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Stratigraphy, and spatial and temporal paleoclimatic trends in Southeastern/Eastern European loess–paleosol sequences

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Abstract

The loess–paleosol sections Batajnica/Stari Slankamen (Serbia), Mircea Voda (Romania) and Stary Kaydaky (Ukraine) are presently located in areas of different types of steppe, and are highly sensitive for recording climatic changes. A stratigraphy for these three Southeastern/Eastern European sections is presented, based on pedostratigraphy and correlation of recently obtained susceptibility records with susceptibility data of other sections of the area (Koriten, Mostistea, Vyazivok), of the Chinese Loess Plateau and with the benthic $\delta^{18}O$ record of ODP 677. Six pedocomplexes were studied at the Serbian and Romanian sections and five at the Ukrainian section. The oldest are related to Marine Isotope Stage (MIS) 17 (Batajnica/Stari Slankamen and Mircea Voda) and MIS 13–15 (Stary Kaydaky). Some points concerning the existing loess chronostratigraphies of Bulgaria, Ukraine and China are discussed. Comparative study of the profiles allows the tracing of paleoclimatic and paleoenvironmental changes in Southeastern/Eastern Europe in time and space. Reconstruction of paleoprecipitation based on susceptibility–rainfall relationships, and calculations of sedimentation rates are evaluated.

1. Introduction

Mid-latitudinal loess originated from silty material blown out of sparsely vegetated areas during dry and cold periods of the Pleistocene. These so-called glacial periods are characterized by extensive glaciations of continental land masses, whereas during the interglacials and most interstadials, soil formation prevailed. Thus, the alternation of cold and warm periods throughout the Quaternary led to the formation of loess–paleosol sequences (LPSS), which potentially provide continuous paleoclimatic and paleoenvironmental information. Therefore, LPSS are one of the most valuable terrestrial archives especially for Southeastern and Eastern Europe, due to their widespread occurrence along the banks of the Danube and Dnieper rivers.

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The origin and distribution of Danube loess was reviewed by Smalley and Leach (1978) almost 30 years ago, and recently has been newly investigated by Buggle et al. (2008) and Újvári et al. (2008). In Serbia, the first description of an LPSS was by Marsigli (1726) (see also Marković et al., 2004a). A milestone in regional loess research was the contribution of Marković-Marjanović (1968) to the activities of the INQUA loess commission, attracting the attention of the post-war scientific community to the Serbian loess sections. The latest works of Kostić and Protić (2000), Marković et al. (2004b, c, 2005, 2006, 2007, 2008, submitted) and Fuchs et al. (2008) put the Serbian loesses in a Eurasian context. The former presented paleoclimatic implications based on mineralogy and grain-size analyses of two Serbian sections for a time span of more than 700 ka. The latter gave paleoclimatic reconstructions using malacology and a revision of the chronology of Serbian LPSS based on magnetic susceptibility and amino acid racemization (AAR). The various

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works of Bronger (1976, 2003) presented detailed paleopedological investigations and a classification of the paleosols of the Carpathian basin by means of micromorphology. Furthermore, he provided a first attempt at transcontinental stratigraphic correlation between European and Asian loess regions. For the lower Danube, one can look back to more than 100 years of loess research (Conea, 1969). For this area, fundamental descriptions were provided by Haase and Richter (1957), Conea (1969) and Minkov (1970). Jordanova and Petersen (1999a, b), Panaiotu et al. (2001) and Jordanova et al. (2007) presented detailed environmental and rock magnetic research and published one of the first stratigraphies for Bulgarian and Romanian sections using magnetic susceptibility. In Ukraine, the first prominent study on loess stratigraphy was carried out by Krokos (1932), later being extensively developed by Veklitch (1969, 1993). Paleoenvironments of the Ukrainian Quaternary have also been profoundly investigated (Matviishina, 1982; Veklitch and Sirenko, 1982; Sirenko and Turlo, 1986; Gerasimenko, 1988, 2004, 2006; Rousseau et al., 2001). However, most of the existing studies either focused on a single LPSS-section or dealt with paleoclimatic records of only the last few glacial cycles, or are lacking a reliable stratigraphic model.

This study considered LPSS sites in Serbia (Batajnica/Stari Slankamen), Romania (Mircea Voda) and Ukraine (Stary Kaydaky). These sites were thought to bear lengthy paleoclimatic records. As the sections are presently located in areas of different kinds of steppe and rather close to the temperate forest and submediterranean types of vegetation (Frey and Lösch, 1998), respectively, they are supposed to be sensitive to climatic changes. On the one hand, the studied sections cover different types of climate zones following a gradient of increasing aridity towards the Black Sea coast. On the other hand, they form a W–E transect across the region, thus, giving the possibility of Mid- and Late-Pleistocene climate reconstruction in space and time.

The purposes of this study are

(1) To establish a stratigraphy for these prominent South-eastern European paleoclimate archives based on pedostratigraphy and correlations of the magnetic susceptibility records with those of Chinese stratotype sections and with the $\delta^{18}O$ record of benthic foraminifera of ODP 677 as proxy for the global ice volume. The obtained stratigraphy will be validated by correlations to other dated sections of the region and, respectively, may give evidence clarifying ambiguous points in existing stratigraphic models of the region. A reliable stratigraphy is required for further paleoclimatic studies in this area.
(2) To calculate sedimentation rates and to evaluate their informative value.
(3) To give a tentative paleoclimatic interpretation of the magnetic susceptibility record and to evaluate the use of the susceptibility–rainfall equation of Maher et al. (1994) for the Danube and Dnieper loess area.

2. Principles of susceptibility enhancement in (paleo-)soils

Generally, the magnetic susceptibility is controlled by the amount and composition of iron-bearing para-, and ferromagnetic (s.l.) minerals and their grain-size distribution. Focusing on iron oxides and oxyhydroxides, as the most common iron-bearing compounds in soils without the influence of water logging, special attention is drawn to the ferrimagnetic minerals (magnetite and maghemite). The susceptibility of these minerals is several magnitudes higher ($4–5 \times 10^{-4}\,m^3\,kg^{-1}$) than the antiferromagnetic minerals hematite and goethite ($6–7 \times 10^{-7}\,m^3\,kg^{-1}$) (Thompson and Oldfield, 1986). Thus, even small amounts of these ferrimagnetics, which are predominantly formed during pedogenesis, significantly influence total magnetic susceptibility.

Besides mineralogy, magnetic susceptibility is also controlled by grain size. Intense research in Eurasian loesses has demonstrated that magnetic grains of superparamagnetic size (SP) ($<\sim 30$ nm) are predominant in paleosols, and singledomain (SD) and multidomain (MD) grains ($>\sim 30$ nm) prevail in loesses (Evans and Heller, 2003). The term "single" or "multidomain" grain means that there exist only one or several regions with parallel coupled atomic magnetic moments, respectively. Below a certain size, no stable domain can exist (superparamagnetism, Thompson and Oldfield, 1986). The susceptibility of a mineral is highest in the SP fraction, because these particles align instantaneously to any ambient field. The susceptibility of magnetite grains with 0.023 μm diameter is, for example, about three times higher than that of magnetite grains with 0.5 μm diameter (Tang et al., 2003). Thus, magnetic susceptibility can reflect the intensity of pedogenesis, as it has been observed at the Chinese loess sequences (Heller and Liu, 1984). The models dealing with the enhancement processes are essential for understanding the direct mineralogical reasons for magnetic susceptibility enhancement. The formation of ferromagnetic minerals in the course of pedogenesis is the most important mechanism. Its rate and the equilibrium between the formation of magnetite/maghemite and other Fe minerals are controlled by conditions in the soil environment such as temperature, moisture (alternating wet and dry periods), pH and content of organic matter (Evans and Heller, 2001). The most widely accepted model (Thompson and Oldfield, 1986; Maher, 1998; Evans and Heller, 2001; Chen et al., 2005) assumes, as a first step, alternating reducing and oxidizing conditions, leading to a release of Fe^{2+} from the weathering of Fe minerals and subsequent ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$) formation. With excess of Fe^{2+} in solution, an intermediate Fe^{2+}/Fe^{3+} compound is formed. For this step, the relevance of iron-reducing bacteria is stressed by several authors (Maher, 1998; Evans and Heller, 2001; Chen et al., 2002, 2005). Prerequisite for this biologically induced mineralization is a sufficient content of organic matter for microbial respiration. As a third step, magnetite of a predominantly superparamagnetic size is formed by dehydration of the Fe^{2+}/Fe^{3+} intermediate at moderately oxidizing conditions. Magnetite is still susceptible to dissolution. Only further oxidation to maghemite results in a more stable ferromagnetic mineral (Maher, 1998). Other mechanisms contributing to susceptibility enhancement of soils are the fire-induced formation of ferromagnetics, the relative enrichment due to carbonate leaching or biologically induced mineralization by magnetotactic bacteria (Evans and Heller, 2001; Tang et al., 2003).

3. Regional setting

3.1. Batajnica/Stari Slankamen (Serbia)

The Batajnica section (44°55′29″N, 20°19′11″E, Fig. 1) is situated along the Danube River bank about 12 km north of Belgrade. The sequence is about 40 m thick and contains at least six strongly developed pedocomplexes. The lowermost pedocomplex is below the Danube level and was only exposed for a short time in a trench. The three lowermost pedocomplexes are influenced by waterlogging. As this leads to changes in mineralogical composition, resulting in a disturbance of the magnetic susceptibility record (Evans and Heller, 2001), these pedocomplexes were sampled at Stari Slankamen, where waterlogging is absent. The Stari Slankamen section (45°7′58″N, 20°18′44″E, Fig. 1) is located about 45 km upstream of Batajnica on the right bank of the Danube river opposite the confluence of the Tisza and Danube rivers. Below the pedostratigraphic analog to the sixth pedocomplex of Batajnica, the Stari Slankamen section contains at least four older loess–paleosol couples (Bronger, 1976), which, however, were buried by colluvial deposits and thus only incompletely exposed during the sampling period. Tertiary limestones, and sandstones form the base of the Quaternary sequence (Bronger, 1976). Both the Batajnica and Stari Slankamen sites are situated in the Vojvodina—the Serbian part of the Pannonian Basin.

The climatic data of the nearby station Belgrade (Fig. 2) show a mean annual precipitation of 683 mm. According to the Köppen classification system (Sträßler, 1998), the area has a Cfb climate with a strong tendency to Cfa. Despite the absence of a prominent drought period, August can be regarded as a dry period. According to Walter (1974), this is characteristic of a forest-steppe type of climate. This kind of vegetation is typical for the dry central Pannonian basin. It is replaced by submediterranean and supramediterranean thermophile mixed oak forests (*Quercion pubescenti*) near the Carpathian Mountains (Fig. 1).

3.2. Mircea Voda (Romania)

The section of Mircea Voda (44°19′15″N, 28°11′21″E, Fig. 1) is located in the Dobrudja plateau (Romania) at a distance of about 13 km from the Danube and 40 km from the Black Sea coast. About 30 m of Quaternary aeolian deposits including six strongly developed pedocomplexes can be observed. The loess–paleosol successions overlie limnic sediments of presumably lower Pleistocene age (Domokos et al., 2000) on Tertiary and Mesozoic sediments.

The climatic station of Constanta recorded a mean annual precipitation of 396 mm. Due to strong northerly

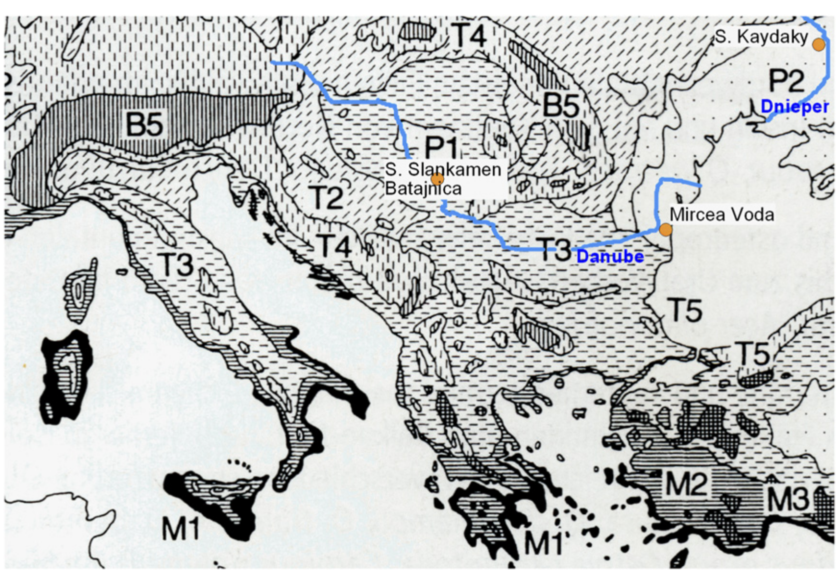

Fig. 1. Location of the investigated loess–paleosol sequences; map of current potential vegetation for Southeastern Europe (Frey and Lösch, 1998, modified). B5: Mountainous and subalpine coniferous forest and krummholz-shrubbery, M1: Thermomediterranean oak forest and olive-carob shrub-forest; M2: Mesomediterranean holm- oak forest, M3: Submediterranean and mediterranean xerotherm coniferous forest, P1: Forest steppe, P2: Feather-grass steppe, T2: Middle-, and Eastern-European mixed oak forest, T3: Submediterranean und supramediterranean thermophile mixed oak forest, T4: West-, Middle-, and Southeastern European common beech-and common beech-fir forest, T5: Euxinian orient-oak forest.

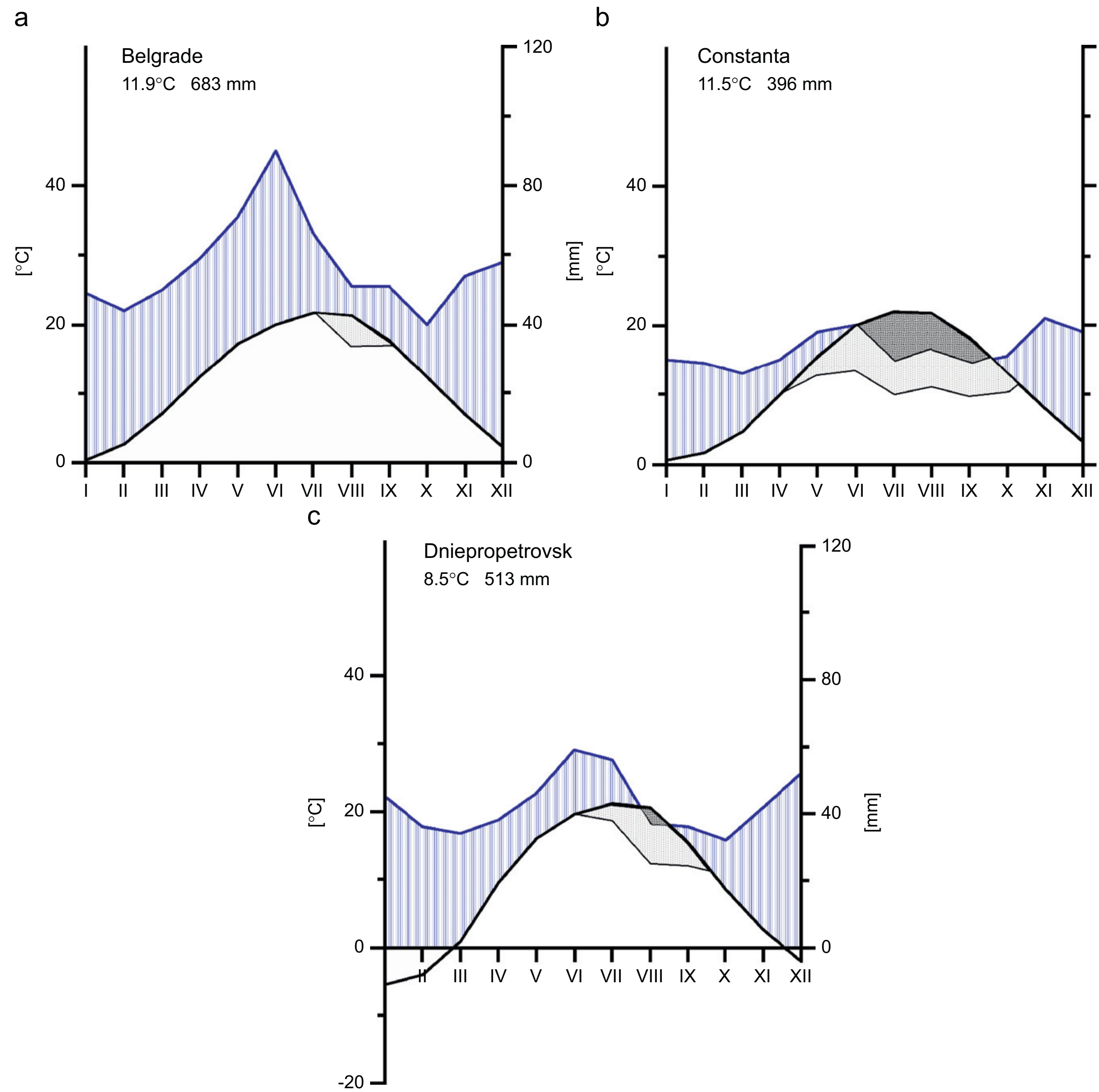

Fig. 2. Climate diagrams of (a) Belgrade (Serbia), (b) Constanta (Romania) and (c) Dniepropetrovsk (Ukraine). The diagrams were created on the basis of the climatological normals for the period 1961–1990 (WMO (World Meteorological Organization), 1996). The heavily dotted area marks months with average precipitation being less than twice the value of the average temperature. This indicates periods of drought according to Walter (1974). The slightly dotted areas show months with average precipitation being less than three times the value of average temperature. This characterizes periods of dryness.

winds prevailing for most of the year (Jordanova and Petersen, 1999a), the regional climate is characterized by hot and dry summers, i.e. Cfa climate with 6 months of dryness and 3 months of drought (Fig. 2). This favors feather-grass steppe vegetation (Fig. 1, Walter, 1974). According to Mavrocordat (1971), the actual mean annual temperature for Mircea Voda (station Cernavoda about 10 km from Mircea Voda) was 0.5 °C higher and the mean annual precipitation was 57 mm higher than for Constanta, resulting in only 4 months of dryness (in the observation periods 1896–1915 and 1921–1955).

3.3. Stary Kaydaky (Ukraine)

The large ''balka'' (Russian term for gently sloping gully in loess) with its system of younger ravines, reaching the Dnieper River near the village Stary Kaydaky (48°22′42″N, 35°07′30″E, about 2 km south from Dniepropetrovsk city, Fig. 1), has multiple outcrops with at least five different pedocomplexes. Some of the outcrops have been primarily investigated as key sections of the Ukrainian Quaternary (Veklitch and Sirenko, 1982). At Stary Kaydaky, special care had to be given to hiati. For instance, the Vytachiv pedocomplex (Marine Isotope Stage (MIS) 3) was eroded at the main sampling site, and thus was sampled at an adjacent site. The climate of the area can be classified as Dfb type, with a drought period of 1 month, and a period of dryness of 3 months (Fig. 2). This site is climatically intermediate between Batajnica/Stari Slankamen and Mircea Voda, which is also reflected by the character of the vegetation. Walter (1974) described the area around Dniepropetrovsk as so-called Northern feather-grass steppe (Hygroherbeto-Stipetum), relatively wet and rich in herbs. About 120 km to the north, the feather-grass steppe is replaced by forest steppe. The aridity gradually increases southwards to the Black Sea coast. Together, these three locations cover a range of different steppe conditions (Fig. 1), following precipitation gradients towards the Black Sea coast.

4. Methods

As further investigations will focus on paleopedology, pedocomplexes were sampled with higher resolution than the loesses. Samples of the pedocomplexes were taken at 10 to maximum 50 cm intervals, depending on horizontation and thickness of a unit. At least 10 samples were taken for each of the younger paleosols (i.e. the uppermost three interglacial pedocomplexes) and at least three samples for each of the older ones. The intercalated loesses were sampled by about three representative samples corresponding to individual loess layers. All samples were stored in air-tight plastic bags and dried at 40 °C in the laboratory. The material was then packed in 6 cm^3 plastic boxes and magnetic susceptibility measurement was carried out using a KLY-3 Kappabridge of Agico (Brno, Czech Republic) at 0.875 kHz and 300 $A\,m^{-1}$. For normalization on density of the packed material and for better comparison with literature data, the susceptibility values were expressed as mass-specific susceptibility ($m^3\,kg^{-1}$). The minimum susceptibilities of the pure loess units of each profile were taken as background susceptibilities.

Field and working nomenclature of the stratigraphic units is similar to the Chinese system, using the following abbreviations for the lithological units: main paleosols/pedocomplexes—'S_x', main loess layers—'L_x', with 'x' being the stratigraphic number of the soil or loess, starting from the youngest soil. For instance, S0 corresponds to the recent soil, S1 to the first main pedocomplex from the top, L1 means the main loess unit above S1 and so on. Subunits of the individual pedocomplexes are abbreviated as S_xS_y for a paleosol (also regarded as pedomember) and S_xL_{y+1} for an intercalated loess layer, with $y = 1$ for the uppermost soil of a pedocomplex. Within main loess units, intercalated weak paleosols are marked with L_xS_z, with $z = 1$ for the youngest paleosol of a loess unit. However, added prefixes designate the locality of the sections, i.e. SK for Stary Kaydaky and MV for Mircea Voda. For Batajnica/Stari Slankamen the prefix V was used, referring to the standard pedostratigraphic framework of the Vojvodina region (Marković et al., 2008; Marković et al., submitted).

To derive a chronostratigraphy for the studied sections, the magnetic susceptibility curve was correlated with the astronomically tuned stacked records of Lingtai and Zhaojiachuan of the Chinese Loess Plateau (Sun et al., 2006), and the benthic $\delta^{18}O$ values of ODP site 677, situated in the Eastern tropical Pacific (1°12′N, 83°44′W, Shackleton et al., 1990). Wherever no clear benchmarks in the ODP record were found for correlating the susceptibility record, a $\delta^{18}O$ value of 4.5‰ was used to determine age boundaries between major warm and cold stages, following Vidic et al. (2004). The obtained chronostratigraphy was validated against existing chronostratigraphic models of other LPSS in the region such as Ruma (Serbia, Marković et al., 2006), Koriten (NE Bulgaria, Jordanova and Petersen, 1999b), Mostistea (SE Romania, 44°9′N, 26°50′E; Panaiotu et al., 2001) and Vyazivok (Dnieper plain, 49°19′N, 32°58′E; Rousseau et al., 2001).

For paleoclimatic deductions, paleorainfall was calculated using Eq. (1) according to Maher et al. (1994):

$$\mathrm{MAP}\ (\mathrm{mm\,yr^{-1}}) = 222 + 199\ \log 10[(\chi_B - \chi_C)10^{-8}\,\mathrm{m^3\,kg^{-1}}] \quad (1)$$

where χ_B is the susceptibility of the subsoil and χ_C the background susceptibility of the loess

Sedimentation rates were only calculated for the Mircea Voda section due to several hiati in the Stary Kaydaky LPSS, and due to the Serbian LPSS, being composed of LPSS of two sites with possibly different rates of dust deposition. Calculating sedimentation rates, one is generally confronted with the problem that the lower boundary of a soil does not reflect the upper boundary of the sediments deposited during the preceding cold and dry period. Hence, sedimentation rates were calculated assuming two different worst-case scenarios. Variant *A* took into account the fact that dust accumulation may still exist during soil development (synpedogenetic sedimentation) and the thickness of paleosols was completely attributed to interglacial dust deposition. Variant *B* assumed dust accumulation was restricted to cold stages. Consequently, each portion of material, comprising both loess layer and the associated overlying pedocomplex, was fully attributed to a cold stage. For better comparison with literature data, sedimentation rates were first calculated using the timescale of Koriten (JP-99b), developed by Jordanova and Petersen (1999b). To test the sensitivity to uncertainties in the age model, calculated sedimentation rates for different timescales were based on

(1) correlation to the benthic $\delta^{18}O$ record of ODP site 677 (Sh-90; Shackleton et al., 1990);
(2) correlation to the susceptibility record of Sun et al. (2006) (Su-06);
(3) the timescale of Jordanova and Petersen (1999b) for the Koriten site (lower Danube basin, Bulgaria);

(4) the timescale of Heslop et al. (2000) (He-00), derived from the astronomical tuning of the Baoji (China) grain size record and the Luochuan susceptibility record; and
(5) an age model of the marine isotope events, developed at the planktonic $\delta^{18}O$ record of core MD900963 (Maldives area, Indian Ocean; Bassinot et al., 1994; Ba-94).

These different timescales represent studies in various regions of Earth with different well-established methods for setting up a Quaternary climate and chronostratigraphy. However, each of the studied regions and applied methods differs in its sensitivity for recording climatic changes. Only for the last glacial cycle was a supposably more reasonable and accurate timescale for Europe available (Guiter et al., 2003). In all calculations, age boundaries for MIS 2–5 were taken from this review of various West and Central European terrestrial records. The lower boundary of the recent soil was set to 11.5 ka according to the Younger Dryas—Preboreal boundary, given by Litt et al. (2001) for Central Europe. Although these compiled datasets from more proximal terrestrial records were used, some minor uncertainties cannot be excluded, as age boundaries of climatic stages are probably not synchronous within all parts of Europe. Furthermore, ages derived from dating of the lower boundaries of paleosols probably overestimate the duration of warm periods. For the purpose of clarity, no further sensitivity analyses with respect to these aspects were carried out. An overview of the applied timescales is given in Table 1.

5. Results

5.1. Magnetic susceptibility variations

For all three profiles, the magnetic susceptibility record follows generally the lithology (Fig. 3), being enhanced in the paleosols compared to the parent loess. The background susceptibilities for Batajnica/Stari Slankamen and Mircea Voda are about two times higher than for the Stary Kaydaky section, in spite of the older loesses at Stary Kaydaky (>SK-L2) showing more pedogenic alteration.

The LPSS of Batajnica/Stari Slankamen has a background susceptibility of $22 \times 10^{-8}\,m^3\,kg^{-1}$. Pedogenic alteration may be the reason for a relatively high susceptibility at the upper and lower parts of the V-L5. The strongest susceptibility enhancement can be observed in the V-S3 and the V-S5, whereas relatively weak enhancement can be found in V-S6, V-S4 and V-L1S1 of Batajnica/Stari Slankamen (Fig. 3). The susceptibility of the recent soil is measured as $61 \times 10^{-8}\,m^3\,kg^{-1}$. In unit V-L1S1, the susceptibility record shows a double peak. Further distinctive peak structures can be observed for the V-S2 pedocomplex, in which the uppermost pedomember has a relatively low susceptibility enhancement and is clearly offset against the rest of the pedocomplex by a thin loess layer with nearly background susceptibility. In general, the high-resolution susceptibility record of Batajnica (Marković et al., submitted) confirms the patterns of the lower resolved record (Fig. 4). The only markable difference is a tephra-layer indicated by a sharp peak in unit V-L2, which was not detected with the low-resolution sampling (Fig. 4).

The background susceptibility of the Mircea Voda record ($21 \times 10^{-8}\,m^3\,kg^{-1}$) is similar to that of the Serbian sections. Confirming field observations, pedogenic alteration of the intercalated loesses can especially be noted in MV-S2L3 and the MV-S6L2 (Fig. 3). Consistent with the results from Serbia, the maximum susceptibility enhancement ($134 \times 10^{-8}\,m^3\,kg^{-1}$) occurs in the MV-S3. Also, the MV-S5 shows a relatively strong magnetic signal ($116 \times 10^{-8}\,m^3\,kg^{-1}$). However, in contrast to the Stari Slankamen record, the magnetic susceptibility of the

Table 1
Overview on the different timescales for mid-Pleistocene LPSS and major isotope stages, respectively, applied for sensitivity analyses of sedimentation rates

Base of/ lower boundary of	Timescale based on Jordanova and Petersen (1999b)	Duration (ka)	Timescale based on correlation to Sun et al. (2006)	Duration (ka)	Timescale based on correlation to Shackleton et al. (1990)	Duration (ka)	Timescale based on correlation to Heslop et al. (2000)	Duration (ka)	Timescale based on correlation to Bassinot et al. (1994)	Duration (ka)
L2/MIS 6	180	54	162	33	188	62	196	70	186	60
S2/MIS 7	245	65	258	70	247.5	59.5	250	54	242	56
L3/MIS 8	280	35	275	17	280	32.5	290	40	301	59
S3/MIS 9	331	51	340	65	333.5	53.5	342	52	334	33
L4/MIS 10	357	26	388	48	373	39.5	386	44	364	30
S4/MIS 11	410	53	427	39	416	43	417	31	427	63
L5/MIS 12	470	60	474	47	453	37	503	86	474	47
S5/MIS 13–15	620	150	623	149	623	170	625	122	621	147
L6/MIS 16	671	51	683.5	60.5	668.5	45.5	693	68	659	38

All values are given in ka.

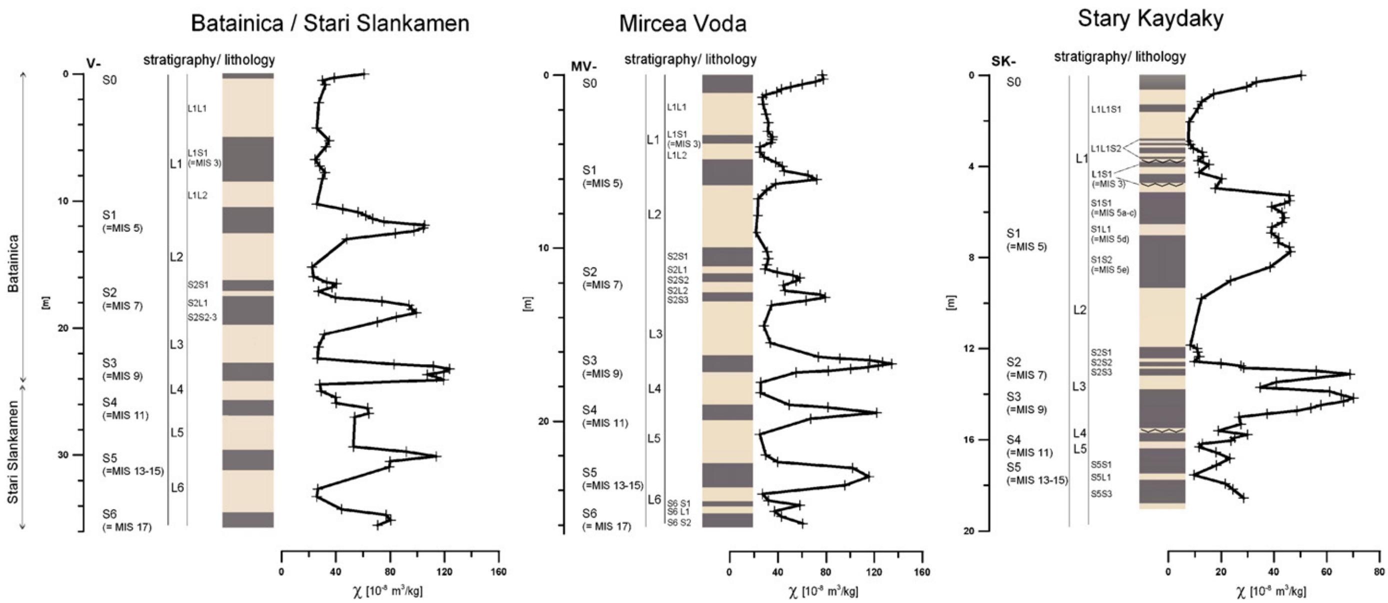

Fig. 3. Variations of magnetic susceptibility (χ) with profile depth and sampling site. The lithology is sketched. Dark layers indicate paleosols (= S-units), light layers indicate loess units or weakly (compared to adjacent paleosol units) pedogenetic altered loess (= L-units). Prefixes designate the locality of the sections, i.e. SK for Stary Kaydaky and MV for Mircea Voda. For Batajnica/Stari Slankamen, the prefix V is used, referring to the standard pedostratigraphic framework of the Vojvodina (Marković et al., 2008). Wiggled lines indicate probable hiati. The assumed chronology, related to marine isotope stages (MIS), resulted from the magnetic susceptibility stratigraphy and pedostratigraphic correlations to the dated sections of the region (see also Fig. 5). Note that the Serbian profile is a composite of the Stari Slankamen (bottom) and Batajnica loess–paleosol sequence (top).

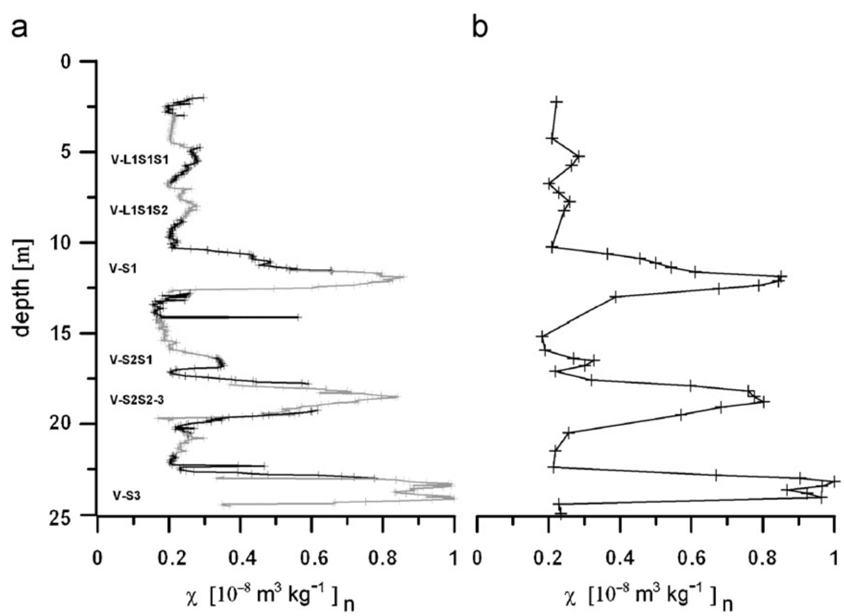

Fig. 4. Comparison of a high-resolution susceptibility record (a, sampling in 5 cm intervals; data taken from Marković et al., submitted) and a lower resolved record (b, sampling in decimeter intervals) for the Batajnica section. Note that in graph a there are 14 subcolumns, which are indicated by a change from black to gray and vice versa. Values are normalized to the maximum value.

MV-S4 ($122 \times 10^{-8}\,m^3\,kg^{-1}$) is almost as high as that of the MV-S3. Only weak enhancement can be found in MV-S6 and MV-L1S1. The susceptibility of the recent topsoil is about $77 \times 10^{-8}\,m^3\,kg^{-1}$. Individual paleosols are indicated most expressively by susceptibility patterns in the MV-S6 (two pedomembers) and in the MV-S2 (three pedomembers).

The magnetic susceptibility record of the Stary Kaydaky section shows remarkable differences in pattern as well as in the numerical values (Fig. 3). The background susceptibility is $7 \times 10^{-8}\,m^3\,kg^{-1}$, clearly lower than in the sections in Serbia and Romania. However, for most of the loess units (SK-L3 and older, as well as for the loess above unit SK-L1L1S1), pedogenic overprint is indicated by higher susceptibilities. The modern soil is characterized by a magnetic susceptibility of about $50 \times 10^{-8}\,m^3\,kg^{-1}$, which is also lower than in the modern soils of the Serbian and Romanian sections. The maximum susceptibility, found in the Ukrainian S2 and S3, is approximately half that at Batajnica/Stari Slankamen and at Mircea Voda. Only relative weak magnetic susceptibility enhancement compared to background values can be observed in SK-S4, SK-S5 and SK-L1S1, whereas the incipient soil SK-L1L1S1 does not exhibit enhanced magnetic susceptibility at all. Further interesting patterns are the three-partitioned record of the SK-S1, the typical peak association of the SK-S2, already described for the Batajnica section, and the two susceptibility peaks in the SK-S5 unit. Several peaks of susceptibility generally point towards discontinuous soil development, forming a pedocomplex, consisting of individual pedomembers separated by layers of less-intensive or different pedogenesis.

5.2. Stratigraphy

The susceptibility record of the profiles can be used for stratigraphic correlation. Though having a relatively coarse sampling design, characteristic susceptibility patterns are similar to the high-resolution records of the area (Fig. 4; http://ns.geo.edu.ro/~paleomag/loess-MV.htm; Rousseau et al., 2001). A comparison between the magnetic susceptibility record of these profiles and the benthic $\delta^{18}O$ dataset of ODP site 677 (Shackleton et al., 1990), reflecting the global ice volume, exhibits concordance in the general patterns (Fig. 5). The match of paleosols/pedocomplexes with enhanced susceptibility to specific interglacials/interstadials and cold stages with reduced magnetic susceptibility comes out more clearly in comparison with the stacked susceptibility record of Lingtai and Zhaojiachuan (Chinese Loess Plateau, Sun et al., 2006, Fig. 5). The chronology also corresponds well with the records of Koriten (Bulgaria) and Mostistea (Romania) and their correlation to the marine $\delta^{18}O$ record (Jordanova and Petersen, 1999b; Panaiotu et al., 2001). This similarity can be distinctly traced for Stari Slankamen/Batajnica and Mircea Voda. However, for the Stary Kaydaky section, a correlation solely based on the magnetic record is in large part ambiguous. Here, the given chronostratigraphy strongly relies on the Ukrainian stratigraphic framework (Veklitch, 1993; Gerasimenko, 2004).

5.2.1. Stratigraphy of Batajnica/Stari Slankamen (Serbia) and Mircea Voda (Romania)

Above the first strong interglacial pedocomplex (V-S1, MV-S1), weak magnetic enhancement within a zone of incipient soil formation points towards an interstadial pedocomplex (V-L1S1, MV-L1S1) of the last glacial cycle, most probably of MIS 3. This corresponds also to the

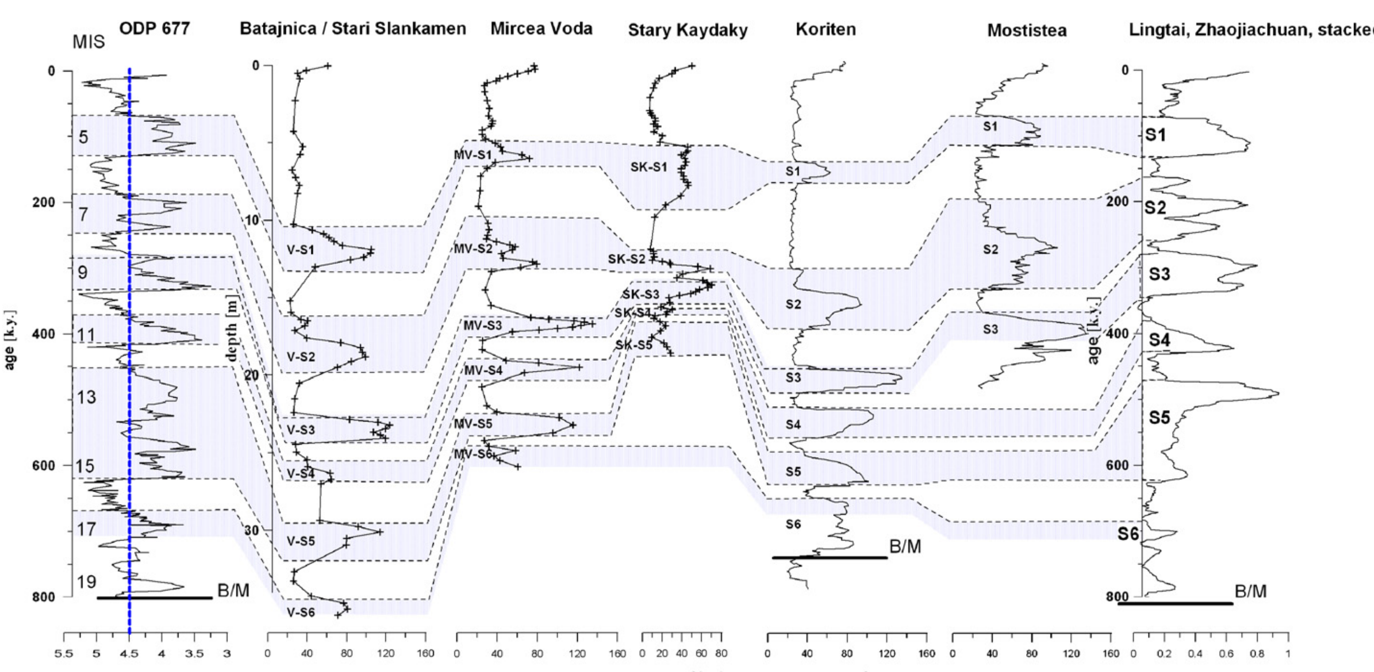

Fig. 5. Correlation of the magnetic susceptibility records of the profiles Batajnica/Stari Slankamen, Mircea Voda, Stary Kaydaky with the astronomically tuned benthic oxygen isotope record from ODP site 677 (Shackleton et al., 1990); a $\delta^{18}O$ value of 4.5‰ was used for the limitations of major isotope stages, following Vidic et al. (2004); comparison with the records of Koriten, Mostistea (redrawn after Jordanova and Petersen, 1999b; Panaiotu et al., 2001) and the stacked normalized magnetic susceptibility curve of Lingtai and Zhaojiachuan (Chinese Loess Plateau); data and astronomical tuning for the latter sections were provided by Sun et al. (2006).

IRSL dates and AAR chronology of other sections in the Vojvodina (Marković et al., 2008) and the chronostratigraphic interpretation of the Batajnica section given by Marković et al. (submitted). The pedocomplex S1 of Batajnica and Mircea Voda, i.e. F2 according to the older nomenclature of Bronger (1976) (see Marković et al. (2008) for comparison of the F and the S–L nomenclature), shows a dominating magnetic susceptibility peak in its basal half, probably representing MIS 5e. This resembles the pattern of Koriten, Lingtai/Zhaojiachuan and the trend visible in the ODP record. For the sections at Durankulak (Romanian–Bulgarian border at the Black Sea coast, 43°43′N, 28°34′E) and Harlets (43°42′16″N, 23°49′55.2″E), Avramov et al. (2006) reported a weakly expressed susceptibility peak at the top of S1 just above the S1-susceptibility maximum. This feature is also indicated by a bend in the record of the profiles from Batajnica and Mircea Voda, potentially resulting from pedogenesis during MIS 5a and 5c. Additional evidence for assigning the S1 unit to MIS 5 is its stratigraphic position as the first strong developed pedocomplex below the surface and above the S_2 with its characteristic susceptibility feature of twin or triple peaks. Further support comes from the amino acid dating of the V-S1 in Ruma (Marković et al., 2006) and IRSL dates of the loess below and above this pedocomplex in Surduk, a section situated between Batajnica and Stari Slankamen (Fuchs et al., 2008). As can be seen in the record of Mircea Voda, Koriten and Mostistea (Fig. 5), the S2 pedocomplex shows actually three peaks, two well-expressed peaks at its base and a weak one at the top. In some cases, as in Batajnica, the two basal peaks are not separated clearly (Fig. 4). The characteristic magnetic susceptibility patterns of the Serbian and Romanian S2-unit can be correlated with corresponding patterns in the susceptibility record of Chinese LPSS (Fig. 5; Heslop et al., 2000) and with the benthic $\delta^{18}O$ record of ODP 677 (Fig. 5). This pedocomplex is attributed to MIS 7, which is in accordance with the amino acid chronology of Ruma (Marković et al., 2006). MIS 9 shows also a characteristic double peak in the isotope curve of ODP 677 and in the magnetic susceptibility curve of Lingtai/Zhaojiachuan (Fig. 5). For this reason, the Batajnica S3 is correlated to MIS 9. At the Mircea Voda section, this feature is not visible, but the magnetic enhancement of the S3 paleosol in this section is the strongest one of the observed time interval, the same as Batajnica, Koriten, Mostistea (Fig. 5) and Ruma (Marković et al., 2006). This, together with the similar stratigraphic position of the S3 in all studied sections, clearly indicates the same range of age of this pedocomplex. The obtained chronostratigraphic placement is in accordance with the AAR results of Ruma (Marković et al., 2006). Further down, the magnetic susceptibility peaks in the V-S4, MV-S4 and V-S5, MV-S5 paleosols are correlated with MIS 11 and MIS 13–15, respectively. In the Chinese loess–paleosol sequences, magnetic enhancement is continuously observed through the whole duration of MIS 13 and 15, and its attenuation during MIS 14 is rather weak (Heslop et al., 2000; Sun et al., 2006). The work of Jordanova and Petersen (1999b) on Koriten and the pedostratigraphy confirm the correlation of the Serbian and Romanian S4 and S5 with these MISs. Being the youngest and best-developed soil of the Brunhes–chron with remarkable rubification and clay illuviation in Stari Slankamen and Mircea Voda, the S5 may serve as a marker horizon for MIS 13–15, in this area. The magnetic susceptibility enhancement in unit S6 of Stari Slankamen is assigned to MIS 17, also supported by the magnetostratigraphy of Marković et al. (2003). At Mircea Voda the susceptibility record of the MV-S6 revealed two peaks. The first one resulted from MIS 17, but the chronological placement of the second was not clear. A comparison with the susceptibility records of Koriten and the Chinese loess plateau (Fig. 5) may point to a MIS 18 interstadial soil. However, pedogenesis of this lower pedomember seems to be even stronger than that of the upper one. Therefore, at the present state of knowledge, it is attributed to the MIS 17 interglacial (Fig. 5) (see for further discussion Section 6.2.2). Preliminary paleomagnetic investigations of Marković et al. (2004c) revealed evidence for the Brunhes–Matuyama (B/M) boundary in the L8 of Stari Slankamen. This represents a further support for the correctness of the chronostratigraphic model. Contrasting TL dates for the S1 to S4 at Stari Slankamen (Singhvi et al., 1989) suffer probably from age underestimation due to methodological reasons (Fuchs et al., 2008).

5.2.2. *Stratigraphy of Stary Kaydaky*

A key in the different stratigraphic models, which are proposed for the LPSS of the Ukraine (Gerasimenko, 2004, 2006; Lindner et al., 2006; Veklich, 1995, cited in Bolikhovskaya and Molodkov, 2006), is the chronological placement of the Kaydaky pedocomplex (SK-S1S2) and the Dnieper loess (SK-L2). In the Ukraine, especially at its type locality at Stary Kaydaky, the Kaydaky pedocomplex is formed by a dark steppe-soil-type paleosol over a forest-soil-type paleosol overlying the Dnieper loess (SK-L2). The Dnieper loess is the unit associated with the moraine of the Dnieper glaciation. In the stratigraphic models of the Ukrainian Quaternary, it is generally argued whether this loess and the respective glaciation occurred during MIS 8 or MIS 6. Therefore, the Kaydaky unit is placed in either MIS 5e or MIS 7. An overview of the stratigraphic schemes for Ukraine, resulting from the different opinions on the chronological placement of the Dnieper and Kaydaky units, is given in Table 2. Clarifying this question allows the development of a chronostratigraphy for the Stary Kaydaky section on the basis of the respective pedo-, and pollen stratigraphic framework of Ukraine.

The S1 pedocomplex of Stary Kaydaky contains a forest steppe/steppe-soil-type paleosol (= Pryluky complex), which is separated by thin pedogenetically altered loess (= Tyasmyn) from the typical Kaydaky pedomplex. The three peaked susceptibility records of S1 reflect the pattern of the benthic $\delta^{18}O$ record of MIS 5 as well as the

Table 2
Compilation of different stratigraphic schemes for Ukraine

Unit (Lindner et al., 2006)	Unit (Veklich, 1995, cited in Bolikhovskaya and Molodkov, 2006)	Unit (Gerasimenko, 2004, 2006)	Marine Isotope Stage
Valday	Prychernomorsk	Prychernomorsk	2
		Dofinivka	
		Bug	
	Dofinivka	Vvtachiv	3
	Bug	Uday	4
	Vytachiv, Uday, Pryluky	Pryluky	5a–c
		Tvasmvn	5d
Pryluky		Kavdaky	5e
Dnieper 2	Tyasmyn	Dnieper	6
Kaydaky	Kaydaky	Potagaylivka	7
Dnieper 1	Dnieper	Orel	8
Potagaylivka	Zawadovka	Zavadivka	9
Orel			10
Zavadivka			11
Tiligul	Tiligul	Tiligul	12
Lubny	Lubny	Lubny	13
			14
			15

The present study favours the scheme of Gerasimenko (2004, 2006).

susceptibility pattern of the S1 pedocomplex in Mostistea and the Pryluky-, Kaydaky complex in Vyazivok (Rousseau et al., 2001, Fig. 6). This good correspondence suggests that the magnetic susceptibility record at least of this younger part of the section reflects paleoclimatic variations and is not affected by strong biases as in the older part of the sequence (see below). With the given susceptibility curve and AAR dates in the range of MIS 6 for the loess below the Kaydaky complex (i.e. Dnieper) in Vyazivok, it appears most reasonable to correlate the Pryluky complex (SK-S1S1) with MIS 5a–5c, the Tyasmyn unit (SK-S1L1) with MIS 5d and the Kaydaky complex (at its type locality) with MIS 5e. This correlation supports the stratigraphic scheme of Gerasimenko (2004, 2006). Having clarified the chronological placement of the S1 (Pryluky, Tyasmyn, Kaydaky) allows the development of the chronostratigraphy of the other units of the Stary Kaydaky section, above and below, based on the respective (pedo-) stratigraphic framework of Ukraine.

At the Stary Kaydaky section, the pedocomplex SK-L1S1 (=Vytachiv in the Ukrainian nomenclature) is situated in its characteristic stratigraphic position above the last interglacial pedocomplex being separated from it by the so-called Uday loess (SK-L1L2). The Vytachiv complex is represented by two pedomembers with a layer of weakly pedogenetically altered loess between them. The lowermost pedomember is most expressed in susceptibility (Figs. 3 and 6). Considering the placement of the Kaydaky- and Priluki-complex, the Vytachiv complex can be best attributed to MIS 3 (Fig. 6, Rousseau et al., 2001; Gerasimenko, 2004). This is also in agreement with ESR and ^{14}C ages between 30 and 40 ka BP reported for the Vytachev-complex at other sites in Ukraine (Gerasimenko, 2006). A line of erosional incision is observed between the Vytachiv pedocomplex and the overlying Bug loess (27–18 k.y., Gerasimenko, 2006). Two soil subunits (SK-L1L1S1 and SK-L1L1S2), separated by loess, were found above the erosional incision. In the Kaydaky section, both have been related to the Dofinivka unit (Veklitch and Sirenko, 1982), though there are two reasons for doubting this assignment: a significant thickness of loess between the two subunits, and the presence of a set of incipient soils within the lower subunit (SK-L1L1S2). A similar succession of incipient soils is present in other sections of Ukraine at the base of the Bug unit (bg1), whereas the upper Bug (bg2) is represented by pure loess (Veklitch, 1993; Gerasimenko, 2000, 2006). Thus, only the uppermost soil (SK-L1L1S1) can be related to the Dofinivka paleosol unit

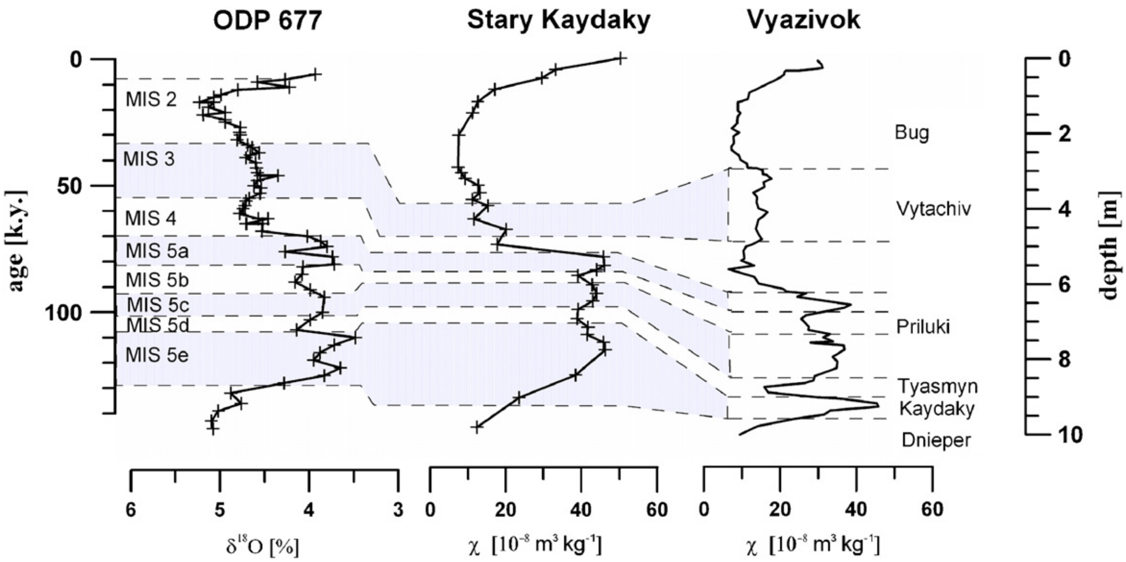

Fig. 6. Correlation of the magnetic susceptibility record of the Stary Kaydaky section to that of the Vyazivok section (Ukraine, Rousseau et al., 2001) and to the benthic $\delta^{18}O$ record of ODP 677 (Shackleton et al., 1990), for the last climatic cycle.

(17–15 k.y., Gozhik et al., 2000). A differentiation between the unit SK-L1L1S1 and the loess above does not clearly appear in the susceptibility record of Stary Kaydaky (Fig. 3), probably due to the low sesquioxide content (Gerasimenko, 2000).

Below the L2 loess (Dnieper, MIS 6), the SK-S2 pedocomplex is formed by a succession of a brownish horizon (incipient soil) on top, a pedomember of steppe-soil-type paleosol and a pedomember of forest/forest-steppe-soil type at the base. This succession can be related to the Potagaylivka complex, i.e. MIS 7 (Gerasimenko, 2004). Thus, the magnetic susceptibility pattern should also correspond to the characteristic twin peak association in the Serbian and Romanian S2. The underlying loess SK-L3 shows cryofeatures, penetrating into the SK-S3 paleosol. Thus, despite its pedogenic overprint from the overlying pedocomplex, SK-L3 can be attributed to glacial conditions, i.e. representing the so-called Orel-loess. The SK-S3 appears to be the pedocomplex of a strongly developed steppe-soil-type paleosol and forest-soil-type paleosol and the SK-S4 is a truncated forest-soil-type paleosol. The SK-S3 and SK-S4 are regarded as upper and lower Zavadivka soil, which can be palynologically correlated with MIS 9 and 11 (Gerasimenko, 2004). Similar to the record of the Mircea Voda and Batajnica section, the SK-S3 shows relatively high magnetic enhancement (Fig. 5). In the pedocomplex units SK-S4 and SK-S5, the magnetic susceptibility is systematically lower. Although currently no explanation is suggested, climatic reasons are excluded, as steppe-soil-type and forest-soil-type paleosols are affected in a similar way.

The SK-S5 paleosol comprises two pedomembers: the upper one is a dark steppe-soil-type paleosol and the lower one is a brown-red forest-steppe-soil-type paleosol. Due to this association, the SK-S5 probably corresponds to the Lubny pedocomplex, correlating with MIS 13–15 (Gerasimenko, 2004). Preliminary investigations by V. Bakhmutov (personal communication, 2006) could not detect the geomagnetic polarity change of the B/M boundary within the studied part of the profile.

5.3. Sedimentation rates

Sedimentation rates were calculated for two worst-case models of dust deposition, i.e. synpedogenetic sedimentation (variant A) and prepedogenetic sedimentation (variant B). Furthermore, sensitivity analyses concerning the timescale model have been conducted.

Variant *A* suggested mostly increased sedimentation rates at the loess units of Mircea Voda compared to the adjacent pedocomplexes, regardless of the applied timescale model (Fig. 4). An exception is the S2 for the timescales of Bassinot et al. (1994) and Heslop et al. (2000). Differences between sedimentation rates of pedomplexes and loess units are most expressed for the JP-99b timescale and for the Su-06 and Sh-90 age models. Considering the duration of the units, the application of the He-00 timescale yields generally lower values for pedocomplex units and higher values for loess units than using the other timescales (Table 1). Thus, in this age model, sedimentation rates for loess units tend to be relatively low and for pedocomplex units relatively high.

The JP-99b timescale shows a tendency of decreasing sedimentation rates towards the older units of the Mircea Voda section (variants *A* and *B*) resembling the pattern of the sedimentation rates at Koriten (Jordanova and Petersen, 1999b). Remarkably high values can be found for the younger loesses L1–L4 and especially for the L1L1 and L3. Low sedimentation rates are obtained for L5 and L6 (variants *A* and *B*). Regarding the paleosols, the pedocomplex S5 exhibits the lowest values and relatively high sedimentation rates were found for S2, due to the intercalated loess layers S2L1 and S2L2 (variant *A*). Furthermore (Fig. 7) synpedogenetic sedimentation is probably the reason for the high sedimentation rates of the L1L2 using variant *B*, judging from the susceptibility pattern of the L1S1. For the other units, synpedogenetic sedimentation cannot be excluded. Minimum sedimentation rates for the S5 and maximum for either the L1 or the L3 are generally confirmed by the other timescale models (Fig. 7). However, not all models produce the lowest sedimentation rate of the major loess units for L5 and L6 of Mircea Voda. This feature is only clearly expressed using the JP-99b timescale (variants *A* and *B*), the He-00 timescale (variants *A* and *B*) and the Su-06 timescale (variants *A* and *B*). With the latter timescale, L4 can be characterized by low and even slightly lower sedimentation rates than L5. Applying the Sh-90 and Ba-94 age models, L5 does not exhibit distinctly lower rates of dust deposition than the younger loess units. Here, only the L6 shows a clear offset towards lower values (variants *A* and *B*).

6. Discussion

As in the Chinese loess records (e.g. Kukla, 1987; Kukla and An, 1989; Maher et al., 1994), magnetic susceptibility at the studied LPSS of Serbia, Romania and Ukraine is clearly enhanced in paleosols. This is, on the one hand, fundamental for stratigraphic correlation based on this proxy of pedogenesis. On the other hand, it allowed paleoclimatic deductions. In this context, the use of the susceptibility–rainfall Eq. (1), presented by Maher et al. (1994), will be discussed. Moreover, the chronostratigraphic model permitted the calculation and evaluation of sedimentation rates. In the following section, the stratigraphic units are regarded as correlatives of the Chinese loess–paleosol sequences, and the use of local stratigraphic names is avoided if possible.

6.1. Sedimentation rates

When calculating the sedimentation rates for LPSS, one is confronted with the following questions: (i) what is the appropriate timescale for the calculation, (ii) are there remarkable hiati in the profile, and (iii) do soils thicken during their formation (synpedogenetic sedimentation) or were sedimentation and pedogenesis non-simultaneous processes (prepedogenetic sedimentation)? As to the second point, there is no field evidence indicating remarkable hiati in the profile of Mircea Voda. For the first point sensitivity analysis for the timescale model was conducted.

Regarding the third point, sedimentation rates were calculated for the two different models of dust deposition: variant *A*, i.e. attributing the whole thickness of a paleosol/pedocomplex to interglacial and interstadial dust sedimentation, and variant *B*, i.e. attributing the total thickness of a paleosol/pedocomplex to sedimentation during the preceding glacial/stadial stage. Both models have their limitations. In the case of low sedimentation rates and/or deep downward pedogenic alteration, variant *A* would distinctly underestimate the sedimentation rates for the loess units. However, when considering paleosols that clearly grew up or pedocomplexes with intercalated loess layers, variant *B* would overestimate sedimentation rates of the underlying loess units to a greater extent. This is the case at the L3 and L1L2 of Mircea Voda and L1L2, L3, L4 of Batajnica/Stari Slankamen (Fig. 7). Furthermore, variant *B* restricts the interpretations to the level of couples of loess and pedocomplex/paleosol units. Though both variants are per se probably unrealistic, they represent worst-case scenarios for the model of dust sedimentation with the truth being between these two extremes. For the Chinese loess plateau, for example, Kohfeld and Harrison (2003) proposed that only a certain fraction ($\frac{2}{3}$) of the soil material is deposited synpedogenetically. The use of both worst-case scenarios, variants *A* and *B*, however, provides a tool for the verification of the observed patterns and trends in the calculated sedimentation rates by testing the robustness of the observed features. Relative trends that result in variant *A* and in variant *B* can be assumed to be reliable with respect to the uncertain extent of synpedogenetic sedimentation. This would be the case for the decrease in dust sedimentation rates (variants *A* and *B*) towards the older units, which was obtained for the Mircea Voda section, using the JP-99b, He-00 and Su-06 timescale. The decrease is markedly expressed below the L4 (Jp-99b, He-00) and below L3 (Su-06) (Fig. 7). At the Koriten site in the Bulgarian part of the lower Danube basin, Jordanova and Petersen (1999b) obtained the lowest rates of dust deposition for the older loesses L4–L6 (Fig. 4). At this section there appears to be a trend of decreasing sedimentation rate from one loess unit to the next older one, regarding the units L2–L6. A similar trend can be observed in Mircea Voda (L3–L6) only when applying the same timescale as Jordanova and Petersen (1999b). One may interpret the lower rates of dust deposition in the older loess units L6, L5 and eventually L4 in a paleoclimatic sense. It could indicate a change in atmospheric circulation and/or a decrease in wind force and/or an increase in humidity towards the older units. Jordanova and Petersen (1999b) speculated about a link to the build-up of a permanent ice cover of the Arctic Ocean with implications on atmospheric circulation. However, the observed patterns are less clear, conducting sensitivity analysis for the applied ages by using other timescale models (Table 1, Fig. 7). Using the Sh-90 and Ba-94 timescale only the L6 shows a distinctly lower sedimentation rate. Differences in the timescales may exist due to the method of astronomical tuning or difficulties in finding benchmarks in the saw tooth pattern of highly resolved marine paleoclimatic records to correlate with less-resolved records of terrestrial archives. This may lead to differences of more than 100% in the duration of a period and consequently to a high uncertainty of the sedimentation rates. Therefore, the sensitivity analysis for the timescale model shows that a trend in sedimentation rates, i.e. a gradual increase of dust

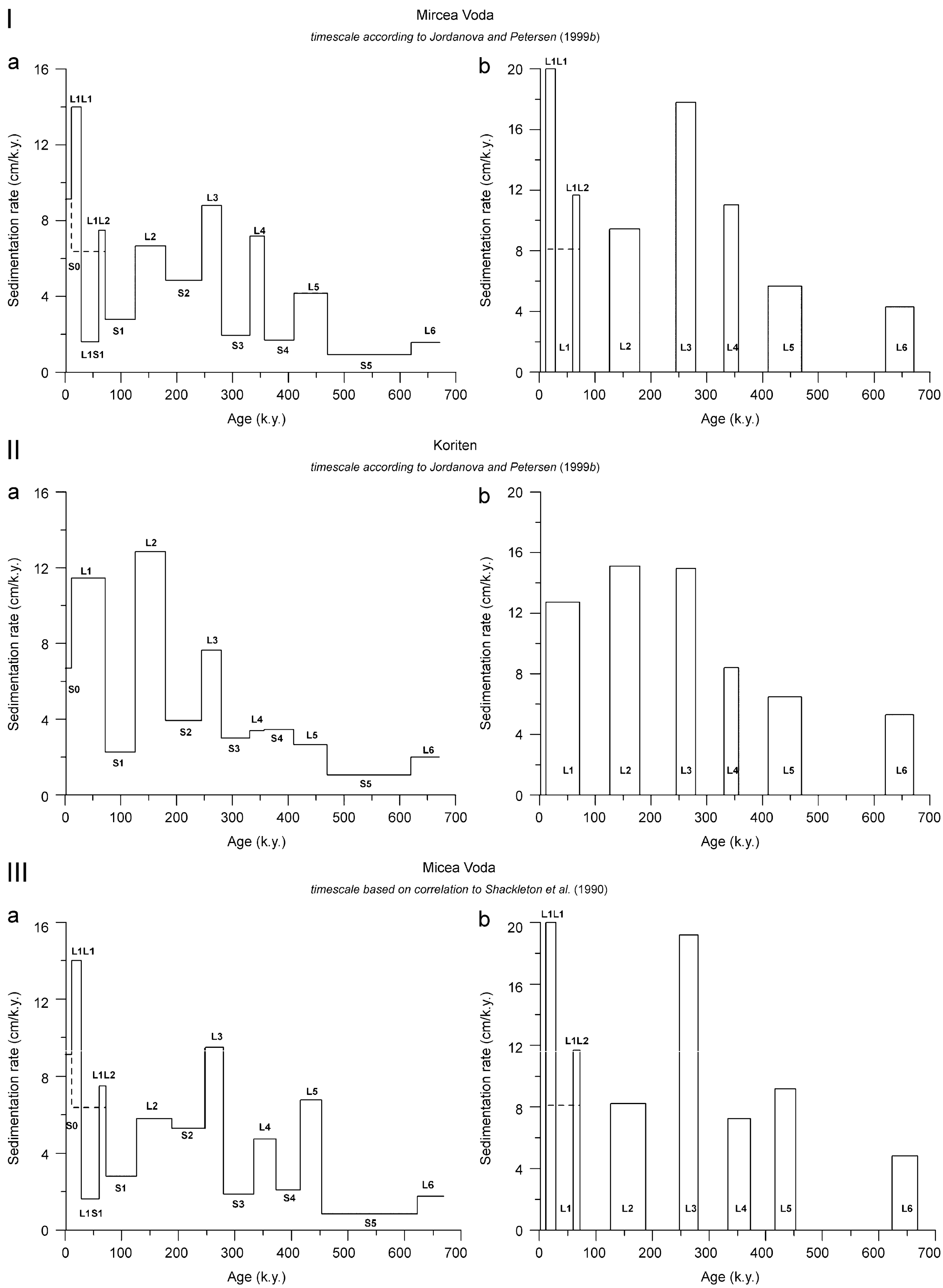

Fig. 7. Sedimentation rates for the sections Batajnica/Stari Slankamen and Mircea Voda. (I) Sedimentation rates for the LPSS Mircea Voda, calculated for the timescale used by Jordanova and Petersen (1999b). This timescale was based on correlation of the magnetic susceptibility record of Koriten to the planktonic $\delta^{18}O$ record of ODP 677. (II) Sedimentation rates for the LPSS Koriten(Jordanova and Petersen (1999b), modified). (III) Sedimentation rates for the LPSS Mircea Voda, calculated for a timescale derived by correlation of the susceptibility records of Fig. 5 to the benthic $\delta^{18}O$ of ODP 677 (Shackleton et al., 1990). (IV) Sedimentation rates for the LPSS Mircea Voda, calculated for the age boundaries of the isotope events, developed by Bassinot et al. (1994) for planktonic foraminifers of core MD900963 (Indian Ocean). (V) Sedimentation rates for the LPSS Mircea Voda, calculated for a timescale derived from correlating the susceptibility records of Southeastern Europe to the susceptibility record of Lingtai and Zhaojiachuan (Chinese Loess Plateau). The astronomical tuning for these sections was done by Sun et al. (2006) using a record of mean grain size of quartz particles (MGSQ). (VI) Sedimentation rates for the LPSS Mircea Voda were calculated using the timescale given by Heslop et al. (2000) for the loess–paleosol units of the Baoji section (China). (a) Sedimentation rates calculated according to variant A (worst case): synpedogenetic sedimentation, the whole thickness of a paleosol is attributed to sedimentation during warm stages. (b) Sedimentation rates calculated according to variant B (worst case): no sedimentation during warm stages (prepedogenetic sedimentation). The dashed line gives the mean sedimentation rate for L1.

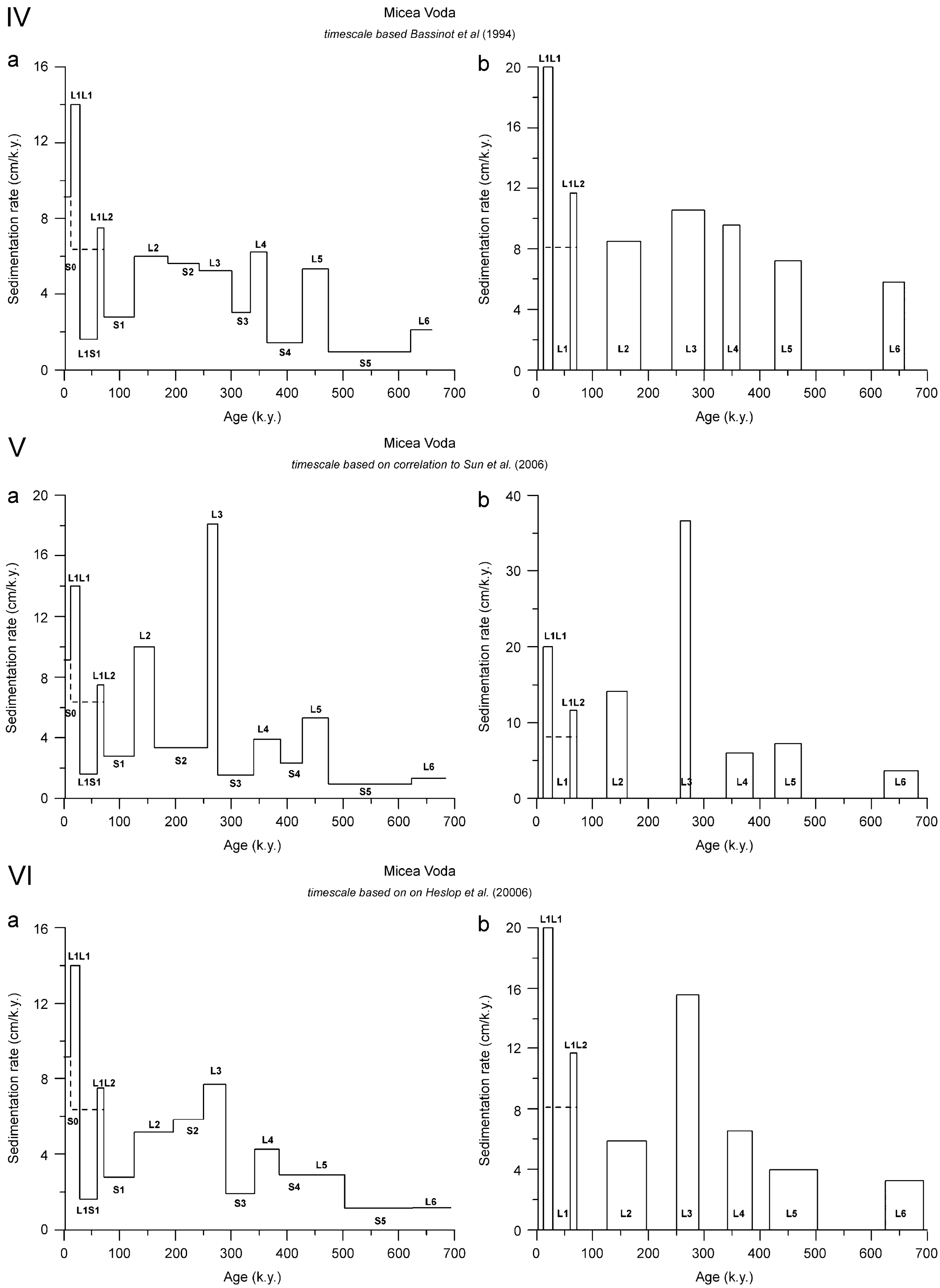

Fig. 7. (*Continued*)

deposition from L6 to L3 or L2, is questionable, though one might have interpreted the results of Koriten (Jordanova and Petersen, 1999b) and Mircea Voda in this sense, using only the JP-99b timescale. However, at Mircea Voda, the sensitivity analysis confirmed that relatively high rates of sedimentation occurred within the period of MIS 2–4 (= L1), MIS 8 (= L3) and the warm stage MIS 7, whereas the lowest rate of sedimentation in cold stages occurred during MIS 16 (L6), and the lowest rate during warm stages in MIS 13–15 (S5). These findings can be interpreted with respect to paleoclimate or atmospheric circulation.

For the last climatic cycle, no sensitivity analysis with respect to timescale was conducted. The applied age model is based on Guiter et al. (2003) and Litt et al. (2001), who compiled the results of several West and Central European studies. Uncertainties, reported in these studies, seem to be negligibly small. However, the onsets of climate variations in Southeastern Europe are not simultaneous to those of Western and Central Europe. Therefore, and due to the rather diffuse lower boundary of the recent soil, sedimentation rates obtained for the Holocene should not be overinterpreted. The short duration of this period makes these results sensitive to uncertainties in the thickness of the corresponding units. High-resolution luminescence dating may provide a suitable tool for a more precise determination of the age boundaries of the upper Pleistocene climatic stages in the profiles (Lai and Wintle, 2006).

6.2. Chronostratigraphic revisions

For setting up a timescale of mid-Pleistocene terrestrial archives, there is a lack of reliable methods of numerical dating. Therefore, relative stratigraphies in combination with astronomical tuning are widely used for working out chronostratigraphies of LPSS. Correlations and tunings are often ambiguous in detail and highly subjective. Continuous validation of existing stratigraphies is crucial for setting up a reliable timescale of the Quaternary. These results can provide a useful contribution to ongoing discussions about the stratigraphy of the region and it may initiate a new discussion concerning the astronomical tuning of Chinese LPSS.

For Batajnica/Stari Slankamen and Mircea Voda, the stratigraphy is well established by the correlation of the magnetic susceptibility records to the $\delta^{18}O$ record of benthic foraminifera of ODP site 677 (Shackleton et al., 1990), to a stacked magnetic susceptibility record of two sections from the Chinese Loess Plateau (Sun et al., 2006) and validated by correlations to other profiles of the study area (e.g. Jordanova and Petersen, 1999b; Panaiotu et al., 2001; Marković et al., 2006; Fig. 5). Contrasting TL ages for the Stari Slankamen S1–S4 (Singhvi et al., 1989, cited in Bronger, 2003) are probably due to a methodological age underestimation (Dodonov et al., 2006a; Fuchs et al., 2008). For the Stary Kaydaky section, the type locality of the Kaydaky pedocomplex, magnetic susceptibility correlations to the dated Vyazivok section (Rousseau et al., 2001) and to the ODP 677 proxy record of the global ice volume gives an important contribution to clarify contrasting stratigraphic frameworks of Ukraine.

Here, the focus is on some implications of our inter-profile correlations concerning the following topics: (1) the S2S1-unit, stratigraphic setting and implications on orbital tuning, (2) the division of the S6 and S7 pedocomplexes, and (3) the local Ukrainian stratigraphy.

6.2.1. The S2S1 unit, stratigraphic setting and implications on orbital tuning

One of the most characteristic magnetic susceptibility patterns of loess profiles covering Southeastern Europe through Tajikistan (Dodonov et al., 2006b) to the Chinese loess plateau (Sun et al., 2006) is an association of three peaks (for example, the Mircea Voda record, Fig. 5), assigned here to the S2 pedocomplex. Probably due to sampling resolution and/or local effects, the two lowermost peaks are not always to distinguish in the profiles (for example, the Batajnica record, Fig. 5). The uppermost pedomember (unit S2S1)—having only weak susceptibility enhancement—is clearly visible in the field. We consider this pedomember as a formation of MIS 7. Correlating the susceptibility feature of the S2 in Southeastern Europe with the stacked astronomically tuned record of Lingtai/Zhaojiachuan, we conclude that the units S2S3 and S2S2 match the susceptibility peaks at 236 and 204 ka (hereafter named LZe and LZc + d, Fig. 5). S2S1 is correlated with the benthic $\delta^{18}O$ peak at 190 ka of ODP 677. There are three possible correspondences of the S2S1 unit in the terrestrial records. The first one is a correlation with the upper part of the slightly split major S2 susceptibility peak in Louchuan (Heslop et al., 2000) and Lingtai/Zhaojiachuan (LZc). This does not seem likely, since the susceptibility enhancement in the Southeastern European S2S1, as well as the intensity of pedogenesis observed in the field for this unit is generally weak and clearly offset from the S2S2. Furthermore, this correlation is not supported by Jordanova and Petersen (1999b) and Panaiotu et al. (2001). The second possibility is a correlation with the bend in the top of the major S2 susceptibility peak in Louchuan and with a peak (LZb) in the susceptibility record of Lingtai/Zhaojiachuan at an age of 192 ka (Sun et al., 2006). This possible correlation would be in accordance with the proposed position of S2S1 at the top of the S2 pedocomplex, attributed to MIS 7 (Fig. 5, Jordanova and Petersen, 1999b; Panaiotu et al., 2001).

Here, the third possibility is favored, correlating the susceptibility peak of the S2S1 unit with the susceptibility peak of 167 ka (LZa) in Lingtai/Zhaojiachuan (Sun et al., 2006). This matches best the susceptibility patterns of the Southeastern European sections (Fig. 5) and is also in agreement with the correlations of Jordanova and Petersen (1999b) and Panaiotu et al. (2001). However with an age of 167 ka following Sun et al. (2006), the S2S1 paleosol would then be assigned to MIS 6. Heslop et al. (2000) presented an orbital tuning for the susceptibility record of the Louchuan section, showing an age of about 175 ka for the corresponding peak of LZa and S2S1. Both the timescales of Sun et al. (2006) and Heslop et al. (2000) seem to underestimate the age of this susceptibility peak, when compared to the benthic oxygen isotope record of Shackleton et al. (1990) (Fig. 5). This record, reflecting the global ice volume, gives an age of 188 ka for the MIS 6/MIS 7 boundary and of 190 ka for the most likely counterpart of the S2S1-susceptibility peak.

Heslop et al. (2000) present a match of the magnetic susceptibility record of Louchuan, the benthic $\delta^{18}O$ record of ODP 677 and the insolation curve. This we take as base to suggest an improvement of the orbital tuning of the questionable period. Heslop et al. (2000) associated three insolation peaks (at about 195, 220 and 240 ka) with MIS 7. The lowermost is attributed to the counterpart of S2S3 and LZe at Louchuan. The younger two peaks are both correlated with the slightly splitted susceptibility peak S2-1 (Heslop et al., 2000), which is the counterpart of the Southeastern European S2S2 and LZc + d of the Chinese Loess Plateau. More reasonable, with respect to magnetic susceptibility stratigraphy, seems to be a match of the uppermost MIS 7 insolation peak, shown by Heslop et al. (2000), with the susceptibility peak at 15 m depth in Louchuan, the LZa in Lingtai/Zhaojiachuan and the uppermost benthic $\delta^{18}O$ peak of MIS 7. The susceptibility pattern of the MIS 7 (= S2 pedocomplex) of Southeastern Europe would then better correspond to the Chinese records. The best Chinese counterpart of the S2S1 paleosol would not belong to MIS 6, due to a back shift in time by about 20 ka according to the Heslop et al. (2000) timescale and by about 25 ka according to the timescale of Sun et al. (2006). In consequence of this improvement, an overall shift in the astronomical tuning of Heslop et al. (2000) and Sun et al. (2006) would not be necessary, if the timescale is stretched for the Chinese L2. Further research is needed to clarify the questions about the L2/S2 and MIS 6/MIS 7 boundaries.

6.2.2. *Division of pedocomplexes S6 and S7*

At Koriten, Jordanova and Petersen (1999b) found a single pedocomplex (regarded as S6) spanning from the L6 to the B/M boundary. There are two reasons to doubt that the Koriten S6, in terms of Jordanova and Petersen (1999b), corresponds to the Chinese S6. First, susceptibility records of Chinese LPSS (Heslop et al., 2000; Sun et al., 2006) exhibit a similar susceptibility pattern, implicating the correlation of the upper part of the Koriten S6 with the Chinese S6 (MIS 17), the middle part of Koriten S6 with MIS 18 (interstadial soil development) and the lower part of Koriten S6 with Chinese S7 (MIS 19). Second, the true position of the B/M boundary is located in S7, as shown by Zhou and Shackleton (1999). Due to the fact that the acquisition of remanent magnetization in loess is diagenetically delayed, the B/M boundary is often found in the underlying L8 loess or even in the upper part of S8 (Zhou and Shackleton, 1999). Therefore, the B/M boundary in Koriten probably indicates the base of the equivalent to the Chinese S7.

At the Mircea Voda section, the S6 showed two susceptibility peaks (Fig. 3). The lower one is most likely to be an interglacial formation, as it is more strongly developed than the upper one. Thus, the S6S2 is most probably a soil formation of either MIS 17 or 19. A preliminary screening on several oriented samples of the underlying loess by the paleomagnetic standard procedure of the laboratory for Paleomagnetism and Environmental Magnetism (University of Bayreuth) did not indicate a geomagnetic reversal. Therefore, at the present state of research, the lowermost susceptibility peak of the Mircea Voda S6 does not seem to represent the Chinese S7: rather, the S6 of Mircea Voda is an equivalent of the Chinese S6. However, more detailed systematic investigations for detecting the B/M boundary in Mircea Voda are required.

6.2.3. *The local Ukrainian stratigraphy*

At the Stary Kaydaky section, erosional capping, pedogenic overprint of loess units and some unknown bias on the susceptibility of the older units, required besides the magnetic susceptibility record, also pollen-, and pedostratigraphic information to develop a chronostratigraphy. However, in the present Ukrainian stratigraphic system, the chronological setting of the Kaydaky and Dnieper units is regarded in two different ways (Table 2): (1) as correlatives of MIS 7 and 8, respectively (e.g. Veklitch, 1993; Lindner et al., 2006), and (2) as terrestrial equivalents of MIS 5 and 6 (e.g. Rousseau et al., 2001; Gerasimenko, 2004, 2006; Bolikhovskaya and Molodkov, 2006). The results of this research (Fig. 6) support the latter model. Having cleared the chronological placement of these key-units, it was possible to suggest a chronostratigraphy for the upper and lower part of the Stary Kaydaky section. Accordingly the oldest studied pedocomplex is assigned to MIS 13–15 (see Table 2).

Two versions can be considered for the refined stratigraphy of L1. In the sections of the Black Sea coast, the uppermost soil within L1 is dated to the Bölling-Alleröd (Gozhik et al., 2000). In the northern and central Ukraine, Bölling-Alleröd deposits are mainly included in the lower layers of the thicker Holocene soils, and the uppermost soil within the loess of MIS 2 belongs to the Dofinivka unit, dated to 15–17 ka (Gozhik et al., 2000). Furthermore, the underlying Bug loess is thick and includes a set of 2–4 incipient soils in its lower part (Gerasimenko, 2006). At the Stary Kaydaky section, a similar succession of incipient soils in the lower part of L1 favors the second version of L1-stratigraphy.

6.3. *Evaluation of the susceptibility–rainfall relationship*

Maher et al. (1994) developed a climate function (Eq. (1)) calculating the mean annual precipitation from the magnetic susceptibility of surface soils of the Chinese Loess Plateau by means of least-squares regression. The equation was then successfully used in paleoprecipitation reconstruction. According to Maher et al. (1994, 2002) and Maher and Thompson (1995), this relationship should also be valid for Southeastern and Eastern European LPSS. Panaiotu et al. (2001) performed a paleorainfall reconstruction based on this formula for the Mostistea section. Eq. (1) was applied to the profiles and to the susceptibility record of Koriten (Jordanova and Petersen, 1999b). The χ_C value was not strictly determined according to Maher et al.

Table 3
Paleoprecipitation for the profiles Batajnica/Stari Slankamen, Mircea Voda, Stary Kaydaky, Koriten, Mostistea

Batajnica/Stari Slankamen		Mircea Voda		Stary Kaydaky		Koriten (calculation done on values of Jordanova and Petersen (1999b))		Mostistea (according to Panaiotu et al. (2001))	
Unit	MAP (mm)	Unit	MAP (mm)	Unit	MAP (mm)	Unit	MAP (mm)	Unit	MAP (mm)
S0	537 (529)	S0	570 (561)	S0	547 (547)	S0	570	S0	587
L1L1	328	L1L1	372	L1L1	Ref.				
L1S1	441 (413)	L1S1	451 (426)	L1S1	442				
L1L2	330	L1L2	331	L1L2	424				
S1	604 (604)	SI	561 (561)	SI	538 (537)	S1	543	S1	580
L2	Ref.	L2	Ref.	L2	188	Ref.			
S2S1	471	S2S1	425	S2S1	348	S2S1	444	S2	603
S2S2-3	597 (593)	S2S2	533	S2S2-3	578	S2S2-3	593		
		S2S3	573 (562)						
L3	341	L3	384						
S3	621 (616)	S3	631 (628)	S3	580	S3	631	S3	627
L4	373	L4	339						
S4	544	S4	620 (617)	S4	491	S4	606		
		L5	330						
S5	612 (609)	S5	615 (609)	S5S1	461	S5	599		
				S5L1	287				
				S5S2	485				
L6	328	L6	371						
S6	573	S6S1	534			S6	580		
		S6S2	539						

Values were calculated from the magnetic susceptibility using Eq. (1), presented by Maher et al. (1994). For Mostistea, the results from the calculation by Panaiotu et al. (2001) are shown. Background susceptibility was taken from a reference loess unit (Ref.) for each section. Wherever it was possible, rainfall calculations were also conducted for background susceptibilities taken from the respective loess unit below a paleosol (results in brackets).

(1994), who used the susceptibility data of the parent material for pedogenesis, i.e. of the respective loess unit below a paleosol as background values. However, due to pedogenic alteration of several loess units, in this study the lowest susceptibility value of the loess for each profile was selected as characteristic background for the respective profile, assuming that the initial background composition of highly susceptible minerals does not change significantly with depth. Loess units with remarkable pedogenetic overprint from the paleosol in the top, as to field observations and elevated susceptibility values, were excluded from the calculation (see Table 3). To test this assumption, rainfall was also calculated by taking the χ_C-values from the loess unit below the respective paleosol unit, wherever it was possible. In most cases both results are very close, and lead to the same interpretation.

The calculated MAP values for the recent soil do not correspond to the numerical values derived from the climatological dataset (Fig. 2). Only for Stary Kaydaky (this study) and for Mostistea (Panaiotu et al., 2001) are the calculated MAP values closer to the true ones. The relative MAP relationship between the sections is reflected neither in the calculated present-day values nor in the reconstructed paleoprecipitation (except for the S2 unit). Therefore, Eq. (1) cannot be simply transferred to the study area. However, it might be valuable for the comparison of relative precipitation patterns on a small regional scale, since it reflects relatively well the Mostistea–Mircea Voda relationship. Improvement of Eq. (1) by increasing the dataset for the susceptibility–rainfall regression would also not ensure realistic values, since the site with the lowest MAP (Mircea Voda) exhibits the highest susceptibility enhancement for the modern soil and also for some paleosols.

For the observed disagreement, several explanations are possible, which are hard to evaluate with the available dataset. First, the magnetic susceptibility of a subsoil horizon (as suggested by Maher et al., 1994) cannot be used to calculate the present-day MAP, because the S0 soils are steppe soils lacking any B horizons. Susceptibility enrichment effects due to surface pollution cannot be discounted, for example by the atmospheric deposition of magnetic spherules out of fossil combustion (Thompson and Oldfield, 1986). Also different fire histories may disturb the MAP–susceptibility relationship (Maher and Thompson, 1995). Further, it can be argued whether the susceptibility of a soil is in equilibrium with the climatic conditions during all the time of pedogenesis. Though gleying was not observed, the optimum humidity conditions for the formation and sustainment of ferrimagnetic minerals may be exceeded in some units. Therefore, the regression function of Maher et al. (1994) has to be critically evaluated. Maher et al. (2002) presented a rainfall–susceptibility analysis of several Russian steppe soils, which fit well with data from the Chinese Loess Plateau. However, some data points of the Russian and Ukrainian steppe, having the same pedogenic susceptibility, show MAP values between about 330 and 510 mm yr^{-1}. Probably other climatic and/or pedogenic factors such as the seasonal distribution of precipitation, temperature and time may be responsible for this scatter (Maher, 1998; Vidic et al., 2004) and may also disturb the MAP–susceptibility relation for these sections. Maher herself found, besides the MAP–susceptibility relation, a significant correlation of temperature and susceptibility (Maher et al., 1994).

Altogether in the study area, the use of magnetic susceptibility as a quantitative MAP proxy does not seem rational for the comparison of absolute MAP values between the sections. However, magnetic susceptibility is sufficiently valid for careful qualitative paleoclimatic deductions within one section due to the general mechanisms of susceptibility enhancement.

6.4. Paleoclimatic conclusions

The magnetic susceptibility records of the studied Southeastern/Eastern European sections show high susceptibility values in the paleosols and low values in the loesses (Fig. 3), reflecting the sequence of interstadial/interglacial and stadial/glacial periods of the Quaternary (Fig. 5). This is in accordance with the susceptibility enhancement model for the Chinese LPSS. Reduction of the magnetic susceptibility of paleosols in comparison to the loess units, due to waterlogged conditions or the wind-vigor model—as described for some sections of Siberia and Alaska (Evans and Heller, 2001)—could not be found. Focusing on the paleosols of Batajnica/Stari Slankamen and Mircea Voda, there is an increase in susceptibility from the S1—in Batajnica, from the S2—to the S3. The S3 shows the strongest susceptibility enhancement of the whole LPSS. This is interpreted as an indication of a warmer and wetter climate during MIS 9 compared to the younger interglacials/interstadials. This observation corresponds to the susceptibility record of other sections of the Northern Black Sea coastal area (Dodonov et al., 2006a), the lower Danube area (Jordanova and Petersen, 1999b; Panaiotu et al., 2001), as well as to the records of the sections Darai Kalon (Dodonov et al., 2006b) and Chashmanigar (Ding et al., 2002) in Tajikistan, whereas the Karamaidan section (Tajikistan; Forster and Heller, 1994) and the stacked record of Lingtai/Zhaojiachuan (Sun et al., 2006) show different susceptibility behavior. A direct climatic trigger mechanism, responsible for these findings, could not yet be identified. Local climatic factors may explain why there are paleosols in some sections, which do not exhibit the observed trend. Below the S3, there is a trend to lower susceptibility values at least upto S6, also described for Koriten by Jordanova and Petersen (1999b). Field observations at the Serbian and Romanian sections, the observations of Marković et al. (submitted), specifically for Batajnica and the study of Bronger on sections of the Carpathian basin (1976), especially the Stari Slankamen site, show a trend from more steppe-soil-type paleosols at the top of the LPSS to stronger developed and more reddish (rubificated) paleosols at the bottom, partly with iron and manganese coating. In the Lingtai/Zhaojiachuan record, S5 has the strongest susceptibility enhancement among the Brunhes–chron–paleosols. Therefore, the susceptibility enhancement of these older paleosols does not fully reflect the intensity of pedogenesis. At the present state, the decrease of susceptibility in the paleosols of MIS 11–17 is tentatively explained by an increase in humidity, so that the optimum conditions for the formation of ferrimagnetic minerals could be exceeded. These results implicate a stronger monsoonal type of climate at the beginning of the mid-Pleistocene, at least for Southeastern Europe. For Stary Kaydaky, a climatic interpretation of the magnetic susceptibility record is difficult, because the signal is significantly diminished in the older units (S4, S5) for some unknown reason. Field observations and the susceptibility record of the younger units do not support a trend as in the Southeastern European sections. Presumably, the (paleo)-climate of this location is controlled by another trigger mechanism. Further paleoclimatic and rock magnetic research on LPSS of Southeastern and Eastern Europe is necessary to validate these rather preliminary interpretations and to find answers for the open questions revealed by this study.

7. Conclusions

(1) Loess–paleosol sequences of the sections Batajnica/Stari Slankamen (Serbia) and Mircea Voda (Romania) comprise at least six and at Stary Kaydaky (Ukraine) at least five paleosol/pedocomplexes. Susceptibility enhancement is generally found in paleosols. Similar patterns in the susceptibility record allowed spatial correlation of the stratigraphic units to profiles in the Chinese loess plateau and also with the benthic $\delta^{18}O$ record of ODP 677. The Mircea Voda and Batajnica/Stari Slankamen sections have paleoclimatic records at least to MIS 17 and the Stary Kaydaky section probably to MIS 13–15. The Kaydaky pedocomplex is correlated with MIS 5e and the underlying Dnieper loess with MIS 6. The presented chronostratigraphy for the studied sections is additionally confirmed by pedostratigraphic correlations to other dated loess–paleosol sequences of Southeastern and Eastern Europe. It provides the possibility to regard the stratigraphic units as correlatives of loess–paleosol units in the Chinese stratotype sections of the Quaternary (Kukla and An, 1989) and to avoid the use of (often confusing) local stratigraphic names in future studies.

(2) This stratigraphic work suggests a rediscussion of the astronomical tuning of the MIS 6/MIS 7 boundary for the Chinese loess–paleosol sequences.

(3) For the calculation of sedimentation rates, it is strongly recommended to use sensitivity analyses with respect to the applied timescale and to the degree of synpedogenetic sedimentation in order to interpret reliable results. At Mircea Voda, relatively high sedimentation rates were clearly obtained for the younger loess units,

especially the L1 and L3. Lowest rates of dust deposition during a cold stage occurred in MIS 16 (= L6) and during a warm stage in MIS 13–15 (= S5). MIS 7 was characterized by relatively high sedimentation rates for an odd-numbered MIS, probably due to intercalated periods of pronounced climate deterioration.

(4) The mean annual precipitation–susceptibility relation obtained by Maher et al. (1994) is not valid for this study area, at least not for the large regional scale from Serbia and Romania to Ukraine. However, magnetic susceptibility can be used for qualitative interpretations within a single section.

(5) Qualitative paleoclimatic interpretations of the obtained susceptibility dataset indicate a gradual increase of paleoprecipitation from the younger to the older warm stages in Southeastern Europe. The tentative paleoclimatic interpretation emphasizes the potential and need for further research in the study area.

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