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A Glacial–Interglacial Malacofauna Record from the Titel Loess Plateau, Serbia, between ~350 and 250 ka

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Citation: Radaković, M.G.; Gavrilović, B.; Gavrilov, M.B.; Marković, R.S.; Hao, Q.; Schaetzl, R.J.; Zeeden, C.; Cai, B.; Perić, Z.M.; Antić, A.; et al. A Glacial–Interglacial Malacofauna Record from the Titel Loess Plateau, Serbia, between ~350 and 250 ka. *Quaternary* **2024**, *7*, 28. https://doi.org/10.3390/quat7020028

Academic Editor: James B. Innes

Received: 20 January 2024
Revised: 29 May 2024
Accepted: 5 June 2024
Published: 14 June 2024

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Abstract: We present data on molluscan fauna within the L3 loess unit (and partially within the S3 paleosol) from the key loess section of Veliki Surduk in Serbia. The section correlates to Marine Isotope Stage (MIS) 8 and late MIS 9 and, thus, spans the time frame from ~350 to 250 ka. The Veliki Surduk loess–paleosol sequence (LPS) is located on the northwestern margin of the Titel loess plateau and comprises ~30 m of sediments. Our focus is on a 5.4 m thick sedimentary interval, which was sampled at 20 cm increments, each sample covering approximately 2 ky. Nine mollusk species were identified in the loess sequence: *Granaria frumentum*, *Helicopsis striata*, *Pupilla triplicata*, *Chondrula tridens*, *Pupilla muscorum*, *Succinella oblonga*, *Punctum pygmaeum*, *Vallonia costata*, and *Vitrina pellucida*, as well as a few unidentified slug taxa (Limacidae, Agriolimacidae, and Milacidae). The majority of the snail assemblage occurs at the transition between MIS 9 and MIS 8, suggesting a mostly dry climate and an open and steppe-like habitat. The fauna identified in the upper part of the paleosol layer S3, below the L3 unit, indicated aridification.

Keywords: malacofauna; Titel loess plateau; L3; MIS 9; MIS 8; Veliki Surduk

1. Introduction

Examination of molluscan (land snail) fauna can provide detailed information about Quaternary paleoenvironments, as the presence of different species indicates shifts in biotopes, which are driven in large part by changes in climate [1–3]. Several studies of malacological (mollusks) assemblages from loess–paleosol sequences (LPS) have been

used to produce paleoenvironment and paleoclimatic reconstruction for parts of Eurasia (e.g., [4–7]).

Studying Quaternary mollusks has a long tradition in Central and Western Europe, e.g., Czechia and Slovakia [1,8], Poland [9,10], France [11,12], the United Kingdom [13,14], and Hungary [15,16]. Even though the classical approach of determining the taxa in Pleistocene sediments is a necessary first step in such investigations, some contemporary European loess mollusks have been studied for different aims, such as (1) to improve the chronology of the LPSs by dating the mollusks with ^{14}C, (2) to obtain relative ages by applying amino acid geochronology methods, (3) to distinguish Dansgaard–Oeschger events according to their abundances in samples, or (4) to reconstruct the past biostratigraphic context of the region by studying their taxonomic assemblages (e.g., [5,17–22]). A new trend in mollusk analysis involves measuring clumped isotopes (Δ_{47}) for temperature estimation [7]. However, concerns remain about how shell treatment before measurement affects the reconstructed temperatures of the growing season [23]. Despite these novel methods in mollusk analysis, we draw attention to the words of the famous malacologist Vojen Ložek: "*It is surprising how little attention has been paid to the mollusc fauna, which occurs so frequently in loess that it can rightly be considered one of the main characteristics of this sediment*" (cited after Rousseau, 2021 [24]). His words continue to highlight the relevance of "classic" malacological investigations.

Vojvodina, the northernmost region of Serbia (Figure 1a,b), has some of the best-studied LPSs of the Middle Danube River basin [25–31]. This region is well-known for its thick (up to 50 m) loess deposits, which are an important and multifaceted paleoenvironmental archive [26,28,32]. Loess on the Titel loess plateau (TLP) spans the last five glacial–interglacial cycles [33] and has the highest loess accumulation rates in the region [28,34], thereby providing finer temporal resolution than other sites. The plateau resembles a broad tableland of loess set within alluvial plains. River valleys separate it from the Bačka loess plateau to the north, the Tamiš loess plateau to the east, and the Srem loess plateau to the south [25,35]. Similar plateau-like conditions were also present during the formation of the older LPSs at the site.

Regardless of the widespread occurrence of loess sediments in the Vojvodina, only several LPSs have been studied for mollusks (Figure 1b). The two Hungarian sites, Katymár and Madaras, have detailed malacofauna data—the highest resolution of any LPSs in the vicinity of the study area [36,37]. The shortfall of these studies is that the data only go back as far as MIS 3. Any of the more southerly loess sites have longer, older malacological records. For example, the malacological record from the Batajnica LPS [38] covers the interval from MIS 7 to MIS 5. In Croatia, Šarengrad I and II and Zmajevac LPSs, which have been analyzed multiple times [39–41], contain malacological material from as far back as MIS 9 and MIS 7, respectively. The oldest investigated record (MIS 10) is from the south-easternmost periphery of the Carpathian Basin, in the Požarevac A and B LPSs [42]. Another Middle Pleistocene record is from the southern slope of the Fruška Gora mountain [43]. Except for these examples of long-term malacological records, LPSs in Serbia have usually been analyzed for only the last (or for the last two) glacial and interglacial cycles, i.e., the latest part of MIS 6, and from MIS 4 to MIS 2. Examples include records from Mišeluk [44], Petrovaradin [45], Susek [46], Irig [47], Titel Brickyard and Rogulićev Surduk [48], Crvenka [6], and Zemun [49].

Previous studies of the loess at the Veliki Surduk LPS did not include malacological investigations [26,28,33,34,50,51]. The aim of this study is to reconstruct the environmental and climatic conditions of the TLP at the Veliki Surduk LPS based on data from its malacofaunal assemblages, which cover the period of transition from interglacial (MIS 9) towards the glacial period (MIS 8).

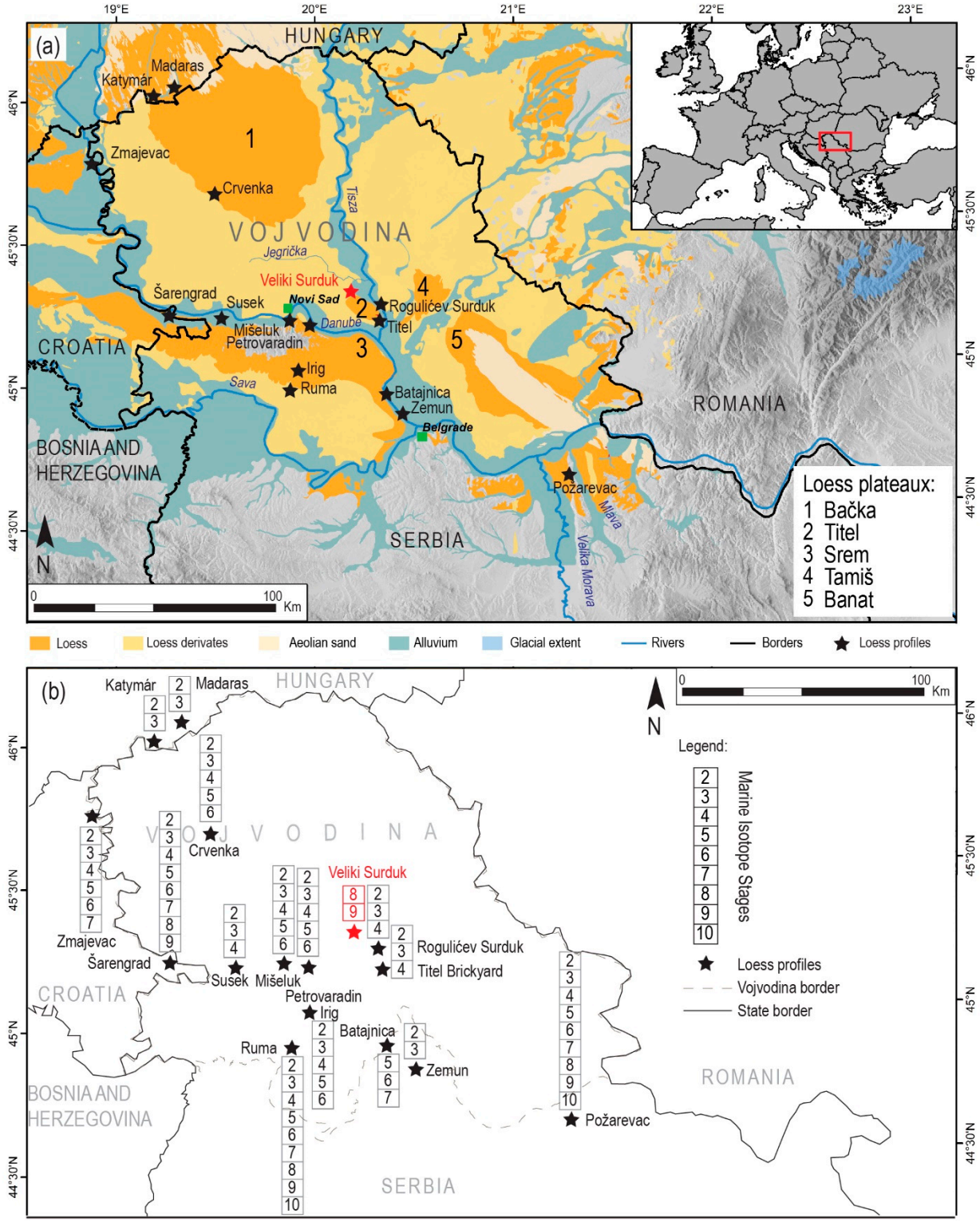

Figure 1. Loess–paleosol sites of interest across the study area. (**a**) The location of the Veliki Surduk LPS and others in the Vojvodina Province (Serbia), and the position of Vojvodina Province (Serbia) in Europe. Map after Lehmkuhl et al. (2018) [52]. (**b**) The temporal coverage expressed as Marine Isotope Stages of existing malacological records in the vicinity of Veliki Surduk: Madaras [37], Katymár [36], Zmajevac [41], Crvenka [6], Roguličev Surduk [48], Šarengrad [39], Ruma [43], Susek [46], Mišeluk [44], Petrovaradin [45], Titel Brickyard [48], Irig [47], Batajnica [38], Zemun [49], and Požarevac [42].

2. Materials and Methods

2.1. Description of the Study Site

The TLP is situated near the confluence of the Tisa and Danube rivers, in the south–central part of Vojvodina, at 45°17′46.01″ N and 20°11′16.06″ E (Figure 1a). Three LPSs that have been studied for their malacological record are situated on the northern edges of the TLP: Rogulićev Surduk [48], the Titel Brickyard [48], and Veliki Surduk—the site from this study. The loess at Veliki Surduk is 30 m thick. The reasons for studying this site are as follows: (1) it is a well-known section with already published proxies [28,32], and (2) no such old malacological record exists for TLP. Based on known Danube loess stratigraphy [26], our loess data from Veliki Surduk span the younger part of the S3 paleosol (~MIS 9) and the L3 loess unit above (~MIS 8). Compared to the Holocene soil on the TLP, the S3 paleosol is more strongly developed, with almost 3 m thickness [26]. In this study, only the malacofauna from the uppermost 0.6 m of the S3 paleosol was sampled, along with the overlying loess. Compared to the younger loess units in this section, the L3 loess is the thinnest. A detailed description of the sampled section is given in Table 1.

Table 1. Description of the Veliki Surduk loess–paleosol sequence. The thickness of the investigated interval (L3 and S3) is shorter than these stratigraphic units.

Unit	Thickness (cm)	Depth (cm)	Description
L3	460	2370–2830	Massive, porous pale yellow (5YR 4/3, 5/4) loess with many humus infiltrations and carbonate concretions (ø 1–3 cm), with Fe and Mn nodules in the lowest half meter, intensively bioturbated in the upper part in contact with the base of paleosol S2 above.
S3	60	2830–2840	Mollic A horizon with brighter color (10YR 6/2–4) and many carbonate pseudomycelia.
		2840–2885	Ah1 lower humic (10YR 6/3, 4/2) horizon with granular structure, carbonate concretions (ø 1–2 cm) and krotovinas.
		2885–2890	Upper lighter Ah2 (10YR 6/3-4) horizon with carbonate concretions (ø 1–2); typical granular structure.

2.2. Sampling Strategy

Loess samples of 10 kg were taken continuously at 20 cm intervals from the studied section. In total, 27 samples were collected from a 5.4 m thick interval spanning from 29.1 m to 23.7 m in depth. Clearly, bioturbated parts of the section were avoided. The uppermost 1 m of loess unit L3 was not sampled due to inaccessibility.

The samples were left in distilled water overnight and then washed through a 0.5 mm sieve with distilled water. The material that remained on the sieve was then air-dried. Shells and shell fragments were identified and sorted using a dissecting stereomicroscope based on the malacological literature [53–57]. We counted a single apex, or a single aperture, as one shell. If both the apex and aperture of the same species were found, they were counted as one shell. Classification of mollusk taxa according to their ecological preferences (temperature, humidity, and vegetation structure) was based on the interpretations of Ložek (1964) [1], Sümegi and Krolopp (2002) [21], Sysoev and Shileyko (2009) [58], and Juřičková et al. (2014) [59], as well as from previously published malacological data from the Serbian LPS [49].

2.3. Malacothermometer July Paleotemperatures

Snails are only active when temperature and humidity conditions allow. They feed on available vegetation and construct their shells during the growing season [60]. Therefore, the reconstructed paleotemperature from snail species data is best interpreted as the mean July temperature (°C) [61]. Because there are almost always multiple snail species in each

loess sample, the formula used for the reconstruction of the mean July temperature is as follows [61,62]:

$$T = \frac{\sum_{i=1}^{n} T_i A_i}{\sum_{i=1}^{n} A_i} \quad (1)$$

In the above equation, the July paleotemperature (T) is dependent on the abundance of snail species in the sample (A_i) and their corresponding temperature, which is unique for each species (T_i). The values of T_i can be found in Sümegi (2019) [63]. This equation has been widely used across the Carpathian Basin [4,42,47,61,62] and has been proven reliable when compared to temperature data derived from non-molluscan proxies, e.g., vole [64], *Coleoptera* [65], or pollen [66], and when compared to regional paleoclimate models [67]. In this study, we present the estimated July paleotemperatures, even if a single shell was presented in a sample, so each temperature estimate has some uncertainty.

2.4. Time-Scale Construction and Grain Size Measurement

Because there is no absolute dating of L3 available, the establishment of the chronology of the Veliki Surduk loess section followed the strategy of Hao et al. (2012) [68]. First, according to the well-accepted correlation scheme between Serbian loess and deep-sea sediments, the absolute age control points are transferred from the MIS boundaries of LR04 [69]. Second, between control points, interpolation, weighted by grain size (content of the >32 mm particles), was used to generate the time scale. The use of grain size in time-scale construction can also be found in Porter and Zhisheng (1995) [70]. This type of age model is more reliable than simple linear interpolation as it encompasses the accumulation rate of loess. A detailed explanation of the formulas used for obtaining the age scale can be found in [68]. As this method requires grain size measurements, loess in the Veliki Surduk section was sampled at 5 cm intervals. The grain size was also used to calculate the U-ratio, as follows [71,72]:

$$U = \frac{< 44\ \text{m} - 16\ \text{m}}{16\ \text{m} - 5\ \text{m}} \quad (2)$$

Particles > 44 μm are excluded from the U-ratio equation because they belong to the predominantly saltation population, and the equation disregards the clay fraction in order to mitigate any potential impact from autogenic clay formation in soils [71,72].

3. Results

Malacology of the Loess Section

The relative contents of all identified molluskan species from the Veliki Surduk LPS are presented on a depth scale in Figure 2. Generally, throughout this sedimentary sequence, snail shells are rare and are often absent. The majority of the snail shells were located in the lowest part of the sampled section. In the S3 paleosol, the dominant taxon was *Pupilla triplicata*, usually comprising >60% of the shells. Other common species include *Pupilla muscorum* and *Vallonia costata*. *Succinella oblonga* made its appearance only in the paleosol, but even there, it typically contributes <10% of the total sample. In the paleosol, only one *Vitrina pellucida* shell was found. With the onset of glacial conditions, *Chondrula tridens* vanishes from the assemblage.

Percentages of snail taxa, as plotted in Figure 2, are normalized by the total abundance in a sample (also shown); the total abundances differed considerably between interglacial (with an average of 128 shells per sample) and glacial (with an average of 14 shells per sample) conditions. The highest diversity within the molluscan assemblages, as well as their abundance, occurs in the lower part of the paleosol S3 and the lower part of the L3 loess. The snail fauna of the antepenultimate glacial unit (L3) of the Veliki Surduk LPS points to a typical loess-steppe environment, as is indicated by the dominance of *Chrondrula tridens*, *Granaria frumentum*, and *Helicopsis striata*, with some yet unidentified slug taxa (Limacidae, Agriolimacidae, and Milacidae). The middle of loess unit L3 is barren of snails—the first time that such a relatively thick loess sequence in Serbia has lacked shell

fragments. Nonetheless, snail abundance gradually increases in the uppermost part of the sampled loess unit but never reaches the abundance of the lowermost samples.

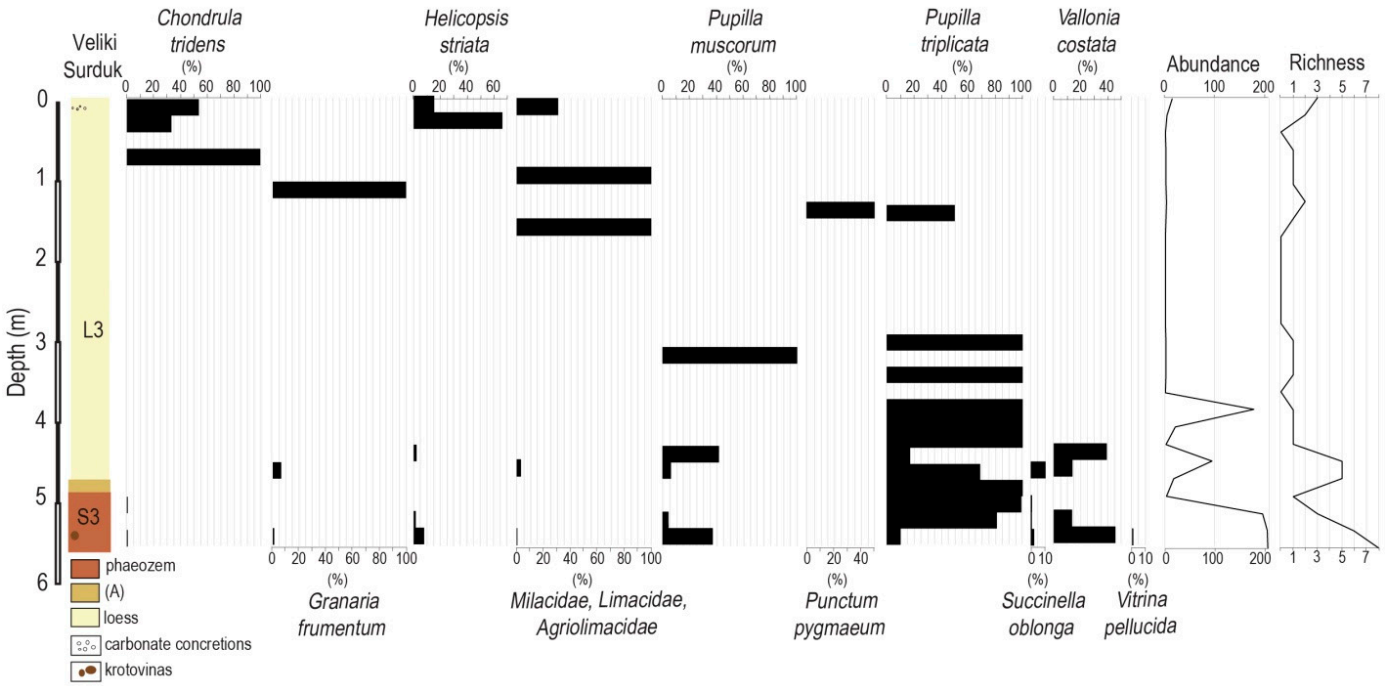

Figure 2. Plot of depth (ordinate) and percentages of snail species for the S3 paleosol and L3 unit at the Veliki Surduk loess section. Abundance and richness are presented on the right.

Figure 3 shows three different environmental classifications (after Sümegi and Krolopp, 1995 [73]) of the malacological fauna. Figure 3a classifies the snail fauna by humidity. During MIS 9, 424 of the 641 identified mollusk shells were aridity-tolerant, with the remaining being mesophilous and hygrophilous. With the start of the antepenultimate glaciation (MIS 8), the aridity-tolerant species increased by 11%.

Figure 3b shows that two-thirds of all identified snails in the loess section are mild preferring, and one-third are highly tolerant according to the temperature classification [73]. The appearance of cold-resistant species *Succinella oblonga* makes up just 1% of all the identified snails in the entire investigated section. The absolute number of highly tolerant snails dropped by a factor of three from the interglacial conditions towards the glacial climate of MIS 8.

Figure 3c classifies the snail species based on their indicative habitats and separates open and transitional habitats. The data indicate that an open grassland habitat was dominant during both MIS 9 and MIS 8; data are more certain for the latter interval. The dominant taxon for the entire period of study—*Pupilla triplicata*—is a good indicator of the general nature of the paleoenvironment: a landscape dominated by aridity-tolerant, mesophilous species in an open grassland environment.



Figure 3. Plot of depth (ordinates) and the percentages of each identified snail species within the S3 paleosol and L3 loess units. Classifications after Sümegi and Krolopp (1995) [73] according to (**a**) humidity, (**b**) temperature, and (**c**) vegetation cover.

4. Discussion

4.1. Chronostratigraphic Context

The sediments in this study belong to the L3 loess unit and the upper part of the S3 paleosol at Veliki Surduk LPS. This stratigraphy, proposed by Marković et al. (2015) [26], is based on clear correlations between key profiles using multiple paleoclimatic proxies. Figure 4 shows the chronostratigraphic interpretation of the nearest sections to Veliki Surduk. Even though radiometric dating from this section is not available, magnetic susceptibility, as well as clearly visible tephra layers, help cement the chronology with the stratigraphy. The overlying loess units of nearby sections have been dated in multiple studies [50,51,74–76]. A recent paper by Namier et al. (2023) [77] explored the volcanic sediments found in loess in Serbia and additionally supported the existing chronostratigraphic interpretations by defining these isochronous markers (red and green in Figure 4).

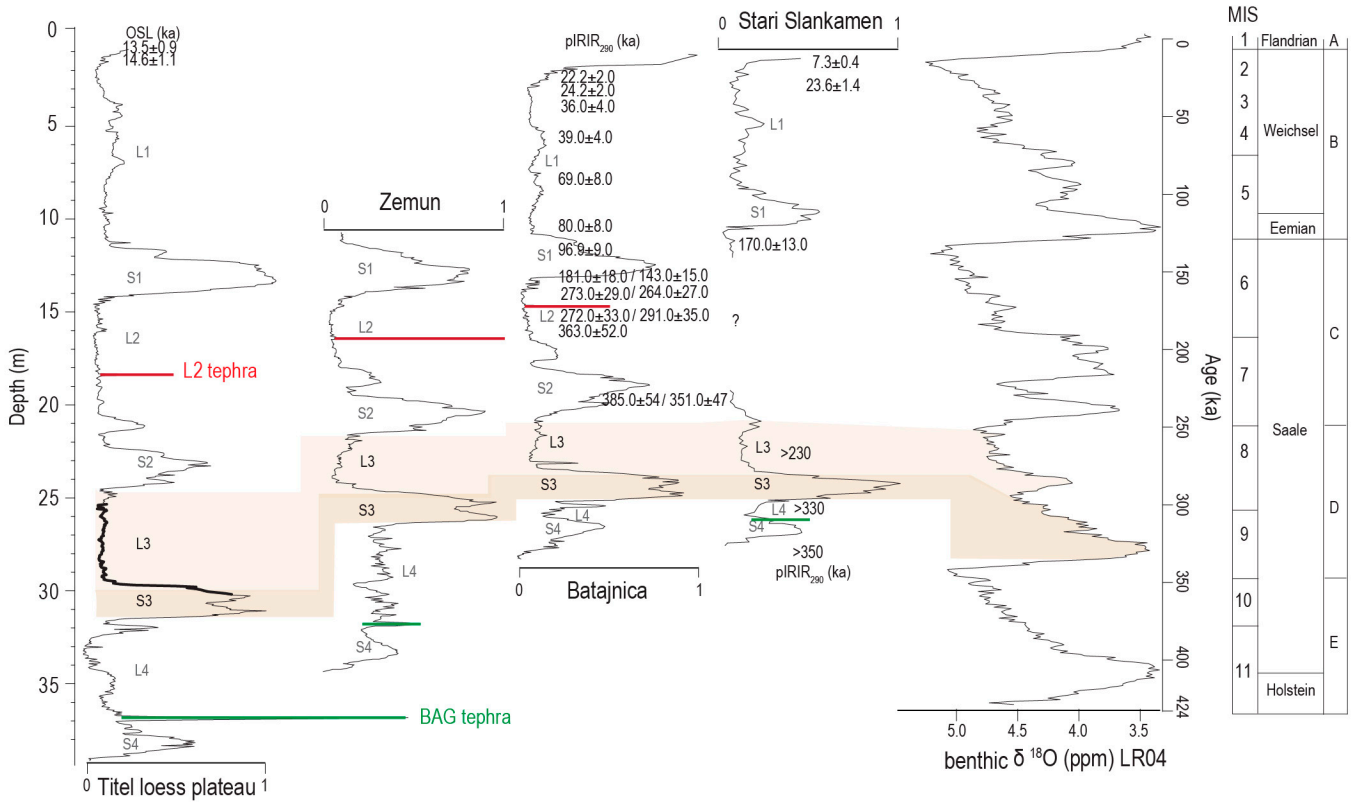

Figure 4. Depth (left ordinate) plot of normalized values of magnetic susceptibility from the Titel loess plateau (from L1 to S3 from Veliki Surduk) [26], Zemun [78], Batajnica [79], and Stari Slankamen [74] loess profiles [80], with luminescence ages for the Titel loess plateau after Constantin et al., 2021 [51], for Batajnica after Avram et al., 2020 [76], for Stari Slankamen after Murray et al. 2014 [73], and the relation to benthic $\delta^{18}O$ from LR04 and Marine Isotope Stages [69] in relation to glacial–interglacial cycles defined by Kukla (1975) [81]. Brown and ochre backgrounds indicate levels of the L3 loess units and the S3 paleosol. Tephra layers are defined according to Namier et al. (2023) [77] and Laag et al. (2021) [78].

Based on the current chronostratigraphic interpretation of the loess profiles in Serbia and the Middle Danube Basin, the L3 loess unit in Veliki Surduk had the highest accumulation rate of all of the studied sections (Batajnica, Zemun, Ruma, and Stari Slankamen), with an average sedimentation rate of ~8 cm/ka [80]. We assume that the section experienced quasi-continuous sedimentation. On the other side of the Danube River, an erosion event on a local scale took place during MIS7 or MIS6 and is visible on the outcrop of Stari Slankamen—no hiatus is visible and assumed here. The tilted paleosols of Stari Slanka-

men [82–85] are evidence for more dynamic neotectonics on the Fruška Gora Mountain than on the Titel loess plateau. The hiatus at Stari Slankamen is indicated with a question mark in Figure 4. Similar hiatuses are not found on the Titel loess plateau.

4.2. Comparison to Other Malacological Records

Malacological investigations in Vojvodina have been conducted on several younger LPSs (Figure 1). On the Bačka Loess Plateau, only the Crvenka LPS is investigated [6,86]. On the Srem Loess Plateau, there are published data from Mišeluk [44], Petrovaradin [45], Susek [46], Irig [47], Batajnica [38], and Zemun [49]. Less than 10 km away from the Veliki Surduk LPS, two sequences at the Titel Brickyard and Rogulićev Surduk have been investigated [48]. Mollusks from other loess plateaus in Vojvodina have not yet been investigated but present great potential for future investigation. All the identified species at Veliki Surduk were also discovered in the younger loess units in the region [6,37,45–49]. The only exception to this is *Vitrina pellucida*, found in the lowermost sample of the studied profile.

Other studies of land snails in Serbia from an equivalent timeframe as our study are only available from Požarevac [42] and Ruma [43]. The main notable trait of the malacofauna at Veliki Surduk is the rich interglacial snail fauna found mainly in the upper part of paleosol S3 and the lower part of L3 (which is not found at Požarevac nor Ruma). The Požarevac LPS is located 115 km to the southeast of the Veliki Surduk LPS (Figure 1b). A malacological interpretation of the Požarevac LPS was given in the study by Marković et al. (2021) [42]. Accordingly, the uppermost part of the L3 loess unit also has a poor malacological assemblage of <5 shells per sample. Concerning the paleohumidity reconstruction based on these two sections, it appears that in both sequences, the majority of the species were aridity-tolerant. Differences exist, however, when the remaining mesophilous and hygrophilous mollusk species are included. The Veliki Surduk site became progressively drier from MIS 9 towards MIS 8. Firstly, we note that the hygrophilous species were absent during MIS 8. Second, the percentage of mesophilous species, mostly encompassed by *Pupilla muscorum* and *Vallonia costata,* declined from MIS 9 to MIS 8 by 10%. At the southeastern edge of the Carpathian Basin, the situation was reversed. The genus *Vallonia* was flourishing during MIS 8 at Požarevac, while it was missing at Veliki Surduk. Most of the snail species at both sites preferred mild conditions during MIS 9 and MIS 8. Furthermore, the snail assemblage indicates that the MIS 8 glacial had generally mild summers, as cold-resistant species were absent. At Veliki Surduk, the percentage of mildness-preferring species increased by 8% during MIS 8.

The calculated Malacothermometer July paleotemperatures for the onset of MIS 8 at Požarevac were 16.0 °C; the temperature was also observed at Veliki Surduk. In the later part of the MIS 8 glacial, the maximum temperatures were 18.5 °C and 20.0 °C, respectively. This indicates that relatively warm summers may have existed during MIS 8, as compared to the modern mean July temperature in the area, 21.5 °C [87]. Finally, if all the snail species are categorized by preferred biotope types, we concluded that the environment was an open grassland during both the interglacial and glacial periods at both Veliki Surduk and Požarevac. The ratio of species that preferred steppe elements to those that lived in forests is almost the same at Veliki Surduk during interglacial and glacial conditions. Contrary to this, the forest-preferring snail taxa at the Požarevac LPS became more pronounced in the MIS 8 glacial, but an open, non-forest environment was still dominant. The transition from grassland to woodlands and vice versa in the Carpathian Basin was proposed to be controlled by available humidity, but the trend over the past 600,000 years indicates that humidity has been gradually decreasing while the continental climate is spreading further south over the Balkans [22,42,47,86,88,89].

The genera *Helicopsis* and *Chondrula* were used for amino-acid racemization at the Ruma LPS, which helps to constrain the relative age of the L3 loess unit based on the values of A/I HYD 0.29 ± 0.04 and 0.34 ± 0.11 for the top and the bottom of the section, respectively [43]. A recent paper [90] reports the relative chronology of the Veliki Surduk

LPS based on the *Pupilla* for the last three glacial periods: (1) GLU D/L: 0.276, 0.277 ± 0.022, 0.313 ± 0.020; (2) A/I: 0.185, 0.202 ± 0.009, 0.331 ± 0.049, corresponding to L1, L2, and L3 loess units, respectively. However, different amino acids measured in different snail genera should not be compared directly but only used as relative values within the same profile to support the chronology. Therefore, the malacological data from the Ruma LPS show the dominance of steppe fauna during MIS 8 glacial conditions but not in a generally cold environment. The discovery of eight bear (*Ursus deningeri*) skeletons in a small area makes the L3 unit unique in Serbia from a paleontological perspective [43].

On the southern bank of the Danube, the Šarengrad II sequence in Croatia also contains sediments from this period. From MIS 10 to MIS 8, the conditions at Šarengrad II showed a switch from flood plain loess deposition to a drier environment; the results were also supported by terrestrial malacological data [39]. Similar to Veliki Surduk, Šarengrad II also had a decreasing number of total shell abundances towards the MIS 8.

High shell abundance is believed to indicate more humid conditions in the region [42]. Finally, based on the malacofauna record of the same period in the wider region (south-eastern Carpathian Basin), the pronounced aridification observed in the antepenultimate glacial MIS 8 was likely typical for the Middle Danube Basin.

4.3. Orbital Forcing

It is well known that Milanković cycles induce changes in global and local insolation. These forcings lead to climatic conditions in which a species can (or cannot) survive due to the narrowing or widening of the preferred biotope [91–96]. Orbital forcing has been shown to play a major role in controlling regional environmental changes and the ecological succession of terrestrial mollusk assemblages on the Chinese Loess Plateau (CLP) [96]. Taxa prefer warm and humid conditions, which are assumed to have been associated with a strong summer monsoon and align with obliquity and precession cycles. *Punctum orphana* is dependent on obliquity and precession in Luochuan and Changwu. These associations are a consequence of the impact of obliquity and precession on the SE Asian summer monsoon when the insolation necessary for the thriving of these thermal–humidiphilous mollusks increases over the CLP [96]. On the other hand, the cold aridiphilous elements, which imply a major period of winter monsoon variations, seem to follow eccentricity and obliquity cycles (*Vallonia tenera* and *Pupilla aeoli*) [96]. Thus, in China, both summer and winter monsoon systems seem tightly coupled through the obliquity cycle from a malacological viewpoint. Yet, precession and eccentricity (~20 and ~100 ka, respectively) cycles have different influences on summer and winter monsoons. Serbia is not influenced by monsoons, and any linkage between snail taxa and orbital parameters has not yet been investigated.

In order to present the results of this study in the context of orbital climate forcing, proxies of the L3 loess unit and S3 paleosol [32] are plotted next to the orbital curves [97] in Figure 5. Here, the transition from MIS 9 to MIS 8 is set at 300 ka, following Lisiecki and Raymo (2005) [69] and Drysdale et al. (2004) [98]. We acknowledge that this transition is sometimes set at ~275 ka in other papers [99–102]. Nevertheless, this discrepancy does not influence the results, as they are plotted from termination IV (337 ka) to termination III (243 ka). Even though these two terminations are shown to last several thousands of years [103], here we used these ages as fixed points. The time-scale for the low-field and frequency-dependent magnetic susceptibility, U-ratio, shell abundance, and Malacothermometer July paleotemperatures in Figure 5 is based on the method of Hao et al. (2012) [68], which fits the magnetic susceptibility from the loess profile to deep-sea sediments, with the interpolation between the fixed points being weighted by grain size. This method, when applied to the Titel loess plateau, provides temporal context for our results. For the validation of the comparison between the Serbian and Chinese loess sections, see, e.g., Marković et al. (2015) [26]. For our sampling resolution of 20 cm, the presented time scale resolution has millennial scale precision.

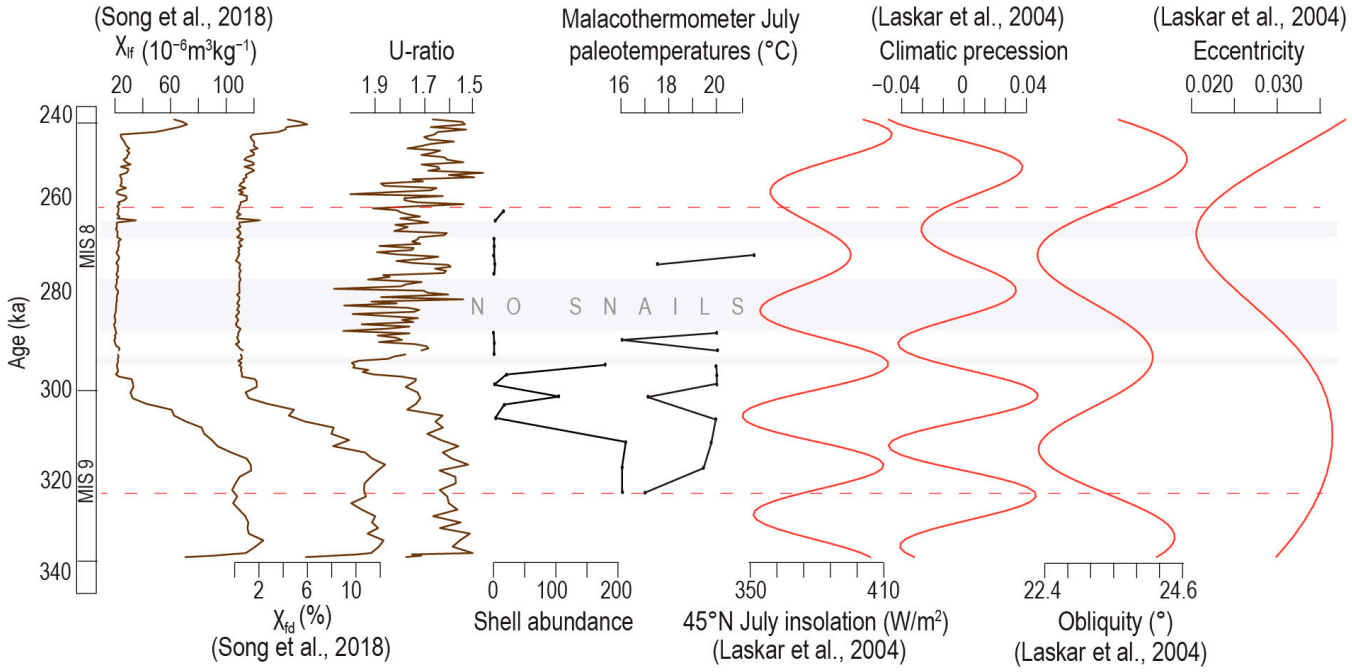

Figure 5. Low-field and frequency-dependent magnetic susceptibility [32], U-ratio (unpublished data), shell abundance, malacothermometer July paleotemperatures of Veliki Surduk LPS, with orbital parameters on their time scale [97]. Gray stripes present samples barren of shells. The part of the graph between the red dashed lines represents the interval studied in this study. Note that malacothermometer July paleotemperatures are calculated based on shells per sample, sometimes even a single shell.

Figure 5 shows that higher mollusk abundances per sample, as seen from the upper part of the paleosol S3 to the lower part of the loess unit L3, correspond with higher global eccentricity. Furthermore, in the middle and upper parts of loess unit L3 (from ~290 ka to 260 ka), which corresponds to low orbital eccentricity, snail shells were less abundant or absent. Due to the snail's absence, calculations of July malaco temperatures were not possible. In the transition period from interglacial to glacial conditions, the calculated Malacothermometer July paleotemperatures aligned well with the variation in July insolation at 45° N (Figure 5).

The low-field and frequency-dependent magnetic susceptibility of the L3 unit and the S3 paleosol roughly parallel the eccentricity and glacial/interglacial cycles. As the eccentricity decreased, magnetic susceptibility values decreased, and the U-ratio shows that the wind began to rapidly oscillate between strong and weak. Even though the sampling resolution was higher for the grain size data, it seems that higher mollusk abundances correspond to more stable U-ratio values. Higher U-ratio values indicate coarse grains in the sediment, i.e., stronger wind activity. Wind intensity fluctuations, in combination with low insolation values, seem to be unfavorable conditions for the snail population on the TLP. The recent paper by Hao et al. (2024) [104] examined the MIS 8 record at the Huining LPS. They proposed that the MIS 8 glacial period, corresponding to the formation of the L3 loess unit on the CLP, is different than the other glacial periods over the last 900,000 years. This is due to the decreasing grain size signal toward the end of the MIS 8 and an unusually mild climate with a warming trend in the middle northern latitudes [104]. In our paper, we show that the U-ratio generally decreases towards the end of MIS 8 at Veliki Surduk, which is in accordance with the trend found by Hao et al. (2024) [104]. They proposed the mechanism behind this finding as an unusual orbital configuration at the time.

Due to a lack of snail shells in the middle of the L3 unit, it is not possible to establish a connection between changes in species' abundance and eccentricity (100 ka cycle), obliquity (41 ka), or precession (19–23 ka) for this interval. The same problem occurred in the L3 unit

of the Požarevac LPS. These linkages between orbital forcings and paleoenvironments (as derived from snail data) at Veliki Surduk are clearly different than those derived from the snail assemblages on the CLP.

4.4. Connection to Regional Records

The Balkan Peninsula has several locations that have preserved records of environmental changes as far back as MIS 9 (~350 ka). Some of these records are from speleothems (OH2 [105,106]) and lacustrine sediments: Tenaghi Philippon [107] and Ohrid [108–111]. Similarities exist between the environmental changes at Veliki Surduk and the oxygen and carbon isotope patterns from the OH2 speleothem record from Northern Macedonia (located near Lake Ohrid [105]) (see Figure 6). Based on this speleothem record, during the period from 325 to 321 ka ago, the conditions were humid in the Balkan Peninsula. This humid episode has also been confirmed by pollen and speleothem records in western and southern Europe [98,100,101,112]. At Veliki Surduk, this period refers to the formation of the S3 paleosol. After this humid period, a dry phase from 321 ka to 313 ka was recorded in the OH2 speleothem. At the end of interglacial MIS 9, this aridification caused forest decline in southern Iberia, the Apennines, and the Balkan Peninsula [108]. From 306 ka ago until 292 ka ago, precipitation started to decline, such that the speleothem OH2 stopped growing (Figure 6). At this time, we observed the last high shell abundance from the L3 unit at Veliki Surduk. Interestingly, the hiatus in spelethem OH2 growth parallels a lack of snail shells at Veliki Surduk. Further records from the Balkan Peninsula confirm this aridification trend. For example, during MIS 8, the pollen record in the lake sediments from Tenaghi Philippon in northeastern Greece shows the presence of a xerophytic steppe environment [107,112]. Simultaneously, from 288 ka to 245 ka ago, at Lake Ohrid (Northern Macedonia and Albania), the pollen concentration was low, and an open vegetation with abundant pollen from Poaceae was inferred [108].

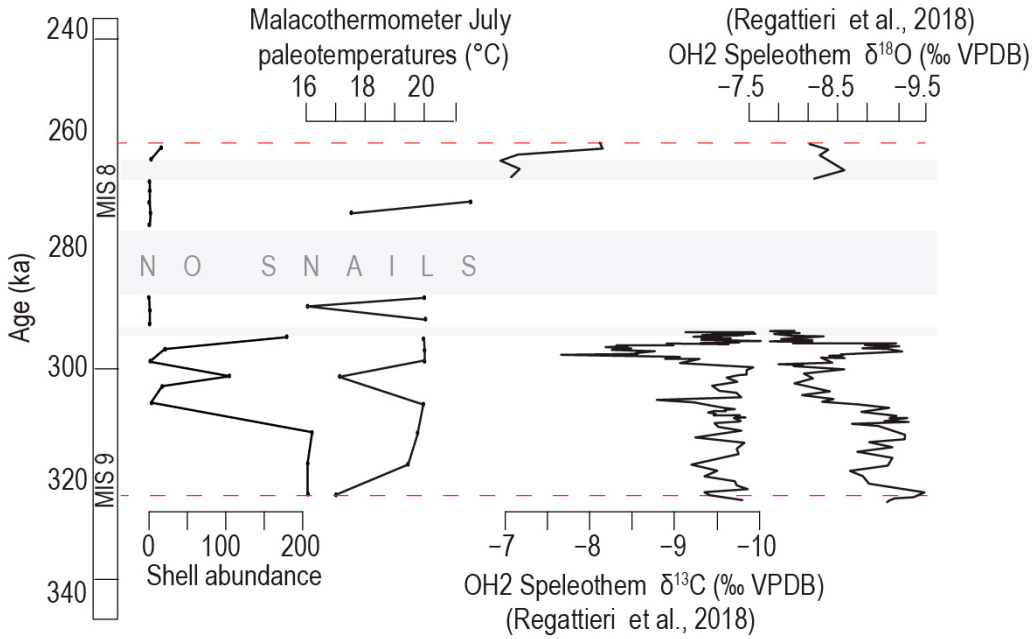

Figure 6. Shell abundance (shells per sample) and Malacothermometer July paleotemperatures from Veliki Surduk, plotted next to the OH2 speleothem record from Northern Macedonia [105]. The absence of shells corresponds to a hiatus in speleothem growth, as is indicated by gray stripes. Note that Malacothermometer July paleotemperatures are calculated based on shells per sample, sometimes a single shell.

The investigated glacial period in our study is, according to Hughes et al. (2020) [113], one of Europe's "missing" glaciations. This name owes to the fact that sediments formed

during this period are very rare, as stronger and younger glaciations eroded evidence that could help establish itsspatial coverage. Reconstructions of ice sheets over Eurasia for this period show a large extent of ice across today's Russia, east of the Ural Mountains. The lack of major ice build-up to the west of the Urals was explained by the pronounced drought, coincident with the onset of glaciation. Hughes et al. (2020) [113] proposed that Atlantic circulation was different during the MIS 8 and that it is possible that the major ice formation for that period occurred in the southern hemisphere. They suggest that the lack of ice in Europe was the consequence of the Western Antarctic Ice Sheet that had "... shutdown... the North Atlantic conveyor, starving ice sheets around the North Atlantic Ocean of moisture, ..." (Hughes et al., 2020, p. 176 [113]). This moisture scarcity could be the reason for the lack of speleothem OH2 growth (Figure 6). Over Lake Ohrid (North Macedonia and Albania), the reconstructed annual precipitation for MIS 8 is ≈200 mm, which is lower than during other glacial periods [114]. In this paper, we suggest that based on the malacological data from loess unit L3, the environment of MIS 8 was not so cold but could have been quite aird.

5. Conclusions

In this study, we report on the oldest malacological record in Serbia and interpret the paleoenvironmental changes in the oldest exposed part of the Veliki Surduk loess profile on the Titel loess plateau. Our research aimed to provide a paleoenvironmental interpretation using snail shells from the paleosol S3 and the overlying L3 loess unit. Nine snail species were identified in this sequence, including *Chondrula tridens*, *Granaria frumentum*, *Helicopsis striata*, *Pupilla muscorum*, *Pupilla triplicata*, *Punctum pygmaeum*, *Succinella oblonga*, *Vallonia costata*, and *Vitrina pellucida*, and numerous shell plates of unidentifiable slug taxa. Based on the snail abundance as well as our interpretations regarding their temperature, humidity, and vegetation preferences, we observed (as expected) distinct differences between the paleoenvironmental conditions at the site during MIS 9 and MIS 8. The main difference between these two periods is the abundance of snail shells; some intervals of the glacial conditions are even barren of snails, marking the first time that malacologically sterile loess was reported in loess in Serbia. Throughout these intervals, the climate was mild and mostly dry, with mostly open grassland (steppe) vegetation. The dominance of thermophilous and aridity-tolerant snails such as *Chondrula tridens*, *Granaria frumentum*, *Helicopsis striata*, and *Pupilla triplicata* during the formation of the L3 loess indicates a predominately dry environment such as a steppe-like grassland. Using a Malacothermometer July Paleotemperatures method (where possible), we estimated that shell abundance variations could be linked to summer insolation cycles.

Author Contributions: Conceptualization, S.B.M. and T.L.; methodology, B.G.; software, M.B.G.; validation, S.B.M.; formal analysis, Q.H.; investigation, R.S.M.; resources, C.Z.; data curation, B.C.; writing—original draft preparation, M.G.R.; writing—review and editing, R.J.S.; visualization, A.A.; supervision, Z.M.P.; project administration, S.B.M.; funding acquisition, M.G.R. and S.B.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Grant No. 451-03-47/2023-01/200125). The authors acknowledge the support of the Provincial Secretariat for Higher Education and Scientific Research of Vojvodina (Serbia), No. 000871816 2024 09418 003 000 000 001 04 002 (GLOMERO), under Program 0201 and Program Activity 1012.

Data Availability Statement: Data are contained within the article.

Acknowledgments: MGR is grateful for the L'Oréal-UNESCO For Women in Science award. SBM is grateful for grant F-178 from the Serbian Academy of Sciences and Arts.

Conflicts of Interest: Author Aleksandar Antić is an employee of MDPI; however, he was not working for the journal Quaternary at the time of submission and publication.

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