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Eustatic sea-level and climate changes over the last 600 ka as derived from mollusc-based ESR-chronostratigraphy and pollen evidence in Northern Eurasia

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Abstract

We reconstruct and correlate palaeoclimatic events and deposits from shelf, glacial, periglacial, and extraglacial zones of northern Eurasia over the last 600,000 years. The chronostratigraphical correlation of identified palaeoenvironmental and sea-level events and corresponding horizons is based on electron spin resonance (ESR) analysis of subfossil mollusc skeletal remains from marine, freshwater and Acheulian-bearing cave-site deposits. Over 230 shell samples from more than 40 sites along the continental margin of Eurasian north, in the Black and Caspian sea basins and terrestrial shells from a Lower Palaeolithic cave-site in the Northern Caucasus were dated via ESR to produce a late Quaternary geochronology. The Pleistocene composite section of the loess-palaeosoil formation includes two reference sections—Likhvin and Arapovichi—from the centre of the East-European plain. The palyno-chronostratigraphic record is interpreted as the product of six warm-climate/high sea-level events including the current interglacial, and six glacial events. They are presented either as complete climatic rhythms of glacial and interglacial rank, or by considerable portions of climatic–phytocoenotic phases constituents of the rhythm. The full-interglacial conditions are centred at about 580, 400, 310, 220 and between 145–70 calendar ka. A broad correspondence between long palynological sequence, directly ESR-dated warm-climate-related events and other palaeoenvironmental records described in the literature has been noted for 11 upper oxygen isotope stages (11 to 1). The results obtained in this study exemplify the potential of integrated chrono-climatostratigraphic sequences in linking marine and terrestrial palaeoclimate records that may eventually span the whole Brunhes chron. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: ESR-dating; Palynological analysis; Chronostratigraphy; Mid–Late Pleistocene; Northern Eurasia; Time scale; Palaeoclimate

1. Introduction

Quaternary climate change has resulted in repeated environmental changes world-wide. Information on the dynamics of these changes is often preserved in sedimentary deposits associated with the margins of marine, lacustrine, or glacial environments. However, most of these palaeoenvironmental records are limited in the degree of age control. The latest Quaternary portion of these records can be dated by radiocarbon methods, but the pre-radiocarbon portion of the history has been dated primarily by interpreted correlation with the orbitally tuned marine isotopic chronology of Imbrie et al. (1984).

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Unfortunately, correlation of these records with the marine isotopic geochronology is usually complicated by incomplete or disturbed stratigraphic sections (Patience and Kroon, 1991). Among the most complete Pleistocene continental palaeoenvironmental sequences is the loess-paleosol formation (LPF). In contrast to glacial, alluvial, and other late Cenozoic formations of northern Europe, LPF contain an almost continuous Quaternary palaeoclimate record and range in thickness to 100 m in the east-European plain and central Asia (Bykova et al., 1986). LPF usually preserve palynological records that allow for long continental climate reconstructions that can be correlated with the marine isotopic record (Velichko et al., 1989).

However, for solving questions related to correlation of palaeoenvironmental events which have occurred in different environments and different regions, temporal correlation of identified palaeoclimatic events and corresponding horizons is particularly important. The relationship between the independent climate-response records–long continental pollen record and the global deep-sea oxygen isotope record–can be established by using combinations of independent control levels, such as dated horizons indicating global palaeoenvironmental events.

Subfossil mollusc shells are often found in Quaternary coastal marine deposits, now emergent because of post-glacial isostatic uplift. Dating of these fossils can provide an independent chronology of sea-level change and deglaciations. Electron spin resonance (ESR) dating of these marine specimens has proven to be useful for establishing a geochronology well beyond the limits of radiocarbon (Ikeya and Ohmura, 1981). Combined with ESR data for freshwater or terrestrial molluscs from lacustrine, loess, or cultural horizons, a framework for direct land–sea correlation can be established.

In this paper, we present an integrated palynochronostratigraphic synthesis of Eurasian LPF (Bolikhovskaya, 1993, 1995, 2000; Bolikhovskaya and Sudakova, 1996) and electron spin resonance (ESR) chronostratigraphy of marine and freshwater sequences (Bolshiyanov and Molodkov, 1999; Gaigalas and Molodkov, 1996, 1997; Molodkov, 1986, 1988, 1989a, 1993, 1995, 1996, 2001; Molodkov and Gaigalas, 1994; Molodkov and Raukas, 1988, 1996, 1998; Molodkov et al., 1987, 1992, 1998). We focus on two important palynological profiles (Arapovichi and Likhvin type sections, central east-European plain) and ESR geochronology of warm-climate deposits of northern Eurasia to demonstrate the interrelationship between different manifestations of the same palaeoenvironmental events. There may be good potential to correlate long marine and terrestrial palaeoclimate records over wide areas and distinguish middle–late Pleistocene warm-climate/high sea-level events.

2. Study area

The most complete late Pleistocene loess-palaeosoil series are situated in the Desna–Dnieper glacial–periglacial loess region in the northeast of the Dnieper lowland, within the limits of the Dnieper (= Saale) ice sheet (European time division referred to in the present paper is given after Bowen et al., 1986). Arapovichi is one of the most representative stratotype sections (51°59′ N and 33°21′ E, Fig. 1) in the region. The section is located at the interfluvial plateau on the right bank of the Desna River, about 12 km southwest of Novgorod–Seversky town.

The section has been thoroughly studied during the last 50 years and is one of the reference sections for the stratigraphic scheme of LPF (Velichko et al., 1984).

In the section, the Dnieper till is overlain by a 14-m-thick late Pleistocene loess-palaeosoil formation. According to sedimentological evidence, sands and loams overlying the till together with superposed Salyn lesseve soil and the lowermost part of sod-chernozem Krutitsk soil represent the Mikulino/Eem Interglacial here.

The character and sequence of the palynozones identified in the section, regularities in the phytocoenotic successions, total composition of the palynoflora and individual significant species (Bolikhovskaya, 1993) testify that the whole series of formations overlying the till and the lower third of the Krutitsa soil belongs to the Eem/Mikulinian Interglacial.

The palaeoenvironmental changes in the northern Central Russian glacial–periglacial loess region that occupies the north of the Central Russian Upland within the limits of the maximal middle Pleistocene (or early–middle Pleistocene according to the stratigraphical scheme of the east-European plain; thereafter, we will use the West-European time division)

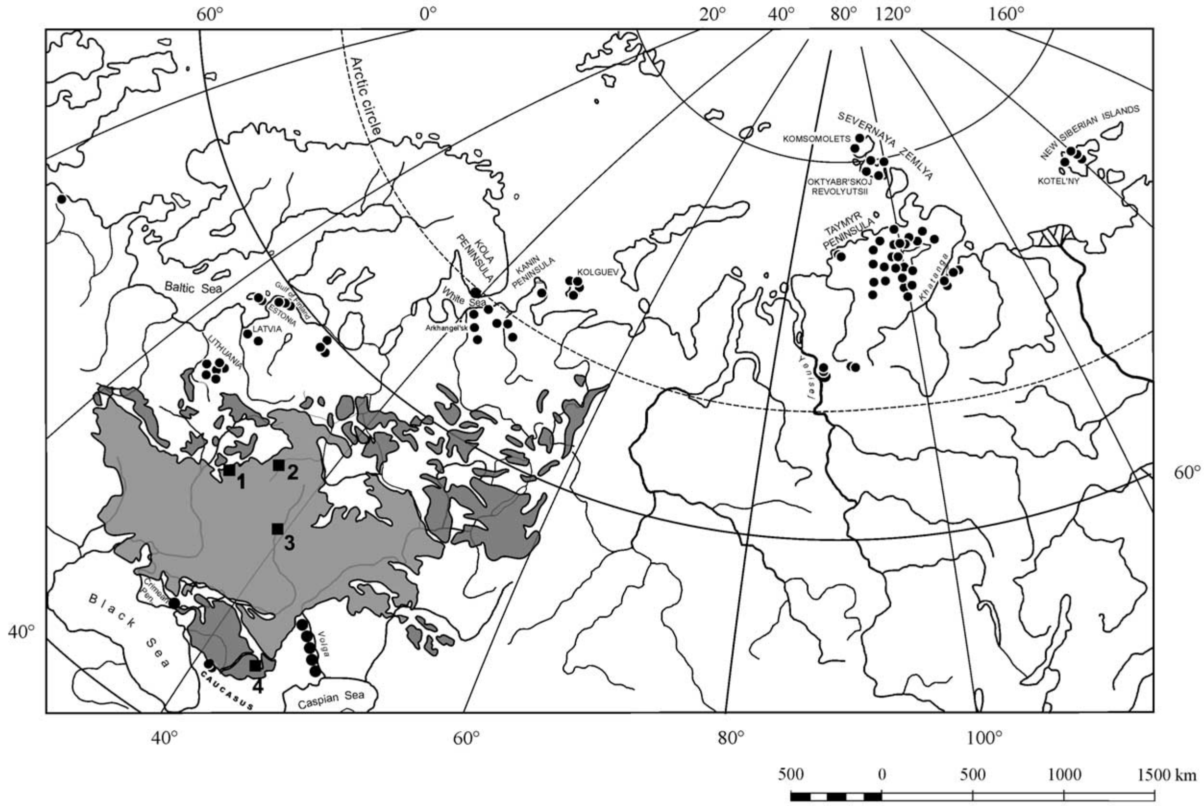

Fig. 1. Map showing the localities of collected shell samples (circles), studied loess-palaeosoil sections (squares: 1—Arapovichi, 2—Likhvin, 3—Strelitsa, 4—Otkaznoe), distribution of loesses on the east-European plain (gray area) and names mentioned in the text.

Dnieper Glaciation are considered on the example of the famous Likhvin reference section situated at approximately 54°07′ N and 36°18′ E on the left bank of the Oka River 1 km north of Chekalin town. A 50-m-thick sequence of loess, palaeosoils, tills and glacio-lacustrine, alluvial, lacustrine and bog sediments is exposed in a 2-km-long scarp extending along the Oka River or in nearby pits and boreholes.

The composition and structure of the middle Pleistocene sediments and the majority of palaeogeographic events of this time interval are most fully represented in this section; sediments of oxbow lake at a depth between 34 and 43 m are unanimously accepted by many investigators as the stratotype for the Likhvin *s. str.* (= Holsteinian *s. str.*) Interglacial on the east-European plain (Fig. 2).

A radiometrically based proxy record of the climate and sea-level changes over the past 600,000 years has been obtained on more than 230 mollusc shell samples. Shells were mostly taken from climate-controlled marine deposits along the continental margin of Northern Eurasia and ESR dated to produce an independent mollusc-based chronology for multiple marine transgressions (sea-level highstands) during which large epicontinental basins occupied vast areas of the Northern Eurasia coast. Some high sea-level evidence has also been obtained from sites in the Caspian and Black Sea basins. In addition, dating results on freshwater mollusc shell samples from interglacial lacustrine deposits in the southern Baltic and terrestrial mollusc fossils from a lower Palaeolithic culture-bearing deposit in the northern Caucasus have also been used. The ESR results presented here comprise the largest database for the late Quaternary warm-climate-related deposits of various origin from the Eurasian north.

Time intervals in the chronostratigraphic record where ESR age determinations are absent can, in turn,

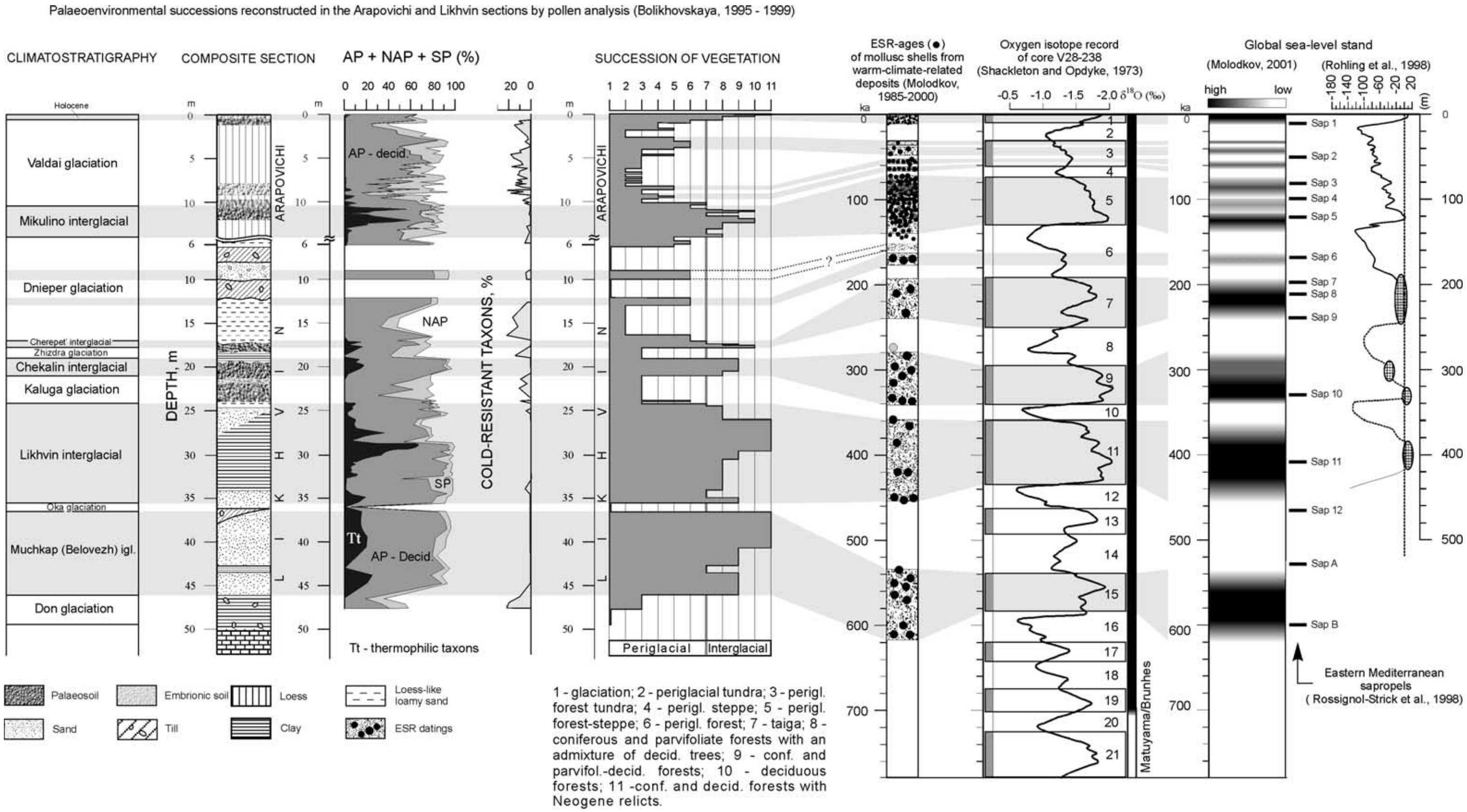

Fig. 2. Chronology and correlation of main palaeoenvironmental events over the last 600,000 years.

be interpreted as indicating relatively cold climate conditions or onset of glaciations in the northern Hemisphere accompanied by a general eustatic sea-level lowering and the sharp palaeoenvironmental changes on land.

We believe that the long vegetational record preserved in an almost continuous LPF has a high potential for showing marked response to climatic changes, and has the ability to be correlated with other records of palaeoclimate, such as marine sequence, ice cores and individual isotopic stages.

3. Methods

We used palynological analysis to reconstruct the evolution of terrestrial environments over the past 600,000 years. Climatic reconstruction was based on the indicator species in the pollen records, i.e., plants with known climatic tolerance.

At present, the palynological method holds the leading position among other palaeobotanic methods, primarily due to the fact that pollen and spores are the only palaeontologic objects which are found practically in all types of sediments including loess and soil formations. This allows a more complete picture of the palaeoenvironmental changes during Pleistocene glacial–interglacial sedimentation cycles and provides a basis for a relative chronology and valuable palaeoenvironmental information relating to the context of deposition.

Long-lasting and detailed palynologic studies on loess-palaeosoil formation showed (Bolikhovskaya, 1995) that loess-palaeosoil interchange in the sections cannot be considered as a direct indication of the corresponding climatic changes. Spore and pollen analyses give unequivocal evidence (see below, Strelitsa) that very often genetical horizons of palaeosoils correspond to a considerable or even to a maximal cooling of the climate and, vice versa, within loess horizons traces of interglacial warming can be revealed. Therefore, the palynology of loess-palaeosoils sequences can be considered as a highly reliable tool for climatic change reconstruction and correlation with the marine isotope record.

Although pollen floras of fossil soils and loesses are usually poorer and more fragmentary than palaeofloras of lacustrine and alluvial accumulations, thick sections of the loess-soil formation at the Arapovichi and Likhvin sites allowed us to reliably reconstruct a continuous succession of vegetation during the whole time interval targeted in this study.

Laboratory preparation of pollen samples from the Arapovichi and Likhvin sections was carried out by modified standard methods. More than 400 pollen samples were analysed for this study. Pollen was analysed at 5–10 to 20–40 cm intervals with additional samples to resolve important finer-scale climate trends. The palynological results are represented both by a total pollen diagram and by a succession of vegetation reflecting glacial–interglacial cycle variations over the last 600 ka providing a long-term proxy record of changing hemispherical (and perhaps global) ice volumes, and of glacio-isostatic oscillations of sea level.

Absolute chronology for the present study has been provided by the electron spin resonance (ESR) dating of subfossil mollusc shells.

The ESR-dating method is based on the direct measurement of the amount of radiation-induced paramagnetic centres (radiation damage), trapped in shell substance and created by the natural radiation resulting from radioactivity in the shell itself and from the environment (embedding matrix and cosmic). A shell sample will therefore have 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.

Since Ikeya and Ohmura (1981) first recognised the mollusc shell material as a possible dating object by electron spin resonance, the ESR method has been gradually improved and has become the major tool for mollusc-based chronostratigraphy for mid-Pleistocene to late Holocene (i.e., within a time range from about a million to a few hundred years BP, Molodkov, 1988, 1989b) shell-bearing deposits of various genesis beyond ^{14}C dating range (Molodkov, 1989a, 1993, 1995, 1996, 2001; Molodkov and Raukas, 1996; Molodkov et al., 1992, 1998; Bolshiyanov and Molodkov, 1999). Combined with the palynological analysis, ESR is becoming a promising approach for the study of sea-level changes, sedimentary dynamics, palaeoenvironmental reconstructions, correlation of Quaternary deposits over broad geographical areas, etc.

ESR-datings of all marine, freshwater and terrestrial mollusc shells (both structural forms of calcite and aragonite) were made at the Institute of Geology, Tallinn Technical University using an advanced version of the ESR-dating method (Molodkov, 1986, 1988, 1989b, 1993, 1996). The ESR measurements were carried out at room temperature using X-band ESR spectrometer (ERS-221) with a 100-kHz field modulation. At present, the dating method applied in this work usually provides overall analytical precision of up to about 10%, when taking into account the standard errors assumed for every parameter used in the age calculation.

More than 230 samples collected from shell-bearing deposits of various genesis produced mid–late Pleistocene ages clustered within warm-climate events providing the basis for timing the glacial–interglacial cycles (or periods of relatively high/low sea-level stands). Comparison of marine and land-based ESR-chronostratigraphical sequences with climatic changes documented by terrestrial palynological records offer one of the best prospects for stratigraphic subdivision and long-distance correlation between late Quaternary marine and terrestrial sequences.

The chronological framework for mid–late Pleistocene warm-climate-related events as well as the pollen-based vegetational signals is compared with other sources of evidence of late Quaternary palaeoenvironments.

4. Palyno-chronostratigraphical synthesis

The structure and composition of Quaternary deposits and majority of middle Pleistocene palaeogeographic events within the limits of the Oka (= Elster) and Dnieper (= Saale) Glaciations is most completely represented in the Likhvin section exposing a 50-m-thick sequence of loess, palaeosoil, tills and glaciolacustrine, alluvial, lake and bog formations. Late Pleistocene time is most completely represented in the Arapovichi section.

A comprehensive layer-by-layer spore-and-pollen profile of the whole sequence represented in two sections permitted its detailed subdivision and made possible the reconstructing of the diversified environmental and climatic events in the centre of the east-European plain (upper Oka River region). The sequence spans the period from the Don (= Glacial C, Cromerian complex) Glaciation to the Holocene, i.e., six glacial epochs (Don, Oka, Kaluga, Zhizdra, Dnieper, Valdai) and six interglacials (Muchkap, Likhvin, Chekalin, Cherepet', Mikulino, and the Holocene); they are presented either as complete climatic rhythms of glacial and interglacial rank, or by a considerable portion of climatic–phytocoenotic phases constituents of the ryhthm (Bolikhovskaya, 1995).

Severe environments of the periglacial tundras with the predominance of cryophytes (*Betula nana*, *B. fruticosa*, *Alnaster fruticosus*, *Dryas octapetala*, *Selaginella selaginoides*, etc.) were characteristic of the time when the oldest Don glaciolacustrine sediments were accumulated in the Likhvin section. This glacial stage is most likely correlated with marine isotope stage (MIS) 16. Severe environments were also typical of the Dnieper and Oka Glaciations, with the ice sheets extending into the upper Oka River valley.

ESR dates of the deposits corresponding to the earliest evidence of a global warming of climate were determined on various shell samples including the terrestrial shells collected from the oldest (610–565 ka, Molodkov, 2001) culture-bearing layer (7a) of an ancient multi-level lower Palaeolithic cave-site (Treugol'naya Cave) situated at approximately 43°54′ N and 41°12′ E, at an elevation of 1510 m above sea level on the northern slope of the greater Caucasus, on marine shells from fauna-bearing deposits in the Eurasian arctic on the Severnaya Zemlya (Komsomolets is., Section K31, 2.3 m a.s.l., 555.0 ka; Molodkov et al., 1992) and New Siberian Islands Archipelago (Kotel'ny is., Section 7, 15.5 m a.s.l., 550.0 ka; ibid.), and also on the marine shells from the Taymyr Peninsula (Section 35012, 50 m a.s.l., 535.5 ka; Bolshiyanov and Molodkov, 1999). In all likelihood, this warm epoch corresponds to the time of a very humid and warm Muchkap (? = Voigtstedt, Cromerian complex) interglacial. This age range (610.0 to 535.5 ka) corresponds most likely to MIS 15 in the orbitally tuned SPECMAP marine isotopic record.

In the Likhvin section describing the history of Pleistocene landscapes of inland eastern-European area, the initial and final phases of this interglacial event are not established. Completely interglacial successions of vegetation are characterised by the Strelitsa reference section (51°37′ N and 39°01′ E) located in the upper Don River region and Otkaznoe reference sections (44°19′ N and 43°51′ E) (Fig. 3) situated in the middle Kuma River region. Here a continuous, detailed record of the vegetation history

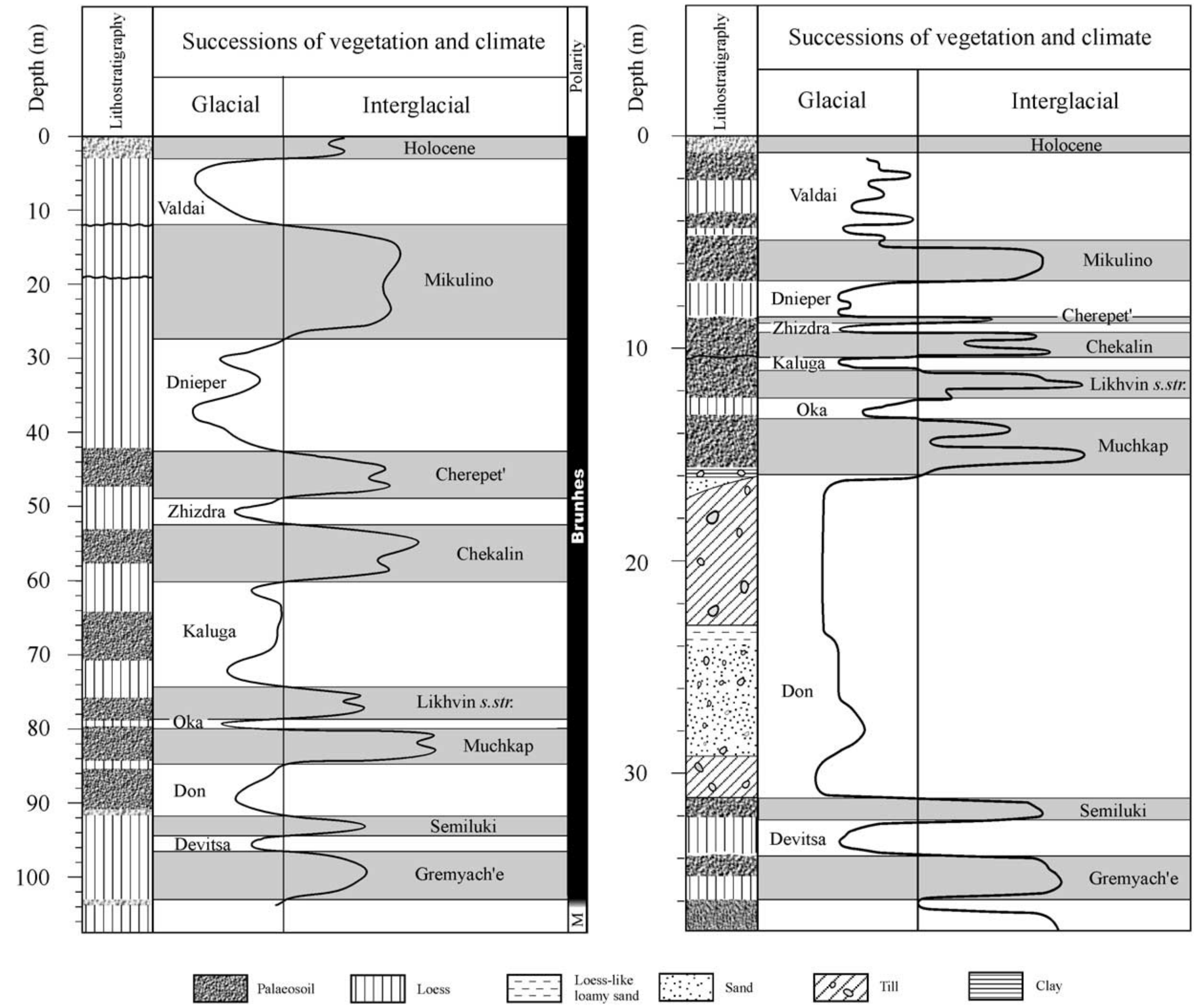

Fig. 3. Loess-palaeosoil formation lithology at Otkaznoe (left) and Strelitsa (right) sites with climatostratigraphic subdivision obtained by pollen data (after Bolikhovskaya, 1995).

in the upper Oka area during the Muchkap Interglacial is presented by the succession in the evolution of the predominant coniferous and coniferous–deciduous forest vegetation (Bolikhovskaya, 1995):

(1a) pine–spruce and elm–lime–hornbeam forests;
(1b) elm–oak–hornbeam and pine–spruce forests (this phase corresponded to the thermoxerotic maximum of the Muchkap Interglacial);
(2) spruce forests of endothermal cooling;
(3) pine–birch and spruce–hornbeam–elm–oak forests;
(4a) spruce and elm–oak–hornbeam forests;
(4b) spruce–elm–oak–linden–hornbeam forests with an admixture of *Tsuga*, *Pinus s. Cembra*, *P. s. Strobus*, *Abies*, *Larix*, *Fagus*, *Ilex*, etc., and predominance in the herb layer of ferns *Polypodiaceae*, *Osmunda cinnamomea*, *O. claytoniana* and *O. regalis* (this phase corresponded to thermohygrotic maximum of Muchkap Interglacial);
(4c) spruce–hornbeam–elm–linden and birch–pine forests.

The next time interval has been established from about 455 to 360 ka. The major part of the ESR age determinations were obtained on the shells from transgressive marine deposits of the Polar basin seas (Kotel'ny is., Section 6, about 6 m a.s.l.; Molodkov et al., 1992) and on the comprehensively studied lake-and-bog deposits of Būtėnai Interglacial in S. Lithuania (Gailiūnaii section, 78 m a.s.l.; Gaigalas and Molodkov, 1996). Two datings (420 and 365 ka) were obtained on the next culture-bearing layer (5B) in the Treugol'naya Cave (Molodkov, 2001). A complex of stratotypical Likhvin *s. str.* deposits with the pollen of most thermophilous flora represents this time interval in the Likhvin section.

During the optimum of the Likhvin *s. str.* Interglacial at first oak–hornbeam forests dominated, later they were replaced by spruce–fir and hornbeam–beech–oak forests. Characteristic taxons of the Likhvin flora are representatives of the European, Mediterranean, east Asian, and North American floras, such as *Larix* sp., *Abies alba*, *Picea s. Omorica*, *P. excelsa*, *Pinus s. Cembra*, *P. s. Strobus*, *P. sylvestris*, *Betula s. Costatae*, *B. pendula*, *B. pubescens*, *Juglans regia*, *Carpinus betulus*, *Fagus sylvatica*, *Quercus petraea*, *Q. robur*, *Q. pubescens*, *Zelkova* sp., *Celtis* sp., *Ulmus propinqua*, *U. laevis*, *U. campestris*, *Fraxinus* sp., *Tilia platyphyllos*, *T. tomentosa*, *T. cordata*, *Acer* sp., *Corylus colurna*, *C. avellana*, *Alnus glutinosa*, *A. incana*, *Ligustrina amurensis*, *Rhododendron* sp., *Vitis* sp., *Myrica* sp., *O. cinnamomea*, *Salvinia natans* and others, including species indicators *Tsuga canadensis*, *Taxus baccata*, *Pterocarya fraxinifolia*, *J. cinerea*, *Castanea sativa*, *Ilex aquifolium*, *F. orientalis*, *Q. castaneifolia*, *Buxus* sp., *O. claytoniana*, etc.

The studied deposits record here the warmest interglacial for the past half-million years that may indicate a lower continental ice volume that must have been accompanied by a marked increase in the glacio-eustatic sea level.

Evidence for such sea-level rise is available from many parts of the world. Those obtained on elevated marine terraces in the tectonically stable (or slowly subsiding) localities indicate that during MIS 11 the ocean stood far above its present level. For example, the occurrence of marine terraces dated at about 420 ka (Hearty et al., 1999) were recorded at ca. +2, +7 and more than 20 m above mean sea level on the archipelagos of Bermuda and the Bahamas (Kindler and Hearty, 2000). At that, a total increase in ocean volume of 20 m of MIS 11 can most likely be associated only with the melting of the world's major ice sheets near the end of that period (Hearty, 1999).

Our pollen data from the Likhvin section provide strong evidence of warmer than present climatic conditions in the centre of the east-European plain which seems to coincide with the trend of sea-level rise recorded on the elevated marine terraces. Succession of vegetation clearly demonstrates gradual warming of the climate during the Likhvin Interglacial. The period of optimum conditions has also been achieved here in the second half of the stage. These climate estimates appear to agree well with suggestions in the literature (e.g., Oppo et al., 1990; Burckle, 1993; Howard, 1997; Scherer et al., 1998; Kindler and Hearty, 2000) that Stage 11 was the warmest interglacial for the past half-million years when ocean volume may have been considerably larger than today and that the end of this exceptionally long period was marked by a considerable (up to +20 m) sea-level rise.

From this isotopic stage and upward, the warm-climate-related signals we recognised show a regular correlation with the time of formation of thick sapropels in the eastern Mediterranean (Sap11–Sap1, Rossignol-Strick et al., 1998) and with the recently published data (Rohling et al., 1998) on sea-level oscillations over the past 500,000 years.

During the Kaluga (=Fuhne/Mehlbeck) cool interval, in the environments of periglacial forest-tundra, lacustrine and fluvial sediments were formed, and the overlying soil typified in the upper part by post-cryogenic structure.

According to our data, the next palaeoclimatic signal of interglacial character observed in the various natural environments falls into the time interval between about 340 and 280 ka (stage 9, initial part of stage 8). The younger horizons of lake-and-bog deposits ascribed to the second stage of the Būtėnai (=Domniz/Wacken) Interglacial in the southeast Baltic (Lithuania, Neravai and Gailiūnai sections; Gaigalas and Molodkov, 1996, 1997), marine deposits on the Taymyr Peninsula (Sections 606, 921, 35066; Bolshiyanov and Molodkov, 1999) and the Severnaya Zemlya Archipelago (Oktyabr'skoi Revolyutsii is., Section 71; Molodkov, 1995; Molodkov et al., 1987, 1992) are dated to that time.

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. Its peak of heat and moisture supply was marked by the dominance of spruce/broad-leaved forests. Characteristic floristic elements of this thermochron are *Picea s. Omorica*, *P. excelsa*, *Pinus s.g. Cembra*, *P. sibirica*, *P. sylvestris*, *Betula pendula*, *B. pubescens*, *Carpinus betulus*, *Quercus robur*, *Tilia cordata*, *T. platyphyllos*, *T. tomentosa*, *Acer* sp., *Ulmus laevis*, *U. glabra*, *U. campestris*, etc.

The Zhizdra (= Saale *s. str.*/Drenthe) cooling is correlated with most of MIS 8. It is fixed in the overlying lake-and-bog deposits of the Likhvin section. The periglacial forest-tundra flora, which dominated at that time, was close to that of the previous Kaluga cooling represented by *Larix* sp., *Pinus sylvestris*, *Betula pubescens*, *B. pendula*, *B. fruticosa*, *B. nana*, *Alnaster fruticosus*, *Dryas octapetala*, *Selaginella sibirica*, *Lycopodium appressum*, *L. pungens*, *Artemisia s.g. Seriphidium*, *Thalictrum* sp., etc., but with less diversified cryophytes.

The significant warming in a rank of interglacial and the corresponding high sea-level stand are fixed by ESR data in the time interval about 220 ka (MIS 7) on the raised marine deposits predating the Mikulinian (= Eemian). Judging from the palynological evidence from the Likhvin section the most probable analogue of this event in the central part of the east-European plain is the Cherepet' (= Drenthe–Warthe) Interglacial during which bog gleyed soil was developed; its optimum phases are marked by hornbeam–oak and coniferous/broad-leaved forests with *Pinus s. Cembra*, *P. sylvestris*, *B. pendula*, *Betula pubescens*, *Carpinus betulus*, *C. cf. orientalis*, *Ostrya* sp., *Quercus robur*, *Q. cf. pubescens*, *Tilia cordata*, *T. tomentosa*, *Ulmus laevis*, *U. campestris*, etc., among characteristic taxa.

During the Dnieper s. lato stage (MIS 6), the following series were deposited: (a) early Dnieper glaciofluvial silts characterised by lemming fauna—*Dicrostonyx cf. simplicior*, *Lemmus sibiricus*, etc., and palynospectra mostly of tundra-steppe type; (b) three-layered sequence of Dnieper and Moscow stadials and the Dnieper–Moscow interstadial deposits. The landscapes of the latter were dominated by open woodlands of pine, Alnaster and dwarf birch; and (c) the late Moscow loess-like sandy loam. An early Dnieper interstadial has been identified in the upper part of silts underlying the till; periglacial open woodlands with pine prevailed at that time. A late Moscow interstadial warming (established in ferruginous sands above the tills) is represented by a phase of periglacial open birch woodlands with *Betula fruticosa* in the shrub layer and a cover of herbs and dwarf shrubs on soil (with *Arctous alpina*, *Cannabis* sp., *Artemisia s.g. Seriphidium*, *Thalictrum cf. alpinum*, etc.). Most likely, this warming corresponds to a climatic amelioration at the end of MIS 6 that further was interrupted by a return to a Younger Dryas-like cold event. This warming would be the reason, as indicated also by ESR-evidence for some elevated marine deposits, that the sea-level rise may have started in the northern Eurasia already prior to the marine isotope stage 5.

Consideration and correlation of the main Pleistocene palaeoclimatic events we will complete by the nearest to the current interglacial and most investigated time interval corresponding to isotopic stage 5.

Up to the middle of the 1960s, many Quaternary scientists correlated this time interval with the Mikulinian (= Eemian) Interglacial including seven pollen assemblage zones (c–i after Jessen and Milthers, 1928, M_2–M_8 after Grichuk, 1961) with the duration of about 60 ka for this period (see e.g., Woillard, 1978; Grichuk, 1982). Later on, Shackleton (1969) first suggested that the NW European Eemian Interglacial was represented in the isotope record by substage 5e. Mangerud et al., 1979 introduced a new chronostratigraphical framework of NW Europe correlating continental stratigraphy with the deep-sea oxygen isotope stages. The proposed chronology implies that the last interglacial existed during substage 5e only and was followed by the two Weichselian glacier advances during substages 5d and 5b, and by two warm interstadials during substages 5c, ca. 100 ka and 5a, ca. 80 ka. Correspondingly, reassessment of the time interval of the development of interglacial flora, c–i (M_2–M_8), also occurred. Many researchers believe, that during the coldest intervals, 5d and 5b, significant glacier advances occurred, often on hundreds of kilometres from glaciation centres. According to the deep-sea oxygen isotope record, there was at least twofold sea-level lowering of around 55 m during stage 5 (Shackleton, 1987). The huge territories submerged by the Eemian Sea in western Europe and the Boreal Sea in Northern Eurasia (Lavrova, 1961), drained, that should have affected the marine sedimentation on the coastal areas.

However, recent ESR-chronostratigraphical investigations and the ages obtained on subfossil mollusc shells, mostly from marine deposits on the Taymyr Peninsula, where numerous dated units (Table 1) lie at altitudes of 84 to 2 m a.s.l. (Bolshiyanov and Molodkov, 1999; Molodkov et al., 1987, 1992; Möller et al., 1999), the eastern part of the White Sea coast (97 to 5 m a.s.l.; Molodkov, 1988; Molodkov and Raukas, 1988, 1998), and lacustrine fauna-bearing deposits of southern Lithuania (Jonionys, 72 m a.s.l., Valakampiai, 89.5 m a.s.l., and Netiesos, ca. 5 m a.s.l.; Molodkov and Gaigalas, 1994; Gaigalas and Molodkov, 1996, 1997) sites, indicate that the duration of the late Pleistocene marine transgression and the period of interglacial lacustrine sedimentation most likely correspond here to the time interval from approximately 145 to 70 ka comparable with the whole of MIS 5 rather than the period of optimum conditions in oxygen isotope substage 5e (Eemian, *s. str.*).

Besides, a set of ESR-datings (120 to 70 ka) on marine units from the eastern coast of the White Sea basin (Zaton section, Arkhangel'sk District; Molodkov, 1988; Molodkov and Raukas, 1988, 1998) that can be correlated with the greater part of the oxygen isotope stage 5, indicates that low sea-level stands, that may be inferred from the deep-sea oxygen isotope record, did not probably cause marked interruption of marine sedimentation in this area during stage 5 although, according to diatom analysis data and field observations, shoreline fluctuations apparently took place during the Boreal transgression (Devyatova, 1982). This observation agrees with an increasing number of reports about significantly higher sea-level stands during substages 5c and 5a. For instance, with the data from the tectonically stable northern Bahamas, Bermuda, and the eastern North America, indicating sea-levels near to, or even higher than present at ca. 105 and 80 ka (Vacher and Hearty, 1989; Muhs, 1992).

The results of detailed palynological analysis of the loess-palaeosoil and other continental deposits formed in post-Dnieper (post-Moscovian) time do not contradict these implications. In the central areas of east Europe, now located within the limits of mixed forest subzone, the period of the highest humidity in the late Pleistocene was the interval from the beginning of the Mikulinian Interglacial up to the end of the Ketrosy (first early Valdai/Weichselian) Interstadial. The complex course of the Mikulinian vegetation cover changes, clear separation of the warm and cold stages within this interglacial climatic rhythm obviously correlating with those in the other palynologically well-studied sections (e.g., La Grande Pile (France), Woillard, 1978; Kukla et al., 1997) allows to suggest, that the Mikulinian Interglacial was long in northern Eurasia.

As an illustration to the above, we have included the materials of the Arapovichi section located in the northeast of the Dnieper lowland in a zone of expansion of the Dnieper ice sheet. The Mikulinian Interglacial is represented here by sands and loams overlying till together with superposed Salyn lesseve soil and the lowermost part of sod-chernozem Krutitsk soil. The Ketrosy Interstadial is fixed in the middle part of the section. During the Mikulinian in the conditions of high humidity and heat supply, the forests predominated in the surrounding area.

Eleven phases in the evolution of the forest vegetation have been established for this thermochron:

(1) pine–birch forests with an admixture of oak, hornbeam, lime and elm;
(2) pine–birch forests with an admixture of spruce and undergrowth represented by *Betula fruticosa* (the first endothermal cooling of the Mikulinian Interglacial);
(3) birch forests with the participation of *Carpinus betulus*, *Quercus robur*, *Q. petraea*, *Tilia cordata*, *T. tomentosa*, *Corylus colurna*, *Ulmus laevis*, etc.;
(4) pine–spruce forests with oak, hornbeam, elm, *C. colurna*, etc.;
(5) hornbeam–oak forests (this phase corresponded to the thermoxerotic maximum of the Mikulino Interglacial);
(6) birch–cedar–spruce and hornbeam–oak forests with an admixture of elm and lime;
(7) pine forests with an admixture of birch and ernik (the second endothermal cooling);
(8) birch–spruce–cedar and hornbeam–oak forests with an admixture of beech, lime, elm, *C. colurna*, *Celtis*, etc.;
(9) oak–hornbeam forests with hazel (this phase corresponded to the thermohygrotic maximum of the Mikulinian Interglacial);
(10) birch–pine forests with oak, hornbeam, lime, and elm;
(11) cedar–spruce and birch forests.

Table 1
ESR-ages of subfossil mollusc shells from warm-climate-related deposits correlated with MIS 5

Lab. no.	Locality/site	Altitude (m)	ESR-age (ka)
134-051	Section F1, Zhokhova is.	20.0	70.0 ± 9.0
254-057	Ledyanaya 1c, Taymyr Pen.	42.0	70.0 ± 25.0
187-095	Loc. 3, Arkhangel'sk District	ca. 5.0	71.5 ± 6.5
277-059	Zajachja River 3, Taymyr Pen.	53.2	71.5 ± 6.1
271-079	Ledyanaya, Taymyr Pen.	30.7	71.5 ± 6.9
237-086	Section III-2, Taymyr Pen.	75.0	72.2 ± 6.9
269-079	Ledyanaya, Taymyr Pen.	25.5	72.3 ± 5.7
173-095	Borehole 34, Kanin Pen.	74.8	72.9 ± 7.4
177-095	Borehole 625, Arkhangel'sk District	97.5	75.6 ± 7.8
117-105	Tsagan–Aman, Lower Volga	7.0[a]	75.6 ± 6.3
145-051	Section 7048, Taymyr	ca. 10.0	76.0 ± 6.0
270-079	Ledyanaya, Taymyr Pen.	30.5	76.4 ± 7.3
178-095a	Borehole 641-A, Arkhangel'sk District	69.0	77.2 ± 7.8
279-059	Severnaya River 2, Taymyr Pen.	35.7	77.8 ± 6.1
253-057	Ledyanaya 1b, Taymyr Pen.	30.4	79.3 ± 7.8
305-060	Serebryanka River 1, Taymyr Pen.	76.0	79.5 ± 6.0
037-047	Bychje, Arkhangel'sk District	ca. 20.0	80.0 ± 8.0
146-051	Section 7048, Taymyr Pen.	ca. 10.0	80.0 ± 6.0
272-059	Oleni River 1, Taymyr Pen.	55.2	80.3 ± 5.8
252-057	Ledyanaya 1b, Taymyr Pen.	30.4	81.4 ± 8.0
026-015	Zaton, Arkhangel'sk District	ca. 15.5	82.0 ± 6.0
036-047	Bychje, Arkhangel'sk District	ca. 20.0	82.0 ± 7.0
040-057	Yëlkino, Arkhangel'sk District	ca. 58.0	82.0 ± 7.0
041-057	Yëlkino, Arkhangel'sk District	ca. 57.5	82.0 ± 11.0
273-059	Oleni River 1, Taymyr Pen.	53.4	82.2 ± 5.7
042-057	Yëlkino, Arkhangel'sk District	ca. 57.0	84.0 ± 8.0
068-097	Section 27, Komsomolets is., Severnaya Zemlya	7.2	84.0 ± 6.0
126-109	Section 644, Taymyr Pen.	ca. 2.0	85.0 ± 15.0
038-047	Bychje, Arkhangel'sk District	ca. 19.0	86.0 ± 8.0
205-D1	Daugmales Tomēni, Central Latvia	7.0[a]	86.0 ± 6.8
257-107	Lenivaya River, Taymyr Pen.	ca. 5.0	86.1 ± 8.5
288-060	Angelica River 1, Taymyr Pen.	65.5	86.3 ± 6.2
289-060	Angelica River 1, Taymyr Pen.	62.3	86.4 ± 6.7
179-095a	Borehole 641-A, Arkhangel'sk District	69.0	86.7 ± 8.8
181-095	Borehole 641-A, Arkhangel'sk District	48.0	87.2 ± 8.4
174-095a	Borehole 34, Kanin Pen.	74.8	87.8 ± 8.5
223-095	Netiesos, South Lithuania	2.7[a]	88.0 ± 8.5
251-057	Ledyanaya 1a, Taymyr Pen.	24.7	88.0 ± 8.6
205-L1	Ličūpe, Central Latvia	2.0[a]	88.5 ± 7.3
282-079	Chernye Yary River, Taymyr Pen.	21.9	89.2 ± 6.3
029-015	Zaton, Arkhangel'sk District	ca. 15.0	90.0 ± 8.0
030-015	Zaton, Arkhangel'sk District	ca. 15.0	90.0 ± 8.0
039-057	Bychje, Arkhangel'sk District	ca. 19.0	90.0 ± 8.0
213-065	Section 910, Taymyr Pen.	ca. 30.0	90.3 ± 8.8
276-059	Zajachja River 2, Taymyr Pen.	52.2	90.3 ± 17.8
221-095	Netiesos, South Lithuania	6.8[a]	90.5 ± 8.8
142-051	Section 6636, Taymyr Pen.	ca. 55.0	91.0 ± 8.0
283-079	Chernye Yary River, Taymyr Pen.	21.9	91.1 ± 6.3
024-015	Zaton, Arkhangel'sk District	ca. 16.0	92.0 ± 6.0
025-015	Zaton, Arkhangel'sk District	ca. 15.5	92.0 ± 7.0
028-015	Zaton, Arkhangel'sk District	ca. 15.0	92.0 ± 9.0

(continued on next page)

Table 1 (*continued*)

Lab. no.	Locality/site	Altitude (m)	ESR-age (ka)
069-097	Section 27, Komsomolets is., Severnaya Zemlya	ca. 7.5	92.0 ± 11.0
180-095a	Borehole 641-A, Arkhangel'sk District	69.0	92.0 ± 9.2
275-069	Zajachja River 1, Taymyr Pen.	52.2	92.8 ± 6.8
112-105a	Lenino, Lower Volga	5.0[a]	93.0 ± 8.0
278-059	Severnaya River 2, Taymyr Pen.	35.1	93.0 ± 8.7
306-060	Serebryanka River 2, Taymyr Pen.	76.7	93.0 ± 6.6
281-059	Severnaya River 2, Taymyr Pen.	44.3	93.1 ± 8.1
141-051	Section 6636, Taymyr Pen.	ca. 55.0	94.0 ± 9.0
057-116	Enotaevka, Lower Volga	ca. 14.0[a]	94.5 ± 14.3
027-015	Zaton, Arkhangel'sk District	ca. 14.5	95.0 ± 15.0
231-086	Ličūpe, Central Latvia	1.5[a]	95.7 ± 8.2
070-097	Section 50, Okt. Rev. is., Severnaya Zemlya	10.1	96.0 ± 7.0
239-086	Section BT-90/95, Taymyr Pen.	ca. 10.0	96.0 ± 9.1
175-095	Borehole 34, Kanin Pen.	74.8	96.2 ± 9.1
218-056	Meetkerke, Belgium	ca. − 1.5	97.1 ± 8.9
230-086	Ličūpe, Central Latvia	1.5[a]	97.8 ± 8.2
227-095	Gailiūnai, South Lithuania	1.2[a]	99.0 ± 28.0
212-065	Section 910, Taymyr Pen.	ca. 30.0	99.5 ± 9.8
136-051	Section 30, Kolguev is.	28.3	100.0 ± 10.0
222-095	Netiesos, South Lithuania	2.7[a]	100.3 ± 9.8
197-083	Jonionys, South Lithuania	ca. 72.0	101.0 ± 11.0
055-116	Kopanovka 2, Lower Volga	ca. 11.0[a]	103.0 ± 25.6
217-056	Meetkerke, Belgium	ca. − 1.5	104.4 ± 9.5
018-124	Section 101, Okt. Rev. is., Severnaya Zemlya	46.5	105.0 ± 11.0
032-015	Zaton, Arkhangel'sk District	ca. 14.5	105.0 ± 10.0
115-105a	Seroglazovka, Lower Volga	7.3[a]	105.0 ± 9.3
205-D2	Daugmales Tomēni, Central Latvia	4.6[a]	105.0 ± 9.2
121-105a	Kopanovka, Lower Volga	4.0[a]	105.2 ± 9.0
058-116	Enotaevka, Lower Volga	ca. 14.0[a]	105.5 ± 15.7
124-105a	Kopanovka, Lower Volga	1.5[a]	108.0 ± 10.0
139-051	Section 6636, Taymyr Pen.	ca. 49.0	108.0 ± 8.0
123-105	Kopanovka, Lower Volga	4.2[a]	108.1 ± 9.2
056-066	Kopanovka 2, Lower Volga	ca. 2.5[a]	109.0 ± 10.0
280-059	Severnaya River 2, Taymyr Pen.	40.2	109.5 ± 11.6
259-100	Valakampiai, Southeastern Lithuania	ca. 89.5	110.0 ± 12.1
132-051	Section 30, Kolguev is.	20.6	111.0 ± 9.0
211-065	Section 910, Taymyr Pen.	ca. 30.0	111.0 ± 11.0
303-060	Kratnaya River 3, Taymyr Pen.	33.8	111.1 ± 7.7
127-109	Section 606, Khatanga, Taymyr Pen.	ca. 22.0	112.0 ± 20.0
140-051	Section 6636, Taymyr Pen.	ca. 49.0	112.0 ± 18.0
125-105	Kopanovka, Lower Volga	1.5[a]	112.5 ± 10.1
225-095	Netiesos, Southern Lithuania	6.8[a]	112.5 ± 10.8
138-051	Section 6636, Taymyr Pen.	ca. 49.0	116.0 ± 11.0
233-086	Section 35066, Taymyr Pen.	ca. 34.0	116.0 ± 11.1
260-100	Valakampiai, Southeastern Lithuania	ca. 89.5	116.0 ± 10.8
101-079	Gailiūnai, Southern Lithuania	79.0	118.0 ± 15.0
198-083	Jonionys, Southern Lithuania	ca. 72.0	118.0 ± 12.0
301-060	Kratnaya River 2, Taymyr Pen.	38.1	118.2 ± 8.3
2978-060	Kratnaya River 1, Taymyr Pen.	41.9	118.4 ± 7.1
022-124	Section 101, Okt. Rev. is., Severnaya Zemlya	46.5	120.0 ± 13.0
031-015	Zaton, Arkhangel'sk District	ca. 13.5	120.0 ± 8.0
135-051	Section 30, Kolguev is.	12.6	120.0 ± 8.0
195-062	Ubojnaya, Yenisej River	18.5[a]	120.0 ± 10.0
238-086	Section BT-70/95, Taymyr Pen.	ca. 84.0	120.0 ± 11.1

Table 1 (*continued*)

Lab. no.	Locality/site	Altitude (m)	ESR-age (ka)
304-060	Kratnaya River 3, Taymyr Pen.	32.3	123.6 ± 9.0
193-062	Ubojnaya, Yenisej River	18.5[a]	124.0 ± 12.0
267-129	Chapoma TH-29, Kola Pen.	9.0	126.2 ± 10.1
302-060	Kratnaya River 2, Taymyr Pen.	37.2	126.8 ± 9.0
194-062	Ubojnaya, Yenisej River	18.5[a]	130.0 ± 14.0
268-010	Chapoma TH-29, Kola Pen.	9.0	131.8 ± 11.2
274-059	Zajachja River 1, Taymyr Pen.	51.4	132.0 ± 14.6
053-057	Section 1, Chokrak Lake, Crimean Pen.	ca. 2.0[a]	135.0 ± 13.0
245-087	Mga, Leningrad District	ca. 2.5	135.3 ± 12.5
192-062	Ubojnaya, Yenisej River	18.5[a]	136.0 ± 11.0
119-105a	Kopanovka, Lower Volga	0.8[a]	136.9 ± 13.3
246-087	Kelkolovo, Leningrad District	30.0	137.2 ± 15.6
247-087	Mga, Leningrad District	ca. 2.5	137.6 ± 12.7
143-051	Section 606, Khatanga, Taymyr Pen.	ca. 19.0	140.0 ± 11.0
299-060	Kratnaya River 1, Taymyr Pen.	41.8	141.9 ± 10.2
120-105	Kopanovka, Lower Volga	0.5[a]	142.5 ± 14.2
291-060	Angelica River 4, Taymyr Pen.	58.3	143.4 ± 10.8
295-060	Bolotny Stream, Taymyr Pen.	46.5	145.1 ± 10.2

[a] Altitude above river water level.

The most typical taxa of the Mikulino pollen flora in the Desna loess region are *Picea s. Omorica*, *P. s. Strobus*, *P. s. Cembra*, *Carpinus betulus*, *Fagus sylvatica*, *Quercus robur*, *Q. petraea*, *Q. pubescens*, *Tilia platyphyllos*, *T. tomentosa*, *T. cordata*, *Ulmus glabra*, *U. laevis*, *Celtis* sp., *Corylus colurna*, *C. avellana*, *Humulus lupulus*, *Lonicera*, etc. (Bolikhovskaya, 1995).

As is seen, even the two intra-Mikulinian cooling events, corresponding most likely to isotope substages 5b and 5d, were characterized by rather humid climatic conditions.

Thus, our results, as a whole, support the hypothesis that implies longer (up to 70,000 years) duration of the first late Pleistocene marine transgression and, in all probability, of the last interglacial. Most likely, this late Pleistocene transgression was an unbroken or, rather, an oscillating geological event reflected in the deposits over the vast areas of Eurasia.

Our observations coincide also with the recent data of multiparameter study from the western Hemisphere. The data indicate that full interglacial conditions there span a time interval comparable with the entire warm marine isotope stage 5 (Bischoff et al., 1997a,b) or that the obvious interglacial climate conditions occurred late in MIS 5 even in the eastern Canadian arctic (Miller et al., 1999).

It is also noteworthy that some ESR-datings and palaeoclimatic records from the Arapovichi and other sites in the different parts of the world (see e.g., Seidenkrantz et al., 1996 for details) suggest climatic amelioration just below the MIS 6/5e boundary that was interrupted by a return to a cold climate. It can be interpreted as an indication of a global warming and sea-level rise at the end of isotope stage 6, ca. 140 ka, which is much older than the insolation maximum in the northern Hemisphere ca. 128 ka (Berger, 1978). This observation together with other independent records on the initial warming preceding the isotope stage 6/5e boundary (e.g., Lorius et al., 1985; Henderson and Slowey, 2000; Winograd et al., 1997) may be regarded as evidence supporting the much earlier start of atmospheric warming than suggested by the SPECMAP chronology (Keigwin et al., 1994).

A more ancient climatic amelioration causing melting of penultimate glaciation (stage 6) ice sheets and, as a result, some rise in the ocean level has been recognised in the end of the first half of isotopic stage 6. Three datings on elevated marine horizons of Eurasian high-arctic regions (Kotel'ny is., Section 29; Khatanga River, Novorybnoe site; Kolguev is., Section 26) indicate that this warming had taken place about 170,000 years ago (Molodkov et al., 1992).

This interval appears to correlate with our pollen event of interstadial rank reflecting the transition from the dominant tundra-steppes to the expansion of pine open woodlands fixed by pollen spectra of Likhvin key section within Dnieper s. lato bed.

Valdai (Weichselian) subaerial and subaqueous deposits of the east-European plain formed during the greater part of the complex, with respect to climatic pattern, Valdai time is correlated with isotopic stages 4 to 2.

5. Conclusions

An integrated approach based on two independent methods and sources of climato-stratigraphical information allowed us to establish close interrelations of the atmosphere–ocean–land system during the late Quaternary. Despite environmental differences, our terrestrial and marine records display close similarity over the last 600 ka and occurrence of periodic pelaeoenvironmental variations that seem to be broadly synchronous with global climatic/sea-level changes. As the direct timing of climatic features is seldom possible in the terrestrial record for this time range, our numerous dating results on warm-climate/high sea-level related marine and lacustrine deposits helped us to establish an independent chronology for continental-scale palaeoenvironmental events and create an ESR-dated record of climate change encompassing isotope stages 15 to 1. The results obtained in this work allow the following conclusions to be drawn.

(1) Climate in Northern Eurasia experienced a pattern of periodic variations over the last 600,000 years which was closely tied to global ice and world ocean volume variations. The formation of the most ancient interglacial horizons studied and the corresponding eustatic sea-level elevation of the world ocean occurred in the time interval between about 610,000 and 535,000 years ago and are tentatively correlated by us to oxygen isotope stage 15 of the deep-sea record.

(2) The comparison of oxygen isotope curves with the ESR-chronostratigraphic levels and the climate-related signals of pollen spectra recognised by us from loess-palaeosoil sequences demonstrates good agreement with the 11 upper stages (11 to 1). Particular point of disagreement concerns loss of correlation with the more ancient isotopic stage 13. It requires careful consideration in further studies on the basis of independent chronological and palynostratigraphic criteria.

(3) The long Oka–Dnieper (= Elster–Warthe) interval integrated into the compound Likhvin upper subhorizon, consists of three independent interglacials divided by two coolings of glacial rank which are correlated with MIS 8 and 10. The Likhvin *s. str.* Interglacial spans the time interval approximately from 450 to 360 ka. Based on the pollen proxy climate record and the series of direct ESR dating, we correlate this interglacial event with marine oxygen isotope stage 11. Our results and those of other studies suggest that stage 11 was a period of prolonged and warmest climatic conditions in the Northern Eurasia over the past 600 ka. Comparison of our terrestrial pollen record with the sea-level data from elevated marine terraces demonstrates that during MIS 11, the proxy-climate trend in the Likhvin section was quite similar to a continuous trend of global sea-level rise.

(4) The subsequent Chekalin (= Domniz/Wacken) Interglacial is found to have occurred from at least ~ 340 to ~ 280 ka (MIS 9 and initial part of MIS 8). The following warming of the interglacial rank—Cherepet', which precedes the Mikulinian Interglacial, is fixed in the time interval of about 220 ka (MIS 7). Identification and chronological justification of the possible analogues of this interglacial in the adjacent regions of Northern Eurasia is the aim of forthcoming investigations.

(5) The palynological materials and chronological evidence from emerged coastal areas confirm the existence of the Dnieper–Moscow Interstadial and some sea-level rise which is ESR-dated to approximately 170 ka.

(6) The range of dates (145–70 ka) obtained on transgressive marine sediments and the results of palynological analysis of loess-palaeosoil and other terrestrial deposits suggests that this palaeoenvironmental event may have been long lasting, correlating most likely with the whole of MIS 5 rather than with the period of optimum conditions in substage 5e only and should belong to the Last Interglacial (MIS 5, sensu lato).

(7) The comparison of the six successive Pleistocene interglacial palynofloras and phytocoenotic successions of the six interglacial climatic rhythms allowed us to conclude that among other interglacial stages in the evolution of LPF and Pleistocene vegeta-

tion over the last 600 ka the Muchkap (? = Voigtstedt) Interglacial was the most humid thermochron, the Likhvin *s. str.*) (= Holstein *s. str.*) was the warmest Interglacial, while the Mikulinian (= Eemian) interglacial was the most continental one (except the Holocene).

(8) The comparison of ESR-chronostratigraphical levels on fauna-bearing warm-climate-related horizons with the phytocoenotic and climatic successions of the interglacial climatic rhythms in LPF sections suggests that no long interruption in the loess-palaeosoil sedimentation has occurred during the Brunhes chron. This indicates the reliability of palaeoenvironmental reconstructions and global correlation of climate-related environmental changes on the basis of integration of evidence from palynological analysis of loess-palaeosoil sections and other data sources, such as absolute geochronology, isotopic analyses of deep-sea and ice cores, palaeo sea-level records, etc.

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References

Berger, A., 1978. Long-term variations of caloric insolation resulting from the Earth's orbital elements. Quaternary Research 9, 139–167.

Bischoff, J.L., Menking, K.M., Fitts, J.P., Fitzpatrick, J.A., 1997a. Climatic oscillations 10,000–155,000 yr B.P. at Owens Lake, California reflected in glacial rock flour abundance and lake salinity in core OL-92. Quaternary Research 48, 313–325.

Bischoff, J.L., Fitts, J.P., Fitzpatrick, J.A., 1997b. Responses of sediment geochemistry to climate change in Owens Lake sediment: an 800-k.y. record of saline/fresh cycles in core OL-92. In: Smith, G.I., Bischoff, J.L. (Eds.), An 800,000-Year Paleoclimatic Record from Core OL-92, Owens Lake, Southeast California. Boulder, Colorado, The Geological Society of America Special Paper, vol. 317, pp. 37–47.

Bolikhovskaya, N.S., 1993. Stratigrafiya i korrelyatsiya pozdnego plejstotsena Russkoj ravniny na osnove detal'nogo palinologicheskogo izucheniya razreza Arapovichi (Stratigraphy and correlation of the late Pleistocene of the Russian plain on the basis of detailed pollen analysis of the Arapovochi key section). In: Kaplin, P.A. (Ed.), Tendency of Pleistocene Environment Evolution (Ocean-Shelf-Continent). Moscow Univ. Press, Moscow, pp. 102–126 (in Russian).

Bolikhovskaya, N.S., 1995. Évolyutsiya Lessovo-Pochvennoj Formatsii Severnoj Evrazii (Evolution of the Loess-Paleosoil Formation of the Northern Eurasia). Moscow Univ. 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, vol. 34. Nauka/Interperiodica Publishing, Moscow, pp. 75–80, Suppl. 1.

Bolikhovskaya, N.S., Sudakova, N.G., 1996. The Chekalin (Likhvin) Sequence of the Russian Plain and Its Significance for the Pleistocene Stratigraphy and Correlation. Stratigraphy and Geological Correlation, vol. 4, no. 3. Nauka/Interperiodica Publishing, Moscow, pp. 88–99.

Bolshiyanov, 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 glaciations in the northern Hemisphere. Report of the IGCP project 24. Quaternary Science Reviews 5, 509–510.

Burckle, L.H., 1993. Late Quaternary interglacial stages warmer than present. Quaternary Science Reviews 12, 825–831.

Bykova, V.S., Larionov, A.K., Minervin, A.V., Sergeev, E.M., 1986. Prostranstvennoe i vremennoe rasprostranenie lessovykh porod (Spatial and temporal distribution of loess rocks). In: Sergeev, E.M., Larionov, A.K., Komissarova, N.N. (Eds.), The Loess Rocks of the USSR. Nedra Press, Moscow, pp. 27–51 (in Russian).

Devyatova, É.I., 1982. Prirodnaya sreda pozdnego plejstotsena i ee vliyanie na rasselenie cheloveka v Severodvinskom bassejne i v Karelii (Late Pleistocene natural environment and its impact on human population in the North-Dvina basin and in Karelia). Kareliya, Petrozavodsk (in Russian).

Gaigalas, A., Molodkov, A., 1996. Geology and freshwater mollusc ESR—age of the Būtėnai Interglacial lacustrine deposits (Gailiūnai, Southern Lithuania). Geologija 19, 41–49.

Gaigalas, A., Molodkov, A., 1997. ESR dates on Merkinė interglacial deposits in Lithuania and Eemian deposits on the Belgian coast. The Eemian-local sequences, global perspectives. Abstract Volume of the INQUA-SEQS Symposium, September 6–11, 1998, Kerkrade (The Netherlands), 25.

Grichuk, V.P., 1961. Iskopaemye flory kak paleontologicheskaya osnova stratigrafii chetvertichnykh otlozhenij (Fossil flora as a palaeontolological basis of the stratigraphy of Quaternary deposits). Topography and Stratigraphy of Quaternary Deposits in the North-West of the Russian Plain. Nauka, Moscow, pp. 25–71 (in Russian).

Grichuk, V.P., 1982. Vegetation of Europe during late Pleistocene. In: Gerasimov, I.P, Velichko, A.A. (Eds.), Palaeogeography of Europe During the Last One Hundred Thousand Years. Nauka, Moscow, pp. 92–109 (in Russian).

Hearty, P.J., 1999. Warm interglaciations, abrupt environmental change, and the Antarctic "Wild Card". In: Fletcher, C.H., Matthews, J.V. (Eds.), The Non-Steady State of the Inner Shelf and Shoreline: Coastal Change on the Time Scale of Decades to Millennia in the Late Quaternary. PDF Version of Abstracts with Programs, Inaugural Meeting of IGCP Project N 437 "Coastal Environmental Change During Sea Level Highstands", University of Hawaii, Honolulu, USA, Nov. 9–12, pp. 77–78.

Hearty, P.J., Kindler, P., Cheng, H., Edwards, R.L., 1999. A +20 m middle Pleistocene sea-level highstand (Bermuda and The Bahamas) due to partial collapse of Antarctic ice. Geology 27, 375–378.

Henderson, G.M., Slowey, N.C., 2000. Evidence from U–Th dating against Northern Hemisphere forcing of the penultimate deglaciation. Nature 404, 61–65.

Howard, W.R., 1997. A warm future in the past. Nature 388, 418–419.

Ikeya, M., Ohmura, K., 1981. Dating fossil shells with electron spin resonance. Journal of Geology 89, 247–251.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Sackleton, N.J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine δ^{18}O record. In: Berger, A., Imbrie, J., Hays, J., Kukla, G., Saltaman, B. (Eds.), Milancovich and Climate. Reidel, Dordrecht, pp. 269–305.

Jessen, A., Milthers, V., 1928. Stratigraphical and palaeontological studies of interglacial freshwater deposits in Jutland and northwest Germany. Danmarks Geologiske Undersøgelse II Raekke 48.

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.

Kindler, P., Hearty, P.J., 2000. Elevated marine terraces from Eleuthera Bahamas and Bermuda: sedimentological, petrographic and geochronological evidence for important deglaciation events during the middle Pleistocene. Global and Planetary Change 24, 41–58.

Kukla, G., McManus, J.F., Rousseau, D.-D., Chuine, I., 1997. How long and how stable was the last interglacial? Quaternary Science Reviews 16, 605–612.

Lavrova, M.A., 1961. Sootnoshenie mezhlednikovoj boreal'noj transgressii severa SSSR s éemskoj v Zapadnoj Evrope (The relation between Boreal Interglacial transgression in the north of the USSR and the Eemian transgression in the western Europe). Proc. Inst. Geol. Acad. Sci. E.S.S.R. VIII, Tallinn, 65–88.

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, 591–595.

Mangerud, J., Sønstegaard, E., Sejrup, H.-P., 1979. Correlation of the Eemian (interglacial) stage and the deep-sea oxygen-isotope stratigraphy. Nature 277, 189–192.

Miller, G.H., William, N.M., Alexander, P.W., Peter, E.S., Bennike, O., Forman, S.L., Susan, K.S., Stafford Jr., T.W. 1999. 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 (3), 49–54.

Molodkov, A., 1988. ESR dating of Quaternary shells: recent advances. Quaternary Science Reviews 7, 477–484.

Molodkov, A., 1989a. Opyt ispol'zovaniya metoda ÉPR-datirovaniya rakovin mollyuskov chetvertichnykh otlozhenij (An experience of ESR-dating of mollusc shell applied for stratigraphic schemes correlation of Quaternary deposits). In: Alekseev, K.V., Nikiforova, K.V. (Eds.), Quaternary Period. Stratigraphy. Nauka, Moscow, pp. 204–213 (in Russian).

Molodkov, A., 1989b. 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., 1995. Dannye ÉPR khronostratigrafii k dinamike razvitiya prirodnykh obstanovok plejstotsena (EPR-chronostratigraphic data for the dynamics of the Pleistocene environments). In: Svitoch, A.A. (Ed.), Correlation of Palaeogeographical Events: Continent-Shelf-Ocean. Moscow Univ. Press, Moscow, pp. 93–98 (in Russian with English summary).

Molodkov, A., 1996. ESR dating of *Lymnaea baltica* and *Cerastoderma glaucum* from low Ancylus level and transgressive Litorina Sea deposits. Applied Radiation and Isotopes 47, 1427–1432.

Molodkov, A., 2001. ESR dating evidence for early man at a lower Palaeolithic cave-site in the northern Caucasus as derived from terrestrial mollusc shells. Quaternary Science Reviews 20, 1051–1055.

Molodkov, A., Gaigalas, A., 1994. The last interglacial site at Jonionys: evidence from the ESR dating of freshwater Gastropod shells. Conference of Geochronology and Dendrochronology of Old Town's and Radiocarbon Dating of Archaeological Findings. Abstracts and Papers, Vilnius, Oct. 31–Nov. 4, 1994, 29.

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., 1996. ESR dating of subfossil mollusc shells of the Limnea Sea. Baltica 9, 29–35.

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.N., Hütt, G.I., Makeev, V.M., Baranovskaya, O.F., Kosmodamiansky, A.V., Ponomareva, D.P., Bolshiyanov, D.Yu., 1987. Opredelenie vozrasta rakovin mollyuskov iz morskikh otlozhenij ostrovov Oktyabr'skoj Revolyutsii i Kotel'ny metodom ÉPR (The ESR age of the mollusc shells from marine deposits the Oktyabr'skoj Revolyutsii Island and the Kotel'ny Island). In: Punning, J.-M.K., Kind, N.V., Chichagova, O.A. (Eds.), New Data in Quaternary Geochronology. Nauka, Moscow, pp. 236–243 (in Russian).

Molodkov, A.N., Raukas, A.V., Makeev, V.M., Baranovskaya, O.F., 1992. K ÉPR khronostratigrafii morskikh otlozhenij Severnoj Evrazii i ikh korrelyatsii s sobytiyami 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 Quaternary Period. Nauka, Moscow, pp. 41–47 (in Russian).

Molodkov, A., Dreimanis, A., Āboltiņš, 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.

Möller, P., Bolshiyanov, D.Yu., Bergsten, H., 1999. Weichselian geology and palaeoenvironmental history of the central Taymyr Peninsula, Siberia, indicating no glaciation during the last global glacial maximum. Boreas 28, 92–114.

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.

Oppo, D.W., Fairbanks, R.G., Gordon, A.L., Shackleton, N.J., 1990. Late Pleistocene southern ocean δ^{13}C variability. Paleoceanography 5, 43–54.

Patience, A.J., Kroon, D., 1991. Oxygen isotope chronostratigraphy. In: Smart, P.E., Frances, P.D. (Eds.), Quaternary Dating Methods—A User's Guide. Technical Guide 4. Quaternary Research Association, Cambridge, pp. 199–228.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G., Caulet, J.P., 1998. Magnitudes of sea-level lowstands of the past 500,000 years. Nature 394, 162–165.

Rossignol-Strick, M., Paterne, M., Bassinot, F.C., Emeis, K.-C., De Lange, G.J., 1998. An unusual mid-Pleistocene monsoon period over Africa and Asia. Nature 392, 269–272.

Scherer, R.P., Aldahan, A., Tulaczyk, S., Possnert, G., Engelhardt, H., Kamb, B., 1998. Pleistocene collapse of the west Antarctic ice sheet. Science 281, 82–85.

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., 1969. The last interglacial in the marine and terrestrial records. Proceedings of the Royal Society of London, Series B 174, 135–154.

Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. Quaternary Science Reviews 6, 183–190.

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 10^5 and 10^6 year timescale. 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, 159–168.

Velichko, A.A., Markova, A.K., Morozova, T.D., Udartsev, V.P., 1984. Problemy geokhronologii i korrelyatsii lessov i iskopaemykh pochv Vostochnoj Evropy (Problems of geochronology and correlation of loesses and fossil soils of eastern Europe). Izvestiya AN SSSR, Ser. geogr. 6, 5–19 (in Russian).

Velichko, A.A., Markova, A.K., Morozova, T.D., Nechaev, V.P., Udartsev, V.P., Tsatskin, A.I., Chepalyga, A.L., 1989. Khronostratigrafiya lessovo-pochvennoj formatsii i ee znachenie v korrelyatsii i periodizatsii lednikovoj, periglyatsial'noj i primorskoj oblastej (Chronostratigraphy of the loess-paleosoil formation and its significance for correlation and periodization of the glacial, periglacial and marine areas). In: Yanshin, A.L. (Ed.), Quaternary Period: Paleogeography and Lithology. Shtiintsa Press, Kishinev, pp. 14–20 (in Russian).

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.