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Loess in the Vojvodina region (Northern Serbia): an essential link between European and Asian Pleistocene environments

S.B. Marković[1,*], U. Hambach[2], T. Stevens[3,1], M. Jovanović[1], K. O'Hara-Dhand[4], B. Basarin[1], H. Lu[5], I. Smalley[4], B. Buggle[2], M. Zech[2,6], Z. Svirčev[7], P. Sümegi[8], N. Milojković[1] & L. Zöller[2]

1 Chair of Physical Geography, Faculty of Sciences, University of Novi Sad, Trg D. Obradovića 3, 21000 Novi Sad, Serbia.
2 Chair of Geomorphology, University of Bayreuth, D-95440 Bayreuth, Germany .
3 Centre for Quaternary Research, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK.
4 Giotto Loess Research Group, Department of Geology, Leicester University, LE1 7RH, UK.
5 School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China.
6 Soil Physics Department, University of Bayreuth, Universitätsstr. 30, D-95440 Bayreuth, Germany.
7 Laboratory for paleoenvironmental reconstruction, Faculty of Sciences, University of Novi Sad, Trg D. Obradovića 2, 21000 Novi Sad, Serbia.
8 Department of Geology and Palaeontology, University of Szeged, 6722, Szeged Egyetem u.2-6, Hungary.
* Corresponding author. Email: slobodan.markovic@dgt.uns.ac.rs.

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Abstract

Loess deposits in the Vojvodina region, northern Serbia, are among the oldest and most complete loess-paleosol sequences in Europe to date. These thick sequences contain a detailed paleoclimatic record from the late Early Pleistocene. Based on the correlation of detailed magnetic susceptibility (MS) records from Vojvodina with the Chinese loess record and deep-sea isotope stratigraphy we here reconfirm and expand on a stratigraphic model of the Vojvodinian loess-paleosol chronostratigraphic sequence following the Chinese loess stratigraphic system.

Variations in MS, dust accumulation rates, and the intensity of pedogenesis demonstrate evidence for a Middle Pleistocene climatic and environmental transition. The onset of loess deposition in Vojvodina also indicates a direct link between dust generation in Europe and that in the interior of Eurasia since the Early Pleistocene. The youngest part of the Early Pleistocene and oldest part of the Middle Pleistocene is characterised by relatively uniform dust accumulation and soil formation rates as well as relatively high magnetic susceptibility values. In contrast, the last five interglacial-glacial cycles are characterised by sharp environmental differences between high dust accumulation rates during the glacials and low rates observed during soil development. The data presented in this study demonstrate the great potential of Vovjodina's loess archives for accurate reconstruction of continental Eurasian Pleistocene climatic and environmental evolution.

Keywords: China, Climate, Eurasia, Loess, Magnetic susceptibility, Pleistocene, Serbia

Introduction

Loess and loess-like deposits cover about 10% of the Earth's continents, mostly concentrated in the mid latitude zone of Eurasia (Fig. 1). These deposits represent one of the world's most outstanding terrestrial archives of paleoclimate change (e.g. Kukla 1970, 1977; Liu, 1985; Smalley et al., 2011). Attaining considerable thickness and forming under high accumulation rates, they preserve long-term paleoclimate signals that can be analyzed at high resolution to uncover millennial-scale climate changes (e.g., Porter, 2001; Stevens et al., 2008). These thick and quasi-continuous Pleistocene loess deposits are mostly preserved in China and Central Asia (e.g. Kukla, 1987; Dodonov & Baizugina, 1995; Bronger et al., 1995; Vandenberghe et al., 1997; Frechen & Dodonov, 1998; Vandenberghe & Nugteren, 2001; Ding et al., 2002; Lu et al., 2002, 2004; Stevens et al., 2007; Dodonov & Zhou, 2008; Machalett et al., 2008).

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Fig. 1. Distribution of the loess sediments modified from Muhs et al. (2007): 1. Loess in northern Serbia; 2. Chinese Central Loess Plateau.

However, significant pre-Late Pleistocene loess-paleosol sequences also sporadically occur in Europe, concentrated predominantly in the middle and lower Danube basin (Fink & Kukla, 1972; Kukla, 1975; Sartori et al., 1999; Bronger, 2003; Buggle et al., 2009; Balescu et al., 2010; Thiel et al., 2011; Újvári et al., 2012). In particular, numerous studies have recently been published focusing on the loess-paleosol sequences of the Vojvodina region in northern Serbia. These have demonstrated that this archive represents one of the most complete and sensitive European terrestrial records of climatic and environmental changes since the late Early Pleistocene. The relative completeness and the pattern of preserved paleoclimatic signals indicates that these Vojvodinian loess-paleosol sequences can be directly correlated across the Eurasian loess belt to the east Asian loess records (e.g. Marković et al. 2008, 2009b, 2011; Stevens et al., 2011).

The data from the Vojvodinian region presented here are directly compared to the Chinese loess record over the Middle and Late Pleistocene for the first time since significant improvements in age models for the sequences have been made. This comparison emphasises the antiquity of the loess-paleosol sequences in the Vojvodina region and demonstrates the significance of the detailed and relatively complete palaeoclimatic record they contain, as well as the nature of the differences and similarities between the records. This is crucial for the development of understanding long-term climatic and environmental evolution over the entirety of Eurasia.

Settings and methods

Here we investigate key Serbian loess-paleosol sections located on the Srem loess plateau (Fig. 2): Ruma, Batajnica and Stari Slankamen, as well as a stacked profile of sections on the Titel loess plateau (Fig. 2). Field investigations were focused on detailed cleaning, sampling, and a precise description of the loess-paleosol sequences. Paleopedological interpretations are based on the WRB soil classification (FAO, 2006).

The Ruma loess-paleosol sequence (44°55'29" N and 20°19'11" E) is exposed in an excavation at a local brick factory on the left bank of the Jelence Stream in the central part of the southern slope of Fruška Gora mountain. The Batajnica loess-paleosol sequence (44°55'29" N and 20°19'11" E) is situated about 15 km northwest of Belgrade. The analyzed profiles crop out close to each other in steep loess cliffs of the southeastern Danube bank. The Batajnica stacked profile was built up on the basis of inter-section correlation. The exposure at Stari Slankamen (45°07'58" N and 20°18'44" E) is located on a steep bank of the Danube River, opposite the Tisa confluence.

The composite loess-paleosol profile of the Titel loess plateau is based on sequences located in the northeastern part of the plateau near Mošorin village, close to Tisa bank about 20 km upstream from its confluence with the Danube river (~45°18' N and 20°11' E). The modern soil (V-S0; see 'Litho- and pedo-stratigraphy of the loess in the Vojvodina region' for explanation of the unit terminology), and loess-paleosol sequences of the last 3 glacial intergalcial cycles including

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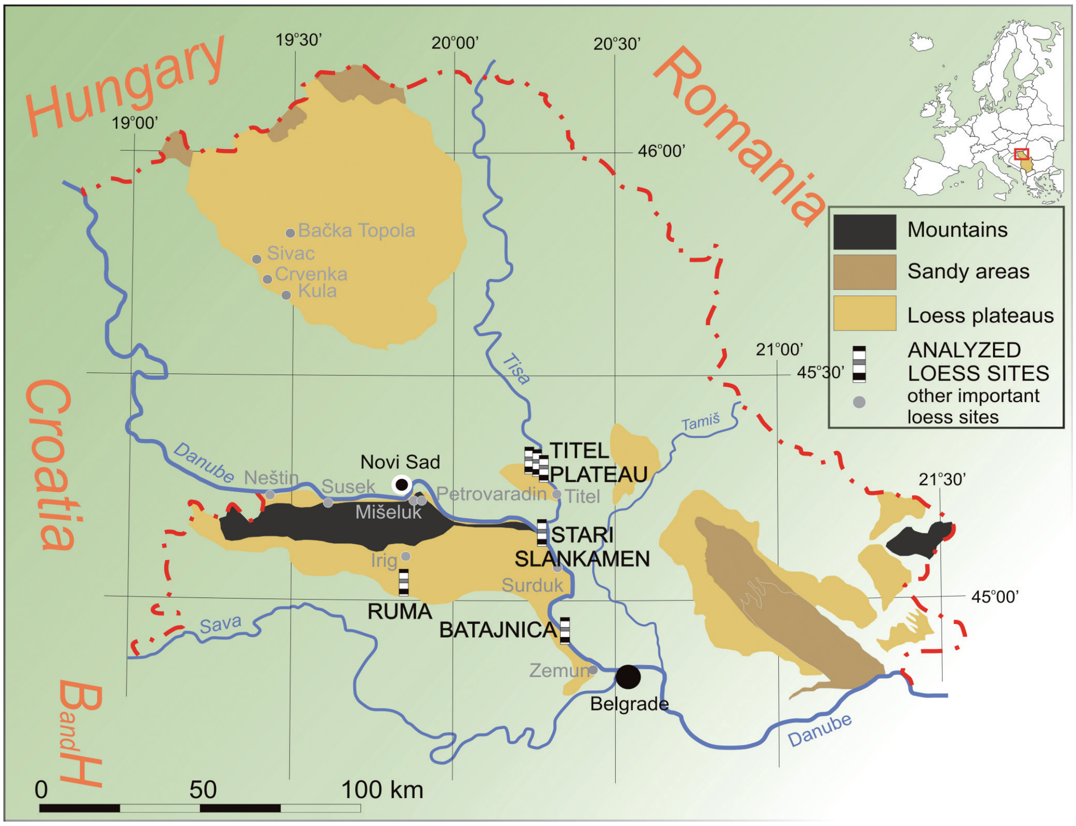

Fig. 2. Topographic map showing the locations of the main Middle Pleistocene loess sites in the Vojvodina region, Northern Serbia.

loess horizons V-L1 and V-L2, and pedocomplexes V-S1, V-S2 and V-S3 are represented in the Veliki Surduk deep gully section. Feudvar section is located in a loess gully and exposes the loess units V-L3 and V-L4 and the V-S3 and V-S4 pedocomplexes. Finally, the Dukatar section includes the lowermost loess-paleosol sequences from V-S4 to the bottom of the section. The Titel plateau stacked profile is constructed on the basis of intersection correlation using overlapping MS records of the subsections.

With the exception of the Stari Slankamen and Ruma sections, samples for initial low field magnetic susceptibility (MS; volume susceptibility, κ) measurements were taken at 5 cm intervals, resulting in more than 3000 individual specimens. The high resolution MS measurements were obtained in the laboratory for paleo- and enviromagnetism at the Chair of Geomorphology, University of Bayreuth using the KLY-3-Spinner-Kappa-Bridge (AGICO, Brno, Czech Republic), operating with an AC-field of 300 A/m at 920 Hz.

At Stari Slankamen, *in situ* and laboratory measurements of low-field MS from the recent soil (V-S0) to the base of loess layer V-L6 were conducted at 10 cm intervals in paleosol horisons and at 15 cm intervals in loess layers. MS variation in the lower part of the profile, below the loess layer V-L5, was measured *in situ* using a portable Bartington MS2 susceptibility meter. At each level, 10 repeat readings were taken and averaged. Samples from the upper part of the exposure were measured on a Bartington susceptibility MS2B meter with a 36 mm opening at the Lamont-Doherty Geophysical laboratory in Palisades, New York. Selected samples from the lower part of the profile were re-measured, which made it possible to cross-calibrate MS values obtained through different instruments. At Ruma *in situ* measurements of MS were performed at 5 cm intervals using a portable Bartington MS2 susceptibility meter. The measured MS variations at the sites were used for interprofile and interregional correlation and correlation to the marine oxygen isotope curve of Lisiecki & Raymo (2005).

A total number of approximately 700 oriented samples (2 per each sampled level) were collected for paleomagnetic investigations continuously in the lower parts Stari Slankamen and Batajnica sections. Paleomagnetic experiments have been conducted from November 2006 in two independent laboratories: Laboratory for Palaeo- and Enviro-Magnetism (PUM), Chair of Geomorphology, University of Bayreuth and in Paleomag laboratory of Geo-research Centre (GFZ) Potsdam. A combination of both alternating field and thermal demagnetisation procedures were used in order to determine the primary magnetic polarity.

Combined MS records from the Titel loess plateau (from V-S0 to V-S5) and from Stari Slankamen (from V-L6 to basal pedocomplex) have been used to construct the time scale, through correlation to Lisiecki & Raymo (2005), with the aim of investigating climatic and environmental evolution and variability over the last million years. This age model is supported by independent dating of the Stari Slankamen section using paleomagnetism, amino acid racemisation in gastropods (Marković et al., 2011) and luminescence dating (Schmidt et al., 2010; under review). Loess-paleosol sequences of the Titel loess plateau covers the time interval between marine oxygen-isotope stages (MIS) 1 and 15, while the lower part of the Stari Slankamen section covers the time frame prior to MIS 16.

The first step towards the development of a timescale was the identification of the initial tie points between insolation values, marine oxygen-isotope stages and the magnetic susceptibility records. The initial anchor points were related to odd numbered marine isotope stages and their correspondence to insolation values. For the purpose of this study northern hemisphere July insolation at 65° N is used as a target curve, which is, according to Milankovitch theory, standard forcing mechanism. The insolation series were calculated using the solution of Berger and Loutre (1991).

We employed the SPECMAP-defined lag of −69° and −78° for obliquity and precession, respectively (Imbrie et al., 1984) and the tuning method of Yu & Ding (1998) was utilised to generate the astronomical timescale. The orbital tuning procedure involves simultaneously tuning MS maxima to insolation maxima. In this study the correlation coefficients between the filtered 41 kyr components of the MS series and the insolation curve and between the filtered 21 kyr components of MS series and the insolation curve are used as the criteria for judging the goodness of fit. It is recognised that this age model will be inaccurate over millennial timescales and not suitable for resolving leads and lags between the records. Nevertheless, for the purposes of cross comparison between broad multi-millennial time scale climate changes in Asia and Europe the age model is adequate.

Sedimentation rates are calculated using the Analyseries software (Paillard et al., 1996) and are based on the orbitaly tuned ages of loess and paleosol units.

Results

Litho- and pedo-stratigraphy of the loess in the Vojvodina region

Marković et al. (2003, 2004a, 2006) designated the loess-paleosol unit names in North-Serbia following the Chinese loess stratigraphic system (e.g. Liu, 1985; Kukla, 1987; Kukla & An, 1989), but inserting the prefix 'SL', referring to the Stari Slankamen site as the standard type section. However, to avoid confusion due to incompleteness in the youngest part of the Late to Middle Pleistocene loess-paleosol sequence preserved at Stari Slankamen, the prefix 'V' is now used to refer to the standard Pleistocene loess-paleosol stratigraphy in Vojvodina (Marković et al., 2008, 2011). The scheme therefore allows for information from the penultimate interglacial to be included, based upon other sections (e.g., Ruma and Batajnica; Marković et al., 2006; 2009b).

Previous stratigraphic description and magnetostratigraphic interpretations of Ruma, Batajnica, Stari Slankamen and the Titel plateau loess-paleosol sequences have been presented by Marković et al. (2004a, 2006, 2009b, 2011), and Hambach et al. (2011, in preparation). Figure 3 and Table 1 present stratigraphic descriptions of the investigated loess-paleosol sequences. These interpretations indicate many similarities between the

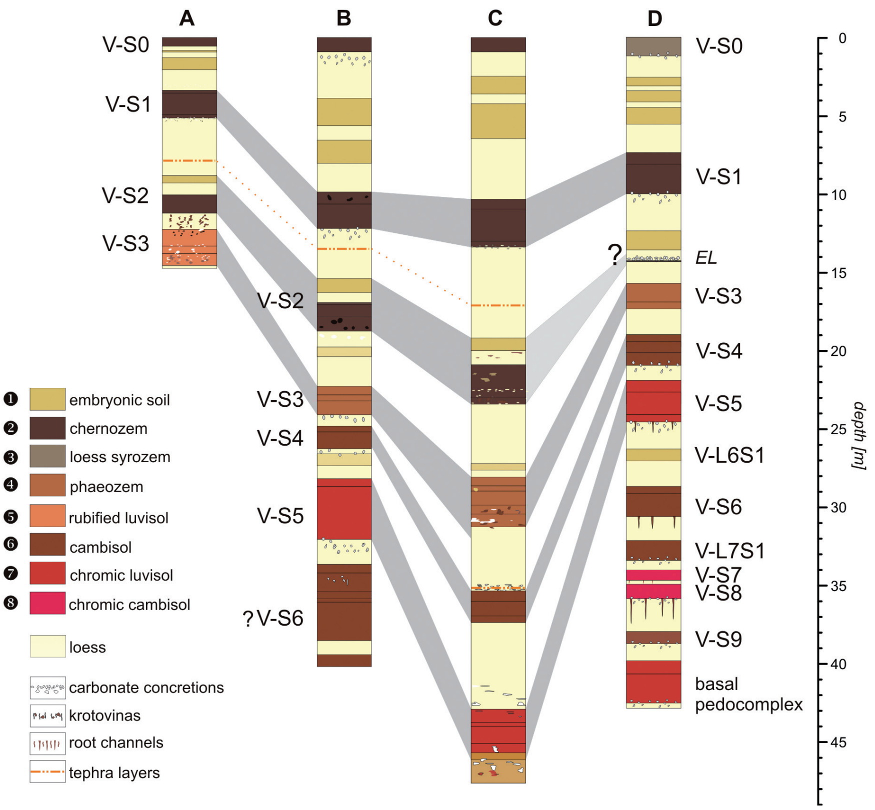

Fig. 3. Lithological and pedological description of the main Middle Pleistocene loess sites in the Vojvodina region: A – Ruma; B – Batajnica; C – Titel loess plateau; D – Stari Slankamen.

Table 1. Morphological description of the Stari Slankamen loess-paleosol sequences. Modified paleosol interpretations according to Bronger (1976), and Marković et al. (2006, 2009, 2011) are adapted to WRB soil classification (FAO, 2006).

	Ruma	Titel plateau	Batajnica	Stari Slankamen
V-S0	Chernozem		Chernozem partly highly disturbed by Neolithic occupation	Loess syrozem partly eroded
V-S1	Weakly developed paleosol although massive chernozem horizons in paleo depressions	Chernozem pedocomplex representing gradual weaking of pedogenesis from interglacial to early glacial with several krotovinas		
V-S2	Double Chernozem pedocomplex. Lower paleosol V-S2S1 is strongly developed contrary to weak upper paleosol V-S2S1			This pedocomplex is not exposed
V-S3	Rubified Luvisol with strongly developed basal BC and C horizons with hudge carbonate concretions	Phaeozem (Degraded Chernozem) pedocomplex with krotovinas in upper part		
V-S4		Cambisol pedocomlex with krotovinas in the uppermost part.		
V-S5		This composite paleosol unit includes a lower yellowish-red weakly rubified B horizon disturbed by many hydromorphic features; the middle dark brown weakly rubified cambic horizon with moderately developed coarse polyhedral structure; and upper pale brown weker developed A horizon.		Cromic Luvisol pedocomplex. A few Krotovinas exist at the contact with loess V-L5. Carbonate concretions in previous root channels are developed in the upper part. A poorly porous Bwt horizon is strongly developed.
V-S6			Cambisiol pedocomplex highly disturbed by hydromorphic features	Cambisol pedocomplex
V-S7				Chromic cambisol
V-S8				Chromic cambisol
V-S9				Weakly developed cambisol with hydromorphic features
Basal complex				Cromic Luvisol pedocomplex with many relatively soft carbonate nodules and fossilised tree remains

investigated sections, demonstrating some close similarities in Pleistocene environmental conditions across the region. Generally, paleopedological interpretations suggest a gradual climatic transition from subtropical to steppe interglacial environments indicating a progressive trend to more arid and more continental interglacials (Marković et al., 2011).

The new magnetostratigraphic and aminostratigraphic based age model proposed for loess-paleosol sequences in northern Serbia covers the last million years (Marković et al., 2011). The two independent chronostratigraphic approaches are sensitive enough to recognise hiatuses of loess-paleosol sequence preservation. For example, MS and evidence from gastropod amino acid racemisation indicates a missing penultimate interglacial pedocomplex V-S2 at Stari Slankamen, characterised by a distinct gravel layer overlying an erosional event. Despite this unconformity, the new results of Marković et al. (2011) demonstrate that the record at Stari Slankamen is one of the most long-term and complete in the region. This length and completeness is unusual and as such the section provides a rare opportunity to investigate long-term climatic change over the late Early and Middle Pleistocene in detail. The lowermost, approximately 11 m of the Stari Slankamen section, from paleosol V-S6 to the basal pedocomplex, contains the best preserved known early Middle and late Lower Pleistocene loess-paleosol successions in Europe (Marković et al., 2011).

The oldest investigated loess unit at the Batajnica site is probably equivalent to loess horizon V-L7. However, the lowermost part of the profile is strongly affected by intensive post-depositional hydromorphic features, disturbing the primary morphological and magnetic properties. Therefore, at present the data from the Batajnica loess-paleosol sequences older than V-S5 are not reliable enough for correlation with marine isotope stratigraphy and equivalent regional loess records (Marković et al., 2009b). Paleosols V-S4, V-S3 and V-S1 are very similar to their likely stratigraphic equivalents at the Stari Slankamen section.

With a total thickness up to 50 m, the sections on the Titel loess plateau preserve the most complete European loess record of the last ca 650 kyr. The Mošorin stacked loess-paleosol sequence represents a high resolution record of the last 5 glacial-

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interglacial cycles from the basal pedocomplex of V-S5 to the recent soil V-S0 (Hambach et al., 2011). Paleopedological characteristics of pedocomplexes from V-S5 to V-S1 are almost identical to those at the Batajnica exposure. Several macroscopically visible tephra layers preserved at the sections of the Titel loess plateau can be established as important regional chronostratigraphic marker horizons.

Finally, the Ruma section includes loess-paleosol sequences of the last 3 glacial-interglacial cycles. The uppermost part of the Ruma section contrasts with that at the other investigated sites in the Vojvodina region. Paleosols V-L1S1 and V-S1 are weakly developed, especially the last interglacial pedocomplex. However, in several paleo-depressions these fossil soils are much thicker and more strongly developed. The penultimate interglacial pedocomplex V-S2 is very similar to that preserved at Batajnica and the Titel loess plateau, while the strongly developed basal luvisol pedocomplex V-S3 is markedly different to V-S3 at the other investigated sections (Marković et al., 2006).

Paleomagnetic time markers

Detailed interpretation of the palaeomagnetic polarity zonation recorded at the Stari Slankamen loess-paleosol sequence is presented by Hambach (2009) and Marković et al. (2011). The data obtained after AF demagnetisation from the main section demonstrate the presence of reversed polarity below a profile depth of 36 m, indicating a Matuyama chron age of the lower part of the lowest loess layer V-L9. Exclusively normal polarity of the Brunhes Chron was found in paleosols V-S6, V-S7 and V-S8, as well as in loess units V-L7 and V-L8. A complex pattern of mixed polarity starts in the upper part of loess unit V-L9 from about 5 m downward, with the transition to the fully reversed polarity of the Matuyama chron in V-L10, just below V-S9. The shift to clear reversed polarity starts in the middle of fossil soil V-S9 (Marković et al., 2011). This complexity is likely to be a result of the interplay between chemical and detrital remanent magnetisation and lock-in depth (e.g. Spassov et al., 2003; Liu et al., 2008). This Matuyama-Brunhes paleomagnetic boundary (MBB; 0.78 Ma according to Cande and Kent, 1995) interval is one of the key control points in the chronostratigraphical subdivision of the Stari Slankamen sequence. A 2 m thick interval from the centre of V-S9 to the top of the basal pedocomplex shows almost fully reversed polarity. The lowermost 1 m of the section, within the basal pedocomplex, exhibits an interval of normal polarity, potentially indicating the Jaramillo Subchron. Furthermore, at the top of V-S6 two individual specimens show a trend to reversed polarity during progressive AF-demagnetisation (Hambach et al., 2009). This interval may correspond to the so-called Stage 17 excursion, giving an age of approximately 0.685 Ma (e.g. Channell et al., 2009).

Paleomagnetic results obtained for the lowermost 6 m of Batajnica section reveal continuous normal polarity, which is in agreement with the proposed chronostratigraphic model shown here. Thus the detailed results from the Batanica and Stari Slankamen sections indicate reverse polarity of the Matauyama chron only in the lower part of the Stari Slankamen section.

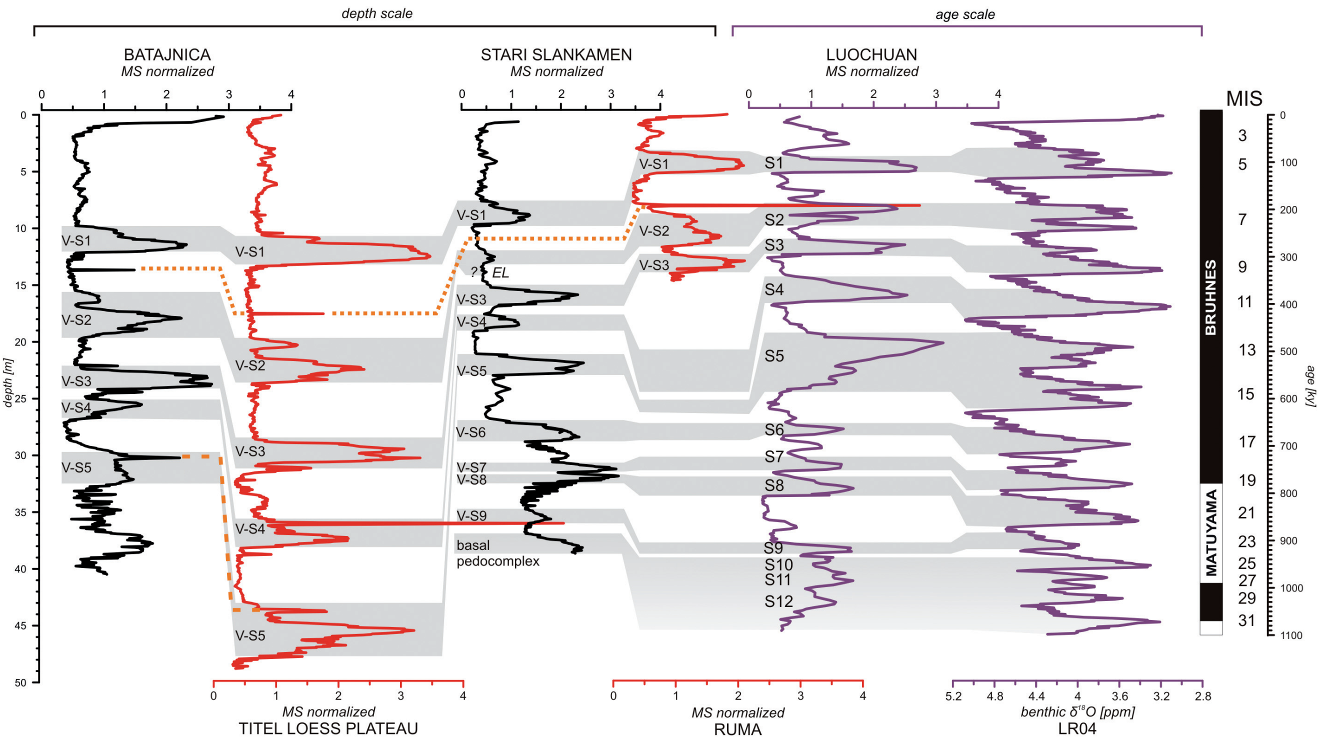

Fig. 4. Correlation between MS records of Ruma (Jovanović, et al., 2011a), Batajnica (Marković et al., 2009b), Titel loess plateau (Hambach et al., 2011, Jovanović, et al., 2011b) and the Stari Slankamen sections (Marković et al., 2011) with the Chinese Louchuan loess site (Lu et al., 1999) and marine oxygen isotope stages (Lisiecki & Raymo, 2005).

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Absolute luminescence and relative amino-acid chronologies

The first thermoluminescence (TL) absolute dating of loess-paleosol sequences in the Vojvodina region were provided by Singnvi et al. (1989) and Butrym et al. (1991). It is now known that these TL methodological approaches are unlikely to yield accurate results (e.g. Muray and WIntle, 2006) but at the time the published results drove significant subsequent revisions in the previous stratigraphic models (e.g. Bronger, 2003). Recently, application of infrared stimulated luminescence (IRSL) techniques have been widely applied to expand on the the last glacial loess chronology of Vojvodinian loess sequences (Marković et al., 2007, 2008; Fuchs et al., 2008; Antoine et al., 2009; Bokhorst et al., 2009, 2011). However, questions remain over the extent to which the effects of feldspar signal instability (anomalous fading) impact these results (Roberts, 2008). Most recently, Schmidt et al. (2010) and Stevens et al. (2011) have applied quartz optically stimulated luminescence (OSL) and polymineral post-IR IRSL dating techniques to overcome these issues, moving towards a moreaccurate chronology of the last two glacial cycles (Fig. 3).

Amino acid racemisation (AAR) geochronology has been successfully applied to fossil gastropod shells recovered from different regions of the world (Oches and McCoy, 2001). The technique has enabled loess sequences across Europe to be ccorrelated and intensive application of this method to the loess of the Vojvodina region in the last several years has initiated significant stratigraphic improvements (Marković et al., 2004a, 2004b, 2005, 2006, 2007, 2008, 2011). Ratios of D to L amino acid isomers obtained from land snail shells recovered from key loess sections in the Vojvodina region show a general increase with stratigraphic depth. These ratios appear capable of distinguishing between glacial-interglacial cycles and can be compared between investigated sections and to other regional aminostratigraphic data in order to ascribe units to specific glacial cycles. At Mišeluk, Petrovaradin and Irig sites AAR data clearly indicate discrimination between the last and penultimate glacial loesses V-L1 and V-L2 (Marković et al., 2004a, 2004b, 2005, 2007). Investigations at Ruma (Marković et al., 2006) and Stari Slankamen (Marković et al., 2011) sections highlight sensitivity of AAR geochronology to define last 4 and 5 glacial-interglacial cycles, respectively.

The magnetic susceptibility record

The low-field MS records of the investigated loess-paleosol sequences related to the pedostratigraphic interpretations are presented on Fig. 3. The MS variations reflect the pedostratigraphy, particularly by the sharp differences between high MS values observed in the pedocomplexes related to interglacial periods, lower values in the interstadial soils and the lowest MS values in loess units. This type of MS pattern reflects magnetic enhancement via pedogenesis and is similar to that in Chinese and Central Asian loess deposits (e.g. Heller & Liu, 1984, 1986; Maher & Thompson, 1999).

While some authors have argued that magnetic susceptibility can be used to quantify palaeoprecipitation (Maher et al, 1994; 2002), Buggle et al. (2009) did not find justification for doing so in Vojvodinian loess, particularly in quantification of differences between sections. For example, MS values of the youngest forest paleosol V-S4 developed during a long interglacial related to MIS 11, previously suggested as potential analogue of the Holocene (Berger & Loutre, 2002), are unexpectedly smaller than in overlaying fossil chernozems V-S3, V-S2, and V-S1, as well as the recent steppe soil V-S0. In case of loess-paleosol sequences in the Vojvodina region, pedogenetic processes are likely a function of other environmental factors, such as seasonal aspects of precipitation, temperature and evapo-transpiration (Buggle et al., 2009). Despite this, MS variations recorded in the Serbian loess-paleosol sequence do appear to reflect Middle and Late Pleistocene palaeoclimatic fluctuations, and in particular, changes in humidity (Marković et al., 2009b, 2011; Stevens et al., 2011). Cyclic alternation of high and low MS values between paleosols and loess units respectively illustrates differences in the degree of pedogenesis between glacial and interglacial climate conditions (e.g. Marković et al., 2009b, 2011).

Several abrupt increases of MS values coincide with possible preserved tephra layers. For example, the most prominent are MS peaks related to what have been suggested to be macroscopically visible tephra layers in the penultimate loess V-L2 at Batajnica, Surduk, Titel plateau and Ruma sections, or at the base of the V-L4 loess horizon on the Titel loess plateau.

Due to the close correspondence of the various MS records, after careful correlation of loess-paleosol units it is possible to identify hiatuses in certain sequences. Incomplete preservation of the loess record in the upper part of the Stari Slankamen loess-paleosol sequence is suggested through correlation of the MS record with other data from Batajnica (Marković et al., 2009) and Ruma (Marković et al., 2006) in the Vojvodina region, and close by loess sites in the Danube Basin, including Paks in Hungary (Sartori et al., 1999), Koriten in northwestern (Jordanova & Petersen, 1999) and Viatovo in northeastern (Jordanova et al., 2007, 2008) Bulgaria, and Mostiştea in southeastern Romania (Panaiotu et al., 2001). In all of the above sections, the second pedocomplex from the top displays a distinct MS variation pattern (two discrete peaks), as it also does at loess sites in China. However, this is not the case with the MS record at Stari Slankamen (Fig. 3). This missing unit is coincident with the appearance of a gravel layer of approximately 20 cm thickness in the loess below paleosol V-L2S1. The validity of this interpretation has been recently confirmed using aminostratigraphic approaches in (Marković et al., 2011).

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Time scale

Figure 5 shows the orbitally tuned time scale for the Serbian loess-paleosol sequences. Two distinct parts of the composite sequence can be identified using the MS record: 1) a high resolution part between the Holocene soil (V-S0) and the base of loess unit V-L5 and; 2) a lower part of the sequence where the temporal resolution is reduced, especially in the pedocomplexes of V-S5 and the base. The lowermost ca 4.5 m contains evidence of magnetic polarity shifts and is the most complicated part of the section for orbital tuning. However, several time control point marker horizons, such as the probable equivalent of the Bag tephra, or the position of the Jaramillo paleomagnetic episode, fit in well with our proposed chronology.

The timescale suggests older than expected ages for a number of the magnetic polarity boundaries, consistent with lock-in depth offsets reported at other loess sequences. However, the chronological framework demonstrates significant downward displacement of the MBB, representing a longer lock-in depth offset than observed in depth in Chinese loess.

Accumulation rates

Accumulation rates were calculated using by Analyseries softwer (Paillard et al., 1996) for the synthetic Titel loess plateau and Stari Slankamen loess-paleosol sequences, which are used also for the construction of the presented age model (Fig. 5).

Generally, accumulation rates are higher in loess than in paleosol units indicating their gradual increase through time. The highest accumulation rates were observed during formation of the three youngest loess layers V-L3 (214.8 cm kyr^{-1}), V-L1 (14 cm kyr^{-1}), V-L2 (12.4 cm kyr^{-1}) and V-L4 (11.9 cm kyr^{-1}), contrasting with mostly slow accumulation recorded in paleosols. Average accumulation rates of approximately from 5 to 6 cm kyr^{-1} were observed during pedogenesis of younger paleosols V-S1, V-S2, V-S3 and V-S4 which is significantly higher than for older paleosols. However, it must be stated that these values are approximate due to uncertainty over the degree of pedogenetic overprinting of pre-deposited material versus accretionary development in soil formation.

In any case, the genera trends in accumulation rates are similar to suggested dust deposition dynamics in Chinese loess (e.g. Heller & Evans, 1995).

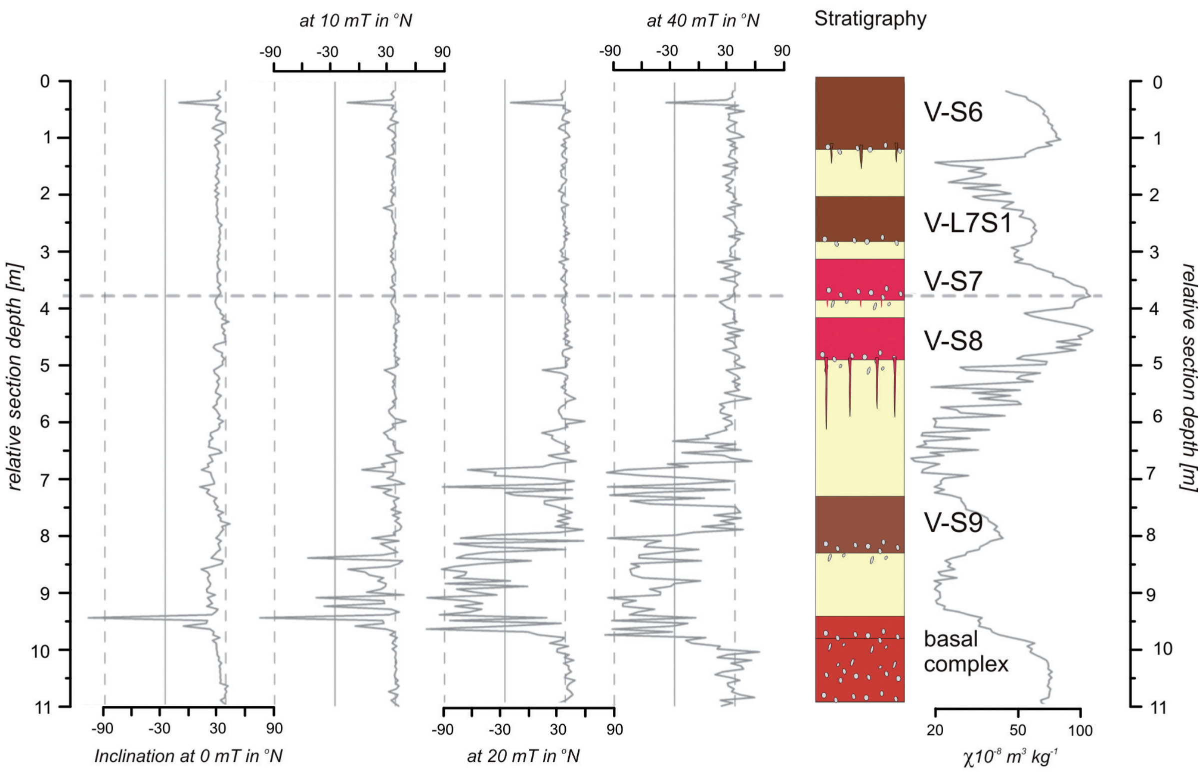

Fig. 5. Results from detailed stepwise alternating field (AF) demagnetisation experiments on specimens at the lowermost part of the profile A at Stari Slankamen. The inclinations of the natural remanent magnetisation (NRM) vectors are shown as function of stratigraphy and AF-amplitude. Inclination values are given as positive numbers when the vector is dipping downward. The progressive change of NRM-Inclinations with the field amplitude during AF-demagnetisation reveals normally overprinted reversed remanences in the lower half of the profile. The lowermost metre and the upper 6 metres obviously stay with normal polarity. AF-demagnetisation in fields up to 40 mT are not enough to clearly separate normal/reversed overprints from primarily reversed/normal remanences, respectively. Mass specific susceptibility vs. depth is displayed at the right. The thin dashed vertical lines indicate the inclination of the today's geomagnetic axial dipole field at the site. The grey horizontal dashed line marks the expected stratigraphic level of the MBB, assuming that V-S7 corresponds to MIS 19 (Marković, et al., 2011, modified).

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Discussion

Investigations of loess-paleosol sequences in northern Serbia have a long tradition characterised by some important, but irregularly occuring discoveries. Significant loess-paleosol exposures on the steep cliffs along the banks of the Danube were noted by Italian scientist Luigi Ferdinando Marsigli (1726) as the first known description of European loess (Marković et al., 2004a, 2009a). Since the pioneering work of Marsigli, many authors have investigated loess sections of this region in varying degrees of detail. In spite of some important papers which presented the great potential of Serbian loess-paleosol sequences for long term Pleistocene climate and environmental reconstructions (Bronger, 1976, 2003; Singhvi et al., 1989; Butrym et al., 1991; Kostić & Protić, 2000) little progress was made for a number of years. However, the attention of the international paleoclimatic community has increased again from 2004 onwards and has resulted in a significant upsurge in papers dealing with Serbian loess (Marković et al. 2005, 2006, 2007, 2008, 2009b, 2011; Fuchs et al., 2008; Antoine et al., 2009; Bokhorst et al., 2009, 2011; Zech et al., 2009; Schmidt et al., 2010, under review; Buggle et al, 2009, 2011; Stevens et al., 2011; Fitzsimmons et al., 2012).

General overview of Eurasian loess

Eurasia as an exceptionally large continent is characterised by extremely continental climatic conditions in the central part, as well as significant regional changes from the north to the south, and from west to east. These features define a considerable diversity of loess sequences from the arid and semi arid zones in Central China, Central Asia and Southeastern Europe to the humid periglacial European loess regions, as well as periglacial and subarctic frozen loess zone in Siberia (e.g. Dodonov & Zhou, 2008; Fig. 1).

A periglacial depositional environment was indicated as one of key conditions in some of classical loess definitions (Kukla, 1975; Pey, 1987). By inertia, many authors applied this European view to wide spread loess deposits over Eurasian continent. Thus, generally we can distinguish two major Eurasian loess provinces: the northern periglacial loess zone of Western, Central and Eastern Europe, and the Siberian loess provinces and southern southern semi arid loess zone.

The perigalcial loess zone is characterised by remarkable pedocomplexes and many preserved cryoturbation features (e.g. Antoine et al., 2001). Although some sections in the periglacial loess province represent several glacial interglacial cycles, such as Kärlich (Candy et al., 2012), Ariendorf (Haesaerts, 1990) and Kurtak (Frechen et al., 2005), the non periglacial loesses are significantly thicker and older.

Spatially, the semi arid loess zone is related to the great contiental belt approximatelly between 45° and 30° N latitude, from the Danube Basin approaching Central Asia; Kazaksan, Uzbekistan and Tadjikistan loess, and extending to the huge Chinese loess province (Fig. 1).

In this study we compare two distant loess regionson the western and eastern sides of Eurasia. From this perspective, the highly resolved Tadjik loess can be regarded as an environmental bridge between Serbian and Chinese loess paleosol sequences (Dodonov & Baiguzina, 1995; Bronger et al., 1995; Frechen et al., 1998; Ding et al.., 2002; Dodonov & Zhou, 2008).

Correlation with Chinese loess and marine oxygen-isotope stratigraphy

Bronger and coworkers (Bronger, 1976, 2003; Bronger & Heinkele 1989; Singhvi et al., 1989; Bronger et al., 1998) presented detailed paleopedological investigations and a classification of the paleosols of the Carpathian basin by means of micromorphology and provided a first attempt at trans-continental stratigraphic correlation between European and Asian loess regions. These stratigraphic models were seriously revised in subsequent studies of Marković et al. (2006, 2008, 2009b, 2011), following advances in age-dating techniques.

Figure 3 shows the correlation between the main Middle Pleistocene Serbian loess sections, the type section for Chinese loess at Luochuan (Lu et al., 1999), and the marine 180 record (Lisiecki & Raymo, 2005). Significant accordance between the Serbian and Chinese loess records opens up the possibility for a transcontinental correlation of European, Central Asian and Chinese loess records (Ding et al., 2002), using a standardised nomenclature and chronostratigraphic model. Below we suggest that the loess chronostratigraphies in the Vojvodina region and Central Chinese loess plateau from V-S0 to V-L9 and S0 to L9 respectively, correspond absolutely to each other. The basal pedocomplex is an equivalent of several welded loess-paleosol units in China, mostly likely from S10 to S12.

The MBB at Stari Slankamen is located stratigraphically deeper than in Chinese loess (Zhou and Shackleton, 1999) where more investigations are needed (Zhu et al., 2006). In China the lock-in of the magnetic signal in loess differs from that in marine cores where the MBB is found in warm period MIS 19, the apparent true age of the reversal, although probably also slightly offset. Clearly the acquisition of geomagnetic signals in Serbian loess is subject to the same, or greater, complexities as Chinese loess. Thus, although the true reversal took place during deposition of V-S7 (MIS 19), the event was only registered in underlying V-L9. The lock-in effect also seems to be greater than at Viatovo in Bulgaria, which places the MBB within Viatovo loess unit L7 (equivalent of MIS 20) (Jordanova et al., 2008), similar to that in Chinese loess. However, at Stari Slankamen, strong root channels stemming from paleosol-complex V-S8 penetrate several metres down into loess V-L9 and most probably also influence the magnetic properties of these sediments. Despite this, the lowermost pedocomplex at Stari Slankamen provides a similar

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palaeomagnetic record to the basal 'red clay' complex at Viatovo (Jordanova et al., 2008) with normal polarity at both possibly related to the Jaramillo normal subchron. These interpretations suggest that the basal pedocomplex was deposited and weathered over several glacial-interglacial cycles and is highly condensed.

Taking into account the loess-paleosol stratigraphy, the character of the MS variations with depth and the tentative paleomagnetic pattern we interpret the double soil complex V-S7/V-S8 as the equivalent of MIS 19 and 21, corresponding to S7 and S8 in the Chinese loess stratigraphy. This supports the above assertion that the normally magnetised basal soil complex at the base of the section is the amalgamated equivalent of S10 and S11 (equivalent to MIS 27 to 31) in China, which spans the Jaramillo subchron (e.g. Lu et al., 1999).

Thus, the lower part of the loess section at Stari Slankamen can be assigned to the late Matuyama and early Brunhes Chrons. Though the directional record is ambiguous in some intervals where strong pedogenesis caused secondary magnetisation, evidence for late Matuyama geomagnetic excursions can be found. In the upper half of V-S9 (equivalent to S9 in China; MIS 25) normal polarity seems to be persistent (compare Table 2) (Marković et al., 2011). This stable normal polarity may represent the incomplete record of the Kamikatsura and Santa Rosa geomagnetic excursions occurring around 0.9 Ma (e.g. Liu et al., 2008).

Table 2. Relationship between Serbian (Marković et al., 2008, 2011) and Chinese (Kukla, 1987; Kukla & An, 1987) loess stratigraphic units and Marine oxygen isotope stage subdivision (Imbrie et al., 1984).

Loess stratigraphy		**MIS**
Vojvodina, Serbia	**China**	
S0	S0	1
L1	L1	2, 3 & 4
S1	S1	5
L2	L2	6
S2	S2	7
L3	L3	8
S3	S3	9
L4	L4	10
S4	S4	11
L5	L5	12
S5	S5	13, 14 & 15
L6	L6	16
S6	S6	17
L7	L7	18
S7	S7	19
L8	L8	20
S8	S8	21
L9	L9	22
S9	S9	23, 24 & 25
L10	L10	26
Basal complex V-S10-?	S10-?	27-?

The MS record of paleosols V-S8, V-S7, V-L7S1, and V-S6 has a similar pattern to equivalent stratigraphic units of Chinese loess, suggesting correlation with MIS 21, 19, 18.3 and 17 respectively. These paleosols are intercalated with thin loess units V-L8, V-L7L2 and V-L7L1, contrasting to the thicker younger loess units V-L6, V-L5, V-L3, V-L2, and V-L1 in both China and Serbia, which correspond with MIS 16, 12, 8, 6, and 4-2 respectively.

Our results support the previous suggestion that the strongly developed paleosol V-S5 at Strari Slankamen, Batajnica and Titel loess plateau was formed during MIS 13-15 (Bronger & Heinkele 1989; Bronger et al., 1998; Bronger, 2003). This pedocomplex shows a much greater degree of pedochemical weathering and clay mineral formation than in modern soils of this region and appears to be a characteristic feature of the middle part of all Brunhes loess-paleosol sediments in Eurasia (Bronger, 2003). It also matches the characteristics of the poorly developed MIS 14 cold stage in the marine record (Lisiecki and Raymo, 2005).

The uppermost 4 pedocomplexes V-S4, V-S3, double V-S2, and V-S1, with the exception of the sequence at the Stari Slankamen section where an erosional event has removed pedocomplex V-S2 (Marković et al., 2006, 2009b, 2011; Hambach et al., 2011), correlate well with the Chinese MS record of paleosol units S4, S3, S2, and S1 (e.g. Lu, 1999), which are also correlated with MIS 11, 9, 7 and 5, respectively (Lisiecki & Raymo, 2005). These stratigraphic interpretations are in good agreement with results of amino acid geochronology (Marković et al., 2006, 2008, 2011) and luminescence dating (Marković et al., 2007, 2008; Fuchs et al., 2008; Bokhorst et al., 2009, 2011; Schimidt et al., 2010, under review; Stevens et al., 2011).

Of additional interest is observation of possible tephra layers in loess layers V-L2 at Ruma, Batajnica and Titel loess plateau, as well as from V-L4 at the Titel loess plateau. A tephra layer at a similar stratigraphic position to the hypothesised V-L2 tephra was also discovered in the penultimate glacial loess at the Gorjanović section in Croatia, and appears to have a minimum luminescence age of about 145 kyr (Wacha et al., 2011). The most probable tephrostarigraphic equivalent of the possible layer in the Titel loess plateau V-L4 horizon is the Bag tephra described from several exposures in Hungary (e.g. Horvath, 2001).

Links between Serbian and Chinese loess

It is notable form Fig. 3 that there are significant similarities between the palaeomagnetic records of the northern Serbian and central Chinese loess plateaux and that the records often have a closer correspondence on multi-millennial timescales to each other than they do with the globally integrated marine record. While Stevens et al. (2011) noted differences between the Crvenka (Vojvodina) and Beiguoyuan (Chinese Loess

Plateau) climate records on millennial timescales, the similarities over multi-millennial timescales are likely to be a consequence of similar controls on deposition in these distant regions on opposite sides of large Eurasian continent, and the similar nature of magnetic susceptibility signal acquisition in the two regions. In Table 3 the main characteristics of loess deposits in the Northern Serbia and Central China are compared.

Table 3. Relationship between the main characteristics of loess deposits in Northern Serbia and Central China.

	Northern Serbia	Central China
Provenance	Material redeposit by rivers	Debated – montane or desert material
Age	Since Early Pleistocene	Since Miocene
Maximal thickness	55 m	Up to 300 m
Current climate	Continental climate strong seasonality	Monsoon climate strong seasonality
Paleoclimate	Gradual trend of aridification since the Middle Pleistocene	Gradual trend of gradual aridification since the Late Miocene
Geomorphology	Plateau morphology	Plateau morphology

Smalley & Leach (1978) suggested that crucial to the formation of loess in northern Serbia was fluvial transport of sediment by the Danube river system after glacial erosion in montaine regions, particularly the Moravian massif and Carpathian Mountains. This statement has recently received support from the geochemical investigations of Buggle et al. (2008). Smalley et al. (2009) provided a conceptual model of Danube loess formation indicating fluvial sedimentation as a key supplier of material for loess accumulation in the Carpathian (Pannonian) Basin. This represents a significantly different provenance model than in case of Chinese loess, although the precise details of the source of the latter are debated. It seems most likely that Chinese loess originates from northern and northwestern desert/Gobi or montaine/ piedmont material (Liu & Ding, 1998; Derbyshire et al., 1998; Prins et al., 2007; Stevens et al., 2010), the latter being more consistent with sources for European loess. Furthermore, exceptionally high accumulation rates recorded on the Mangshan loess plateau in China suggest dust supply from the lower Huang He (Yellow River) river floodplain (Prins et al., 2009). Zheng et al. (2006) and Jiang et al. (2007) proposed that the upper Mangshan loess does not derive directly from aeolian transport from the northwest, as is accepted opinion for the Chinese Loess Plateau. They hypothesised that the Mangshan loess sediments have been sourced from the proximal Huang He floodplain and the ancient alluvial fan lying at the eastern end of the Sanmen Gorge.

Aeolian deposits in China potentially extend to the base of the Miocene (Guo et al., 2002). However, the thickest and spatially most extensive loess sediments are of Quaternary age (e.g. Liu & Ding, 1998). Due to this significantly longer period of dust deposition in China the thickness of loess in the Vojvodina region is not as great. In general, the thickness of the loess deposits in the central and southern parts of the Loess Plateau ranges from 130 to 180 m (the thickest is more than 300 m), and over 30 loess-soil units are recognisable within the loess deposits (e.g. Liu & Ding, 1998). The maximal thickness of loess in the northern Serbia is about 50 m

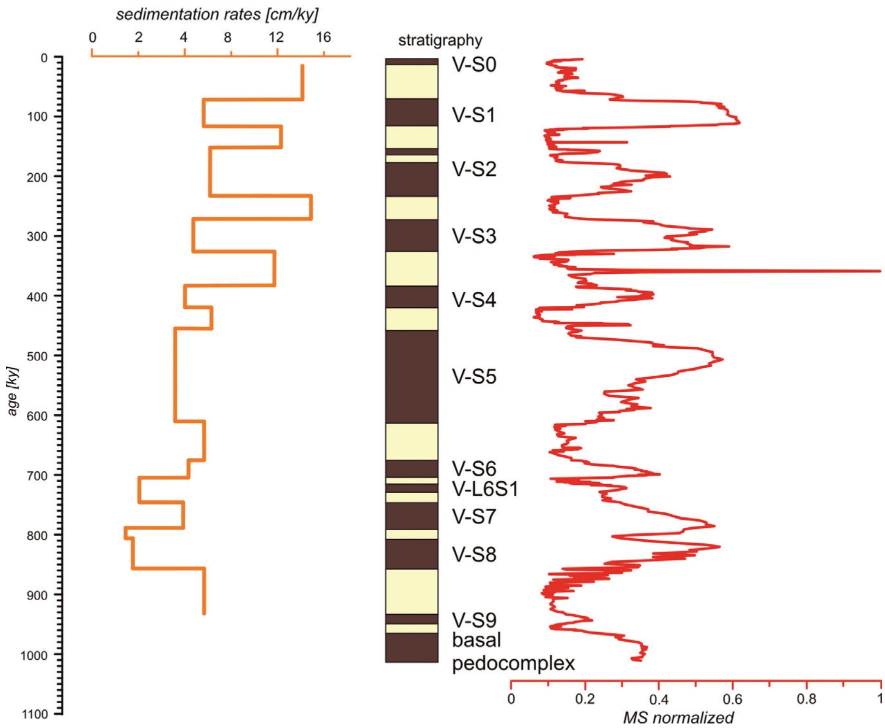

Fig. 6. Comparison of the orbitally tuned MS record and calculated sedimentation rates of the composite Serbian loess-paleosol sequence.

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including 10 major loess and palesols couplets deposited during the last ~1 Myr. However, the average thickness of loess in China covering the last 1 Myr is more comparable with the observed thickness of loess in Serbian Vojvodina. For example at the Luochuan loess section 1 Myr old deposits are approximately 70 m thick (Lu et al., 1999).

The almost parallel position of the multiple loess-paleosol sequences preserved as plateaus in the Vojvodina region reflects a similar style of deposition to the Central Chinese Loess Plateau (Kukla & An, 1989). This model implies a relatively flat tableland topographic situation during aeolian deposition, as well as during periods of soil formation. As such, long-term erosional processes on Serbian loess plateaus should be confined only to relatively small and short-lived gullies or on the steep loess cliffs (Zeeden et al., 2007; Lukić et al., 2009). Due to the significantly smaller total thickness of Serbian as compared to Chinese loess deposits the dimensions of the loess landforms are also proportionally smaller. However, even gentle relief differences can cause significant differences in current vegetation cover. For example, on the top of plateaus and on steep slopes steppe vegetation is dominant, contrasting with some gullies that covered by shrubs and trees. This is likely a consequence of the need certain plants have of additional water that may be supplied from more shallow ground waters in deeper loess depressions. The more strongly developed paleosol V-S3 at the base of the Ruma site as compared to other investigated sections is also a consequence of more intensive pedogenesis due do to different environmental conditions controlled by shallow underground water which is currently expressed at the site in the deepest parts of the quarry.

Sedimentation on Serbian loess plateaus appears to occur almost continuously on multi-millennial timescales, with an only limited impact of postdepositional processes on the preservation of the record (Marković et al., 2007, 2008; Fuchs et al., 2008; Schmidt et al., 2010; Ujvari et al., 2010; Stevens et al., 2011). This contrasts with most European loess provinces that are generally characterised by slope-type of loess formations (Kukla, 1975; Haesaerts et al., 2010). Under such conditions, a more dynamic landscape negatively affects the preservation potential of loess sediments, although during some periods high rates of dust deposition are recorded (e.g. Antoine et al., 2001; Frechen et al., 2003; Haesaerts et al., 2010; Ujvari et al., 2010).

According to the Köppen classification system, the Vojvodina region experiences a Cfb climate with a strong tendency to Cfa. This typical continental climate is represented by cold and wet winters and hot summers. Primary precipitation maxima occur in late May and June, and are controlled by zonal westerly flow, although July and August can generally be regarded as a dry periods (Ducić & Radovanović, 2005; Buggle et al, 2009). The central Chinese Loess Plateau is generally characterised by a semi-arid climate, with extensive meridional monsoon influence. Winters are cold and dry, while summers are very warm and in many places hot. Rainfall tends to be heavily concentrated in summer (e.g. Liu & Ding, 1998). Thus, in spite of significantly different current climatic modes, continental, westerly dominated Serbian Vojvodina and monsoonal central Chinese Loess Plateau, a common climatic seasonality characterised by a relatively prominent dry period can be observed. There are also further similarities in Pleistocene environmental evolution between Serbian and equivalent Chinese loess records (Bronger & Heinkele 1989; Vidić et al., 2004). Bronger (2003) provided a direct comparison between the paleopedological characteristics of Chinese Luochuan and Serbian Stari Slankamen and Neštin sections. Here we re-assess these comparative paleopedological interpretations according to our new stratigraphic moderl, which results in an even better even fit between the sequenvces. According to these results, the paleosols S11, S8, S7 and S5 at Luochuan (Bronger et al., 1998) are strongly developed and similar to their Serbian stratigraphic equivalents: the strongly rubified basal pedocomplex, V-S8, V-S7 and V-S5 fossil soils. Their paleopedological characteristics are clearly different from the temperate soils Chinese S4 and Serbian V-S4 of the mid-late Middle Pleistocene and the steppe-like interglacial soils of the later Middle and Late Pleistocene (S3, S2 and S1 in China, as well as V-S3, V-S2 and V-S1 in Serbian Vojvodina).

These palaeopedological observations have been confirmed by employing quantitative a soil colour rubification index and geochemical weathering proxies (Buggle et al., 2009, 2011) and support the previous assertion (Bronger, 1976) that interglacial climate over the Pleistocene has become progressively more arid in the region (Marković et al., 2009b, 2011). The Vojvodinian loess rubification values significantly increase in the older pedocomplexes (basal pedocomplex, V-S8, V-S7 and V-S5) and are in good agreement with previous studies of paleosol rubification at other Eurasian loess sites (e.g. Vidić et al., 2004). However, our results indicate an even stronger trend of paleoclimatic transition from sub Mediterranean to dry continental climate in this part of Europe during the last five glacial-interglacial cycles than has previously been suggested. Similar results of rubification values from paleosols exposed at Mircea Voda in southeastern Romania are presented by Buggle et al. (2009), indicating a regional climatic trend. The geochemical results of Ding et al. (2002) also indicate similar paleoclimatic trends in Chinese loess records. This trend contrasts to the globally integrated marine oxygen-isotope record, implying urgent need to reconsider continental records in understanding continental environmental evolution.

Simultaneously with this trend to interglacial aridification, calculated accumulation rates in Serbian loess units also increase, indicating a concurrent trend to colder, drier and more dusty glacial conditions. This observed intensity of dust deposition in the Vojvodina region is also in good agreement with Chinese loess accumulation dynamics (e.g. Lu et al., 1999) as well as with dust evidence from the Antarctica ice EPICA core (Lambert et al., 2008), and also parallels the trend to deeper glaciations evidenced in the marine ice volume indices (e.g. Lisiecki & Raymo, 2005). Thus, two distant loess records on the western and eastern sides of Eurasia provide a similar pattern of climatic and environmental changes probably controlled by global increases in ice volume, a progressive aridification initiated in the inner Asian continent, and regional sensitivity to moisture bearing systems.

Conclusions

The results of multidisciplinary investigations of loess-paleosol sequences in the Vojvodina region over the last several years have improved knowledge and understanding of their formation, distribution, chronostratigraphy, and the preserved palaeoclimatic and paleoenvironmental record. Loess-paleosol series preserved in the northern part of Serbia are exceptionally complete and as such represent one of the most detailed European terrestrial climatic records available, made especially valuable by their spatial extent. The better preservation of Serbian loess in comparison to that to the north and west is most likely related to the continuous presence of much drier climatic conditions in this region and the persistence of stable 'plateaux'of accumulation. This relatively dry climate in Vojvodina may also further explain why the loess climate record there shows some similarities to Chinese records. A direct correlation between Serbian and Chinese loess magnetic susceptibility (MS) records suggests the possibility of a link between long-term environmental change in Europe and Asia. A key similarity between Serbian and Chinese loess records is the remarkable trend to increased interglacial aridity over the course of the Middle Pleistocene. Furthermore, this trend is in sharp contrast to the globally integrated marine oxygen-isotope record, suggesting that this record does represent the true long-term environmental trends observed in continental mid latitude Eurasia over the Pleistocene. This observation is even more important because the consequences of future climate change need to be modelled for specific continental regions in order that the impact on humans can be predicted. The information derived from the marine record appears not to characterise what happens over the Eurasian continent.

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