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Long-term palaeoenvironmental changes recorded in palynologically studied loess–palaeosol and ESR-dated marine deposits of Northern Eurasia: Implications for sea–land correlation

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Abstract

Original materials of pollen analysis and ESR-chronostratigraphic studies provided a basis for reconstruction, chronological subdivision and inter-regional correlation of palaeoclimatic events and sediments of palaeo-shelf, glacial–periglacial and extra-glacial regions of Northern Eurasia within the scope of the Brunhes Epoch. Chronostratigraphic position of the identified palaeoenvironmental events and corresponding horizons in the composite chronostratigraphic column is established on the base of ESR-analyses of subfossil mollusc shells collected from marine, freshwater and terrestrial deposits. The palyno-chronostratigraphic record displays a sequence of 8 intervals (the Holocene included) of warm climate and high sea-level stands, when marine sedimentation occurred on palaeo-shelves, and 7 glacial epochs. The alternating intervals are either fully recorded as complete glacial-interglacial rhythms, or represented by a large enough number of consecutive climatic-phytocoenotic phases. The rhythmic regularity in the sequence of glacial and interglacial events has been inferred from detailed palynological data on reference sections of loess–palaeosol series in the centre of the East European Plain (Arapovichi, Otkaznoe, Likhvin, Strelitsa sections). A clear agreement between long pollen record, directly dated warm-climate-related deposits and other records of palaeoenvironmental evolution known from literature has been established for the upper 15 oxygen isotope stages (OIS 15 to 1). Finally, we come to a conclusion that the integrated climate-chronological sequence may be taken as a basis for inter-regional correlations of palaeo-shelf and terrestrial sediments within Northern Eurasia; it may be used as an intermediate link in the continent–ocean correlations.

1. Introduction

One of key problems in the Quaternary geology is timing and reconstruction of palaeoenvironmental evolution on the basis of available fragments of geological record. There are two aspects directly related to the problem: first, how to arrange discovered events in a correct chronological order; and second, how to establish chronological relationship between the studied sections, that is to correlate events and corresponding deposits in the sections spaced far apart. In case the sections are complete and individual horizons are dateable, the problem could be easily solved.

Unfortunately, long-range correlation is not always possible in practice. There are often gaps in the geological record, and the absolute age of its constituents is frequently unknown. Local stratigraphic schemes are often difficult to correlate with interregional time divisions and with the global palaeoclimatic levels of the deep-sea oxygen isotope record.

Typical examples are the Baltic countries where the Late Pleistocene glacial erosion over this area could have been very intensive and, therefore, palaeoenvironmental records here may consist of a number of hiatuses. Probably, this is the reason why the upper part of the stratigraphical schemes of the Quaternary deposits in all the three Baltic states compiled before the mid-1990s are rather similar and relatively simple. Within the second half of the Middle Pleistocene, two glacial episodes separated by interglacial deposits are distinguished; the latter are correlated either with OIS 11 or with OIS 9 (Fig. 1A).

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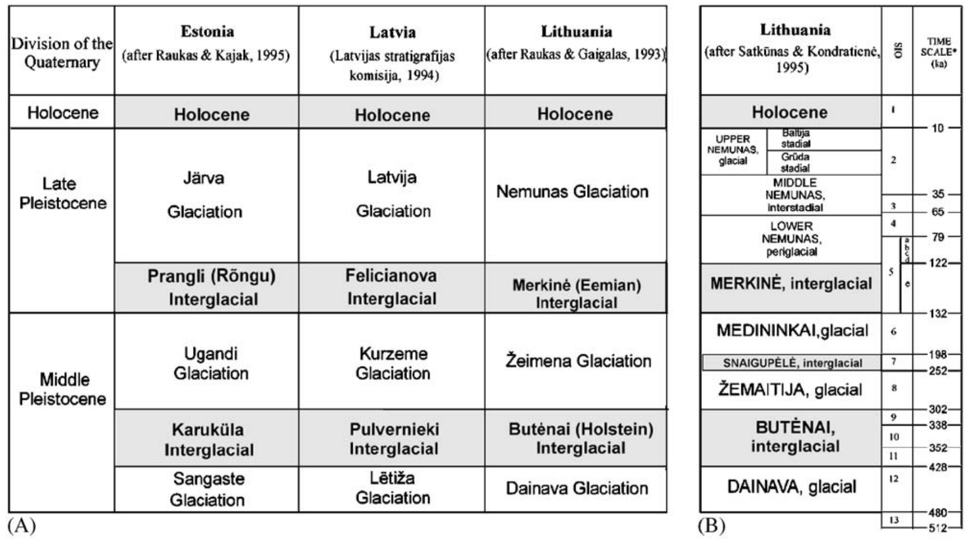

Fig. 1. The modern stratigraphical scheme of Quaternary deposits in the Eastern Baltic Region. *Time scale and oxygen isotope stages (OIS) after Bowen et al., 1986. See refs: Raukas and Kajak (1995), Latvijas Stratigrafijas Komisja (1994), Raukas and Gaigalas (1993) and Satkūnas and Kondratienė (1995).

Recently, however, one more stratigraphic unit has been identified in Lithuania within the penultimate glaciation. It is tentatively denoted as the Snaigupėlė Interglacial, which divides this glacial interval into two separate glaciations (Fig. 1B). This addition to the Lithuanian stratigraphic scheme, however, has not been yet sufficiently substantiated with reliable data.

Nevertheless, in spite of all the indicated uncertainties, it is important that in all the three stratigraphic schemes of this palaeogeographically complicated region the principal stratigraphic units correspond to the two best pronounced Pleistocene interglacials: Holsteinian (Butėnai, Karuküla, Pulvernieki) and Eemian (Merkinė, Prangli, Felicianova). Usually, the first of them—Holsteinian—is correlated with OIS 11, and the Eemian with stage 5 (or substage 5e). This allows correlation of at least these two units (and events) with those recognised in neighbouring areas.

At the same time a new disquieting tendency appeared in the last years. In many modern stratigraphic schemes of this and adjacent regions, the units corresponding to the Holsteinian Interglacial are correlated with isotope stage 9, while the units corresponding to the last interglacial with substage 5e (Yakubovskaya et al., 2002). This situation cannot but complicate the problem of interregional correlations.

A possible way out of the difficulties may be suggested as follows: (a) to identify events of global occurrence that took place during the considered interval; (b) to assess a degree of resulting environmental changes, and (c) to determine the position of the events on the chronological scale. In other words, it seems necessary to develop a climate-chronostratigraphic framework in which the major palaeoenvironmental changes should be recognised and recorded in chronological order, and they should have correlatives in the terrestrial, marine, ice-core and deep-sea records.

To develop such a framework, the following conditions should be complied with: first, it must be based on a comprehensive record of environmental changes spanning a long enough period; second, any palaeoclimatic event needs to be recorded distinctly and unambiguously enough to permit its correlation with a corresponding signal in the oxygen isotope record; and finally, a time-frame should be substantiated with reliable numerical dating.

2. Methods

For the construction of the Pleistocene climate-chronostratigraphic framework, we used the data obtained in the course of long-term palynological studies of the loess–palaeosol formation (LPF) and absolute geochronology. Data on climatic changes during the Middle and Late Pleistocene were obtained from two unique sources of palaeoclimatic information: first, from palynological studies of reference sections in the glacial–periglacial and extraglacial zones, and second, from electron spin resonance (ESR) chronology of deposits associated with warm intervals.

The ESR palaeoclimatic record is based on chronostratigraphy of the fauna-bearing sediments related to the warm phases of global climatic rhythms, such as deposits of marine transgressions and ancient lakes. Marine transgressions repeatedly covered the northern margins of the Eurasian continent. Being directly related to periods of global warming and ice sheet melting, they are of particular importance for reconstructions of global environmental changes. Frequency distribution of ESR dates of shells collected from palaeo-shelf sediments revealed a series of intervals correlative with marine transgressions. Intervals lacking ESR dates may be, in turn, correlated with coolings or with periods of ice sheet expansion in the Northern Hemisphere. The latter was accompanied by ocean regression and a considerable deterioration of environments on continents.

The evolution of terrestrial environments is recorded in the loess–palaeosol sequence exposed in a number of complete reference sections in the glacial–periglacial and extraglacial zones of the East European Plain. Pollen assemblages recovered from the sections contain comprehensive information on continuous evolution of the ecosystem through the Pleistocene and provide the most complete 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 may be compared directly both with the main signals of the resonance palaeoclimatic record and with reference levels of the climate-dependent variations in the deep-sea oxygen isotope record. The integrated approach based on the two independent methods and sources of climate-chronostratigraphic information provided a means for the development of absolute chronology of the main palaeogeographic events during the last 600,000 years.

3. Study area

Reference sections in the central and southern regions of the East European Plain and numerous sections on the palaeo-shelves of the Eurasian North (Fig. 2) were chosen as subjects of detailed research aimed at reconstructing a continuous palaeogeographic record. During the Pleistocene, this vast area was repeatedly subjected to ice sheet expansion, frost processes and loess formation, as well as influenced by transgressions and regressions of the Arctic seas. All this allows use of the area as a basis for solving the problems of timing and climatestratigraphy of the Pleistocene deposits.

The region of periglacial loess formation most remote from the area of cover glaciations is the East Caucasian Piedmonts. The longest and palynologically best studied sequences of the loess–palaeosol formation are situated here. There are subaerial, deluvial–proluvial and alluvial sediments with a total thickness of 140 m exposed in the reference section near Otkaznoe village (Fig. 3).

The Oka-Don glacial–periglacial region within the limits of the Don glaciation moraine occupies a major part of the lowland of the same name and the eastern margins of the Central Russian Upland. A Neogene–Pleistocene sequence,

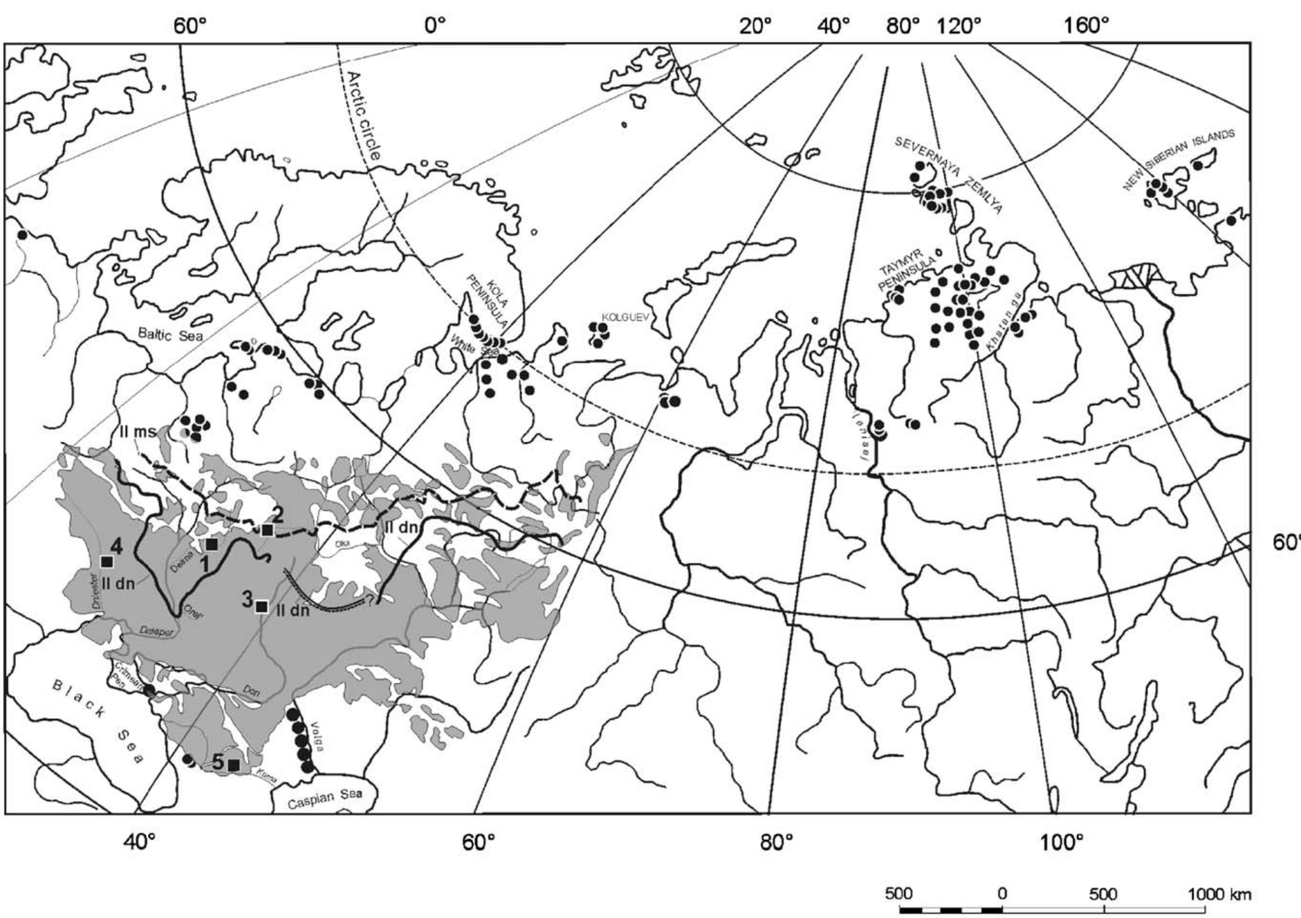

Fig. 2. Map showing the localities of collected shell samples (circles), studied loess–palaeosol sections (squares: 1—Arapovichi, 2—Likhvin, 3—Strelitsa, 4—Molodova, 5—Otkaznoe), distribution of loesses on East-European Plain (grey area), limits of Dnieper (II dn) and Moscow (II ms) glaciations (after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

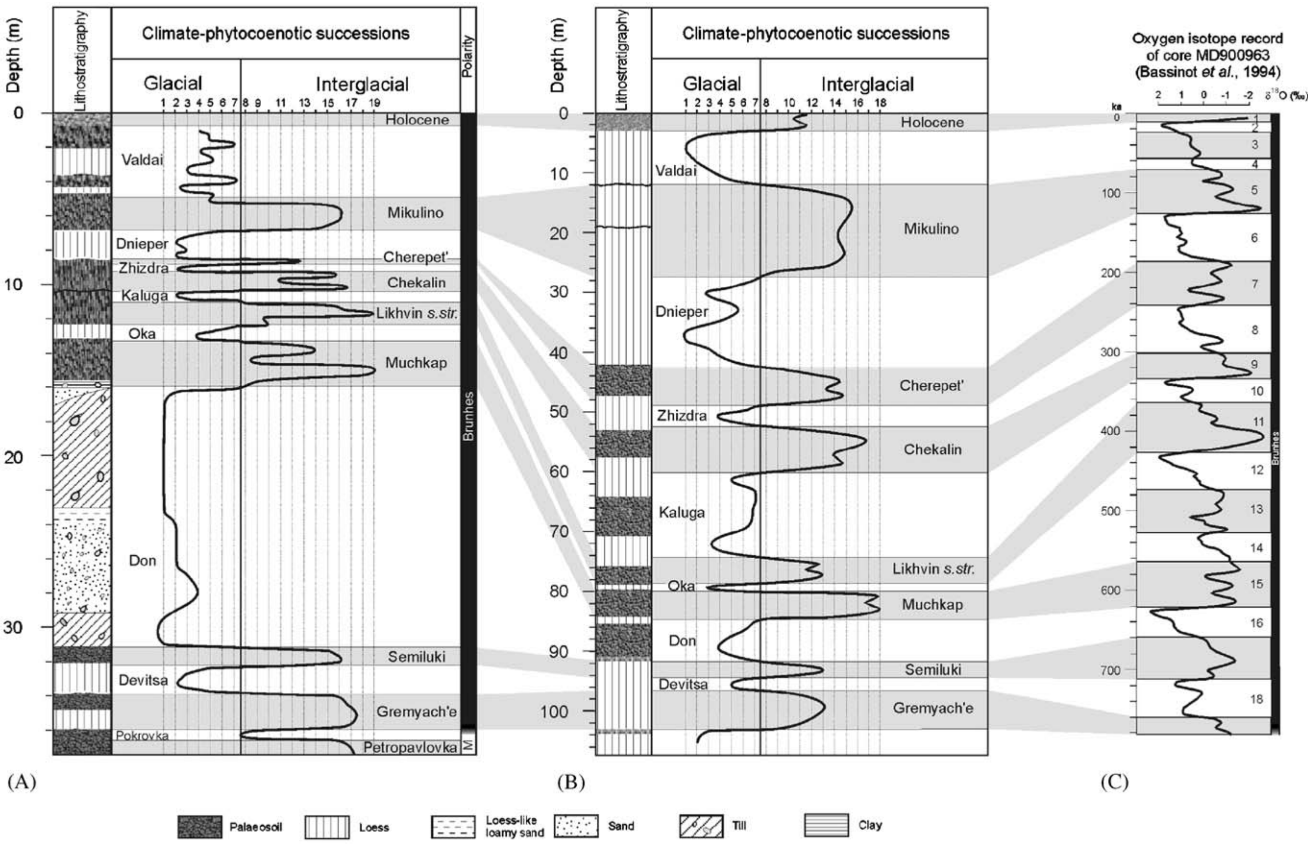

Fig. 3. Two examples of climatostratigraphic subdivision and reconstruction of vegetation and climate by pollen data: (A)—Strelitsa, (B)—Otkaznoe. The structure and major palaeoclimatic signals of these record can be directly compared with the climate-dependent curve of oxygen isotope record (after Bassinot et al., 1994) (C).

more than 60 m thick, is exposed near Strelitsa village, 20 km west of Voronezh (Fig. 3).

The North-Central Russian glacial–periglacial region is located in the north of the Central Russian Upland, within the limits of the Dnieper ice sheet. The Quaternary sequence and most of the Pleistocene palaeogeographic events are represented most completely in the classic Likhvin section situated on the left bank of the Oka River 1 km north of Chekalin (formerly Likhvin). The section is the stratotype of the Likhvin Interglacial of Eastern Europe.

The Late Pleistocene loess–palaeosol horizons have been studied in particular detail in two regions. The Desna–Dnieper Region is located in the north-eastern part of the Dnieper Lowland once covered by the Dnieper ice sheet. There is a 14 m sequence of the Late Pleistocene loess and palaeosols exposed in the Arapovichi section (right bank of the Desna River, 12 km south-west of the city of Novgorod–Seversky). Pollen spectra recovered from the series characterise successions of vegetation and climate of the Mikulino Interglacial and of the majority of the Valdai Interstadials and stadials.

In the extraglacial zone a detailed subdivision of the Late Pleistocene horizons and palaeoenvironmental reconstructions have been performed for the middle reaches of the Dniester River, a part of the Dniester–Prut region. The most representative Late Pleistocene series are exposed in sections of the second terrace of the Dniester River composed of 10 m alluvial sediments and loess-like eolian-deluvial formation more than 25 m thick; the latter contains 8 palaeosols.

The palaeodosimetric proxy record of climate changes and sea level fluctuations during the last 600 ka has been obtained on more than 250 samples of mollusc shells collected mostly from transgressive marine series of the Northern Eurasia continental margin (see Fig. 2). The shells were ESR-dated for the purpose to develop absolute chronology of recurring marine transgressions—sea-level high stand events, when vast epicontinental basins expanded onto vast lowlands of the northern coasts of Eurasia. Evidence of relatively high sea-level stands has also been obtained from shells in the Black and Caspian Sea basins. Dates of freshwater molluscs shells from interglacial lake deposits (Gaigalas and Molodkov, 2002) and those of terrestrial molluscs from the Early Palaeolithic cultural layers (Molodkov, 2001) were also taken into account.

4. Palaeoenvironmental changes during the Brunhes Chron

Nowadays, many difficulties encountered in chronological subdivision and correlation of palaeogeographic events

		Horizons and subhorizons of interregional scale (after Alekseev et al.,1997)	Polarity	Stages of evolution of loess-paleosoil formation (Bolikhovskaya, 1995)		OIS
		Holocene	Brunhes	Holocene Interglacial	IV	1
Pleistocene	Late	Valdai glacial horizon		Valdai Pleniglacial	IIIv	4 3 2
		Mikulino interglacial horizon		Mikulino Interglacial	III mk	5
	Middle	Central Russian glacial horizon		Dnieper Glacial	II dn	6
		Likhvin interglglacial superhorizon		Cherepet' Interglacial	II chr	7
				Zhizdra Glacial	II zh	8
				Chekalin Interglacial	II ch	9
				Kaluga Glacial	II kl	10
				Likhvin Interglacial	II l *ss*	11
		Oka glacial horizon		Oka Glacial	I ok	14 13 12
		Belovezhsk interglglacial horizon		Muchkap Interglacial	I mch (=bv)	15
		Don glacial horizon		Don Glacial	I dns	16
		Il'inka interglacial		Semiluki (Late Il'inka) Interglacial	I sm	17
				Devitsa (Middle Il'inka) Glacial	I dv	18
				Gremyachie (Early Il'inka) Interglacial	I gr	19
		Pokrovka glacial horizon	M	Pokrovka Glacial	I pk	20

Fig. 4. East-European Plain event succession. See refs: Alekseev et al. (1997) and Bolikhovskaya (1995).

arise from the fact that the dynamics and succession of palaeoenvironmental changes are reconstructed using data from different stratotypes and parastratotypes of interglacial horizons, often spaced far apart, and not from a single section presenting continuous record of natural system evolution through the Pleistocene. Besides, such investigations are usually lacking an adequate geochronological basis. That is the reason why this study aimed at the Pleistocene palaeoenvironmental reconstructions were carried out along two lines: first, detailed palynological analysis of reference sections of the loess–palaeosol series (Bolikhovskaya, 1976, 1989, 1991, 1995; and others), comparable with deep-sea sediments in the completeness of palaeoclimatic record; and second, chronostratigraphy of palaeo-shelf sediments (Bolshiyanov and Molodkov, 1999; Molodkov, 1995; Molodkov and Bolikhovskaya, 2002; Molodkov and Yevzerov, 2004). The latter serve as a connecting link between sea and land and provide a basis for using our results for reconstruction and correlation of global climatic rhythms. Our investigations have established 8 interglacial and 7 intervening glacial stages in the environment evolution on the East European Plain during the Brunhes Epoch (Fig. 4).

4.1. Il'inka time

Palynological data suggest two interglacials within the Il'inka horizon, with a colder interval between them. In the southern and south-eastern loess regions of Eastern Europe the interglacials featured chiefly forest-steppe landscapes with dry summer and wetter winter. The long and complex Il'inka interval (~780 to 660 ka BP, according to the oxygen isotope scale) has been comprehensively studied in the sections of the upper Don River and middle reaches of the Kuma River. In the Strelitsa section it is represented by a loess–palaeosol series overlying red layers dated to the Early Pleistocene (Fig. 3). It includes two fossil soils and a loess-like sandy loam between them. The lower palaeosol of the series formed under conditions of interglacial steppe and forest-steppe at the *Gremyachie* (*Early Il'inka*) time. The intervening loess-like horizon developed during the Devitsa (intra- Il'inka) cold interval in environments of periglacial tundra and forest-tundra. The upper palaeosol features a thick humus horizon which in all probability developed in the forest-steppe of the *Semiluki* (*Late Il'inka*) *thermochron*; the uppermost part of the horizon was probably removed by the Don ice sheet.

4.2. Don Glacial

The Don Glacial (approximately 660–610 ka BP) corresponds to OIS 16. At its coldest phase (climatic pessimum), periglacial tundra and forest-tundra prevailed in the drainage basins of the Oka and upper Don rivers, periglacial forest-steppe and steppe dominated in the extraglacial Dnieper lowland, and coniferous-birch open woodlands with cold-tolerant dwarf shrubs—in the East Caucasian forelands (Bolikhovskaya, 1995). In the Strelitsa section (the upper reaches of the Don River) the Don Glacial complex includes two till horizons interlayered with fluvioglacial sands. Glacio-lacustrine sediments accumulated during that cryochron at the Likhvin locality.

4.3. Muchkap (Belovezhsk) Interglacial

ESR data place this global warming at about 610 to 535 ka BP (Fig. 5) (Bolikhovskaya and Molodkov, 2002; Molodkov, 2001). According to palynological data, coniferous-broadleaf forests with some Neogene exotics dominated the major part of the East European loess area at the Muchkap Interglacial optimum; the eastern Caucasian forelands were covered with polydominant broadleaf forests of *Carpinus*, *Fagus*, *Carya*, *Pterocarya*, *Liquidambar*, *Juglans*, *Castanea* and other thermophilic and hygrophilic species (Bolikhovskaya, 1995). At the same time the soil complex developed over the till in the Strelitsa region. Forests were dominant during most of the interglacial. The Likhvin section lacks deposits of the initial and final phases of the interglacial. There are exposed lacustrine sediments attributed to the optimum phases and to intervening endothermal cooling; in the upper Oka reaches coniferous and coniferous-broadleaf forests alternated in the forest formations during the considered interval see Fig. 5.

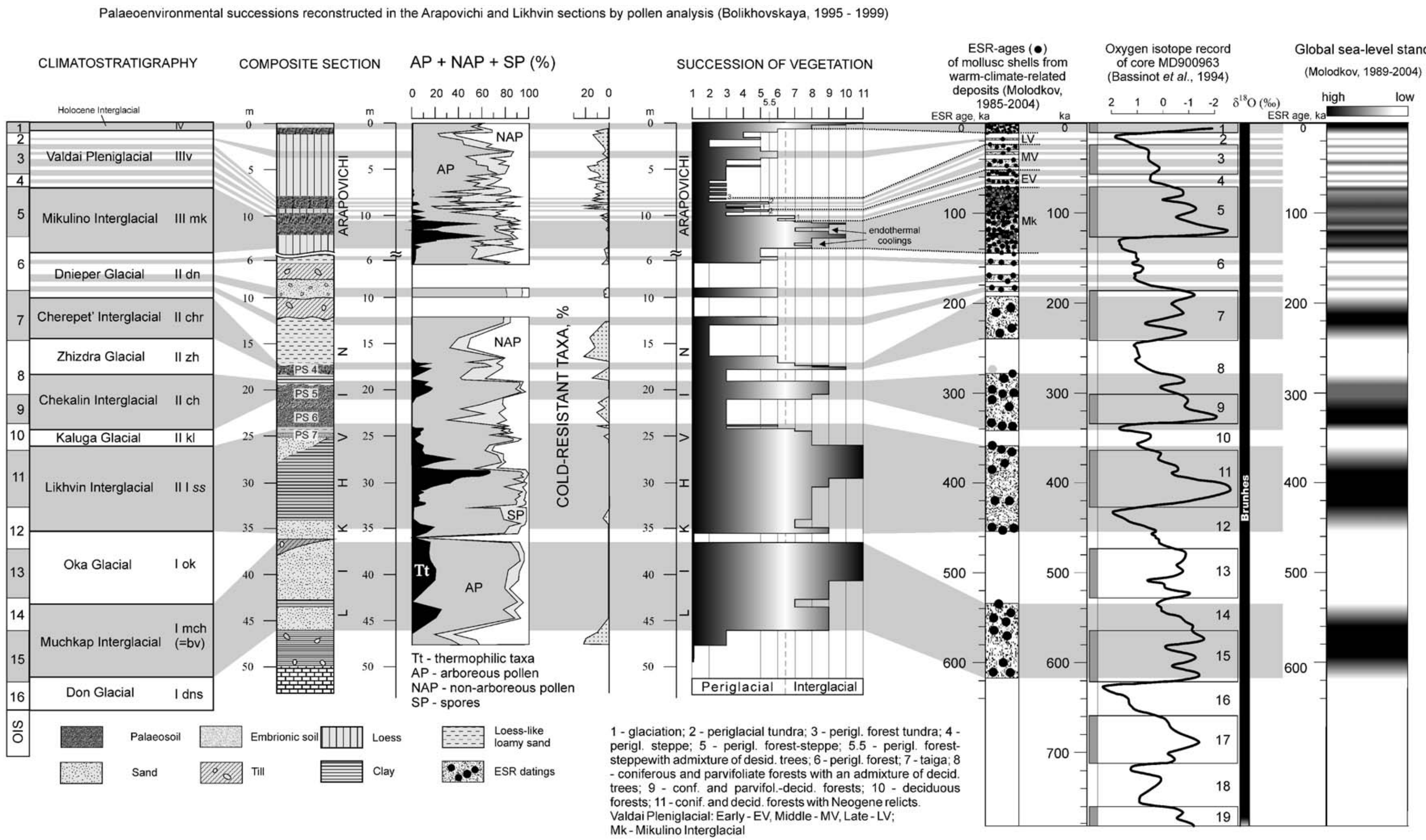

Fig. 5. Chronology and correlation of major palaeoenvironmental events over the Brunhes Chron (modified from Molodkov and Bolikhovskaya, 2002). Climate warmings of interglacial rank can be traced in different terrestrial and marine palaeoenvironmental records. Oxygen isotope record from Bassinot et al., 1994.

4.4. Oka Glacial

Within its stratotype region in the upper Oka River basin the 5-m-thick Oka Glacial deposits are exposed along Likhvinka Brook and near Bryankovo village (Sections of Deposits of the Central Russian Plain Glacial Regions, 1977). In the upper Don River basin the Oka cold stage (~535–455 ka BP) was distinct for tundra-steppe and tundra-forest-steppe. Periglacial steppe was widespread within extraglacial regions along the Dnieper River, and periglacial forest-steppe—in the eastern Caucasian forelands.

According to the resonance palaeoclimatic record, the Oka Glacial epoch spans the interval from OIS 14 to OIS 12 (see Fig. 5). That does not agree with the oxygen isotope climate-rhythmics where odd numbers denote "warm" interglacial stages; on this formal basis, as well as on the oxygen isotope ratio, OIS stage 13 should correspond to a warm interval. Recently, however, the conclusion on the long duration of the Oka Glacial 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 found there either (Lambert et al., 2003).

4.5. Likhvin s. str. Interglacial

This spans an interval of about 455 to 360 ka BP (Gaigalas and Molodkov, 1996, 2002; Molodkov et al., 1992; Molodkov, 2001). We have studied in particular detail the whole sequence of this interglacial (lacustrine, bog and alluvial deposits up to 20 m thick) in the Likhvin stratotype section (Bolikhovskaya, 1995). Characteristic taxa of the interglacial are representatives of European, Mediterranean, East Asian and North American floras. At the climatic optimum of the Likhvin thermochron dominant in the central regions of Eastern Europe were first oak-hornbeam forests, then spruce-fir and hornbeam-beech-oak forests. At the thermoxerotic maximum (the first half of the interglacial) grass and herb-grass steppes formed zonal vegetation in the loess regions of the southern Russian Plain. Thermohygrotic maximum recorded in the second half of the interglacial featured a wide expansion of thermophilic and hygrophilic species (*Tsuga*, *Pterocarya fraxinifolia*, *Juglans regia*, *Fagus orientalis*, *F. sylvatica*, *Carpinus betulus*) in the forest and forest-steppe (the latter was confined to the south-east of the East European Plain).

The Likhvin Interglacial (corresponding to OIS 11) was the warmest interval recorded during the last 600 ka. Sea level varied between 2 and 20 m above that of today (Rohling et al., 1998; Hearty et al., 1999). Many authors agree in that the highest ocean level (+20 m) occurred in the second half of the interglacial, about 400 ka BP, and resulted from 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.

4.6. Kaluga cooling

In the Likhvin section this interval (~360–340 ka BP) is represented by lacustrine and alluvial sediments. At its coldest phase (correlative with stage 10 of the oxygen isotope scale) the upper Oka and upper Don regions were occupied by periglacial tundra and forest-tundra, 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.

4.7. Chekalin Interglacial

The studied loess regions of Eastern Europe were under steppe and forest-steppe vegetation, with much less participation of Pliocene exotics in the dendroflora as compared with earlier interglacials. According to our data (Bolshiyanov and Molodkov, 1999; Gaigalas and Molodkov, 1997, 2002; Molodkov et al., 1992; Molodkov, 1995), the palaeoclimatic signal of interglacial type recorded in various palaeoenvironments falls within an interval between 340 and 280 ka BP (stage 9 and beginning of stage 8).

4.8. Zhizdra cooling

The Zhizdra event corresponds to a major part of OIS 8. In the East 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 for cryoarid landscapes of the East Caucasian forelands.

4.9. Cherepet' Interglacial

A considerable warming of interglacial rank preceding the Mikulino event has been established by the ESR data on raised marine sediments within an interval of about 220 ka BP; it corresponds to a larger part of OIS 7. There were xerophytic broadleaf formations of *Carpinus orientalis*, *Ostrya* sp., *O. carpinifolia*, etc. dominant 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. 5). Hornbeam–oak and mixed (of Siberian pine and broadleaf species) formations became dominant in the upper Oka basin at the optimum phases.

We succeeded in obtaining more extensive material on the two last glacial–interglacial cycles. The first of them began with a sharp deterioration of climate and onset of glaciation; the latter is known as the Dnieper glaciation on the East European Plain. At the maximum stage, the Dnieper ice sheet covered vast areas in the north of the plain and penetrated into the Dnieper River valley as far as the Orel River mouth (see Fig. 2).

4.10. Dnieper Glacial

The Dnieper *s. lato* Glacial is dated at approximately 200–145 ka BP and corresponds to a major part of OIS 6. In the Likhvin section it is represented by a thick series including the following units: (1) Early Dnieper fluvioglacial silts containing predominantly tundra-steppe pollen assemblages; (2) three-layer till corresponding to the Dnieper and Moscow stages and to the Dnieper–Moscow Interstadial, with pine open woodlands, shrubs of *Alnaster* and dwarf birch prevailing in landscapes of the latter; (3) Late Moscow loess-like sandy loam.

The first amelioration of climate, which resulted in the Dnieper ice sheet melting, is noted in the upper part of the fluvioglacial silts at the very beginning of OIS 6. Three ESR dates of mollusc shells collected from raised marine sediments in the high Arctic place 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 transition from tundra-steppe to periglacial open woodlands of pine. As follows from the isotope record of the Greenland ice core (GRIP Project Members, 1993), there are two positive anomalies on the oxygen isotope curve within the interval of 183.9–186 ka BP. Judging from the oxygen isotope ratio, the climate conditions could be similar to those of today or even warmer (Fig. 6).

During the second (Dnieper–Moscow) Interstadial open pine woodlands, frutescent formations of *Alnaster* and dwarf birch dominated. Four ESR dates on marine shells sampled in the Eurasian Arctic indicate that the second interstadial occurred about 172 ka BP. The dates, as well as corresponding palaeoclimatic signal in the pollen diagram, are most probably correlative with the next relatively warm episode recorded in the GRIP ice core and coincide with a high latitude peak of insolation (Berger and Loutre, 1991).

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. Based on three ESR dates of mollusc shells taken from marine sediments on the Taimyr Peninsula, the third interstadial of the Dnieper time is dated at ~155 ka BP. This age coincides with two very warm, though relatively short-term, signals of interstadial rank identified from the GRIP ice core record in the range of 153.5–158.8 ka BP.

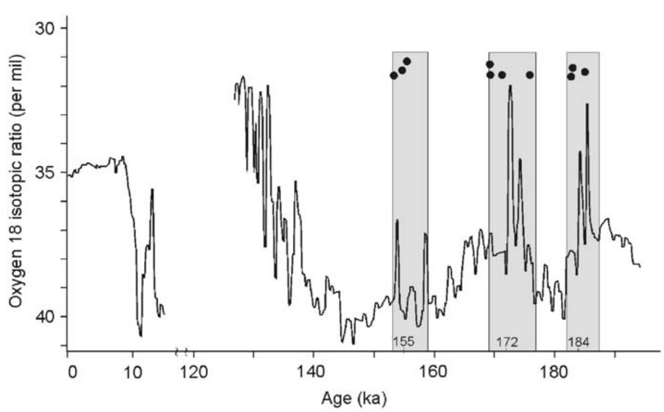

Fig. 6. About 184, 172 and 155 ka ESR age determinations (dots) on subfossil mollusc shells from raised marine deposits of the Eurasian North record the relatively warm intervals during penultimate (Dnieper/Saale) glaciations as also indicated by the positive anomalies in the 190 to 130 ka interval of the GRIP ice-core record.

4.11. Mikulino Interglacial

The Mikulino Interglacial is noted for its most complicated structure of climatic fluctuations. The ESR studies carried out recently on shells from marine sediments of the Eurasian North (Bolshiyanov and Molodkov, 1999; Molodkov and Raukas, 1998; Molodkov et al., 1998; Molodkov and Bolikhovskaya, 2002; Molodkov and Yevzerov, 2004) and from ancient lacustrine deposits of Lithuania (Gaigalas and Molodkov, 1997, 2002; Molodkov et al., 2002) put the marine transgression and lacustrine sedimentation within an interval between ~145–140 and 70 ka BP which corresponds to the whole stage 5 and the final phase of stage 6.

Time-dependent frequency distribution of all the ESR dates falling within the range of the last *s. lato* interglacial (mainly obtained on the raised marine sediments of marginal and shelf seas of the Eurasian North) revealed several high-frequency intervals (Fig. 7, peaks I to V) dated at about 135, 120, 110, 90 and 70 ka BP; we correlate those intervals with periods of relative warming and marine

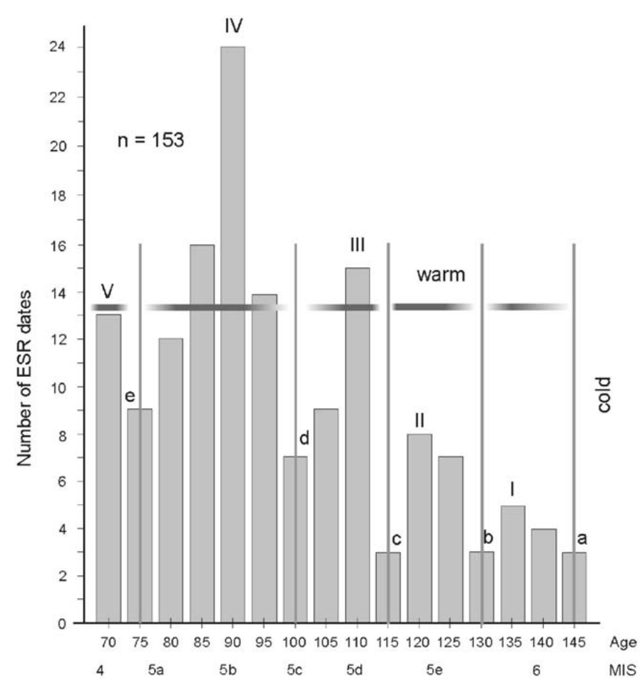

Fig. 7. Frequency distribution of ESR-ages between 145 and 70 ka obtained on marine ($n = 146$) and lacustrine ($n = 7$) interglacial deposits (Molodkov, determinations 1985–2003) and phases of relatively warm and cool climate.

transgressions onto coastal lowlands. The low frequency intervals (Fig. 7(b–e)) dated at about 130, 115, 100, and 75 ka BP are correlated with cooler climate and retreat of the sea from the flooded coasts.

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 the 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 Mikulino Interglacial to the end of the first Early Valdai Interstadial. As for south-western regions (broadleaf forest zone of today), the interval of maximum moisture supply continued to the end of the second Early Valdai Interstadial. Hereafter the Late Pleistocene is divided into Mikulino interglacial (OIS 5) and Valdai Pleniglacial. The latter is divided in turn into Early (OIS 4), Middle (OIS 3) and Late (OIS 2) Valdai. The Mikulino Interglacial was a rather prolonged interval, during which this region experienced a succession of complicated changes in vegetation. There are a number of distinct climatic stages within the interglacial, including several coolings with climate of interstadial type; for the latter Bolikhovskaya (1991) suggested the term "endothermal coolings".

The dynamics of palaeo-environments through this interval is most clearly presented in the Arapovichi reference section (north-eastern part of the Dnieper lowland, the Desna River valley). 14-m-thick series of the Late Pleistocene loess and palaeosols overlies the Dnieper till there (see Fig. 5). According to pollen data, sands and loams immediately overlying the till are attributed to the Mikulino Interglacial, as well as the major part of the Mezin soil complex, including the Salyn palaeosol (lessive) and the lower third of the soddy-chernozem Krutitsa palaeosol. The first (Ketrosy) Interstadial of the Early Valdai Pleniglacial has been identified in the middle part of this fossil soil. Forests were dominant in the region during the whole Mikulino Interglacial, under conditions of relatively high heat and moisture supply.

Climate-phytocoenotic and floristic characteristics of the Mikulino Interglacial forests are given in works by Bolikhovskaya (1995, 2000). ESR ages of 145–140 ka BP (Bolikhovskaya and Molodkov, 1999; Molodkov and Bolikhovskaya, 2002) and evidence of sharp warming of climate at the very end of OIS 6 (Seidenkrantz et al., 1996) suggest that the rise of sea level and global warming could begin even long before OIS 6. The beginning of the latter is dated at 128 ka BP (Martinson et al., 1987).

4.12. Valdai Pleniglacial

The Valdai Pleniglacial is correlative with stages 4–2 of the oxygen isotope curve, that is with an interval of 70 to 10 ka BP. Based on palynological studies of the most complete and representative Arapovichi reference section (see Fig. 5), a number of units have been identified within the Valdai Pleniglacial, namely two Early Valdai and three Middle Valdai Interstadials and five cold stadials. In the Late Valdai one interstadial, three interphasials and five cold stadials were recognised. Every unit has distinctive floristic, phytocoenotic and climatic characteristics (Bolikhovskaya, 1986, 1995).

The first Early Valdai cooling is most clearly pronounced in the Arapovichi section; in this respect it is comparable with classic sections of Western Europe, such as Grande Pile (Woillard, 1978) and Les Echets (de Beaulieu and Reille, 1984). At the Ketrosy Interstadial the temperatures became noticeably higher; pollen assemblages suggest dominance of pine-birch forests with an admixture of oak, lime and elm, similar to interglacial assemblages of this region. Later, since the second Early Valdai cooling and up to the beginning of the Holocene, the Desna valley was constantly occupied by periglacial forest-steppe, steppe, forest-tundra and tundra existing under conditions of low temperature and precipitation not exceeding 350–450 mm per year.

ESR dates of marine mollusc shells falling within the limits of OIS 4–OIS 2 are also grouped in 6 intervals (see Fig. 5). The first group consisting of 6 dates falls on about 65 ka BP and indicates the first post-Mikulino global rise of sea level as a result of ice sheet melting at the time of the first Early Valdai (Ketrosy) Interstadial within a rather short isotope stage—OIS 4.

The second group includes 8 dates falling on the very beginning of OIS 3. The dates give grounds to place the second warming at about 56 ka BP; this palaeoclimatic signal may be confidently correlated with the 2nd peak in the continental palaeoclimatic record based of palynological data from the Arapovichi reference section.

The third group consists of 5 dates (40.0–47.5 ka BP) falling in the middle of OIS 3. Taken together they are indicative of the next warming and corresponding sea level rise during the Last Ice Age. The fourth interval, corresponding to the warmest interstadial identified in the pollen assemblages of the Arapovichi section, is represented as yet by only one date, ~32 ka BP.

The next amelioration of climate occurred at the very end of OIS 3. That was the last Middle Valdai warming and associated rise of sea level placed within 28.4 to 23.0 ka BP on the basis of 5 dates.

A single date ~17 ka BP marks the first post-glacial sea level rise. It agrees well with the Late Valdai Interstadial identified in the Arapovichi section, which is correlative with an interstadial dated by radiocarbon at 16.5–15.0 ka BP (Arslanov, 1992). In the section this interval corresponds to layers at a depth of 2.75 to 4.00 m. At the time of their deposition cryophytes of the fern and clubmoss group disappeared completely. Dominant were forests of pine (*Pinus sylvestris*), those of *P. sylvestris* and *P. sibirica*, and birch-pine forests with undergrowth of shrub birch, *Alnaster*, juniper and willows, and with dense cover of Polypodiaceae.

5. Conclusion

The results of studies may be summarised as follows:

1. Environmental changes on the East European Plain are proved to be in good agreement with global climatic changes; 8 interglacials and 7 intervening glacials have been identified over the Brunhes Epoch.
2. When compared with oxygen isotope curves, the climate-dependent marine transgressions dated by ESR and palynostratigraphic reconstructions of the Pleistocene climatic rhythms based on loess–palaeosol sequences, appeared to correspond to the upper 15 oxygen isotope stages. The loss of correlation with interglacial corresponding to "warm" OIS 13 in our climate-chronostratigraphic records seems to be corroborated by the results of recent analysis of the Antarctic (Dome C) ice core.
3. When considering a series of interglacials over the last 780 ka, a comparison between consecutive interglacial palynofloras in the most complete, almost continuous, Pleistocene sequences in the loess regions of the East European Plain and successions of phytocoenoses within interglacial climatic rhythms made it apparent that the Muchkap Interglacial was the must humid thermochron, the Likhvin Interglacial—the longest and warmest one, and the Mikulino Interglacial featured the most continental climate of all interglacials (except the Holocene). On the basis of ESR dates obtained, the Likhvin Interglacial may be confidently correlated with stage 11 of the oxygen isotope scale. The highest ocean levels also correspond to that interval.
4. There are two interglacials identified between Likhvin and Mikulino corresponding to OIS 9 and 7, as well as three glacial intervals (OIS 10, 8 and 6). Warmings at the time of OIS 9 and 7 were most probably of global occurrence.
5. Three global warmings of interstadial rank dated at about 184, 172 and 155 ka BP have been recognised within the Dnieper glacial epoch.
6. The last (Mikulino *s. lato*) Interglacial has an estimated age of 145–140 to 70 ka BP. During this interglacial, relatively short coolings and corresponding phases of low sea level repeatedly occurred. Pollen spectra clearly show three thermal maximums separated by considerable intra-interglacial coolings; pollen assemblages of the latter indicate a rather humid climate and are distinct for almost complete absence of thermophilic plants.
7. The Valdai glacial epoch featured much colder and continental climate. Palynological materials and ESR dating permitted to identify six interstadials within the Valdai glacial climatic rhythm dated at about 65, 56, 44, 32, 26 and 17 ka BP.
8. Comparison between ESR-chronostratigraphical levels on fauna-bearing warm-climate-related horizons of Eurasian North and phytocoenotic and climatic successions of interglacial climatic rhythms in the loess–palaeosol series of the East European Plain permits to conclude that the latter present a continuous stratigraphic sequence spanning at least the whole Brunhes Epoch; therefore, the results of pollen analysis of the loess–palaeosol series may be applied to global correlations of climate-dependent changes of environments in the ocean–land system.

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References

Alekseev, M.N., Borisov, B.A., Velichko, A.A., Gladenkov, Yu.B., Lavrushin, Yu.A., Shik, S.M., 1997. On general stratigraphic scale of the Quaternary system. Stratigraphy. Geological correlation 5 (5), 105–108 (in Russian).

Arslanov, Kh.A., 1992. Late Pleistocene geochronological scale of the Russian Plain. In: Murzaeva, V.E., Punning, J.-M., Chichagova, O.A. (Eds.), Geochronology of Quaternary Period. Nauka, Moscow, pp. 133–137 (in Russian).

Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J., Lancelot, Y., 1994. The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. Earth and Planetary Science Letters 126, 91–108.

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews 10, 297–317.

Bolikhovskaya, N.S., 1976. Palynology of loess and fossil soils of the Russian Plain. In: Agadjanian, A.K., Dobrideev, O.P. (Eds.), Problems of general physical geography and paleogeography. Moscow University Press, Moscow, pp. 257–277 (in Russian).

Bolikhovskaya, N.S., 1986. Paleogeography and stratigraphy of Valday (Wurm) loesses of the south-western part of the East-European Plain by palynological data. Problems of Stratigraphy and Paleogeography of Loesses. Annales Universitatis M. Curie-Sklodowska, Lublin, sect. B, XLI, 111–124.

Bolikhovskaya, N.S., 1989. About role of palynological data in stratigraphy of loess formation of Russian plain. In: Yanshin, A.L. (Ed.), Quaternary Period: Paleontology and Archaeology. Stiintsa, Kishinev, pp. 83–90 (in Russian, with English summary).

Bolikhovskaya, N.S., 1991. Paleogeography, stratigraphy and genesis of the loess–paleosol formation of Northern Eurasia (palynological data). GeoJournal. Kluwer Academic Publishers, Dordrecht/Boston/London 24 (2), 181–184.

Bolikhovskaya, N.S., 1995. The Evolution of Loess–Paleosol Formation of Northern Eurasia. Moscow University Press, Moscow 270pp. (in Russian).

Bolikhovskaya, N.S., 2000. Palynofloras and phytocoenotic successions of the Mikulino (Eemian) Interglacial period within different stratigraphic regions of the southern Eastern-European Plain. Paleontological Journal 34 (Suppl 1), 75–80.

Bolikhovskaya, N.S., Molodkov, A.N., 1999. On the correlation of the Quaternary continental and marine sediments of the Northern Eurasia by pollen data and results of ESR dating. In: Bolikhovskaya, N.S., Rovnina, L.V. (Eds.), Urgent Problems of Palynology on the Boundary of the Third Millenium. IGiRGI, Moscow, pp. 25–53 (in Russian, with English summary).

Bolikhovskaya, N.S., Molodkov, A.N., 2002. Dynamics of Pleistocene paleoclimatic events: a reconstruction based on palynological and electron spin resonance studies in North Eurasia. Archaeology, Ethnology and Anthropology of Eurasia 2, 2–21.

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, 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.

de Beaulieu, J.-L., Reille, M., 1984. A long upper Pleistocene pollen record from Les Echets, near Lyon, France. Boreas 13, 11–132.

Gaigalas, A., Molodkov, A., 1996. Geology and freshwater mollusc ESR-age of the Butėnai 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, Kerkrade, The Netherlands, September 6–11, 1998, p. 25.

Gaigalas, A., Molodkov, A., 2002. ESR ages of three Lithuanian Mid-Late Pleistocene Interglacials: methodical and stratigraphical approach. Geochronometria 21, 57–64.

GRIP Project Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. Nature 364, 203–207.

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.

Lambert, F., Bigler, M., Kaufmann, P., Stauffer, B., Castellano, E., Migliori, A., Udisti, R., Wolff, E.W., Jouzel, J., Ruth, U., 2003. Where is interglacial 13 in the Dome ice core? Findings from the dust and the chemical records. Presentation at the International Conference "Polar Regions and Quaternary Climate", San Feliu de Guixols, Spain, 04–09 October 2003.

Latvijas Stratigrafijas Komisja, 1994. Minutes of Latvian Stratigraphy Commission from 20th and 27th May, Riga.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.S., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0–300,000-year chronostratigraphy. Quaternary Research 27, 1–30.

Molodkov, A., 1995. EPR-chronostratigraphic data for the dynamics of the Pleistocene environments. In: Svitoch, A.A. (Ed.), Correlation of Palaeogeographical Events: Continent–shelf–ocean. Moscow University Press, Moscow, pp. 93–98 (in Russian with English summary).

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., Bolikhovskaya, N., 2002. Eustatic sea-level and climate changes over the last 600 ka as derived from mollusc-based ESR-chronostratigraphy and pollen evidence in Northern Eurasia. Sedimentary Geology 150, 185–201.

Molodkov, A., 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., Yevzerov, V., 2004. ESR/OSL ages of long-debated sub-till fossil-bearing marine deposits from the southern Kola Peninsula: stratigraphic implications. Boreas 33, 123–131.

Molodkov, A., Raukas, A., Makeev, V.M., Baranovskaya, O.F., 1992. 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.

Molodkov, A., Bolikhovskaya, N., Gaigalas, A., 2002. The last Middle Pleistocene interglacial in Lithuania: insights from ESR-dating of deposits at Valakampiai, and from stratigraphic and palaeoenvironmental data. Geological Quarterly 46 (4), 363–374.

Raukas, A., Kajak, K., 1995. Quaternary stratigraphy in Estonia. Proceedings of the Estonian Academy of Sciences, Geology 44 (3), 149–162.

Raukas, A., Gaigalas, A., 1993. Pleistocene glacial deposits along the eastern periphery of the Scandinavian ice sheets—an overview. Boreas 22, 214–222.

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.

Satkūnas, J., Kondratienė, O., 1995. Quaternary stratigraphic scheme of Lithuania for national geological mapping. INQUA XIV International Congress, Berlin, August 3–10, 1995. Abstracts. Terra Nostra, 239pp.

Sections of Deposits of the Central Russian Plain Glacial Regions, 1977. Moscow University Press, Moscow 189pp. (in Russian).

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.

Woillard, G.M., 1978. Grande Pile peat bog: a continuous pollen record for the last 140,000 years. Quaternary Research 9, 1–21.

Yakubovskaya, T.V., Velichkevich, F.Yu., Rylova, T.B., San'Ko, A.F., Khursevich, G.K., Zernitskaya, V.P., 2002. Stratigraphic scheme and problems of the Belarus Quaternary deposits correlation. In: 3rd All-Russian Meeting on Quaternary research. Smolensk, Conference Proceedings, September 2–7, 2002. I, pp. 147–150.

Zarrina, E.P., 1991. Quaternary deposits of the northwestern and central areas of the European part of the USSR. Nedra, Leningrad 187 pp. (in Russian).