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Middle–Upper Pleistocene bio-climatic and magnetic records of the Northern Black Sea Coastal Area

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Abstract

Loess-palaeosol sequences are widespread in the northern Black Sea coastal area. Unlike the quasi-continuous loess-palaeosol series in Central Asia and the Loess Plateau of China, the incomplete geological record of loess-palaeosol successions in Europe provokes different stratigraphical interpretations for different sections. Despite a long history of investigation, many uncertainties still remain in the geochronology of the regional stratigraphy. In this study, some of the most representative loess-palaeosol sections of Moldova, the Dniester Republic, Southern Ukraine and Southern Russia were examined. A multidisciplinary approach was used to establish stratigraphical markers. Seven palaeosols/pedocomplexes are distinguished within the Brunhes chron in the loess-palaeosol sequence in the studied area. The position of the Matuyama-Brunhes (M-B) reversal is drawn at the base of the Kolkotova palaeosol complex in the Khadzimus section. The Jaramillo subchron was revealed at the base of the loess formation. This magnetostratigraphic framework is confirmed by biostratigraphical data. Small mammals are valuable, serving as very important evidence for long-distance correlation. Paleopedological data combined with magnetic susceptibility profiles provide additional stratigraphic control for a loess-palaeosol correlation. The results allow us to conclude that the main paleoenvironmental changes occurred ca. 1 Ma ago when lagoon and alluvial sedimentation was replaced by increasing loess accumulaton. During some intervals, erosion or variation in the loess sedimentation rate at different sites are responsible for the variability of the loess-palaeosol alternation. The correlation of the loess-palaeosol succession in the Brunhes chron with marine oxygen isotope stages suggests that the beginning of the loess-palaeosol formation of the Middle Pleistocene was forced by more pronounced long paleoclimatic cycles than are noticed prior to the M-B reversal.

1. Introduction

The Middle–Upper Pleistocene loess-palaeosol formation and underlying alluvial and lagoon sediments are represented along the northern Black Sea and Azov Sea shorelines. In the coastal area the thickness of the loess formation attains 50 m while the visible thickness of subaqueous deposits does not usually exceed 10–20 m. The loess formation is replaced by marine deposits to the south of the Black Sea shelf and by glacial deposits to the north. Despite a long period of investigation (Velichko et al., 1973a, b; Velichko, 1975; Tretyak and Volok, 1975, 1982; Veklich, 1982; Tretyak, 1983; Faustov and Virina, 1989, 2001; Pokatilov and Bukatchuk, 1989; Tretyak et al., 1989; Mikhailesku and Markova, 1992; Gozhik et al., 1995; Tsatskin et al., 1998), uncertainties about stratigraphy and correlation of loess and palaeosol horizons remain. There is still no agreement on the stratigraphic position of Matuyama-Brunhes (M-B) geomagnetic reversal and on the interpretation of thermoluminescent (TL) dates. In this study, we examined eight of the most representative sections: Tiraspol, Khadzhimus, Varnitsa, Kolkotova Balka, and Komarova Balka in Moldova and the Dniester Republic, Roksolany/Nikoni in the Ukraine, and Pekla and Platovo in the Azov Sea area (Southern Russia) (Fig. 1). The main purpose of our investigation is therefore to clarify the scheme of the Middle and Upper Pleistocene deposits in the Black Sea coastal area using a

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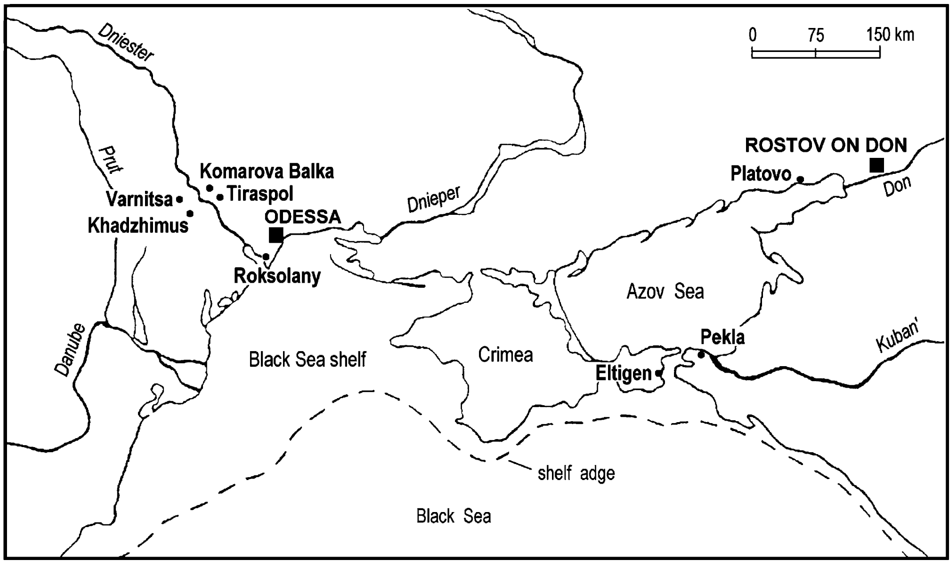

Fig. 1. Location map of studied sections of the Middle–Upper Pleistocene deposits along the Northern Black Sea and Azov Sea coastal area.

multidisciplinary approach, which involves paleontological, lithological, paleopedological, and magnetic analysis, as well as radiocarbon dating.

2. Biostratigraphy of lagoon and alluvial deposits

Several stratigraphic levels with mammal fauna in lagoon and alluvial deposits, underlying subaerial formation, are shown in Fig. 2. In the alluvial deposits of Khadzhimus, the large mammal fauna association includes *Archidiskodon meridionalis tamanensis* and *Dicerorhinus etruscus* which were found with a mollusc fauna of *Unio sturi* M. Hoern., *U. sturi* var. *rodsjankoi* Bog., and *Margaritana* sp. The same forms of large mammals (*A. m. tamanensis* and *D. etruscus*) characterize lagoon deposits in the Roksolany/Nikoni section. This large fauna, listed in guidebooks (Guidebook, 1982, 1984), corresponds to the Tamanian mammal age. New paleomagnetic data (Figs. 3 and 4) indicate that this fauna is older than the Jaramillo subchron.

Small mammals were determined from two layers in coarse channel sands of the Khadzhimus alluvial deposits. The lower layer includes remnants of *Hypolagus* sp., *Ellobius* ex gr. *kujalnikensis*, *Clethrionomys sokolovi*, *Borsodia petenyii*, *B. fejervaryi*, *Lagurodon arankae*, *Mimomys savini*, *Mimomys* ex gr. *reidi*–*M. pusillus*, *Mimomys pitymyoides*, and *Allophaiomys pliocaenicus deucalion*. The upper layer with small mammal fauna, lying 2 m above the lower one, differs from the lower layer by the occurrence of *Prolagurus ternopolitanus* (Table 1). The presence of *Mimomys pitymyoides*, *Mimomys* ex gr. *reidi*, *Borsodia petenyii,* and *Allophaiomys pliocaenicus deucalion* in the Khadzhimus section provides evidence for the latest phase of the Odessa small mammal complex (Late Villafranchian).

In the lagoon deposits of the Roksolany/Nikoni section, remains of *Ochotona* sp., *Clethrionomys* ex gr. *glareolus*, *Mimomys reidi*—*M. pusillus*, *M. savini*, *Lagurodon arankae*, *Prolagurus pannonicus*, *Laguridae* gen., and *Allophaiomys pliocaenicus* were found (Mikhailesku and Markova, 1992). This fauna, being younger than fauna from Khadzhimus, can be correlated with the Nogaisk fauna complex that corresponds to the Tamanian complex of large mammal fauna. The upper age limit for small faunas in Khadzhimus and Roksolany/Nikoni is the lower boundary of the Jaramillo subchron. Based on small mammals and new paleomagnetic measurements in the studied section, we conclude that the lower boundary of the Tamanian fauna is older than the lower limit of the Jaramillo subchron (>1.1 Ma).

The next, younger mammal age is the Tiraspol one, which is represented in the Tiraspol alluvium (Tiraspol and Kolkotova Balka sections). The Tiraspol large mammal fauna includes: *Canis* sp., *Vulpes* sp., *Ursus deningeri*, *Pachycrocuta* sp., *Panthera* sp., *Archidiskodon trogontherii* (= *wüsti*), *Equus* aff. *süssenbornensis*, *E.* cf. *mosbachensis*, *Dicerorhinus etruscus* (late form), *D. kirchbergensis* (or *D. merki*), *Paracamelus* sp., *Bison schoetensacki*, *Alces latifrons*, *Praemegaceros verticornis*, *Praedama* cf. *süssenbornensis*, and *Cervus acoronatus*. Large mammal bones were excavated mainly in the lower and upper parts of alluvial strata and apparently characterize a unified fauna stage, which corresponds to the early Middle Pleistocene (Nikiforova et al., 1971; Stratigraphy of the USSR, 1982). The Tiraspol mammals differ from the more ancient Tamanian fauna by the presence of *Archidiskodon trogontherii*, as well as by the abundance and diversity of deer.

Small mammal remains were collected from three levels in the alluvial "Tiraspol Gravel" by Alexandrova (1976) (see Table 1). The lower level yielded small mammal

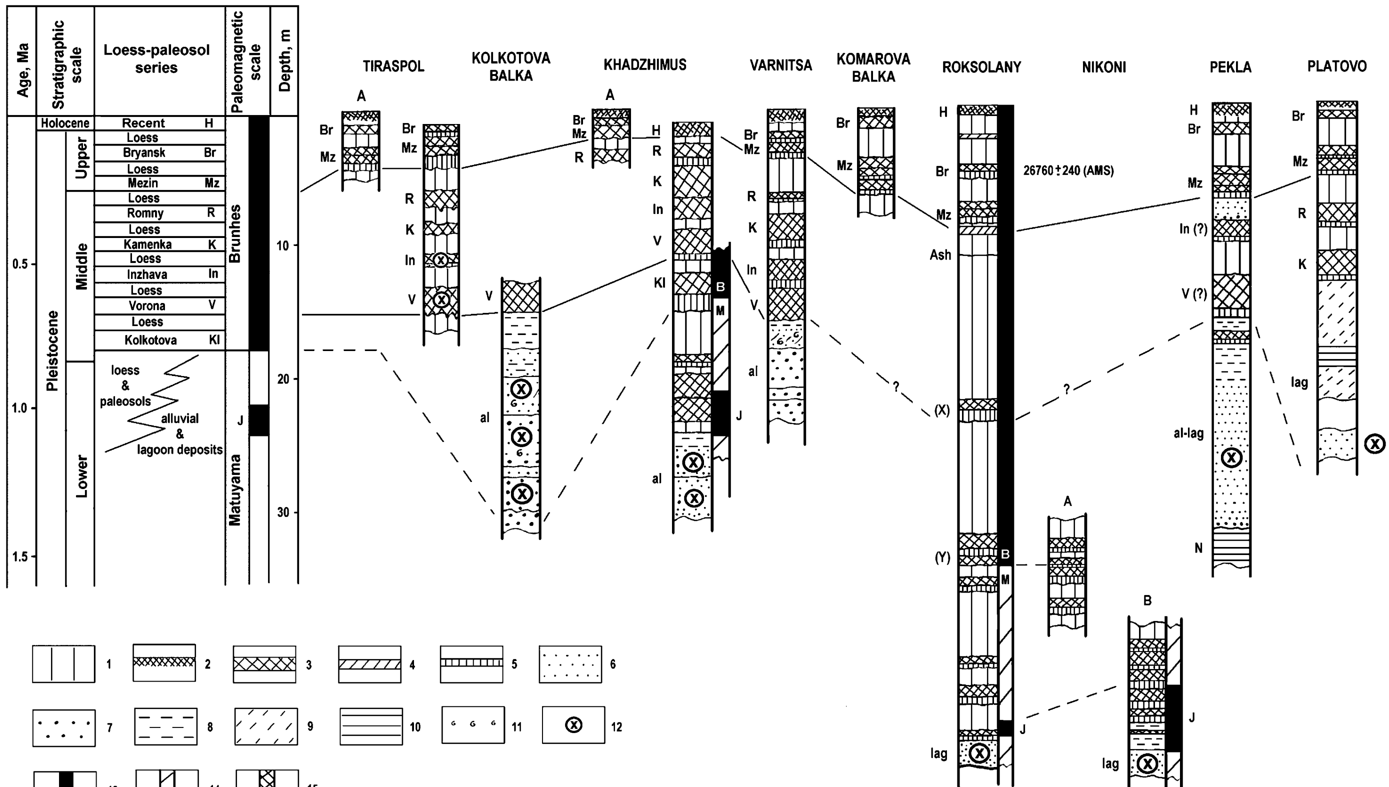

Fig. 2. Correlation scheme of the Middle–Upper Pleistocene deposits in the studied area. 1—loess, 2—recent soil, 3—palaeosol, 4—weakly developed palaeosol, 5—illuvial carbonate horizon, 6—sand, 7—gravel, 8—aleuvrite, 9—loam, 10—clay, 11—mollusc fauna, 12- mammal fauna; magnetization: 13—normal, 14—reversed, 15—anomalous. B—Brunhes chron; M—Matuyama chron; J—Jaramillo subchron.

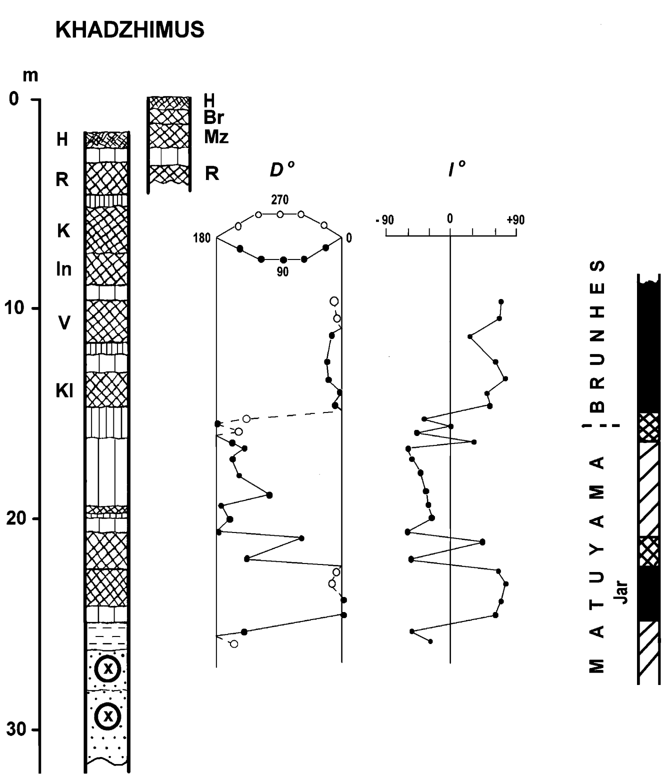

Fig. 3. Khadzhimus section and its paleomagnetic characteristic (for legend see Fig. 2).

remains: *Spalax* sp., *Citellus* sp., *Allactaga* sp., *Ellobius*., *Clethrionmys* cf. *glareolus* Shreb., *Prolagurus posterius* Zazhigin, *Lagurus* cf. *transiens* Janossy, *Eolagurus* cf. *luteus* Eversm., *Mimomys intermedius* Newton, *M. savini* Hinton, *M. majori* Hinton, *Pitymys arvaloides* Hinton, and *Microtus arvalinus* Hinton. The middle level, studied by Alexandrova, includes: *Ochotona* sp., *Spalax* sp., *Cricetus* sp., *Clethrionomys* cf. *glareolus* Shreb., *Mimomys intermedius* Newton, *M. majori* Hinton, *Pitymys arvaloides* Hinton, *P.* cf. *hintoni* Kretzoi, *Microtus arvalinus* Hinton, *M. nivaloides* F. Major, and *M. ratticepoides* Hinton. In the upper level of the alluvial deposits *Citellus* sp., *Allactaga* sp., *Ellobius* sp., *Lagurus* aff. *lagurus* Pall., *Praedicrostonyx* sp., and *Pitymys gregaloides* Hinton were defined. The fauna from the upper level of the "Tiraspol Gravel" was given the name "Nistrus association" in descriptions by Alexandrova (1976). As a whole, the small mammal fauna from the Tiraspol alluvium correlates with analogous fauna from the middle part of the West European Cromerian.

In the Pekla section, on the northern coast of the Taman Peninsula, new material on small mammals from alluvial-lagoon deposits yielded: *Spermophilus* sp., *Eolagurus gromovi, Mimomys* sp., *Microtus* (*Terricola*) *arvalidens*, *Microtus arvalinus*, *Microtus* ex. gr. *oeconomus*, and *Microtus* sp. This association corresponds to the advanced level of small mammals in the Tiraspol assemblage.

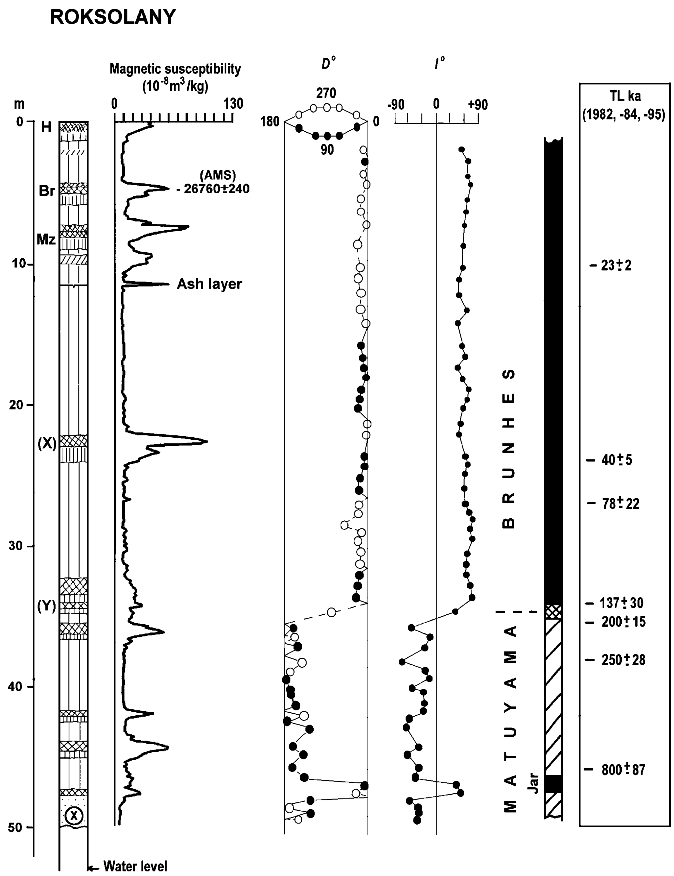

Fig. 4. Roksolany section and its magnetic characteristic. Thermoluminescence (TL) dates are given according to Guidebooks (1982, 1984) and after Gozhik et al. (1995).

3. Loess-palaeosol sequence

Loess horizons and palaeosols were used as the main climatostratigraphical subdivisions for regional and interregional correlation. Among the studied sections, the most complete loess-palaeosol succession is represented at three sites: Tiraspol, Khadzhimus and Varnitsa (Fig. 2). Seven palaeosols (some of which pedocomplexes) were determined in the loess formation of the Brunhes epoch. Below the recent soil (H), the following palaeosols were recognized (from top to bottom): Bryansk (Br), Mezin (Mz), Romny (R), Kamenka (K), Inzhava (In), Vorona (V), and Kolkotova (Kl). We used the nomenclature of the existing stratigraphic scheme compiled by Velichko with co-authors (Velichko, 1990; Velichko et al., 1992, 1997). All these palaeosols are recorded in the Khadzhimus section, but the lowest Kolkotova palaeosol is replaced by alluvium in the Tiraspol and Varnitsa sections (Fig. 2). Other loess-palaeosol sections in the studied area are less complete but they are very important for stratigraphical correlations.

The most puzzling loess-palaeosol succession is observed in the Roksolany/Nikoni section located in the Dniester liman. In this section, the Bryansk palaeosol and Mezin pedocomplex are recognized in the upper part of the subaerial sequence; the red-brown palaeosol (conventionally—*X*) and triple soil complex (*Y*) were established in the middle part of the loess stratum (Fig. 4). It should be noted that our stratigraphical interpretation of the upper part of this section differs from that suggested by Tsatskin et al. (1998) which is discussed below. The M-B reversal is recorded beneath two soils in the triple soil complex. It is remarkable that palynological data revealed prominent changes beneath the Mezin pedocomplex, at a depth of 11–12 m, where a thin (2–3 cm) ash layer was found. In the lower part of the loess (22–12 m), many exotic forms such as *Tilia multiflora, Tilia caucasica, Cedrus,* Taxodiaceae, and *Fagus* are characteristic, pointing to a relatively old age for this interval, while at the top of the loess (12–9 m), herbs predominate with very small amounts of pollen grains of *Betula, Alnus, Carpinus orientalis,* and *Elaeagnus*. Such changes in the paleovegetation can be interpreted as indirect evidence of a sedimentation gap indicating a stratigraphical unconformity. In the ash layer, tephra material is mixed with loess. According to Murav'ev and Tsekhovski (personal communication), a basaltic composition of volcanic glasses (1–2% content) is excluded. It is proposed that the ash from Roksolany can correlate with ashes of trachytic composition known from sites near Kishinev, Sofievka settlement (Lower Dniepr), and Lake Staroe (north of Crimea Peninsula), where according to geological data the age of the tephra was determined in the range Late Riss–Würm (Tsekhovski et al., 1998).

Paleomagnetic measurements in Khadzhimus put the M-B reversal at the base of the Kolkotova soil complex (Fig. 3). Three palaeosols in the Khadzhimus and about eight palaeosols in the Nikoni sections were established below the M-B boundary. The completeness of loess-palaeosol series below the M-B boundary is not consistent from section to section, depending on facial replacements and hiatuses. The better pronounced buried soils below the M-B reversal are represented in the Nikoni section (Fig. 2). The position of the Jaramillo subchron in the lower part of loess-palaeosol formation (Khadzhimus, Roksolany, Nikoni) proves that loess sedimentation started in the studied region definitely not later than 1 Ma ago.

The subaerial sequence is characterized by a great variety of palaeosols. Chernozems, brown and red-brown soils are distinguished. Some palaeosols/pedocomlexes have two- or three-fold structures.

The Bryansk palaeosol consists of brownish-pale poorly structured loam, slightly enriched by humus; a cryogenic microstructure is noticed, and krotovinas are observed at the basal part of the soil profile. It can be assigned to brown coloured steppe soil, slightly leached, with a poorly expressed illuvial-carbonate horizon. Palynological data on Roksolany show that the Bryansk palaeosol was formed in xeric conditions with forest-steppe and steppe vegetation. It should be noted that the recent soil often lays over the Bryansk soil, partly truncating it. A new AMS radiocarbon date (OxA-7970) of 26,760 ± 240 yr BP on humic matter from the Bryansk palaeosol in the Roksolany/Nikoni

Table 1
The distribution of small mammals in the studied sections of the northern Black Sea and Azov Sea coastal area. (see text for all comments)

Mammals \ Locations, horizons, sediments	Tiraspol Inzhava paleosol	Tiraspol Vorona paleosol	Pekla Lagoon deposits	Kolkotova Balka "Tiraspol Gravel" Upper level	Kolkotova Balka "Tiraspol Gravel" Middle level	Kolkotova Balka "Tiraspol Gravel" Lower level	Roksolany/Nikini Lagoon deposits	Khadzhimus Alluvium Upper level	Khadzhimus Alluvium Lower level
INSECTIVORA:									
Crocidura sp.								×	
LAGOMORPHA:									
Hypolagus sp.									×
Ochotona sp.					×		×		×
RODENTIA:									
Spermophilus sp.			×	×		×		×	×
Spermophilus (*Spermophilus*) sp.	×	×							
Castor sp.									×
Spalax sp.					×	×			
Spalax microphtalmus	×	×							
Allactaga ex gr. *major*	×	×							
Allactaga sp.				×		×			
Ellobius ex gr. *kujalnikensis*									×
Ellobius sp.				×		×			
Allocricetus ehiki	×	×							
Cricetus cricetus		×							
Cricetus sp.					×				
Clethrionomys sokolovi									×
Clethrionomys ex gr. *glareolus*	×				×	×	×		
Praedicrostonyx sp.[a]				×					
Borsodia petenyii								×	×
Borsodia fejervaryi								×	×
Lagurodon arankae							×		×
Prolagurus ternopolitanus								×	
Prolagurus pannonicus							×		
Prolagurus posterius						×			
Lagurus transiens	×	×			×	×			
Lagurus aff. *lagurus*	×			×					
Eolagurus gromovi			×						
Eolagurus luteus volgensis	×	×							
Eolagurus cf. *luteus*[a]						×			
Laguridae gen.							×		
Mimomys pitymyoides								×	×
Mimomys ex gr. *reidi* – *M. pusillus*							×	×	×
Mymomys savini						×	×		×
Mimomys intermedius[a]					×	×			
Mimomys majori[a]					×	×			
Mimomys sp.			×						
Allophaiomys pliocaenicus deucalion								×	×
Allophaiomys pliocaenicus							×		
Microtus (*Stenocranius*) *hintoni*					×				
Microtus (*Stenocranius*) *gregaloides*				×					
Microtus (*Stenocranius*) *gregalis*		×							
Microtus (*Terricola*) *arvalidens*			×		×	×			
Microtus arvalinus			×		×	×			
Microtus nivaloides[a]					×				
Microtus ratticepoides[a]					×				
Microtus ex gr. *oeconomus*			×						
Microtus ex gr. *agrestis*	×								
Microtus sp.	×		×						

[a]After L.P. Alexandrova (1976).

section provides a valuable geochronological constraint on the upper part of the section.

The Mezin pedocomplex consists of two or three superimposed palaeosols. For instance, in the Roksolany section the upper palaeosol is red-brown composed of loam with blocky structure; the middle palaeosol is a chernozem-like decalcified soil consisting of gray-brown coloured loam with indications of degradation under the influence of upper soil formation. The absence of primary carbonates in the middle chernozem soil can be explained by its development under forest-steppe conditions. In this section, the lower unit of the Mezin pedocomplex is represented by calcified loess, strongly reworked by krotovinas. At the Komarova Balka section, the Mezin pedocomplex has a more prominent three-fold structure. The two upper units are represented by red-brown paleosoils, whereas the lower unit is a well-developed chernozem. Palynological data for the Mezin pedocomplex in Roksolany demonstrate the predominance of forb steppes during the chernozem phase and some extension of forest phytocoenosis with *Betula*, *Pinus*, and *Picea* for the late phase. Small (width up to 10 cm) cryogenic wedges filled with loess were noticed in the upper palaeosol of the Mezin pedocomplex at the Roksolany section.

Well-developed Romny, Kamenka and Inzhava palaeosols are represented in the middle part of the Khadzhimus and Tiraspol sections. The Romny soil consists of reddish-brown loam, enriched by ferruginous-clayey plasma with an admixture of humus; most likely it can be defined as a chernozem-like soil of steppe and forest-steppe with a xerophylous forest stage of brownozem soil formation in the early stage of development. Rather frequently the profile of the soil is punctuated by vertical tortuous cracks (drying cracks), filled with pale loess. The Kamenka soil is a well-developed weakly decalcified chernozem with krotovinas. The Inzhava palaeosol is represented by a grayish-brown loam with a reddish shade, structured, with calcareous concretions; microzonal accumulation of clayey plasma is microscopically documented; primary carbonates and secondary formed microcrystalline calcite are present. Apparently, the Inzhava palaeosol was formed as a result of superposition of semi-arid soil on the chernozem; a xerophylous forest phase is possible in the early stage of development.

In the Pekla section, the lack of the Romny and Kamenka palaeosols is proposed due to erosion between the Inzhava palaeosol and the Mezin pedocomplex. This interval is represented by a sandy layer.

In the Tiraspol section, the Inzhava fossil soil contains bone remains of small mammals: *Spermophilus* (*Spermophilus*) sp., *Allactaga* ex gr. *major* Kerr, *Spalax microphtalmus* Guld., *Allocricetus ehiki* Schaub, *Clethrionomys* ex gr. *glareolus* Schreb., *Lagurus transiens* Janossy–*Lagurus lagurus* Pall., *Eolagurus luteus volgensis* Alex., *Microtus* ex. gr. *agrestis*, and *Microtus* sp. (Table 1). In this soil a considerable part of the finds of rodent bone remains is connected with krotovinas. The fauna composition includes steppe species and sporadic forest forms of animals. Taking into account the species composition and morphotype of teeth, the small mammal fauna from the Inzhava palaeosol correlates with the Likhvin interglacial fauna from the Russian Plain and the Holstein interglacial fauna from Western Europe (Markova, 1998, 1999).

The Vorona pedocomplex is recognized in the Tiraspol, Khadzhimus and Varnitsa sections. Two horizons are defined in its structure—Bm and Bmt, which are formed by red-brown loam. The massive structure and lack of clay illuviation is characteristic for the upper Bm horizon, whereas a blocky structure and clay illuviation are typical for the underlying Bmt horizon. Clayey plasma and secondary formed carbonates, involved in the pedoturbated structure, are microscopically fixed in both horizons. Horizon Bm is pierced by tortuous cracks from the top to bottom, which can be traced to the Bmt horizon. Such cracks may reflect processes of periodic drying out during the latest stage of soil development. The Vorona pedocomplex, which can be regarded as red-brown, passed through not less than two stages of formation: the first one took place in a humid climate and with forest vegetation, the second occurred in conditions of a relatively arid climate and a xerophylous forest.

In the red-brown Vorona pedocomplex in the Tiraspol section, where it overlays Tiraspol alluvium, the following small mammals were defined: *Spermophilus* (*Spermophilus*) sp., *Allactaga* ex gr. *major* Kerr, *Spalax microphtalmus* Guld., *Allocricetus ehiki* Schaub, *Cricetus cricetus* L., *Lagurus transiens* Yanossy, *Eolagurus luteus volgensis* Alex., and *Microtus* (*Stenocranius*) *gregalis* Pall. (Table 1). Evolutionary this fauna is considered to be of Tiraspol age. The Vorona palaeosol fauna correlates with the Muchkap fauna from the Don River basin (Markova, 1998, 1999). This allows us to correlate the Vorona palaeosol with the Muchkap interglacial horizon overlying the Don moraine.

The palynological data from the Roksolany section show that the red-brown palaeosol (*X*), at a depth of 22–24 m, is characterized by a moderate prevalence of arboreal pollen spectra. Pollen grains of *Picea*, *Picea* sect. *Omorica*, *Pinus* sp., *Pinus* sg. *Haploxylon*, *Pinus* sect. *Strobus* are noticeable. Rarely identified were pollen grains of *Liquidambar*, *Ostrya*, Moraceae, *Acer*, and *Ulmus*, and spores of Polypodiaceae, Filicales, and *Microlepia*. Herbs are represented by Asteraceae, Chenopodiaceae, Cyperaceae, and Polygonaceae. Forest-steppe and steppe paleolandscapes were predominant during formation of this red-brown soil. The composition of palynospectra of red-brown soil in Roksolany and a comparison with pollen data from Ukrainian and Moldavian sections (Grichuk, 1989; Bolikhovskaya, 1995) suggest its correlation with the lower Middle Pleistocene palaeosol unit of the Vorona pedocomplex.

The Kolkotova pedocomplex is represented by red-brown loam with vertical cracks (1–5 cm wide) filled with reddish-pale loess. The cracks must have been formed as a result of periodic drying of the soil. Horizon Bmt has a blocky structure, and clayey-manganese films are noticed on structural particles. The absence of primary carbonate is microscopically confirmed and there are accumulations of secondary calcite in some microzones localized mostly around the porous spans. According to morphological characteristics, the similarity of the Kolkotova and Vorona pedocomplexes seems to be obvious, although the former has less rubefication.

It is important to note a considerable content of slightly weathered glauconite in the loess fraction throughout the Roksolany section. This shows that the marine shallow water deposits, which underwent active deflation during marine regressions, were one of the sources of dust material.

4. Magnetic susceptibility record

Magnetic susceptibility (χ) measurements are widely applied in loess-palaeosol studies. Research of the magnetic characteristics of loess-palaeosol formation in north China and Central Asia demonstrates their high stratigraphic and paleoclimatic potential (Kukla, 1987; Heller et al., 1987; Kukla et al., 1988; Zhou et al., 1990; Forster and Heller, 1994; Dodonov et al., 1999). Previous studies in Moldova and in south Ukraine and Russia confirmed the value of high resolution magnetic susceptibility profiles in loess-palaeosol successions (Pospelova and Levkovskaya, 1994; Tsatskin et al., 1998, 2001; Virina et al., 2000). In our investigation, the sampling interval is 10 or 15 cm and measurements were made using a Bartington MS2. We aimed to get additional data for a regional correlation of loess-palaeosol formation. The low-field magnetic susceptibility record shows high peaks for palaeosols ranging from 30 to 110–120 $\times 10^{-8}$ m^3/kg, and a low signal for loess of 15–30 $\times 10^{-8}$ m^3/kg (Fig. 5). Recent soil has variable χ values from 50–60 to 100–110 $\times 10^{-8}$ m^3/kg depending on the completeness of the soil profile, since truncated soils usually lose the part with the highest χ reading.

A comparative analysis of magnetic susceptibility profiles between sections shows a relatively low signal in the Varnitsa section, which can be explained by less-developed palaeosol profiles due to the geomorphological position of this site. This section is located close to the inner part of the terrace where palaeosols obviously have been subjected to slope processes. The Bryansk palaeosol was truncated at many sites, which resulted in the lowering of its magnetic susceptibility parameter. Relatively higher χ values for the Bryansk palaeosol enriched by humus or organic matter were determinded in the Roksolany section. The Mezin soil complex has a double χ peak in the Tiraspol, Pekla, Roksolany and Platovo sections (Figs. 4 and 5). The ash layer in the Roksolany section gives a very sharp peak which is not seen at other sites. The magnetic susceptibility record of the Romny, Kamenka and Inzhava palaeosols is very distinct in the Tiraspol and Khadzhimus sections, which is expressed as a triple fluctuation with the highest χ value in the middle corresponding to the Kamenka palaeosol (Fig. 5). The Inzhava palaeosol has a reduced peak in both sites because it was partly eroded or

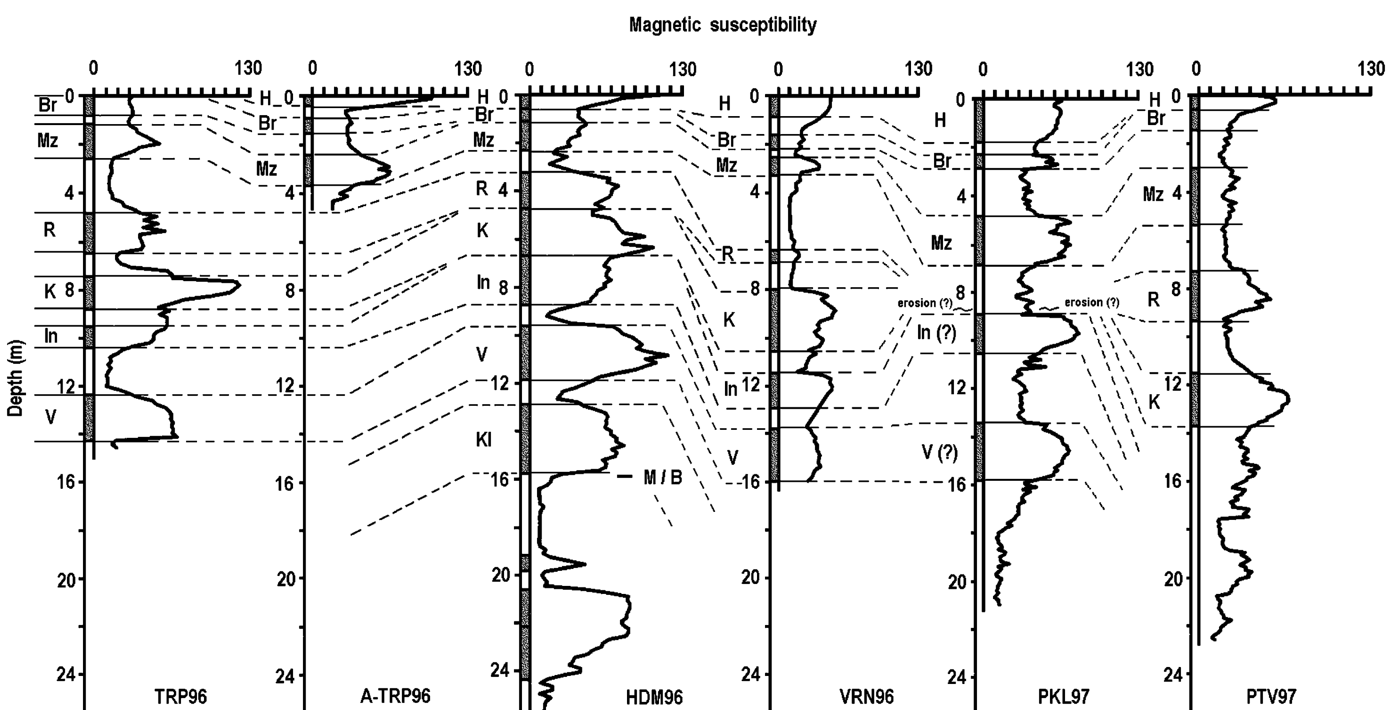

Fig. 5. Correlation of magnetic susceptibility ($\times 10^{-8}$ m^3/kg) curves of loess-palaeosol sections: Tiraspol (TRP96, A-TRP96), Khadzhimus (HDM96), Varnitsa (VRN96), Pekla (PKL97), Platovo (PTV97). M/B–M-B reversal. For indexes of palaeosols (Br, Mz, R, K, In, V, Kl) see Fig. 2.

reworked by the soil above. In the Varnitsa section, the Romny palaeosol is very weakly developed and has very low χ values, whereas at Platovo the magnetic susceptibility characteristic is comparable with those at Tiraspol and Khadzhimus. It is noticeable that the Kamenka palaeosol displays a consistent χ signal in studied sections with more expressed χ peaks in Tiraspol and Khadzhimus. The absence of Romny and Kamenka palaeosols in the Pekla section can be explained by erosion. The Vorona palaeosol complex is characterized by a relatively high χ peak in all studied sections. The Kolkotova soil complex measured in Khadzimus yielded a well-pronounced magnetic susceptibility signal which is slightly lower than χ values of the Vorona soil complex. Generally speaking, in the Middle and Upper Pleistocene subaerial strata the magnetic susceptibility signal is variable for palaeosols depending on the morphological pattern of soil profiles and paleoenvironmental conditions. Palaeosols subjected to erosion and hydromorphism or reworked and truncated by overlapping soils have reduced χ values.

5. Discussion

The M-B boundary is one of the most important stratigraphic markers for Eurasian loess sequences although its exact position is still under discussion (Zhou and Shackleton, 1999). According to the new paleomagnetic measurements on the Khadzhimus section, the M-B reversal is drawn at the base of the Kolkotova pedocomplex, unlike the previous positioning of the M-B boundary determined by Tretyak and Volok (1975, 1982) and Tretyak (1983), who interpreted it as lying between subaqueous sediments and the loess-palaeosol stratum. Our paleomagnetic data for the location of the M-B boundary in the Roksolany section coincide with the data of Tsatskin et al. (1998).

At the top of the Roksolany section, there are two palaeosol units considered as the Bryansk palaeosol and Mezin pedocomplex, as well as a weakly developed humus layer in the loess horizon above the Bryansk soil. A new AMS radiocarbon date of $26{,}760 \pm 240$-year BP for the Bryansk palaeosol in the Roksolany section supports its stratigraphical position and allows a more reliable stratigraphical interpretation for the Mezin palaeosol complex located beneath it. We should add that this radiocarbon date lies within the range of the age period 30 ± 1–23 ± 1 ka radiocarbon years for the Bryansk palaeosol, provided by many radiocarbon determinations (Chichagova and Cherkinsky, 1993). The ash layer represented at a depth of 11.5 m, below the Mezin pedocomplex, gives additional age control, being evidently not older than the late Riss. Such a geochronological understanding for the top of the Roksolany section is in contradiction with TL dates published in Guidebooks (1982, 1984) (Fig. 4), as well as with the stratigraphical interpretation suggested by Tsatskin et al. (1998). The last interglacial interval equal to Oxygen Isotope Stage 5 suggested in the latter work for the Bryansk palaeosol cannot be accepted on account of the new radiocarbon date. Moreover, an underestimation of the TL dates in the upper part of the Roksolany section is obvious. A similar TL age underestimation must exist in the middle and lower part of the Roksolany section. In this connection, the Roksolany section represents an example of very complicated relationships between paleopedological and geochronological data. Many TL dates, especially below the Mezin pedocomplex in the area of the northern Black Sea shore, strongly require reconsideration. Such a situation of TL underestimation for the upper-Middle and Upper Pleistocene interval took place in other loess provinces, for example Hungary, the Rhine Valley, Tadjikistan, and Uzbekistan (Singhvi et al., 1989; Frechen, 1992; Zhou et al., 1995; Dodonov et al., 1999). More recent developments in optical dating offers a promising opportunity to obtain more accurate time controls on loess sequence (Roberts and Wintle, 2001; Zhou and Shackleton, 2001; Little et al., 2002).

The loess sedimentation rate in the northern Black Sea coastal area was very irregular, resulting in thickness variability of loess horizons from site to site. The most changeable sedimentary environment occurred in the mouth of the Dniester river (Roksolany section, Dniester lagoon), where a huge quantity of silt material provided by the Paleo-Dniester was blown away and settled down in the surrounding area. This mechanism would not have been very consistent due to changes in the disposition of the Paleo-Dniester delta, resulting in either an increase in the thickness of loess horizons or an absence of some soils due to erosion and strengthening of deflation processes.

As for marker horizons we should emphasize that at the top of the sections the Bryansk palaeosol and Mezin pedocomplex are well recognized. Generally, the Bryansk palaeosol is situated just underneath the recent soil being partly truncated by the latter. The Mezin soil complex consists of two or three palaeosols. The three-fold structure of the Mezin pedocomplex is well expressed in the sections of Komarova Balka and Pekla.

At the base of the loess-palaeosol succession, the Jaramillo subchron and M-B reversal are the main geochronological markers for the studied sections. The location of paleomagnetic events is in agreement with biostratigraphical data. In the Khadzhimus and Roksolany/Nikoni sections the large mammal fauna with *Archidiskodon meridionalis tamanensis* and *Dicerorhinus etruscus*, assigned to the Tamanian complex, derives from the level below the Jaramillo subchron.

The next, younger marker is the Tiraspol biostratigraphical horizon, which is recorded in the "Tiraspol Gravel" in the Tiraspol and Kolkotova Balka sections. The Tiraspol complex is represented by the forms: *Archidiskodon trogontherii* (= *wüsti*), *Equus* aff. s*üssenbornensis*, *E.* cf. *mosbachensis*, and *Dicerorhinus etruscus* (late form), as well as by small mammals. As a whole, the small mammal fauna from the Tiraspol alluvium is correlated with the analogous fauna from the middle part of the Cromerian in

Western Europe. New findings of small mammals in lagoon sands of the Pekla section correspond to the Tiraspol mammal assemblage, supporting the early Middle Pleistocene age for the lower part of the subaerial formation.

It is remarkable that in the lower part of the loess-palaeosol succession within the Brunhes chron of the studied sections, the Inzhava palaeosol and Vorona pedocomplex contain small mammals. The red-brown Vorona pedocomplex is a very well-pronounced regional marker horizon, which is characterized by a relatively high peak of magnetic susceptibility. A small mammal assemblage of the Vorona pedocomplex is considered as of late Tiraspol association. It corresponds to the Muchkap fauna of the Don River basin which provides a reason to correlate the Vorona pedocomplex with the Muchkap interglacial horizon. It is known that the Muchkap Interglacial consists of at least two optimums. It should be mentioned that so far there is no agreement regarding the correlation of Muchkap with the oxygen isotope stages (Velichko et al., 1997; Krasnenkov et al., 1997; Iossifova, 2001). The precursor of the Don glaciation is the most pronounced glacial event in the early Middle Pleistocene, which can be reasonably correlated with the deep fluctuation of cold Stage 16 in the oxygen isotope record. Such a correlation of the Don glaciation would allow us to assign the Vorona pedocomplex to stages 13 and 15, δ^{18}O. The small mammal fauna from the Inzhava palaeosol corresponds to the Likhvin interglacial fauna in Eastern Europe (Markova, this volume). According to these data, the correlation of the Inzhava palaeosol with stage 11, δ^{18}O, seems to be the most probable.

6. Conclusions

The composition and facial features of the Lower and Middle Pleistocene deposits in the northern Black Sea coastal area demonstrates that the main paleoenvironmental shift took place ca. 1 Ma ago. At this time, the lagoon and alluvial-deltaic sedimentation was replaced by increasing loess accumulation. Changes of sedimentation processes were obviously connected to the late phase of the Gurian regressive basin which developed in the Black Sea depression during the Early Pleistocene (Tchepalyga, 1997). This geological event represents a major shift to arid and relatively cool conditions in the region.

Similar to other loess areas in Europe, we are faced with many uncertainties in the loess and palaeosol alternation due to the variability of depositional processes and erosion. Fig. 6 gives a summary of the data obtained, combining the paleomagnetic characteristics, main mammal ages, loess-palaeosol successions, and correlation with marine oxygen isotope stages. In the northern Black Sea coastal area, seven horizons of fossil soils/pedocomplexes are recognized within the Brunhes chron. The M-B boundary at the base of the Kolkotova pedocomplex serves as a marker for long-distance correlation. According to paleomagnetic data the

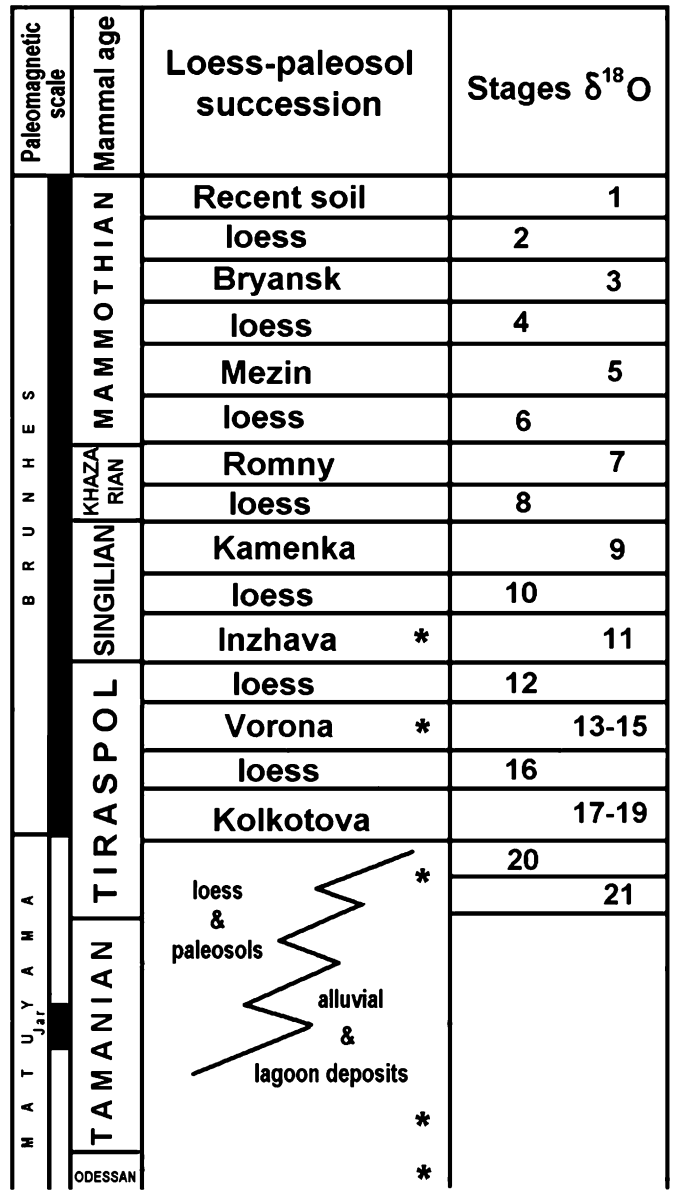

Fig. 6. The principal stratigraphic scheme of loess-palaeosol succession for the northern Black Sea and Azov Sea coastal area and its correlation with marine oxygen isotope stages. Asterisk shows the position of mammal fauna. Jar—Jaramillo subchron.

lower boundary of the Tamanian mammal age should be placed at a level definitely below the Jaramillo subchron. Consequently, the two strongly developed Kolkotova and Vorona pedocomplexes within the Brunhes chron apparently correspond to two joined warm stages 17–19 and 13–15, δ^{18}O. The M-B reversal at the basal part of the Kolkotova pedocomplex serves as a marker point for this interpretation. Such a stratigraphical correlation is in accordance with a similar interpretation of the stratigraphical position and correlation with the oxygen isotope curves of the strongly developed palaeosol F6 and the superimposed palaeosols F7-F8 in the Stari Slankamen section of Central Europe, as suggested by Bronger et al. (1998). The new AMS radiocarbon date for the Bryansk palaeosol at the top of the Roksolany outcrop allows us to improve the geochronology of the Upper Pleistocene loess-palaeosol strata in this section. Our version of the loess-palaeosol correlation with oxygen isotope stages suggests that during the Middle Pleistocene the development of loess and palaeosol horizons was forced by more pronounced long paleoclimatic cycles than those observed (Nikoni section) below the M-B reversal.

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References

Alexandrova, L.P., 1976. Anthropogene Rodents of the European Part of USSR. Nauka, Moscow 96pp. (in Russian).

Bolikhovskaya, N.S., 1995. Évolyutsiya lessovo-pochvennoj formatsii Severnoj Evrazii (The Evolution of Loess-Paleosol Formation of Northern Eurasia). Moscow University Press, Moscow (in Russian).

Bronger, A., Winter, R., Sedov, S., 1998. Weathering and clay mineral formation in two Holocene soils and buried paleosols in Tadjikistan: towards a Quaternary paleoclimatic record in Central Asia. Catena 34, 19–34.

Chichagova, O.A., Cherkinsky, A.E., 1993. Problems in radiocarbon dating of soils. Radiocarbon 35 (3), 351–362.

Dodonov, A.E., Shackleton, N., Zhou, L.P., Lomov, S.P., Finaev, A.F., 1999. Quaternary loess-paleosol stratigraphy of Central Asia: geochronology, correlation and evolution of paleoenvironments. Stratigraphy and Geological Correlation 7 (6), 581–593.

Faustov, S.S., Virina, E.I., 1989. Problems of paleomagnetic stratigraphy of loess-soil formation in Ukraine and Moldova. In: Alekseev, M.N., Nikiforova, K.V. (Eds.), Quaternary Period. Stratigraphy. Nauka, Moscow, pp. 96–102 (in Russian).

Faustov, S.S., Virina, E.I., 2001. About the stratigraphic position of the Matuyama-Brunhes boundary in loess formation of the Russian Plain. Bulletin of the Commission on Quaternary Research 64, 21–31 (in Russian).

Forster, Th., Heller, F., 1994. Loess deposits from the Tajik depression (Central Asia): magnetic properties and paleoclimate. Earth and Planetary Science Letters 128, 501–512.

Frechen, M., 1992. Systematic thermoluminescence dating of two loess profiles from the Middle Rhine area, FRG. Quaternary Science Review 11, 93–101.

Gozhik, P., Shelkoplyas, V., Khristoforova, T., 1995. Development stages of loessial and facial formation in Ukraine (Stratigraphy of loess in Ukraine). Lublin. Annales Universitae Mariae Curie-Sclodowska. Sec. B. 50, 65–74.

Grichuk, V.P., 1989. The History of Flora and Vegetation of the Russian Plain during the Pleistocene. Nauka, Moscow 183pp. (in Russian).

Guidebook for Excursions A-7, C-7, 1982. Moldovia and the Odessa Region XI Congress INQUA. Moscow, 45pp.

Guidebook. Excursion 013, 1984. Late Cenozoic climate-stratigraphy of the North-Western Black Sea shore. XXVII Intern. Geol. Congress. Kishinev. Timpul. 44pp.

Heller, F., Meili, B., Wang, J., Li, H., Liu, T.S., 1987. Magnetization and sedimentation history of loess in the central Loess Plateau of China. In: Aspects of Loess Research. China Ocean Press, Beijing, pp. 147–163.

Iossifova, Iu.I., 2001. Climate-stratigraphy of the Middle Pleistocene in the upper Don drainage basin. In: The Ukraine Quaternary explored: The Middle and Upper Pleistocene of the Middle Dnieper area and its Importance for East–West European correlation, p. 35 Volume of abstracts, Kyiv.

Krasnenkov, R.V., Iosifova, Yu.I., Semenov, V.V., 1997. The Upper Don Basin is the most important region for climatostratigraphy of the lower Middle Pleistocene. In: Quaternary Geology and Paleogeography of Russia. GEOS, Moscow, pp. 82–96 (in Russian).

Kukla, G., 1987. Loess stratigraphy in central China. Quaternary Science Reviews 6, 191–219.

Kukla, G., Heller, F., Liu, X.M., Xu, T.C., Liu, T.S., An, Z.S., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology 16, 811–814.

Little, E.C., Lian, O.B., Velichko, A.A., Morozova, T.D., Nechaev, V.P., Dlussky, K.G., Rutter, N.W., 2002. Quaternary stratigraphy and optical dating of loess from the east European Plain (Russia). Quaternary Science Reviews 21, 1745–1762.

Markova, A.K., 1998. Pleistocene rodents of the central and southern Russian Plain. In: Saunders, J.J., Styles, B.W., Baryshnikov, G.F. (Eds.), Quaternary Paleozoology in the Northern Hemisphere, vol. XXVII. Illinois State Museum, Springfield, pp. 119–143.

Markova, A.K., 1999. Early Pleistocene fauna of small mammals in Eastern Europe. Sratigraphy and Geological Correlation 7 (2), 79–89.

Markova, A.K., this volume. Likhvin interglacial small mammal faunas of Eastern Europe.

Mikhailesku, C.D., Markova, A.K., 1992. Paleogeographical Anthropogene Stages of Fauna Development in the Southern Moldova. Kishinev, Shtiintsa 309pp. (in Russian).

Nikiforova, K.V., Beliajeva, E.I., Vangengeim, E.A., Konstantinova, N.A., Negadaev-Nikonov, K.N. (Eds.), 1971. The Pleistocene of Tiraspol. Kishinev, Shtiintsa 187pp. (in Russian).

Pokatilov, V.P., Bukatchuk, P.D., 1989. Eopleistocene terraces of the Dniester basin and their paleogeography. In: Yanshin, A.L. (Ed.), Quaternary Age. Paleogeography and Lithology. Kishinev, Shtiintsa, pp. 81–91 (in Russian).

Pospelova, G.A., Levkovskaya, P.P., 1994. Reflection of climatic changes in magnetic susceptibility of sedimentary rocks. Geophysics 334 (2), 222–227 (in Russian).

Roberts, H.M., Wintle, A.G., 2001. Equivalent dose determination for polymineralic fine-grains using the SAR protocol: application to a Holocene sequence of the Chinese Loess Plateau. Quaternary Science Reviews 20, 859–863.

Singhvi, A.K., Bronger, A., Sauer, W., Pant, R.K., 1989. Thermoluminescence dating of loess-paleosol sequences in the Carpatian Basin (East Central Europe): a suggestion for a revised chronology. Chemical Geology 73, 307–317.

Stratigraphy of the USSR, 1982. Quaternary. Part 1. Nedra, Moscow 443pp. (in Russian).

Tchepalyga, A.L., 1997. Detail event stratigraphy of Black Sea Pleistocene. In: Alekseev, M.N., Khoreva, I.M. (Eds.), Quaternary Geology and Paleogeography of Russia. GEOS, Moscow, pp. 196–201 (in Russian).

Tretyak, A.N., 1983. Remanent Magnetization and the Problem of Paleomagnetic Stratigraphy in Sedimentary Sequences. Naukova Dumka, Kiev 254pp. (in Russian).

Tretyak, A.N., Volok, Z.E., 1975. Paleomagnetic characteristic of Upper Cenozoic deposits in South-West Ukraine and Moldova. Geophysical volume. Academic Science, Ukraine SSR 64, 43–46 (in Russian).

Tretyak, A.N., Volok, Z.E., 1982. Reference paleomagnetic section of the Pliocene-Quaternary deposits in Dniester area and south-west Moldova. In: Mikhailova, N.P., Tretyak, A.N., Volok, Z.E., et al. (Eds.), Paleomagnetic Stratigraphy of Mezo-Cinozoic Deposits. Naukova Dumka, Kiev, pp. 31–36 (in Russian).

Tretyak, A.N., Vigilyanskaya, L.I., Makarenko, V.N., Dudkin, V.P., 1989. Secular Variation of the Geomagnetic Field in the Late Cenozoic. Naukova Dumka, Kiev 156pp. (in Russian).

Tsatskin, A., Heller, F., Hailwood, E.A., Gendler, T.S., Hus, J., Montgomery, P., Sartori, M., Virina, E.I., 1998. Pedosedimentary division, rock magnetism and chronology of the loess/paleosol sequence at Roxolany (Ukraine). Palaeogeography, Palaeoclimatology, Palaeoecology 143, 111–133.

Tsatskin, A., Heller, F., Gendler, T.S., Virina, E.I., Spassov, S., Pasquier, J., Hus, J., Hailwood, E.A., Bagin, V.I., Faustov, S.S., 2001. A new scheme of terrestrial paleoclimate evolution during the last 1.5 Ma in the Western Black Sea Region: integration of soil studies and loess magnetism. Physics and Chemistry of the Earth (A) 26 (11–12), 911–916.

Tsekhovski, Yu.G., Murav'ev, V.I., Babushkin, D.A., 1998. Quaternary volcanic ashes of the Eastern Europe Platform. Lithology and Mineral Resources 3, 292–307 (in Russian).

Veklich, M.F., 1982. Paleostages and Stratotypes of Soil Formations of Late Cenozoic. Naukova Dumka, Kiev 202pp. (in Russian).

Velichko, A.A., 1975. Problems of Pleistocene events correlation in glacial, periglacial and loess and littoral regions of the east European Plain. In: Velichko, A.A. (Ed.), Problems of Regional and General Paleogeography of the Loess and Periglacial Regions. Moscow, Geographical Institute, Russian Academy of Science, pp. 7–26 (in Russian).

Velichko, A.A., 1990. Loess-paleosol formation on the Russian Plain. Quaternary International 7/8, 103–114.

Velichko, A.A., Morozova, T.D., Pevzner, M.A., 1973a. Structure and age of loess and fossil soil horizons on the main terrace levels of the northern Azov region. In: Paleomagnetic Analyses in Studies of Quaternary Deposits and Volcano Formations. Nauka, Moscow, pp. 48–70 (in Russian).

Velichko, A.A., Morozova, T.D., Pevzner, M.A., Khalcheva, T.A., 1973b. Sequences of loesses and fossil soils on Chaudian-Bakinian deposits in the Taman Peninsula and their paleomagnetic characteristics. In: Paleomagnetic Analyses in Studies of Quaternary Deposits and Volcano Formations. Nauka, Moscow, pp. 70–76 (in Russian).

Velichko, A.A., Markova, A.K., Morozova, T.D., 1992. Loess-Paleosol Geochronology of the South-West Russian Plain on New Data. Quaternary Geochronology. Nauka, Moscow, pp. 28–33. (in Russian).

Velichko, A.A., Gribchenko, Yu.N., Gubonina, Z.P., 1997. The main parten of structure of loess-paleosol formation. In: Velichko, A.A. (Ed.), Loess-Paleosol Formation of East European Plain, Part I. Geographical Institute, Russian Acad. Sci., Moscow, pp. 5–25 140pp. (in Russian).

Virina, E.I., Faustov, S.S., Heller, F., 2000. Magnetic "climatic" record in loess-soil formation of the Russian Plain. In: Kaplin, P.A., Sudakova, N.G. (Eds.), Problems of Pleistocene Paleogeography and Stratigraphy. Moscow University, Moscow, pp. 259–279 (in Russian).

Zhou, L.P., Shackleton, N.J., 1999. Misleading positions of geomagnetic reversal boundaries in Eurasian loess and implications for correlation between continental and marine sedimentary sequences. Earth and Planetary Science Letters 168, 117–130.

Zhou, L.P., Shackleton, N.J., 2001. Photon-stimulated luminescence of quartz from loess and effects of sensitivity change on palaeodose determination. Quaternary Science Reviews 20, 853–857.

Zhou, L.P., Oldfield, F., Wintle, A.G., Robinson, S.G., Wang, J.T., 1990. Partly pedogenic origin of magnetic variations in Chinese loess. Nature 346, 737–739.

Zhou, L.P., Dodonov, A.E., Shackleton, N.J., 1995. Thermoluminescence dating of the Orkutsay loess section in Tashkent region, Uzbekistan, Central Asia. Quaternary Science Reviews 14, 721–730.