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Danube loess stratigraphy –towards a pan-European loess stratigraphic model

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Abbreviations

CLP – Chinese Loess Plateau

CLPS – Chinese loess-palaeosol sequences

DB – Danube Basin

DLPS – Danube loess-palaeosol sequences

ELSA -Eifel Laminated Sediment Archive

EMF – Earth’s magnetic field

MS – Magnetic susceptibility

MBB - Matuyama-Brunhes palaeomagnetic polarity boundary

MSS – Mošorin/Stari Slankamen

post IR IRSL - Post-IR infrared stimulated luminescence dating

OSL – Opticaly stimulated luminescecne

TL - Thermoluminescence

TT OSL - Thermally transferred optically stimulated luminescence dating

VADM - virtual axial dipole moment

†*This paper is dedicated in the memory of our teacher, colleague and friend George J. Kukla, who passed away on Saturday, May 31*st *2014 during preparation of this paper.*

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Abstract

The Danube River drainage basin is the second largest river catchment in Europe and contains a significant and extensive region of thick loess deposits that preserve a record of a wide variety of recent and past environments. Indeed, the Danube River and tributaries may themselves be responsible for the transportation of large volumes of silt that ultimately drive loess formation in the middle and lower reaches of this large catchment. However, this vast loess province lacks a unified stratigraphic scheme. European loess research started in the late 17th century in the Danube Basin with the work of Count Luigi Ferdinand Marsigli. Since that time numerous investigations provided the basis for the pioneering stratigraphic framework proposed initially by Kukla (1970, 1977) in his correlations of loess with deep-sea sediments. Loess-palaeosol sequences in the middle and lower reaches of the Danube River basin were a key part of this framework and contain some of the longest and most complete continental climate records in Europe, covering more than the last million years. However, the very size of the Danube loess belt and the large number of countries it covers presents a major limiting factor in developing a unified approach that enables continental scale analysis of the deposits. Local loess-palaeosol stratigraphic schemes have been defined separately in different countries and the difficulties in correlating such schemes, which often change significantly with advances in age-dating, have limited the number of basin-wide studies. A unified basin-wide stratigraphic model would greatly alleviate these difficulties and facilitate research into the wider significance of these loess records. Therefore we review the existing stratigraphic schemes and define a new Danube Basin wide loess stratigraphy based around a synthetic type section of the Mošorin and Stari Slankamen sites in Serbia. We present a detailed comparison with the sedimentological and palaeoclimatic records preserved in sediments of the Chinese Loess Plateau, with the oxygen isotope records from deep-sea sediments, and with classic European Pleistocene stratigraphic subdivisions. The hierarchy of Danubian stratigraphic units is determined by climatically controlled environmental shifts, in a similar way to the Chinese loess stratigraphic scheme. A new unified Danube loess stratigraphic model has a number of advantages, including preventing confusion resulting from the use of multiple national schemes, a more transparent basis, and the potential to set Pleistocene palaeoenvironmental changes recorded in the Danube catchment area into a global context. The use of a very simple labelling system based on the well-established Chinese loess scheme facilitates interpretation of palaeoenvironmental information reported from the Danube Basin loess sites in a wider more accessible context that can be readily correlated world-wide. This stratigraphic approach also provides, for the first time, an appropriate framework for the development of an integrated, pan-European and potentially pan-Eurasian loess stratigraphic scheme.

Key words: Danube, Europe, loess, Pleistocene, stratigraphy, Chinese Loess Plateau

1. Introduction

Loess deposits cover 10% of the world’s continents and even larger parts of Eurasia (Pécsi, 1990), and represent some of the most important climate archives available (Porter, 2001). Perhaps equally significant, loess deposits contain uniquely widespread records of past atmospheric dust dynamics (e.g., Újvari et al., 2010), a major component of global climate forcing, which have the potential to be linked to other dust records in ice cores and the marine realm (Maher et al., 2010). Loess deposits are therefore of critical importance in understanding past climate change. Despite this, interpretation of loess deposits has been greatly limited by difficulties in stratigraphic correlation between deposits and other records, a result of the complex nature of soil development in loess, the use of national stratigraphic schemes, a lack of precise numerical age-dating methods for loess, and potential hiatuses in records. Loess deposits have enormous potential for global, hemispheric and regional climate interpretation if they can be placed within a larger and widely applicable stratigraphic framework that covers basin scale depocentres. With the exception of Chinese loess-palaeosol sequences (CLPS) (Liu, 1985) this has not been fully achieved and is therefore a major focus for immediate research.

Smalley et al. (2009) recently reiterated the association of major loess depocentres with major rivers, and a possible causal relationship has been proposed based on empirical data in Eastern Europe and China (Újvari et al., 2012; Stevens et al., 2013). The Danube is Europe's second largest river in terms of catchment area (app. 800,000 km^2) and an important "loess river" (*sensu* Smalley and Leach, 1978), as it flows through extensive loess and alluvial deposits. The Danube Basin (DB) contains the largest and most significant European loess region east of the Russian Plain, preserving a palaeoenvironmental record that extends back over the last million years (Marković et al., 2011) and is distributed across 19 countries. However, analysis of these sequences basin-wide has been greatly restricted, preventing large-scale climate interpretations or correlations.

The Danube River and its tributaries originate in the German Black Forest, the central European Alps, the Bohemian massif, and the Carpathian, Dinaric and Balkan mountains, and connects the Central and South-Eastern European plains. In the middle and lower part of the basin, several large rivers converge with the Danube, including major tributaries such as the Sava, Drava (Dráva, Drau), Morava, Tamiš (Timiș), Tisa (Tizsa, Theiss), Olt, Ialomiț a, Argeș , Jiu, Buzau, Siret and Prut (Figure 1). While precise sources of material are debated, the term "Danube loess" describes the likely importance of river transport of silt-sized material over long distances across different environments from the mountains to the river's delta at the Black Sea. During glacial periods, the Danube transported large quantities of glacially-ground silt from the Alpine ice caps and foreland glaciers, as well as from glaciated headwaters including the Carpathians (Reuther et al., 2007) and Balkans (Kuhlemann et al., 2008; Hughes et al., 2006; 2010, 2013) (Figure 1A). This was one reason for Kukla's (1975) early definition having a strong Danubian perspective in characterizing the loess as 'periglacial' sediment. In recognizing the role of fluvial activity Smalley et al. (2009) proposed that both, glacial and periglacial factors, can be crucial for the production of silt material in the case of most European loess deposits, supported by river erosion and transport. The Alps are probably the most significant source of proto-loess material to the Danube and its huge loess belt downstream (Buggle et al., 2008; Újvári et al., 2008; 2012), although there were also likely to be contributions from other regional or local sources such as the Caspian lowlands and coastal plains (Kukla, 1975), and large proglacial plains south of the Scandinavian ice-sheet, especially relevant for the Lower Danube area (e.g. Buggle et al., 2008; Bokhorst et al., 2011). Beyond the middle Danube confluences with its major tributaries, large amounts of sediment input from the river has likely resulted in the great thickness of loess cover in the Middle and Lower DB, in some places exceeding 70 m (Haase et al., 2007; Fitzsimmons et al., 2012; Jipa, 2014).

Danubian loess-palaeosol sequences (DLPS) are among the longest and most complete in Europe (Marković et al., 2009a; 2011; Buggle et al., 2013). Pleistocene climatic variations have been recorded in detail in the DLPS, providing among the oldest and most complete European continental archives of environmental change (Fink and Kukla, 1977; Marković et al., 2012a). Investigations into the large number of loess sequences contained within the DB (Figure 1B) have been made by a great number of loess scholars, many of whom have lived and worked in the region. Indeed, this research has led to some very important events in the global history of loess research (Smalley et al., 2001, 2010).

Given this enormous potential of the DLPS records for providing archives of palaeoclimatic change on the European continent, it is perhaps surprising that there are not many basin-wide studies of Danubian loess (Smalley and Leach, 1978; Fitzsimmons et al., 2012). This is perhaps due to the historical, political and scientific separation between Danubian countries, which have resulted in a large number of country-specific loess stratigraphic models. However, recent advances in understanding the chronostratigraphy of some key loess exposures in the Middle and Lower DB provide promising opportunities to develop a unified stratigraphic model following the famous Chinese loess L(oess) and S(oil) stratigraphic nomenclature (Kukla, 1987; Kukla and An, 1989), at least for the Middle and Late Pleistocene loess sequences (e.g. Panaiotu et al., 2001; Jordanova et al., 2007, 2008; Marković et al., 2009b, 2011; Buggle et al., 2009; Balescu et al., 2010; Timar-Gabor et al., 2011; Varga et al., 2011; Radan, 2012; Újvári et al., 2014). Similar stratigraphic models have also been applied to the Ukrainian (e.g. Bogutsky and Łanzont, 2002; Buggle et al., 2009; Bokhorst et al., 2011) and Polish loess deposits (Bokhorst et al., 2011; Jary, 2009; Jary and Ciszek, 2013), indicating the potential for defining an integrated, pan-European loess stratigraphic system.

The aim of this study is hence to define a unified DLPS chrono-stratigraphic model, preceded by a review of the existing loess stratigraphic models in the Danube area, and then to indicate possible links between the stratigraphic models of “classical” European and Asian loess provinces. The potential continental stratigraphic correlations have great potential for developing an integrated understanding of spatial and temporal variations in Pleistocene environmental dynamics at the Eurasian continental scale. It is hoped that this will act as a catalyst for the future use of a catchment or even continental scale approach for understanding the palaeoenvironmental record, as contained within these highly significant deposits.

2. Comparison of the existing loess-palaeosol stratigraphic models in the Danube Basin

As a consequence of current and past environmental diversity, the Danube loess belt includes two main landscape zones characterised by different models for loess formation. The first represents a discontinuous slope loess cover usually associated with fluvial terraces in the upper part of the DB and in hilly parts of tributary basins. In this zone, higher relief and higher humidity means that the loess deposits and inherited fossil soils are more prone to erosion. The stratigraphic record preserved in this loess zone is therefore often incomplete and characterised by the reworking of fossil soil and loess units due to slope processes. Loess stratigraphic subdivisions in Austrian, Czech and Slovakian sequences of this zone are complicated by this greater erosion potential and also by the more humid climate and shifted seasonality compared to further down the Danube loess belt, leading to complex soil stratigraphy (Sprafke et al., 2014). The second zone includes the relatively continuous plateau-like mantles in the Middle and Lower Danube lowlands, covering an area approximately from the northern and western limits of the Great Hungarian plain to the Black Sea coast (Hosek et al., 2014; Jipa, 2014; Neugebauer-Maresch et al., 2014). The greater preservation potential of these plateau deposits leads to an easier correlation of soil horizons between sites, and the stratigraphy of Southeastern Pannonian and Lower Danube Basin loess plateaus in particular is clear-cut as a result of the more arid, stable environmental conditions in the region (Fitzsimmons et al., 2012). Thus, southeastern European loess sediments have more in common with those in Central Asia (Dodonov and Baiguzina, 1995; Machalett et al., 2008) and central China (e.g. Kukla, 1987, Kukla and An, 1989; Ding et al., 1995; Lu et al., 1999; Guo et al., 2000) than with other European loess provinces such as northern France, Germany and Belgium (Antoine et al., 2001), Austria, Czech and Slovak Republic (Antoine et al., 2013) and central Ukraine (Buggle et al., 2009).

Despite geomorphologically and climatically controlled differences in the loess-palaeosol records within the DB, recent studies suggest that it is possible to assign a basin-wide stratigraphic scheme for DLPS (Marković et al., 2011, 2012a; Fitzsimmons et al., 2012). The record of alternation between dominant aeolian deposition and pedogenetic overprinting, clearly represented by environmental magneto-stratigraphic parameters, should allow for direct DLPS inter-profile correlations from the Alpine foothills to the Black Sea coast. These correlations can be further extended to Central Asian and Chinese loess regions creating a pan-Eurasian loess stratigraphic system that takes advantage of widespread deposits in hemispheric climate reconstructions.

The proposed stratigraphic model outlined below is mainly based on environmental magneto-stratigraphic information, essentially magnetic susceptibility (MS). The MS variations sensitively reflect changes in litho- and pedo-stratigraphy. The application of MS as a palaeoclimatic proxy and correlative stratigraphic tool in the Eurasian loess steppe environments is based on (1) the mineralogical homogeneity of the loess and (2) the neo-formation of ferrimagnetic minerals in the course of silicate weathering and pedogenesis. The latter depends largely on the temporal variation of soil humidity and thus of palaeoclimate variations. Thus, increasing pedogenesis in purely aeolian loess is concurrent with the enhancement of mineral magnetic signals and provides a climatostratigraphic metronome (cf. Buggle et al., 2008, 2014).

However, these correlative stratigraphic interpretations require underpinning through independent chronostratigraphical means via amino-acid recemisation (AAR) relative dating, and absolute luminescence dating geochronologies. To minimise the influence of local environmental conditions on themineral magnetic record, we have focused on the loess palaeosol-sections located on loess plateaus, where loess deposition was a relatively stable process and preservation potential highest. While loess deposits on slopes are frequently impacted by reworking and erosion, loess plateau deposits such as those on the CLP are generally held to contain a mostly continuous sequence of aeolian sediments with few major hiatuses in deposition (Porter, 2001). While some plateau deposits may contain short hiatuses, luminescence dating and palaeomagnetic profiling have demonstrated that these are generally of short duration (<4 kyrs; Stevens et al., 2007; Zhu et al., 2007) and that on the longer timescales that are relevant to basin-wide, long-term unified stratigraphic models, these are not significant. Many Danubian sequences are formed in plateau-like depositional environments comparable to the Chinese Loess Plateau, where relatively continuous, uniform and well-preserved loess records facilitate relatively straight-forward cross correlations between sites (Marković et al., 2012a). We deliberately target these and avoid using other Danubian non-plateau loess sequences, which are characterised by a greater influence of erosional or slope processes (e.g. Terhorst et al., 2014).

2.1. Pedostratigraphy

It is often possible to establish a pedostratigraphy, in the sense of a stratigraphy of soils and intercalated loess layers, preferably based on complete regional terrestrial sequences. The basic conditions in this context are firstly the re-occurrence of certain types of palaeosols at the same stratigraphic position within a regional-specific sequence of palaeosols, and secondly the presence of pedostratigraphic marker horizons. There are several examples of such marker horizons: the “Mende-Base” soilcomplex (Pécsi et al., 1977), the “F5” palaeosol (Bronger, 1976, 2003) in the loess of the Carpathian basin, the “S5” palaeosol in the Chinese loess (Kukla, 1987), as well as the characteristic succession of “PK III” and “PK II” in Czech and Slovakian loesses (cf. Hošek et al., 2014). This pedostratigraphic fingerprinting was observed by Kukla (1970) in Central European loess-palaeosol-sequences and then transferred to the Chinese Loess Plateau (CLP) (Kukla, 1987). Kukla (1970) explained the characteristic features of almost every individual Late and Middle Pleistocene palaeosol complex by assigning these complexes to individual warm marine isotope stages. Subsequently, when Heller and Liu (1984) recognised the same pattern in the CLP on the basis of rock magnetic records, the characteristic succession of distinctive palaeosol complexes in the Eurasian loess led to a revolution in loess stratigraphy. However, many decades passed before this scheme was successfully applied to European loess sequences (cf. Marković et al., 2009).

In the contrast to the national schemes discussed above, Bronger was the first researcher who developed a unified Danube basin-wide stratigraphic model (Bronger, 1976, 2003) (Table 1). This stratigraphic scheme was based on pedostratigraphic inter-profile correlation and introduced the label F (fossil soil) for the individual pedocomplexes supplemented with a numerical suffix (e.g. F1, F2 etc) according to the stratigraphic position of the individual pedocomplexes at the investigated section. Initially based on pedostratigraphic criteria, Bronger’s stratigraphic model has been revised several times (Bronger, 1976, 2003; Bronger and Heinkele, 1989; Bronger et al., 1998). Following a proposed set of dominant pedostratigraphic criteria formulated in 1961 at the 6th INQUA Congress in Warsaw, Poland, the youngest Brown Forest Soil or Brown Forest Soil-Lessivé palaeosol exposed at different loess profiles was taken to represent the last (Riss/Würm or Eemian) interglacial, an equivalent of MIS 5e (Fink, 1962). However, this model did not consider the strong Pleistocene environmental gradients over the DB catchment, where forest soils did not form in some locations during the last interglacial. Thus, Bronger (1976) correlated palaeosols F5 in Hungary (Mende Base (MB) soil complex - Oches and McCoy, 1995a) and V-S4 inSerbia (Marković et al., 2008), formed during MIS 11, with the Czech PKIII pedocomplex or lower part of the Austrian Stillfried A complex, both formed during the last interglacial period.

A good example of the ongoing chonostratigraphical improvements to the DLPS over the few decades are the changing stratigraphic interpretations of the Serbian Stari Slankamen loess-palaeosol sequence (Table 1). Thermoluminescence (TL) dating by Singhvi et al. (1989) suggested that the fossil chernozems F2 and F3 were formed no earlier than during MIS 5a and 5e (Tables 1). Pedostratigraphic interpretations have been improved considerably by the application to these sequences of recent advances in magneto- and amino-stratigraphy, as well as luminescence dating techniques (Schmidt et al., 2010; Murray et al., 2014).

2.2. Magnetic stratigraphy

Both the natural remanent (palaeo-)magnetisation and the rock magnetic properties allow indirect dating of soils and sediments. Magnetic dating includes all approaches dealing with the temporal variation of the Earth's magnetic field (EMF) as well as with the application of climate dependent variations of rock/mineral magnetic properties of sedimentary sequences and their correlation to independently dated palaeoclimatic archives. Palaeomagnetic dating employs the temporal variation of the direction as well as the intensity of the EMF on time scales from 10^2 to 10^7 years. The well-known temporal pattern of changing polarity and (relative) palaeo-intensity variation on time scales from 10^3 to 10^5 years provides an excellent tool for stratigraphic subdivisions, especially of Quaternary continental deposits (cf. Hambach etal. 2008a).

Here we consider both magnetic polarity zonation and mineral magnetic records (mainly magnetic susceptibility, MS) as a means to derive chronostratigraphic models. Attempts to recognise the standard polarity sequence (Cande and Kent, 1995) in DLPS date back over 40 years, when Kukla and colleagues first used palaeomagnetic approaches in loess stratigraphy. Certainly the most famous is the palaeomagnetic zonation at the Moravian Red Hill (Červeny Kopec) loess site (Buha et al., 1969; Kukla and Koči, 1972; Kukla, 1970, 1975, 1977). Subsequent palaeomagnetic investigations were undertaken at Krems and Stratzendorf in Austria (Fink and Kukla, 1977; Kukla, 1978; Kukla and Cilek, 1996) (Figure 2) and Paks in Hungary (Pécsi et al., 1977; Márton, 1979). However, in spite of these pioneering palaeomagnetic approaches performed at several key Danube loess sections and subsequent models developed for certain key sites, for example at Stari Slankamen in Serbia (Marković et al., 2011), there is still no consistent magnetic polarity record recorded at the DLPS as exists for the CLPS (e.g. Evans and Heller, 2001).

Beyond environmental differences between sites, the most probable reason for differences in interpretation of palaeomagnetic zonation could be related to differences in the methodological approaches (including sampling, measurements and most importantly data treatment and analyses) performed by many research groups over a long time period (e.g. Evans and Heller, 2001). Older palaeomagnetic interpretations at individual sites of Early Pleistocene age that are still applied in Austria and the Czech Republic (e.g. Kukla, 1975; Fink and Kukla, 1972), despite their undeniable historical significance, should be viewed with some scepticism because of probable limitations with instrumentation and discontinuous preservation of the loess record in the investigated region. In addition to palaeomagnetic polarity records, mineral magnetic parameters as function of stratigraphy (such as MS) serve as a chronometric method in loess research. Following the seminal work of Heller and Liu (1986) studies by Forster et al. (1996), Sartori et al. (1999) and Jordanova and

Petersen (1999) were the first to apply an MS-based stratigraphic approach to DLPS in the middle and in the lower Danube catchment, respectively. Following these initial MS measurements, we have had the opportunity to provide sensitive inter-profile correlations between numerous Danubian loess sections (Buggle et al., 2009; Marković et al., 2011; Fitzsimmons et al., 2012)

2.2.1. Palaeomagnetic reversal zonation (polarity stratigraphy)

Loess sections in the DB have a number of stratigraphic limitations that vary by location, notably poor preservation of older Early and Middle Pleistocene units and a diversity of local and regional morphological and vegetation expressions and dust accumulation rates. Austrian, Slovakian, Czech and geomorphologically more dynamic slope loess linked with fluvial terrace landscapes and local tectonic basins (Antoine et al., 2013; Hosek et al., 2014; Sprafke et al., 2014) yield more complex and incomplete stratigraphic records than those in Hungary or Croatia (Novothny et al., 2009; Wacha and Frechen, 2011; Wacha et al. 2013), or in the semi-arid Serbian, Romanian and Bulgarian loess plateau zone (Buggle et al. 2009; Marković et al., 2012a). These environmental differences limit the preservation of primary palaeomagnetic and environmental magnetic records, as well as dictating the post-depositional magnetic overprints. Additional problems are the limited number of preserved Early and Middle Pleistocene sequences in the region and the reduced resolution of these sediments. These condensed sedimentary intervals mainly contain evidence of the Matuyama reversed polarity Chron. Therefore, the delineation of a reliable magnetic polarity based stratigraphy for the Early Pleistocene DLPS is a challenging task and requires careful evaluation of the available palaeomagnetic datasets. By contrast, magnetostratigraphical interpretations of Middle and Late Pleistocene DLPS are more consistent, especially because of the greater availability of records located over the entire Danube loess belt for this time interval, as discussed below.

2.2.1.1. Evidence for the Matuyama-Brunhes palaeomagnetic polarity boundary

On supra-millennial time scales, palaeomagnetic reversals occur synchronously around the world, allowing the reversal boundary recorded in different archives to be used as a time marker for correlating different continuous sedimentary records (Zhou and Shackleton, 1999). The youngest major magnetic polarity reversal, the Matuyama-Brunhes palaeomagnetic polarity boundary (MBB), 788 ka, is found in marine sediments within MIS 19 which is an interglacial stage (Channellet al., 2010; Tauxe et al., 1996), while in the CLPS it is documented stratigraphically lower in a loess unit L8 which is a glacial stage corresponding to MIS 20 (Heller and Liu, 1986; Zhou and Shackleton, 1999). This age offset has led to confusion when correlating palaeoclimatic records of the CLPS with marine and ice core records. Several explanations for this important chronostratigraphic problem have been proposed, and are still hotly debated, including the delayed remanence lock-in, magnetic overprinting, complicated remnance acquisition or retention, or errors in the loess chronologies (Liu et al., 2008; Kong et al., 2014; Wang et al., 2014; Singer, 2014 see as a review). However, evidence of the MBB position is even more varied and problematic at the key Danubian loess sections than in China, where the transition is generally stratigraphically shallower andmore consistent between investigated sections (Liu et al., 2008), at least on the main central Chinese Loess Plateau.

Using the local stratigraphic schemes, the MBB position is observed withinthe uppermost part of the pedocomplexes PKX at the Czech Red Hill section (Forster at al., 1996), and PD2 at the Hungarian Paks sections (Sartori et al., 1999) (Figure 3 and Table 2). These strongly developed pedocomplexes are formed above the oldest preserved depositional units that consist of up to 3 m thick accumulations of sediments with typical loess characteristics (in this context a “typical loess” deposit is considered to be a unit that is homogeneous, silt dominated with a high percentage of carbonate content, low MS values and negligible evidence for pedogenic alteration (e.g. Smalley et al., 2011). The presence of the MBB within these loess units has resulted in them being assigned as chronostratigraphic equivalents of MIS 19 (Újvári et al., 2014). However, this assignment does not account for the likely impact of lock-in depth and soil forming processes that have been widely shown to impact loess sequences as stated above. This position is significantly different from the identified level of the MBB in the Serbian Stari Slankamen (Marković et al., 2011), Bulgarian Viatovo and Koriten (Jordanova et al., 2008), and Romanian Tuzla (Balescu et al., 2003) sections. Despite the fact that different stratigraphic schemes have been used for these sections, which confuses their correlation, the recorded location of the MBB in the uppermost part of the oldest thick loess unit L7 at Viatovo, Koriten and at Tuzla sections is in good agreement with the apparent position of the MBB at the base of the lowermost thick loess unit, termed V-L9, at Stari Slankamen. Here, the primary remanence is heavily masked or even destroyed by deep rooting and related pedogenic processes. V-L9 has been correlated with MIS 22 (Marković et al., 2011) and is separated from the centre of the MIS-19 equivalent V-S7 unit by more than 1.5 m, where the reversal should be located according to the marine isotope stratigraphy. Radan (2012) reported the position of the MBB in the Zimnicea borehole in Romania as within loess layer L8, although again differences in stratigraphic nomenclature mean this loess unit actually corresponds to L7 layer at Tuzla, Viatovo and Koriten and V-L9 in Stari Slankamen (Figures 3 and 4). These differences are a consequence of the situation that palaeosols V-S6, V-L7S1, V-S7 and V-S8 at Stari Slankamen correspond to the welded pedocomplex S6 in Viatovo, Koriten and Tuzla sections, or the double palaeosol S6 at Mircea Voda and Zimnicea (Buggle et al., 2009, Radan, 2012). While there is considerable uncertainty about these positions, made more complex due to different stratigraphic models, evidence for the MBB polarity transition preserved at key sections of the Danube loess belt seemingly has an even deeper stratigraphic position than on the CLPS. It is also worth noting that this complexity would be greatly alleviated by a unified stratigraphic scheme, which we propose in this paper.

To some extent these differences in MBB position can be explained by the diversity of loess stratigraphic features and the different existing stratigraphic models across the DB, and by the influence of complexities in remanance acquisition and retention (Spasov et al., 2003), as in Chinese loess. The contrasting processes of detrital and chemical remnant magnetisation have been shown to interact in CLPS sequences to yield an alternating signature of reversed and normal polarity, even where the geomagnetic field may not have varied (Spassov et al., 2003), and indeed at high dust sedimentation rate sites, spurious signals may be preserved (Wang et al., 2014). This may account for some of the complexities seen here, accompanied by the substantial effect of pedogenesis and root activity on the generally lower accumulation rate sequences in the Danube basin. For example, at the Stari Slankamen site bioturbation resulting from penetration by large root channels associated with massive carbonate concretions and hydromorphic features strongly affect the critical interval from V-S7 to V-L9 (Marković et al., 2011).

2.2.1.2. Episodes of normal polarity within the Matuyama and the boundary with the Gauss palaeomagnetic Chron

The main Danubian loess sections also exhibit different stratigraphic positions of the Matuyama normal palaeomagnetic subchrons. Initially, Fink and Kukla (1972) reported evidence of two normal polarity intervals in the lower parts of Austrian sections Krems and Stranzendorf, most likely representing equivalents of the Jaramillo and Olduvai palaeomagnetic subchrons. One interval of normal polarity within a reversed palaeomagnetic zone in the lower part of Czech Red Hill loess-palaeosol sequence has been interpreted as an equivalent of the Jaramillo subchron (Fink and Kukla, 1977; Kukla and Cilek, 1996) (Figure 2). Forster et al. (1996), however, demonstrated that these conclusions were based on an incorrect correlation of sub-profiles and that the sections record only the MBB.

Initially the loess-palaeosol sequences from Krems and Stranzendorf (Figure 2) were interpreted as covering the interval from the lower Brunhes to the uppermost Gauss (Fink and Kukla, 1977). However, Kukla and Cilek (1996) reported revised combined results from Red Hill, Krems and Stranzendorffollowing the suggestion of the probable incompleteness of the Krems sequence after investigation of micro-vertebrates by Rabeder (1981). However, based on the fact that Austrian loess-palaeosol sequences are highly susceptible to erosion and re-deposition processes (Sprafke et al., 2014), the revised correlation by Kukla and Cilek (1996) should also be viewed with caution. An additional challenge to improving the chronostratigraphic model for Austrian slope loess is the limited possibility of using MS for stratigraphic correlation. It has not been possible to use MS variations to clearly differentiate loess layers and different types of fossil soils and pedocomplexes. For example, at the Wels-Aschet section, loess unit AS9 has significantly higher MS values than the strongly developed interglacial palaeosol, AS7c (Scholger and Terhorst, 2013, see Table 2).

The Jaramillo subchron has been also found in Hungarian loess deposits, in the Dunaföldvár exposure and the Dunakömlőd borehole (red and ochre red soils of Dv1-6 in the Dunaföldvár complex (Újvári et al., 2014). Koloszár (2010) presented evidence for the Jaramillo subchron being recorded in the Tengelic red clay formation in the Udvari 2A borehole.

The Tengelic red clay formation (Ujvari et al., 2014) is similar to the proposed Bulgarian ‘red clay complex’ that underlies the loess in this region (Jordanova et al., 2008). At the Viatovo loess section two normal magnetozones were also found in this lowermost reddish clay rich sequence, most probably corresponding to the Jaramillo and Olduvai subchrons of the Matuyama reversed chron (Jordanova et al., 2008). Here, it is important to stress the problematic nature of the nomenclature, as the famous Chinese Red Clay Formation at the base of thick Quaternary loess formations of the Central Chinese Loess Plateau (Ding et al., 1999) is of Pliocene age and represents a fundamental shift in depositional and weathering conditions between loess and red clay units. The boundary is sharp and well defined. The formation of the so called “red clay” sediments in the Danube area (Jordanova et al., 2008) does not necessarily correspond to the formation interval of the Chinese “Pliocene Red Clay formation” and the former are more akin to weathered loess and an extension of the loess stratigraphic framework. Indeed, Kovács et al. (2012) reviewed the geochronological and stratigraphical framework of the red clay in the Carpathian Basin and showed that the DB red clay exhibits depositional ages from 0.5 to ~ 3.5 Ma years, with strong local and regional differences of the upper and lower boundary age. To avoid confusion and the incorrect stratigraphic correlation of the Bulgarian red clay complex and Chinese Red Clay Formation, as well as with other unrelated and diachronous ”red clay” formations in the Danube basin, Marković et al. (2011) proposed the term 'Basal Complex' for the equivalent stratigraphical unit at Stari Slankamen to that named the “Red Clay Complex” by Jordanova et al. (2008). Similar palaeomagnetic evidence is also expressed at the Stari Slankamen site as a normal polarity interval in the lowermost part of the Basal Complex which most probably corresponds with Jaramillo normal subchron (Marković, et al., 2011). Thus, the Basal Complex in Serbia, Bulgaria and Romania corresponds to the Czech and Austrian alternation of loess and palaeosol units formed during the Matuyama Chron.

2.2.1.3. Short geomagnetic excursions within the Brunhes palaeomagnetic chron

Kukla and Koči (1972) identified the Blake palaeomagnetic event (120–110 ka) within the double pedocomplex PKII and PKIII confirming astratigraphic link between these two palaeosols and the MIS 5 period. Recently, Scholger and Terhorst (2013) performed detailed palaeomagnetic investigation at the Wels-Aschet section and recognised many excursions of reversed polarity within the Bruhnes. These short-lived geomagnetic reversals were regarded as equivalents of the Blake (120–110 ka), Albuquerque - Fram Strait (165–155 ka), Jamaica - Pringle Falls (215–205 ka), Calabrian Ridge 1 (325–315 ka) and Emperor - Big Lost - Calabrian Ridge 3 (570–560 ka) geomagnetic excursions of the geomagnetic reference timescale based on their positions in the sedimentary column. For the excursion in the loess complex AS4e, depending on which reference time scale is used, either the Calabrian Ridge 2 (525–515 ka), West Eifel 5 (528+-16 ka) or a much younger age excursion were deemed plausible (Table 2). At Krems, Hambach et al. (2008b) reported evidence for the Mono Lake and Laschamp geomagnetic excursions from last glacial loess using both detailed palaeomagnetic direction and intensity variations.

Similar detailed palaeomagnetic sampling and measurements were performed on the lower part of the Stari Slankamen loess-palaeosol sequence. Evidence of the so-called Stage 17 reversed polarity excursion has been identifiedinpalaeosol V-S6 and independently confirms its proposed chronostratigraphic correlation with MIS 17, based on MS variations (Marković, et al., 2011).

2.2.2. Magnetic susceptibility interprofile correlation

Since the seminal work of Heller and Liu (1984, 1986), mineral magnetic parameters became fundamental palaeoclimate proxies in loess/palaeosol research. Magnetic susceptibility (MS; induced magnetisation/applied magnetic field) and its dependence on the frequency of the applied field (MS_{fd}) turned out to be, along side grain size (GS) and geochemical indices of climate/environment, a highly sensitive proxy for temperature and humidity during loess accumulation (cf. Buggle et al. 2014). The application of MS and MS_{fd} as palaeoclimatic proxies in the Eurasian loess steppe environments is based, in addition to the mineralogical homogeneity of the loess, mainly on the neo-formation of ferrimagnetic minerals in the course of silicate weathering and pedogenesis. The latter depends largely on the temporal variation of soil humidity and thus the temporal course of palaeoclimate. Thus, increasing pedogenesis goes along with the enhancement of the mineral magnetic signals. However, the properties of a given magnetic assemblage in loess depends not only on the concentration and mixture of the minerals, but largely on the grain size distribution of the magnetic particles. For a given ferromagnetic (s.l.) mineral concentration, MS varies widely, depending only on grain size, being largest for very fine so called superparamagnetic (SP) particles. These SP-particles precipitate from weathering solutions largely controlling the mineral magnetic signal in loess palaeosol sequences and are the main cause of the enhancement of the mineral magnetic signals. Accordingly, the weathering and pedogenesis controlled magnetic enhancement, therefore, provides a sensitive proxy for soil palaeo-humidity and hence for palaeoclimate (e.g. Buggle et al. 2014; Evans and Heller 2003; Singer and Verosub, 2007).

Since Heller and Liu (1984, 1986) promoted MS variations as a sensitive palaeoclimatic proxy, and due to relative simple measuring procedure (in the field, as well as in the laboratory), it became the most commonly measured global proxy from the loess-palaeosol sequences. MS fluctuations recorded in DLPS apparently reflect the pedostratigraphy well (Marković et al., 2008, 2011). This is a typical example of the model involving magnetic enhancement via pedogenesis, similar to that seen in Chinese and Central Asian loess deposits (e.g. Heller and Liu, 1984; Maher and Thompson, 1992). This enhancement of the magnetic signal as a consequence of pedogenetic processes appears to be valid for a huge Eurasian semi-arid loess belt (Ding et al., 2002; Dodonov and Zhou, 2008). Measurement of loess MS is therefore a rapid and consistent tool for inter-profile correlations, even on very long distances across Europe and Asia. It is striking in fact how some intervals of MS patterns seen in Serbian and Chinese loess-palaeosol sequences match each other (Marković et al., 2012a; Figure 5).

Several important conditions allow the use of MS records of the DLPS as a key stratigraphic tool. As a consequence of the drier Pleistocene environmental conditions in the region compared to other parts of Europe, the oldest and most complete European loess records (e.g. Marković et al., 2011, 2012a) were preserved within the Middle and Lower DB. As noted above there were drier conditions in the middle and lower Danube basin during the Pleistocene and this results in the DLPS satisfying one of the most important stratigraphic criteria for use as a basis for a stratigraphic scheme: quasi-continuity of the depositional record, at least on multi-millennial timescales. An additional important criterion is a relatively uniform stratigraphy over a wide region, with a relatively small number of stratigraphical units in comparison with other European loess provinces

(Marković et al., 2008; Buggle et al., 2009); this also being facilitated by the drier lower to middle basin climate.

Figure 4 shows proposed correlations between MS records of the main sections of the Danube loess area: Paks in Hungary (Sartori et al., 1999), the composite profile of Sedlec near Prague-Sedlesovice-Sedlec close to Mikulov-Červeny Kopec (Forster et al., 1996), the Serbian sections Batajnica (Marković et al., 2009b), Ruma (Marković et al., 2006), Stari Slankamen 1 (Marković et al., 2003) and Stari Slankamen 2 (Marković et al., 2011), Koriten (Jordanova and Petersen, 1999) and Viatovo (Jordanova et al., 2008) in Bulgaria, and the Romanian sites Mircea Voda (Timar-Gabor et al., 2011), Mostiştea (Panaiotu et al., 2001) and Zimnicea (Radan, 2012). A broad-scale correlation with marine oxygen isotope stratigraphy (Lisiecki and Raymo et al., 2005; Berger, 2008) and a potential palaeomagnetic zonation up to the Olduvai Subchron is also proposed (Sartori et al., 1999; Jordanova et al., 2008; Marković et al., 2011).

The 'background' (i.e. less weathered or unweathered) MS recorded in loess units is very similar in all analysed sections (Buggle et al., 2008; Buggle et al., 2013; Buggle et al., 2014) indicating a generally similar origin, which is mainly silt-sized deflated material. However, the amplitude of MS values is quite different when comparing chronostratigraphically equivalent interglacial pedocomplexes from Czech (Forster et al., 1996), Hungarian (Sartori et al., 1999), Serbian, Romanian and Bulgarian sections (Marković et al., 2009b, 2011, 2012a; Jordanova et al., 2008; Radan, 2012). As these palaeosols are formed in a very similar plateau-like situation and from presumably (from the similar MS values in loess units) very similar parent material, the differences in absolute MS values are mostly related to different climatic, environmental and local geomorphic conditions.

In spite of these regional differences in MS peak magnitude, following the common variability of signal recorded in Middle and Lower DLPS, the definition of basin-wide stratigraphic correlation is relatively simple. While previous stratigraphic schemes even in these areas have at times required substantial revision (for example the famous Hungarian section of Paks), this has generally been due to a lack of available techniques to detect gaps or inconsistencies in the records. This has meant that schemes have been developed based on approaches that use either a counting downwards from the top technique, or one based on counting from a recognised reference unit. For example, the absence of the V-S2 (MIS 7) pedo-complex at the Stari Slankamen exposure can be detected visually by using the presence of a distinct erosional horizon. However, what would be less clear from either visual, or even from magnetic susceptibility, is the exact number of units removed. The application of independent stratigraphic/geochronological approaches, such as amino-acid recemisation (AAR) relative geochronology (Marković et al., 2011) and luminescence dating (Schmidt et al., 2010; Murray et al., 2014) (Figure 8) can be used along with comparison of recorded MS patterns to a reference column to constrain this information. In this way the use of visual and MS stratigraphy can be augmented to develop secure stratigraphic schemes that are readily correlatable across the lower and middle Danube basin. In some cases the fit of the magnetic susceptibility profile to expected patterns can be used to determine the stratigraphic integrity of a sequence. For example, several hiatuses in the uppermost part of the Paks exposure yield an atypical Late Pleistocene MS pattern at the site, in comparison to that typically seen in other Danube loess sections (Figure 4). However, ideally independent evidence should be used to better constrain these missing intervals.

As such, using the characteristic MS pattern as a stratigraphic tool for correlating loess sites in various parts of the Danubian loess belt, alongside ground truthing using independent geochronological tools where possible, allows the establishment of a basin-wide stratigraphic model, at least with regard to the most recent eight glacial-interglacial loess-palaeosol couplets.

2.3. AAR relative geochronology

The racemisation/epimerisation of amino-acids preserved in Quaternary fossils provides relative geochronological information applicable to a wide range of stratigraphic problems, depositional environments, and timescales (Penkman and Kaufman, 2012). AAR ratios of isomer pairs measured from land snails have been successfully used for the correlation of loess stratigraphic units across the northern hemisphere: loess provinces in Europe, Asia and North America (Oches et al., 2000; Oches and McCoy, 2001). Previous applications of the AAR geochronological approach to European loess-palaeosol sequences were almost completely related to the DLPS (Oches and McCoy, 1995a, 1995b, 1995c). However, the potential of the AAR method for solving long-term stratigraphical issues has, as yet, not been widely recognised within the research community. At present, environmental magnetism, coupled with absolute dating using luminescence or radiocarbon techniques, is the preferred approach for reconstructing chronostratigraphies within loess in general.

The first phase of the application of AAR to loess was completed in the 1990s at the classical sections in Austria, Slovakia, Czech Republic and Hungary (Oches and McCoy, 2001). The use of the AAR technique by Zöller et al. (1994), as well as Oches and McCoy (1995a, 1995b, 1995c) in these countries substantially improved our understanding of Danubian loess stratigraphy. The most abundant shells of the taxa, including *Succinea, Helicopsis*, *Trichia* and *Pupilla*, offer the most direct aminostratigraphic comparison with data from loess elsewhere in the DB. While the aminostratigraphic data arising from these studies have provided limited resolution on stadial/interstadial time scales, stratigraphic subdivision into younger glacial/interglacial couplets was very successful. These resulting chronostratigraphic interpretations for the four youngest glacial/interglacial cycles enabled revision of the previous 'classical' stratigraphic schemes. More advanced reverse-phase liquid chromatography AAR was subsequently applied to northern Serbia (Marković et al., 2004a, 2004b, 2005, 2006, 2007, 2011) and Hungary (Novothny et al., 2009) approximately one decade later. This technique has the considerable advantage that multiple amino acids can be measured, with varying racemization rates, meaning for the first time stadial-interstadial differentiation was plausible. However, as yet, the technique has not been applied to loess sections in the lower Danube regions in Bulgaria and Romania.

Figure 6 shows comparison between marine isotope stratigraphy and glacial cycles defined by Kukla (1975, 1977), and the stratigraphic subdivisions of Czech, Slovak, Austrian, Hungarian (Oches and McCoy, 1995a, 1995b), and Serbian (Marković et al., 2006, 2008, 2011) loess pedocomplexes, as refined using AAR to reliably facilitate basin-wide correlation of the interglacial pedocomplexes for the most recent four interglacial-glacial cycles.

Shells of the typical loess genus *Pupilla,*which are abundant in all of the investigated Danubian loess sites in Serbia, Hungary, Austria, Germany, Ukraine, Czech Republic and Slovakia, offer the possibility of direct aminostratigraphical comparison. Figure 7 summarises the gradual increase of D-alloisoleucine/L-isoleucine epimerization rates measured from *Pupilla* shells collected from sites in Central Europe across to the Middle DB across all stratigraphic units. This trend is most likely to be a consequence of regional gradients in mean annual temperatures, which would have persisted throughout the Pleistocene. This gradient must be taken into account when establishing aminostratigraphic correlations (Marković et al., 2006, 2008, 2011).

Recently, Marković et al. (2011) presented application of AAR relative geochronology to the long-term loess-palaeosol sequence at Stari Slankamen in order to test the resolution of the method. These results indicate that the AAR methodological approach can be a powerful tool in resolving glacial interglacial cycles younger than 700 ka. However, the erosional hiatus suggested by the MS record and presence of a gravel unit at the site was confirmed using AAR and shown to indicate that pedocomplex V-S2 and part of the bracketing loess units are missing at the site (Figure 8).

2.4. Recent results from improved luminescence absolute chronology

Compared to many other Quaternary deposits, loess has a distinct advantage because of the possibility for absolute dating by luminescence techniques. Indeed, early developments in TL dating and new luminescence methodologies such as thermally transferred optically stimulated luminescence dating (TT-OSL) and post-IR infrared stimulated luminescence dating (post-IR IRSL), were undertaken on loess samples due to the suitability of loess for luminescence methods (see Roberts, 2008 for a review). Early TL chronologies from the DLPS (e.g. Wintle, 1987; Singhvi et al. 1989) were obtained using protocols which have since been shown to be potentially unreliable in loess environments (Frechen et al., 1997). Subsequently, optically stimulated luminescence dating (OSL) on quartz, and infrared stimulated luminescence dating (IRSL) on feldspars and polymineral samples dominated by feldspar signals were adopted and thought to provide more reliable age estimates (Balescu et al. 2003, 2010; Novothny et al. 2009, 2010; Lang et al. 2003; Timar et al. 2010). However, these methods are not without limitations. Direct dating of sediments by OSL, IRSL, TL, TT-OSL and post-IR IRSL methods is a rapidly developing field of Quaternary geochronology. Significant recent advances in this field have arisen from studies of loess deposits generally (e.g. Roberts, 2008), and in a number of cases, Danubian loess (Anechitei-Deacu et al., 2014; Stevens et al., 2011; Thiel et al., 2011; Timar-Gabor et al., 2011; Schmidt et al., 2010; Timar-Gabor and Wintle, 2013; Fitzisimmons and Hambach, 2014; Zöller et al., 2014). These developments in luminescence dating have been reviewed elsewhere (e.g. Roberts, 2008, Fitzsimmons et al., 2012), and will only be summarised briefly here in terms of studies of the Danubian loess.

While quartz OSL dating is widely considered to be the most reliable method of choice for loess work, OSL dating of loessic quartz is generally acknowledged to have an upper age limit ranging from 50 to 100 ka (Wintle and Murray, 2006; Timar et al., 2010; Timar-Gabor et al., 2011; Timar-Gabor and Wintle, 2013). Investigations into the OSL characteristics of quartz of different size fractions from Romania, from sites with independent age control, suggest that the reliability and upper dating limit is partially dependent on the grain size chosen for measurement (Constantin et al., 2012; Timar-Gabor et al., 2011, 2012; Timar-Gabor and Wintle, 2013); it has been suggested that this may reflect variations in depositional processes and source sediment of the different size fractions (Anechitei-Deacu et al., 2014) but at present the cause of these discrepancies is unclear. At present, the most reliable quartz OSL dating results for Danubian loess appear to derive from fine-grained material, for ages up to ca. 70 ka (Timar-Gabor et al., 2012), and loess sections in Romania have been successfully dated within these limitations (Anechitei-Deacu et al., 2014; Constantin et al., 2012 Fitzsimmons et al., 2013; Fitzsimmons and Hambach, 2014), alongside sections in Serbia (Schmidt et al., 2010, Stevens et al., 2011). However, studies employing quartz OSL in Hungary have sometimes met with poor quartz luminescence properties such as low signals and reproducibility, although reliable ages may be obtained (Schatz et al., 2012).

The feldspar IRSL signal is, by contrast with quartz, subject to fading of the luminescence signal through time, resulting in the need to substantially correct the age estimates (Auclair et al., 2003). However, IRSL techniques have readily been applied to European deposits but fading was either not measured or reported to be absent (see Roberts, 2008 for review). This seems surprising given recent development in post-IR IRSL that have involved measuring fading rates for standard IRSL protocols, which have shown this phenomenon to be widespread. It seems that methods of fading measurement on European loess sequences used previously have been inadequate to quantify fading rates in loess feldspars (Roberts, 2008). The recent development of the post-IR IRSL protocol appears to access a more stable signal, showing no or much lower fading rates, and thereby reducing the need for an empirical correction that is likely to only be valid for younger age samples. This technique, partially developed on European loess, extends the dating range beyond that of quartz, potentially to up to 300 ka (Thiel et al., 2011; Buylaert et al., 2012). This protocol has been successfully applied to a number of Austrian, Hungarian, Croatian, Serbian and Romanian sites, and confirm or extend existing chronostratigraphic models (Schmidt et al., 2010; Thiel et al., 2011, 2014; Stevens et al., 2012; Schatz et al., 2012; Wacha and Frechen, 2011; Vasiliniuc et al. 2012; Murray et al., 2014) and provides an independent age control (Fitzsimmons et al., 2013). For example, Schmidt et al. (2010) obtained coupled post IR-OSL and IRSL dating results from loess units V-L1 and V-L2 at Stari Slankamen in Serbia which support the existing chronostratigraphic model. Luminescence data from last glacial loess unit V-L1 yield ages of approximately 25 to 65 ka. These results are similar to recent IRSL or OSL dating for the last glacial loess at other investigated sites in the Vojvodina region reported in recent papers (Marković et al., 2007, 2008; Fuchs et al., 2008; Bokhorst et al., 2009; Újvári et al., 2010; Stevens et al., 2011; Hatte et al., 2013). Further, dates from loess unit V-L2 yield minimum ages of between 100 to 193 ka, supporting our suggestion of a penultimate glacial age for the unit (Schmidt et al., 2010). In the study of Vasiliniuc et al. (2011, 2012) (Figure 9) post IR-IR_{225} ages in agreement with fine (4-11µm) quartz OSL ages for the uppermost Romanian loess unit have been obtained while for L2, L3 and L4 the (uncorrected for fading) ages obtained by applying post IR-IR_{225} on polymineral fine grains yielded ages of 156±24 ka, 269±46 ka and 360±71 ka, respectively. The ages are in good agreement with the palaeomagnetic time-depth model and assign these units to MIS6, MIS 8 and MIS 10. However, there are still uncertainties with the post-IR IRSL technique, notably in the size of the residual (Stevens et al., 2011) and the upper age limit (Thiel et al., 2014).

The reliability of luminescence techniques, including new protocols such as post-IR IRSL and of different grain sizes of quartz, can be assessed very well within parts of the DLPS due to the excellent preservation of volcanic tephra layers which provide independent age control (e.g. Veres et al., 2013a; Fitzsimmons et al., 2013; Anechitei-Deacu et al., 2014; Constantin et al., 2012; Wacha and Frechen, 2011). The lower Danubian loess represents one of the few regions in Eastern Europe which can be used to test the accuracy of luminescence dating techniques, although species specific AMS ^{14}C dating of small gastropod shells may also prove important for younger deposits (Pigati et al., 2013).

An additional important advance is the application of luminescence chronologies to estimating sedimentation rates of loess (Újvári et al., 2010; Fitzsimmons and Hambach, 2014). This approach is generally constrained to the last glacial cycle as reliable quartz OSL ages are limited to last glacial loess (Timar-Gabor and Wintle, 2013) and age estimations of older loess and palaeosol units decrease in reliability as the post-IRIRSL$_{290}$ signal approaches saturation towards ~300 ka (Murray et al., 2014; Thiel et al., 2014). Nevertheless, a number of useful estimates of sedimentation rates have been determined by using luminescence dating from sites in Serbia (Stevens et al., 2011), Hungary (Újvári et al., 2010; Novothny et al., 2011; Schatz et al., 2012; Thiel et al., 2014) and Romania (Timar et al., 2010; Vasiliniuc et al., 2010; Constantin et al., 2014; Fitzsimmons and Hambach, 2014). At the site of Urluia in southeastern Romania, substantial deposits of the Campanian Ignimbrite volcanic tephra provide a useful upper age limit (ca. 39 ka) to investigating the variability of sedimentation rates from MIS 3 to the present, and indicate substantial loess accumulation during the last glacial maximum period on the order of 6-8 m within several thousand years (Fitzsimmons and Hambach, 2014). Thiel et al. (2014) confirmed previous stratigraphic expectations related to the loess wall in the Paks brickyard, Hungary (Sartori et al., 1999; Horváth, 2001; Marković et al., 2009b; 2011, 2012a) (Figure 10). This demonstrates that the loess-palaeosol sequences at Paks are not a continuous record. Such unconformities are also common in other DLPS and point to the fact that all these sequences are only quasi-continuous records. The study does demonstrate that the Basaharc Double soil (BD1+2) complex is correlated with MIS 7. The Basaharc Lower soil (BA) likely corresponds to MIS 9, however, below this the signal approaches saturation. Finally, Stevens et al. (2011) demonstrate that there are differences in calculated sedimentation rates over the last glacial cycle between Danubian loess sites, notably some sites that show very little glacial loess accumulation during the early part of the last glacial, compared to others where loess sedimentation increases early in the glacial. Site specific differences and different luminescence protocols cannot be ruled out as factors that account for these discrepancies, however, and these differences require further investigation in order to develop fully integrated basin scale models of dust accumulation that can be of use to communities that model modern and past fluxes of atmospheric dust (Albani et al., 2014).

Luminescence dating has also been used to assess the timing of transitional intervals in loess deposition and alteration, as well as palaeosol development. A current study by Marković et al. (2014c) has raised an important question about the temporal accordance between the main loess-palaeosol stratigraphical boundaries andthe equivalent MIS transitions. The synchronicity between the start of the Holocene and theinitiation of soil formation on Serbian loess plateaus is checkedthrough application of luminescence dating of the transitional interval between the last glacial loess and modern soil. The two uppermost luminescence dates from the Orlovat loess section clearly demonstrate an Early Holocene age almost 0.7 m below the Holocene soil V-S0 to loess boundary. Critically, this contrasts with other sites in the basin in terms of when soil-forming conditions regain dominance in the region during the Holocene and whether the lower boundary of soil V-S1 chronologically corresponds to Termination 1 (Bard et al., 1992). The luminescence dating results from this and various other sites in the Vojvodina region (Stari Slankamen, Rogulić, Surduk and Crvenka) indicate that the precise timing of these transitions, such as the decrease in loess accumulation and initiation of Holocene soil formation, may vary between locations. The results at the Orlovat section indicate thatloess deposition continued well into the Holocene. Chernozem soil formation started considerably later than the beginning of the Holocene. This interpretation is supported by very young luminescence ages (7.6 ± 0.5 ka) from the lower part of modern soil V-S0 at Stari Slankamen (Schmidt et al., 2010) and from the last glacial loess V-L1 (10.0 ± 1.1 ka) 1.6 m deeper than the lower boundary of the modern soil in the Rogulić gully on the Titel loess plateau (Bokhorst et al., 2011). It is also supported by a very young ^{14}C age (7.3 ± 0.38 cal ^{14}C ka BP) for the uppermost part of the last glacial loess at Surduk (Hatte et al., 2013). This would be in marked contrast to CLPS where Holocene soil formation extends well in to last glacial loess (Stevens et al., 2008). By contrast, in northern Serbia at Crvenka, quartz OSL dates from the Holocene soil and the boundary with last glacial loess unit V-L1 suggest that soil formation began at the onset of the Holocene (Stevens et al., 2011).

The increasingly widespread adoption of absolute dating using luminescence techniques clearly demonstrates their applicability for testing stratigraphic correlations between sites, in addition to elucidating rates of loess accumulation and pedogenesis. Furthermore, the presence of the well-dated Campagnian Ignimbrite tephra in the eastern Danubian loess enables reliable assessment of the accuracy of the different protocols in some areas over a limited time range. Absolute chronologies are fundamental to the development of a regional stratigraphic model, despite the existing age limits and challenges with the current luminescence dating techniques.

3. A unified Danube loess stratigraphic model

Our proposed chronostratigraphic model spans the Middle Pleistocene transition through to the present (Ruddiman et al., 1989; Heslop et al., 2002). The climatic changes of the mid-Pleistocene transition resulted in a shift to more arid conditions in the DB (Buggle et al. 2013; Fitzsimmons et al. 2012), making it relatively difficult to subdivide stratigraphic units straddling this time period. Regional environmental responses to these significant global climate changes were not uniform in the DB area resulting in a high spatial and temporal diversity of palaeosols. For example, during the last interglacial period, quite different palaeosols have developed simultaneously in the basin, including luvisols in Austria, cambisols in Hungary, or chernozems in Serbia, resulting in some important differences in loess-palaeosol stratigraphy of the key loess sections. An additional problem for valid stratigraphical correlations is the considerable environmental diversity over the entire Danube loess belt, resulting in some important differences in the loess-palaeosol stratigraphy of the key loess sections. This is related to the high propensity of the DLPS to erosion and re-deposition, in turn driving a low sedimentary preservation potential, which seriously limits detailed stratigraphic interpretations. However, even more confusing are the often highly complicated national stratigraphic nomenclatural schemes. In these national schemes 14 different letters have been used (Fitzsimmons et al., 2012), or in some cases a particular pedocomplex received the names of the local settlements, such as: Stillfried, Paudorf and Göttweig in Austria (Fink, 1962; 1965), Mende, Basharc and Paks in Hungary (Pécsi and Schweitzer, 1993), or Surduk in Serbia (Antoine et al., 2009a). While important regional differences in soil type are of significance and a way to distinguish time equivalent soils under contrasting environmental conditions, this type of loess stratigraphical nomenclature is valuable only to a narrow number of regional loess specialists and is a major inhibitor for the wider use of the Danube loess records in regionally, hemispherically or globally integrated palaeoclimatic and palaeoenvironmental research. As such, a unified scheme, much like that of the Loess Plateau in China and in the deep marine records (where significant differences in depositional conditions also occur) is required to utilise the basin-wide deposits to their full potential.

After comprehensive stratigraphic analyses of the key Danube loess sections and critical evaluation of the existing stratigraphical models, we propose the direct correlation presented in Tables 1 and 2. This compares the classical Austrian and Czech stratigraphic models (Fink and Kukla, 1977; Kukla, 1975; Zöller et al., 1994; Forster et al., 1996; Kukla and Cilek, 1996) with current stratigraphic models based on magnetic stratigraphic analysis and supported by luminescence dating and AAR geochronology (Sartori et al., 1999; Marković et al., 2006, 2009b, 2011; Buggle et al., 2009; Panaiotu et al., 2001; Timar et al., 2010; Timar-Gabor et al., 2011; Jordanova et al., 2007, 2008; Radan, 2102; Újvari et al., 2014). Loess-palaeosol units are correlated to each other, to Chinese loess stratigraphy (Kukla and An, 1989), and to the equivalent MIS (Lisiecki and Raymo, 2005) andglacial cycles as defined by Kukla (1975). This is a crucial part of integrating these important sequences into the global network of long-term palaeoclimate records.

Bulgarian sites such as Ljubenovo, Viatovo, and Koriten, as well as Zimnicea, Mircea Voda, Tuzla and Costinesti in Romania have apparently greatly reduced resolution in the older part of the Middle Pleistocene (Figure 4). This is a serious limitation for stratigraphic interpretations over this interval. For example, the welded pedocomplex S6 in Bulgaria and Romania corresponds to several separate loess-palaeosol units in Serbia, Hungary, and the Czech Republic. At the site of Mircea Voda (Romania), Buggle et al. (2009) subdivided the S6 pedocomplex into S6S1, S6L1, and S6S2 indicating that S6S1 is an equivalent of MIS17. Also, at the site of Zimnicea (Romania), Radan (2012) labelled the upper palaeosol as S6 (MIS 17) and the lower one as S7, correlating it with MIS 19. Furthermore, at the site of Viatovo (Bulgaria), Jordanova et al. (2008) correlated the S6 pedocomplex with MIS 17, 18, 19 and 21, whilst relating the thin interbedded loess units within S6 to formation during MIS 18 and 20. However, a comparison of the MS pattern and the position of the Brunhes-Matuyama boundary between the Stari Slankamen record and the Bulgarian S6 pedocomplex suggests that the latter could have been formed even prior to the end of MIS 21.

Contrary to the complicated and problematic stratigraphic interpretations for older DLPS, inter-profile correlation of younger loess palaeosol units is much simpler and more consistent. Loess units accumulated during MIS 16 are exposed at all sections as a thick, typical loess layer. An important stratigraphical marker is also a strongly developed pedocomplex formed from MIS 15 to 13 (PK7+8 in the Czech Republic, Phe and MTp1+2 in Hungary, V-S5 in Serbia, and S5 in Romania and Bulgaria). This pedocomplex shows a much greater degree of pedochemical weathering and clay mineral formation than in modern soils of this region, a feature that appears to be a characteristic of the middle part of all Brunhes loess-palaeosol sediments in Eurasia (Bronger, 2003). It also matches the characteristics of the poorly developed MIS 14 cold event in the marine record (e.g. Bassinot et al., 1994; Lisiecki and Raymo, 2005) and covers the same interval as the Chinese Loess Plateau S5. This wide scale similarity led Vandenberghe (2000) to underline the importance of this long warm period, as expressed in V-S5 soil formation and palaeobotanical evidence, as a key element in linking Chinese and European stratigraphies.

The pattern of MS variations and the aminostratigraphical assignments in the upper part of the profiles suggest a correlation of the youngest four major palaeosols (PKVI, PKV, PKIV+III, and PKII in the Czech Republic; MB, BA, BD2+1, and MF2 in Hungary; VS4, VS3, VS2, and VS1 in Serbia; S4, S3, S2, and S1 in Romania and Bulgaria) with MIS 11, 9, 7, and 5 respectively (Table 2; Figure 4), with the uppermost fossil soil confirmed as MIS 5 equivalent using luminescence techniques. In Serbia, Romania and Bulgaria the 4th pedocomplex (S4), which is an equivalent to interglacial MIS 11 (Candy et al., 2010; 2014), is expressed as the youngest forest fossil soil. These fossil complexes are separated by thick typical loess horizons corresponding to MIS 10, 8, 6, and 4-2 respectively. These loess and palaeosol couplets were originally named as the young loess formation (Pécsi, 1995; Oches and McCoy, 1995a). A successful inter-profile correlation of the main loess and palaeosol units within the Danube loess belt requires a uniform definition of loess and palaeosol boundaries, combined with a standard stratigraphical classification. To ensure the application of uniform stratigraphic criteria, we follow the same definitions for stratigraphic units as previously established by Kukla (1987) and Kukla and An (1989). The most accurate, objective, and easily reproducible delimitation of stratigraphic units is based on the low field MS supported by independent methods such as luminescence dating, amino-acid geochronology and identified palaeomagnetic reversal boundaries.

Following the widely recognised CLPS stratigraphic model (Kukla, 1987, Kukla and An, 1989), we designate the Danubian L (loess) and S (palaeosol) stratigraphic units, numbered in order of increasing age. Early attempts to develop a Danube loess stratigraphic model proposed the prefix "D" to refer to the standard Pleistocene loess-palaeosol stratigraphy in the Middle DB loess area (Marković et al., 2003, 2008, 2012a). However, including such a prefix "D" would again cause unnecessary complications for wide applications of this stratigraphic model. Thus, for labelling the

Danube loess we propose the same nomenclature already well established for the Chinese loess stratotype sections, i.e. a system based on the "S" and "L" labelling systematic without any specific regional prefixes. For labelling hierarchically lower units, there are two modes in the Chinese system. For example, according to the initially established scheme the uppermost (youngest) interstadial palaeosol within the L1 loess would be labelled L1-2 and the loess that directly underlies it would be termed L1-3 (see Liu et al., 1985; Liu and Ding, 1998). Later on, an alternative nomenclature for lower units was proposed by Kukla and An (1989), according to which the same units would be labelled as L1SS1 and L1LL2, respectively. Today, the Kukla and An (1989) version is widely accepted for Chinese loess sites. In some previous DLPS studies the last glacial interstadial pedocomplexes have been labelled (V)L1S1 and the underlying loess (V)L1L2 (Panaiotu et al., 2001; Jordanova and Petersen, 1999; Marković et al., 2006, 2009, 2011; Buggle et al., 2009, 2013).

The newly proposed stratigraphic scheme for the DLPS strictly follows the rules defined by Kukla and An (1989) for the Chinese loess stratigraphy:

1. The upper boundary of a loess unit and the lower boundary of an interglacial pedocomplex unit is drawn at the *top* of the primary unweathered calcareous loess usually coincident with accumulation of carbonate concretions and bioturbation mostly related to humic infiltrations from overlying soil in former root channels. The boundary is characterized by a rapid increase upwards of the MS values. Average MS values in "S" units are at least 50% higher than in the "L" units that underly them.
2. The lower boundary of a loess unit or the upper boundary of a soil unit is drawn at the level of the first appearance of typical sub-aerial loess that is unaltered or only partly affected by bioturbation. The transition from interglacial palaeosol unit to the overlying loess unit is less sharp, but still this stratigraphic boundary is clearly indicated by significant gradual decrease of MS values from the palaeosol to the loess unit above.

3. The units of the first-order are prefixed by a single capital letter L for loess layers and S for pedocomplexes and palaeosols. They are numbered in order of increasing age.

4. The second or third-order units are named by the designation of the corresponding first order unit, followed with only one additional capital letter 'L' for loess, and 'S' for soil, for each stratigraphic level. They are also numbered in increasing order. Usually, second-order stratigraphic units can be recognised by the more gentle changes of MS values within the magnitude and range that characterizes the first-order unit.

5. The nature of the boundaries of the second- and third-order units, because of their more complicated origin and more problematic chronological determination, will be discussed in more detail.

6. Stratigraphical units of higher order, so-called 'super-units', include several integrated couplets of loess and palaeosol units, with the lower and upper boundary of the terminating units as their lower and upper boundaries. They are numbered in order of increasing age. This situation gives an opportunity for the definition of older 'Super-units' following improvements in understanding of the stratigraphy of older sequences.

3.1. The synthetic Mošorin/StariSlankamen loess-palaeosol type section

The most detailed stratigraphical record in the Danubian loess, in terms of number of studies undertaken and data currently available, comes from the combined sections in the wider ‘Titel loess plateau’. The three main sections (including the Mošorin section) are situated close to the village of Mošorin and the famous section at Čot, near Stari Slankamen, in the Vojvodina region of northern Serbia (Bronger, 2003; Marković et al., 2011, 2012a, 2012b) (Figure 11). These two localities are only 15 km distant from each other.

The Mošorin composite section is situated in the northern part of the Titel loess plateau (45°17-18'N and 20°12-15'E, top of the section is 120 m a.s.l.). The modern soil (S0) and the most recent three glacial loess units L1, L2, and L3 and palaeopedocomplexes S1, S2, and S3 are represented in profile Mošorin 1, located in the Veliki Surduk deep loess gully at the eastern edge of the village. The Mošorin 2 sub-profile, in the Feudvar loess gully, exposes the loess units L3 and L4, and pedocomplexes S3 and S4, and is situated 3 km west of the Mošorin 1 subprofile.

An important stratigraphic marker in the Mošorin 2 subprofile is the abrupt increase of MS in L4 loess unit, which is suggested to represent a tephra horizon. This is the probable equivalent to the Bag tephra identified in South Slovakia and Hungary (e.g. Pouchlet et al., 1999; Horváth, 2001; Bradák, 2009). Pouchlet et al. (1999) suggested that the Vulsini and Alban Hills (central Italian volcanic area) as likely sources of the volcanic ash, and it was correlated with Villa Senni Tuff, dated to around 350 ka. Although the lack of reliable glass chemical data for this tephra in the loess sections currently precludes a secure correlation, this age estimate fits very well with the age of the abrupt L4 MS peak in our proposed timescale. Finally, Mošorin 3 subprofile is exposed in steep cliffs near the Tisa River at Dukatar. It includes the lowermost loess–palaeosol sequences L5 and pedocomplex S5 at the base of the section (Figure 13). The site at Dukatar has been previously investigated by many researchers (Marković-Marjanović et al., 1972; Bronger, 1976, 2003; Singhvi et al., 1989; Butrym et al., 1991). The composite Mošorin section was reconstructed on the basis of the cross-matching pedo- and MS variations at the sections. The total thickness of Mošorin composite sequence is 47.3 m. As a result of the unusually high accumulation rates, this is one of the most detailed European loess records covering the last five glacial–interglacial cycles.

The completeness of the last five glacial/interglacial cycles at the Mošorin section was tested by comparison with the Batajnica loess–palaeosol sequence. These two sites are approximately 45 km apart. The Batajnica loess section occurs about 15 km northwest of Belgrade (44°55'29"N; 20°19'11"E; top of the section is 111 m a.s.l.). Similar to the Mošorin composite section, the composite Batajnica section was reconstructed on the basis of inter-profile correlation, using pedo- and MS stratigraphy. The total thickness of the Batajnica composite profile is 40.5 m, and the depth of the lower base of palaeosol S5 is 33.45 m (Marković et al. 2009b, 2012b). Despite being 45 km apart, the patterns of MS records are almost identical in these sections, although there are clear differences in the thickness of the stratigraphic units. Even some details, such as the appearance of highly weathered remnants of tephra shards, observed in the loess units L2 and L3 (very base) are identified at both sections (Figure 12). However, the latter layer has been missed at Titel when the sections were sampled in detail employing 5 cm sample spacing, but was undoubtedly visually identified when the sections were cleaned for the detailed description of palaeosols.

The Stari Slankamen profile (45^{o}07’58’’ N and 20^{o}18’44’’ E, top of the section is 130 m a.s.l.) is approximately 40 m thick. This section is located some 20 km south of the Mošorin locality (Figure 10). In this study we focus on the lowermost 14.3 m of the section that probably includes the oldest loess deposits of the region so far observed (Marković et al., 2011). Initial palaeomagnetic analysis indicates potential for palaeoclimatic reconstructions extending at least one million years. Details of field and laboratory investigations and of the current litho- and pedo-stratigraphical time scale are presented by Marković et al. (2009b, 2011, 2012a, 2012b).

The synthetic stratigraphic column from the Mošorin and Stari Slankamen (MSS) localities and their MS records are shown in Figure 13. Without doubt the synthetic MSS sequence is the most complete in the DB.

3.2. Stratigraphic status of interstadial palaeosols

Designating the stratigraphic status of interstadial or stadial units is more complex than higher order sub-divisions. Terrestrial sub-aerial clastic sedimentary records are characterised by unconformities and discontinuities of accumulation, which are frequently referred to as being disadvantageous in comparison to the supposedly more continuous ice, marine and lacustrine archives. Nevertheless, despite being subject to complexities such as variable accumulation rates and more dynamic environmental thresholds, loess-palaeosol sequences represent some of the longest and most continuous records of environmental change on land. Global climate change initiates spatially and temporally diverse regional terrestrial responses. The precise timing of climatic terminations does not necessarily occur coevally with the dated boundaries of loess and palaeosol units (Stevens et al., 2008; Marković et al., 2014c). This complicates the assignment of uniform stratigraphic schemes over wide areas at stadial-interstadial levels. Nonetheless, we consider this possible with detailed analysis of stratigraphic and age dating information.

An additional problem is that loess can very rapidly transform into sediment with an initial soil structure, or under extended periods, into a well developed soil. As a result of the significant palaeoenvironmental diversity over Danube region during the last glacial interstadial (MIS 3), the intensity of the pedogenic overprint on the local loess matrix was highly variable. As such, the character of the resulting palaeosol represents a wide variety of habitats from ancient analogues of modern boreal to Arctic brown soils (Antoine et al., 2013), to soils related to the parklands and grasslands in the Middle Danube (Marković et al., 2008; Schatz et al., 2011; Kovács et al., 2012), and to the dry steppe bioclimatopedo-zone soils in the Lower Danube lowland (Buggle et al., 2009).

This middle last glacial L1S1 unit is usually correlated with MIS 3 (a period between 24 and 60 ka, van Kreveldet al., 2000; Thompson and Goldstein, 2006). Recent luminescence chronological studies have generally confirmed this statement (Fuchs et al., 2008, 2013; Novothny et al., 2009; Stevens et al., 2011; Timar-Gabor et al., 2011; Constantin et al., 2014) presenting results that are in good agreement with MIS3 time frame. However, these results also suggest the occurrence of local sedimentary hiatuses within the L1S1 pedocomplex (Fitzsimmons and Hambach, 2014; Wacha and Frechen, 2011; Wacha et al., 2013; Fuchs et al., 2013). Loess sub-layers and the CI tephra intercalated in L1S1 preserve evidence of sudden changes in climatic and environmental conditions.

With the exception of the youngest loess sequences at Krems (Austria) (Hambach et al., 2008b; Terhorst et al., 2014), the formation and further preservation of palaeopedological and loessic horizons of the L1S1 pedocomplex could not be directly correlated with individual NW European interstadials, such as the Denekamp, Hengelo, Moershoofd or Glinde, or the Greenland Interstadials (GI) 8, 12, 13, 14, respectively. Thus, labelling of the third order stratigraphical units, such as L1S1S1or L1S1L1 in the present stratigraphic model, does not at this stage have chonostratigraphic significance. It just illustrates the morphological diversity of the L1S1 subunit in representing local environmental responses. In this case the labelling has a dynamic character. For example, the mid last glacial interval is represented in the Vojvodina region in northern Serbia by a weakly developed soil complex L1S1. This appears either as a single, complete pedohorizon (Ruma site), or as a double palaeosol (Batajnica, Irig, Mišeluk, Susek and Petrovaradin) or multiple (Stari Slankamen, Titel loess plateau and Crvenka) palaeosols (Marković et al., 2008). These sections are located inside an area of only 100 km diameter.

How can such diversity in the L1S1 pedocomplex structure over such a small distance under similar plateau-like deposition conditions be explained? During the last glacial period in the Vojvodina region, dry semi-arid conditions prevailed around the threshold between loess formation and initial pedogenesis and led to the formation of weakly developed pedological horizons (Marković et al., 2006, 2007; Hatté et al., 2013). This offers some explanation of why it is very hard to distinguish differences between loess and initial pedogenetic layers in these sections and why over short distances the same stratigraphical subunits have quite different expressions (Figure 14). These non-uniform environmental conditions are further accentuated by the fact that during the whole last glacial, or even the last interglacial, different types of the grassland vegetation predominated in different areas (Marković et al., 2008; Zech et al., 2013). Stratigraphically the position of the weakly developed palaeosols of the last glacial within the loess subunit L1L1 is also very interesting. Figure 14 shows the variable position of these initial pedogenetic horizons in three adjacent sections on the

Titel loess plateau, in spite of the unambiguous inter-profile correlation based on MS records. The characteristics are also considerably different from the upper last glacial record of the famous Dolní Věstonice section where loess is intercalated with several tundra gley palaeosols (Antoine et al., 2013). The tundra gleyed pedohorizons represent a cold wetland environment, but do not influence significant changes in the MS, grain size, carbonate, or organic carbon content variations.Some of the last glacial sedimentary intervals in Hungarian (Sümegi et al., 2012) and Austrian loess sections (Terhorst et al., 2014, 2015) also provide detailed records of environmental changes with exceptionally good age models. However, overall the Hungarian and Serbian embryonic palaeosols and Austrian and Czech tundra gley palaeosols reflect different short-term last glacial environmental dynamics across the basin. Thus, the last glacial DLPS cannot currently be directly linked with events in the Greenland ice-core stratigraphy, especially given age model limitations and accepted precision.

3.3. Is there a possible correlation between the Danube loess and Greenland ice-core event stratigraphy?

One of the most important palaeoclimatic discoveries in the last decades of the 20th century has been the identification of abrupt climate changes during the last glacial cycle in the North Atlantic region. These are now known as Dansgaard–Oeschger and Bond cycles, and Heinrich events (Bond et al., 1992, Dansgaard et al., 1993; Bond and Lotti, 1995). In the meantime, the specific patterns of short relative warm intervals known as Greenland Interstadials (GI) became a stratigraphic standard for the last glacial period (Björck et al., 1998; Blockley et al., 2012).

Recent results of the ELSA (Eifel Laminated Sediment Archive) project confirm the dominant climatic influence of the abrupt climatic events in the North Atlantic region and provide additional important environmental evidence that during the last glacial period the atmosphere over

Central Europe was permanently dusty (Sirocko et al., 2005, 2013; Seelos et al., 2009). The ELSA dust stack comprises the last glacial/interglacial period of the last 133 ka. The record indicates that the coldest periods of the last glacial cycle, MIS 4 (70 – 60 ka BP) and MIS 2 (29 – 14.7 ka BP), were characterised by relatively stable climate conditions related to the accumulation of homogenous dust sediments. Conditions during MIS 3 were generally dusty, but several periods of reduced dust deposition have also been detected over this interval. Even in MIS 5 high frequencies of dust storm events during the cold events C24 and C23 after the last warm stage (MIS 5e) have been detected (Sirocko et al., 2005, 2013; Seelos et al., 2009) (Figure 15).

The high level of correspondence between the dust records from the Greenland ice-cores and the Eifel maar lakes indicates a substantial opportunity for direct linkage between marine, ice-core and terrestrial records. However, recent reviews of central and eastern European climate over the last glacial period highlight how such correlations are substantially less well understood than in western European sequences (Feurdean et al., 2014). Thus, is it possible to correlate the DLPS and Greenland ice-core event stratigraphy? Seelos et al. (2009) reported evidence of continuous dust deposition during the last glacial period over Central Europe. Similar aeolian dust input was probably occurring over most of Europe during the last glacial. However, with the potential exception of several semi-continuous Danubian loess records, loess formation was not continuous at least on millennial timescales. These sedimentary interruptions are related to the nature of loess formation, a process controlled not only by atmospheric dust abundance but also by different local trapping, geomorphic and preservation conditions. This is a significant limiting factor for continuous loess deposition, as well as for suitable reconstruction of climatic and environmental dynamics.

However, despite these limitations some sedimentary intervals preserved in the Danube loess belt hold the potential for correlation with Greenland ice-core event stratigraphy (Blockley et al., 2012). The famous Dolní Věstonice site has long been believed to record the terrestrial equivalent of climatic oscillations known from marine and ice-core records (Demek and Kukla, 1969; Kukla and

Cilek, 1996). The lower part of the Dolní Věstonice sequence provides an exceptionally well-preserved soil complex composed of three chernozem palaeosols intercalated with five aeolian silt layers (Kukla (1975) defined these layers as a loess markers). This pedocomplex is the most complete record of dust response to environmental dynamics in the European loess belt for the period 110-70 ka. It has been proposed, based on luminescence ages combined with sedimentological and palaeopedological analysis, that this soil complex recorded all the main climatic events expressed in the North GRIP record from GI-25 to GI-19 (Antoine et al., 2013; Rousseau et al., 2013) (Figure 15). However, a great deal of questions still remain, not least whether the lowermost Bt horizon was effected by post depositional processes, and critically whether the luminescence chronologies are sufficiently precise to make the proposed temporal correlations with higher–resolution Greenland ice-core records. Given 1σ uncertainties on a luminescence age are at best 5% this equates to ±3.5-5.5 ka uncertainty, far too large to allow such fine correlations over this time interval. However, the argument lies over whether the sedimentological and palaeopedological evidence can be used to tune these age estimates sufficiently to allow correlation. These sudden environmental shifts represented by the appearance of the dust markers have great stratigraphic significance.

Bokhorst and Vandenberghe (2009) have extensively discussed the limitations of correlating short climatic oscillations recorded in the Greenland ice cores with loess records. They found that the reliability of tuning on the basis of the climatic proxy signal between two nearby loess sections should be considered carefully. They argue that a multi-proxy approach can strongly improve the validity of age tuning between two terrestrial records because this procedure may separate local from regional or global signals. However, the issue of the precision of age models is still critical here as the oscillation wave-length of a particular set of climatic shifts is often shorter than the errors on the age model, meaning that miscorrelations are statistically very likely and at the very least leads and lags are entirely lost.

Some sedimentary intervals of the Nussloch (Middle Rhine, Germany) loess-palaeosol sequence have also been directly correlated with Greenland stadial-interstadial cycles (Rousseau et al., 2002, 2007; Antoine et al., 2009b). The ^{14}C and luminescence chronologies suggest that the upper partof the Nussloch loess site corresponds to the interval starting with GI-8 (correlated with the Lohner Boden, see Zöller and Semmel, 2001), while the top loess unit is correlated with the sequence younger than the GI-2 in Greenland. The tundra gleys exposed at the site, G1a, G1b, G2a, G2b, G3, G4 and G7, were correlated to GI-7 to 2 in Greenland (Rousseau et al., 2007). Similarly, although less continuous and detailed, the late last glacial grain-size record at Dolní Věstonice shows strongly contrasting variations with numerous abrupt coarse-grained events in the upper part of the sequence spanning the interval between approximately 30 to 20 ka (Antoine et al., 2013). Similar, abrupt grain size compositional changes are also observed in sections over the Titel loess plateau and in Katymar in southeastern Hungary (Marković et al., 2008; Bokhorst et al., 2011). However, we are still far from achieving a valid correlation between the Greenland ice-core and the Danube loess records and similar reservations about timescale precision in the loess sequences apply to the last glacial of Nussloch and Dolní Věstonice.

3.4. ‘Super-units’ as higher order stratigraphical units

The long-term Plio-Pleistocene climatic variations indicate a gradual cooling trend associated with increasing amplitude of benthic δ^{18}O values over time (Lisiecki and Raymo, 2005; Rohling et al., 2014). Following the first significant cool phase related to MIS 22, several even cooler episodes occurred during MIS 16, MIS 12, MIS 6 and MIS 2. These events correspond to Danubian and Chinese loess units L9, L6, L7, L2, and L1 (more precisely L1L1), as well as to the Elsterian, Saalian and Weichselian ice advances. This synchronicity indicates a direct link between global climate changes recorded in the deep-sea sediments and northern ice-sheet and Eurasian dust deposition dynamics (Kukla and Cilek, 1996).

According to the palaeoenvironmental signature of preserved Danube loess record we can subdivide the six major higher order stratigraphical units ('Super-units'). These 'Super-units', generally coincide with 'Super-cycles' as defined by Kukla (2005). 'Super-cycles' were established in order to bring the classical continental stages into correspondence with the marine isotope stratigraphy. They are composed of more than one glacial-interglacial cycle, beginning with an initial interglacial phase and finishing with the next most substantial glacial period. Kukla (2005) compared the structure of these 'super-cycles' with an enlarged individual glacial-interglacial cycle. Thus, a 'Super-cycle', as defined by Kukla (2005), includes: an introductory interglacial (equivalent of an interglacial period in a classical interglacial/glacial cycle), the alternation of several lower but increasing amplitude glacials (representing early glacial conditions) and finally, the coldest glacial phase of 'Super-cycle' (corresponding to full-glacial conditions).

The oldest 'Super-cycle' 5 is probably an equivalent of the basal palaeosol complex in Stari Slankamen (Marković et al., 2011), the so-called the ‘Red Clay Formation’ at Viatovo (Jordanova et al., 2008) and the lowermost sedimentary interval in the Zimnicea borehole (Radan, 2012). These records represent several fused interglacial palaeosols, possibly reflecting more humid climate conditions during the latest part of the Early Pleistocene, and certainly a lower loess sedimentation rate (Figure 16). This 'Super-cycle' also corresponds to the palaeosols of L and K glacial cycles at the Red Hill, the discontinuous sequence at Krems (Kukla, 1975), and the loess-palaeosol column at Stranzendorf (Fink and Kukla, 1977; Kukla and Cilek, 1996) (Figure 2).

Subsequently the Danube loess stratigraphic 'Super-cycle’ 4 includes the oldest thick loess layer L9, closely spaced palaeosols from S8 to S6, separated by thin loess units, and finally the thick loess unit L6. In the Lower DB these palaeosols are more condensed, and include less pronounced silty layers. This 'Super-cycle' is composed of light yellowish-brown compact loess, partly affected by pedogenesis, interbedded with rubified palaeosols including large carbonate concretions.

The overlying 'Super-cycle' 3 consists of the oldest thick typical loess layer L6 and the strongly developed pedocomplex S5 which represents a long period from MIS 15 to 13. This distinct pedocomplex is noticeable at key exposures from the Alpine slopes to the Black Sea coast (Fitzsimmons et al., 2012). The main characteristic of this unit is a sharp environmental difference between the full-glacial loess unit L6, and the prolonged interglacial pedocomplex S5.

'Super-cycle' 2 is delimited by 'super-terminations' III and II, and coincides with terminations V and II. It begins with pedocomplex S4, an equivalent of MIS 11, and terminates with the penultimate glacial loess L2 (MIS 2). The loess units L4 and L3 are relatively poorly developed in comparison to the youngest loess layers L2 and L1. In contrast, the fossil interglacial pedocomplexes S3 and S2 are more strongly developed than the Holocene soil, but less than the S5 and S4 pedocomplexes.

The ‘Super-cycle’ 1 includes the last glacial-interglacial cycle or palaeosol S1 loess unit L1, as well a modern soil S0and is not likely to have terminated with a coldest glacial stage yet (Kukla, 2005). The average duration of the Danube loess 'super-units' is about 250 ka. Marković et al. (2012b) reported spectral analyses of orbitally tuned loess-palaeosol records the most prominent spectral peak of 256 ka indicating that the climate dynamics in Vojvodina is dominated mainly by the Earth's orbital eccentricity cycle. This observation is generally consistent with other Eurasian terrestrial records and could have continental significance. However, natural processes controlling the appearance of a 256 ka cycle in Eurasian continental records are still unknown (Basarin et al., 2014).

3.5. Advantages of the proposed Danube loess stratigraphic model

The advantages of this stratigraphic model over the existing, numerous European terrestrially based chronostratigraphies are as follows.

1. The proposed stratigraphic scheme is based on a type sequence – the composite MSS loess sequence. In this way the formal standard stratigraphic criteria required for chronostratigraphic schemes are fulfilled. This also brings European sequences in line with CLPS where the Luochuan section is considered the type-section for the Chinese Loess Plateau (Liu et al., 1985). Moreover, the type sequence provides a quasi-continuous (continuous at least on multi-millennial scale), high-resolution proxy record of the last eight glacial-interglacial cycles (Figures 5 and 13). This record can be regarded as one of the oldest, most detailed and complete European continental proxy archives. Hence, the composite MSS loess sequence offers the potential as a master sequence (or reference section) for the Danube area, if not for the European loess belt in general.
2. By using the same nomenclature that is already well accepted for CLPS, the chronological synchronization between the Danube and Chinese stratigraphic units is facilitated. Therefore, this novel stratigraphic scheme allows standardization of the previously region/country specific stratigraphies of European loess sections and offers greater potential for correlating the complex diversity of European loess stratigraphic records across the Eurasian loess belt and to Central Asian and Chinese sections.
3. The basis of the proposed system is much more transparent than many previously complicated national stratigraphic schemes. This is particularly important given the increasing focus on past dust cycling in climate literature. Hence, a unified chronostratigraphic scheme, greatly promotes the high potential of the DB loess sites for Quaternary and climate research to the geoscience community and for the first time allows the sequences to be used to their full regional and global context potential.

4. The use of multiple different national-based schemes has no basis in environmental, fluvial or aeolian similarities or differences. Furthermore, the terminologies used are often inconsistent, vary through time with new data and publications, and often use incompatible or overlapping nomenclature despite no implied genetic association. A unified scheme provides a consistent reference point upon which to base these national or local schemes and alleviates this confusion.

4. Direct comparison with the Chinese loess stratigraphical model

Eurasia is characterised by extreme continental climatic conditions in its inner part, with maritime climates on the margins, as well as significant climatic variability from north to south, and from west to east. These features give rise to 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 the periglacial and subarctic frozen loess zone in Siberia (e.g. Dodonov and Zhou, 2008; Marković et al., 2012a). The oldest, thickest and most complete loess-palaeosol successions are related to a great middle Eurasian semi arid loess zone. Spatially, this great continental loess belt spans approximately 45° and 30° N latitude, from the DB, through Central Asia (Kazakhstan, Uzbekistan and Tajikistan), across to the huge Chinese loess province.

The remarkable accordance between Danubian and Chinese loess records (Figure 5)opens up the possibility for a transcontinental correlation of European, Central Asian and Chinese loess sequences, using a standardised nomenclature and chronostratigraphic model. In the following discussion, we apply the unified stratigraphy of the DLPS for a direct correlation of two very distant loess regions, the Danube loess region, represented by the composite type sequence MSS, and the CLPS represented by the type sequence of Luochuan (e.g. Kukla and an, 1989; Hao et al., 2012). Bronger and co-workers (Bronger, 1976, 2003; Bronger and Heinkele 1989; Bronger et al., 1998) presented the first attempt at a transcontinental stratigraphic correlation between European and Asian loess regions. This correlation was based on palaeopedological investigations of palaeosols in the middle DB and the Chinese Loess plateau. These stratigraphic interpretations were revised in subsequent studies of Marković et al. (2011, 2012a). The main limitation of the earlier correlations was related to an idealised concept of the uniform response of such diverse terrestrial environments to global climate change. Even within the DB the nature of soil conditions is extremely diverse over time equivalent units, making correlation based only on pedostratigraphy extremely difficult(Figure 4).

Aeolian deposits in China extend to the base of the Miocene (Guo et al., 2002). The Basal complex in the DLPS, as represented in the MSS composite, is of Early Pleistocene age. In other parts of the DB region, the basal complex may extend to the Pliocene, but no older units have been detected (Kovács et al., 2013) and more research is needed on the lower part of the aeolian DB sequence. Hence, due to a significantly longer period of dust deposition and already high sedimentation rates during the Pliocene and Early Pleistocene, the total thickness of the aeolian deposits on the Chinese Loess Plateau tend to be greater than loess deposits in the DB (Marković, 2012a). However, from the latest part of the Early Pleistocene onwards it is possible to apply direct correlation between Danubian and Chinese loess records.

Figures 5 and 17 show the correlation between the MSS loess-palaeosol type sequence and the equivalent for the Chinese loess at Luochuan (Liu et al., 1985; Hao et al., 2012). Below we suggest that the loess chronostratigraphies in the Vojvodina region and in the central CLP from S0 to L9, correspond strongly. This transcontinental correlation reveals also that there are significant similarities between the magnetic records of northern Serbia and the central CLP. Not only is the general multi-millennial and longer pattern of MS variations almost identical in loess sections from DB and CLP but these distant MS successions often have a close correspondence on shorter timescales. This correspondence appears to be stronger than the correlation with the globally integrated marine records, potentially suggesting a similar response of continental climate to global changes that differs from shifting ice volume. This is well illustrated by the normalized MS records, plotted on a relative depth scale, for the Serbian and Chinese the Late Pleistocene and early Middle Pleistocene (Figure 17). What are the reasons for such high similarities over multi-millennial timescales between loess records from the DB plateaux and the Chinese loess plateau?

If we accept that the similarities are not solely a function of the way that MS is recorded and preserved in continental loess records, a similar environmental evolution needs to be postulated for these distant regions situated on opposite sides of the Eurasian continent. For example, several recent studies highlight corresponding trends of Pleistocene aridification in the DB as well as in the Chinese Loess Plateau (Marković et al., 2009b, 2011; Buggle et al., 2013, 2014). In any case, it is apparent that the similar nature of MS signal acquisition in the two regions provides the base for comparable environmental records based on magnetic signal enhancement via pedogenesis (Marković et al., 2012a). Bronger (2003) provided a direct comparison between the palaeopedological characteristics of the middle Danube loess sites and the Chinese Louchuan section. These comparative palaeopedological interpretations are a better fit after our modification of Bronger's initial stratigraphical subdivision. Based on these results, palaeosol units S11, S8, S7 and S5 at Luochuan (Bronger et al., 1998) are strongly developed and similar to their stratigraphic equivalents at Stari Slankamen: the strongly rubified basal pedocomplex, S8, S7 and S5. The palaeopedological characteristics of these units clearly differ from the temperate forest S4 palaeosols and the steppe-like interglacial pedocomplexes S3, S2 and S1 in Serbia and China. The apparently different climatic conditions under which the Danubian pedocomplexes developed are not only seen macroscopically, but also in their mineralogy, geochemistry and micromorphological properties (Buggle et al., 2013). A detailed analysis of the changes in palaeoenvironmental conditions in terms of temperature, rainfall and seasonality has been given by Buggle et al (2014) comparing the different interglacials from the early Middle Pleistocene to the present. Evaluating potential triggers of this aridification of interglacial periods, Buggle et al. (2013) suggested that progressively increasing dryness of the interglacials and cooling during glacials in the DB as well as other Asian loess regions reflects increasing continentality caused by Pleistocene surface uplift of Eurasian mountain ranges.Our proposed new stratigraphic scheme makes the geographical extent of this transition clear.

Simultaneously with this trend of interglacial aridification, the calculated accumulation rates in Danubian loess units also increase, indicating a concurrent trend to colder, drier and dustier glacial conditions. The thickest loess units in DB and China are L9, L6, L2 and L1. This observed intensity of dust deposition in the DBalso correlates to the Chinese loess accumulation dynamics (e.g. Hao et al., 2012), as well as with dust evidence from the EPICA ice-core from Dome C, Antarctica (Lambert et al., 2008). In addition it also parallels the trend to more intense glaciations indicated in the marine ice-volume indices (e.g. Lisiecki and 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, especially on the Eurasian continent in particular, and the Northern Hemisphere in general.

The second reason for the similarity of the DLPS and CLPS is climatic seasonality. Despite fundamental differences in dominant climate modes in the DB (temperate continental) and China (monsoonal), the significant imprint of the dry season’s influence on these distant loess records is similar between the records (Marković et al., 2012a). The presence of a marked dry season in both climate zones has been shown to have a fundamental control on the development of the magnetic mineral content by promoting the repeated reduction and then oxidation of the weathering horizon (Buggle et al., 2014).

The third factor influencing similarities between the Danubian and the Chinese loess records is the plateau-like deposition model, operating at least in the middle to lower parts of the DB. For example, the almost parallel position of the multiple loess-palaeosol sequences preserved in Danubian and Chinese loess plateaus indicate generally the same style of deposition (Marković et al., 2012a). This model implies almost continuous plateau topography throughout the history of both aeolian deposition and pedogenesis. According to existing relief and climate, erosional processes on the Danubian loess plateaus should be confined only to relatively small-scale landforms visibly related to the steep cliffs and gullies. A consequence of the significantly lower total thickness of Danubian compared to Chinese loess deposits is that the dimensions of the loess landforms are also proportionally smaller.

In spite of the general similarities, there are also some significant differences between these loess records. The absolute magnitude of these MS values is significantly higher in the CLPS than in the DPLS. The most likely reason for this is the higher background MS of the parent material.More importantly, contrary to the almost uniform amplitude of the absolute MS values in Danubian loess and palaeosol units, the Chinese palaeosols from S8 to S6 are significantly smaller in comparison to the younger fossil soils. Additionally, accumulation rates differ in the Danube Basin and China over this time interval. This can be recognised, when comparing the thickness of units L9 to L6, representing the time interval from about 650 to 900 ka, in the two type sections. However, regarding the five last glacial-interglacial cycles, the sedimentation rates at several key sites in the Danube area have at times been even higher than at Chinese key sections (Figure 5). Stevens et al. (2011) also noted specific differences between the Crvenka (Vojvodina, Serbia) and Beiguoyuan (Chinese Loess Plateau) climate and accumulation records on millennial time scales, notably in the timing of peak sedimentation and recording of abrupt fluctuations in MS and grain size. These differences suggests that while overall continental scale climate changes are relatively uniform, there are differences in the shorter, more abrupt events and in the climatic nature of certain periods. The nature and reasons for these differences is an exciting avenue of future research that should bring significant insight into the dynamics and forcing of regional scale climate in the context of global and hemispheric shifts.

5. Comparison to other European stratigraphic models

The development of the extensive Danube loess belt coincides with fundamental changes in Earth's climatic cyclicity during the so-called Early-Middle Pleistocene transition. (Marković et al., 2011). It is therefore logical that the general pattern of Danube loess stratigraphy should broadly correspond to these large-scale climatic and environmental shifts, as do other European stratigraphical systems such as the ones described below.

Two classical stratigraphical subdivisions, developed during the long tradition of investigations into European Pleistocene stratigraphy, are still mostly in use: the Fennoscandian or North European, and the Alpine classification schemes. The North European Pleistocene stratigraphical scheme has several regional subdivisions in Britain, the North Sea basin, Poland and Russia (van Gijjsel, 2006; Figure 18). Kukla (2005) questioned this approach by asking whether these classical European stratigraphical systems that are pieced together from discontinuous sets of glacial moraines, river terraces and marine transgressions are comparable with the more continuous marine, ice-core or loess stratigraphical records. Under this interpretation, previous discrepancies between European stratigraphic subdivisions have occurred because of the different expressions of the basic Pleistocene climatostratigraphical units (the glacials and the interglacials) and their interpretation in local, discontinuous geological records.

Across northern Eurasia, the first major glacial event recorded in the lowlands is represented by the Hattem Beds of the Netherlands, which are related to the Menapian Stage, or ~MIS 36-34 (Laban and van der Meer, 2004). In upland areas, Scheidt et al. (2015) demonstrate that the onset of the Alpine glaciation started just after the Gauss-Matuyama boundary, as evidenced by changes in the characteristics of deposits of the River Rhine.

Collective evidence from all the northern continents indicates that MIS 22 is the first major cold-climate period when large boreal regions of North America, Eurasia and most of the European

Alpine area were significantly glaciated (Head and Gibbard, 2005). This glacial advance event coincided with the deposition of the first relatively thick loess L9 in the DB, hinting at the potential of loess accumulation to derive information on the intensity of European glaciations where no direct stratigraphic or geomorphic record is preserved.

There is relatively weak direct evidence of glaciations during MIS 20 and 18 in marine and terrestrial records (Lisiecki and Raymo, 2005; Tzedakis et al., 2006). However, the glaciation during MIS 16 corresponds to the Donian Stage glaciation which is characterised by first significant ice advance in large parts of Europe. This is one of the most extensive cold phases yet experienced in the Northern Hemisphere during the mid-Pleistocene transition. These global ice volume variations (Head and Gibbard, 2005) also correspond well with the Danube loess record. Thin loess units L8 and L7 contrast with the thick typical loess layer L6, corresponding to MIS 20, 18 and 16, respectively (Figure 13).

The extended MIS 15 to 13 interglacial intervals in the marine record,(Lisiecki and Raymo, 2005), associated with the Danubian pedocomplex S5, were followed, during MIS 12, by another extensive glaciation in Europe, known as the Elsterian (Anglian, San 2 or Oka) (Head and Gibbard, 2005; van Gijjsel, 2006; Gibbard and Cohen, 2008). During MIS 12, evidence for the oldest glaciers in the Mediterranean mountains also appears (Hughes et al., 2006, 2010, 2013; Kuhleman et al., 2008). This significant continental ice advance is related to the anomalously thick loess unit L5 in the Danubian loess, again reinforcing the link between loess accumulation in the basin and glacial intensity. This is also similar to the CLP record, where a strongly developed palaeosol S5 and relative thick loess horizon L5 is represented in the time equivalent record (Figure 5).

The glaciations of MIS 10, 8 and 6 are classified as parts of the large, polycyclic Saalian (Rissian) glaciation in Europe. The MIS 10 and 8 glacial phases were characterised by the relatively weak growth of continental ice, as shown by evidence for reduced ice extent in marine and ice-core records (Kukla, 2005). By contrast, the MIS 6 glaciation (the coldest interval of Saalian, Wolstonian, Odrainan, Dniepr or Rissian III phases) is very strongly expressed in the marine record. During MIS6 the advances of Eurasian ice margins were significantly more southerly than during the last glacial period (Weichselian and equivalents) (Head and Gibbard, 2005). Again, global pulses of glacial ice advance took place coevally with increased dust deposition, represented by the relatively thin Danubian loesses L4 and L3 corresponding to MIS 10 and 8, as well as the relative thick penultimate glacial loess L2 as an equivalent of MIS 6 (Figure 12 and 13).

Finally, the last glaciation (Weichselian) begins with an early glacial, cool and dry MIS 5d event indicating initial ice advance and sea level drop (Sirocko et al., 2005). Global ice volume then continued to gradually increase, culminating in two periods with maximal ice extension during MIS 4 and finally with the last glacial maximum during MIS 2 (Lambeck and Chappell, 2001). The greatest thickness of the Danubian loess deposits formed during this period, especially during the cold MIS 4 and 2 intervals associated with the lower and upper last glacial subunits L1LL2 and L1LL1. Finally, after the termination of the last glacial, dust covered almost the whole basin, which was pedogenically altered during the Holocene (Flandrian or Postglacial) to form the modern soil (S0). Strong erosion by the Danube River and its tributaries also began, which has greatly reduced the distribution of loess sediments and uncovered the profiles that we study today.

6. Possibilities for further improvements of the Danubian loess stratigraphic model

In spite of the significant improvements related to understanding the stratigraphy of the Danube loess belt presented above, there are several important limitations that currently exist in our stratigraphic interpretations. The most important issue is the limited number of known sections containing long-term loess-palaeosol successions. The key sections such as those at Red Hill (Červeny Kopec), Krems (Schießstätte), Stranzendorf, Mende, Basaharc, Paks, Dunaföldvár, Süttő, Stari Slankamen, Batajnica and Stalać have been known for some time. However, some of these crucial sections have since been destroyed. After a long period of exploitation and excavation of construction material in the Red Hill brickyard, the majority of the loess-palaeosol units are now missing. Apart from this destruction caused by human activity, loess sequences are also highly vulnerable to erosion. The realisation of this has recently resulted in the preservation of some sequences as unique geoheritage sites (Vasiljević et al., 2011a, 2011b, 2014). However, the question of why there are so few long-term loess depositional site preserved in Europe is an open question. It may also offer an alternative explanation for the increasing sedimentation rates in loess units seen in the Danubian deposits. Other serious limitations are the spatial differences in structure and resolution of contemporaneous stratigraphical units across the Danube loess belt, problems related to identification of magnetic reversals and the difficulties associated with dating sequences beyond the range of luminescence dating techniques. Additional problems arise from the variability in accumulation rates of the individual strata due to site-specific influences and the welding of palaeosols into complexes which cannot be distinguished as representing either multiple interglacial or interstadial phases. High-resolution conversion of the litho- and pedostratigraphy to a chronostratigraphy is limited by the methodological restrictions on the precision of dating techniques.

Fortunately, some of the problems may be solved in forthcoming years through methodological advances and the discovery of new loess profiles. Recently, several important exposures such as those at Ruma and Nosak in Serbia (Marković et al., 2006, 2014b), Ljubenovo and Viatovo in Bulgaria (Jordanova et al., 2007, 2008) and Mircea Voda in Romania (Buggle et al., 2009; Timar et al., 2010) have been promoted as new important sites while advances in luminescence techniques, for example, have greatly improved the accuracy of the Danube loess stratigraphy beyond the last glacial cycle (e.g. Thiel et al., 2011).

6.1. Towards a detailed tephrochronostratigraphy for Danubian loess

Tephrochronology provides an important stratigraphic tool for linking, dating, and synchronising geological, palaeoenvironmental and archaeological sequences or events. Volcanic ashes deposited within loess have the potential to act as reliable marker horizons across loess sequences, particularly when chemically tied to specific eruptions, and precisely dated (Lowe, 2011). Pioneering tephrostratigraphic investigations have been applied to DLPS (Pouclet et al., 1999; Horvath, 2001), however, as the region is favourably located in the dispersal area of several major volcanic fields, including the nearby Carpathian, western and central European eruptive zones, and the more distal, but exceptionally productive, central and eastern Mediterranean volcanic provinces, the full potential of this technique has yet to be exploited (Veres et al., 2013b; Fitzsimmons et al., 2013).

The Middle Pleistocene Bag tephra is distributed from southern Slovakia, over the Great Hungarian plain (Pouclet et al., 1999; Horváth, 2001), and potentially extends to the Vojvodina region in northern Serbia where a thin dark layer of anomalously high MS is located in L4 at approximately the correct stratigraphic level (Marković et al., 2012a, 2012b). Recently, a remnant of a tephra unit (represented by ghost structures of volcanic glass shards and weathered mafic minerals) has been identified in the penultimate glacial loess L2 at several Serbian (Marković et al., 2009b, 2012a) and Croatian (Wacha and Frechen, 2011) sections. Moreover, initial rock magnetic investigations indicate the potential occurrence of crypto tephras, such as in the upper part of the distinct pedocomplex S5 at Batajnica and Mošorin sections (Marković et al., 2012a). However, all these layers lack reliable glass chemical data that makes comparison between records only tentative. In this context, one of the most useful marker horizons is the Campanian Ignimbrite (CI/Y5), which originated in the Campi Flegrei region of central Italy around 39 ka (e.g. De Vivo et al., 2001; Giaccio et al., 2008). The fine ash of this this eruption spread in a plume eastwards and northeastwards as far as North Africa, the eastern Mediterranean and the Russian Plain (Costa et al., 2012). It is at the moment one of the most important chronologic/stratigraphic markers of western

Eurasia and provides an independent basis for establishing age-depth relationships for the enclosing deposits. Recent geochemical finger printing research coupled with luminescence dating identified unexpectedly thick CI occurrences within both the loess unit L1 and in alluvial sequences in southern Romania (Veres et al., 2013b; Constantin et al., 2012; Fitzsimmons et al., 2013; Fitzsimmons and Hambach, 2014).

The numerical Ar/Ar age of the CI tephra (De Vivo et al. 2001) means that it also provides a particularly useful independent age control for assessing the accuracy of loess luminescence dating (Timar-Gabor et al., 2011). Quartz OSL age estimates obtained at several sites match the known age of the eruption (Constantin et al., 2012, Fitzsimmons et al., 2013, Anechitei-Deacu et al., 2014), and confirm the reliability of luminescence dating using a variety of protocols. These results highlight the important role that tephra layers could play as marker horizons at sub-continental scale, provided that the potential tephra layers mentioned previously are more thoroughly investigated, both chemically and chronologically (Veres et al., 2013b).

The known distribution of stratigraphically significant tephra horizons in the DB is summarised in Table 3 and Figure 19. It is certain that this database will be expanded in the near future and thereby provides an independent chronological framework. Figure 19shows our current knowledge of the spatial distribution of the major tephra layers preserved in the Danube loess.

6.2. Dating of a loess sequences by relative geomagnetic palaeointensity

Application of relative geomagnetic intensity to dating the Danubian loess-palaeosol sequences is a new approach (Hambach et al., 2008b; Zeeden et al. 2009, 2011; Fitzsimmons et al., 2013; Rolf et al., 2014). Although these studies only provide results for the Late Pleistocene loess-palaeosols sequences, dating by this chonostratigraphical approach also indicates the great potential for defining a valid chronology for older loess-palaeosol sequences. The well-known temporal pattern of the

Earth's magnetic field intensity variations, on time scales from 10^4 to 10^7 years, provides an excellent independent tool for stratigraphical subdivision and correlation, although there are ambiguities if the studied sequences are fragmentary or contain sedimentary hiatuses that are poorly understood. The record of variations in the intensity of the Earth's magnetic field also serves as a dating tool and has been successfully applied to various sedimentary archives (e.g., Tauxe, 1993; Roberts et al., 2013; Rolf et al., 2014). Hambach et al. (2009) applied the relative palaeomagnetic intensity to the lower part of the Stari Slankamen section. The relative palaeointesity record from Stari Slankamen matches the palaeointensity of Earth's magnetic field for the past 4 Ma relatively well (the data are expressed as the virtual axial dipole moment (VADM)). The relative palaeomagnetic intensity record matches the VADM model published by Valet and Meynder (1993) quite well, and is a much better match to the chonostratigraphical interpretation based on MS correlation, rather than the palaeomagentic polarity directional evidence where lock-in effects and signal stability strongly impact the record.

7. Conclusions

Some of the most important events in the history of loess research occurred in the DB loess region. Through his description of the DLPS, Kukla (1977; 1978) created the glacial-interglacial cycle palaeoclimatic paradigm in loess research, and provided an opportunity for direct Pleistocene land-sea correlations. However, over the following decades, the majority of research interests have been shifted to the CLPS, generally accepted as the most important global terrestrial record of Quaternary climatic and environmental changes. What are the reasons that Chinese loess became a much more globally important palaeoclimatic record than DLPS? Although the fact that the Chinese loess is both older and usually thicker than the DLPS will undoubtedly have contributed to its dominance, it appears that the crucial limitation for wider use of the DLPS in global palaeoclimatic studies stems from complicated separate national stratigraphic models employed in the basin. The classical loess stratigraphies used for DLPS subdivisions still use a total of 14 different letters of alphabet and are very confusing even for loess specialists. It is evident that future DB loess research needs simplified chronostratigraphic model following the well-accepted Chinese loess stratigraphy.

We propose a DLPS climato-, chrono- and pedo-stratigraphical model based on the widely accepted chronology of the main Pleistocene global palaeoclimatic variations. The major stratigraphic formations are designated on the basis of significant environmental shifts affecting the area during the uppermost Matuyama Chron, about 850 ka, and after two intense glacial episodes; MIS 16 and 12 at about 650 ka and 450 ka, respectively. These are recorded in the changing properties of the stratigraphic units, such as: sedimentation rates, as well as environmental expressions of the palaeosol and loess units.

This is the first basin-wide integrated stratigraphical approach to Danubian loess and highlights the importance of the sequences as the most complete long-term, and spatially extensive Pleistocene terrestrial sedimentary recordin Europe. These sequences and the proposed model provide a unique opportunity to fill in gaps within other European continental Pleistocene records and related stratigraphical subdivisions, as well as to link regions with diverse climates. In terms of the time span and continuity of these loess sections, the chronostratigraphy of DB loess sites, especially the composite key section MSS, have the potential to serve as master sequences for Pleistocene glacial – interglacial changes in Europe.

Contrary to the ice records, deep-sea or lacustrine sediments that are characterised by more or less continuous sedimentation, loess-palaeosol sequences are more complex depositional systems with significantly different accumulation rates, more dynamic environmental thresholds and higher sensitivity to erosion. Thus, beyond the last two glacial-interglacial cycles when luminescence techniques are not available, valid correlations on regional or even continental scale are only possible on the level of first order units (i.e. MIS or glacial loess and interglacial pedocomplex units).

However, rapid improvements in numerical dating techniques, associated with tephrochronological approaches, may yet improve our understanding of the DLPS chronostratigraphic mosaic over forthcoming years.

Finally the proposed Danube loess chronostratigraphical model can be regarded as an important step towards the development of a transcontinental Eurasian stratigraphic system. This opens up possibilities for detailed temporal and spatial environmental reconstructions across the largest continent on Earth and the initial relationships explored here hint at significant future developments for our understanding of loess depositional systems and terrestrial responses to global climate changes over a wide area.

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Table and Figure Captions

Table 1. Varying chronostratagraphic models proposed for the Stari Slankamen loess-palaesol sequence by different researchers and their comparison to the traditional Alpine subdivision (Bronger, 1976) and MIS stratigraphy (Singhvi et al., 1989; Butrym et al., 1991; Bronger, 2003; Marković et al., 2011).

Table 2. The proposed Danube loess stratigraphic model, covering the last approximately one million years, and its relation to the Chinese loess record, marine isotope stratigraphy, glacial cycles and national loess stratigraphies in the Czech Republic (Kukla and Cilek, 1996), Austria (Scholger and Terhorst, 2013), Hungary (Sartori et al., 1999; Újvári et al., 2014, modified), Serbia (Marković et al., 2011), Romania (Buggle et al., 2009) and Bulgaria (Jordanova et al., 2008).

FIGURE CAPTIONS

Figure 1. A) Distribution of the loess sediment across Europe with reconstruction of the continental ice caps and sea level during the last glacial maximum (modified from Moine et al. (2002), Rousseau (2001) and Marković et al. (2007)) and the permafrost zone (Vandenberghe et al., 2004). Key: 1) Loess; 2) Ice caps; 3)Area of the modern Danube Basin;4) Dry continental shelf; 5) Boundary of permafrost zone south of the Alps.B) Topographic map showing the locations of the main Middle Pleistocene loess sites in the Danube Basin.

Figure 2.Alternative correlation of the loess palaeosol stratigraphy in central China, Xifeng section (Liu et al., 1985), with Red Hill (Cerveny Kopec), Krems and Stranzendorf in central Europe (Fink and Kukla, 1977; Rebeder, 1981), following Kukla and Cilek (1996). Depth scale is plotted from the profile topographic surface. Earlier polarity interpretations are modified(Kukla and Cilek, 1996).

Figure 3. Comparison between the Matuyama/Brunhes Boundary position indeep-sea sediments (Lisiecki and Raymo, 2005) and key loess sections in DB: Paks (Sartori et al., 1999) and Red Hill (Forster et al., 1996), Stari Slankamen (Marković et al., 2011) and Koriten (Jordanova and Petersen, 1999).

Figure 4. Correlation of the MS records from the longest measured loess profiles in the Danube Basin region, extending to MIS 21, along with the global Plio-Pleistocene stack of Lisiecki and Raymo (2005). Loess records are illustrated in terms of location, from the most upstream (Paks, Hungary) to the most downstream (Mircea Voda, Romania) in the basin and are presented as follows: composite profile, Czech Republic (Forster et al., 1996) Paks (Sartori et al., 1999), Ruma

(Marković et al., 2006), Stari Slankamen (Marković et al., 2003, 2011), Batajnica (Marković et al., 2009b), Koriten (Jordanova and Petersen, 1999), Viatovo (Jordanova et al., 2008), Mostistea (Panaiotu et al., 2001), Mircea Voda (Buggle et al., 2009; Timar-Gabor et al., 2011) and Zimnicea (Radan, 2012). χ denotes mass specific low field initial susceptibility. The grey shading denotes the inter-profile correlation of the magnetic susceptibility pattern of the main pedocomplexes across the Danube loess belt.

Figure 5. Direct correlations between the Mošorin and Stari Slankamen synthetic (MSS) loess-palaeosol sequence and the Louchuan loess type section on the Central Chinese Loess Plateau (Hao et al., 2012). Dark grey zones labelled S*n* represent well-developed palaeosols/pedocmplexes, white zones labelled L*n* represent typical loess units and light grey zones (unlabelled) represent weakly developed palaeosol/pedocomplexes. The uncertain stratigraphic interval in the transition between L2 and S2 units is indicated with "?".

Figure 6. Summary of the national loess stratigraphy nomenclatures from Austria, Czech Republic, Slovakia, Hungary (Oches and McCoy, 1995a, 1995b, 1995c) and Serbia (Marković et al., 2004a, 2004b, 2005, 2007, 2011). Proposed correlation with the deep-sea oxygen isotope stratigraphy and glacial cycle designations are also shown (after Kukla, 1977). Termination ages are from SPECMAP (Bassinot et al., 1994).

Figure 7. Total acid hydrolosate D-alloisoleucine/L-isoleucine aminostratigraphy of the Danubian loess. The values are compared between Danubian localities for the older part of the B glacial cycle (MIS 2-5), as well as glacial cycles C (MIS 7-6) and D (MIS 9-8) for the terrestrial land snail *Pupilla*. SRB = Serbia, H = Hungary, A = Austria, SK = Slovakia, UA = Ukraine, D = Germany and

CZ = Czech Republic (Oches and McCoy, 1995a, b, c, 2001; Oches et al., 2000; Marković et al., 2008, 2011). Countries are presented in approximate order of decreasing mean annual temperature.

Figure 8.Results of the luminescence dating and AAR relative geochronology at Stari Slankamen. Legend: I. Luminescence dating by Murray et al. (2014); II. Luminescence dating by Schmidt et al. (2010); III. Pupilla D/L Glutaminic acid ratios; IV. Linearly plottedage model based on the proposed chronology of the main Terminations (Aitken and Stokes, 1997); EL – erosional layer.

Figure 9. Results of fine (4-11µm) quartz (Timar et al. 2010) and coarse (63-90 µm) quartz SAR OSL dating (Timar-Gabor et al. 2011), as well as post IR-IR$_{225}$ using polymineral fine grains (Vasiliniuc et al. 2012) ages on the MirceaVoda section. Fine and coarse quartz dates are represented by red squares and blue circles respectively, while upside-down triangles represent post IR-IR$_{225}$ dating.Ages are compared toanage depth model based on magnetic susceptibility measurements. The inset gives an expanded view of the luminescence ages in L1.

Figure 10. Log of the composite profile of Paks in Hungary and pIR-IR$_{290}$ ages. The grey shaded areas show MIS 3, 5, 7, and 9 respectively. The three lowermost age estimates have to be interpreted as minimum ages because the pIR-IR$_{290}$ signal is close to saturation. Note the break in the age axis (Thiel et al., 2014).

Figure 11. Location of the Mošorin and Stari Slankamen loess sites (i.e. 1 = Veliki Surduk, 2 = Feudvar, 3 = Dukatar, 4 = Rogulićev Surduk, 5 = Stara Ciglana). Embedded legend shown in Fig. 1and represents A) Investigated sections; B) Contours (m); C) Settlement; D) Rivers.

Figure 12. Comparison between MS records of the Batajnica (Marković et al., 2009b) and Mošorin sections in Serbia with map showing distance between these sections (Marković et al., 2012b).

Figure 13. Comparison between MS record and palaeopedology of Mošorin and Stari Slankamen synthetic (MSS) loess-palaeosol sequence related to equivalent stratigraphic units. Legend: I. Loess; II. Embryonic pedogenic layer; III. A horizon; IV. Ah horizon; V. B horizon; VI. Bwt rubified horizon; VII. sand beds; VIII. possible tephra layers; IX. Hydromorphic features; X. carbonate concretions; XI. krotovinas (Marković et al., 2012b, modified).

Figure 14. Comparison between pedostratigraphy and MS records of the Late Pleistocene Mošorin Big gully (Marković et al., 2012b), Mošorin Rogulić gully and Titel old brickyard (Bokhorst et al., 2011, modified) sections plotted on the same depth scale. The positions of luminescence samples are indicated with arrows with related IRSL dates (Bokhorst et al., 2011). The location of these three sites is shown in Figure 11.

Figure 15. Comparison of climate proxy records for the period 132 – 0 ka: (a) North GRIP δ18O-record as a temperature proxy for the last glacial cycle in Greenland; (b) the North GRIP microparticles record, measured particle diameters; (c) ELSA dust detection stack as a normalized probability record; (d) frequency of single dust storms in a 100-years-segmentation from the ELSA stack; (e) the coverage of the four core sequences of the ELSA stack, SM3 is a sediment core of a recent maar lake, DE3, OW1 and HL2 are cores from dry maars; (f) radiometric dating:AMS 14C and OSL and tephrochronology as age control for the ELSA stack (Seelos et al., 2009); (g) combined grain-size records from Madaras (Bokhorst et al., 2011), Titel (Bokhorst et al., 2011) and Dolni Vestonice (Antoine et al., 2014);(h) the coverage of the three loess sequences used for grain-size records in (g).

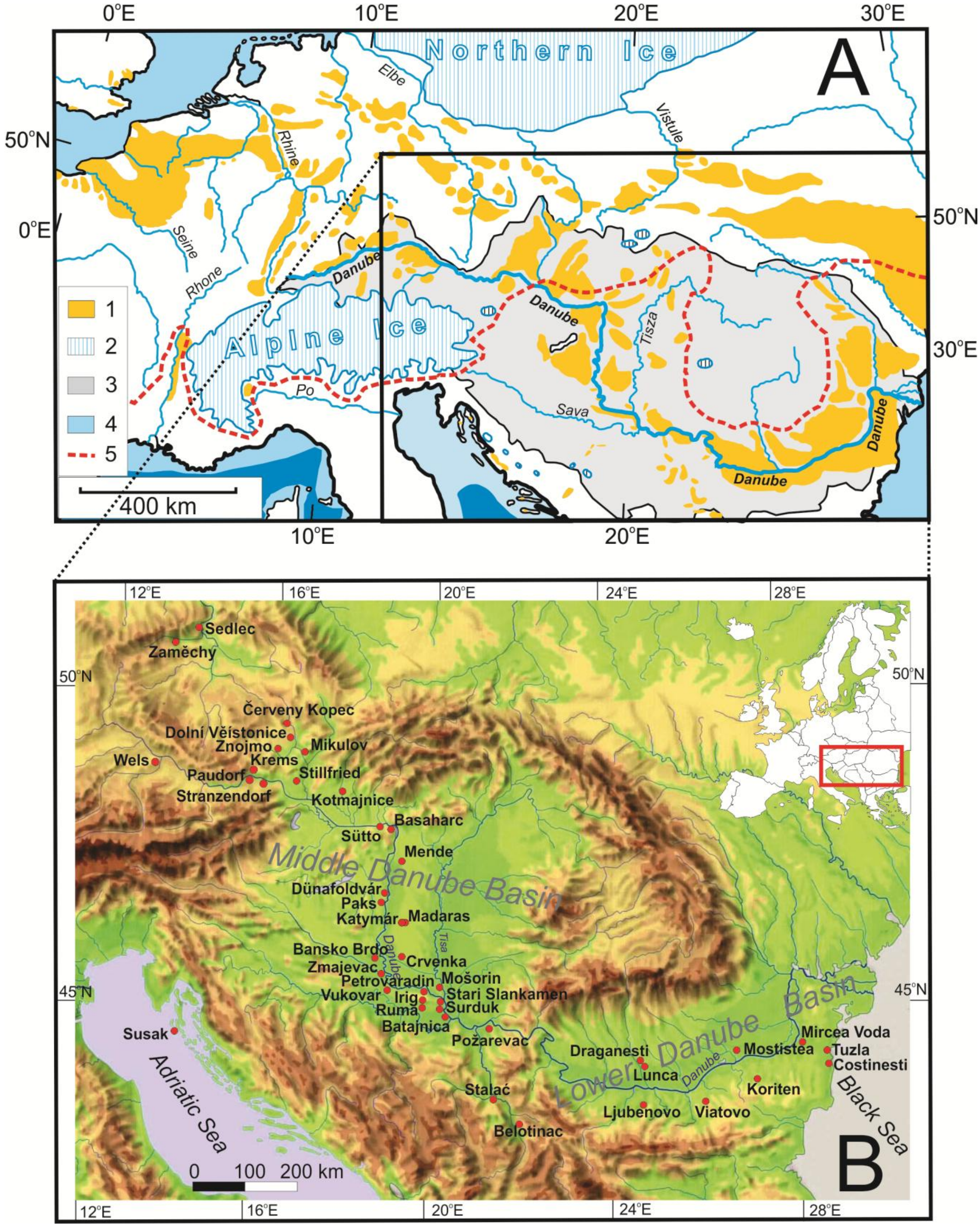
Figure 16. Danube loess stratigraphic Super-units presented as variations of the MIS record plotted on a time-scale compared with the LR04 stack (Lisiecki and Raymo, 2005) and Chinese MIS record (Sun et al., 2006).

Figure 17. Comparison of normalised MS records of the Mošorin and Stari Slankamen synthetic (MSS) loess-palaeosol sequence (lower, thicker line) and the Louchuan loess type section (upper, normal line) on the Central Chinese Loess Plateau (Hao et al., 2012) during the Late Pleistocene (A), and over the interval between S6 and S8 (B).

Figure 18. Overview of the European terrestrial Pleistocene stratigraphical schemes and terminology (van Gijssel, 2006) compared with our proposed Danube loess stratigraphic model.

Figure 19. (A) Geographical distribution of the sites with identified tephra layers. Legend: I) Campagnean Ignimbrite (CI/Y5) tephra; II) L2 tephra; III) Bag tephra according to Horvath (2001), modified. (B) Map of Europe showing the spread of CI/Y5 tephra according to Costa et al. (2012), as well as our hypothesised potential spread of the L2 and BAG tephras. Note that these are based on location of sites where these tephra layers have been observed (Fig 19A). Dashed lines represent the current known extent of each tephra; coarse-dashed line = known distribution of the CI/Y5 tephra, medium dashed line = known distribution of the L2 tephra, fine dashed line = known distribution of the BAG tephra.

Figure 1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Northern Ice
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Mikulov
Wels
Krems
Paudorf
Stillfried
Stranzendorf
Kotmajnice
Basaharc
Sütto
Mende
Middle Danube Basin
Dünafoldvár
Paks
Katymár
Madaras
Bansko Brdo
Danube
Tisa
Crvenka
Zmajevac
Petrovaradin
Mošorin
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Irig
Ruma
Surduk
Batajnica
Požarevac
Susak
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Draganesti
Lunca
Lower Danube Basin
Danube
Mostistea
Mircea Voda
Tuzla
Costinesti
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Figure 2

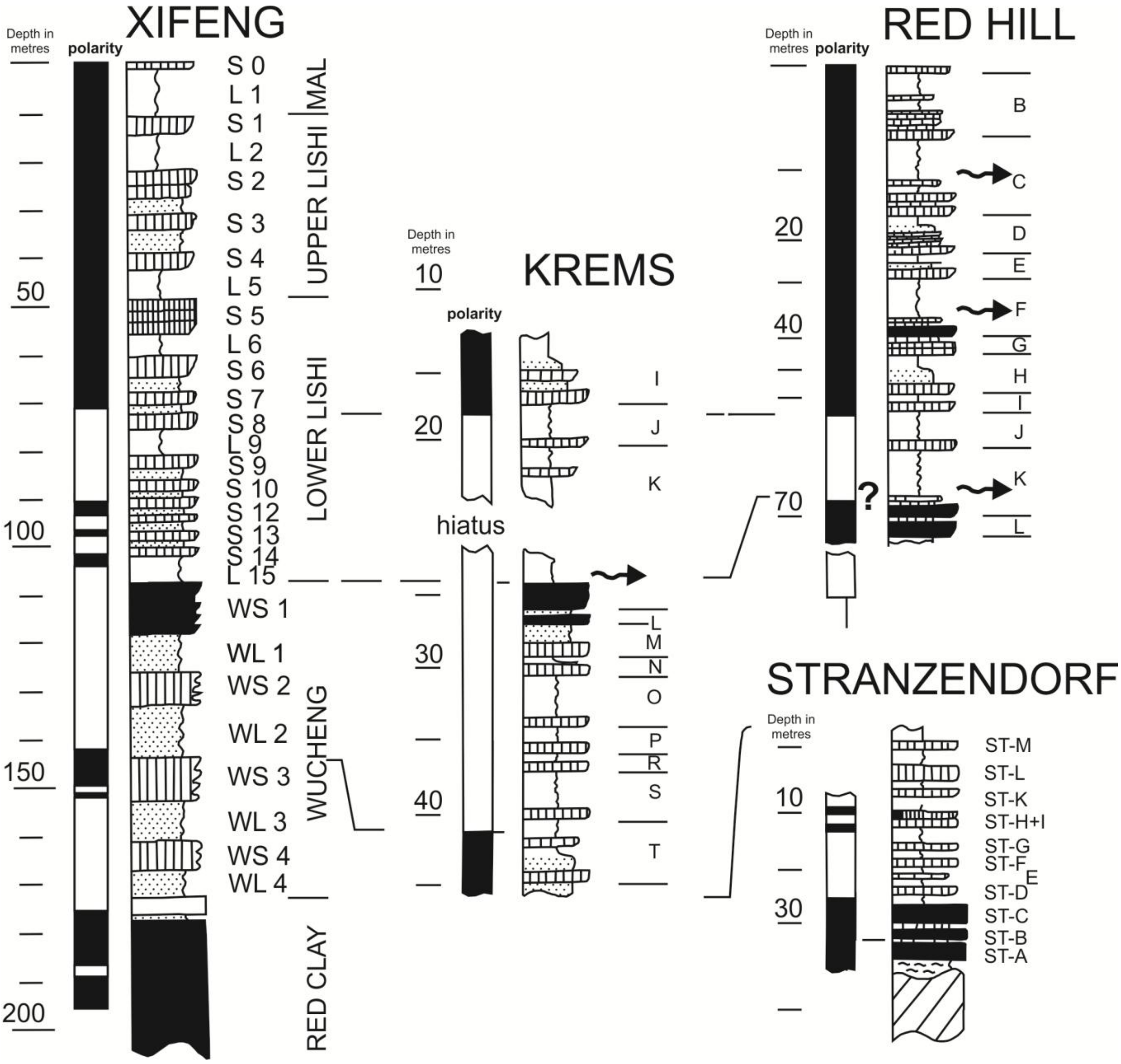
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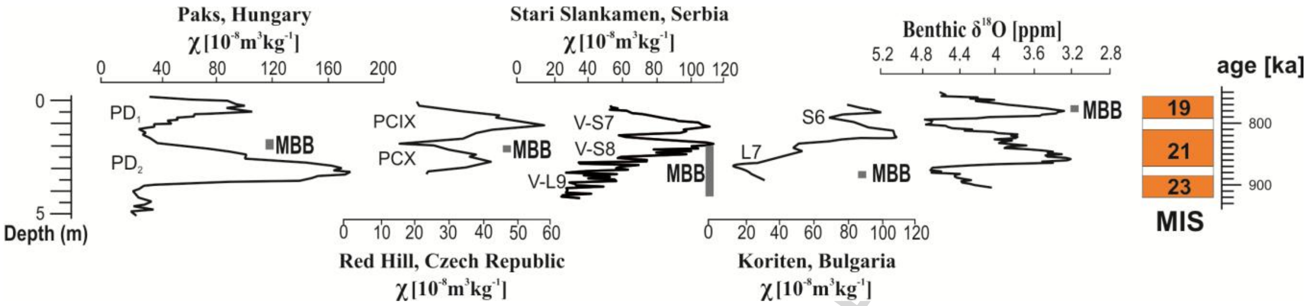
Figure 3


Paks, Hungary
χ [10⁻⁸m³kg⁻¹]
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Red Hill, Czech Republic
χ [10⁻⁸m³kg⁻¹]
Stari Slankamen, Serbia
χ [10⁻⁸m³kg⁻¹]
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V-S7
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Koriten, Bulgaria
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Benthic δ¹⁸O [ppm]
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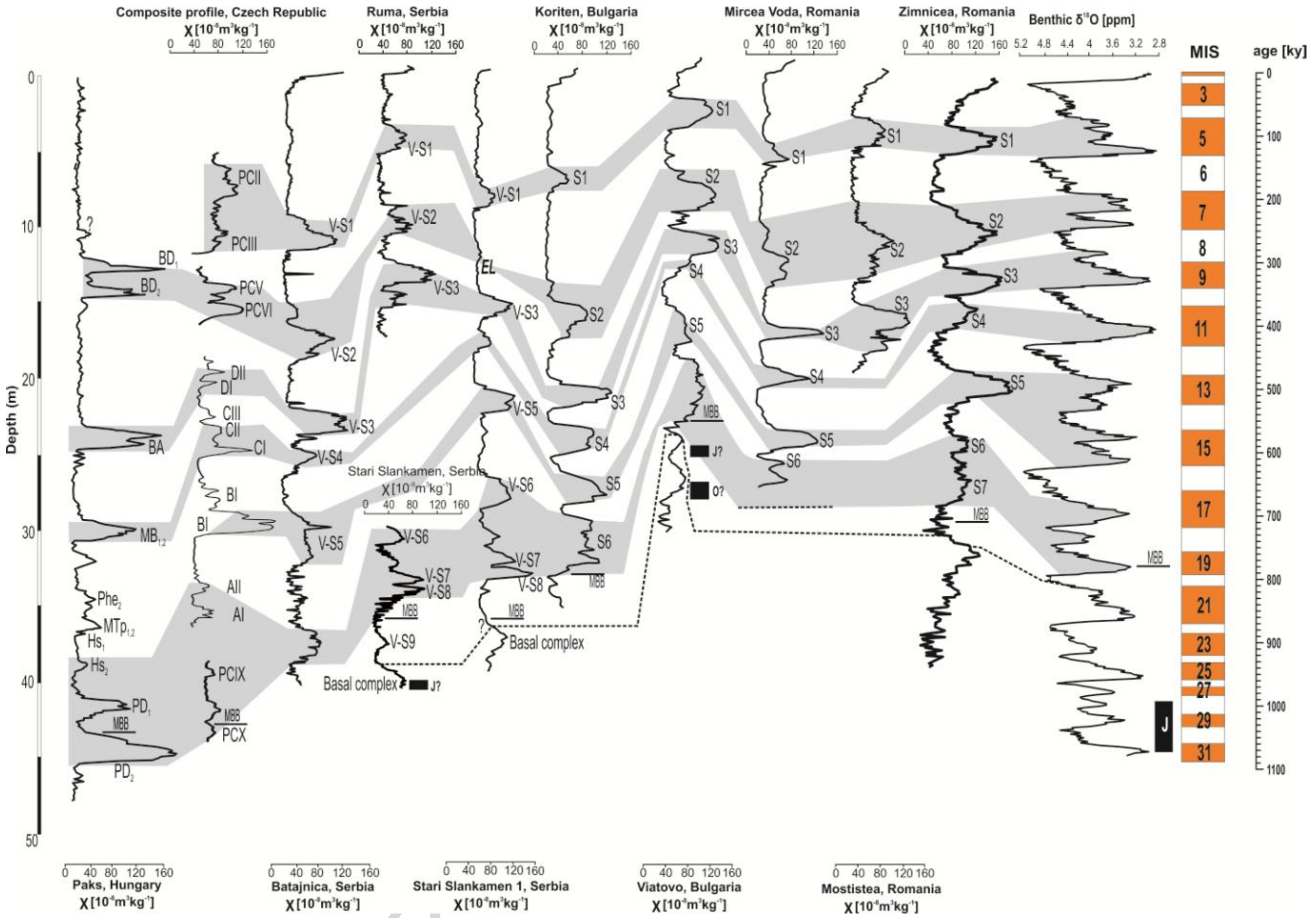
Figure 4


Composite profile, Czech Republic
Ruma, Serbia
Koriten, Bulgaria
Mircea Voda, Romania
Zimnicea, Romania
Benthic δ18O [ppm]
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Depth (m)
Stari Slankamen, Serbia
Basal complex
Paks, Hungary
Batajnica, Serbia
Stari Slankamen 1, Serbia
Viatovo, Bulgaria
Mostistea, Romania
χ [10⁻⁸m³kg⁻¹]
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PCIX
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Hs1
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Figure 5

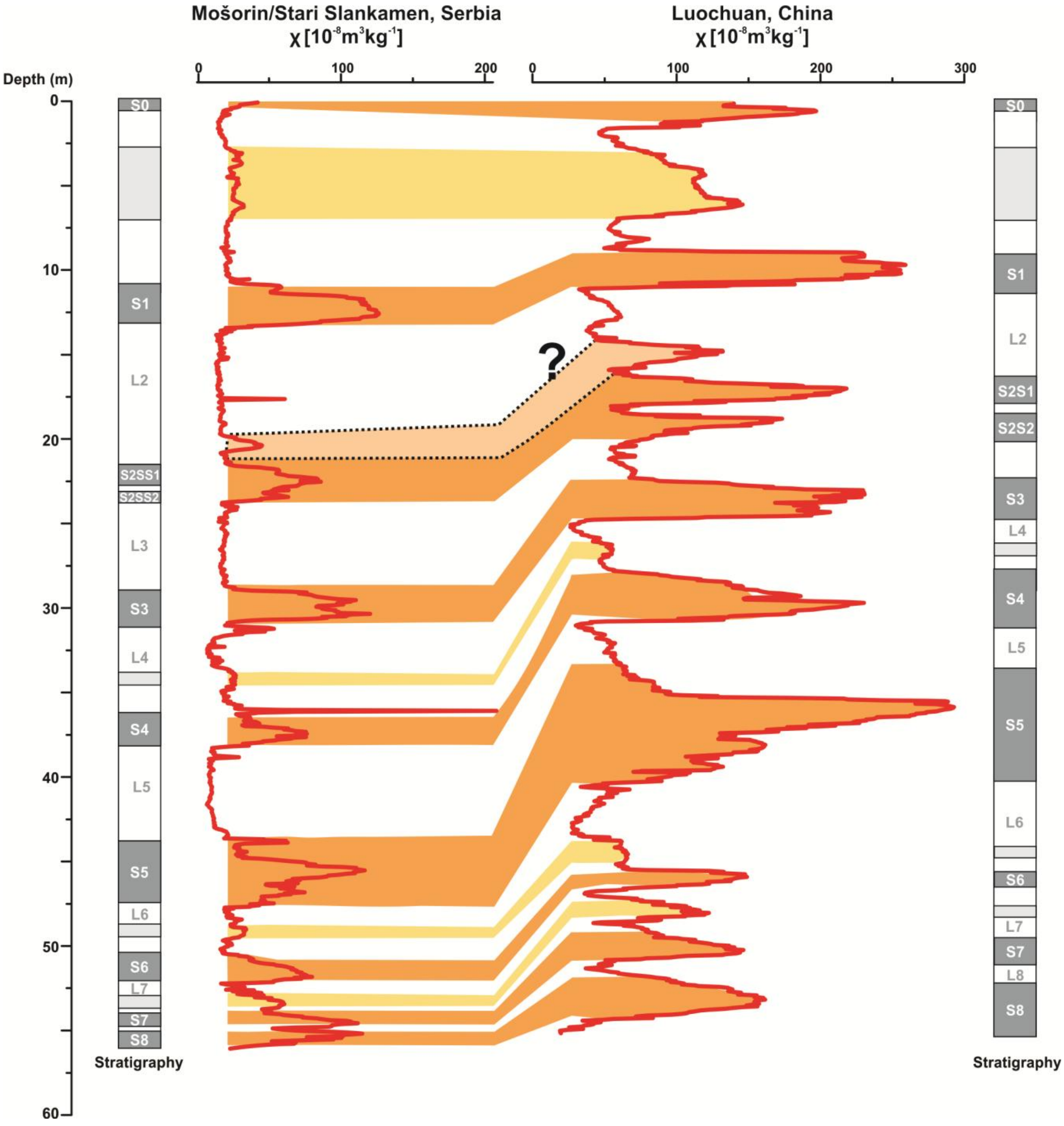
Mošorin/Stari Slankamen, Serbia
χ [10⁻⁸m³kg⁻¹]
Luochuan, China
χ [10⁻⁸m³kg⁻¹]
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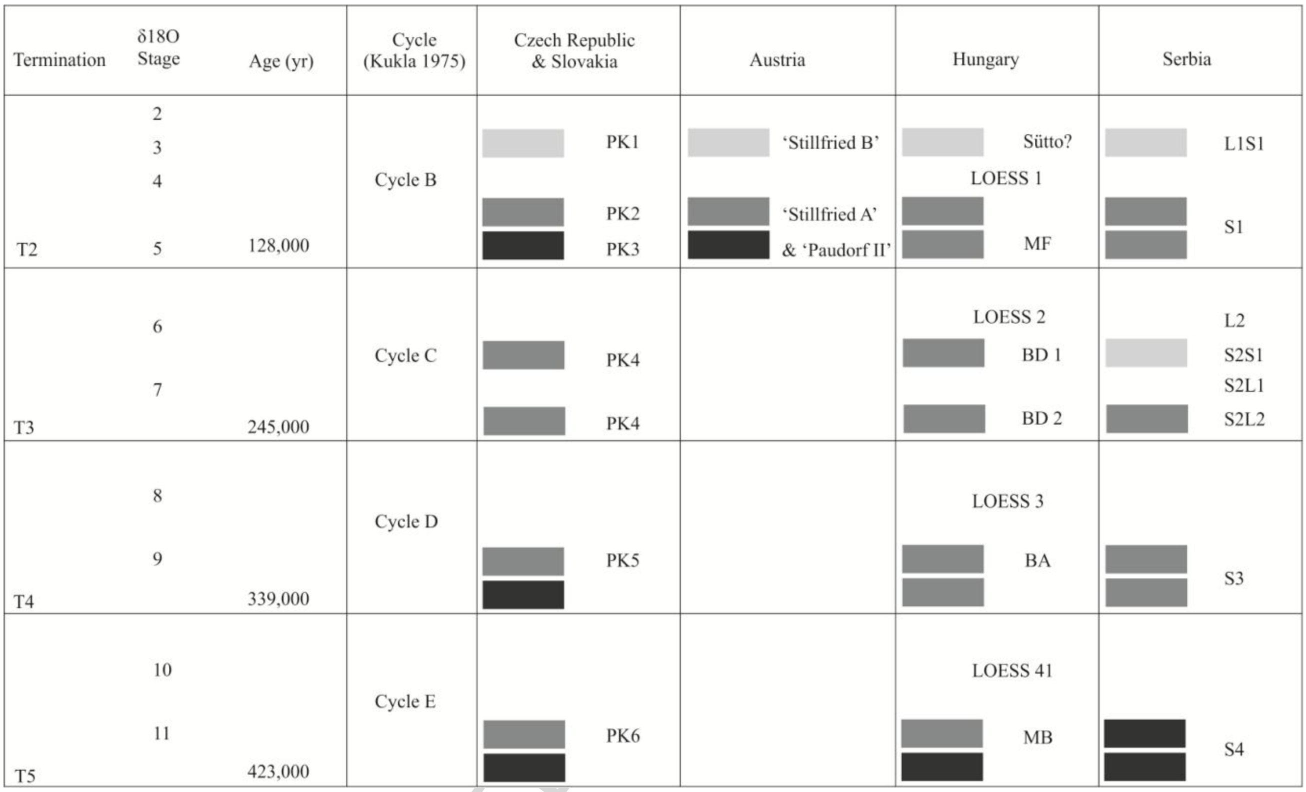
Figure 6



Termination	δ18O Stage	Age (yr)	Cycle (Kukla 1975)	Czech Republic & Slovakia	Austria	Hungary	Serbia
	2						
	3			░ PK1	░ 'Stillfried B'	░ Sütto?	░ L1S1
	4		Cycle B			LOESS 1	
				▒ PK2	▒ 'Stillfried A'	▒	▒ S1
T2	5	128,000		▓ PK3	▓ & 'Paudorf II'	▒ MF	▒
	6					LOESS 2	L2
			Cycle C	▒ PK4		▒ BD 1	░ S2S1
	7						S2L1
T3		245,000		▒ PK4		▒ BD 2	▒ S2L2
	8					LOESS 3	
			Cycle D				
	9			▒ PK5		▒ BA	▒
T4		339,000		▓		▒	▒ S3
	10					LOESS 41	
			Cycle E				
	11			▒ PK6		▒ MB	▓
T5		423,000		▓		▓	▓ S4

Figure 7

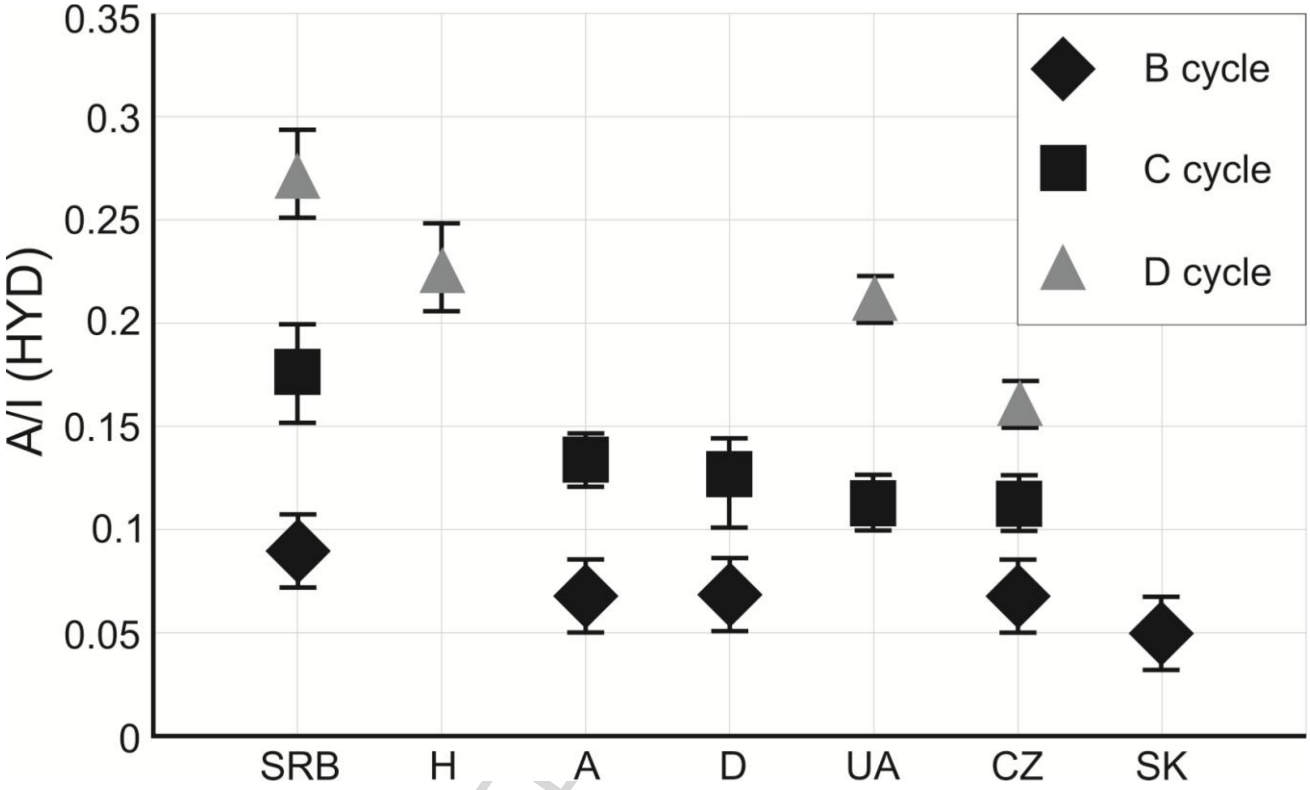

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
A/I (HYD)
SRB
H
A
D
UA
CZ
SK
B cycle
C cycle
D cycle

Figure 8

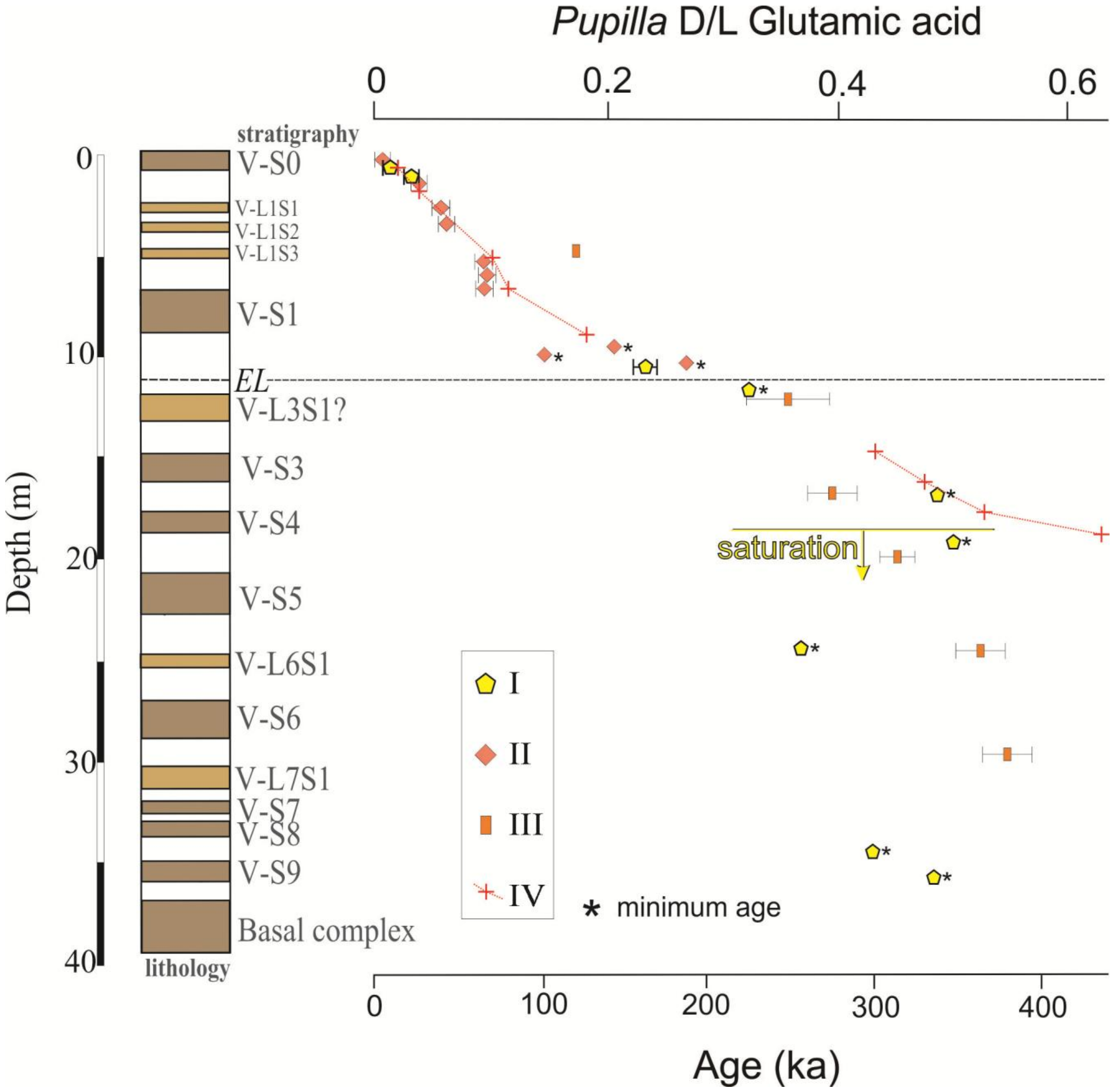

Pupilla D/L Glutamic acid
0
0.2
0.4
0.6
stratigraphy
Depth (m)
0
10
20
30
40
V-S0
V-L1S1
V-L1S2
V-L1S3
V-S1
EL
V-L3S1?
V-S3
V-S4
V-S5
V-L6S1
V-S6
V-L7S1
V-S7
V-S8
V-S9
Basal complex
lithology
saturation
I
II
III
IV
* minimum age
0
100
200
300
400
Age (ka)

Figure 9

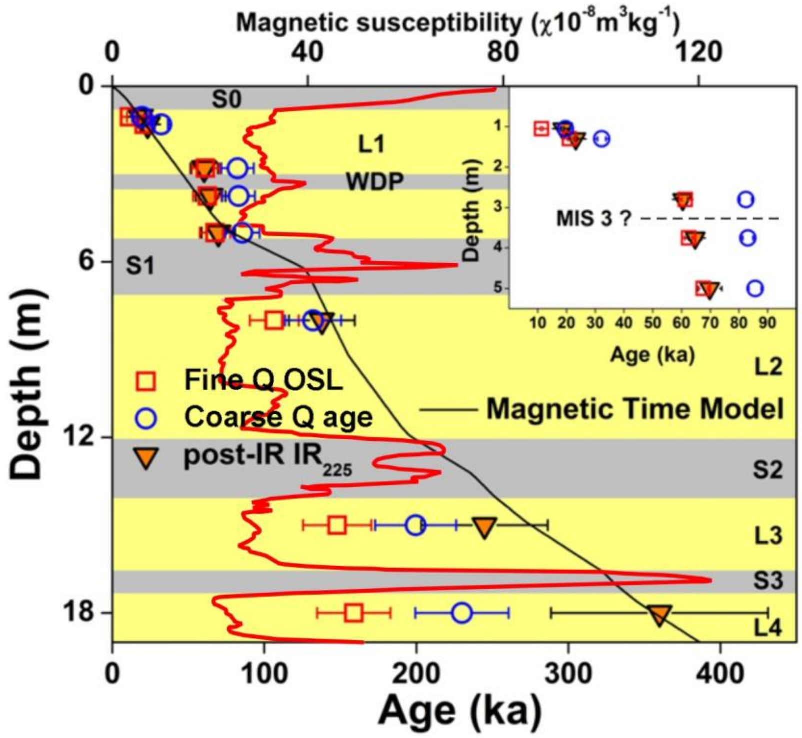

Magnetic susceptibility (χ10⁻⁸m³kg⁻¹)
0
40
80
120
Depth (m)
0
6
12
18
S0
L1
WDP
S1
L2
S2
L3
S3
L4
Fine Q OSL
Coarse Q age
post-IR IR225
Magnetic Time Model
MIS 3 ?
Depth (m)
1
2
3
4
5
10
20
30
40
50
60
70
80
90
Age (ka)
0
100
200
300
400
Age (ka)

Figure 10

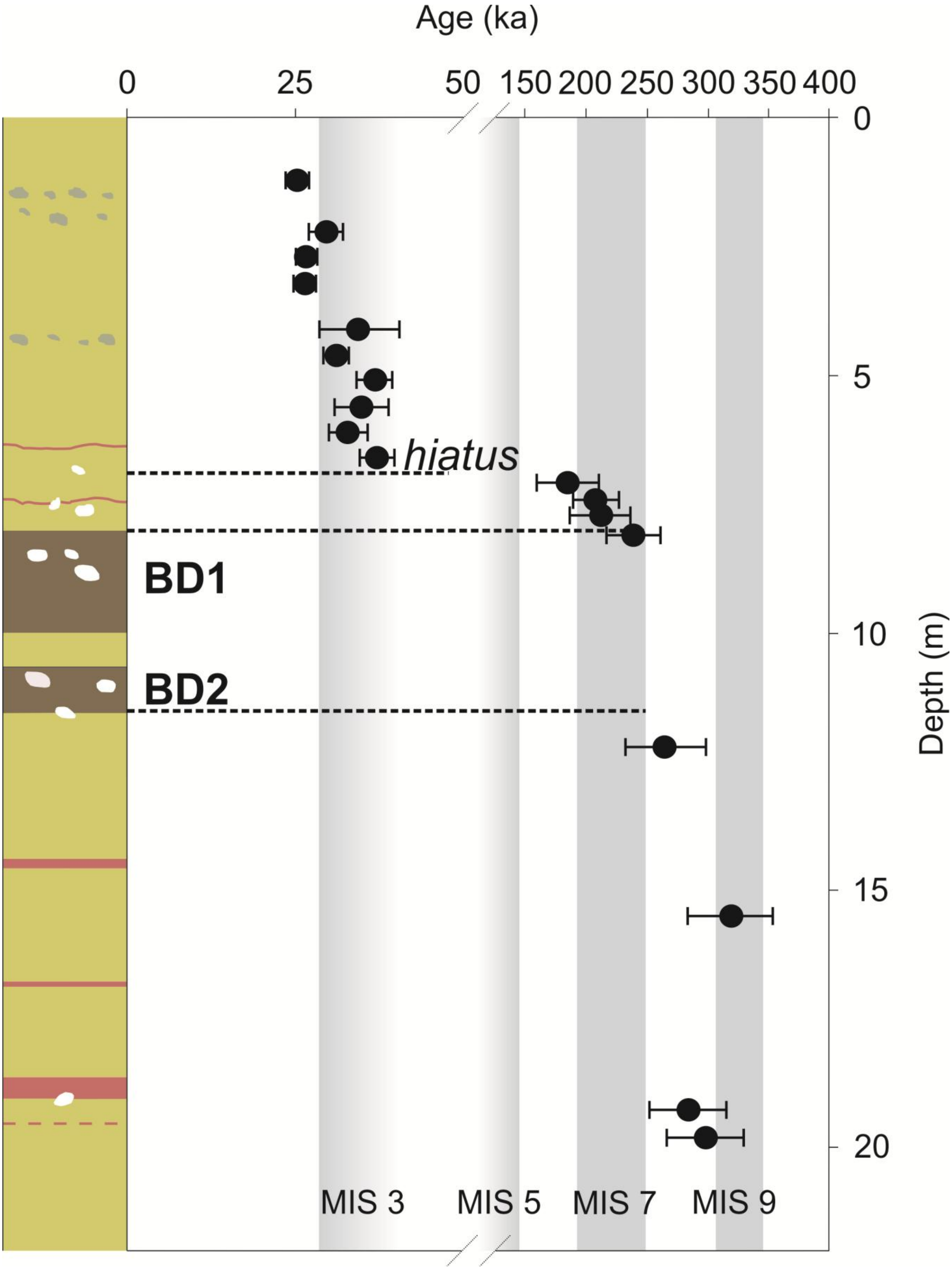

Age (ka)
0
25
50
150
200
250
300
350
400
0
5
10
15
20
Depth (m)
hiatus
BD1
BD2
MIS 3
MIS 5
MIS 7
MIS 9

Figure 11

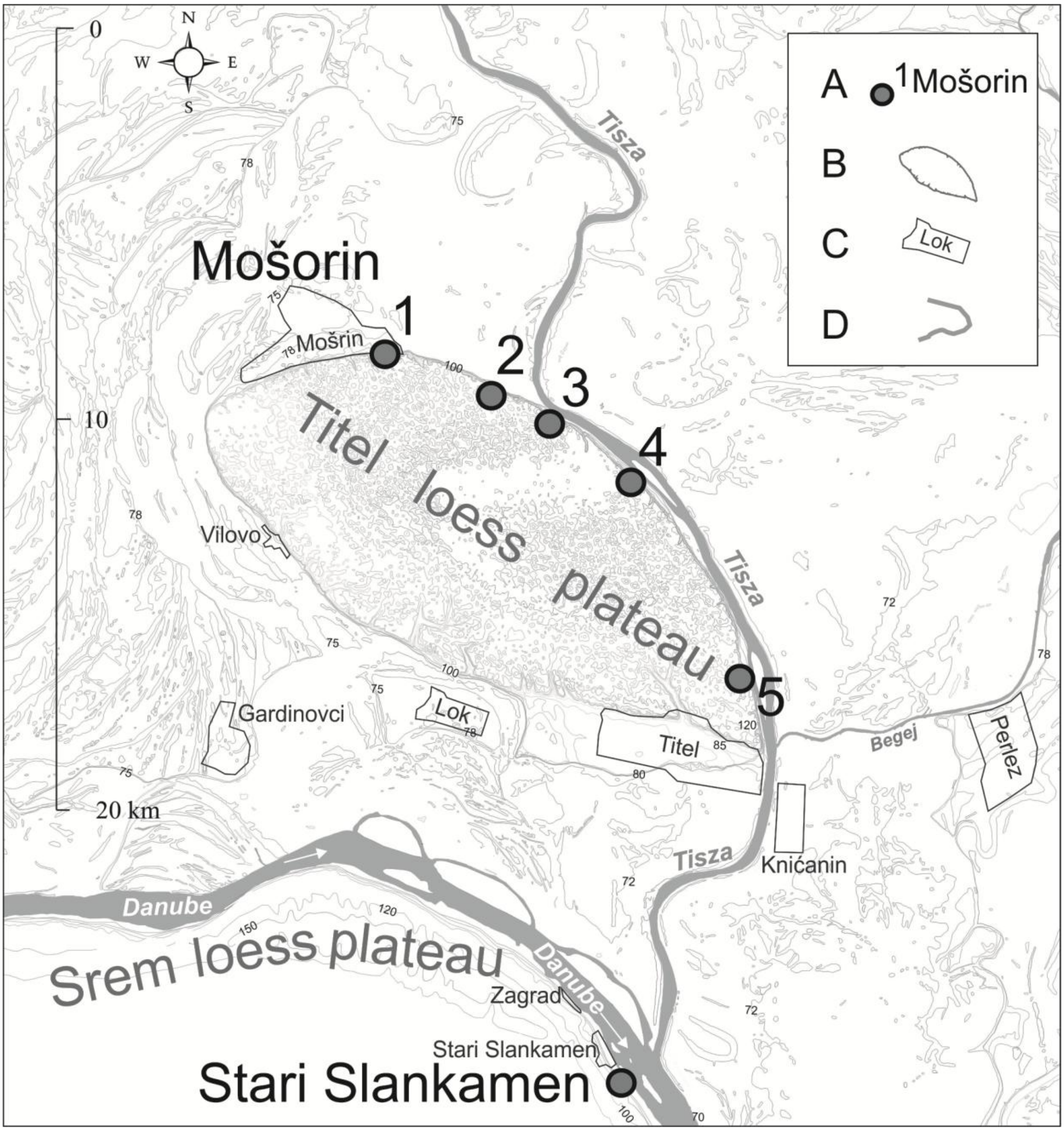

0
10
20 km
N
W
E
S
A
1
Mošorin
B
C
Lok
D
Mošorin
Mošrin
1
2
3
4
5
Titel loess plateau
Tisza
Tisza
Tisza
Vilovo
Gardinovci
Lok
Titel
Knićanin
Begej
Perlez
Danube
Danube
Srem loess plateau
Zagrad
Stari Slankamen
Stari Slankamen
75
78
78
75
78
100
78
75
100
75
78
120
85
80
75
72
78
72
120
150
72
100
70

Figure 12

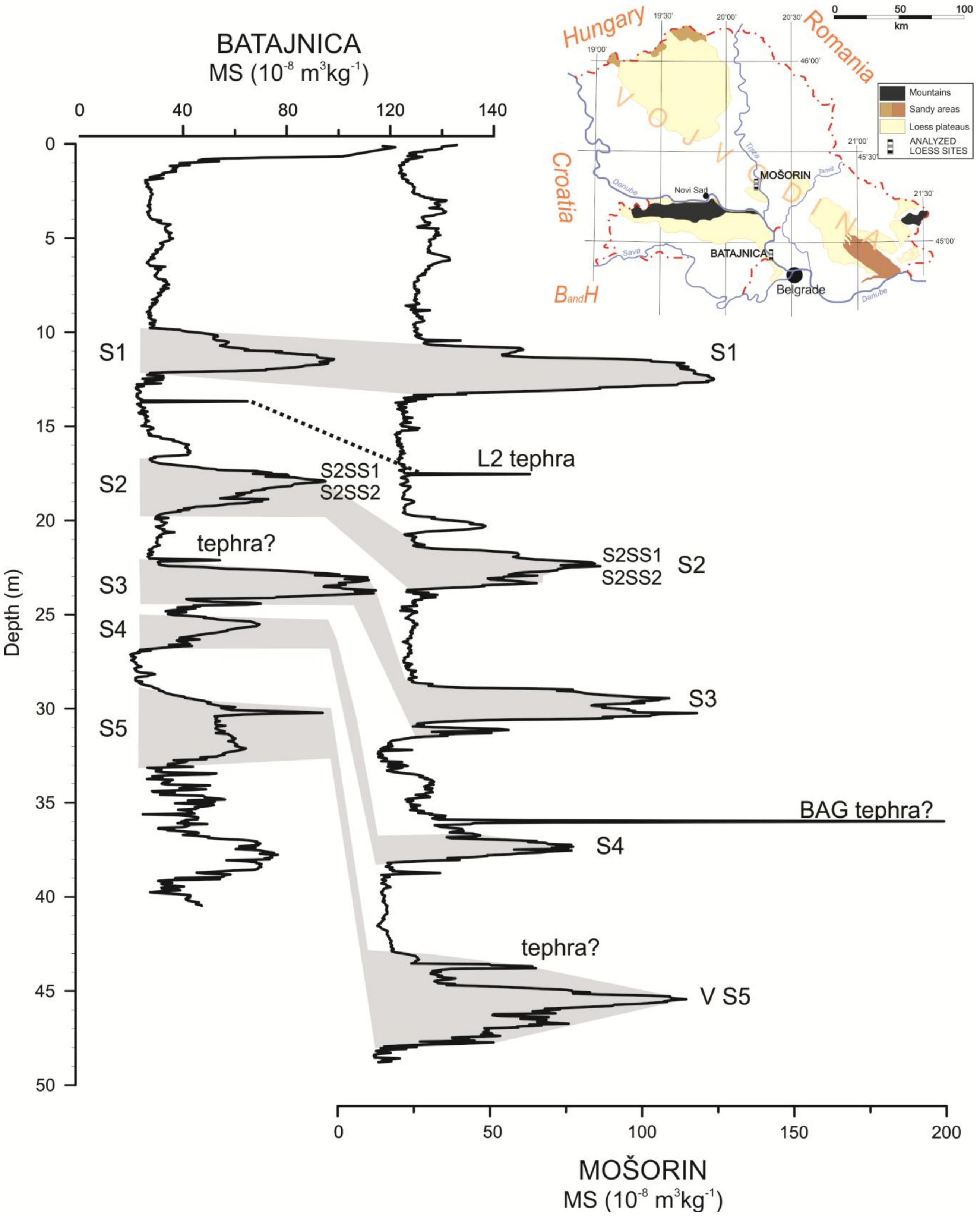

BATAJNICA
MS (10^{-8} m^3kg^{-1})
0
40
80
120
140
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
S1
S2
S2SS1
S2SS2
tephra?
S3
S4
S5
L2 tephra
S1
S2SS1
S2SS2
S2
S3
BAG tephra?
S4
tephra?
V S5
0
50
100
150
200
MOŠORIN
MS (10^{-8} m^3kg^{-1})
Hungary
Romania
Croatia
BandH
V O J V O D I N A
19°00'
19°30'
20°00'
20°30'
21°00'
21°30'
46°00'
45°30'
45°00'
0
50
100
km
Mountains
Sandy areas
Loess plateaus
ANALYZED LOESS SITES
Tisza
Tamiš
Danube
Sava
Novi Sad
MOŠORIN
BATAJNICA
Belgrade

Figure 13

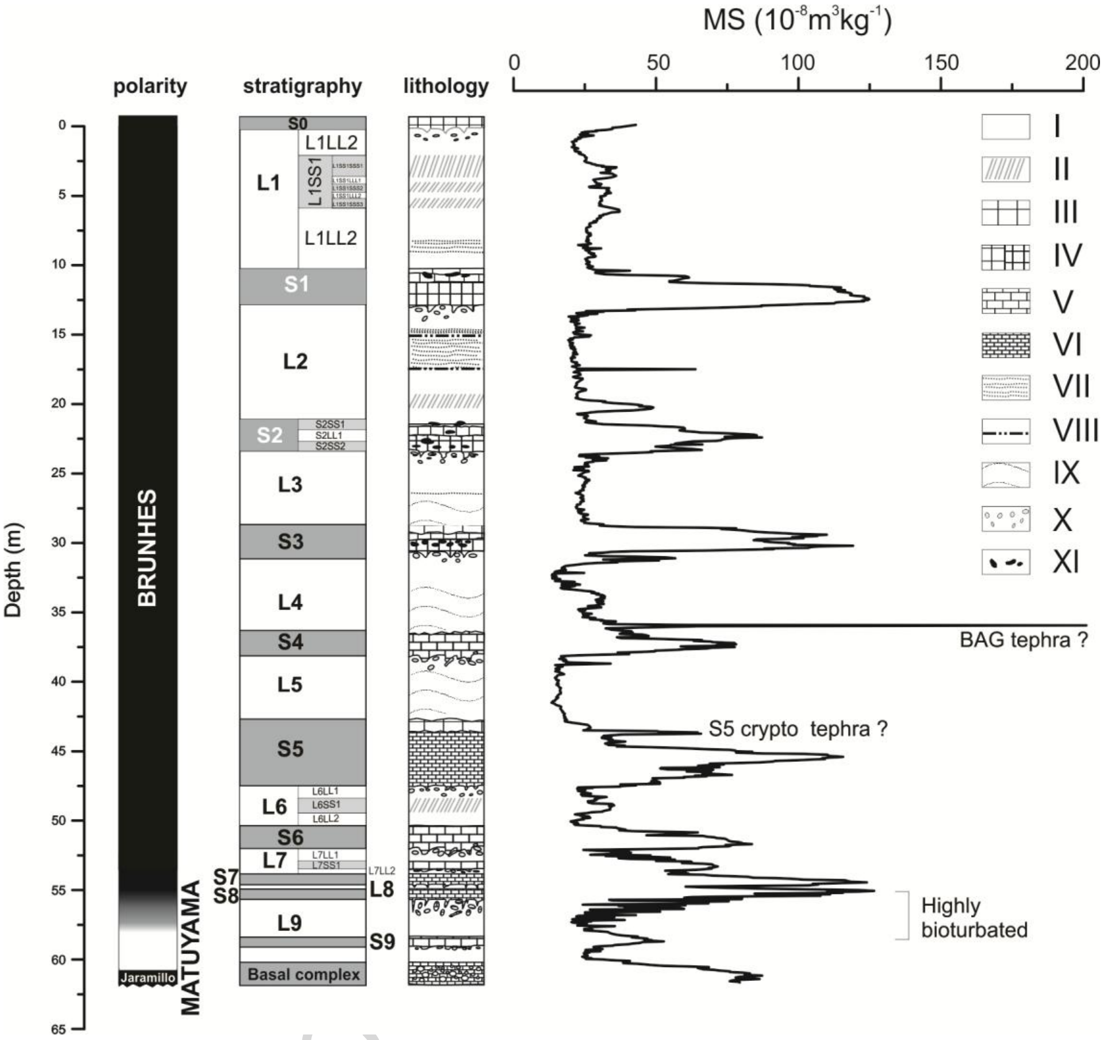

MS ($10^{-8}m^3kg^{-1}$)
0
50
100
150
200
polarity
stratigraphy
lithology
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
BRUNHES
MATUYAMA
Jaramillo
S0
L1
L1LL2
L1SS1
L1SS1SS1
L1SS1LL1
L1SS1SS2
L1SS1LL2
L1SS1SS3
L1LL2
S1
L2
S2
S2SS1
S2LL1
S2SS2
L3
S3
L4
S4
L5
S5
L6
L6LL1
L6SS1
L6LL2
S6
L7
L7LL1
L7SS1
L7LL2
S7
S8
L8
L9
S9
Basal complex
I
II
III
IV
V
VI
VII
VIII
IX
X
XI
BAG tephra ?
S5 crypto tephra ?
Highly bioturbated

Figure 14

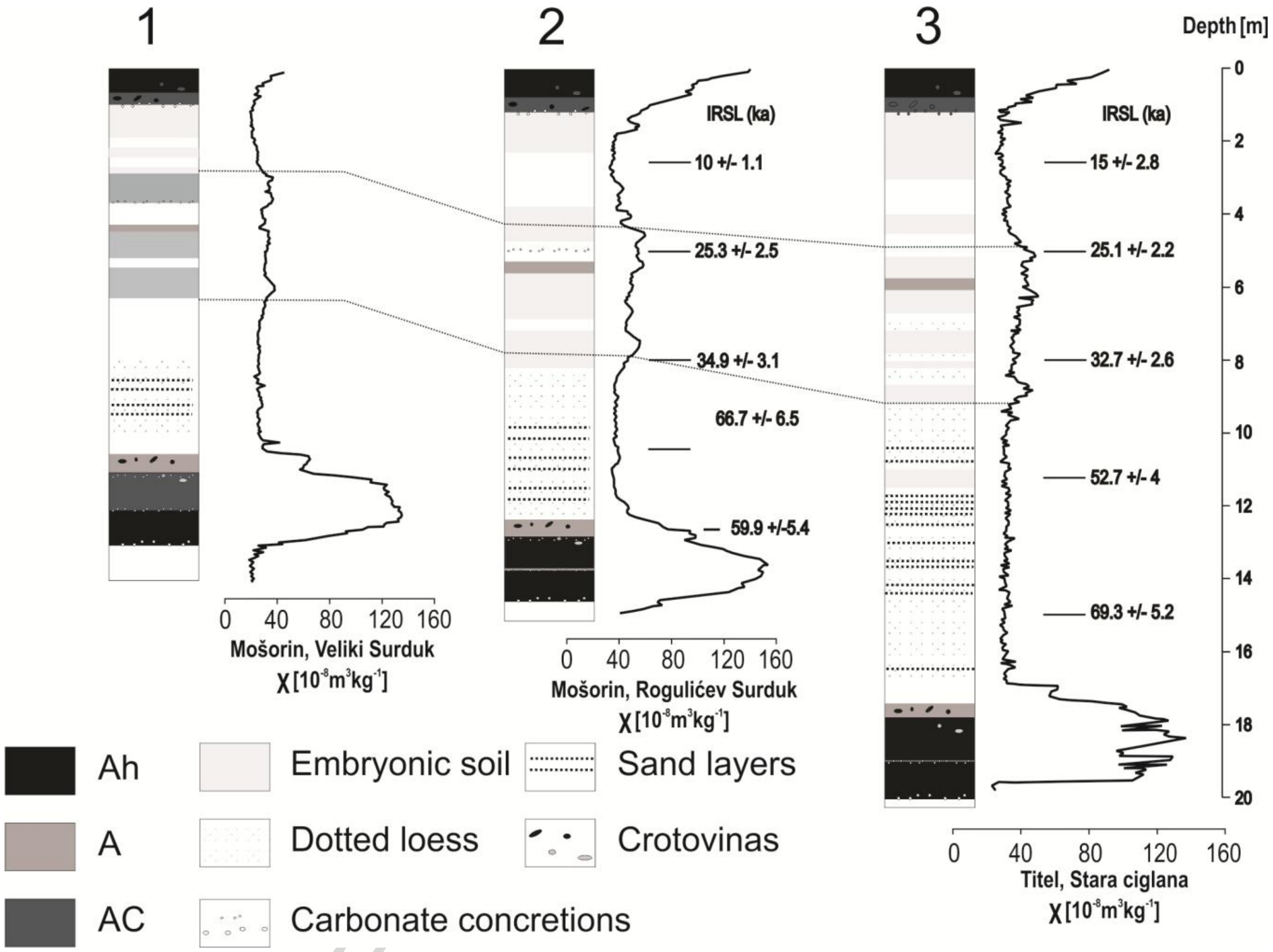

1
2
3
Depth [m]
0
2
4
6
8
10
12
14
16
18
20
IRSL (ka)
10 +/- 1.1
25.3 +/- 2.5
34.9 +/- 3.1
66.7 +/- 6.5
59.9 +/-5.4
IRSL (ka)
15 +/- 2.8
25.1 +/- 2.2
32.7 +/- 2.6
52.7 +/- 4
69.3 +/- 5.2
0 40 80 120 160
Mošorin, Veliki Surduk
χ [10⁻⁸m³kg⁻¹]
0 40 80 120 160
Mošorin, Rogulićev Surduk
χ [10⁻⁸m³kg⁻¹]
0 40 80 120 160
Titel, Stara ciglana
χ [10⁻⁸m³kg⁻¹]
Ah
A
AC
Embryonic soil
Dotted loess
Carbonate concretions
Sand layers
Crotovinas

Figure 15

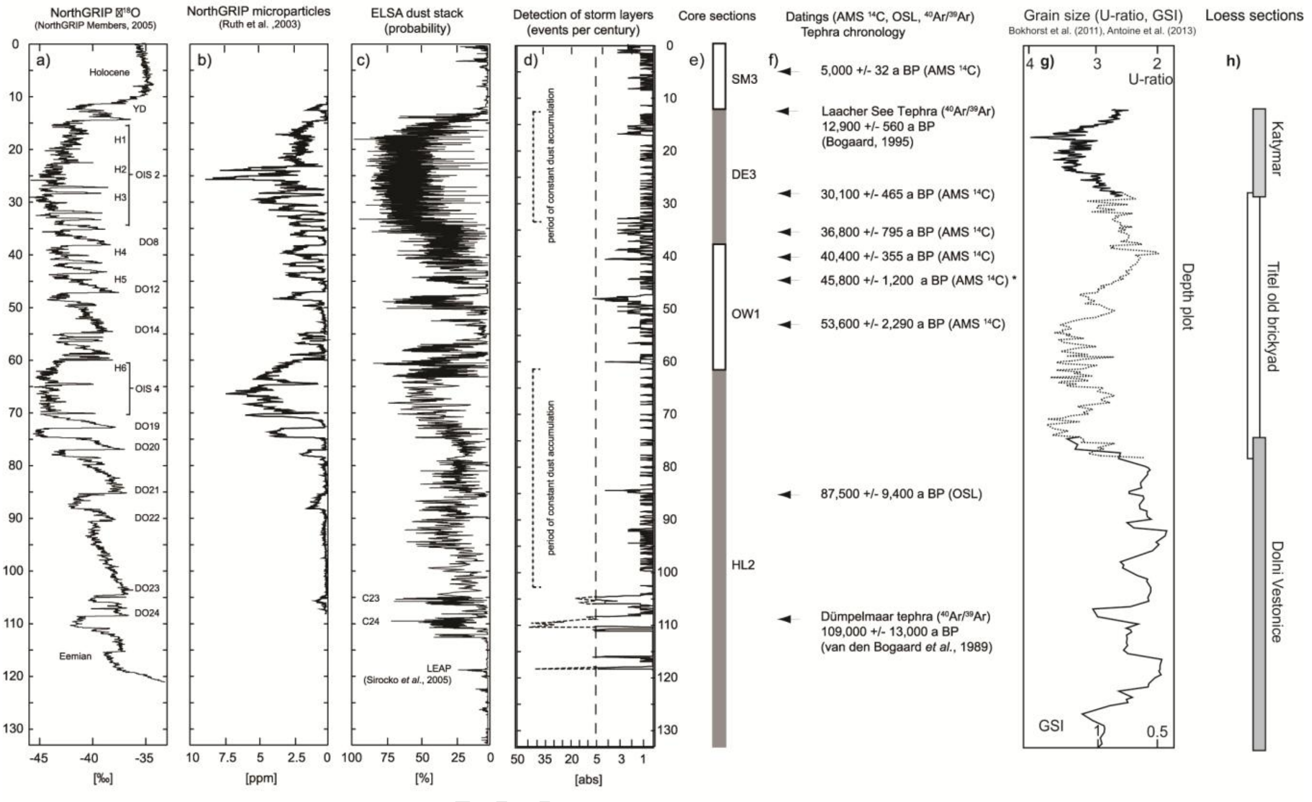

NorthGRIP δ18O (NorthGRIP Members, 2005)
NorthGRIP microparticles (Ruth et al. ,2003)
ELSA dust stack (probability)
Detection of storm layers (events per century)
Core sections
Datings (AMS 14C, OSL, 40Ar/39Ar) Tephra chronology
Grain size (U-ratio, GSI) Bokhorst et al. (2011), Antoine et al. (2013)
Loess sections
a)
b)
c)
d)
e)
f)
g)
h)
Holocene
YD
H1
H2
OIS 2
H3
DO8
H4
H5
DO12
DO14
H6
OIS 4
DO19
DO20
DO21
DO22
DO23
DO24
Eemian
C23
C24
LEAP (Sirocko et al., 2005)
period of constant dust accumulation
period of constant dust accumulation
SM3
DE3
OW1
HL2
5,000 +/- 32 a BP (AMS 14C)
Laacher See Tephra (40Ar/39Ar) 12,900 +/- 560 a BP (Bogaard, 1995)
30,100 +/- 465 a BP (AMS 14C)
36,800 +/- 795 a BP (AMS 14C)
40,400 +/- 355 a BP (AMS 14C)
45,800 +/- 1,200 a BP (AMS 14C) *
53,600 +/- 2,290 a BP (AMS 14C)
87,500 +/- 9,400 a BP (OSL)
Dümpelmaar tephra (40Ar/39Ar) 109,000 +/- 13,000 a BP (van den Bogaard et al., 1989)
U-ratio
Depth plot
GSI
Katymar
Titel old brickyad
Dolni Vestonice
[‰]
[ppm]
[%]
[abs]

Figure 16

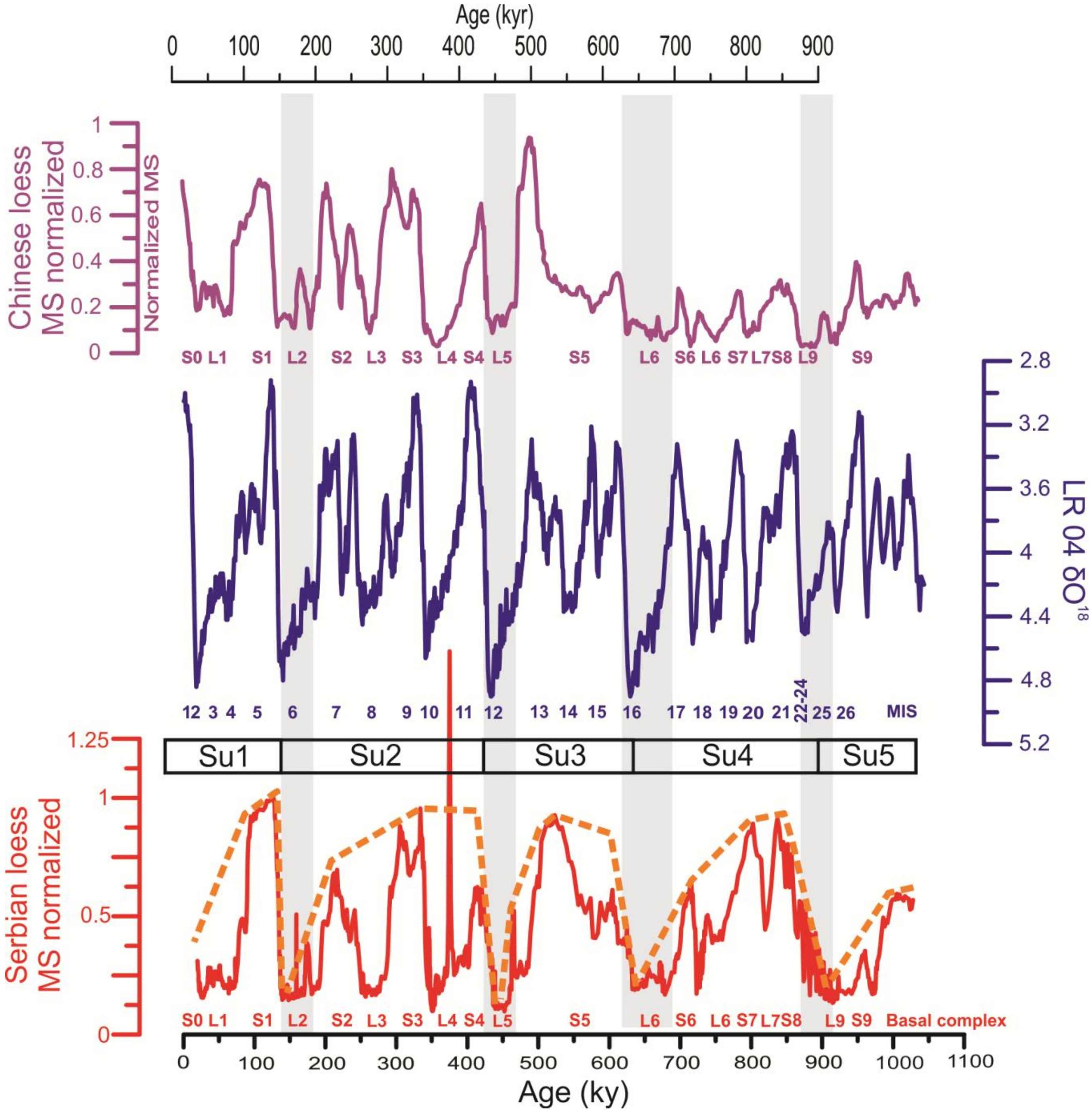

Age (kyr)
0 100 200 300 400 500 600 700 800 900
Chinese loess MS normalized
Normalized MS
1 0.8 0.6 0.4 0.2 0
S0 L1 S1 L2 S2 L3 S3 L4 S4 L5 S5 L6 S6 L6 S7 L7 S8 L9 S9
LR 04 δO18
2.8 3.2 3.6 4 4.4 4.8 5.2
12 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22-24 25 26 MIS
Su1 Su2 Su3 Su4 Su5
Serbian loess MS normalized
1.25 1 0.5 0
S0 L1 S1 L2 S2 L3 S3 L4 S4 L5 S5 L6 S6 L6 S7 L7 S8 L9 S9 Basal complex
0 100 200 300 400 500 600 700 800 900 1000 1100
Age (ky)

Figure 17

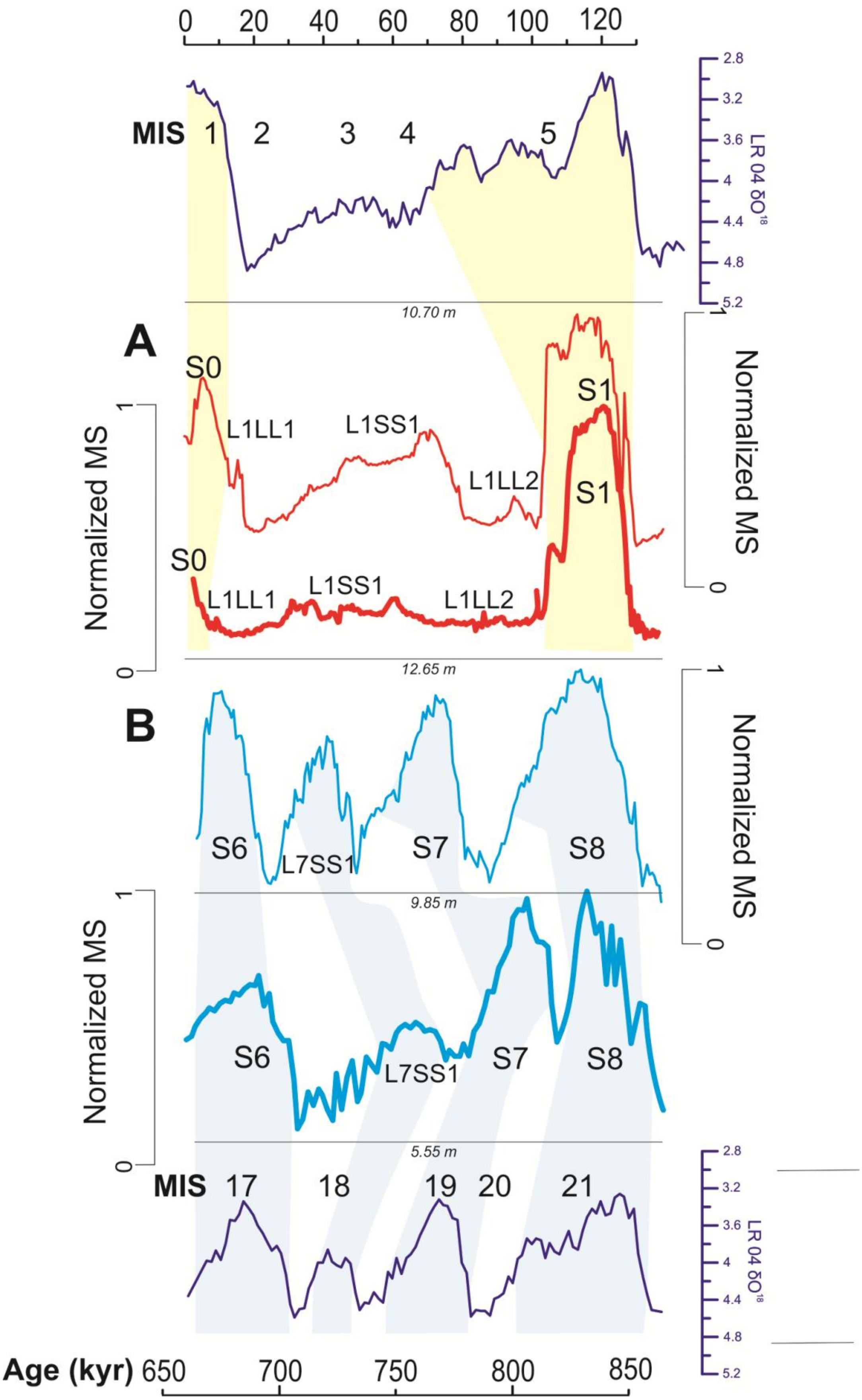
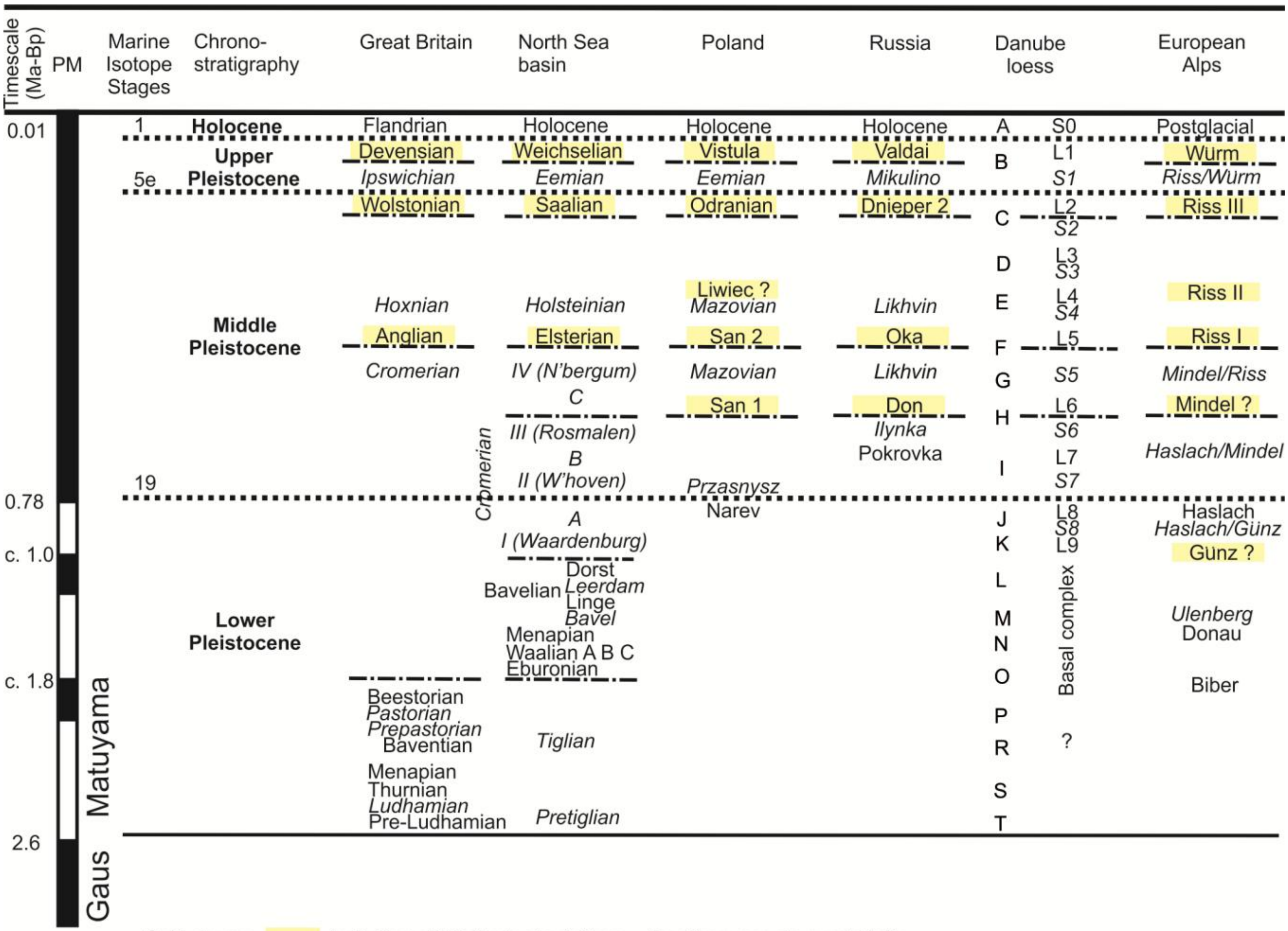

0
20
40
60
80
100
120
MIS 1 2 3 4 5
2.8
3.2
3.6
4
4.4
4.8
5.2
LR 04 δO18
10.70 m
A
S0
L1LL1
L1SS1
L1LL2
S1
S1
S0
L1LL1
L1SS1
L1LL2
Normalized MS
1
0
Normalized MS
1
0
12.65 m
B
S6
L7SS1
S7
S8
9.85 m
S6
L7SS1
S7
S8
Normalized MS
1
0
Normalized MS
1
0
5.55 m
MIS 17 18 19 20 21
2.8
3.2
3.6
4
4.4
4.8
5.2
LR 04 δO18
Age (kyr) 650
700
750
800
850

Figure 18



Timescale (Ma-Bp)	PM	Marine Isotope Stages	Chrono-stratigraphy	Great Britain	North Sea basin	Poland	Russia	Danube loess		European Alps
0.01		1	**Holocene**	Flandrian	Holocene	Holocene	Holocene	A	S0	Postglacial
			Upper Pleistocene	Devensian	Weichselian	Vistula	Valdai	B	L1	Würm
		5e		*Ipswichian*	*Eemian*	*Eemian*	*Mikulino*		*S1*	*Riss/Würm*
				Wolstonian	Saalian	Odranian	Dnieper 2	C	L2	Riss III
									S2	
								D	L3	
									S3	
						Liwiec ?		E	L4	Riss II
			Middle Pleistocene	*Hoxnian*	*Holsteinian*	*Mazovian*	*Likhvin*		*S4*	
				Anglian	Elsterian	San 2	Oka	F	L5	Riss I
				Cromerian	*IV (N'bergum)*	*Mazovian*	*Likhvin*	G	*S5*	*Mindel/Riss*
					C	San 1	Don	H	L6	Mindel ?
					III (Rosmalen)		*Ilynka*		*S6*	*Haslach/Mindel*
					B		Pokrovka	I	L7	
		19			*II (W'hoven)*	*Przasnysz*			*S7*	
0.78					*Cromerian* A	Narev		J	L8	Haslach
					I (Waardenburg)				*S8*	*Haslach/Günz*
c. 1.0								K	L9	Günz ?
					Bavelian Dorst *Leerdam* Linge *Bavel*			L	Basal complex	
			Lower Pleistocene		Menapian *Waalian* A B C Eburonian			M N		*Ulenberg* Donau
c. 1.8								O		Biber
	Matuyama			Beestorian *Pastorian* *Prepastorian* Baventian	*Tiglian*			P R	?	
				Menapian Thurnian *Ludhamian* Pre-Ludhamian	*Pretiglian*			S T		
2.6	Gaus									

Cold stages 🟨 including mid-latitude glaciations *Eemian* warm stages *in italic*

Figure 19

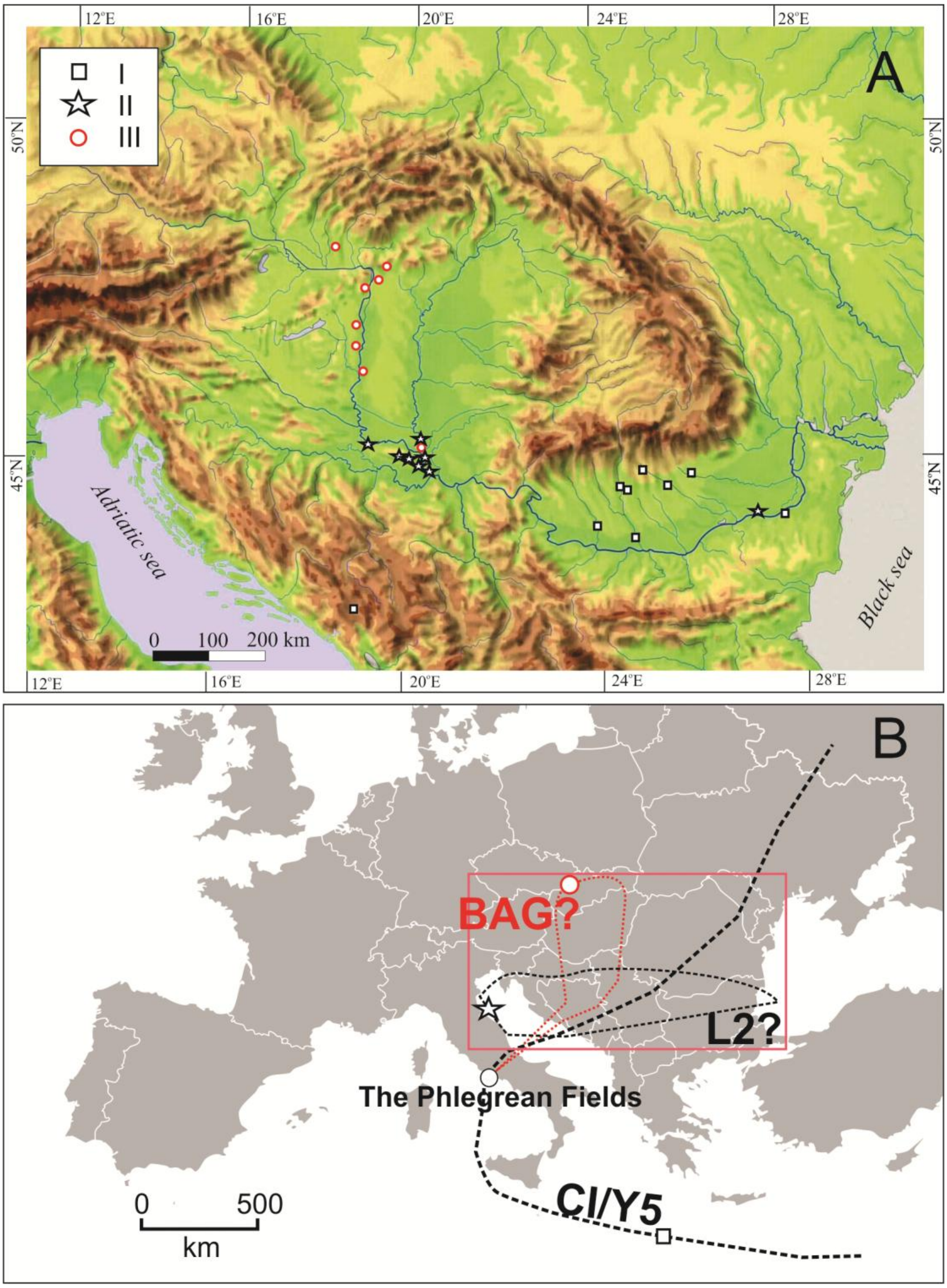

12°E
16°E
20°E
24°E
28°E
50°N
45°N
A
□ I
☆ II
○ III
Adriatic sea
Black sea
0 100 200 km
B
BAG?
L2?
The Phlegrean Fields
CI/Y5
0 500
km

Table 1. Varying chronostratagraphic models proposed for the Stari Slankamen loess-palaesol sequence by different researchers and their comparison to the traditional Alpine subdivision (Bronger, 1976) and MIS stratigraphy (Singhvi et al., 1989; Butrym et al., 1991; Bronger, 2003; Marković et al., 2011).

Bronger (1976)		Singhvi et al. (1989)	Butrym et al. (1991)		Bronger (2003)		Marković et al. (2011)	
paleosol	Alpine sudivision	MIS	paleosol	MIS	paleosol	MIS	paleosol	MIS
F2	Würm paleosols W	5a	D	5a	F2	5a	V-S1	5
F3		5e	Not observed		F3	5e	Not observed	
F4			G	5c	F4	7	V-S3	9
F5	R-W		I	5e	F5	9 or 11	V-S4	11
F6			L	7	F6	13-15	V-S5	13-15
F7			n1	9			V-S6	17
F8			n2	9			V-L7S1	18.3
F9							V-S7	19
F10							V-S8	21
							V-S9	25
F11							basal complex	29-?

Table 2. The proposed Danube loess stratigraphic model, covering the last approximately one million years, and its relation to the Chinese loess record, marine isotope stratigraphy, glacial cycles and national loess stratigraphies in the Czech Republic (Kukla and Cilek, 1996), Austria (Scholger and Terhorst, 2013), Hungary (Sartori et al., 1999; Ujvari et al., 2014, modified), Serbia (Marković et al., 2011), Romania (Buggle et al., 2009) and Bulgaria (Jordanova et al., 2008).

MIS	CLP	Glacial cyclle	Czechia	Austria	Hungary	Serbia	Romania	Bulgaria	DB
1	S0	A	Recent soil			V-S0	S0	S0	S0
2	L1LL2	B		AS16		V-L1L2	L1L2	L1LL2	L1LL2
3	L1SS1		PKI	AS15+14	MF1	V-L1S1	L1S1	L1SS1	L1SS1
4	L1LL2			AS13		V-L1L2	L1L2	L1LL2	L1LL2
5	S1		PKII+III	AS12-10	MF2	V-S1	S1	S1	S1
6	L2	C		AS9		V-L2	L2	L2	L2
7	S2		PKIV	AS8	BD1+2	V-S2	S2	S2	S2
8	L3	D		AS8a?		V-L3	L3	L3	L3
9	S3		PKV	AS7a+7b? + 7c?	BA	V-S3	S3	S3	S3
10	L4	E		AS6?		V-L4	L4	L4	L4
11	S4		PKVI	AS5?	MB1+2	V-S4	S4	S4	S4
12	L5	F-G		AS4?		V-L5	L5	L5	L5
13-15	S5		PKVII + VIII	AS3-1?	Phe+Mpt+Hs1?	V-S5	S5	S5	S5
16	L6	H				V-L6	L6	L6	L6
17	S6		?		Hs2?	V-S6	S6S1?		S6
18.1	L7LL1	I				V-L7L1			L7LL1
18.2	L7SS1					V-L7S1			L7SS1
18.3	L7LL2					V-L7L2			L7LL2

19	S7		PKIX		PD1?	V-S7	S6S2?	S6	S7
20	L8	J				V-L8			L8
21	S8		PKX		PD2?	V-S8			S8
22-24	L9	K-?				V-L9	L7	L7	L9
25-?	S9-?		PKXI			Basal complex	?	Red clay	Basal complex