurasia over the last 600 ka (Bolikhovskaya and Molodkov, 2002; Molodkov and Bolikhovskaya, 2002).

In the present study, we attempted to link marine mollusc-based age analysis from the two last glacial intervals and an interglacial between them with the palaeoclimatic data derived from the pollen-based vegetation signals of terrestrial environment from the East European loess province. The linkage of these two independent climatic records is our first attempt to insight palaeoenvironmental changes during the last two glacial periods where radiometrically dateable materials typically are scarce both in terrestrial and marine sediments.

The development of the loess–palaeosol formation (LPF) within the East European loess province has been closely related to ice sheet dynamics. Therefore, the long continuous loess–palaeosol sequences located in the glacial and extraglacial zones of this area, when thoroughly analysed palynologically, can provide the most detailed middle-late Pleistocene climatic records ever retrieved in this palaeoenvironmentally important geographical region. The best known sections here are the Likhvin-Chekalin (Upper Oka), Strelitsa (Upper Don), Arapovichi (Middle Desna), Molodova and Ketrosy (Middle Dniester), and Otkaznoe (Middle Kuma) (Fig. 1), because they provide evidence of almost complete and continuous deposition and contain enough pollen to construct a record of climate-driven vegetation changes since the penultimate glaciation (Bolikhovskaya, 1995).

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**Fig. 1.** Map showing the localities of collected shell samples (circles), studied loess-palaeosol sections (squares: 1 – Arapovichi, 2 – Likhvin, 3 – Strelitsa, 4 – Molodova, 5 – Otkaznoe), distribution of loesses on the East European Plain (grey area), limits of Dnieper (Il dn) and Moscow (Il ms) glaciations (after Zarrina, 1991) and names mentioned in the text.

However, time control in a long-term continental record is often poor. For a reliable understanding of the climate changes in the past, it is fundamental to integrate the long and continuous continental record in a physically dated time stratigraphic framework. For this purpose we use two independent sources of palaeoenvironmental data: electron spin resonance (ESR) chronology of warm-climate-related marine deposits and terrestrial record of vegetation response to climatic variability and palaeoenvironmental events.

Marine deposits of Northern Eurasia are palaeoenvironmentally the most important for Quaternary studies, as they are located in a climate-sensitive area, are characterized by a wide distribution, continuous sedimentation, and by usually well-preserved fossil material. Among the latter, mollusc shells are often found in uplifted coastal marine deposits. Dating of these fossils from transgressive deposits can provide an independent chronology of global ice volume and sea level/climate change. In other words, the raised mollusc-rich marine deposits can be considered to be a proxy indicator of global climate change that should be reflected both in marine and terrestrial records.

The palynological data of reference sections of the glacial-periglacial and extraglacial zones, reflecting the succession of vegetation following changes of moisture and heat supply in the Pleistocene, can provide the most complete record of climatic conditions on land, the assessment of the stratigraphic position of sediments, intra- and inter-regional correlations of geological bodies and palaeogeographical events. The structure of this record can be directly compared with the climate-dependent curve of deep-sea oxygen isotopy.

Together, this multi-proxy data from the continental and marine records should provide important evidence about the remote linkage between marine and terrestrial sedimentary environments:

mollusc-rich raised marine deposits in the coastal areas of Northern Eurasia can be readily correlated to key palynological signatures of interglacial deposits in the complete terrestrial record and used as the basis for determining their chronostratigraphical position and their age. Besides, in such a way it is possible to demonstrate the presence of a chronological hierarchy of palaeoenvironmental events in the late middle and late Pleistocene sedimentary sequence that would allow us to interpret this observation in terms of climate changes. Such an integrated approach is of great importance for establishing event-to-event land-sea correlations, for understanding relatively long-term large-scale naturally induced climate changes, and for linkage of terrestrial and ESR-dated marine sequence to the standard measure of Pleistocene climate change like the global marine isotope stage sequence.

## 2. Study area

Reliable absolute datings and detailed palynological study of complete late Pleistocene sequences can help bridge the gap between different points of view on late Quaternary palaeoenvironmental history. Some of such sequences were revealed in the complete loess-palaeosol sections in the different parts of the East European Plain.

Peculiarities of phytocoenotic and climatic successions and composition of characteristic taxa over the last 200 ka are considered in the present paper with an example of two most typical stratoregions of the central part of the Russian Plain – The Northern Central Russian glacial loess region and the Middle Desna glacial loess region.

The Northern Central Russian loess region occupies the north of the Central Russian Upland within the limits of the maximal middle Pleistocene (Dnieper/Saale) glaciation. The composition and

structure of the late middle Pleistocene sediments are most fully represented in the Likhvin situated at approximately 54.07° N and 36.18° E (Fig. 1) on the left bank of the Oka River, 1 km north of Chekalin town.

The Middle Desna region is situated in the northeast of the Dnieper Lowland, within the limits of the Dnieper ice sheet. A complete late Pleistocene sequence is preserved in Arapovichi – in one of the most representative stratotype sections (51.57° N, 33.19° E, Fig. 1) in the region. The section is located on the interfluvial plateau on the right bank of the Desna River, about 12 km southwest of the town of Novgorod-Seversky. In this section the vegetation and climate of the Mikulino Interglacial and the majority of Valdai interstadials and stadials are considered.

A comprehensive layer-by-layer characterisation of the whole sequence permitted its detailed subdivision and allowed reconstruction of the diversified environmental and climatic events in these regions. The greater part of the sections examined for this study appears to contain a well-preserved and almost continuous pollen record that spans a climate interval correlative to MIS 6 through the latest part of MIS 2.

A palaeodosimetrically based proxy record of the climate and sea level changes over the past 200,000 years has been obtained on more than 200 mollusc shell samples. They were mostly taken from climate-controlled marine deposits along the continental margin of Northern Eurasia. The shells were dated using an advanced version of the ESR method (Molodkov 1986, 1988, 1989, 1993, 1996) to produce an independent mollusc-based chronology for multiple marine transgressions (relatively high sea level stands) during which large epicontinental basins occupied vast areas of the Northern Eurasian coast (Fig. 2). In addition, some few dating results on freshwater mollusc shell samples from interglacial lacustrine deposits in the southern Baltic have also been used. The ESR results presented here comprise the largest database at least for the late Quaternary warm-climate-related deposits from the Northern Eurasia. The greater part of the datings (over 150) was obtained on the last interglacial. Time intervals in the chronostratigraphic record where ESR age determinations are relatively rare or entirely absent can, in turn, be interpreted as indicating cold climate conditions or the onset of glaciations in the Northern Hemisphere accompanied by a general eustatic sea level lowering and a large-scale palaeoclimatic deterioration on land.

### 3. Methods

The principal method applied to derive the terrestrial palaeoclimate proxy was the palynological one. It holds a leading position among the other palaeobotanic methods, primarily due to the fact that pollen and spores are the only palaeontological objects which are found practically in all types of sediments, including even the commonly spore-and-pollen poor sedimentary environment such as loesses and palaeosols.

Materials obtained in the course of our palynologic research, together with published data on pollen spectra from subrecent samples of soils and results of palynological studies of soil profiles, show that in most cases pollen spectra of the subaerial formations adequately reflect the zonal type and dominant formations of the vegetation of the time in question. A close examination of the detailed palynological results and data on LPF composition and properties enabled us to establish principal factors controlling the formation of the LPF pollen spectra. Detailed and careful study of the loess–palaeosol formation allows a reliable reconstruction of continuous succession of vegetation during the whole time interval targeted in this study (Bolikhovskaya, 1995).

Our reconstructions of landscapes and climate for the Eemian and other thermochrons and cryochrons of the late middle and late Pleistocene were based on a detailed palynological analysis of about 500 pollen samples. At present, the results of palynological studies of reference sections of the glacial and extraglacial zones, reflecting the succession of the vegetation following changes of moisture and heat supply in the late middle and late Pleistocene, yield the most complete record of terrestrial climatic conditions for this area. The structure of this record can directly be compared with the climate-driven ratio of oxygen isotopes in ice cores and deep-sea sediments (Shackleton and Opdyke, 1973; Johnsen et al., 1992; Bassinot et al., 1994).

The ESR-dating of mollusc shells is based on the fact that buried mollusc skeletal remains act as natural palaeodosimeters and preserve a record of natural irradiation received through the time of burial. A shell sample will, therefore, have radiation-induced paramagnetic centres the amount of which relates to the total radiation dose the shell has received during its burial, and the age of the shell. ESR-datings of all marine and freshwater mollusc shells were made at the Research Laboratory for Quaternary

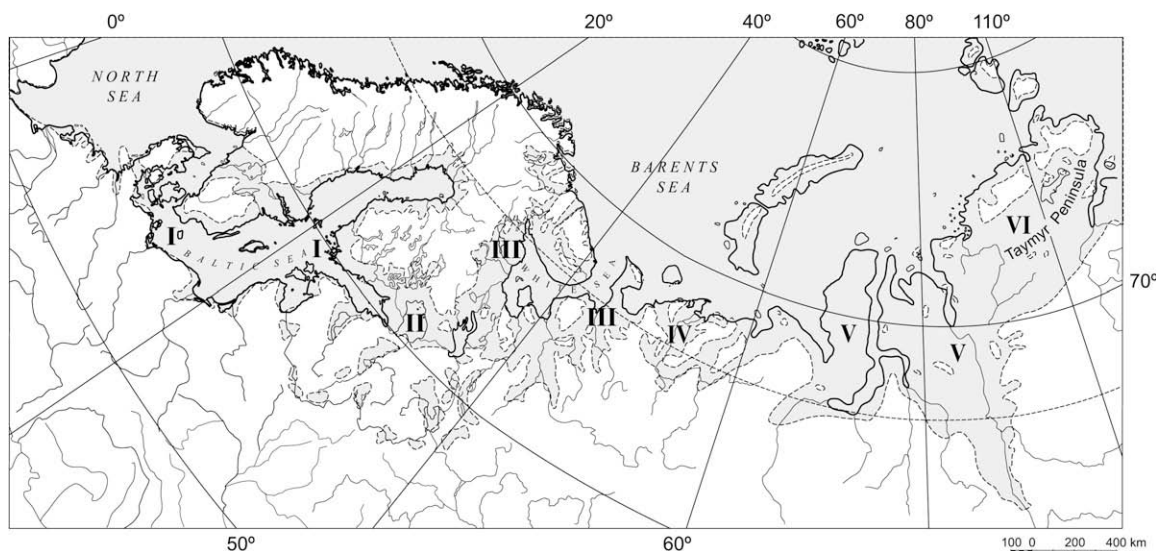


Fig. 2. Map with Eemian/Boreal shorelines (dotted) and submerged areas in Siberia (after Lavrova, 1961) and NW Europe (after Grichuk, 1982). Basins: I – Baltic, II – Mginiskian, III – White Sea, IV – Petchora, V – West-Siberian, VI – Taymyr.



Geochronology (RLQG), Institute of Geology, Tallinn University of Technology. The ESR-dating technique which we use has been detailed elsewhere (e.g., Molodkov et al., 1998).

Concerning the correlation of Pleistocene events, the ESR-dating method is highly promising because it allows the use of subfossil mollusc shells (the most frequent and widespread group of palaeofauna remains in Pleistocene deposits) in determining the ages of many geological formations of the Pleistocene such as marine and palaeolacustrine sediments, loesses, palaeosols, glacial lacustrine loam, cave deposits, archaeological sites, etc. ESR analysis of shells provides a basis for a detailed large-scale chronostratigraphic correlation of fauna-bearing deposits belonging to different facies.

#### 4. Pollen stratigraphy in relation to the mollusc-based ESR-chronostratigraphic record

##### 4.1. Dnieper glaciation

The late middle Pleistocene has been marked by an extreme glacial phase of the Dnieper (Saale 2–3, MIS 6, after Bowen et al., 1986) glaciation. At the maximum of the transgressive stage of this glaciation, the ice sheet occupied vast areas of the northern part of the Russian Plain penetrating into the Dnieper River valley up to the Orel' River mouth (see Fig. 1).

Palynological analysis of loess–palaeosol sections both in glacial and extraglacial zones reveals climate instability of the Earth's penultimate glaciation. The Dnieper glacial rhythm is divided by an intermediate interstadial into two (Dnieper and Moscow) stages with the early Dnieper and late Moscow interstadials within them (Bolikhovskaya, 1995). During these stadials, the landscapes in the Upper Volga region near the ice sheet margins were represented by periglacial tundra and forest-tundra, and the Upper Oka and Upper Dnieper regions by tundra-steppes. The latter extended eastward into the Upper Don valley where they were alternated with periglacial forest-tundra and tundra-forest-steppe. Further to the south, in the extraglacial loess regions, periglacial steppes and forest-steppes prevailed, while periglacial semi-deserts during some of the phases developed in the extreme southeast of the loess province (in the Caucasian piedmont). During interstadials pine, pine–birch and birch light periglacial forests dominated in the glacial–periglacial zone of the Russian Plain. In the loess areas in the south of the Russian Plain the periglacial woods, forest-steppes, steppes and extraglacial light forests were spread during these warm intervals.

The deposits of the Dnieper glaciation are most completely represented in the Likhvin section, which exposes a 50-m-thick sequence of loess, palaeosol, tills and glacio-lacustrine, alluvial, lake and bog sediments.

In the Likhvin section, the early Dnieper glaciofluvial silts are characterized by a lemming fauna – *Dicrostonyx* cf. *simplicior*, *Lemmus sibiricus* etc., and tundra-steppe vegetation. An earlier climatic amelioration causing the melting of penultimate glaciation ice sheets has been recognised in the upper part of these glaciofluvial silts at the very beginning of MIS 6. Three ESR-datings on elevated marine horizons of Eurasian high-Arctic regions indicate that this warming took place about 184 ka ago. This interval seems to correlate with the recorded pollen event of interstadial rank reflecting the transition from the dominant tundra-steppes to the expansion of open pine woodlands. These ESR-ages and pollen palaeoclimatic signal appear to correlate also with the relatively warm event in the Arctic region recorded within the interval of 183.9–186.0 ka BP in the GRIP ice core (Fig. 3) (GRIP Project Members, 1993).

The landscapes during the second Dnieper–Moscow interstadial were dominated by open woodlands of pine, Alnaster and dwarf birch. The age of this event (warmer subinterval within glacial

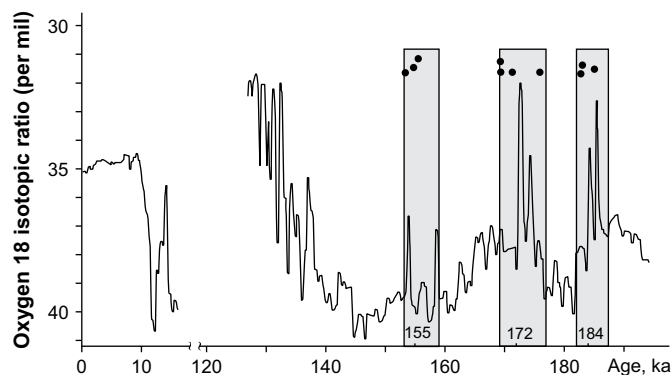


Fig. 3. About 184, 172 and 155 ka ESR age determinations (dots) on subfossil mollusc shells from raised marine deposits in the Siberian Arctic record the relatively warm intervals during penultimate (Dnieper/Saale, MIS 6) glaciations as also indicated by the positive anomalies in the 190–130 ka interval of the GRIP ice record (redrawn from Molodkov and Bolikhovskaya, 2006).

interval) is estimated to be about 172 ka on the basis of the four ESR-age determinations on mollusc shells collected from elevated marine deposits of the Eurasian Arctic. This age, as well as a corresponding palaeoclimatic signal in the pollen diagram, coincides well with the next relatively warm episode recorded in the GRIP ice core (Fig. 3) and with a high latitude peak of insolation (Berger and Loutre, 1991).

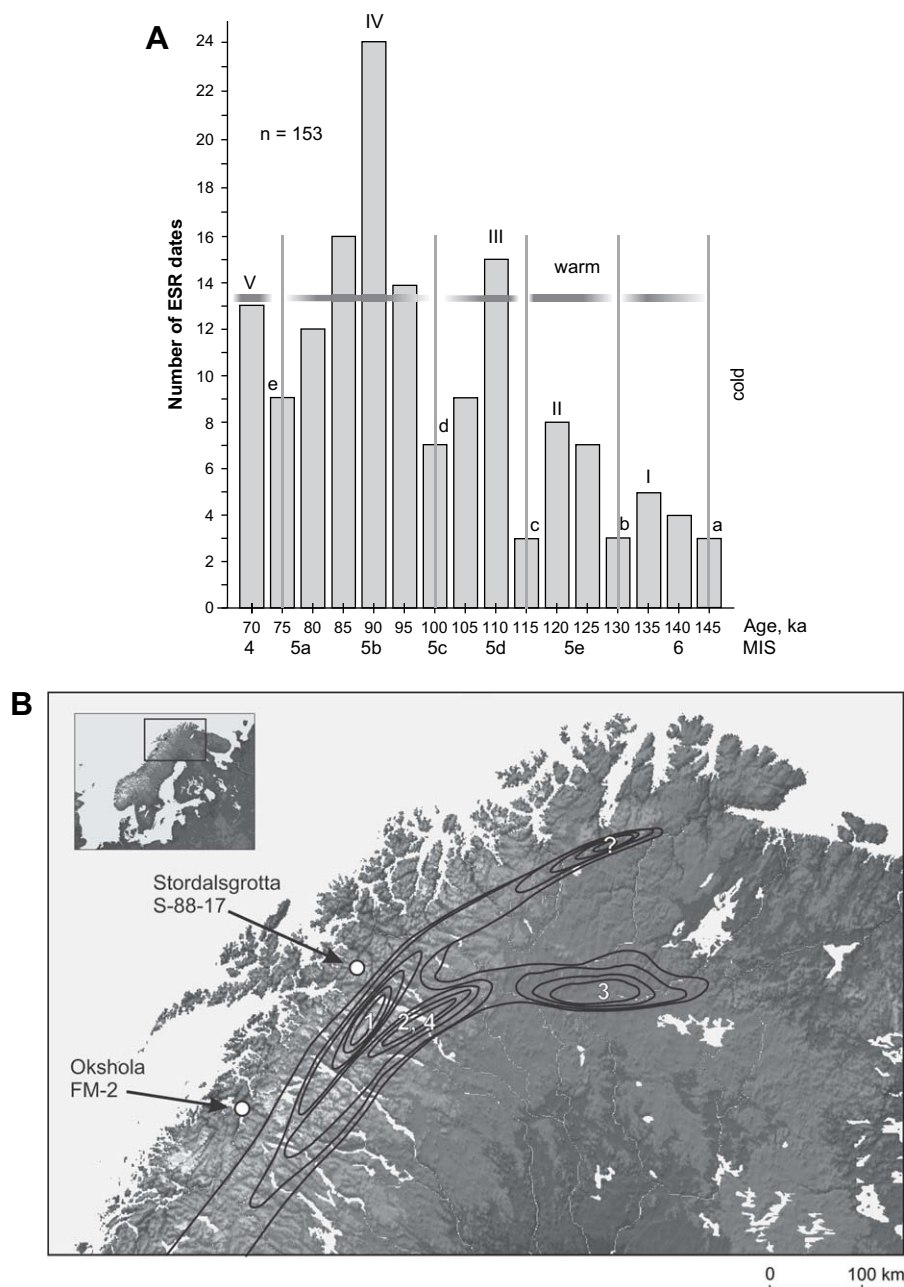
The third – late Moscow – interstadial warming established in loess-like sandy loam above the tills is represented by the periglacial open birch woodlands with *Betula fruticosa* in the shrub layer and herbs and dwarf shrubs on the ground (with *Arctous alpina*, *Cannabis* sp., *Artemisia* s.g. *Seriphidium*, *Thalictrum* cf. *alpinum*, etc.). Judging from the three ESR-dates of mollusc shells taken from marine sediments on the Taimyr Peninsula, the third interstadial of the Dnieper time is dated at about 155 ka BP. This age coincides with two rather warm, though relatively short-term, signals of interstadial rank identified from the GRIP ice core record in the range of 153.5–158.8 ka.

The above palaeoenvironmental terrestrial and marine proxy records suggest that these three warm-climate events within the Dnieper glaciation (MIS 6) are of a great transcontinental, even hemispherical, significance rather than being a local phenomenon in the centre of the East European Plain.

##### 4.2. Mikulino/Eemian Interglacial

Recent ESR-chronostratigraphical investigations and the ages obtained from subfossil marine mollusc shells (Molodkov, 1988; Molodkov and Raukas, 1988, 1998; Molodkov et al., 1992; Bolshiyakov and Molodkov, 1999; Molodkov and Bolikhovskaya, 2002) from Northern Eurasia, indicate that the duration of the late Pleistocene marine transgression, and also the last interglacial, most likely correspond here to the time interval from approximately 145–140 to 70 ka, comparable with the whole of MIS 5 and with the final phase of MIS 6 rather than the period of first optimum conditions in marine isotope substage 5e (Eemian, s. str.).

The time-dependent frequency distribution of all the ESR-dates obtained by us for the last interglacial mostly on uplifted marine sediments along the climate-sensitive marginal zone of Northern Eurasia demonstrates the presence of high-frequency intervals (peaks I–V, Fig. 4A) at ca 135, 120, 110, 90, and 70 ka, which may be correlated with periods of a relatively warm climate and the submergence of coastal parts of the land. Low-frequency intervals (troughs b–e, Fig. 4A) at 130, 115, 100 and 75 ka may be correlated with coolings and phases of sea regression.



**Fig. 4.** (A) Frequency distribution of ESR-ages between 145 and 70 ka and phases of relatively warm (horizontal bars) and cool (vertical lines) climate after [Lauritzen \(1995\)](#) and [Lauritzen and Onac \(1999\)](#); (B) The ice domes (1–4) during the “Till 3” (substage 5d?) glaciation in North Fennoscandia after [Olsen \(1988\)](#). The circles indicate localities of two speleothem samples from coastal lowland and an alpine cave site in northern Norway investigated by [Lauritzen \(1995\)](#). The “Till 3” glacier has not overrun these caves. The total growth period of speleothem in the caves, indicating nonfrozen, nonglacial conditions in this area, lasted between 150 and 71 ka ([Lauritzen, 1995](#)).

Our findings concerning the frequency distribution of ESR-dates for Northern Eurasia are in good agreement with the results of isotope and chronological analyses of speleothems from the caves of Stordalsgrotta and Okshola, northern Norway ([Fig. 4B](#)). A continuous growth of speleothems in the interval of 150–71 ka indicates the absence of thick ice cover (i.e. the existence of interstadial or interglacial conditions) at that time ([Lauritzen, 1995](#)). Periods of cooling, which however did not result in a considerable growth of the Scandinavian glaciation or the emergence of an ice sheet in the coastal zone of northern Norway in the vicinity of the caves, were registered here according to U-series dating ([Lauritzen, 1995](#)) at ca 145, 139, 129, 114, and 100 ka. Although the cold interval at 75 ka has not been revealed in these caves, its isotope temperature signal is clearly visible in speleothems from caves in

northwestern Romania ([Lauritzen and Onac, 1999](#)). Also, in the series of sections from the eastern coast of the White Sea studied by us ([Molodkov and Raukas, 1998](#)) there is no interruption of marine sedimentation during the 120.0–75.5 ka interval, and neither were any deposits suggestive of glaciation revealed for that period ([Molodkov and Yevzerov, 2004](#)).

In addition, an ESR-age of ca. 80 ka obtained on mollusc shells collected directly from mammoth-bearing deposits in the north of Eastern Siberia implies a relatively warm climate with a rich variety in temperate climate plant life and a volume of vegetation enough for food supply for mammoths at the end of MIS 5. Therefore, it is quite probable that about 80 ka ago (substage 5a) the climate of the Siberian Arctic was not the same as the present climate: most likely, this area was not protractedly covered with ice and snow as it is

now, nor was the ground frozen, and the climate here was much warmer than it is today. It is noteworthy to indicate also that a series of luminescence dates ( $\sim 85$  ka) and palaeoclimatic records from the Eastern Canadian Arctic (Miller et al., 1992) suggest a climatic amelioration of interglacial rank close to the same time interval. This environment remained stable here for at least 10 ka. As a whole it may be interpreted as an indication of a global warming or continuation of the long warm period of the last interglacial up to the end of isotope stage 5. These observations, together with the other independent indications of the warming during isotope stage 5a (see e.g., Vacher and Hearty, 1989; Muhs, 1992; Fauquette et al., 1999; Muhs et al., 2006), may be regarded as evidence supporting the viewpoint that a quite warm climate existed at that time, even in the Arctic regions of the Earth, and that the last interglacial lasted much longer than suggested by the SPECMAP chronology (Keigwin et al., 1994).

All the above observations attest to a higher sea level, greater duration of the first late Pleistocene transgression and, possibly, of the last interglacial than would follow from the oxygen isotope curve or from the correlation of the Mikulino/Eemian Interglacial with substage 5e alone. Results of a detailed pollen analysis of loess–palaeosol and other continental deposits that formed during the post-Dnieper (post-Moscow) period do not contradict these conclusions.

In the central regions of Eastern Europe, now situated in the mixed forest subzone, the richest water supply during the late Pleistocene was characteristic of the interval from the beginning of the Mikulino Interglacial up to the end of the first early Valdai (Ketrosoy) interstadial, and in the southwestern parts, now occupied by broad-leaved forests, up to the end of the second early Valdai (Kishlyansky) interstadial (Bolikhovskaya, 1995; Bolikhovskaya and Molodkov, 2006). A complex pattern of change of the Mikulino vegetation, a distinct climatic subdivision of this interglacial, and the presence within it of several coolings with a climate of interstadial type (or endothermals after Bolikhovskaya, 1991a) obviously correlating with those in the other palynologically well-studied sections (e.g., La Grande Pile section, France; Woillard, 1978), suggest that the Mikulino was a long-lasting and generally warm

event. Although this interval is characterized by noticeable changes in vegetation and climate, the palaeoenvironmental conditions in the studied area during most of MIS 5 were typically interglacial ones. The comparison of floristic phytocoenotic, and climatic successions of the Mikulino period (reconstructed according to LPF sections) and the Holocene clearly demonstrates that the Mikulino Interglacial was several times longer than the modern interglacial that lasted just 10 ka.

The above can be illustrated by materials from the Arapovichi section in the Middle Desna region. Here, the Dnieper till is overlain by 14-m-thick late Pleistocene loesses and palaeosols. According to the palynological analysis, sands and loams overlying the till and most of the Mezin palaeosols overlying them (Salyn lessive and the lower third of the sod-chnozem Krutitsa soil) are dated as the Mikulino Interglacial in age (Bolikhovskaya, 1991b). The Ketrosoy interstadial was recorded in the middle of the Krutitsa soil. Over the entire Mikulino period, under relatively high heat and moisture supply, forests covered most of this territory (Fig. 5). Climato-phytocoenotic and floral features of Mikulino Interglacial forests fall into 11 successive stages:

- Mk1 – pine–birch forests with oak, hornbeam, and elm;
- Mk2 – pine–birch forests with spruce and undergrowth of *B. fruticosa* (first endothermal);
- Mk3 – birch forests with *Carpinus betulus*, *Quercus robur*, *Quercus petraea*, *Tilia cordata*, *T. tomentosa*, *Corylus colurna*, *Ulmus laevis*, etc.;
- Mk4 – pine–spruce forests with oak, hornbeam, elm, etc.;
- Mk5 – hornbeam–oak forests (thermo-xerotic maximum);
- Mk6 – birch–Siberian cedar pine (*Pinus sibirica*)–spruce and hornbeam–oak forests;
- Mk7 – pine forests with birch and yernik tier (second endothermal);
- Mk8 – birch–spruce–Siberian cedar pine and hornbeam–oak forests with beech, linden, elms, hazel tree, etc.;
- Mk9 – oak–hornbeam forests (thermo-hygrotic maximum);
- Mk10 – birch–pine forests with oak, hornbeam, linden, and elm;
- Mk11 – Siberian cedar pine–spruce and birch forests.

As can be seen, even endothermal coolings were characterized by a rather moist climate (Fig. 6). The first early Valdai cooling

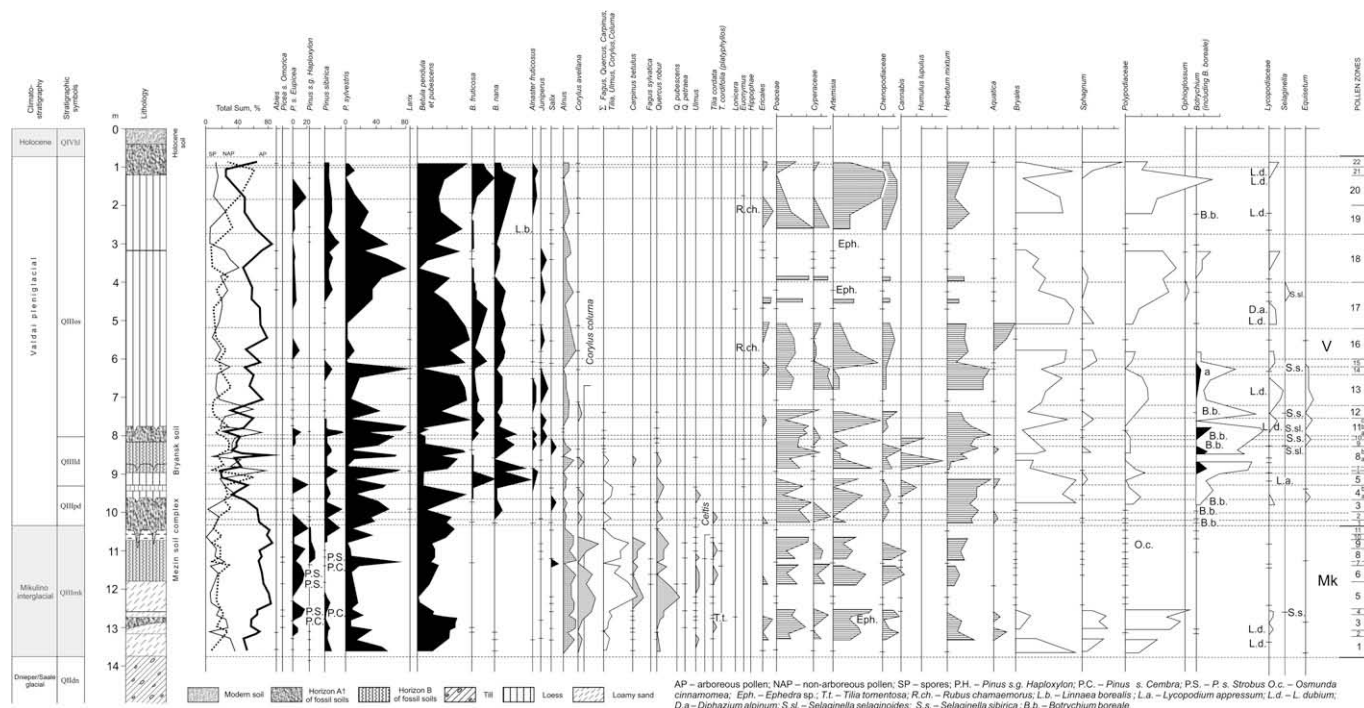


Fig. 5. Pollen diagram of the late Pleistocene sediments of the Arapovichi section in the Middle Desna region.





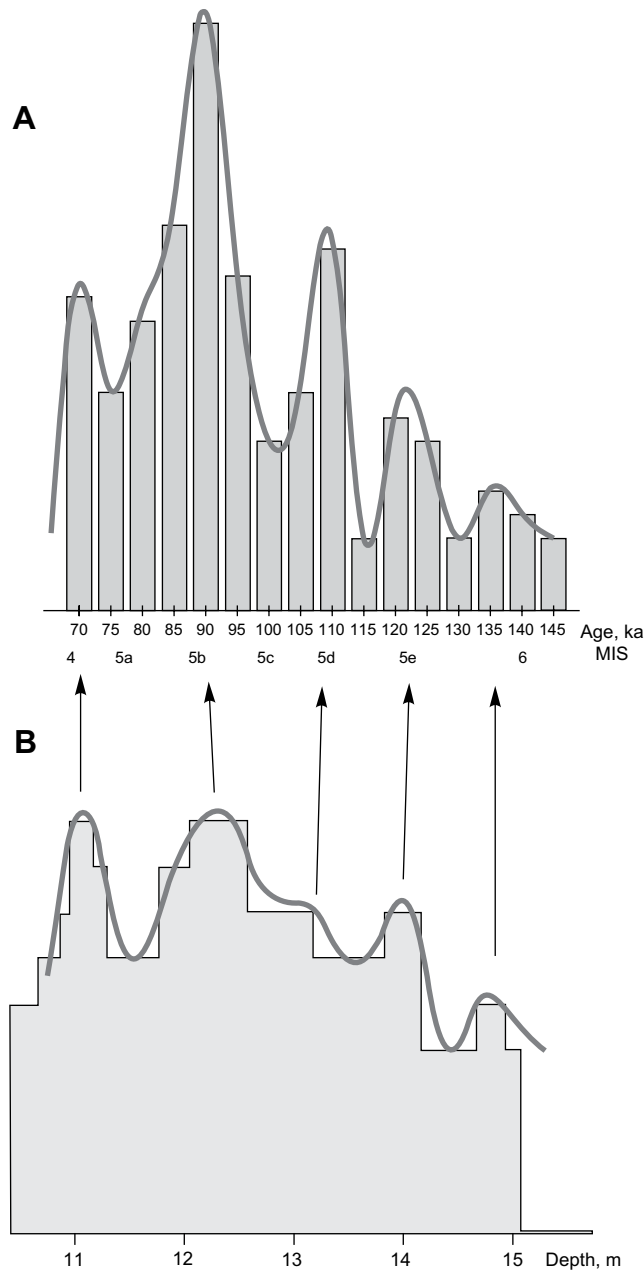


Fig. 7. Comparison of envelope of the time-dependent frequency distribution of all the ESR-dates obtained for the last interglacial period (A) and that of the succession of vegetation from the Arapovich section (B).

The first early Valdai cooling is well recorded in the Arapovich section by the expansion of open pine–birch forests with *B. nana*, *B. fruticosa*, and *A. fruticosus* in the undergrowth into this territory (see Fig. 5). However, during the subsequent Ketrosy interstadial, pine–birch forests with oak, linden and hornbeam, similar to interglacial forests of the same territory, were predominant. The first and the fourth middle Valdai landscape-climatic situations resembling interglacials in some extent, which were named Kishlyansky and Dniester interstadials, correspondingly have the most conspicuous manifestation in the middle Dniester region.

The dated intervals in mollusc-based ESR record cluster within MIS 4–2 into six groups. The first group centred at about 65 ka consists of six ages within MIS 4 and indicates the first global sea level rise since the last interglacial due to the contribution of glacier and ice sheet melt during the first early Valdai interstadial. The

second group consisting of eight ages clustered in the very beginning of MIS 3. The dates suggest that the second global-scale warming occurred at approximately 56 ka; this compares favourably with the stratigraphical position of the second peak in the terrestrial pollen-based record. The third group consists of 5 ages (40.0–47.5 ka) falling in the middle of MIS 3. Taken together, these 5 ages do provide evidence for the next climate warming/relative sea level rise during the last ice age. An age of about 32 ka obtained on raised marine deposits implies climate amelioration within the second half of MIS 3.

The next amelioration of the climate occurred at the very end of MIS 3, placed between about 28 and 23 ka BP on the basis of 5 dates (centred at about 26 ka). That was the last middle Valdai warming and associated sea level rise predating the Last Glacial Maximum (LGM).

A single ESR-date of about 17 ka BP marks the first post-LGM sea level rise. It agrees well with the late Valdai interstadial identified in the Arapovich section where this interval corresponds to layers at a depth of 2.75–4.00 m. At the time of their deposition dated by  $^{14}\text{C}$  at 16.5–15.0 ka BP (Arslanov, 1992), cryophytes of the fern and club moss group disappeared completely. Dominant were forests of pine (*Pinus sylvestris*), those of *P. sylvestris* and *P. sibirica*, and birch–pine forests with undergrowth of shrub birch, *Alnaster fruticosus*, juniper and willows, and with dense cover of Polypodiaceae.

It is noteworthy here that there is a surprisingly good visual match between the envelope shape of the succession of vegetation from the Arapovich section and that of the time-dependent frequency distribution of all the ESR-dates obtained for the last interglacial period (Fig. 7). The first post-interglacial interval, ESR-dated at about 65 ka, can most likely be correlated with the first early Valdai (Ketrosy) interstadial of interglacial rank. However, the further correlation of the different palaeoclimatic events within the last ice age is still a difficult task due to the complex dynamics of climatic changes during this period of the late Quaternary history. For instance, detailed palynological analysis and luminescence datings of the samples taken from the new terrestrial reference section at the Voka site, situated in the glacial zone of the north-western part of the East European Plain (NE Estonia), have provided convincing evidence of the occurrence of two severe and two considerably milder climate intervals even in the relatively narrow time span between 39 ka and 33 ka (Bolikhovskaya and Molodkov, 2007). A multi-disciplinary study aimed at elucidating the presence and chronostratigraphical position of the other palaeoclimatic events within the late Pleistocene period is currently in progress within the frames of the Estonian Science Foundation project no. 6112.

## 5. Conclusions

Using pollen and mollusc-based ESR data, we have identified palaeoenvironmental events that we believe to correlate with a number of large-scale late middle and late Pleistocene climatic features in Northern Eurasia, including the penultimate glacial period (Dnieper/Saale, MIS 6), with three warmings within it, last interglacial (Mikulino/Eemian s. lato, MIS 5), and subsequent glacial–periglacial period (Valdai/Weichselian, MIS 4–MIS 3), interrupted by at least four to nine relatively warm episodes of interstadial rank. Mollusc-based ESR age-control levels we compared with the pollen palaeoclimatic signals. The close correspondence of the palynological signatures of terrestrial sedimentary sequences and directly ESR-dated warm-climate-related deposits from the continental margins of Northern Eurasia suggests that these two records are highly correlated. Each record spans a time interval from ca 200 to ca 30 ka and has clear climate-



induced components that can be extended to an area lacking a complete thoroughly studied section or a well-dated sedimentary sequence. Besides, our suite of ESR-datings can be regarded as a transitional series from a terrestrial sedimentary sequence with a long pollen-based record to climate-driven variations in the oxygen isotope ratios from deep-sea sediments.

Our proxy climate records within MIS 6 prove to be coincident with ice core proxy data. The terrestrial pollen climate-induced signals, as well as ESR-dated marine deposits at about 184, 172 and 155 ka, appear to correspond closely to those climate signals derived in this time interval (MIS 6) from the ice core stratigraphy data.

The pollen response in the sections examined in this paper documents strong climatic signals bottom-up, covering an interval from MIS 6 to MIS 2. Cold (glacial) phases are characterized by the spread of tundra-steppes, tundra-forest-steppes, periglacial forest-steppes, periglacial steppes and periglacial semi-deserts in the time of the Dnieper glacial pessimum, and the development of periglacial tundras, periglacial forest-tundras, tundra-steppes, tundra-forest-steppes and periglacial steppes in the Valdai glacial pessimum. Warm (interglacial) phases are characterized by successions of interglacial forests, forest-steppes and steppes. The visual match between the deep-sea oxygen isotope record and key features of the palynological and mollusc-based ESR-chronostratigraphical records is quite reasonable and has no essential distinctions during the last 200 ka.

The above data demonstrate also that the last interglacial event in Northern Eurasia may have been long-lasting, correlating most likely with the whole of isotope stage 5 rather than the first climatic optimum within substage 5e only. During most of the period (MIS 5), the vegetation cover has evidently been of interglacial character in Eastern Europe. At the same time, pollen and ESR records suggest that this interglacial was variable rather than stable in nature. During this interglacial period the warm climate was repeatedly interrupted by rather cold phases. Our palynological studies have revealed two endothermal coolings within the Mikulino Interglacial. The main one occurred between two phases of the thermohygrotic stage of the Mikulino Interglacial and has been recorded in all investigated regions. Another cooling has been established in the Arapovichi section only in the first half of the interglacial. Coolings may have been quite deep although of relatively short duration and appear to be less dramatic in Northern Eurasia than suggested by the oxygen isotope variability in the deep-sea isotopic records. Our ESR studies show that during these intra-Mikulino cold periods of isotope stage 5, coastal areas of Northern Eurasia were partly occupied by transgressive basins. Time-dependent frequency distribution of all the ESR-dates obtained for the last interglacial displays at least four time intervals that can likely be correlated with the coolings and phases of sea regression. It implies that the occurrence of some palynologically unrecognised yet intra-interglacial coolings cannot be excluded.

The analysis of two climate proxies from the different sedimentary environments indicates that the climate in Northern Eurasia experienced a pattern of periodic variations over the last 200 ka, which was closely linked to the global ice volume variations.

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## References

- Arslanov, Kh.A., 1992. Geokhronologicheskaya shkala pozdnego pleistocena Russkoj ravniny (Late Pleistocene geochronological scale of the Russian Plain). In: Murzaeva, V.E., Punning, J.-M., Chichagova, O.A. (Eds.), *Geochronology of the Quaternary Period*. Nauka, Moscow, pp. 133–137 (in Russian).
- Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J., Lancelot, Y., 1994. The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. *Earth and Planetary Science Letters* 126, 91–108.
- Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews* 10, 297–317.
- Bolikhovskaya, N.S., 1991a. Osnovnyye problemy paleogeografii lessov i iskopyemykh pochv. (The main problems of the loesses and palaeosols palaeogeography). In: Kaplin, P.A. (Ed.), *Paleobotanical Methods in Pleistocene Paleogeography investigations. Science and Techniques Results. Paleogeography*, vol. 7. VINITI Press, Moscow, pp. 41–69 (in Russian).
- Bolikhovskaya, N.S., 1991b. Paleogeography, Stratigraphy and Genesis of the Loess–Paleosol Formation of Northern Eurasia (palynological data). In: *Geojournal*, vol. 24. Kluwer Academic Publishers, Dordrecht/Boston/London. 181–184.
- Bolikhovskaya, N.S., 1995. The Evolution of Loess–Paleosol Formation of Northern Eurasia. Moscow University Press, Moscow (in Russian).
- Bolikhovskaya, N.S., 2000. Palynofloras and Phytocoenotic Successions of the Mikulino (Eemian) Interglacial Period within Different Stratigraphic Regions of the Southern Eastern-European Plain. *Paleontological Journal* 34 (Suppl. 1), 75–80.
- Bolikhovskaya, N.S., Molodkov, A.N., 1999. On the correlation of the Quaternary continental and marine sediments of Northern Eurasia by pollen data and results of ESR dating. In: Bolikhovskaya, N.S., Rovnina, L.V. (Eds.), *Urgent Problems of Palynology on the Boundary of the Third Millennium*. IGIRI, Moscow, pp. 25–53 (in Russian, with English summary).
- Bolikhovskaya, N.S., Molodkov, A.N., 2002. Dynamics of Pleistocene paleoclimatic events: a reconstruction based on palynological and electron spin resonance studies in North Eurasia. *Archaeology, Ethnology and Anthropology of Eurasia* 2, 2–21.
- Bolikhovskaya, N.S., Molodkov, A.N., 2006. East European loess–paleosol sequences: palynology, stratigraphy and correlation. *Quaternary International* 149, 24–36.
- Bolikhovskaya, N., Molodkov, A., 2007. Pollen and IR-OSL evidences for palaeoenvironmental changes between ca 39 kyr to ca 33 kyr BP recorded in the Voka key section, NE Estonia. In: Johansson, P., Sarala, P. (Eds.), *Applied Quaternary Research in the Central Part of Glaciated Terrain*. Geological Survey of Finland, Special Paper, vol. 46, pp. 103–112.
- Bolshiyonov, D., Molodkov, A., 1999. Marine Pleistocene deposits of the Taymyr peninsula and their age from ESR dating. In: Kassens, H., Bauch, H.A., Dmitrenko, I.A., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timochov, L.A. (Eds.), *Land–Ocean Systems in the Siberian Arctic: Dynamics and History*. Springer-Verlag, Berlin, pp. 469–475.
- Bowen, D.Q., Richmond, G.M., Fullerton, D.S., Sibrava, V., Fulton, R.J., Velichko, A.A., 1986. Correlation of Quaternary glaciations in the Northern Hemisphere. *Quaternary Science Reviews* 5, 509–510.
- Fauquette, S., Guiot, J., Menut, M., de Beaulieu, J.-L., Reille, M., Guenet, P., 1999. Vegetation and climate since the last interglacial in the Vienne area (France). *Global and Planetary Change* 20, 1–17.
- Grichuk, V.P., 1982. 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)*. Nauka, Moscow, pp. 9–15 (in Russian).
- GRIP Project Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature* 364, 203–207.
- Henderson, G.M., Slowey, N.C., 2000. Evidence from U–Th dating against northern hemisphere forcing of the penultimate deglaciation. *Nature* 404, 61–65.
- Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B., Steffensen, J.P., 1992. Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* 359, 311–313.
- Keigwin, L.D., Curry, W.B., Lehman, S.J., Johnsen, S., 1994. The role of the deep ocean in North Atlantic climate change between 70 and 130 kyr ago. *Nature* 371, 323–325.
- Lauritzen, S.E., 1995. High-resolution paleotemperature proxy record for the Last Interglaciation based on Norwegian speleothems. *Quaternary Research* 43, 133–146.
- Lauritzen, S.E., Onac, B.P., 1999. Isotopic stratigraphy of a Last Interglacial stalagmite from Northwestern Romania: correlation with the deep-sea record and northern-latitude speleothem. *Journal of Caves and Karst Studies* 61, 22–30.
- Lavrova, M.A., 1961. The Relation between the Boreal Interglacial Transgression in the North of the USSR and the Eemian Transgression in Western Europe. *Transactions of the Institute of Geology of the Academy of Sciences of the ESSR VIII*, Tallinn, pp. 74–88. (in Russian, with English summary).
- Lorius, C., Jouzel, J., Ritz, C., Merlivat, L., Barkov, N.I., Korotkevich, Y.S., Kotlyakov, V.M., 1985. A 150,000-year climatic record from Antarctic ice. *Nature* 316, 591–596.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.S., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. *Quaternary Research* 27, 1–30.
- Miller, G.H., Mode, W.N., Wolfe, A.P., Sauer, P.E., Bennike, O., Forman, S.L., Short, S.K., Stafford Jr., T.W., 1992. Stratified interglacial lacustrine sediments from Baffin Island, Arctic Canada: chronology and paleoenvironmental implications. *Quaternary Science Reviews* 18, 789–810.

- Molodkov, A., 1986. Application of ESR to the dating of subfossil shells from marine deposits. *Ancient TL* 4, 49–54.
- Molodkov, A., 1988. ESR dating of Quaternary shells: recent advances. *Quaternary Science Reviews* 7, 477–484.
- Molodkov, A., 1989. The problem of long-term fading of absorbed palaeodose on ESR-dating of Quaternary mollusc shells. *Applied Radiation and Isotopes* 40, 1087–1093.
- Molodkov, A., 1993. ESR-dating of non-marine mollusc shells. *Applied Radiation and Isotopes* 44, 145–148.
- Molodkov, A., 1996. ESR dating of *Lymnaea baltica* and *Cerastoderma glaucum* from low Ancyclus level and transgressive Litorina Sea deposits. *Applied Radiation and Isotopes* 47, 1427–1432.
- Molodkov, A., Bolikhovskaya, N., 2002. Eustatic sea-level and climate changes over the last 600 ka as derived from mollusc-based ESR-chronostratigraphy and pollen evidence in Northern Eurasia. *Sedimentary Geology* 150, 185–201.
- Molodkov, A., Bolikhovskaya, N., 2006. Long-term palaeoenvironmental changes recorded in palynologically studied loess–palaeosol and ESR-dated marine deposits of Northern Eurasia: implications for sea–land correlation. *Quaternary International* 152–153, 37–47.
- Molodkov, A., Dreimanis, A., Ābolītiņš, O., Raukas, A., 1998. The ESR age of *Portlandia arctica* shells from glacial deposits of Central Latvia: an answer to a controversy on the age and genesis of their enclosing sediments. *Quaternary Science Reviews* 17, 1077–1094.
- Molodkov, A., Raukas, A., 1988. The age of Upper Pleistocene marine deposits of the Boreal transgression on the basis of electron–spin–resonance (ESR) dating of subfossil mollusc shells. *Boreas* 17, 267–272.
- Molodkov, A., Raukas, A., 1998. ESR age of the Late Pleistocene transgressions in the eastern part of the White Sea coast. *Geologija* 25, 62–69.
- Molodkov, A., Raukas, A., Makeev, V.M., Baranovskaya, O.F., 1992. К ÉPR khronostratigrafii morskikh otlozhenij Severnoj Evrazii i ikh korrelyatsii s sobyitiyami plejstotsena. (On ESR–chronostratigraphy of the Northern Eurasia marine deposits and their correlation with the Pleistocene events). In: Murzaeva, V.E., Punning, J.-M., Chichagova, O.A. (Eds.), *Geochronology of the Quaternary Period*. Nauka, Moscow, pp. 41–47 (in Russian).
- Molodkov, A., Yevzerov, V., 2004. ESR/OSL ages of long-debated subfossil bearing marine deposits from the southern Kola Peninsula: stratigraphic implications. *Boreas* 33, 123–131.
- Muhs, D.R., 1992. The last interglacial–glacial transition in North America: evidence from uranium-series dating of coastal deposits. In: Clark, P.U., Lea, P.D. (Eds.), *The last Interglacial–Glacial Transition in North America*. Boulder, Colorado. Geological Society of America Special Paper, vol. 270, pp. 31–51.
- Muhs, D.R., Simmons, K.R., Kennedy, G.L., Ludwig, K.R., Groves, L.T., 2006. A cool eastern Pacific Ocean at the close of the Last Interglacial complex. *Quaternary Science Reviews* 25, 235–262.
- Olsen, L., 1988. Stadials and interstadials during the Weichsel glaciation on Finnmarksvidda, northern Norway. *Boreas* 17, 517–539.
- Seidenkrantz, M.-S., Bornmalm, L., Johnsen, S.J., Knudsen, K.L., Kuijpers, A., Lauritzen, S.-E., Leroy, S.A.G., Mergeai, I., Schweger, C., van Vliet-Lanoë, B., 1996. Two-step deglaciation at the oxygen isotope stage 6/5e transition: the Zeifen-Kattegat climate oscillation. *Quaternary Science Reviews* 15, 63–75.
- Shackleton, N.J., Opdyke, N.D., 1973. Oxygen isotope and palaeomagnetic stratigraphy of Equatorial Pacific core V28–238: oxygen isotope temperatures and ice volumes on a 10<sup>5</sup> and 10<sup>6</sup> year scale. *Quaternary Research* 3, 39–55.
- Vacher, H.L., Hearty, P.J., 1989. History of stage 5 sea level in Bermuda: review with new evidence of a brief rise to present sea level during substage 5a. *Quaternary Science Reviews* 8, 158–168.
- Winograd, I.J., Landwehr, J.M., Ludwig, K.R., Coplen, T.B., Riggs, A.C., 1997. Duration and structure of the past four interglaciations. *Quaternary Research* 48, 141–154.
- Woillard, G.M., 1978. Grande Pile peat bog: a continuous pollen record for the last 140,000 years. *Quaternary Research* 9, 1–21.
- Zarrina, E.P., 1991. Chetvertichnye otlozheniya severo-zapadnykh i tsentral'nykh rajonov evropeiskoi chasti SSSR (Quaternary deposits of the northwestern and central areas of the eastern part of the USSR). Nedra, Leningrad (in Russian).