Geochemistry
Geophysics
Geosystems
G3
AN ELECTRONIC JOURNAL OF THE EARTH SCIENCES
Published by AGU and the Geochemical Society

Article
Volume 8, Number 9
19 September 2007
Q09008, doi:10.1029/2006GC001565
ISSN: 1525-2027

Malacological and sedimentological evidence for "warm" glacial climate from the Irig loess sequence, Vojvodina, Serbia

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[1] Four loess units and three paleosol layers are preserved in the Irig brickyard, Vojvodina, Serbia. Amino acid geochronology provides stratigraphic correlations between loess units V-L1 and V-L2 at the Irig section with loess of glacial cycles B and C, respectively, described from other central European localities. Luminescence dating results for the upper loess layers V-L1L1 and V-L1S1L1 confirm the geological interpretations, although in samples below paleosol V-L1S1S2, the age increase with depth is less than in our proposed age model. Magnetic susceptibility and sedimentological evidence from the Irig loess-paleosol sequence show general similarities with the MIS 6-1 pattern of the SPECMAP oxygen-isotope curve. Malacogical investigations at the Irig site reveal the continuous presence of the *Chondrula tridens* and *Helicopsis striata* faunal assemblages throughout the last glacial and final part of the penultimate glacial loess. The loess snail fauna, which is characterized by the complete absence of cold-resistant species, suggests a stable, dry, and relatively warm glacial climate, compared with other central European loess localities. Furthermore, these data suggest that the southern slope of Fruška Gora was a refugium for warm-loving and xerophilus mollusc taxa during the otherwise unfavorable glacial climates of the Late Pleistocene.

Components: 6668 words, 7 figures, 2 tables.

Keywords: Irig; Serbia; loess; molluscs; Late Pleistocene; paleoclimate; paleoenvironment.

Index Terms: 3344 Atmospheric Processes: Paleoclimatology (0473, 4900); 3305 Atmospheric Processes: Climate change and variability (1616, 1635, 3309, 4215, 4513).

Received 21 December 2006; **Revised** 17 May 2007; **Accepted** 3 July 2007; **Published** 19 September 2007.

Marković, S. B., E. A. Oches, W. D. McCoy, M. Frechen, and T. Gaudenyi (2007), Malacological and sedimentological evidence for "warm" glacial climate from the Irig loess sequence, Vojvodina, Serbia, *Geochem. Geophys. Geosyst.*, *8*, Q09008, doi:10.1029/2006GC001565.

1. Introduction

[2] The processes of formation, transport, deposition, and post-depositional modification of aeolian dust are intimately coupled to changes in regional and global climate. Present global aeolian dust deposition is significantly lower than it was during glacial periods. Intensive glacial-period dust accumulation was widespread across the midlatitude regions of the globe. In contrast, during interglacials, the climate was warmer and generally wetter, which led to enhanced pedogenesis, accompanied by minor dust influx. Numerous climatic oscillations are marked by alternating loess and soil units documenting Pleistocene paleoclimatic and paleoenvironmental evolution. Recently, the last glacial-interglacial loess-paleosol record has received considerable research attention because of high accumulation rates, widespread occurrence, and a well developed chronological framework [e.g., *Evans and Heller*, 2001; *Porter*, 2001; *Frechen et al.*, 2003; *Roberts et al.*, 2003; *Prins et al.*, 2007].

[3] The loess-paleosol sequences of the last glacial-interglacial cycle from western, central, and eastern Europe recorded many climatic oscillations and different environments ranging from tundra-like landscapes to humid interglacial forests [e.g., *Kukla*, 1975, 1977; *Kukla and Cilek*, 1996; *Vandenberghe et al.*, 1998; *Vandenberghe and Nugteren*, 2001; *Rousseau et al.*, 1998, 2001, 2002; *Antoine et al.*, 1999, 2001]. In contrast, climate reconstructions from loess of the Vojvodina region in northern Serbia indicate a smaller range of temperature and precipitation variations and reduced late Pleistocene malacofaunal diversity through the last interglacial-glacial cycle, compared with more northerly sites [e.g., *Marković et al.*, 2004a, 2004b, 2005, 2006, 2007; *Gaudenyi et al.*, 2003].

[4] In this study we investigate the sedimentological and malacological record of late Pleistocene climate and environment from the loess sequence at Irig, on the south slope of Fruška Gora, in Vojvodina, Serbia. Using amino acid racemization and optically stimulated luminescence dating methods, combined with a detailed reconstruction of paleoenvironmental parameters, we present evidence for "warm and dry" loess accumulation in this region of Serbia. This contrasts with paleoclimatic reconstructions from other parts of the loess belt of Europe, where loess typically formed in a periglacial, or tundra-steppe environment. This study highlights the importance of the Irig loess-paleosol sequence for understanding the environmental dynamics recorded in southeastern European loess deposits and how it differs from other European regions for the time period of the last 150,000 years.

[5] The Irig loess-paleosol sequence (45°05′N latitude; 19°52′E longitude) is exposed in a brickyard situated on the east bank of Jelence Stream in the central part of the south loess slope of Fruška Gora (Figures 1 and 2). An approximately 80 km long, 15 km wide, E-W trending range of mountains, reaching only about 540 m elevation, Fruška Gora is flanked by a thin mantle of loess, from the Danube and Sava alluvial plains up to an elevation of approximately 400 m. Four loess layers and three fossil soils are exposed in the approximately 8 m thick sediment sequence at Irig.

[6] Present-day climate in the region is continental, with air masses from northern and western Europe funneling into the southern Carpathian (Pannonian) Basin. The Dinaric Alps to the west block most Mediterranean influence, although warm, moist Adriatic air reaches the southern part of Serbia. The investigated region is characterized by mean annual temperatures of 11.1°C, with summers averaging about 21°C and winters averaging only 0.6°C. Mean annual precipitation, which is dominated by summer rainfall, is about 610 mm.

2. Material and Methods

[7] The investigations of the loess-paleosol sequences at the Irig quarry began in 2001. Bulk sediment samples were collected at 5-cm intervals for granulometric analysis, and at 25-cm intervals for malacological studies. Dry and moist colors of

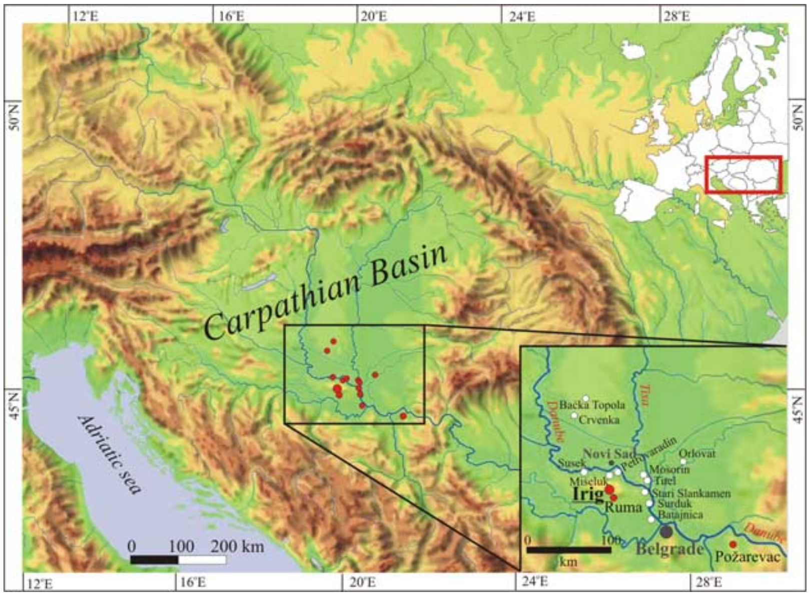

Figure 1. Geographic position of the Irig brickyard exposure and other relevant sites in the Vojvoida loess region.

the loess and paleosol were described using Munsell Soil Color Charts. Grain size (GS) fractions (<2, 2–20, 20–200, >200 μm) were measured by sieving and pipeting, following procedures noted in *Marković et al.* [2004a], and carbonate content was analyzed gas volumetrically. Magnetic susceptibility (MS) variations were measured in the field using a portable Bartington susceptibility meter. Measurements were recorded at 5-cm intervals; ten independent readings were averaged for each level.

[8] Fifteen-kilogram bulk sediment samples for malacological investigations were sieved through 0.7 mm mesh. After fossil gastropod shells were identified, paleoenvironmental classification was done by comparison with the interpretations of *Ložek* [1964], but also extended with some local

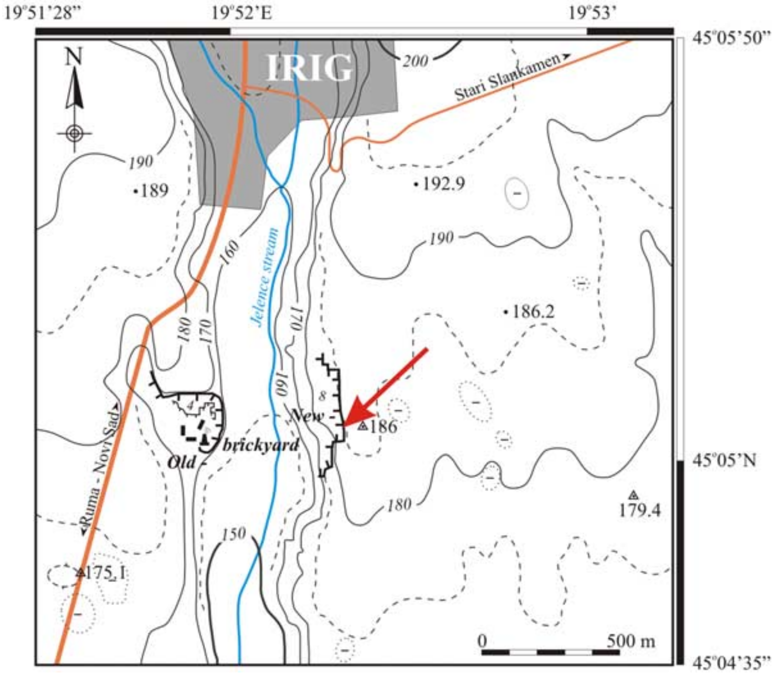

Figure 2. Topographic map of the area surrounding the Irig brick mine. Position of the investigated exposure is indicated by arrow.

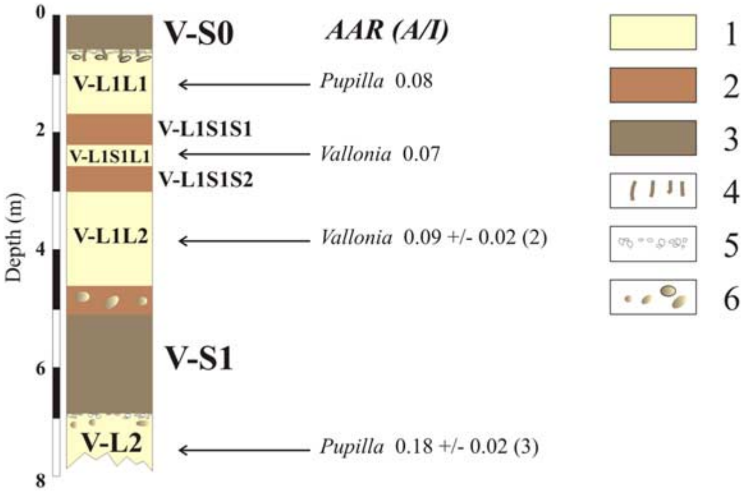

Figure 3. Stratigraphy of the Irig brickyard exposure. Positions of samples for amino acid analysis are indicated by arrows. Total hydrolysate (HYD) alloisoleucine/isoleucine (A/I) values are shown for the gastropod genera *Pupilla* and *Vallonia*. Number in parentheses indicates the number of individual shells separately prepared and analyzed. Legend: 1, loess; 2, chernozem-like A horizon; 3, chernozem A horizon; 4, root infiltrations; 5, carbonate concretions; 6, crotovinas.

variants, as defined by *Krolopp and Sümegi* [1995] and *Sümegi and Krolopp* [2002]. July paleotemperatures were estimated using the malaco-paleothermometer method of *Sümegi* [1989, 1996] and *Herelendi et al.* [1992]. This method is based on modern geographic and climatic ranges of 11 dominant gastropod species from a composite malacofauna [*Sümegi*, 1996]. For selected gastropod species, optimal climatic conditions can be determined along the minimum and maximum temperature values of tolerance (activity range of gastropods) with respect to actual climatological data.

[9] Gastropod shells were collected from three levels within V-L1 (last glacial loess) and the uppermost part of V-L2 (penultimate glacial loess) for amino acid racemization analysis in order to correlate the stratigraphy independently with presumed synchronous loess-paleosol units elsewhere in Europe. Details of the sample preparation and analytical procedures are presented by *Oches and McCoy* [2001].

[10] Infrared optically stimulated luminescence (IRSL) measurements were carried out on 4 loess samples, three of which were taken from above the strongly developed paleosol V-S1 and one from below the paleosol. IRSL samples were collected in light-proof containers at depths of 1.70 m, 3.40 m, 5.30 m and 7.50 m. Polymineral fine-grained material (4–11 μm) was prepared for the determination of equivalent dose, as described by *Frechen et al.* [1996]. The samples were beta irradiated by a ^{90}Sr beta source in at least seven dose steps with five discs each and a maximum radiation dose of 750 Gray (Gy). All discs were stored at room temperature for at least four weeks after irradiation. The irradiated samples were preheated for 1 minute at 230°C before infrared stimulation. Equivalent dose values were determined using IRSL. A Schott BG39/Corning 7–59 filter combination was placed between photomultiplier and aliquots for IRSL measurements. A 10 s IR exposure was applied to obtain their IRSL signals. The equivalent dose was obtained by integrating the 1–10 s region of the IRSL decay curves using an exponential fit. Alpha efficiency was estimated to a mean value of 0.08 ± 0.02 for all samples [cf. *Lang et al.*, 2003]. Dose rates for all samples were calculated from potassium, uranium and thorium contents, as measured by gamma spectrometry in the laboratory, assuming radioactive equilibrium for the decay chains. Cosmic dose rate was corrected for the altitude and sediment thickness, as described by *Aitken* [1985] and *Prescott and Hutton* [1994]. The natural moisture content of the sediment was estimated to 15 ± 5% for all samples.

3. Results

3.1. Lithostratigraphy and Pedostratigraphy

[11] The stratigraphic framework of loess in the Vojvodina region is relatively simple. Eolian dust

Table 1. Morphological Description of the Loess-Paleosol Sequence at the Irig Brickyard Exposure

Unit/ *Subunit*	Thickness, cm	Depth, cm	Description
V-S0	45	0–45	Modern soil is a chernozem on the loess plateau. The lower Ck horizon contains many $CaCO_3$ nodules of 1–3 cm diameter and numerous crotovinas and root channels filled with humic material. A transitional AC horizon (10YR 5/1–3/3) is 10 cm thick and consists of silt loam with fine blocky structure and abundant pseudomycelia. The Ah horizon (10YR 6/3–4/4) is a 20 cm thick silt loam with granular structure and some carbonate pseudomycelia.
V-L1	405	46–450	Porous pale yellow loess (5YR 7/3, 5/4).
V-L1L1	135	46–180	Very porous, pale yellow loess (10YR 7/4–5/3) with many humic infiltrations and soft spherical carbonate concretions (ø –5 cm), intensively bioturbated.
V-L1 S1	125	181–235	V-L1S1S1: the upper 10YR 6/4 = 2–4/2) mollic Chernozem-like A horizon with weak granular structure.
		236–250	V-L1S1L1: thin loess layer (10YR 6/3 4/2) with carbonate concretions (ø 1–2 cm).
		251–305	V-L1S1S2: the lower 10 YR 6/3–4/2 mollic Chernozem-like A horizon with carbonate pseudomycelia.
V-L1L2	145	306–450	Porous pale yellow loess (5YR 7/3, 5/4).
V-S1	245	451–695	Strong developed chernozem-pedocomplex: the lower Ah horizon has weak platy structure (10YR 5/2–3); the upper mollic A horizon with brighter color (10YR 6/2–4) and many carbonate pseudomycelia.
V-L2	∼100?	696-?	Porous yellow (5YR 7/3, 5/4) loess with many humus infiltrations and carbonate concretions (ø 1–3 cm).

accumulated semi-continuously on a nearly horizontal platform of the Pannonian plain, which is a morphologically similar setting to the Chinese loess plateau [e.g., *Liu*, 1985; *Kukla*, 1987; *Kukla and An*, 1989]. Following the same criteria presented in more recent studies [*Marković et al.*, 2004b, 2005, 2006, 2007], we describe and stratigraphically characterize three paleosol and four loess layers at the Irig quarry (Figures 2 and 3 and Table 1). We use the prefix "V" to refer to the standard Pleistocene loess-paleosol stratigraphy in the Vojvodina region. Loess unit V-L2 is about 100 cm thick, correlates to the penultimate glacial period, and is exposed in the lower part of profile as a result of the brickyard excavation. V-L2 loess is covered by the strongly developed interglacial-early glacial soil complex V-S1, which has a thickness of 245 cm. The last glacial loess unit V-L1 and the Holocene soil V-S0 have thicknesses of 405 cm and 45 cm, respectively. Major changes in color, sedimentology and magnetic properties occur at the contacts of loess horizon V-L2, paleosol V-S1, loess layer V-L1, and recent soil V-S0. These lithological changes correlate very likely to marine oxygen-isotope stage (MIS) 6/5, 5/4, and 2/1 transitions. Table 1 shows the detailed morphological description of the loess-paleosol sequence at the Irig section.

3.2. Geochronology

[12] Stratigraphic correlations with the marine oxygen-isotope record are supported by interpretations based on relative dating of V-L1 and V-L2 loess by amino acid racemization (AAR) and numerical age estimates on V-L1 loess from infrared optically stimulated luminescence (IRSL) methods.

[13] Amino acid racemization geochronology, using fossil terrestrial gastropod shells, has been successfully applied to mollusks from loess-paleosol sequences in different regions of the world [*Oches and McCoy*, 2001] resulting in a more reliable correlation and paleoclimatic interpretation than previously. Shells of the gastropod genera *Pupilla*, *Vallonia*, and *Helicopsis* were found in different levels at the Irig section. They were analyzed for D- and L-stereoisomers of several amino acids by reverse-phase liquid chromatography following the methods described by *Kaufman and Manley* [1998]. This study focuses on the ratios of diastereoisomers D-alloisoleucine and L-isoleucine (A/I) in *Pupilla* and *Vallonia* shells. Data from other amino acids, including D/L-aspartic acid, glutamic acid, valine, and phenylalanine, are in agreement with A/I data. The results of total hydrolysate (HYD) A/I measurements on representative samples are shown in Figure 3. *Pupilla* and *Vallonia* shells yielded reproducible

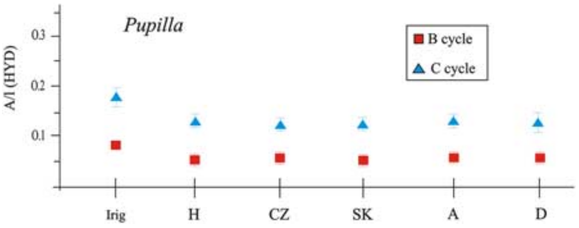

Figure 4. Aminostratigraphy of the Irig brickyard section compared with other representative central European localities for glacial cycles C and B, corresponding to marine oxygen-isotope stages 7–6 and 5–2, respectively, for the genus *Pupilla.* H, Hungary; CZ, Czech Republic; SK, Slovakia; A, Austria; D, Germany.

A/I measurements from V-L2 and V-L1 loess units and offer the most direct aminostratigraphic comparison with data from synchronous loess units at Austrian, Czech, Slovakian, Hungarian and German sites [*Zöller et al.*, 1994; *Oches and McCoy*, 1995a, 1995b, 2001; *Oches et al.*, 2000; *Novothny et al.*, 2007] (Figure 4). Amino acids in *Pupilla* and *Vallonia* shells racemize at comparable rates, and the A/I ratio can be directly compared between the two taxa [*Oches and McCoy*, 1995a]. HYD A/I values measured in *Pupilla* and *Vallonia* from V-L2 loess (0.18 ± 0.02, n = 3) are twice as high as those from V-L1 loess (0.08 ± 0.01, n = 4), which is typical for the differences in ratio observed in samples bracketing the last interglacial paleosol. Furthermore, we determined comparable, though slightly lower, values in shells from loess of the penultimate and last glacial loess investigated elsewhere in central Europe, as shown in Figure 4.

[14] Present-day mean annual temperatures are higher in southern Hungary and Serbia than in the more northern regions. A higher effective diagenetic temperature can explain the more rapid rate of racemization, and therefore higher A/I values, in samples from the Vojvodina loess, compared with synchronous loess units from other central European sites [*Marković et al.*, 2004b, 2005, 2006, 2007; *Oches et al.*, 2004]. The HYD A/I values measured in *Pupilla* and *Vallonia* show that the method can clearly distinguish between loess of the two last glacial cycles. These data support the correlation of V-L2 and V-L1 loess with MIS 6 and MIS 4-2, respectively. Note, however, that these amino acid data cannot distinguish between V-L1L1 and V-L1L2 at Irig.

[15] Luminescence dating (Table 2) provides a means for establishing numerical ages for the last glacial loess, although age underestimation is apparent for the sample taken from the V-L2 loess. Similar observations were made for samples from other European loess regions [*Wintle and Packman*, 1988; *Frechen*, 1992; *Frechen et al.*, 1997]. Uranium, thorium and potassium content range from 3.20–3.27 ppm, 10.93–12.99 ppm, and from 1.50–1.96%, respectively, resulting in a calculated dose rate between 3.90 and 4.40 Gy/ka. The mean dose rate is 4.09 Gy/ka (n = 4), which is in the range of central European loess [cf. *Frechen et al.*, 2001]. The IRSL equivalent dose values increase with depth from 72.5–368.3 Gy. IRSL age estimates are 18.6 ± 1.6 ka for the uppermost loess layer V-L1L1, 42.3 ± 3.3 ka for loess associated with the weak interstadial paleosol, 34.5 ± 2.8 ka for the lower unit of the V-L1 loess horizon, and 83.6 ± 6.4 ka for the uppermost part of the penultimate glacial loess V-L2 (Table 2). An unexplained stratigraphic inversion is apparent in IRSL ages between samples 3 (V-L1S1L1) and 2 (V-L1L2). The lowermost age estimate is very likely significantly underestimated by >50%. Results for samples from penultimate glacial loess in Hungary [*Wintle and Packman*, 1988; *Frechen et al.*, 1997], Germany [*Frechen*, 1999] and Kazakhstan [*Machalett et al.*, 2006] gave similar age underestimations. Anomalous fading could be

Table 2. Luminescence Data and Ages, Including Depth Below Surface, Uranium, Thorium, and Potassium Content, Cosmic Dose Rate, Total Dose Rate, Paleodose, and IRSL Age Estimates[a]

Sample	LUM Lab Number	Depth, m	Strat. Unit	U, ppm	Th, ppm	K, %	Cosmic, μGy/a	Dose Rate, Gy/ka	Paleodose, Gy	Age, ka
4	400	1.70	V-L1L1	3.27 ± 0.06	10.93 ± 0.12	1.50 ± 0.03	190 ± 10	3.90 ± 0.30	72.5 ± 3.1	18.6 ± 1.6
3	401	3.40	V-L1S1L1	3.20 ± 0.05	11.98 ± 0.10	1.59 ± 0.02	168 ± 8	4.04 ± 0.31	171.1 ± 3.4	42.3 ± 3.3
2	399	5.30	V-L1L2	3.36 ± 0.07	11.26 ± 0.12	1.64 ± 0.03	149 ± 7	4.05 ± 0.31	139.4 ± 4.0	34.5 ± 2.8
1	398	7.50	V-L2	3.22 ± 0.05	12.99 ± 0.10	1.96 ± 0.03	129 ± 7	4.40 ± 0.34	368.3 ± 3.9	83.6 ± 6.4

[a] U, uranium; Th, thorium; K, potassium. Alpha efficiency is 0.07 ± 0.01. Moisture (estimated) is 15 ± 5%.

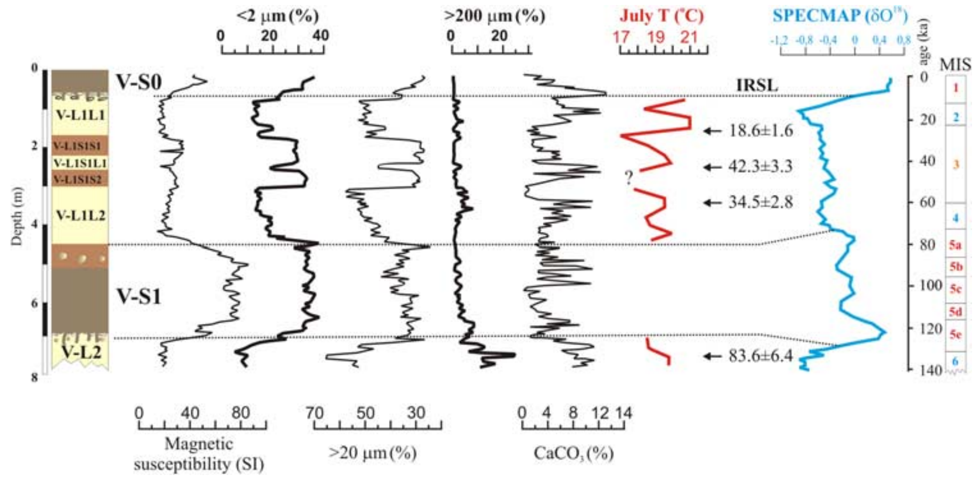

Figure 5. Depth plots of magnetic susceptibility, clay content (<2 μm), particle size fractions 20–200 μm and >200 μm, carbonate content, and inferred July paleotemperatures based on the malaco-thermometer method, and IRSL ages at the Irig exposure, compared with the SPECMAP paleoclimate record [*Martinson et al.*, 1987].

the reason for these age underestimations, although short-time fading tests have not indicated a significant fading rate.

3.3. Sedimentological and Magnetic Investigations

[16] Sedimentological data parallel lithologic variations within the profile, which reflect changes in past climatic and environmental conditions. Magnetic susceptibility (MS), grain-size (GS), and carbonate content measurements reveal patterns that can be correlated with the SPECMAP marine oxygen-isotope record of the last 150,000 years [*Martinson et al.*, 1987]. Variations of MS are related to soil forming processes and reflect differences in composition, concentration, and particle size of magnetic minerals between interglacial and glacial-age sediments [e.g., *Evans and Heller*, 2001]. At Irig MS values measured in soils V-S1 (average 61.1 SI units) and V-S0 (average 40.0 SI units) are higher than those measured in loess units V-L1 (average 21.8 SI units) and V-L2 (average 18.7 SI units) (Figure 5). Interstadial paleosols V-L1S1S2 and V-L1S1S1 have relatively low MS values, compared with interglacial soils V-S1 and V-S0, and are only slightly higher than values measured in loess. This type of MS pattern reflects magnetic enhancement via pedogenesis and is similar to that observed in Chinese and Central Asian loess deposits [e.g., *Heller and Liu*, 1986; *Maher and Thompson*, 1999].

[17] Variations in GS distribution also coincide well with the pedostratigraphy of the Irig sequence (Figure 5). Variability in clay content (<2 μm) mostly parallels the MS record. High clay content is observed in fossil soils (about 30–40%), and low clay content (∼10–15%) is typical for loess. The interstadial soils V-L1S1S2 and V-L1S1S1 have very high clay contents, which approach values measured in full interglacial soils. Variations of coarse silt and sand (20–200 μm) show many abrupt small amplitude changes, possibly linked to variations in wind transport intensity. The coarse fraction (>200 μm) is rather invariant, except for a significant enhancement in the upper part of the penultimate glacial loess, V-L2, and minor increases near the base of paleosol S1 and within V-L1L2 (Figure 5).

[18] At the Irig section, the carbonate content throughout the profile ranges from 0 to 16%, independent of (paleo)soil formation (Figure 5). In contrast to other investigated loess profiles in the Vojvodina region [*Marković et al.*, 2004a, 2004b, 2005], the Irig section is characterized by a lower abundance and smaller sizes of carbonate concretions. Carbonate content variations in the Irig loess-paleosol sequence show a different pattern, compared with carbonate records from other loess sequences in the Vojvodina region. In general, loess from other profiles in Vojvodina have a high carbonate content, but the soils are mostly decalcified [*Marković et al.*, 2004a, 2004b, 2005].

3.4. Malacological Investigation

[19] In our malacological analysis, shells of 735 individuals representing 14 species (12 genera)

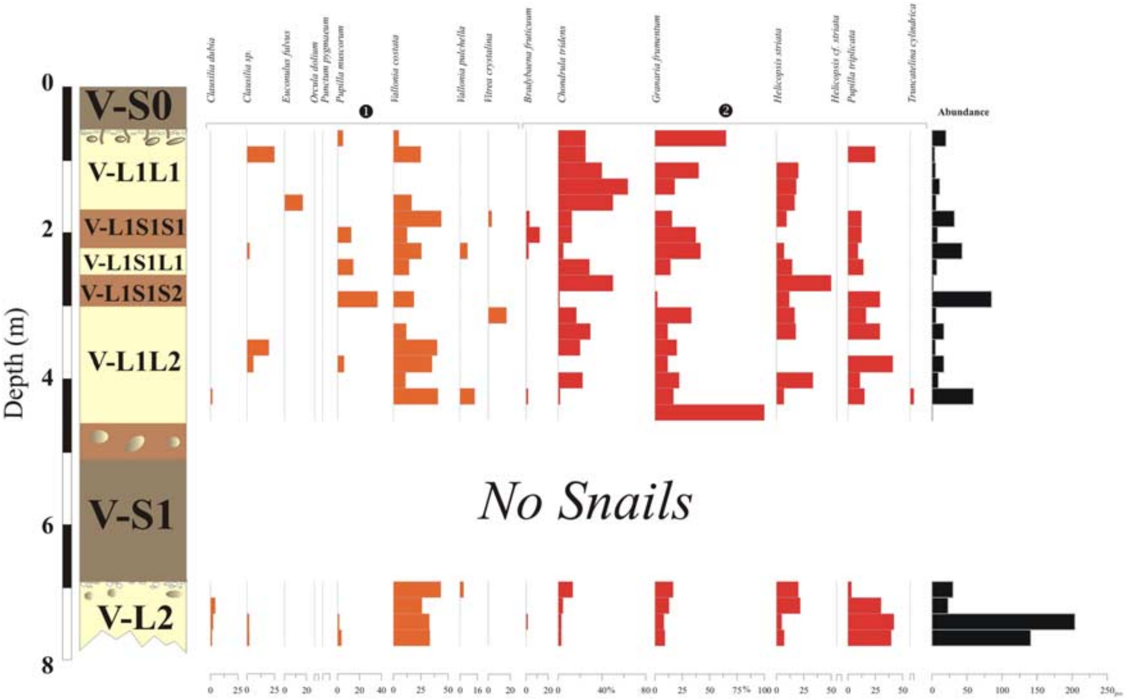

Figure 6. Relative abundance diagram of the identified mollusc species in the Irig brickyard loess exposure. The species (as % of total) are clustered in ecological groups based on temperature sensitivity, as defined by *Ložek* [1964], *Krolopp and Sümegi* [1995], and *Sümegi and Krolopp* [2002]: (1) mesophilous and (2) thermophilous.

were collected from 32 samples. Results are summarized in Figure 6. The fossil gastropod assemblage from the upper part of the V-L2 horizon is characterized by a higher abundance of shells per sample than those from the last glacial loess V-L1. The final stage of the penultimate glacial interval is characterized by the presence of species such as *Vallonia costata* and *Clausilia dubia* indicating relatively cold and somewhat semi-arid climate [*Ložek*, 1964; *Sümegi and Krolopp*, 2002]. No land-snail shells were found in the lower parts of paleosol S1 due to poor preservation and leaching of primary carbonates in the soil. The dominance of temperate thermophilous and aridity-tolerant snails such as *Chondrula tridens*, *Granaria frumentum*, *Helicopsis striata*, and *Pupilla triplicata* in loess V-L1 indicates open vegetation and a mostly dry environment related to steppe-like grassland [*Ložek*, 1964]. Generally, our identified land snail record represents equivalents of the *Chondrula tridens* fauna, which is a typical community associated with interstadial chernozem soils, and the *Helicopsis striata* fauna, which is a characteristic assemblage of the "warm" loess environment in central Europe, as defined by *Ložek* [1964, 2001]. Overall, the terrestrial malacological assemblages reflect a dominantly grassland environment at Irig.

4. Discussion

[20] Paleoclimatic and paleoenvironmental reconstructions derived from the loess-paleosol sequence at the Irig quarry show similarities with previously investigated Late Pleistocene loess sites in the Vojvodina region [*Marković et al.*, 2004a, 2004b, 2005, 2006]. The uppermost part of the penultimate glacial loess V-L2 and three last glacial loess layers V-L1L2, V-L1S1L1 and V-L1L1 accumulated during dry and temperate stadial intervals. During interstadial and interglacial periods, the climate was warmer and generally wetter, which led to enhanced pedogenesis. The interglacial soils S1 and S0 tend to be strongly developed and have significant magnetic susceptibility enhancement. In contrast, interstadial paleosols V-L1S1S2 and V-L1S1S1 are weakly expressed and have MS values only slightly higher than loess, although they have similar grain-size and carbonate values as V-S1 and V-S0. Paleoclimate proxies determined from the loess-paleosol sequence at Irig conform with the general trends in the SPECMAP

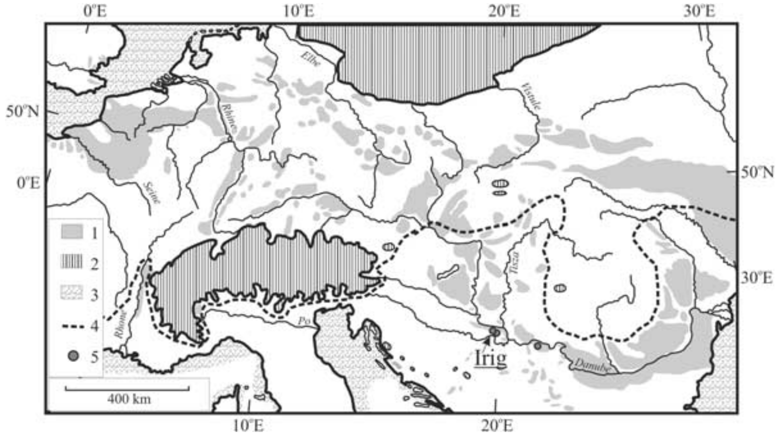

Figure 7. Distribution of the loess sediment across Europe with reconstruction of the continental ice caps during the last glacial maximum (modified from *Moine et al.* [2002] and *Rousseau* [2001]) and the permafrost zone [*Vandenberghe et al.*, 2004]. Legend: 1, loess; 2, ice caps; 3, dry continental shelf; 4, boundary of permafrost zone south of the Alps; 5, sites with "warm" glacial climate record.

[*Martinson et al.*, 1987] model of global paleoclimatic evolution (Figure 5). However, sedimentary proxies from the MIS-3 correlative paleosols at Irig (V-L1S1S1 and V-L1S1S2) suggest that conditions were more similar to the last interglacial period along the southern slope of Fruška Gora than indicated by the globally integrated SPECMAP record.

[21] The glacial landscape and paleoenvironment, as recorded in the Irig loess profile, is characterized by the continuous presence of *Chondrula tridens* and *Helicopsis striata* faunas throughout the sequence, which are typical communities of interstadial periods in other parts of central Europe, as defined by *Ložek* [1964, 2001]. The most important characteristic of the last glacial and late penultimate glacial land-snail assemblages is the absolute absence of cryophilous elements and cold resistant species at the Irig section, which are typical in full-glacial loess deposits elsewhere in Europe. Continuous semi-arid conditions may have reduced the environmental amplitude between the warm and dry interglacial steppe and the "warm" glacial grassland landscape.

[22] Mean July paleotemperatures at Irig are calculated on the basis of the malaco-thermometer method of *Sümegi* [1989, 1996] and *Herelendi et al.* [1992]. The highest (21°C) and lowest (17°C) malacologically determined July paleotemperatures occurred during the accumulation of the lower part of loess horizon V-L1L1. Reconstructed paleotemperatures suggest large temperature changes around the last glacial maximum (Figure 6). In the upper part of loess V-L1L1, the malacofauna indicate stable maximum summer temperatures between about 18°–19°C. On the basis of snail assemblages from pedocomplex V-L1S1 and loess layers V-L1L2 and V-L2, reconstructed July paleotemperatures ranged from about 17°–20°C during those periods of loess accumulation and interstadial soil formation. Generally, summer conditions during the warmer phases of the last glacial period and final part of the penultimate glacial interval at Irig were similar to present (21.5°C). Paleotemperature reconstructions show somewhat higher values for the late pleniglacial loess at Irig than in Hungarian loess sections [*Krolopp and Sümegi*, 1995; *Sümegi and Krolopp*, 2002]. Furthermore, the absence of cryogenic features in loess at Irig and elsewhere in Vojvodina suggests warmer winters than indicated for central European sites to the north and west.

[23] Previous investigations of *Ložek* [1964] and *Kukla* [1975, 1977] indicate that the European loess belt formed under cold and dry continental climate. During the stadial periods, two main cold assemblages were dominant, i.e., the *Pupilla* and the *Columella* communities, essentially correlating to loess-steppe and tundra-like environments, respectively. *Rousseau* [2001] compared the general climate evolution during the last pleniglacial in the European loess belt with the present climate of the cold temperate higher latitudes. However, those interpretations are related only to central, western, and eastern European loess regions and have not been extended into the southeastern European region.

[24] Figure 7 shows the distribution of loess deposits over Europe and the reconstruction of the continental ice caps (modified from *Moine et al.* [2002] and *Rousseau* [2001]) and the extension of the permafrost zone [*Vandenberghe et al.*, 2004] during the last glacial maximum. In contrast to "classical" European periglacial loess provinces, the loess of the Carpathian Basin was deposited beyond the periglacial zone. Late pleniglacial climatic and environmental reconstructions provide evidence for higher mean July paleotemperatures and decreasing humidity from the northern to southern parts of the Carpathian Basin during the late Pleistocene [*Krolopp and Sümegi*, 1995; *Sümegi and Krolopp*, 2002]. The Vojvodina region is presently the warmest and driest part of the Carpathian Basin, and a similar climatic gradient most likely existed during the late pleniglacial period. The absence of cryogenic features and snail assemblages having only few cold-resistant species give strong evidence that the last glacial loess deposits in the Vojvodina region accumulated mainly under dry and relatively warm conditions during the glacial periods [*Marković et al.*, 2007]. Recent studies of the Ruma [*Marković et al.*, 2006] and Požarevac [*Jovanović et al.*, 2006] loess-paleosol sequences suggest similar results for paleoclimatic and paleoenvironmental reconstructions and strongly indicate that the southeastern margin of the Carpathian Basin was very likely situated at the northern extent of a southeastern European "warm" glacial province.

[25] This study raises questions about the importance of local environmental conditions for loess deposition. The most important criteria for classifying loess deposits are the global climatic conditions under which they accumulated. However, deflation and aeolian dust deposition are dependent more on regional climatic characteristics than on local climatic and environmental conditions [e.g., *Wright*, 2001; *Smalley et al.*, 2006], including temperature, moisture and wind regime under which particle generation, entrainment, transport and deposition occurred. The loess of the Irig section can be classified according to local environmental conditions as the "dry warm" variety of the "glacial" loess deposition model based on general climatic predispositions. In general, loess at the Irig site accumulated and formed when global climate was in a glacial mode. However, reconstruction of local climatic conditions during the period of loess deposition indicate significantly warmer and drier glacial summers and warmer winters than in other well investigated localities within the European loess belt [e.g., *Kukla*, 1975, 1977; *Vandenberghe et al.*, 1998; *Rousseau et al.*, 1998, 2001, 2002; *Antoine et al.*, 1999, 2001].

5. Conclusions

[26] Investigations of the loess-paleosol sequence at Irig have established the importance of this site as a record of late Pleistocene paleoclimate and paleoenvironment in Serbia. The Irig section, as the one of the most extensively investigated Serbian exposures, provides an opportunity to reconstruct local and regional environmental processes and conditions during the late Pleistocene.

[27] Sedimentological, pedological, magnetic, and paleontological evidence recorded in the Irig loess-paleosol sequence suggest periods of warmer and drier environmental conditions in this region than in other parts of the Pannonian (Carpathian) basin during the last ~150,000 years. Identified malacofauna reveal important paleoclimatic and paleoenvironmental interpretations. The southern slope of the Fruška Gora was a biogeographical "island" during the last glacial period, where a temperate grassland with dry-tolerant and warm-loving faunal elements remained, even in the coldest phases of late Pleistocene glacial episodes.

Acknowledgments

[28] We thank Mladjen Jovanović and Stevan Savić for their help during the fieldwork and laboratory measurements. We also wish to thank the Irig Brick factory for allowing the team to work in the quarry. We are grateful to Jef Vandenberghe, Ulrich Hambach, and Maarten Prins for helpful, substantive reviews of this manuscript. This research was supported by Project 146019 of the Serbian Ministry of Science and Environmental Protection and U.S. National Science Foundation grants ATM-0081754 to Oches and ATM-0081115 to McCoy.

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