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# The history of Danube loess research

Slobodan B. Marković [a, *], Kathryn E. Fitzsimmons [b], Tobias Sprafke [c], Darko Gavrilović [d], Ian J. Smalley [e], Vidojko Jović [f], Zorica Svirčev [a], Milivoj B. Gavrilov [a], Milivoj Bešlin [g]

[a] Laboratory for Paleoenvironmental Reconstruction, Trg Dositeja Obradovića 2, Faculty of Sciences, University of Novi Sad, 21000 Novi Sad, Serbia
[b] Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology, Deutscher Platz 6, 04103 Leipzig, Germany
[c] Institute of Geography and Geology, University of Würzburg, Am Hubland, 97074 Würzburg, Germany
[d] Chair of Social Geography, Trg Dositeja Obradovića 3, Faculty of Sciences, University of Novi Sad, 21000 Novi Sad, Serbia
[e] Giotto Loess Research Group, Geography Department, Leicester University, Leicester LE1 7RH, UK
[f] Serbian Academy of Sciences and Arts, Knez Mihajlova 35, 11000 Belgrade, Serbia
[g] Provincial Secretariat for Science and Technological Development, Government of the Autonomous Province of Vojvodina, Bulevar Mihajla Pupina 16, 21000 Novi Sad, Serbia

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ABSTRACT

The loess-paleosol sequences of the Danube basin contain the longest and most complete terrestrial records of Middle and Late Pleistocene paleoclimates in Europe. Consequently it is no surprise that scientific research into European loess began in this region and has a long and distinguished history. European loess research was initiated by Count Marsigli in the Serbian Vojvodina in the late 17th century, formed the focus of the international Loess Commission which straddled both sides of the Iron Curtain from 1961, and culminated with George Kukla's seminal studies in the 1970s correlating the loess archives with deep-sea sediments. The rise in popularity of the longer Chinese loess sequences in the early 1980s shifted the international research focus away from Europe, and it was not until the change of century that scientific investigation intensified in the region – this time with much more sophisticated tools for analysis.

Despite its potential as one of Europe's most valuable Quaternary archives, scientific research into Danube loess has until recently been hindered both by landscape heterogeneity and the large number of countries it covers. These have presented a major limiting factor in developing a unified research approach. For decades, regional/national loess stratigraphic models were defined separately. Difficulties in correlating such schemes persist, especially since these often change significantly with advances in dating methodologies. A cooperative effort is necessary to synthesize the available data, which requires not only the insights from but also the perspective provided by an appreciation of the history of the research.

In this study we present a critical historical overview of loess research in the Danube region. We classify the major research phases throughout the long tradition of Danube loess investigations into five categories: (1) the Early period (late 17th century until 1920) extending from Marsigli to Penck; (2) the Classic period (1920–1961) encompassing the contributions of Milanković and the development of pedostratigraphy; (3) the Modern period (1961-present) which oversaw Czech innovations and developments in geochronologic methods, in particular Amino Acid Racemisation (AAR) and luminescence dating; and (4) Contemporary research from Bronger's unified pedostratigraphy to orbitally-tuned timescales. Finally, (5) we present a vision of future Danube loess research.



## 1. Introduction

The lowlands of the Danube River catchment are dominated by extensive and thick deposits of loess (Haase et al., 2007). The river and the loess share a common history, not only geomorphologically and genetically (Smalley and Leach, 1978), but also in terms of human (pre)history. Hominins are known to have roamed the loess steppe near the Danube delta from at least 300 ka (Iovita et al., 2012). The flanks and especially the (lower) terraces of the Danube River are posited to have represented a conduit for modern human dispersal into Europe (e.g. Mellars, 2006), although the conditions under which this migration occurred may have been

* Corresponding author.
*E-mail address:* slobodan.markovic@dgt.uns.ac.rs (S.B. Marković).

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challenging (Fitzsimmons et al., 2013; Veres et al., 2013). In addition, some of the most important European civilizations from prehistory into history have been closely linked to the fertile soils formed on Danubian loessic deposits, from the early Neolithic colonies (e.g. Willis and Bennett, 2004) and Roman Empire expansion (Bunardžić, 2005), to battles for supremacy by the Austrian and Ottoman powers.

More recently, significant advances in scientific research into Quaternary loess archives have been made in the Danube Basin. These form the focus of this study and include, but are not limited to, early investigations of loess stratigraphic sequences (Marsigli, 1726; Penck and Brückner, 1909), hypotheses of loess formation processes (Smalley and Leach, 1978; Pécsi, 1990), correlations between loess and marine records (Kukla, 1970; Fink and Kukla, 1977; Kukla and Nakagawa, 1977; Kukla and Cilek, 1996), and between loess profiles on a Eurasian continental scale (Marković et al., 2008, 2015; Fitzsimmons et al., 2012), and fundamental methodological developments in the dating of loess deposits (Singhvi et al., 1989; Zöller and Wagner, 1990; Oches and McCoy, 1995a, 1995b; Frechen et al., 1997; Timar-Gabor et al., 2011; Thiel et al., 2011).

This review aims to provide a critical historical account of scientific research in the Danube basin. We also review the diversity of loess-paleosol sequences (LPS) in the region and its (pre)history. From this foundation and state of the art we suggest the future perspectives for loess research.

## 2. Geological and physio-geographical setting

The geological formation of the Danube catchment can be traced back to the Cretaceous collision of the Eurasian with the African continental plates, leading to the successive elimination of the Tethys Sea throughout the Tertiary period (Harzhauser and Piller, 2007). The Paleogene Alpine orogeny oversaw complex interactions between several microplates, involving both compression and extension dynamics across Central to Southeastern Europe, creating several mountain ranges and basins. On the northeastern flank of the Alpine orogeny – the present-day upper Danube catchment as far east as Bohemia – the Variscan basement and Mesozoic platform rocks were only slightly displaced. Further east, in the lowland region now occupied by the Pannonian and Wallachian Plains, a basin was created which was filled by the Paratethys Sea (Harzhauser and Piller, 2007).

The final regression of the Paratethys Sea during the Neogene resulted in the formation of a large lake (Pannon) (e.g. Ivanov et al., 2011; Leever et al., 2011), and finally the Danube River system (Fink, 1966; Kiss et al., online published). The uplift of the Carpathian mountains effectively separated the central Paratethys Sea (which became Lake Pannon, and later the Pannonian/Carpathian basin) from its eastern counterpart (which became the Wallachian basin) (Sanders et al., 1999). Reconnection between the Pannonian (Carpathian) and Wallachian basins was later established at the Iron Gates Gorge (Clauzon et al., 2005), located in the border region between present-day Serbia, Romania and Bulgaria. The Dobrogea Plateau of southeastern Romania was uplifted relative to the Wallachian basin to its west somewhat later, c. 700 ka (e.g. Munteanu et al., 2008). This affected a northwards diversion of the Danube River and ultimately influenced the depositional regime of the Quaternary loess deposits in the lower Danube basin (Jipa, 2014).

The Danube River is the longest in the European Union, and exceeds 2800 km in length. The present watershed divide between the Danube, Rhone and Rhine Rivers lies in the border region between France, Germany and Switzerland. The stream gradient in the Danube River headwaters, as far as Bratislava on the western edge of the Pannonian (Carpathian) Basin, is relatively steep. In the vicinity of the Alps, large moraine systems and glaciofluvial terraces – often with a significant loess cover – formed in response to Quaternary glaciation events (Penck and Brückner, 1909; Doppler et al., 2011; Ellwanger et al., 2011; Van Husen and Reitner, 2011). In comparison, the lowland river in the Pannonian (Carpathian) and Wallachian basins further downstream has a gentler stream gradient (Fink, 1966). The lowland Pannonian (Carpathian) and Wallachian basins are filled with thick polycyclic sedimentary deposits of Pliocene and Quaternary age including significant amount of loessic sediments (Munteanu et al., 2008; Jipa, 2014). Glaciofluvial and fluvial activities in the Danube headwaters have therefore necessarily influenced the timing and nature of sedimentation downstream.

The model for loess production and deposition within the Danube basin describes a process of increased silt production through glacial grinding and periglacial erosion in the mountainous headwaters during Quaternary glacial phases, with associated downstream transport of this fine sediment by the Danube and its tributaries, and aeolian deposition from the river banks to the plains (Smalley and Leach, 1978; Smalley et al., 2009). This model is supported by observations of generally increasing loess thickness, and higher aeolian content, from the Alpine piedmont slopes, which contain a periglacial admixture of allochthonous aeolian silt and colluvium (Semmel, 1989), to the lower gradient plains of the Pannonia and Wallachian basins downstream, which more frequently comprise pure aeolian loess (Haase et al., 2007). Local variability in loess thickness and aeolian content does exist – typically on leeward slopes which acted as more stable sediment traps – but typically the thickest, purest aeolian loess cover of the Danube basin extends across the lowlands, which have been less affected by erosional processes.

According to the proposed model for loess production and deposition (Smalley and Leach, 1978; Smalley et al., 2009), glacial silt production and loess deposition in the Danube basin was enhanced during Quaternary glacial phases, and strongly reduced during the interglacial stages, especially in the more oceanic influenced loess regions. The milder, more stable climatic conditions during the interglacials and interstadials, and reduced loess accretion during these phases, facilitated pedogenesis. Over multiple glacial–interglacial cycles, therefore, LPS of varying thickness have accreted across the basin (e.g. Fink and Kukla, 1977; Kukla, 1977). These sequences form some of the most comprehensive terrestrial paleoenvironmental archives available in continental regions, and are described in more detail in the next section.

Fig. 1 shows the spatial distribution of loess and loess-like deposits across the Danube basin, superimposed upon the major features associated with the interglacial and glacial periods of the Quaternary. Natural processes dominating during interglacial periods are indicated by average annual precipitations as shown; ice covered zones, dried continental shelf and the southern boundary of the periglacial zone reflect glacial conditions.

The climate of the Danube basin lies at the interface between the European continental, Atlantic, Mediterranean and central Asian systems (Mavrocordat, 1971; Richard et al., 2000; Hrnjak et al., 2014). However, the climatic conditions and influences vary along its >2800 km reach, and have likewise changed through time (Stevens et al., 2011). There is a general trend towards increased continentality in the eastward, downstream, direction (WMO, 1996). This is due to the diminishing influence and contribution of North Atlantic moisture from the Danube headwaters eastward to its delta. The Dobrogea and Danube delta regions are some of the driest in Europe, experiencing an average ~350 mm precipitation annually (Richard et al., 2000). Mediterranean influences and precipitation regimes are more significant in the southern Serbian and Croatian sections of the Danube basin. On the mesoscale, topographical barriers and continental influences modify the general