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# Pleistocene Climate Change in Central Europe

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## Abstract

Loess is terrestrial, clastic sediment formed by the accumulation of wind-blown dust. It is usually inter-bedded with paleosol horizons, forming loess-paleosol successions (LPS). Due to their characteristics LPS's represent valuable records of climate changes during Pleistocene. The thickest LPS sections in Croatia are in the Baranja region. Stable oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) isotope analysis were made on loess malacofauna in order to quantify paleo-temperature changes and describe paleo-vegetation in this part of Central Europe.  $\delta^{18}\text{O}$  values show significant paleotemperature changes during the Upper Pleistocene (130 ky - 20 ky) in Baranja region. Average growing season (AGS) temperature varied 13.2 °C or 9.5 °C during that time period, depending on which formula is applied for calculations. Magnetic susceptibility (MS) measurements show strong peaks in the paleosol horizons pointing to more humid climate. The overall climate was much cooler than present. Stable carbon isotope values point to dominance of C3 vegetation type during the Late Pleistocene in southern part of Central Europe. Climate change in the Late Pleistocene is very likely a significant but not the only factor that influenced the extinction of Neanderthal population which paved the way for the dominance of anatomically modern humans (AMH) in Central Europe.

**Keywords:** Pleistocene, climate change, loess, stable isotopes, Central Europe, Neanderthals

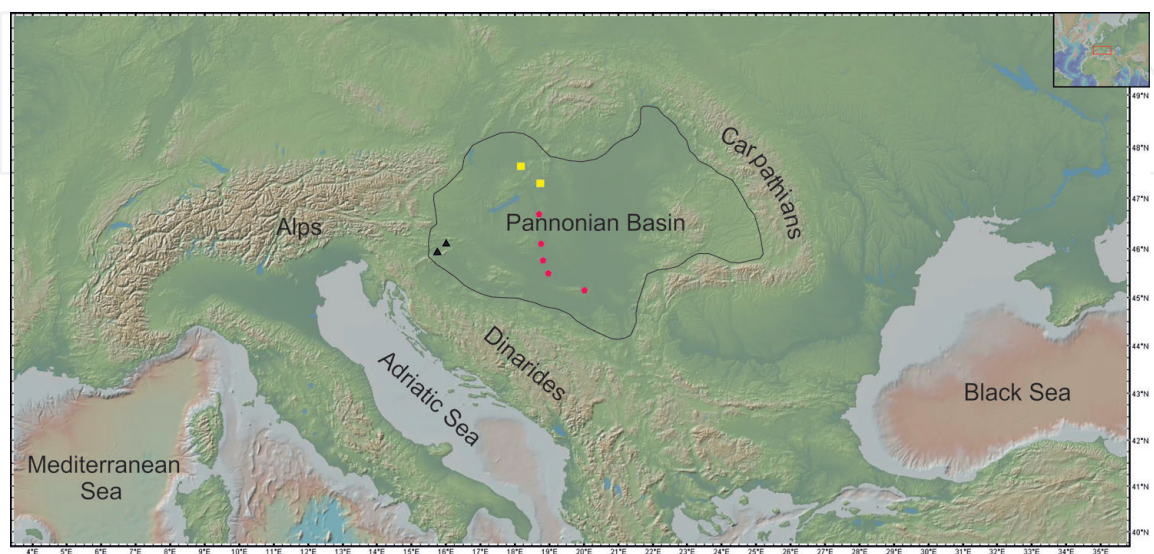
## 1. Introduction

Definition of loess: It is a terrestrial, clastic sediment, composed dominantly of silt-sized particles and formed by the accumulation of wind-blown dust. It covers up to 10% of the world's surface area and is usually inter-bedded with paleosol horizons forming loess-paleosol sequences, or LPS [1]. Such successions provide very detailed insight into Pleistocene climatic fluctuations [2–4]. Due to this characteristic, LPS's provide very good records of palaeoclimate and environmental changes in the Pannonian Basin for at least 1 Ma [5]. The region of Baranja situated in the north-eastern part of Croatia is located in the southern edge of Pannonian Basin which is a part of Central Europe (**Figure 1**). It was selected for this research because some of the thickest loess successions in Croatia are exposed along the Danube River in Baranja. The total thickness of these loess deposits (above and under the surface) probably exceeds 50 m [6]. The Zmajevac locality was selected because it is accessible, contains four paleosols in loess and has a total thickness of almost 20 m.

Grain-size distribution indicates that the loess from Zmajevac LPS in Baranja is typical loess, comparable with other loess profiles in the Pannonian Basin [3, 4].

The LPS of Baranja and northeastern Croatia have a long history of investigation [7, 8]. The molluscan fauna within LPS were investigated and provided an overview on warm periods in the Late Pleistocene of northeastern Croatia [9]. Other researchers focused on the molluscan fauna from LPS at the Vukovar and Đakovo loess plateaus, situated 20–30 km south of Baranja region [10–12].

Focus of this chapter is to describe the climate change during the Late Pleistocene based on the  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values measured in land-snail (mollusk) shells from loess samples of the Zmajevac LPS. Overall, the results of this study will provide a better insight into the impact of climate change on the populations of Neanderthals and anatomically modern humans (AMH) in Central Europe, and the disappearance of the aforementioned. Emphasis is on  $\delta^{18}\text{O}$  values which are used for determination of paleotemperature changes. This is especially important because it provides the temperature changes during the appearance of AMH in Central Europe and the disappearance of the Neanderthals from the same region. The values of stable isotopes of oxygen ( $\delta^{18}\text{O}$ ) and carbon ( $\delta^{13}\text{C}$ ) can be used as a paleothermometer, as characteristic of mollusk assemblages [13, 14], or in a wider sense, as a tool to reconstruct the climatic conditions of the Late Pleistocene [15–17]. Previous research in the Pannonian Basin did not include stable isotope analysis of fossil mollusk shells for palaeoclimatic reconstructions in this specific time frame (130 ky - 20 ky). The only paper which included stable isotope analysis ( $\delta^{18}\text{O}$  values) as a part of a comprehensive loess study in this region is limited to the Last glacial maximum (LGM), which is only a part of MIS2 [18] and does not cover the entire Upper Pleistocene. Most researchers used mollusk assemblages only as a malacothermometer tool, and to establish mean annual temperature (MAT) values and/or average summer month temperatures represented by mean July temperatures – MJT [4, 14, 19]. Most recently, X-ray fluorescence (XRF) and magnetic susceptibility (MS) based palaeoclimatic data have been established in the Pannonian Basin and they determined the paleotemperatures in the 6.7–8.9°C range [20]. However, other researchers in Southern [21] and Western Europe [16, 22, 23], in Eastern Mediterranean [17, 24] and also in North America [15, 25, 26] used stable isotope analysis widely in the last three decades.



**Figure 1.** Pannonian Basin with loess profiles from Croatia, Serbia and Hungary marked with red polygons. Neanderthal and early modern human sites marked with black triangles (Krapina and Vindija in Croatia) and yellow squares (Remete Felső and Šal'a in Slovakia). This position map is made and adjusted by using a global multi-resolution topography map [78] (<http://www.geomapapp.org>).



Before using the stable isotope method in paleoenvironmental reconstruction it is necessary to understand the physical and chemical processes, or flux-balance model that takes place in mollusk shell  $\leftrightarrow$  environment system. The most detailed explanation of that flux-balance model, and subsequent incorporation of isotope ratios in mollusk shells is given by Balakrishnan and Yapp [27]. The authors provide detailed insights into possible interpretational mistakes and constraints of this method and give all the necessary formulas which ensure better understanding of complex model used in palaeoclimatic research. That research lays the foundation for any future research which tends to use stable isotope data as a tool for paleoclimate or paleoenvironmental reconstruction.

## 2. Research methods

Field investigation and sampling in Baranja region is done during winter and early spring, because the lush vegetation in spring, summer and fall does not allow easy access to loess profiles (**Figure 2**). The aim of sampling is to identify the maximum thickness of chosen LPS. Bulk samples (8–10 kg) were collected from Zmajevac outcrop for malacological, sedimentological and stable isotope analysis.

Samples for grain size analysis were decalcified with 5% HCL acid and dried in a heater for 24 h. Grain size analyses combined wet sieving and the pipette method. Classification of the grain size distribution was done according to [28]. Each loess sample was sieved to obtain whole mollusk shells for stable isotope analysis. Shells were derived from samples by screen-washing in distilled, deionized water for the purpose of saving primary ratios of stable oxygen and carbon isotopes. The identification of mollusk species followed taxonomic concepts that were established in previous researches [13, 29]. Assemblage analysis is done according to Ložek [13]. Selected mollusk shells are then prepared for stable isotope analysis. This was done in IAMC - CNR laboratory in Naples (Italy). First the shells were crushed into powder which is then heated to 500°C for 30 min to remove the organic matter. Ratios were measured by automated continuous flow carbonate preparation GasBench II device and Thermo Electron Delta Plus XP mass spectrometer. Acidification of samples was performed



**Figure 2.**  
*Sampling at the Zmajevac LPS in Baranja region, Eastern Croatia. Beige colored sediment is loess and reddish – brown colored sediment is paleosol (Photo: Danijel Ivanišević).*

at 50°C. Every sixth sample was compared with an internal standard (Carrara Marble with  $\delta^{18}\text{O} = 2.43\text{‰}$  versus VPDB; and  $\delta^{13}\text{C} = 2.43\text{‰}$  vs. VPDB) and for every 30th samples, the NBS19 international standard was additionally measured. Standard deviations of carbon and oxygen isotope results were estimated as 0.1% and 0.08%, respectively and based on 20 measured samples, three times each.

The magnetic mineral content recorded at Zmajevac LPS in a form of magnetic susceptibility (MS) signal was gathered from 44 samples collected into 200 ml plastic containers. Magnetic susceptibility measurements were performed in HGI-CGS laboratory, Zagreb (Croatia) using a Bartington MS2 device. Each sample was measured three times for better precision and statistical analysis.

### 3. Results

Grain-size analysis were also done in HGI-CGS laboratory, Zagreb (Croatia) following procedure by [30]. Results indicated silt as the dominant grain size fraction in all loess samples from the Zmajevac profile (**Table 1**). Average share of silt-size particles in samples is 88.11% and coarse-grained silt fraction is dominant with average percentage of 41.38%. The laminated horizon seen at the top of the middle part of the LPS, 1.5 m above the ladder (**Figure 2**) is composed of 81% sand, 11% silt and 8% clay. Silt dominance at the Zmajevac LPS confirms that this sediment was deposited during strong eolian activity in colder periods of Upper Pleistocene.

Magnetic susceptibility (MS) analysis provides the data about ferrimagnetic mineral content in sediment and/or soil. This is important because increased concentration of magnetic minerals indicates more humid and/or warmer climate conditions, while decreased concentration points to more arid and/or colder climate conditions. This method is also useful when data comparison from different localities is needed, in order to get the interpretation of palaeo-environmental evolution. MS values from Zmajevac LPS loess and loess like sediment range from  $5$  to  $28.5 \times 10^{-6}$  SI (**Figure 3**). MS values from L1 horizon from the upper part of the Zmajevac LPS range from  $15$  to  $20 \times 10^{-6}$  SI, which is typical for loess. The uppermost paleosol horizon (F2) shows the highest measured MS values within the LPS ( $82.5 \times 10^{-6}$  SI). MS values in the loess unit L2 are again lower, with a mean of  $14 \times 10^{-6}$  SI and this is expected difference between loess and paleosol. However, one notable peak within this loess horizon was detected with MS value of  $28.5 \times 10^{-6}$  SI. The pedo-complex consisting of P3a and P3b paleosols is marked by significant peaks in MS values. They are however lower than MS values recorded in the F2 paleosol horizon. Upper paleosol F3a displays MS values of  $67.7 \times 10^{-6}$  SI, while underlying paleosol P3b displays MS values of  $53.2 \times 10^{-6}$  SI. Loess and loess like sediment under pedo-complex display MS values in range of  $11$  to  $23.7 \times 10^{-6}$  SI. The lowermost paleosol P4 shows again a somewhat higher MS value of  $58.3 \times 10^{-6}$  SI, and the lowermost loess horizon displays MS value of  $25.1 \times 10^{-6}$  SI.

The mollusk paleontology of the Zmajevac LPS was analyzed from 13 bulk loess samples [30]. A total of 1705 terrestrial gastropod shells were collected. 13 species-level taxa was determined. Specimen richness related to the number of mollusk shells within the loess samples varies significantly in Zmajevac LPS. Results show that the malacofaunal shell concentration is moderate in lower loess horizons L7 (85) and L6 (117). It is strongly decreased in L5 (5) and L4 (7) loess horizons, and then increased in L3 (90), L2 (213), and L1 (136) loess horizons. The identified mollusk species have been classified according to their palaeoenvironmental preferences following previous, well documented research in Pannonian Basin [14, 19]. The presence and abundance of each mollusk species in loess samples can be used to determine paleoclimate and/or type of palaeovegetation. These information are basis for palaeoenvironmental reconstruction that shaped the Pannonian Basin area during the deposition of loess sediment.

Sample	>0,063 mm	0,032- 0,063 mm	0,016- 0,032 mm	0,004- 0,016 mm	<0,004 mm
Kot 1/1	12	33	31	24	0
Kot 1/2	8	42	23	22	5
Kot 1/3	5,5	46,5	24	17	7
Kot 1/4	11	37	22	19	11
Kot 1/5	7,5	35,5	28	22	7
Kot 1/6	9,5	39,5	27	19	5
Kot 1/7	14,5	31,5	27	27	0
Kot 1/8	8	44	27	21	0
Kot 1/9	12,5	39	24,5	24	0
Zma 1/1	15	40	20	19	6
Zma 1/2	14,5	57,5	12	8	8
Zma 1/3	10	45	28	17	0
Zma 1/4	12,5	47,5	25	15	0
Average	10,8	41,4	24,5	19,5	3,8

**Table 1.**  
*Grain size distribution in Zmajevac LPS.*

Therefore, each sample is characterized by a certain malacofaunal assemblage [13]. The obtained quantified data [30] allowed the definition of mollusk assemblages in the Zmajevac LPS for each loess horizon (from top L1 to lowermost L7). Species tolerating open and dry habitats are abundant in the Zmajevac LPS. Five specific assemblages which are all cold – resistant were determined in 13 loess samples.

*Helicopsis striata* assemblage is the most dominant among five assemblages detected in Zmajevac LPS. The *Helicopsis striata* assemblage indicates climate conditions preceding the last glacial/stadial maximum and it is characteristic assemblage of the ‘warm’ loess environment in Central Europe [13]. This ‘warm’ should not be considered warm in absolute terms, but relatively compared to the extremely cold periods during the Upper Pleistocene.

*Chondrula tridens* and *Arianta arbustorum* are generally abundant species in Zmajevac LPS, but their concentration in loess samples is never high enough for definition of a pure *Chondrula tridens* or *Arianta arbustorum* assemblage. This is not unusual, because it is not often that pure assemblages are found.

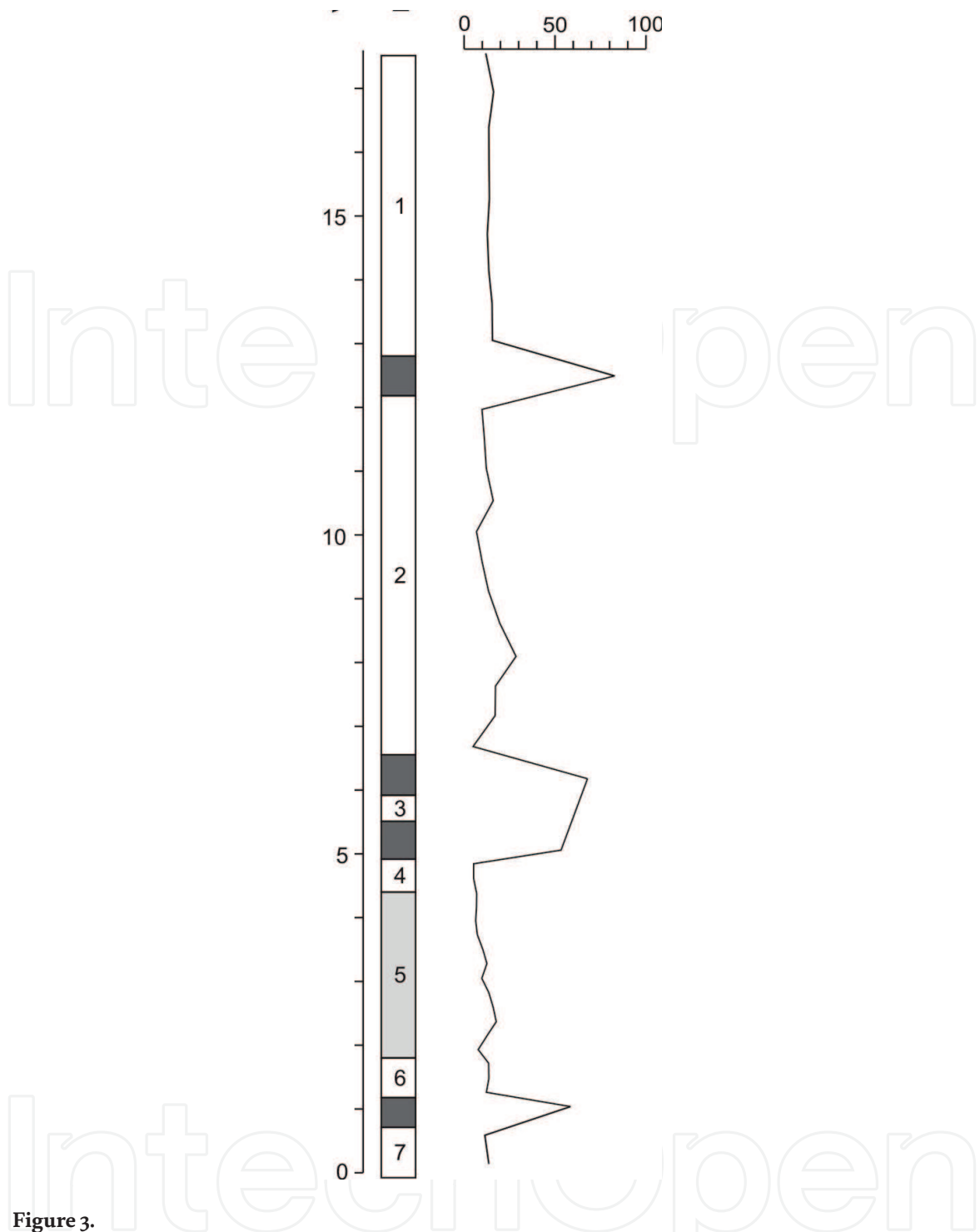
*Arianta arbustorum* species is cryogenic, hygrophilous species and related assemblage is typical for humid forests, hillsides and lowland areas.

Contrary to that, *Chondrula tridens* species is a warm steppe species and related assemblage is representative of interstadial, mild, dry steppe to forest steppe environment.

The *Pupilla loessica* and *Columella columella* assemblages are typical loess faunas and they represent glacial/stadial maximum. Arid and cold climate conditions are indicated by the *Pupilla loessica* assemblage, while more humid conditions are represented by the *Columella columella* assemblage.

The two most common mollusk species which appear in all of the samples from the Zmajevac LPS are *Helicopsis striata* (WAGNER) and *Arianta arbustorum* (LINNAEUS). Precisely because of their presence in all loess horizons they were used for stable isotopes ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) analysis. They Stable oxygen isotope values for these two species range from  $-5.76\text{‰}$  to  $-2.45\text{‰}$  (Table 2). Stable carbon isotope values range from  $-8.83\text{‰}$  to  $-6.84\text{‰}$  (Table 2). Average value for  $\delta^{18}\text{O}$  is  $-3.91\text{‰}$  and average value for  $\delta^{13}\text{C}$  is  $-7.95\text{‰}$  (Table 2). It is obvious that  $\delta^{13}\text{C}$  values vary to





**Figure 3.** MS values measured at Zmajevac LPS. Note: loess horizons in white and light gray color are numbered from 1 to 7. Four paleosols from top to bottom are: F2, F3a, F3b and F4; and they are represented with dark gray color.

a lesser extent than  $\delta^{18}\text{O}$  values. The values in each sample vary depending on which mollusk species is analyzed, but that is to be expected. Regularity, which would indicate that one analyzed mollusk species shows constantly lower or higher  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values in relation to the other analyzed species, was not registered. The values for stable oxygen isotope are in accordance with results from other loess profiles in the Pannonian Basin with emphasis on MIS 2 stage [18].

#### 4. Comparison of mollusk assemblages with others in Central Europe (Pannonian Basin)

Data obtained from paleontological analysis from the Zmajevac LPS are valuable, but it is necessary to put them in a broader context and compare them

with paleontological research from other sites in the Pannonian plain. Previous research of malacofauna conducted on loess profiles in Eastern Croatia [10, 12] show significant congruence with the results obtained by Banak et al. [30, 31] from the Zmajevac LPS.

In Erdut loess profile [10] which is situated 30 km to the southeast from Zmajevac LPS determined malacofauna was detected in four loess horizons. The base horizon is characterized by a *Columella columella* assemblage, while in the three remaining horizons *Helicopsis striata* assemblages is dominant. These results are comparable and almost identical to the results obtained from the Zmajevac LPS on Bansko Brdo hill (30). Still, there are some minor differences in faunal assemblages that probably reflect micro climate conditions during the Upper Pleistocene. The L4, L5 and L6 loess horizons of the studied Zmajevac LPS with dominant *Helicopsis striata* assemblage show strong influence of *Arianta arbustorum* and *Columella columella* assemblage. In Erdut loess profile dominance of *Helicopsis striata* assemblage with minor influence of a *Chondrula tridens* assemblage is detected [10]. The topmost L1 horizon from this study and the topmost horizon from the Erdut LPS [10] display similarity, with the dominant *Helicopsis striata* assemblage being accompanied by a *Chondrula tridens* assemblage. The lowermost horizons at Zmajevac LPS (L7 and L6) and from the Erdut LPS [10] display differences which are marked by dominant *Helicopsis striata* assemblage at the Erdut profile and *Columella columella* assemblage at Zmajevac LPS.

The mollusk species distribution of the Zmajevac LPS shows certain similarities also with the Irig loess profile on the southern slope of Fruška Gora Mt. in NW Serbia [2] which is less than 100 km away in east - southeast direction. *Chondrula tridens* and *Helicopsis striata* assemblages dominate in the Irig loess profile and are also present in the Zmajevac LPS, but *Chondrula tridens* is not so dominant in Zmajevac LPS. Further, in Irig loess profile *Vallonia costata* and *Clausilia dubia* species are present in the lowermost part of the LPS, but in contrast two lowermost loess horizons in the Zmajevac LPS bear cooler climate representative in form of *Columella columella* assemblage. This assemblage in Zmajevac LPS is reflecting the Middle Pleistocene Penultimate Glacial (MIS 6) conditions. Based on this compared data it is obvious that these two loess profiles are dominated by *Helicopsis striata* assemblage, but they differ significantly from each other, especially in lower horizons.

Sample	Stable oxygen ( $\delta^{18}\text{O}$ )	Stable carbon ( $\delta^{13}\text{C}$ )
Kot 1/1	-2,45	-7,45
Kot 1/2	-3,84	-6,96
Kot 1/3	-4,05	-6,84
Kot 1/4	-4,41	-7,75
Kot 1/5	-3,26	-8,83
Kot 1/6	-3,16	-7,47
Kot 1/7	-4,85	-8,04
Kot 1/8	-5,15	-8,82
Kot 1/9	-5,27	-8,31
Zma 1/1	-2,15	-9,21
Zma 1/2	-3,35	-8,62
Zma 1/3	-3,16	-7,84
Zma 1/4	-5,76	-7,23
Average	-3,91	-7,95

**Table 2.**  
Stable isotope values from Zmajevac LPS malacofauna. Upper four samples represent MIS 2 stage.



The Upper Pleistocene malacofaunal assemblages from the Petrovaradin loess profile in NW Serbia show colder and more humid conditions than in either the Irig or Zmajevac LPS [3, 32]. This is probably an effect of the palaeogeographic position at the northern slope of Fruška Gora Mt. [3, 32], which is opposite to the positions of Zmajevac and Irig LPS's at the southern slopes.

The fauna from middle and upper loess horizons (L3, L2 and L1) of the Zmajevac LPS displays certain similarity also with Madaras loess section in South Hungary [33]. There are some differences present as well. Uppermost L1 loess horizon in the Zmajevac LPS differs from K L1 LL1 loess horizon in Madaras because *Helicopsis striata* and *Chondrula tridens* assemblages dominate here, while *Columella columella* and *Vallonia tenuilabris* species dominate in Madaras LPS. Also, opposite to Madaras LPS *Columella columella* species is scarce at Zmajevac LPS. L2 loess horizon from the Zmajevac LPS differs from K L1 LL2 loess horizon at Madaras section, because *Vallonia costata* and *Pupilla muscorum* species dominate in that LPS, while in the Zmajevac LPS *Pupilla muscorum* is present, but not dominant. Also, *Vallonia costata* species is not present at all. L3 loess horizon in the Zmajevac LPS and K L1 LL3 loess horizon from Madaras LPS both contain *Helicopsis striata* assemblage and show the greatest similarity.

Described mollusk assemblages from Zmajevac LPS show small but important differences to other Pannonian Basin LPS's. It is especially noticeable in loess horizons L7, L6 and L3 of Zmajevac LPS. Results of malacofaunal assemblages from nearby loess profiles in Serbia and Hungary suggest that climate conditions that dominated in this part of Central Europe were similar, with some differences which were a result of paleogeography and microclimate conditions driven by it.

Sedimentological and magnetic susceptibility (MS) data obtained from Zmajevac LPS show similarities with other LPS's in the Pannonian Basin that were described in last decade [2, 7, 8]. MS values are in the expected range, especially in loess horizons (**Figure 3**). MS values from four paleosols are comparable with those from Irig LPS in neighboring Vojvodina region [2]. The lowermost P4 paleosol from Zmajevac LPS displays significantly weaker signals, than the P2 paleosol, but it is stronger than signals from the overlying P3b paleosol horizon. The MS value of  $58.3 \times 10^{-6}$  SI in the P4 paleosol is lower than expected for a long, interglacial period in which favorable climatic conditions prevailed, thus enabling fully developed soil. Even though P4 is the oldest paleosol in Zmajevac LPS, a weaker signal than in the youngest F2 paleosol may indicate that the relatively low MS values are result of mineral leaching. Such a decrease in the MS signal in clayey horizons was also detected in LPS in Germany [34] and in Hungary [35], therefore, it is not a specificity of Zmajevac LPS. It is very likely that similar processes affected the P4 paleosol horizon in Zmajevac. In agreement with previous research of this area [7], the P4 horizon is correlated with the MIS 5e interglacial period. The pedo-complex forming paleosol horizons P3a and P3b is similar to a pedo-complex from the Vojvodina [2]. Reminiscent of synchronous horizon of Hungarian Sütto LPS [4], the signal from the P3 pedo-complex is higher than the one measured in Vojvodina. Finally, the strongly increased MS value of  $82.5 \times 10^{-6}$  SI suggests that the uppermost paleosol P2 could represent an interglacial, rather than an interstadial phase.

## 5. Late Pleistocene climate reconstruction based on $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values

Stable isotope ratios of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  were measured from fossil shells of two species: *Helicopsis striata* and *Arianta arbustorum*. Modern European land snails are active in the +10 to +27°C temperature range and hibernate or become inactive at temperatures below +10°C [36, 37]. This implies that stable isotope ratios recorded in mollusk shells represent a warmer period when snails formed their shells. This period

that spans from spring to fall can be 160–210 days long [38, 39] and it reflects an average growing season (AGS) temperature. The same principle can be applied on fossil snails. It is known that snails are active in building their shells during and immediately after the rain [40]. This information is crucial, because it provides a direct link from rainwater  $\delta^{18}\text{O}$  values and  $\delta^{18}\text{O}$  values that we measured in the mollusk shells. This complex relationship between the  $\delta^{18}\text{O}$  value of meteoric water and the values measured in land-snail shells has been studied for more than 40 years [15–17, 24, 41]. Today it is reliable and well established method often used for paleoclimate and paleoenvironmental research. Variations in land snail shell  $\delta^{18}\text{O}$  is a function of temperature, relative humidity,  $\delta^{18}\text{O}$  of water vapor, and  $\delta^{18}\text{O}$  of liquid water ingested by the snail [16, 27]. It is worth mentioning that intra-shell variation of values measured in snail shells from LGM ranges from 0‰ to –5.5‰ [18] in some studied areas.

To avoid errors and to obtain the average  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values, whole snail shells were crushed and analyzed. The  $\delta^{18}\text{O}$  value in mollusk shells is enriched on average by 5‰ relative to equilibrium with ingested rainwater [16]. This means that a  $\delta^{18}\text{O}$  value of palaeo rainwater incorporated in a mollusk shell which displays a  $\delta^{18}\text{O}$  value of approx. –3‰ was approx. –8‰.

In order to compare climate conditions in the Upper Pleistocene with recent climate and to obtain relative temperature changes, it is necessary to know the  $\delta^{18}\text{O}$  values of recent meteoric water and recent AGS temperatures from the same or nearby region. The nearest measured  $\delta^{18}\text{O}$  value of rainwater to Zmajevac LPS is recorded in city of Zagreb, Croatia, which is located 250 km to the west from Zmajevac LPS. This  $\delta^{18}\text{O}$  value is –6.11‰ for summer months of June, July and August (JJA) and it is measured in the last two decades [18]. This values represent shorter periods than AGS, but it is the closest approximation as we can get. In the last two decades mean JJA temperature recorded in Zagreb was +19.7°C. If we compare  $\delta^{18}\text{O}$  values from Zmajevac LPS mollusk shells, enlarged for 5‰, we can clearly see that  $\delta^{18}\text{O}$  values of meteoric water in the Upper Pleistocene ranged from approx. –7.45‰ to approx. –10.76‰.

If we compare these approximate and indirect  $\delta^{18}\text{O}$  values with  $\delta^{18}\text{O}$  value of –6.11‰ from present JJA measurements in Zagreb, it is clear that  $\delta^{18}\text{O}$  values were constantly lower/more negative. This means that AGS temperatures during the Upper Pleistocene in Baranj region were much lower than present temperature in city of Zagreb. The mean, annual  $\delta^{18}\text{O}$  value of rainwater for Zagreb is –8.33‰ [18] and mean annual temperature (MAT) for Zagreb in last two decades is +12°C. As most of the samples from Zmajevac LPS display more negative  $\delta^{18}\text{O}$  values than –8.33‰, we can say with some certainty that even the AGS temperatures (which represent the warmest period of the year) during the Upper Pleistocene were lower than the present MAT in Zagreb. It is hard to determine what was the absolute value of temperature in the Upper Pleistocene, but we can calculate relative values and compare them to present one.

Researchers [42] estimated the MAT for MIS 2 stage is in range from 6.2°C to 11.2°C. It was reconstructed from oxygen isotopes values measured in mammoth tooth enamel from sites in the Czech Republic and Slovakia [42]. This paleotemperature data represents climate conditions from part of the Central Europe that is quite north of Zmajevac LPS (more than 200 km). Still, it can serve as a marker if we assume that the decrease in temperature is indeed related with latitude increase. Other researchers [20] estimated temperatures of 6.7 C (based on MS values),  $8.5 \pm 0.6$  C (based on XRF-1 values) and  $8.9 \pm 4.4$  C (based on XRF-2 values) in Northern Hungary for the same period of the Upper Pleistocene (MIS 2 stage). Finally, researchers [43] calculated a MAT of 4.5 C in Central Europe using noble gas thermometry (NGT). This result displays significantly lower MAT than other results, which is probably due to this specific method.

Results from our research show that  $\delta^{18}\text{O}$  values from Zmajevac LPS are in fair accordance with  $\delta^{18}\text{O}$  values from North America and other LPS's in Central Europe, but they are partly different from  $\delta^{18}\text{O}$  values from southern Europe (**Figure 4**).

$\delta^{18}\text{O}$  values measured in fossil shells indirectly reflect paleotemperature at a time when these fossil snails lived. This is useful if we want to reconstruct paleotemperature changes over longer period of time if we have enough data, that is, fossil findings. We know from previous research that if the  $\delta^{18}\text{O}$  value in the shell changes by 0.5‰ it reflects a paleotemperature change of approximately 2°C [24]. The formula for calculating AGS paleotemperature changes in the Zmajevac LPS, adjusted according to [24], is as proposed:

$$\Omega(^{\circ}\text{C}) = (\delta^{18}\text{O}_{\text{max.}} - \delta^{18}\text{O}_{\text{min.}} / 0,5\text{‰}) \times 2^{\circ}\text{C} \quad (1)$$

where:

$\Omega$  is: relative paleotemperature change

$\delta^{18}\text{O}_{\text{max.}}$  is: maximal  $\delta^{18}\text{O}$  value measured in a gastropod shell

$\delta^{18}\text{O}_{\text{min.}}$  is: minimal  $\delta^{18}\text{O}$  value measured in a gastropod shell

We used the  $\delta^{18}\text{O}$  values measured from Zmajevac LPS fossil shells and according to this formula AGS paleotemperature changes through entire Upper Pleistocene in Baranja region is: 13.2°C.

Other researchers propose different ratios and interdependence of  $\delta^{18}\text{O}$  values and paleotemperature. According to [26] if the  $\delta^{18}\text{O}$  value in shell changes by 0.35‰ it reflects a paleotemperature change of approximately 1°C. We can adjust the formula according to this research and then it is:

$$\Omega(^{\circ}\text{C}) = (\delta^{18}\text{O}_{\text{max.}} - \delta^{18}\text{O}_{\text{min.}} / 0,35\text{‰}) \times 1^{\circ}\text{C} \quad (2)$$

where:

$\Omega$  is: relative paleotemperature change

$\delta^{18}\text{O}_{\text{max.}}$  is: maximal  $\delta^{18}\text{O}$  value measured in a gastropod shell

$\delta^{18}\text{O}_{\text{min.}}$  is: minimal  $\delta^{18}\text{O}$  value measured in a gastropod shell

If we use the same  $\delta^{18}\text{O}$  values from Zmajevac LPS fossil shells in this formula, AGS paleotemperature changes through the Upper Pleistocene in Baranaj region is: 9.5°C.

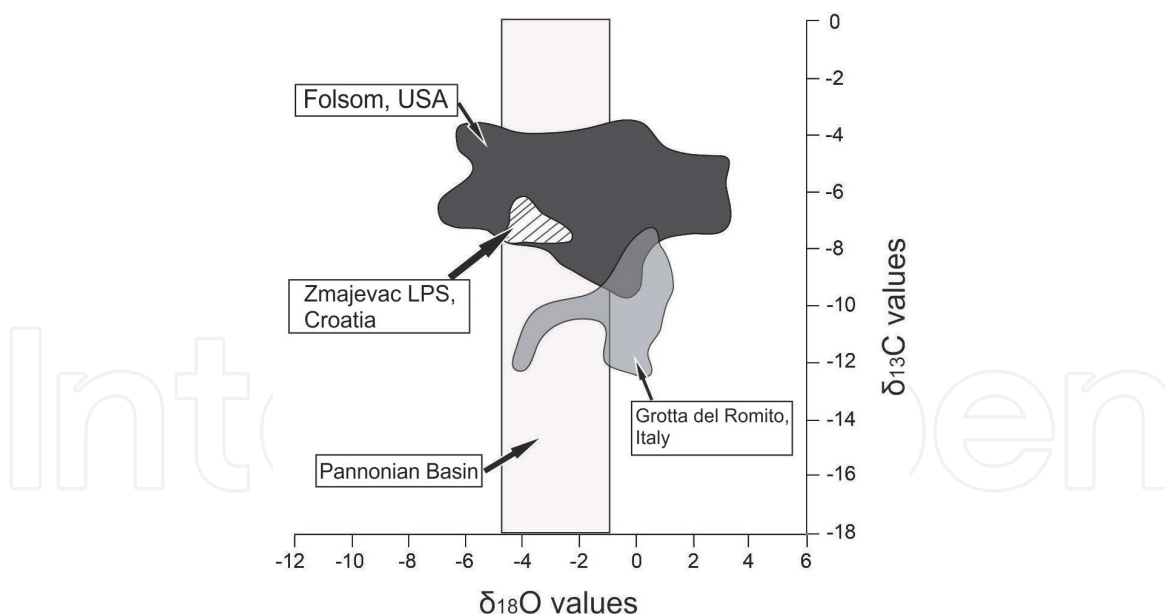
If we compare these results with MAT temperatures for other Pannonian Basin LPS, it is plausible to conclude that the second formula and the range of 9.5°C are more accurate. Both of these values suggest strong and constant changes of paleotemperature during the Upper Pleistocene in the Baranja region.

It is worth mentioning that the  $\delta^{18}\text{O}$  values from Zmajevac LPS displays some deviation in regards to paleotemperatures or paleoclimate conditions determined by malacofaunal assemblages. These deviations are probably a result of complex flux-balance model between the rainwater used by the fossil snails and their shell, which does not respond with the same intensity to palaeo temperature changes [27].

Climate changes during the glacial and interglacial periods are the main cause for changes in vegetation which are reflected in  $\delta^{13}\text{C}$  values of plants [44, 45]. Therefore,  $\delta^{13}\text{C}$  values from fossil shells can be used to determine the diet of land snails, which can then help in palaeoenvironmental reconstruction. The  $\delta^{13}\text{C}$  value of atmospheric  $\text{CO}_2$  does not affect the  $\delta^{13}\text{C}$  value of snail shells, so these values are a relevant and reliable indicator of fossil snail diet [27]. If the  $\delta^{13}\text{C}$  values are more negative, it is an indication that the mollusks consumed more C3 plants in their diet and that the climate was cooler and more humid [22, 25]. If the  $\delta^{13}\text{C}$  values are more positive, it is an indication that the snails consumed more C4 plants in their diet, which indicates a more arid environment [22, 46].

Research from central parts of Pannonian Basin (Hungary) [47] shows that relatively stable woodland-grassland ecotone was the dominant vegetation type in the Pannonian Basin between 140 ky and 16 ky. This is a time span which largely coincides with Upper Pleistocene period. Described woodland-grassland ecotone





**Figure 4.**  
 Comparison of results for MIS2 from Zmajevac LPS with ones recorded in other European and north American LPS profiles from late Pleistocene.

was preserved even during the strongest cooling, when a treeless steppe dominated the landscape of Pannonian Basin [47]. In this mixture of temperate, arctic and alpine ecosystems C3 plants typically dominate [48]. Soils formed in Tokaj region (southern Hungary) at the southern edge of the Pannonian Basin, display  $\delta^{13}\text{C}$  values in really narrow range from  $-24\text{‰}$  to  $-25\text{‰}$  [48]. This is typical for soils developed under plants using the C3 photosynthetic pathway [49].

The variation of  $\delta^{13}\text{C}$  values measured in fossil shells from Zmajevac LPS loess samples ranges from  $-8.83\text{‰}$  to  $-6.84\text{‰}$ . Therefore, C4 vegetation as a diet source for these fossil snails obtained from Zmajevac LPS can be excluded. C4 plants display very different  $\delta^{13}\text{C}$  values, ranging from  $-8\text{‰}$  to  $-16\text{‰}$  [49] and this is contrary to our results from Baranja region.  $\delta^{13}\text{C}$  values measured in any fossil mollusk shells are enriched by 8–19‰ compared to the values of the plants that they ingested [50]. This means that  $\delta^{13}\text{C}$  values of plants that mollusk from Zmajevac LPS ingested, were approximately in the range from  $-14.84\text{‰}$  to  $-16.83\text{‰}$ , if we use the minimal 8‰ enrichment approach. This is very close to the most negative margin for C4 plants. If we apply maximal 19‰ enrichment, these values are more negative and in range from  $-25.84\text{‰}$  to  $-27.83\text{‰}$ . Results from nearby areas [2, 4, 47, 48] that were compared with the results from this study suggests that for the entire time span during which the Zmajevac LPS was accumulated, C3 plants have been the main vegetation type for analyzed fossil snails. This indicates that Upper Pleistocene climate in the Baranja region was similar to the paleoclimate in other regions in the Pannonian Basin. Certain differences in paleoclimate exist and they are probably an effect of local geomorphology and microclimate conditions.

## 6. Impact of paleoclimate changes on Neanderthals and anatomically modern humans (AMH) in Central Europe

The Balkan peninsula was likely the migration route of anatomically modern humans (AMH) into Europe [51], and the Danube valley which cuts the Pannonian Basin is one of the most important pathways of these population movements [52]. This region consists of vast lowlands associated with the middle Danube drainage basin and surrounded by the Carpathian Mountains, the Alps, Dinarides and the



Bohemian Massif. The Last Glacial loess provides widely extended sedimentary coverage of the area and provides valuable paleoclimate records [2–4]. Additional stratigraphic records are present in caves located in the highlands and peripheral mountain zones. The Zmajevac LPS, described above is located in this region. This geographical setting allows us to determine with considerable certainty the impact of climate change in the Late Pleistocene on Neanderthal and early modern human populations.

The Neanderthals clearly represent the autochthonous population of eastern Central Europe according to various research [53–55]. This is documented by a group of fossil finds, spread over space and time and in the various environments, ranging from the last interglacial to the temperate oscillations of the early Würmian glacial (OIS 5a–e). Some of the most important fossil finds of Neanderthals and AMH are located in the Pannonian Basin, especially in its central, western and southern parts (**Figure 1**). Here we briefly describe localities from Pannonian Basin: two in Croatia, one in Hungary and one in Slovakia.

*Krapina (Croatia)*: Excavated layers 3–8 yielded more than 900 skeletal fragments of several Neanderthal individuals, especially cranial fragments, mandibles, teeth, and postcranial fragments. This makes Krapina one of the most important Neanderthal sites in Europe. ESR and U-series dating provided results between 178 and 120 ka, with average values pointing to 130 ka, i.e., to the last interglacial peak OIS 5e [56]. The Lithic industry is a variant of the Mousterian.

*Vindija, G3 layer (Croatia)*: All layers in this cave are characterized by abundance of cave bear skeletal remains, especially in some of the layers. Within the sequence of the Mousterian industries, the Neanderthal fossils [54] appear in layer G3 in association with some endscrapers and possible leaf-point fragments [57, 58]. Age of neanderthal tibia fragment in G3 layer was dated and it is 38 ka B.P. [59].

*Vindija G1 layer (Croatia)*: This layer yielded several human fragments of archaic morphology, which do not differ radically from the Neanderthals of the underlying layers and elsewhere in Central Europe [54]. However, the associated lithics, even if typical for the Initial Upper Paleolithic period in general, allow for somewhat contradictory interpretations. The leaf point suggests the Szeletian industry [59] and on the other hand the bone split-base point and the Mladeč type point suggest an Aurignacian [57, 60]. The Aurignacian industry that marked replacement of Neanderthals by anatomically modern humans (AMH) lasted from 43 to 26 ka years B.P. and it is characterized by worked bone or antler points with grooves cut in the bottom [61]. Their flint tools include fine blades struck from prepared cores rather than using crude flakes [61]. Mester [62] describes the problem of distinguishing these two cultural units and points to a possibility that Szeletian tools had been made by AMH. From this point of view Szeletian represents a sub variant of the Aurignacian. In this interpretation, Aurignacian bone points may have been the functional equivalents of Szeletian bifacial leaf points.

The associated bear bones were dated to 36–32 ka B.P., but dating of the human bones provided AMS radiocarbon dates of 29–28 ka B.P. [63]. Given the association of these objects in an 8–20 cm thick layer which is partially cryoturbated, we cannot exclude the possibility of some mixture of fossils and artifacts of various ages, as some researchers suggest [60]. However, since the two types of projectiles—the lithic leaf points and the polished bone-and-antler points – appear together in several other cave sites of the region (Dzeravá skala, Mamutowa Cave, Istá lloskö Cave, etc.) [64], it is rather unlikely that mechanical mixing was responsible in all cases. It seems that associations of these projectiles made from different materials and thus with different advantages and functions [65] with predefined cultures may not be as local as expected. The “Aurignacian” bone projectiles are actually being found more frequently in non-Aurignacian contexts, not only in the Central European caves,

but also in other regions as far away as northeast Russia [57, 60]. This indicates that certain communication between separated Neanderthal groups could have existed.

*Remete Felső (Hungary)*: The stratigraphy of this cave includes two glacial horizons or layers marked as: 5 and 4. The upper one, which is a layer characterized by loess contains limestone debris. Three human teeth (right I1-I2 and C) belonging to the same individual were found and analyzed. They are rather large and worn, but nothing more can be said about their specific features. The fauna, including cave bears, hyenas, lions and musk ox, suggests a tendency to cooling between the lower and upper horizon. All this faunal remains point to Szeletian in sensu latu and age is determined as OIS 3 [65]. The associated industry is characterized by typical leaf points and retouched flakes (including a Levallois flake), and has been classified generally as Szeletian, or, as a specific Transdanubian form of the late Middle Paleolithic—the Jankovichian [66].

*Šal'a (Slovakia)*: Two Neanderthal cranial fragments, Šal'a 1 and the subsequently discovered Šal'a 2, were found in two different locations in the Vah river gravel deposits, but in secondary position and without precise dating. According to the correlation of the phylogenetic stratigraphic ranges of the vertebrate finds, the primary position of the Neanderthal Šal'a 1 specimen could be—with high probability – set into the terrestrial layers of the last interglacial age, approx. 100–75 ka years B.P., which fits into OIS 5 stage [67].

Generally, eastern part of Central Europe provides solid evidence for the association of Neanderthals with the various Middle Paleolithic cultural entities of the interglacial and early glacial: the Taubachian, Mousterian, and Micoquian [68, 69]. Recent findings from the Neanderthal type locality Kleine Feldhofer Grotte site in the Neander Valley (Germany) also provide solid insights in various Middle and Upper Paleolithic cultural entities [70]. Preliminary analysis of the thousands of lithic artifacts recovered from this site has shown that two specific Paleolithic assemblages are represented: Micoquian artifacts typical of the late Middle Paleolithic and Upper Paleolithic artifacts from the Gravettian [70].

The question of the last Neanderthals and their relationship to the transitional or Initial Upper Paleolithic cultural entities of the region—the Szeletian and the Bohunician is far more susceptible to debate. Their “transitional” character is understood as a combination of archaic Middle Paleolithic patterns in technology, combined with the introduction of Upper Paleolithic tool-types [69].

The moment of AMH appearance in the Balkans and Central Europe has become better documented, since the new discovery at Pestera Țu Oase 36–34 ka B.P. [71] and revisions of human fossil sites such as Mladeč which points to age of 35–34 ka B.P. In addition, the expansion of Aurignacian sites in Central Europe shows a specific time and space dynamic. While the early Aurignacian sites, dated as early as 42 ka B.P., are extremely rare and isolated (Willendorf II in Austria and Geissenklösterle in Germany) [72–74], the middle Aurignacian, dated between 34 and 29 ka years B.P., forms a kind of network of sites over large parts of the region. It also includes the emergence of Aurignacian figurative art. This findings point to interesting and probable conclusion. If the Aurignacian can be identified with AMH then the increased site density reflects their demographic growth. Also, if the art represents their higher social complexity and more advanced cognitive abilities, then the whole process may demonstrate the final “victory” of AMH over Neanderthals in Central Europe.

Various authors have listed several possible reasons for the extinction of Neanderthals. Some have discussed the possibility that their extinction was stimulated by violent conflict with *Homo sapiens* [75]. Violence in early hunter-gatherer societies usually occurred as a result of resource competition following major natural disasters. Another possibility, proposed recently is the spread of pathogens or parasites carried by *Homo sapiens* into the Neanderthal population [76]. The fact of coexistence also leaves open the possibility of interbreeding which resulted

with a genetic heritage left by the Neanderthals in the anatomically modern human (AMH) population of the Upper Paleolithic Europe.

Neanderthals possessed the brain that enabled them greater visual acuity than *Homo sapiens* did, but the latter had better language-processing abilities [77]. It can be stated with certainty that Neanderthal brains were more adapted to vision and spatial memory and that resulted in less available area for cognition and social interactions [77]. This difference in brain structure could also lead to extinction of Neanderthals during short period of competition with *Homo sapiens*.

A separate set of factors that are not connected to the interaction of Neanderthals and AMH are climate change and natural disasters. It is well documented and described that the general characteristic of the paleoclimate in Central Europe (particularly in Pannonian Basin) is repeated succession of oscillations with varying intensity. This climate teeter started with an expansion of dense forests during the interglacial peak (OIS 5e). In OIS 5e the climate was very similar to today's climate. It continued throughout the long transitional stage of the early glacial (OIS 5a–d) with several oscillations that shaped a dry, steppe environment [2, 4, 5, 31]. This climate change has affected the whole region, but we must not forget that geomorphology has conditioned specific micro-climatic conditions within [2, 4, 20, 31]. As discussed in this book chapter, climate change was constant during the Upper Pleistocene in Central Europe. Average summer temperature changes were in range from 9.5°C and up to 13.2°C [24, 26, 31] compared to present day temperatures which are significant changes that have certainly affected the Neanderthal population.

Climate changes during the glacial and interglacial periods were also the main cause for changes in vegetation. C3 plants have been most probably the main vegetation type during the Late Pleistocene. These include trees and cold steppe grasses [31]. Changes in plant life were reflected in herbivore, mammal population and they would have led to a corresponding decline in big, plant-eating mammals hunted by the Neanderthals [78].

From the aforementioned sites and findings within, we can assume that the Neanderthal extinction in eastern Central Europe was not the result of just adverse climatic conditions during the Lower Pleniglacial maximum (OIS 4), but rather originated from several millennia of coexistence with the emerging early modern humans during the OIS 3 [79]. Data indicate that the disappearance of Neanderthals occurred at different times in different regions of Europe and Asia. Comparing the data with results obtained from the earliest dated AMH sites in Europe allowed the quantification of the temporal overlap between the two groups. The results reveal a significant overlap of 2600–5400 years (at 95.4% probability) [78]. It is clear that the coexistence with AMH population was long enough for the transmission of cultural and symbolic behavior, as well as possible genetic exchanges (interbreeding), between the two groups [78], but it is hard to conclude that it was the main cause of Neanderthal extinction. After the interbreeding episode(s), Neanderthals and their material culture disappeared and was replaced across Europe and Asia by AMH [79]. The precise timing of this transitional period has remained difficult to identify in the absence of a reliable chronological framework [79, 80].

In the end and as the most obvious conclusion, we can say that the extinction of Neanderthals and the rise of AMH population in Central Europe is due to a combination of all the factors mentioned in above, but it is difficult to reliably determine which one prevailed.

## 7. Conclusion

Data obtained from sedimentological and magnetic susceptibility analysis of Zmajevac LPS show a fairly good similarity with results from other LPS's in the



Pannonian Basin [2, 4, 8]. Stable oxygen values measured in fossil snail shells show significant paleotemperature changes during the Upper Pleistocene in the Baranja region. Average growing season (AGS) temperature changes during that period were 13.2°C [24] or 9.5°C [26], depending on which formula is applied. The second calculated value is more plausible and in accordance with other results from Pannonian Basin. The overall climate was much cooler than present day climate. Stable carbon isotope values show that the C3 plants have been the main vegetation type of fossil snails for the entire time span during which the Zmajevac LPS was accumulated. This indicates that they lived in environment dominated by trees and cold steppe grasses. Comparison of the results from Zmajevac LPS with other LPS's from Central Europe [2, 4, 81] suggests that Upper Pleistocene climate in the Baranja region was similar to the paleoclimate in other regions in the Pannonian Basin. Certain differences in paleoclimate existed and they are probably an effect of local geomorphology and microclimate conditions.

The described climate change in the Upper Pleistocene is very likely a significant but not the only factor that influenced the extinction of the Neanderthal population which paved the way for the dominance of anatomically modern humans (AMH) in Central Europe and everywhere else in the World.

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