Climato-chronostratigraphic framework of Pleistocene terrestrial and marine deposits of Northern Eurasia, based on pollen, electron spin resonance, and infrared optically stimulated luminescence analyses

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Abstract. Marine and terrestrial records spanning the Brunhes Chron (0–780 000 years) were synthesized using data from palaeoshelf, glacial, periglacial, and extraglacial zones of Northern Eurasia. The chronostratigraphic position of the identified palaeoenvironmental events and respective horizons in the composite chronostratigraphic column were established on the basis of electron spin resonance analysis of subfossil mollusc shells collected from marine, freshwater, and terrestrial deposits. Environment and vegetation evolution during this period is characterized by pollen data from a series of spaced-apart reference sections on the East European Plain. The climate-chronostratigraphic record displays a sequence of eight intervals (the Holocene included) of warm climate and sea level highstand when marine sedimentation occurred on North Eurasian palaeo-shelves, and seven glacial epochs. A clear agreement between long pollen records and reliably dated warm-climate-related deposits was established for at least the last 600 000 years (from marine isotope stages 15 to 1). When integrated, these records have a potential of assigning warm/cold-climate-related deposits to the chronostratigraphically-organized sequence of the middle and late Quaternary palaeoenvironmental events.

Key words: climate-chronostratigraphic framework, electron spin resonance, palaeoclimatic record, palynostratigraphy, correlation, Quaternary.

INTRODUCTION

The youngest period in the Earth's history, the Quaternary, is characterized by a series of large-scale environmental changes that have heavily affected landscapes and life on the planet. The most distinctive features of the Quaternary have been repeated continental-scale glaciations alternating with warm interglacial periods. Investigations of a great number of Quaternary scientists have been aimed to reconstruct and interpret changes in geological processes and climate through this time. Their task is most difficult in the areas affected by multiple Pleistocene glaciations because most of the Quaternary deposits were formed there during and after the last glaciation. These deposits are very young (mostly of late late Pleistocene and Holocene age) compared to those in non-glaciated areas. A good example is the territory of Estonia, where due to severe glacial erosion the thickness of the Quaternary cover, with the exception of the Fore-Klint Lowland, heights of southeastern Estonia, and old buried valleys and depressions, usually does not exceed a few metres (Raukas 1978). As a result, the Quaternary is represented here only partially. Reliably identified lower and middle Pleistocene deposits are almost absent. Therefore, there arise at least three aspects directly related to the timing and reconstruction of palaeoenvironmental evolution: (1) how to arrange the discovered palaeoenvironmental events in a correct chronological order, (2) how to correlate a specific event with the true counterpart in the North Eurasian palaeoenvironmental record, and (3) how to establish chronological relationship between the studied sedimentary successions, that is, to correlate the events and respective deposits in the sections located far apart. The problem could be easily solved if the sections were complete and ages of individual horizons could be dated. Unfortunately, this is rarely the case in the geological record. Palaeoenvironmental sequences often contain gaps, and the absolute age of their constituents are mostly unknown.

The solution can be obtained if we are able: (a) to identify events of continental extent that took place during the considered interval, (b) to assess the degree of the resulting environmental changes, and (c) to determine the position of the events in the chronological scale. In other words, it seems necessary to construct a climato-chronostratigraphic framework in which major palaeoenvironmental changes should be recognized and recorded in chronological order, and they should have correlatives in the terrestrial, marine, ice-core, and deep-sea records.

Therefore, the primary objective of our long-term research was to develop a climato-chronostratigraphic framework for the North Eurasian Pleistocene, at least for the time interval of the Brunhes palaeomagnetic epoch (0–780 000 years). To construct such a framework, the following conditions should be complied with: (1) it must be based on several representative records of environmental changes spanning a period that is long enough; (2) any palaeoenvironmental event needs to be recorded distinctly and unambiguously to permit its correlation with respective signals in other palaeoenvironmental records documented, e.g., by $\delta^{18}O$ variations in ice cores, deep-sea sediments, stalagmites, etc.; and (3) a time-scale should be substantiated with reliable absolute datings.

This paper presents the results of the development of a climato-chronostratigraphic framework for the North Eurasian Pleistocene in order to provide a template for the correlation of palaeoenvironmental events during the Brunhes Chron. It can be used as a tool to correlate the locally or regionally recognized palaeoenvironmental events with global proxy records.

THE METHODOLOGICAL APPROACH AND MATERIALS

For the construction of the Pleistocene climato-chronostratigraphic framework we have integrated unique data from our individual databases obtained in the course of long-term palynological studies of the nearly continuous Pleistocene sections and absolute chronology of deposits mainly from raised marine sequences. Data on climatic changes during the middle and late Pleistocene were obtained from two independent sources: from palynological studies of reference sections in the glacial–periglacial and extraglacial zones and from mollusc-based electron spin resonance (ESR) chronology of deposits associated with warm intervals. In some cases valuable data were also provided by feldspar-based infrared optically stimulated luminescence (IR-OSL) chronology of deposits from various parts of the palynologically studied sedimentary sequences.

The ESR palaeoclimatic record is based on the chronostratigraphy of mollusc-bearing sediments dated to warm phases, such as marine deposits (that are the results of marine transgressions) as well as sequences from ancient lakes and archaeological sites. Marine transgressions repeatedly covered the northern margins of the Eurasian continent. Being generally directly related to periods of global warming and ice sheet melting, they are of particular importance for the reconstruction of global environmental changes. Clusters of ESR dates in the distribution of ages of mollusc shells collected from palaeoshelf sediments revealed a series of intervals correlative with marine transgressions. Intervals lacking ESR dates (ESR dating hiatuses) may be, in turn, interpreted as indicating relatively cold climatic conditions or the onset of glaciations in the Northern Hemisphere, accompanied by sea regressions, climate deterioration, and changes in the environments on the continent.

An ESR-based proxy record of the climate and sea level changes over the past 600 000 years has been derived from more than 300 Pleistocene shell fossils collected between 1981 and 2008 in the frame of a number of international research projects. The ESR results obtained by the first author form the largest database for the late Quaternary warm climate-related shell-bearing deposits of various origin from Northern Eurasia. Most of them come from the palaeoshelf deposits of the Eurasian continental margin, from the Kola Peninsula in the west to the Taymyr Peninsula in the east (Molodkov 1986, 1988, 1989a, 1995; Molodkov et al. 1987, 1992; Molodkov & Raukas 1988, 1998; Bolshiyanov & Molodkov 1999; Molodkov & Bolikhovskaya 2002; Korsakova et al. 2004; Molodkov & Yevzerov 2004; Möller et al. 2006; Korsakova 2009). Some data of a pre-Brunhes/Matuyama boundary age were recently obtained from the Southern Hemisphere (Bolshiyanov et al. 2009).

The evolution of terrestrial environments has been recorded in several complete reference sections in the glacial-periglacial and extraglacial zones of the East European Plain (Bolikhovskaya 1976, 1984, 1991a, 1991b, 1993, 1995, 2000; Bolikhovskaya & Sudakova 1996). These sections, situated within the areas of the maximum advance of the Don, Oka, and Dnieper ice sheets as well as outside the glacial zone, contain key palaeogeographic markers, such as moraines left by these glaciations, loess horizons correlative to them, stratotypic (Likhvin, Chekalin, and others) interglacial horizons of palaeosols, lacustrine and alluvial sediments, etc. The chronostratigraphic position of the levels bearing small mammal fauna and the location of the Brunhes/Matuyama reversal (about 780 000 years BP) were determined in these sections.

Pollen assemblages recovered from the sections contain comprehensive information on continuous evolution of the ecosystem through the Pleistocene and provide the most complete terrestrial record of climatic fluctuations in this part of the European subcontinent. The structure of the record of those climate-controlled changes and principal palaeoclimatic signals recorded in it can be directly compared with both the main signals of the ESR-based palaeoclimatic record and with reference levels of the climate-dependent $\delta^{18}O$ variations in deep-sea and on-land sequences. The integrated approach based on the two independent methods and sources of climato-chronostratigraphic information has provided a means for the elaboration of an absolute chronology of main palaeogeographic events during the last 600 000 years (Bolikhovskaya & Molodkov 1999, 2000, 2002, 2006; Molodkov & Bolikhovskaya 1999, 2002, 2006, 2009).

DETAILS OF THE METHODS APPLIED

As mentioned in the previous section, palynological data form a base for the terrestrial palaeoclimate proxy. The palynological method holds a leading position among the other palaeobotanical methods, primarily due to the fact that pollen and spores are the only palaeontological objects found practically in all types of sediments, including even deposits that are commonly poor in spores and pollen, such as loesses and palaeosols. Detailed and thorough study of the loess–palaeosol formation allows a reliable reconstruction of a continuous succession of vegetation.

Our reconstructions of landscapes and climate for the whole time interval considered are based on detailed palynological analysis of about 500 pollen samples. At present, the results of palynological studies of reference sections of glacial and extraglacial zones yield the most complete record of terrestrial climatic conditions for this area. The structure of this record can be directly compared with the climate-driven ratio of oxygen isotopes in ice cores and deep-sea sediments (Bassinot et al. 1994; Jouzel et al. 2007).

Mollusc-based ESR and feldspar-based IR-OSL dating methods have been used to provide an absolute chronology and complementary palaeoclimatic record for the present study. The ESR dating method consists in a direct measurement of the number of radiation-induced paramagnetic centres, formed in the shell exposed to natural radiation. At the time of formation the lattice of shell biogenic carbonate has no radiation-induced centres, but ionizing radiation from the shell itself and the environment (enclosing matrix and cosmic) causes their gradual accumulation. A shell sample will therefore have long-lived (about 10^6 to 10^8 years, Molodkov 1988, 1989b, 2001) paramagnetic centres, the number of which relates directly to the total radiation dose that the shell has received. The presence of paramagnetic carbonate centres in mollusc shell material can be detected by ESR spectrometry. It produces a plot of the microwave absorption spectra where each individual paramagnetic centre is characterized by a specific signal (line), the amplitude of which is related to the accumulated palaeodose, and hence to the age of the shells. The position of an ESR line in a spectrum is described by the *g*-value, which characterizes the type of the paramagnetic centre, whereas the height of the signal represents a measure for concentration of that centre.

All ESR age determinations in the present study were carried out at the Research Laboratory for Quaternary Geochronology (RLQG), Institute of Geology at Tallinn University of Technology, and are based on an advanced version of the ESR dating method developed by A. Molodkov since the early 1980s. The main differences of this method from a common approach are as follows.

1. An interference-free analytical signal with a g factor of 2.0012, line width $\Delta B_{pp} = (2.65 \pm 0.55) \times 10^{-4}$ T, was discovered in ESR spectra of a large number of fossil carbonates, including mollusc shells. This signal was not detected earlier in the multicomponent differential ESR spectrum of the shells because of its interference with lines of other centres having different energetic parameters (life-time of the paramagnetic centre, energetical trap depth, frequency factor). As a result of such interference distortion between different signals, a faulty product of this interaction, for instance, the so-called ‘dating signal’ at $g = 2.0006$, has been commonly used for dating in other laboratories.
2. Several unconventional methods have been developed in an effort to provide reliable quantitative analysis of different shell material, for instance, the over-modulation method (Molodkov 1988). The phase-sensitive detection method was developed to date calcitic shells, the ESR spectra of which are strongly affected by the superposition of very intense Mn^{2+} signals, which mask weak radiation-induced lines (Molodkov 1993). These shells were generally considered to be unsuitable for ESR dating, in contrast to shells composed of aragonite.
3. To overcome the problems related to differently directed post-depositional uranium migration in shells, an ESR open system dating method (ESR-OS) has been developed (Molodkov 1988, 1992).
4. For the first time, terrestrial shells have been studied and successfully ESR dated (Molodkov 1996, 2001).

The upper limit of the mollusc-based ESR dating method developed in the RLQG is several million years.

Owing to the latest developments of the IR-OSL method by the RLQG (for details see, e.g., Vasilchenko et al. 2005; Molodkov & Bitinas 2006; Molodkov et al. 2007a; Jaek et al. 2007a, 2007b, 2008), this technique produces reliable absolute chronology of the events using feldspar, the most abundant mineral in the Earth’s crust. The ‘luminescence clock’ used by IR-OSL dating is the trapped charges (electrons) in the crystal structure of minerals, the number of which is related to the time elapsed since mineral grains were last subjected to light, for instance, during their predepositional transport (luminescence clock zeroing). Liberating the trapped charge through infrared irradiation of the feldspar sample in the laboratory results in the emission of a weak light signal called luminescence. The brightness of the luminescence signal is a measure of the amount of the charge trapped, which, in turn, is a measure of natural ionizing radiation received by the mineral from the outer space and surrounding sediments since its last exposure to light, i.e. the time of sediment burial or its age. The upper limit of the feldspar-based IR-OSL dating method (depending on conditions) is 300–500 ka.

The reliability of our dating methods that have been used in the present study is proved by cross-dating between ESR and IR-OSL. Direct cross-dating (on sediments by IR-OSL and on shells embedded in these sediments by ESR) was performed on six late Pleistocene samples (Table 1). The results of both dating methods agree well within uncertainties in their date, which confirms the accuracy and utility of either method for solving a wide series of Quaternary problems.

STUDY AREA AND SITES

Continuous terrestrial records of climatic changes spanning even two latest glacial-interglacial cycles – from the Dnieper/Saale glaciation to the recent interglacial, i.e. from marine isotope stage (MIS) 6 to MIS 1 – are rare. Therefore, loess–palaeosol sections of the southern and central parts of the East European Plain covering up to eight cycles can be regarded as unique and of special interest. It is not surprising that many Quaternary geoscientists consider them to be sources of the most comprehensive data for tracing environmental changes on the continent through the series of glacial and interglacial periods. The sections are mostly located within the limits of the most extensive ice sheets – Don (MIS 16) and Dnieper (MIS 6) ones – and in the periglacial zone of the Valdai/Weichselian and some previous glaciations (Fig. 1). Reconstructions of climatic and phytocoenotic changes based on detailed pollen analyses of these key sections allow extraction of principal palaeoclimatic signals inferred from terrestrial sources and their correlation with signals from other palaeoclimatic records.

Palaeoenvironmental reconstruction of the majority of late and middle Pleistocene thermochrons and cryochrons was carried out by N. Bolikhovskaya on the basis of her detailed pollen analysis involving complex (lithological, palaeopedological, microteriological, etc.) investigation of reference sections. The structure and composition of the middle and late Pleistocene vegetation are best characterized by the famous Likhvin reference section (54°08′N, 36°17′E) situated in the North–Central Russian glacial-periglacial region, Strelitsa reference section (51°36′N, 38°55′E) in the upper Don River region, and Otkaznoe reference sections (44°20′N, 43°51′E) in the middle Kuma River region (Fig. 1; Bolikhovskaya 1995, 2004).

Late Pleistocene deposits have been studied in particular detail in a 14 m thick part of the Arapovichi section located in the Desna–Dnieper Region in the northeastern area of the Dnieper Lowland, which was once covered by the Dnieper ice sheet. Pollen spectra recovered from the sequence characterize successions of vegetation and climate of the last interglacial and of the majority of the Valdai (Weichselian, Järva) pleniglacial interstadials and stadials. The first and the fourth middle Valdai interstadials (MVI 1 and 4) are most conspicuously manifested in the Molodova section, middle Dniester region (Bolikhovskaya 1986; Bolikhovskaya & Molodkov 2006).

Table 1. Mollusc-based ESR and feldspar-based IR-OSL cross-dating results

Location	ESR age, ka	IR-OSL age, ka
Bol′shezemel′skaya tundra; ~67.9N, 60.1E	72.0 ± 4.8[a]	74.7 ± 8.3[a]
Bol′shezemel′skaya tundra; ~67.8N, 60.7E	90.3 ± 10.9[b]	88.2 ± 5.4[b]
Southern Kola Peninsula; ~66.4N, 36.6E	103.0 ± 4.2[c]	104.0 ± 8.3[c]
Bol′shezemel′skaya tundra; ~67.8N, 60.7E	107.6 ± 12.4[b]	109.8 ± 6.9[b]
Eastern Kola Peninsula; ~67.0N, 41.1E	73.0 ± 7.5[d]	71.9 ± 8.2[d]
Eastern Kola Peninsula, ~67.1N, 41.2E	73.0 ± 5.7[d]	74.4 ± 6.8[d]

Mollusc-based ESR and feldspar-based IR-OSL ages were determined by the Research Laboratory for Quaternary Geochronology, Institute of Geology at Tallinn University of Technology.
[a] Molodkov & Bitinas 2006, [b] Bolshiyanov 2006, [c] Molodkov & Yevzerov 2004.
[d] Unpublished data by A. Molodkov, obtained in 2009.

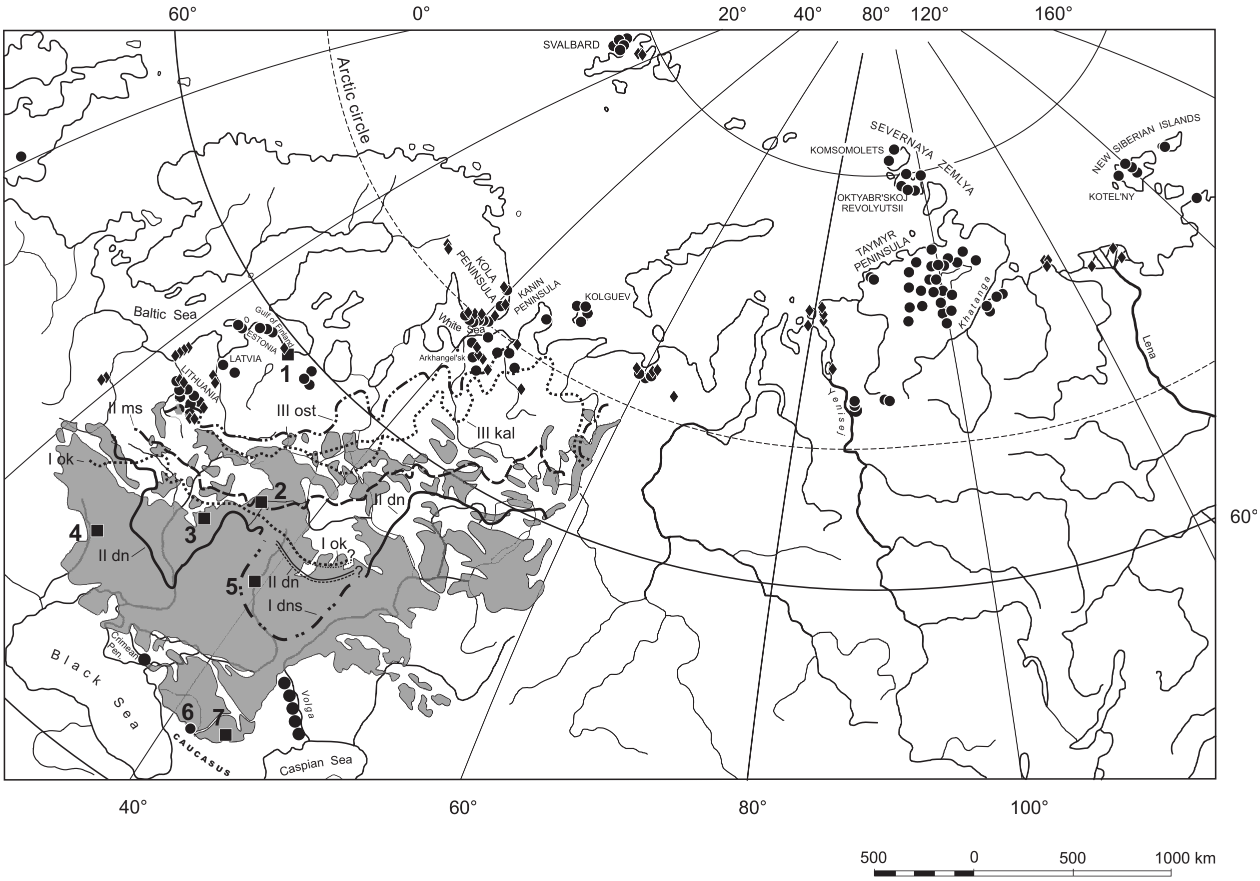

Fig. 1. Map of the study area showing location of the investigated sections mentioned in the text (1, Voka; 2, Likhvin; 3, Arapovichi; 4, Molodova; 5, Strelitsa; 6, Treugol′naya Cave; 7, Otkaznoe); distribution of loesses on the East European Plain (grey area); and location of the main palynologically studied sections (squares), sedimentary samples collected for IR-OSL analyses (diamonds), shell samples for ESR analysis (circles), and limits of Pleistocene glaciations (after Zarrina 1991): 1, Don (I dns); 2, Oka (I ok); 3, Dnieper (II dn); 4, assumed Dnieper and Oka (II dn, I ok); 5, Moscow (II ms); 6, Kalinin (III kal); 7, Ostashkovo (III ost).

Unfortunately, the chronology of loess–palaeosol sequences has not been adequately studied, especially beyond the range of radiocarbon dating. To overcome this imperfection, since the beginning of our collaboration (Bolikhovskaya & Molodkov 1999; Molodkov & Bolikhovskaya 1999, 2002) the Pleistocene palynostratigraphy, based on the most complete and thoroughly studied loess–soil sections, has been calibrated to the geochronologic time scale using correlation between principal palaeoclimatic signals inferred from pollen data on the one hand and the World Ocean transgressions on the other. The latter were dated by the ESR method applied to subfossil mollusc shells collected from the Eurasian Arctic palaeoshelf area, which is highly sensitive to global climatic changes and, therefore, can be regarded as a highly sensitive recorder of these changes in the past. Several shells were recently collected from elevated marine deposits in East Antarctica.

A unique opportunity to realize fully the potential of the integrated approach based on a joint and detailed palynological and geochronological investigation of one and the same sedimentary sequence appeared in the mid-2000s, with the discovery of a thick well-exposed continuous late Pleistocene section on the southeastern coast of the Gulf of Finland in the vicinity of the Voka village (Molodkov et al. 2007b). This section seems to be one of the most complete sequences of this age in the Baltic region.

PALAEOCLIMATIC COUNTERPARTS OF THE TERRESTRIAL AND MARINE RECORDS

The structure and composition of the Quaternary deposits and majority of the middle Pleistocene palaeogeographic events within the limits of the Oka (Elster) and Dnieper (Saale) glaciations is most completely represented in the 50 m thick Likhvin section of loess, palaeosoil, tills, glacio-lacustrine, alluvial, lake, and bog formations. In the extraglacial zone the most complete interglacial successions of vegetation are represented in the Strelitsa and Otkaznoe reference sections. In the former even an entire pre-Brunhes/Matuyama boundary glacial-interglacial cycle is distinguished (Bolikhovskaya 1995, 2004), consisting of the Petropavlovka interglacial and subsequent Pokrovka glacial (Fig. 2). The Brunhes/Matuyama reversal marks here the transition from the Pokrovka glacial to the Gremyachie interglacial horizon. The Petropavlovka interglacial can most likely be correlated with MIS 21, and tentatively with the corresponding sea level rise recorded by our two ESR datings (about 860 ka) of shells collected from the lower parts of the 360–380 m thick marine bed in Eastern Antarctica (~71°33′S, ~67°43′–67°47′E) at a distance of about 350 km from the modern shoreline (Bolshiyanov et al. 2009).

A comprehensive layer-by-layer spore-and-pollen study of the whole sequence represented in the reference sections permitted its detailed subdivision and reconstruction of the diversified environmental and climatic events in the centre and south of the East European Plain. The sequence spans the period from the last pre-Brunhes/Matuyama interglacial (Petropavlovka) to the Holocene (Fig. 2), i.e. eight glacial epochs (Pokrovka, Devitsa, Don, Oka, Kaluga, Zhizdra, Dnieper, Valdai) and nine interglacials (Petropavlovka, Gremychie, Semiluki, Muchkap, Likhvin, Chekalin, Cherepet′, Mikulino, and the Holocene), which are represented either as complete climatic rhythms of glacial and interglacial rank, or as considerable portions of climatic-phytocoenotic phases – constituents of the rhythm (Bolikhovskaya 1995, 2004).

The ESR dates of the deposits corresponding to the earliest and most prominent evidence of the global warming of climate during the Brunhes Chron were determined on various shell samples, including marine shells from trangressive deposits of the Eurasian Arctic and the terrestrial shells collected from the oldest (610–565 ka, Molodkov 1996, 2001, 2007) culture-bearing layer (7a) of an ancient multi-level Lower Palaeolithic cave-site – Treugol′naya (English *Triangular*) Cave (43°59.54′N, 41°17.39′E) – situated on the northern slope of the Greater Caucasus at an elevation of 1500 m a.s.l. This site has provided the earliest evidence for human settlement in southeastern Europe on the one hand and multidisciplinary evidences of the prominent early mid-Pleistocene palaeoenvironmental changes on the other (Doronichev et al. 2007).

The first post-Brunhes/Matuyama palaeomagnetic boundary cluster of ESR dates (610.0–535.5 ka)

The first cluster of ESR dates is within the time span of 610.0–535.5 ka (Fig. 2), in an interval of sea level rise related to global warming. The deposits palynologically studied in two reference sections (Otkaznoe and Strelitsa) refer to one of the warmest interglacials of the past half-million years. This may indicate a lower continental ice volume that must have been accompanied by a marked glacio-eustatic sea level rise. In all likelihood, this warm epoch corresponds to the very humid and warm Muchkap interglacial (Bolikhovskaya 2004). The age range of the cluster (610.0–535.5 ka) most likely corresponds to MIS 15 and part of MIS 14 in the orbitally tuned SPECMAP marine isotopic record (Imbrie et al. 1984).

Severe conditions in a periglacial tundra with the predominance of cryophytes (*Betula nana*, *B. fruticosa*, *Alnaster fruticosus*, *Dryas octapetala*, *Selaginella selaginoides*, etc.) were characteristic of a period predating the Muchkap interglacial when the oldest Don glacio-lacustrine sediments accumulated in the Likhvin section. In the Strelitsa section the Don glacial complex includes two till horizons interlayered with fluvioglacial sands. This glacial stage is most likely correlated with MIS 16 (about 660–610 ka).

Our ESR results from the lowermost lithic assemblage from layer 7a in Treugol′naya Cave (~600 ka) imply that the first humans probably appeared here and then in Southern Eastern Europe soon after the Don glaciation, i.e. after the start of global climate amelioration and consequent decay of the mountain ice domes in the Caucasus (Molodkov 1996, 2001).

A single ESR date of 715 ka obtained from the Taymyr Peninsula (77°21.08′N, 102°43.62′E, 39.5 m a.s.l) can imply sea level highstand during MIS 17, which can be correlated with the time of development of the upper pre-Don palaeosol in the Strelitsa section. It features a thick humus horizon, which in all probability developed in the forest-steppe of the Semiluki (late Il′inka) thermochron.

The first post-Brunhes/Matuyama ESR dating hiatus (535–455 ka)

In the upper Don River basin this hiatus includes the Oka cold stage, with a distinct tundra-steppe and tundra-forest-steppe environment. Periglacial steppe conditions were widespread within extraglacial regions along the Dnieper River, and periglacial forest-steppe – in the eastern Caucasian forelands.

On the basis of the ESR palaeoclimatic record the relatively cold epoch, which includes also the Oka stage,

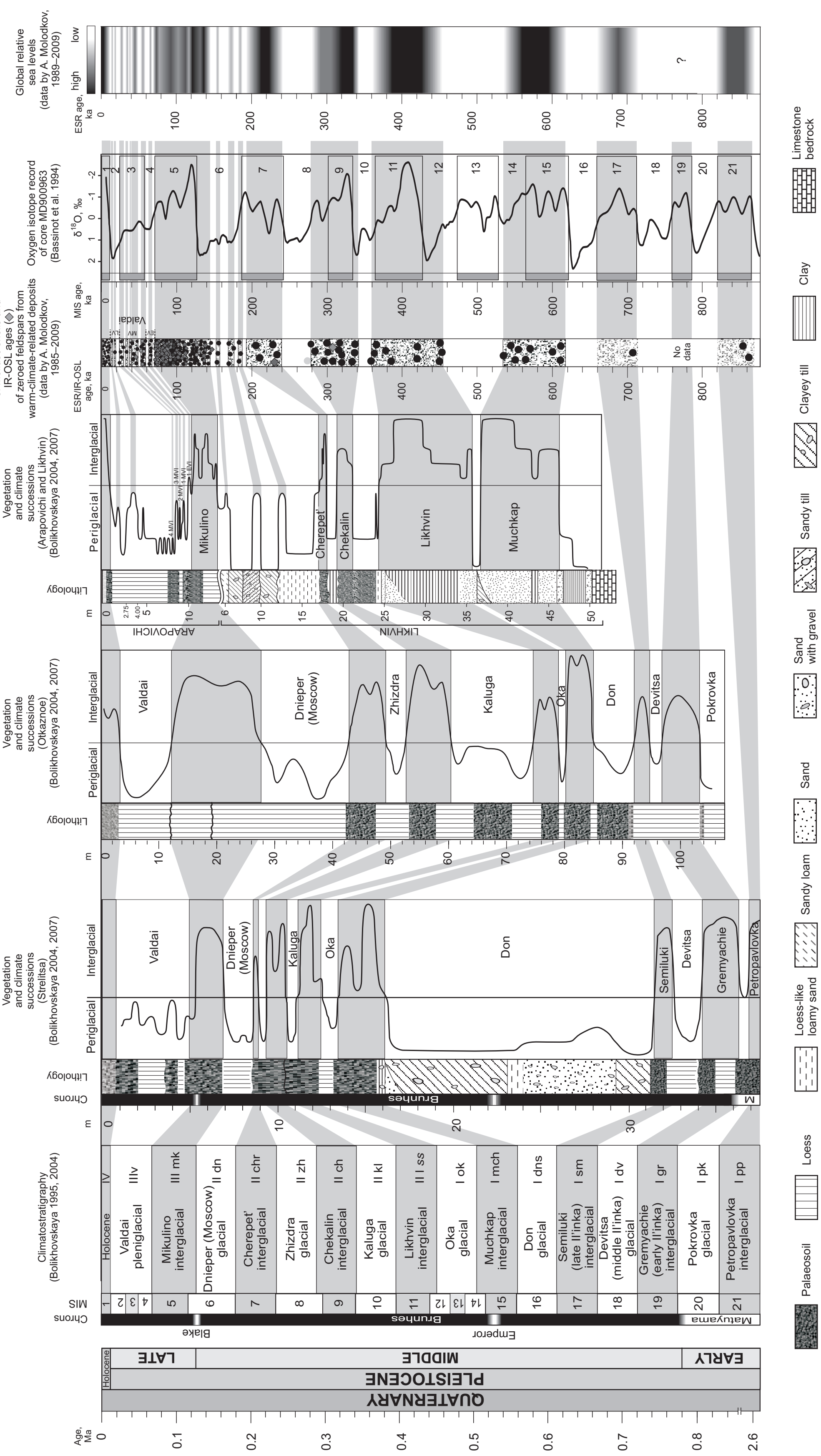

Fig. 2. A palyno-chronostratigraphic framework for Northern Eurasia. Climatic changes are traced in different terrestrial and marine records over the last 900 000 years.

spans the interval from MIS 14 to MIS 12. That does not agree with the oxygen isotope climate-rhythmics where odd numbers denote 'warm' interglacial stages; on this formal basis MIS 13 should correspond to a warm interval. Recently, however, the conclusion on the long duration of the relatively cold epoch has been corroborated by the analysis of the Antarctic (Dome C) ice core; no interglacial event corresponding to the 'warm' stage 13 could be detected there either from the dust or chemical records (Lambert et al. 2003). In addition, the oxygen isotopic composition of deep-sea sediments (Bassinot et al. 1994) and the deuterium temperature record of the EPICA ice core (EPICA community members 2004) show that globally MIS 13 appears to be the most glaciated and coolest interglacial of the last one million years.

An unusual worldwide phenomenon with signs of a globally cool (more ice) MIS 13 is also considered by Yin & Guo (2008). Other exceptional climatic events have also been found worldwide, in particular in India and Africa (Yin et al. 2008).

In Treugol′naya Cave this hiatus corresponds to archaeologically sterile layer 6 sandwiched between cultural layers 7a and 5b (see fig. 4 in Molodkov 2001), which may be indicative of the time when ancient man left the cave shelter. Probably, the climate became notably cooler, the mountain glaciation developed, the altitude of the snow line fell well below the cave bottom (Molodkov 1996, 2001), and man was forced to move down to the valleys and foothills. Subsequent climatic amelioration during the interglacial promoted further penetration of man deep into the plain.

The second cluster of ESR dates (455–360 ka)

Mollusc-based ages within this cluster were obtained from palaeolacustrine (Gaigalas & Molodkov 1996, 2002) and marine deposits (Molodkov et al. 1992) and the next culture-bearing layer (5b) of the Treugol′naya Cave deposits (Molodkov 2001). This cluster can be correlated with the Likhvin interglacial (MIS 11) – the warmest interval recorded during the last 600 ka (Bolikhovskaya 1995, 2007). Several lines of evidence from marine terraces in the tectonically stable, or slightly subsident archipelagos of Bermuda and The Bahamas (see, e.g., Hearty 1998; Hearty et al. 1999; Kindler & Hearty 2000) indicate three successive ancient relative sea level stands at about +2 m, +7 m, and more than +20 m (van Hengstum et al. 2009) during MIS 11. The ocean level was the highest in the second half of the interglacial, about 400 ka ago, due to the melting of the largest ice sheets in Greenland and Antarctic. Palaeoclimatic characteristics inferred from palynological studies of the Likhvin section show similar dynamics of environments in the centre of the East European Plain: the climatic optimum falls into the second half of the Likhvin interglacial. However, in most records (see, e.g., Fig. 2), the $\delta^{18}O$ curve for stage 11 shows a single prominent peak in the first half of the stage, whereas marine terrace stratigraphy, as mentioned above, suggests the occurrence of three sea level highstands during this time period – at about +2, +7, and +20 m. Therefore, this is a good example showing that caution is required when directly translating $\delta^{18}O$ curve wiggles in terms of global climate and sea level changes (Kindler & Hearty 2000, p. 55).

The second ESR dating hiatus (360–340 ka)

During the coldest phase of this time interval the upper Oka and upper Don regions were covered by periglacial tundra and forest-tundra vegetation, with patches of tundra-forest-steppe and tundra-steppe. Periglacial forest-steppe and steppe prevailed in the southern part of the East European Plain beyond the limits of ice sheets. This period is correlated with the Kaluga glacial stage known from the East European Plain (MIS 10).

The third cluster of ESR dates (340–280 ka)

This palaeoclimatic signal of interglacial character is observed in various palaeoenvironmental records. Correlatives of these formations in the Likhvin section are represented by a well-developed pedocomplex (paraburozem soil in the lower and podzolic soils in the upper part) formed in forest landscapes during the Chekalin interglacial (MIS 9). The optimum in temperature and moisture was marked by the dominance of spruce/broad-leaved forests.

The third ESR dating hiatus (280–240 ka)

This low sea level event corresponds to the Zhizdra glacial and a major part of MIS 8. In the Eastern European loess province it resulted in the dominance of periglacial tundra, forest-tundra, and steppe in the northern glacial-periglacial regions, while open birch woodlands and dwarf shrub formations were typical of cryoarid landscapes of the East Caucasian forelands.

The fourth cluster of ESR dates (240–205 ka)

A considerable warming of interglacial rank has been established by the ESR data on Arctic palaeoshelf sediments, within an interval correlated with MIS 7. Xerophytic broadleaved formations of *Carpinus orientalis*, *Ostrya* sp., *O. carpinifolia*, etc. were dominating all over the loess regions of the East European Plain. In the Likhvin section a bog-gleyed soil is attributed to the

Cherepet′ warming (see Fig. 2). Hornbeam–oak and mixed (of Siberian pine and broadleaved species) formations became dominant in the upper Oka basin at the optimum phases.

Three small subclusters within the time interval of the penultimate (MIS 6) glacial (200–145 ka)

This penultimate glaciation is attributed to the Dnieper *sensu lato* glacial stage on the East European Plain and to the Saalian in NW Europe. In the Likhvin section it is represented by a thick series including the following units (see Fig. 2): (1) early Dnieper fluvioglacial silts containing predominantly tundra-steppe pollen assemblages; (2) tills corresponding to the Dnieper and Moscow cold stages and a layer corresponding to the Dnieper–Moscow interstadial, with pine open woodlands, shrubs of *Alnaster*, and dwarf birch prevailing in landscapes of the latter; and (3) late Moscow loess-like sandy loam.

The first amelioration of climate, which resulted in the melting of the Dnieper ice sheet, is noted in the upper part of the fluvioglacial silts at the very beginning of MIS 6. The first ESR subcluster places the warming at approximately 184 ka BP. In the pollen record of the Likhvin section it may be correlated with a signal of interstadial warming, marked by the transition from tundra-steppe to periglacial open woodlands with pine.

During the second (Dnieper–Moscow) interstadial open pine woodlands, frutescent formations of *Alnaster*, and dwarf birch dominated. The next ESR subcluster indicates that the second interstadial occurred at about 172 ka BP.

Pollen assemblages recovered from deposits of the third – late Moscow – interstadial warming suggest periglacial birch woodlands with *Betula fruticosa* in the shrub layer and the ground layer of *Arctous alpina*, *Cannabis* sp., *Artemisia* s.g. *seriphidium*, *Thalictrum* cf. *alpinum*, and others. The third ESR subcluster dates this event at ~155 ka BP. All three subclusters seem to correlate with positive anomalies of the Greenland Ice Core Project (GRIP) ice-core record from the penultimate glacial period (see fig. 3 in Molodkov & Bolikhovskaya 2009).

A wide cluster indicative of the end of MIS 6 and of MIS 5 (~145–140 to 70 ka ago)

Most of the Quaternary palaeoenvironmental reconstructions focus on the late Pleistocene. This is because abundant evidence is preserved in various records to allow detailed reconstructions, whereas evidence of earlier Quaternary environmental changes is usually quite fragmentary.

The largest number of our mollusc-based ESR datings (more than 190) was obtained from a vast area of northern Eurasia (see Fig. 1) for the time period of 145–70 ka, which covers the whole of MIS 5 and the final phase of MIS 6. Such a great number of dates from the sites spatially spaced apart from each other strongly indicates that the occurrence of marine shells in what is now dry land is a sign of the presence of palaeo-shelves of Arctic Seas far away from the present seashore (see, e.g., fig. 2 in Molodkov & Bolikhovskaya 2009). It is most reasonable to assume that this period of the flooding of large areas of northern Russian and Siberian coastal lowlands is connected with the late Pleistocene transgressions within MIS 5, in the North known as the Boreal, and with the global warming during this stage. Global eustatic sea level maximum was 4–6 m higher than today as a result of extensive melting of glaciers and thermal expansion of ocean volume.

These observations are corroborated by the data of detailed analysis of pollen assemblages recovered from loess–palaeosol series and from other continental formations of post-Dnieper (post-Moscow) age; the sampled sections are located in central Eastern Europe, within the limits of the present-day zone of mixed forests. The results of pollen analysis suggest the highest moisture supply from the beginning of the last interglacial to the end of the first early Valdai (Weichselian, Järva) pleniglacial within MIS 4. In southwestern regions (present broadleaved forest zone) the interval of maximum moisture supply continued to the end of the second early Valdai pleniglacial. As a whole, our results both from ESR and palynological analyses suggest longer (up to 70–75 ka) duration of the Boreal transgression with climatic conditions during this time predominantly of interglacial character. Our data indicate that despite several coolings with climate of interstadial type and phases of sea regression (see, e.g., figs 4, 5 in Molodkov & Bolikhovskaya 2009), they did not probably cause any significant interruption of marine sedimentation in the studied area during MIS 5 (~130 to 70 ka) (Molodkov & Raukas 1996; Molodkov & Yevzerov 2004). In all likelihood, during this period the area from the Kola Peninsula in the west to the Taymyr Peninsula in the east was covered by waters of transgressive seas with typical marine fauna (*Hiatella arctica*, *Mya truncata*, *Macoma* ssp., *Astarte* ssp., etc.), dated by ESR between 145 and 70 ka. However, according to recent reconstructions (see, e.g., Svendsen et al. 2004), during the period between ~100 and 80 ka this area was covered by the huge Eurasian ice sheet, which blocked the northbound drainage of rivers towards the Arctic Ocean and led to the formation of huge ice-dammed freshwater lakes. At present, to solve this apparent contradiction, the greatest hopes are laid on climato-chronostratigraphic investigation of a thick well-exposed continuous Voka section, revealed recently in the glacial zone of the northwestern part of the East European Plain (NE Estonia, 59°24.86′N, 27°35.88–35.94′E). Our preliminary results suggest that the Voka outcrop might be one of the most complete late Pleistocene sequences in the Baltic region, the visible part of which spans from at least about 120 to 30 ka (Molodkov et al. 2007b). The investigation of this section can give a rare opportunity to get detailed data about the development of the late Pleistocene palaeoenvironment during this highly contentious period (MIS 5).

A series of interstadial-related terrestrial and marine events from the last pleniglacial (MIS 4–2, ~70 to 11 ka ago)

Four clusters and three single-date events were detected within the MIS 4–2 mollusc-based ESR record. The first cluster (66.0–61.1 ka) consists of eight ages in the early MIS 4 and indicates the first post-MIS 5 global sea level rise due to the contribution of glacier and ice sheet melt during the first early Valdai (Weichselian, Järva) interstadial. The second cluster (58.7–52.0 ka) consists of 13 ages. The dates suggest that the second global-scale warming occurred at the very beginning of MIS 3; this compares favourably with the stratigraphic position of the second peak in our terrestrial pollen-based record. The third cluster (47.5–40.0 ka) consists of seven ages falling in the middle of MIS 3. Taken together, these seven ages do provide evidence for the next climate warming/relative sea level rise during the last pleniglacial. An age of about 32 ka obtained on raised marine deposits implies climate amelioration within the second half of MIS 3.

The fifth amelioration of the climate occurred at the very end of MIS 3. The corresponding cluster consists of six dates between 28.4 and 23.0 ka. That was probably the last late pleniglacial warming associated with the sea level rise predating the last glacial maximum (LGM).

A single ESR date of about 17 ka marks obviously the first post-LGM sea level rise. The date of 13.5 ka, obtained from a shell taken from the northwestern part of Svalbard (78°56.898′N, 11°24.964′E) at an elevation of about 34 m a.s.l. (H. Alexanderson pers. comm. 2008) seems to indicate sea level rise due to the onset of the Bølling–Allerød interstadial event. This event marked the termination of the last glacial period.

In many areas of the East European Plain the early and middle Valdai pleniglacial (MIS 4–3) was characterized by non-glacial, although rather severe palaeoclimatic conditions. Thanks to detailed pollen studies of the most complete sections in the glacial-periglacial and extraglacial regions of the Russian Plain (e.g. Arapovichi, Likhvin, Strelitsa, Molodova, see Fig. 1), it was possible to distinguish a series of stadials, interstadials, and interphasials within this period (Bolikhovskaya 1986, 1991a, 1995, 2000, 2007).

The first early Valdai cooling is well reflected in the Arapovichi section by the expansion of open pine–birch forests with *Betula nana*, *B. fruticosa*, and *Alnaster fruticosus* in the undergrowth into this territory. However, during the subsequent first early Valdai interstadial (EVI 1) (see Fig. 2), pine–birch forests with oak, linden, and hornbeam, similar to interglacial forests of the same territory, were predominant.

At the time of the first post-LGM interstadial identified in the Arapovichi section at a depth of 2.75–4.00 m (see Fig. 2), cryophytes of the fern and club moss group disappeared completely. Forests of pine (*Pinus sylvestris*, *P. sibirica*), and birch–pine forests with undergrowth of shrub birch (*Alnaster fruticosus*), juniper, and willows and with a dense cover of Polypodiaceae were dominating.

However, it recently turned out that the last pleniglacial had a more complicated climatic structure and that a much greater number of individual palaeoclimatic events can be detected within this period of the late Quaternary. For instance, our detailed palynological analysis and IR-OSL datings of the samples taken from the new terrestrial reference section at the Voka site have provided convincing evidence of the occurrence of two severe and two considerably milder climate intervals of interstadial rank even in the relatively narrow time span between 39 and 33 ka. Besides, two minor warmings dated at 34.2 and 33.7 ka were recognized within the last cold phase (Bolikhovskaya & Molodkov 2007).

The first interstadial (38.6–37.6 ka) was marked by the dominance of mainly periglacial forest-tundra, locally with open forest patches of spruce and common pine with an admixture of larch and Siberian cedar pine. During the following relatively short (37.6–36.8 ka) interval of a colder and dryer climate landscapes of tundra-steppe and tundra-forest-steppes prevailed. The next interstadial (36.8–35.3 ka), much warmer than the previous one, was characterized by a new expansion of boreal forest species onto the study area. The last interval (35.3–32.6 ka) was characterized 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. It suggests that this interval was close to the final part of the middle Järva (Weichselian) period preceding the late Weichselian ice sheet expansion into the region. 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 (Fig. 3).

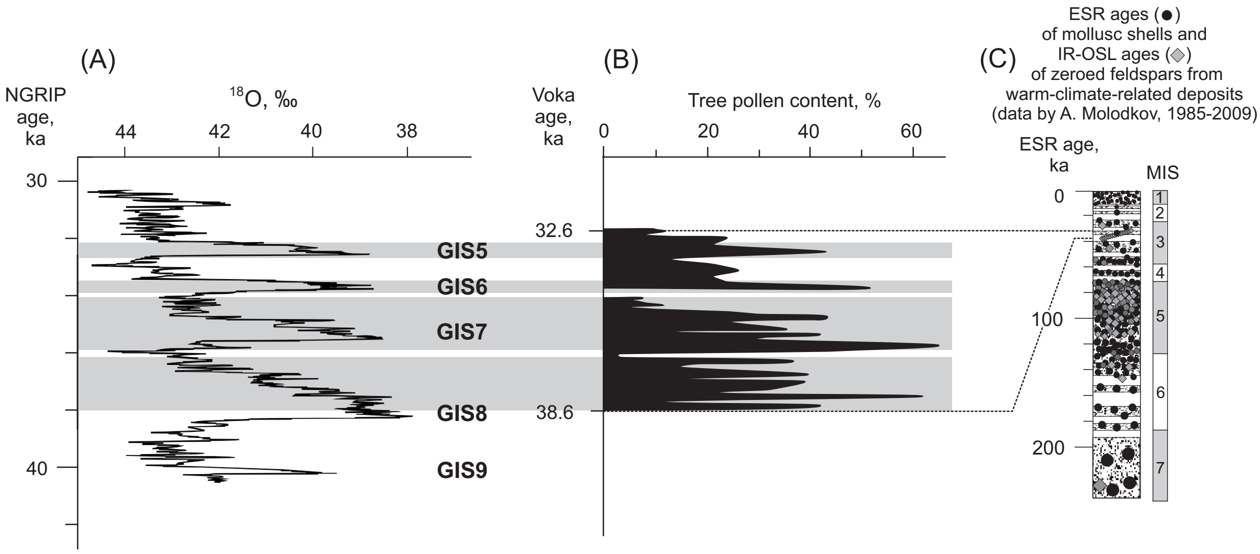

Fig. 3. Matching the Voka chronoclimatic pattern (B) (after Bolikhovskaya & Molodkov 2007) to $\delta^{18}O$ variations in the NGRIP ice-core (A) (after Andersen et al. 2006). The best fit lies between Greenland Interstadial (GIS) 8 and GIS 5. (C) Palaeoenvironmental changes over the last 200 ka reconstructed from mollusc-based ESR chronostratigraphy in Northern Eurasia (after Molodkov & Bolikhovskaya 2009).

CONCLUSIONS

During the last decades a palyno-chronostratigraphic framework has been developed for the North Eurasian Pleistocene based on two independent sources of palaeoenvironmental information: electron spin resonance (ESR) chronology of warm-climate-related deposits and palynological record of vegetation response to climatic variability and palaeoenvironmental events. It allowed us to create a record of palaeoenvironmental changes and provide absolute chronology for major continental-scale climatic events over the past 600 000 years: six interglacials and five intervening glacials have been confidently identified over this period. In addition, three interglacials and glacials have been distinguished between about 900 000 and 600 000 years. The correlation of terrestrial palaeoclimatic signals from the East European Plain with those of the mollusc-based ESR climato-chronostratigraphic record obtained from Northern Eurasia suggests that the detected climate events have a large continental or even global significance. Therefore, such a palyno-chronostratigraphic framework may offer an excellent guide for searching missing regional or local stratigraphic units equivalent to palaeoenvironmental events recorded in the framework. Hence, from our point of view, some of the problems related to the middle and late Pleistocene stratigraphy in the Baltic States could be solved now by a twofold approach: first, by using this record as a palaeoenvironmental reference for Central and Eastern Europe and the Baltic area, and second, by carrying out purposeful search for the deposits correlative with the main palaeoclimatic markers recognized by us in the neighbouring and more remote areas, and by dating them with the latest and most promising geological dating methods – mollusc-based ESR and feldspar-based IR-OSL. The framework is still under development and refinement and is continuously ready to incorporate new climate-chronostratigraphic data that will be obtained during further investigations.

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Õietolmu-, elektron-paramagnetresonants- ja infrapunase kiirgusega optiliselt stimuleeritud luminestsentsanalüüsi andmetel põhinev Põhja-Euraasia Pleistotseeni maismaa ning mereliste setete klimato-kronostratigraafiline skeem

Anatoly Molodkov ja Nataliya Bolikhovskaya

Autorid sünteesisid maismaalisi ja merelisi salvestusi Brunhesi paleomagneetilise sündmuse ulatuses (0–780 000 aastat), kasutades oma andmeid Põhja-Euraasia paleošelfi, ekstra-, peri- ning glatsiaalse vööndi alalt. Tuvastatud paleokeskkonna sündmuste ja vastavate settekihtide kronostratigraafiline asend stratigraafilises koondtulbas on kindlaks määratud setete eri (merelistes, järvelistes ning terrigeensetes) geneetilistes tüüpides sisalduvate subfossiilsete molluskite kodade elektron-paramagnetresonantsanalüüsi alusel. Taimestiku ja keskkonna arengulugu sel ajavahemikul on iseloomustatud õietolmu andmetega Ida-Euroopa tasandiku ruumiliselt hajutatud tugiläbilõigetest. Klimato-kronostratigraafiline salvestus näitab kaheksast sooja kliima ja kõrge maailmamere taseme intervallist ning seitsmest jäätumisperioodist koosnevat suktsessiooni. On kindlaks tehtud selge vastavus pikkade õietolmusalvestuste ja vahetult dateeritud sooja kliimaga seotud setete vahel vähemalt viimase 600 000 aasta vältel (alates 15. kuni 1. merelise isotoopstaadiumini). Saadud tulemused näitavad, et olles integreeritud, lubavad need salvestused viia sooja/külma kliimaga seotud setteid vastavusse kronostratigraafiliselt korraldatud Hilis-Kvaternaari paleokeskkonna sündmuste suktsessiooniga.