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Paleoclimate record in the Upper Pleistocene loess-paleosol sequence at Petrovaradin brickyard (Vojvodina, Serbia)

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Abstract: Four loess units and three paleopedological layers are preserved in the ~8 m thick Petrovaradin exposure, Vojvodina, Serbia. Amino acid geochronology provides stratigraphic correlations between loess units L1 and L2 at Petrovaradin with loess of glacial cycles B and C, respectively, at other Central European localities. Magnetic susceptibility and sedimentological evidence of the Petrovaradin loess-paleosol sequence are used for correlation with the SPECMAP paleoclimatic record. Late Pleistocene climate dynamics recorded in the Petrovaradin brickyard loess-paleosol sequence present temperate humid and warm interglacial and temperate cold glacial climatic conditions. The last glacial paleoclimatic record provides two main cold and dry stadial periods corresponding to deposition of two loess layers L1L1 and L1L2, as well as one moderate cold and relatively dry interstadial. Many episodes of alternating cold-dry and warm-wet paleoclimatic conditions suggest a possible correlation with abrupt paleoclimatic fluctuations recorded in the North Atlantic region. The results of malacological investigations of the Petrovaradin site demonstrate significant similarities to the Paleopreillyrian fauna of the southern Transdanubia region in Hungary, which suggests that the Petrovaradin site has a refugial character during the periods of dust accumulation.

Key words: Late Pleistocene, Serbia, paleoclimate, amino acid geochronology, magnetic susceptibility, loess, grain size.

Introduction

The thick loess-paleosol succession of the Vojvodina region contains a detailed record of Middle and Late Pleistocene paleoclimatic and paleoenvironmental changes (Marković et al. 2003). Previous investigations were focused on well known open loess sections at Stari Slankamen, Neštin, Batajnica and Mošorin (Bronger 1976, 2003; Singhvi et al. 1989; Butrym et al. 1991; Kostić & Protić 2000; Marković et al. 2003) located on the steep banks of the Danube and Tisza (= Tisa/Theiss) rivers. However, recent research interests have extended to the loess-paleosol exposures uncovered in the brickyards at Ruma, Irig and Petrovaradin (Marković 2001; Marković et al. 2000, 2004b, in print; Gaudenyi et al. 2003).

The Petrovaradin brickyard loess exposure (45°16' N Latitude and 19°52' E Longitude) is situated in the central part of the north loess slope of the Fruška Gora (Vojvodina, Serbia) (Fig. 1). Initial investigations focus on the four loess layers and three paleosols preserved in the ~8 m thick exposure. This study points to the importance of Petrovardin's loess-paleosol sequences for understanding paleoclimatic and paleoenvironmental variations in the southeastern part of the Carpathian (Panonnian) Basin during the last ~145 ka.

Material and methods

Investigations of the loess-paleosol sequences of the Petrovaradin brickyard began in 2001. Samples were collected at 5-cm intervals for sedimentological analysis, and at 25-cm intervals for malacological studies. Grain size (GS) fractions (<2, 2–20, 20–200, >200 μm) were measured by sieving and pipeting, carbonate content was analysed by gas volumetrically. The low-field magnetic susceptibility (MS) was measured in the field using a portable Bartington MS2 susceptibility meter. Measurements were made at 5-cm intervals and at each level, ten independent readings were taken and averaged. 10-kg bulk sediment samples for malacological investigations were sieved through 0.7 mm mesh. After fossil gastropod shells were identified, paleoenvironmental classification and interpretation was done based on the methods of Ložek (1964), but also extended with some local variants defined by Krolopp & Sümegi (1995). Gastropod shells were collected from six levels within L1 (last glacial loess) and the upper part of L2 (penultimate glacial loess) for amino acid racemization (AAR) analysis in order to independently correlate the stratigraphy with loess-paleosol units elsewhere in Europe. Details of the sample preparation and analytical methodology are presented in Oches & McCoy (2001).

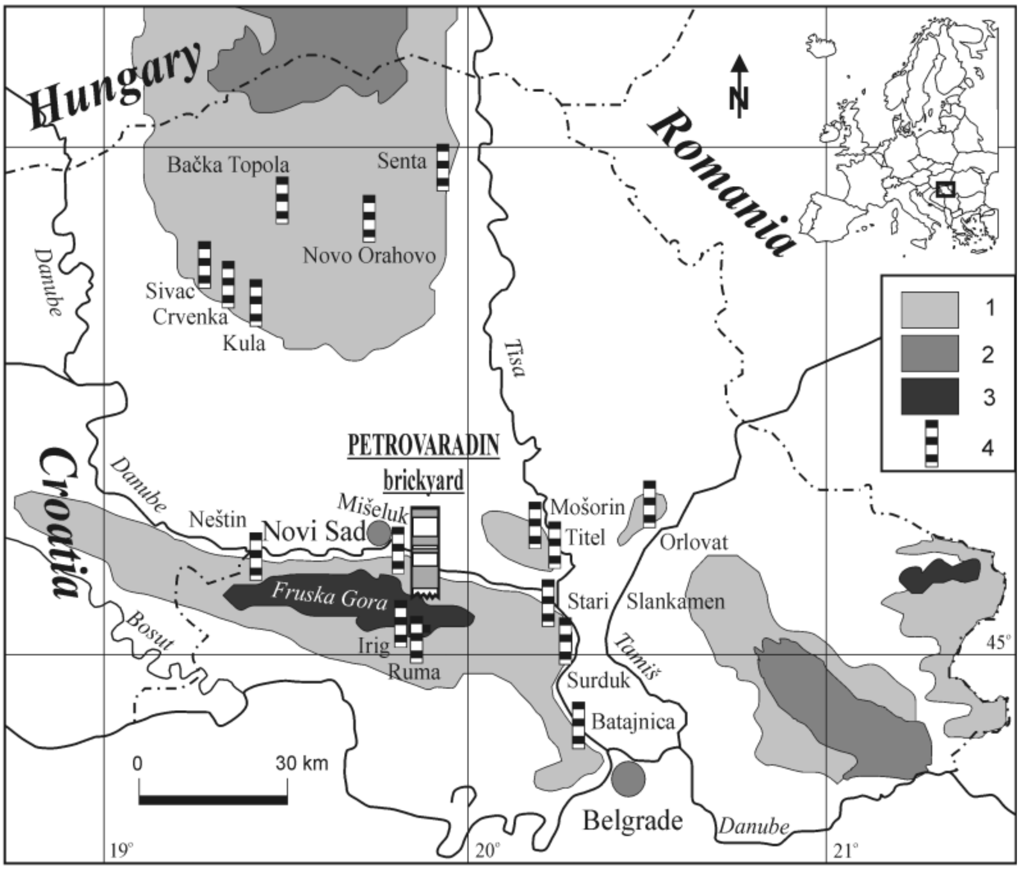

Fig. 1. Geographical position of the Petrovaradin brickyard exposure and other relevant sites in the Vojvodinian loess area. **1** — loess plateau, **2** — sandy area, **3** — mountain, **4** — main loess sections.

Results

Litho- and pedostratigraphy

Stratigraphic studies of loess and paleosols at various exposures in the Vojvodina region have used lithological and pedogenic criteria and MS variations as the primary bases for correlation. Marković et al. (2003, 2004a, in print) designated the Vojvodinian loess-paleosol chronostratigraphic units by names that follow the Chinese loess stratigraphic system (Kukla 1987), beginning with the prefix "SL" referring to the standard section at the Stari Slankamen site. According to the current chronostratigraphic model (Marković et al. 2004b), the penultimate glacial loess L2 accumulated during the marine isotope stage (MIS) 6. The last interglacial–early glacial paleosol S1 correlates with MIS 5. This palaeosol is overlain by composite loess unit L1, correlated with MIS 4–2. The structure of the last glacial loess L1 varies in different loess localities across the Vojvodina region. The lower sub-horizon of the upper loess, L1L2, accumulated above palaeosol S1. The Middle Pleniglacial is represented in the area by a weakly developed soil complex L1S1. The youngest loess layer L1L1 accumulated during the Late Pleniglacial period.

Three paleosols and four loess layers are distinguished at the Petrovaradin quarry (Fig. 2). Table 1 shows the morphological description of the loess-paleosol sequence. The oldest pale yellow (5Y 7/3, 5/4) loess unit L2 is uncovered only in the lowest 75 cm of the profile. The lower part of this loess unit is not excavated during the raw material exploitation. Many carbonate concretions (1–4 cm diameter) and humus infiltrations appear near the contact of the S1 soil complex and the underlying L2 loess. The reddish-brown pedocomplex S1, 205 cm thick, contains lower slightly brownized, middle typical and upper weak developed chernozems. The lower darker transitional A(B) horizon (10YR 5/2–3) is darker than the middle Ah horizon (10YR 6/2–4) that contains some preserved carbonate pseudomycelia. The uppermost relatively weakly developed A horizon is characterized by many krotovinas.

The composite loess unit L1 is 460 cm thick and contains three loess layers (L1L1, L1S1L1 and L1L2) separated by two paleopedological subunits (L1S1S1 and L1S1S2). The 130 cm thick loess layer L1L2 accumulated above the S1 paleosol. This light yellow gray (5Y 7/3 5/3) loess layer is porous, loosely cemented and in some parts finely laminated with thin fine sand beds. The superimposed paleopedological horizon L1S1S2 (5Y 6/3–4) is 35 cm thick. It is a weak, incipient pedohorizon with small and soft carbonate spots. Loess stratum L1S1L1 is 35 cm thick with morphological characteristics similar to loess layer L1L2. The youngest paleosol L1S1S1 is a 75 cm

Table 1: Morphological description of loess-paleosol at Petrovaradin brickyard exposure.

Unit / *subunit*	**Thickness (cm)**	**Depth (cm)**	**Description**
S0	70	0–70	Modern soil, 70-cm thick chernozem slightly melanized with weak blocky structure
L1	460	70–530	
L1L1	185	70–255	Very porous, pale yellow loess (10YR 7/4–5/3) with many humic infiltrations and carbonate concretions (ø 1–4 cm)
L1S1S1	75	255–330	Weakly developed mollic chernozem-like soil (10YR 6/3–4/2)
L1S1L1	35	330–365	Light yellow grey (5Y 7/3, 5/3) porous loess with soft and small carbonate concretions
L1S1S2	35	365–400	Weakly developed, yellowish brown (5Y 7/3 5/3) incipient (A) horizon with granular strucrure
L1L2	130	400–530	Light yellow grey (5Y 7/3, 5/3) porous, loosely cemented partly finely laminated calcareous loess
S1	225	530–735	Thick transitional chernozem pedocomplex: the lower slightly brownized AB horizon has weak platy structure (10YR 5/2–3); the middle typical chernozem part has brighter colour (10YR 6/2–4), and the upper weakly developed chernozem has blocky structure with many krotovinas in the uppermost level
L2	75	735–800	Porous yellow (5Y 1/3, 5/4) loess with many humus infiltrations and carbonate concretions

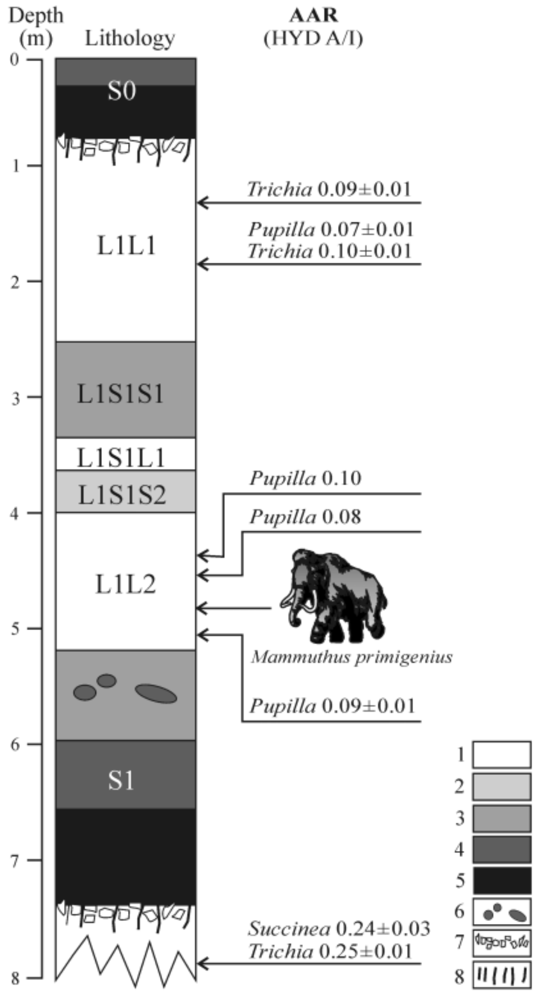

Fig. 2. Stratigraphy of the Petrovaradin brickyard exposure. Positions of samples for amino acid analysis and *Mammuthus primigenius* skeletal remains are indicated by the arrows. HYD A/I values are shown for gastropod genera on which analyses were made. **1** — Loess, **2** — Embryonic pedogenetic layer (incipient soil horizon), **3** — A horizon, **4** — Ah horizon, **5** — Transitional AB horizon, **6** — Krotovinas, **7** — Carbonate concretions, **8** — Humus infiltrations.

thick poorly developed chernozem-like pedological horizon. Loess layer L1L1 is 185 cm thick, very porous and in some parts intensively bioturbated. Many spherical, relatively soft carbonate nodules and humus infiltrations in old root channels are found at the contact zone with the modern soil S0.

The Holocene soils developed on the loess plateau surface in the area surrounding Petrovaradin brickyard are chernozem eroded and chernozem slightly melanized (Miljković 2001). At the top of the investigated section, the modern soil is a 70 cm thick chernozem slightly melanized. The lower Ck horizon contains many $CaCO_3$ nodules of 1–5 cm in diameter and numerous krotovinas and root channels filled with humic material. A transitional AC horizon (10YR 5/1–3/3) is a 15 cm thick, very porous, silt loam with fine blocky structure. The A(B) horizon is 35 cm thick, reddish-brown (7.5YR 4/2–4/4), and porous with blocky structure. The Ah horizon (10YR 6/3–4/4) is a 20 cm thick silt loam with granular structure and some carbonate pseudomycelia.

AAR chronostratigraphy and correlations

Amino acid racemization (AAR) geochronology using fossil gastropod shells has been successfully applied to the stratigraphic correlation of loess-paleosol sequences in different regions of the world (Oches & McCoy 2001). The Petrovaradin profile is one of the first Serbian loess sites in which AAR analyses have been carried out. Three different genera of terrestrial gastropod shells have been analysed, including samples from six levels within the loess sequence at Petrovaradin. Sampled genera include *Pupilla, Succinea* and *Trichia*. Alloisoleucine/Isoleucine total acid hydrolysate (A/I-HYD) measurements on representative samples are shown in Fig. 3. Shells of the genus *Pupilla* and *Trichia* were the most abundant and offer the most direct aminostratigraphic comparison with data from loess units elsewhere in central and eastern Europe. HYD A/I values measured in *Trichia* from the Petrovaradin brickyard profile can be compared with data from Austrian, Czech, Slovak, Hungarian and German sites (Oches & McCoy 1995a,b, 2001; Oches et al. 2000) (Fig. 3). Present-day air and ground temperatures in Hungary and Serbia are higher than in the more northern sites. This higher temperature explains the more rapid rate of racemization in Vojvodina loess than in the equivalent age loess units in other Central European sites. These data show that the method can clearly distinguish between loesses of the last two glacial cycles.

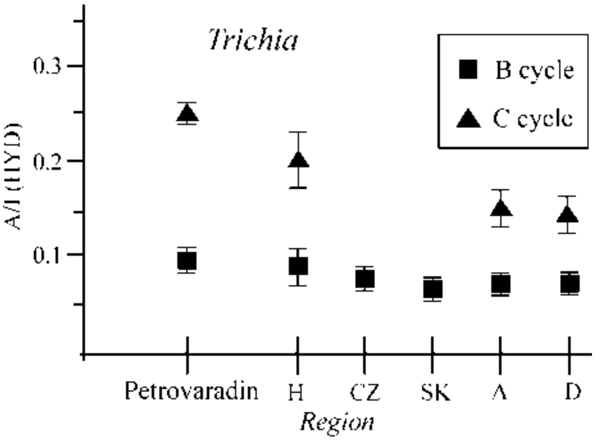

Fig. 3. Aminostratigraphy of the Petrovaradin brickyard section compared with other Central European localities for glacial cycles B and C, corresponding to marine oxygen-isotope stages 2–5 and 6–7, for the genus *Trichia*. **H** — Hungary, **CZ** — Czech Republic, **SK** — Slovakia, **A** — Austria, **D** — Germany.

The *Pupilla* data at Petrovaradin come only from loess of the last glacial cycle. *Pupilla* HYD A/I values from below L1S1 are only slightly greater than from shells in the loess above that soil complex, despite being tens of thousand of years older. This can only be possible if the soil does not represent an interglacial period. A warm interglacial would induce very much more epimerization as is demonstrated by the *Trichia* HYD A/I ratios from below S1.

AAR geochronology results from the Petrovaradin section support the previous chronostratigraphic scheme of Marković (2000, 2001). According to that chronostratigraphic model, loess-paleosol sequences L1 and S1 formed during glacial cycle B (Kukla 1975) and correspond to MIS 2, 3, 4 and 5. The exposed part of the L2 loess horizon was deposited during the youngest part of glacial cycle C (MIS 6).

Low-field magnetic susceptibility (MS)

According to our investigations, the variations in the low-field MS are related to the pedostratigraphy in the Petrovaradin brickyard section. MS values observed in soils S0 (average 44.7 SI units) and S1 (average 29.5 SI units) are higher than in the loess units L1 (average 22.4 SI units) and L2 (average 13.3 SI units) (Fig. 4). This type of MS pattern reflects magnetic enhancement via

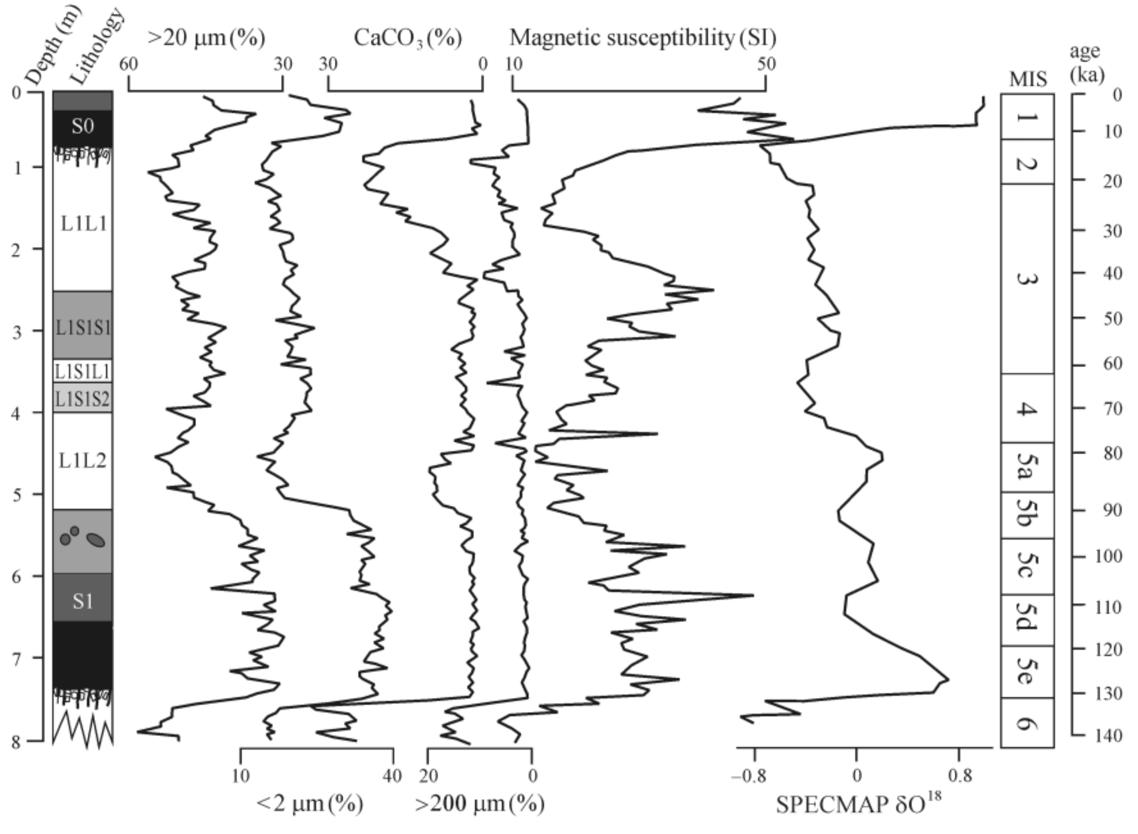

Fig. 4. Depth plots of magnetic susceptibility, clay content, carbonate content, and particle size fractions >20 μm and >200 μm at the Petrovaradin exposure related to SPECMAP paleoclimatic model (Martinson et al. 1987).

pedogenesis and is similar to that in Chinese and Central Asian loess deposits (e.g. Maher & Thomson 1999).

The basal penultimate glacial loess unit L2 shows the lowest MS values: less than 15 SI units. Readings in lower part of the S1 soil complex increase to 37 SI units. MS increases to 49 SI units in the middle part of the soil where it is the highest in the S1 paleosol. A sharp decrease of MS occurs in the base of the overlying lighter horizon with minimal value 21 SI units. Close to the top of paleosol S1, MS values again increase to nearly 40 SI units and above that continuously decreased to relatively low values in loess subunit L1L2: ~18 SI units, with one strong peak of 33 SI units (425 cm depth). The L1S1S2 shows higher, stable values (range of 21 to 26 SI units). In the thin loess inter layer, L1S1L1, MS is essentially unchanged ~22 SI units. MS values of the interstadial paleosol L1S1S1 increase to 43 SI units. MS of the youngest loess layer L1L1 is low: ~17 SI units. The Holocene soil S0 shows an increasing trend from ~30 SI units at the base to more than ~50 SI units in its middle part (Fig. 4).

Grain-size (GS) distribution and carbonate content

Measured variations in GS distribution also coincide well with the pedostratigraphy of the Petrovaradin loess-paleosol sequence. Generally, the pedogenic horizons have a lower proportion of coarse material than the loess layers (e.g. Vandenberghe & Nugteren 2001). Variability in clay content (<2 μm) parallels the MS record. The highest value of clay content is observed in lower part of palaeosol S1 (close to 40 %) in contrast with low values detected in loess layers (ca. 15 %). Variations of coarse material (>20 μm) content show many abrupt small amplitude changes possibly linked to wind transport intensity. High values of >20 μm content are also associated with several peaks of coarse sand (>200 μm) deposition in both loess units L1 and L2 (Fig. 4).

High values of carbonate content are detected in loess units: more than 30 % in L2; L1L1 is greater than 20 %; L1L3 is characterized by values about 10 %; and L1L2 has more than 7 % carbonate, in contrast to very low values of carbonate (less than 5 %) in fossil soils. Peaks of the coarser material deposition are connected with relative minima of carbonate content inside the loess and paleosol units (Fig. 4).

Malacology

Shells of 5053 individuals land snails representing 33 species (26 genera) were found in 30 samples taken from the Petrovaradin section. Generally, the terrestrial malacological assemblages reflect humid and relatively cold paleoenvironmental conditions with mosaic vegetation (Fig. 5).

The snail assemblage from the upper part (final stage) of the L2 horizon is characterized by relatively large abundance of shells per sample (more than 200 individuals per sample) with a dominance of humid-preferring species of different biotopes. The dominance of *Trichia hispida, Vitrea crystallina, Punctum pygmaeum, Aegopinella ressmanni* and *Clausilia dubia* indicate humid environmental conditions characterized by woodland steppe like vegetation. The closed-canopy woodland, humid environment preferring species *Ena montana* and *Discus ruderatus* have been found with very low frequency in the rest of the samples. The presence of cold resistant species such as *Vallonia tenuilabris* and *Succinea oblonga* indicates relatively cold climatic conditions.

No land snails were recovered from the lower parts of paleosol S1. Because of poor preservation and leaching in the soil, this unit was not valuable for malacological investigations.

Dominance of aridity-tolerant snails such as *Pupilla triplicata, P. muscorum, Helicopsis striata, Vallonia costata, Granaria frumentum* and *Chondrula tridens* in loess layers L1L2 and L1S1L1 and weak pedo-horizon L1S1S2 represents open vegetation and a mostly dry environment related to steppe-like grassland.

The snail assemblages of the youngest paleosol L1S1S1 and loess L1L1 provided different environmental conditions. The increase in mollusc abundance and the presence of forest snails such as *Aegopinella ressmanni*, *Orcula dolium* and *Clausilidae* in the loess layer L1L1 indicates more humid conditions.

During the last glacial period we note the presence of two relatively cold episodes. The coldest one was during the accumulation of loess layer L1L1 indicated by the presence of the cold-resistant species *Vallonia tenuilabris*, *Columella columella*, *Vertigo parcedentata* and *Succinea oblonga*. The earlier cold period occurred during the deposition of loess horizon L1L2 characterized by low frequency of species such as *Vallonia tenuilabris* and *V. pulchella.*

Discussion

Paleoclimatic and paleoenvironmental interpretations

The multi-proxy data set and identified pedo-stratigraphy in the Petrovaradin sequence indicates a sharp contrast between glacial and interglacial climatic conditions. The final part of penultimate glacial loess cycle L2 and two last glacial loess layers L1L2 and L1L1 accumulated during temperate, cold, stadial intervals. By contrast, during interstadial and interglacial times, the climate was warmer and generally wetter and this led to enhanced pedogenesis. Whereas interglacial soils tend to be strongly developed, interstadial paleosols L1S1S2 and L1S1S1 are weakly expressed. Generally, all paleoclimatic proxies determined from the loess-paleosol sequence of Petrovaradin correlate well with the SPECMAP paleoclimatic model (Martinson et al. 1987) (Fig. 4).

Besides climatic changes related to interglacial–glacial and stadial–interstadial conditions, especially, GS and carbonate-content variations in the loess units recorded paleoclimatic instability characterized by many episodes of cold-dry and warm-wet paleoclimatic conditions (Fig. 4) indicating possible teleconections with Dans-

Fig. 5. Relative abundance diagram of the identified mollusc species in the Petrovaradin brickyard loess exposure. The species are clustered in ecological groups, as defined by Ložek (1964), but also extended with some local variations defined by Krolopp & Sümegi (1995) and Sümegi & Krolopp (2002). **1** — tundra-like, **2** — dry steppe, **3** — grassland, **4** — transitional zone, **5** — forest, **6** — wetland. Star mark shows snail ambudance less than 1 % per sample.

gaard-Oeschger (D/O) cycles (e.g. Dansgaard et al. 1993) and cold events recorded in the North Atlantic region (e.g. McManus et al. 1994).

The AAR data show that the interstadial climatic conditions may have been somewhat warmer than during the stadials, but it was not nearby as warm as during the integlacial represented by paleosol S1.

According to the paleopedological interpretation and the identified land snail fauna of the Petrovaradin sequence, the Late Pleistocene was characterized by different environments, ranging from temperate warm interglacial forest-steppe, across dry lower and Middle Pleniglacial grassland, to a relatively cold and humid mosaic environment during the end of the Penultimate glacial and again during the Late Pleniglacial. The snail assemblage of Petrovaradin's loess layers is similar to the nearby loess site at Mišeluk (Marković et al. 2004b). Both mollusc records show more humid and relatively colder environments than in other sites of the Vojvodina region (Marković et al. 2000). Therefore, we think that the north slopes of Fruska Gora Mountain had an important role during the Late Pleistocene. It was perhaps a refugium, that is one of those rare places in the southeast part of the Carpathian Basin where the Paleoillyrian snail assemblage (e.g. *Macrogastra ventricosa, Aegopinella ressmanni* and *Trichia edentula*; Sümegi & Krolopp 2002) survived.

In 1978, during excavation of brickyard raw materials only 1 km away from the present section, workers found fragments of a woolly mammoth skeleton (*Mammuthus primigenius*) at the base of the L1 loess (L1L2), at a depth 4.7 m below the present surface (Milić 1978), adding to the paleoecological picture of the Late Pleistocene environment.

Relation with other loess records in the Carpathian Basin

The investigations of the Petrovaradin brickyard loess-paleosol sequence provide a reconstruction of the complex Late Pleistocene paleoclimatic and environmental evolution in this area. These results are comparable with recent studies of other loess-paleosol sequences in the Carpathian Basin that also have paleoclimatic and paleoenvironmental reconstructions based on luminescence age estimations, amino-acid geochronology, sedimentological, rock magnetic and malacological evidence from the last glacial period (Zöller & Wagner 1990; Zöller et al. 1994; Oches & McCoy 1995a,b; Krollopp & Sümegi 1995; Frechen et al. 1997; Sartori et al. 1999; Sümegi & Krolopp 2002).

The stratigraphic pattern of the Petrovaradin brickyard site is generally similar to other Upper Pleistocene loess-paleosol sequences in Hungary (Pécsi 1993; Horváth 2001). However, all analysed proxies at Petrovaradin and other loess exposures in the Vojvodina region (Marković et al. 2004a,b) indicate that Late Pleistocene paleoclimatic and paleoenvironmental evolution was relatively uniform compared to Hungarian loess sites (Pécsi 1993; Horváth 2001). Stratigraphic equivalents of Hungarian Upper Pleniglacial humus horizons h1 and h2 are not found in the Petrovaradin brickyard. In addition, Petrovaradin's Middle Pleniglacial paleopedocomplex L1S1 is weakly developed in comparison with the corresponding paleosol MF1 in Hungarian loess. However, characteristics of Lower Pleniglacial loess L1L2 and the last interglacial-Lower Pleniglacial soil S1 are similar to Hungarian loess l2 and paleosol MF2.

Conclusions

The multidisciplinary study of the loess-paleosol sequence reveals a very detailed Late Pleistocene record at the Petrovaradin brickyard section. These results have established the importance of this site as a record of the last interglacial-glacial paleoclimate and paleoenvironment in the southeastern part of the Carpathian Basin.

Detailed AAR data provide aminostratigraphic correlation between loess units L1 and L2 at Petrovaradin with loess of glacial cycles B and C, respectively, at other European loess localities. Sedimentological, paleopedological, and paleontological evidence recorded in the Petrovaradin sequence, all demonstrate different intensities and scales of climate instability: glacial-interglacial, stadial-interstadial and abrupt millennial-scale variability.

The identified fossil snail assemblages indicate more humid environmental conditions in this region than in other parts of the Vojvodina region (North Serbia) during the last glacial and the final part of the penultimate glacial. As a result the northern slope of the Fruska Gora was a biogeographical "island" during the last two glacials; that is a refugium where the Paleopreillyrian snail assemblage survived.

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