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Late Pleistocene climate evolution in Southeastern Europe recorded by soil bacterial membrane lipids in Serbian loess

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ABSTRACT

Loess–paleosol sequences in the Vojvodina region in the southeastern Carpathian Basin have been intensively studied to obtain a high-resolution stratigraphical framework for the Upper Pleistocene in this part of Europe. In these studies, millennial-scale sedimentation variations in the Upper Pleniglacial have been coupled to the Greenland Ice dust record, indicating that the rapid climate variability characterizing the North Atlantic and Greenland areas, is reflected in the loess deposits at the southern edge of the European loess belt. Rapid variations were recently also reported for the stable isotopic composition of organic matter in the Surduk loess-paleosol sequence, located in the Vojvodina region, and were interpreted as episodes of increased C_4-vegetation over the last glacial period. Based on potential coinciding changes in oceanic and atmospheric circulation patterns, these episodes were attributed to plant moisture stress rather than by fluctuations in temperature, although exclusive proof has not yet been provided. Here we report a high-resolution record of continental air temperature and precipitation over the past 40,000 years based on soil bacterial lipid signatures preserved in the Surduk loess–paleosol sequence. Our temperature record shows a gradual warming trend, suggesting that moisture availability indeed seems to be the main factor driving the excursions to C_4-vegetation around Surduk. We also find that continental air temperature changes in this region may be seasonally biased, and were driven by regional influences rather than by Northern Hemisphere climate forcings, likely as a result of the inland isolation of the Carpathian Basin by surrounding mountains. Support for a regional climate driver comes from comparison of our lipid-based temperature and precipitation records with similar records from the near-by Crvenka loess–paleosol sequence, which resemble the climatic trends recorded at Surduk.

1. Introduction

During the Quaternary, windblown dust has accumulated as loess deposits over large parts of Europe and Asia. Especially on the Chinese Loess Plateau these deposits have been well studied, where the alternations of loess and paleosol layers have been related to cold and dry glacials and warm and wet interglacials, respectively (e.g. An, 2000). But also in Europe, loess–paleosol sequences are widespread (Haase et al., 2007) and have been studied to gain more insight into Quaternary climate change, especially the last glacial period (e.g. Buggle et al., 2009; Antoine et al., 2001; Rousseau et al., 2002). In Western Europe, loess grain size variations and the alternation of loess and gleys in the sequences have been linked to the dust record of the Greenland ice core (Rousseau et al., 2007), suggesting a connection between the atmospheric circulation and associated wind regimes in the North Atlantic and Europe. This connection is also visible in loess–paleosol sequences located in the Carpathian Basin in Southeastern Europe, where abrupt increases in loess grain size indicate a succession of short events during the Upper Pleniglacial (ca. 37–20 kyr BP), reflecting the variations in aeolian dynamics related to rapid climate variability, as also recorded in North Atlantic and Greenland records (e.g. Marković et al., 2005, 2008; Antoine et al., 2009; Stevens et al., 2011).

A recent study focusing on the Surduk loess–paleosol sequence, located in the southern part of the Carpathian Basin (Fig. 1), showed that also the stable isotopic composition of organic carbon ($\delta^{13}C$) has recorded similarly rapid changes (Hatté et al., 2013). The isotope record indicates several episodes of ^{13}C enrichment during the Late Pleistocene, which have been interpreted as temporary dominance of C_4 vegetation in this region. The excursions to C_4 vegetation have been explained by dry and short summers caused by coinciding changes in oceanic and atmospheric circulation patterns, unfavorable for moisture transport from the Mediterranean Sea and Atlantic, and consequently resulting in less precipitation on the Balkans. However, exclusive proof for moisture availability as main driver of vegetation change is hard to obtain, as it is difficult to disentangle whether the variability in the

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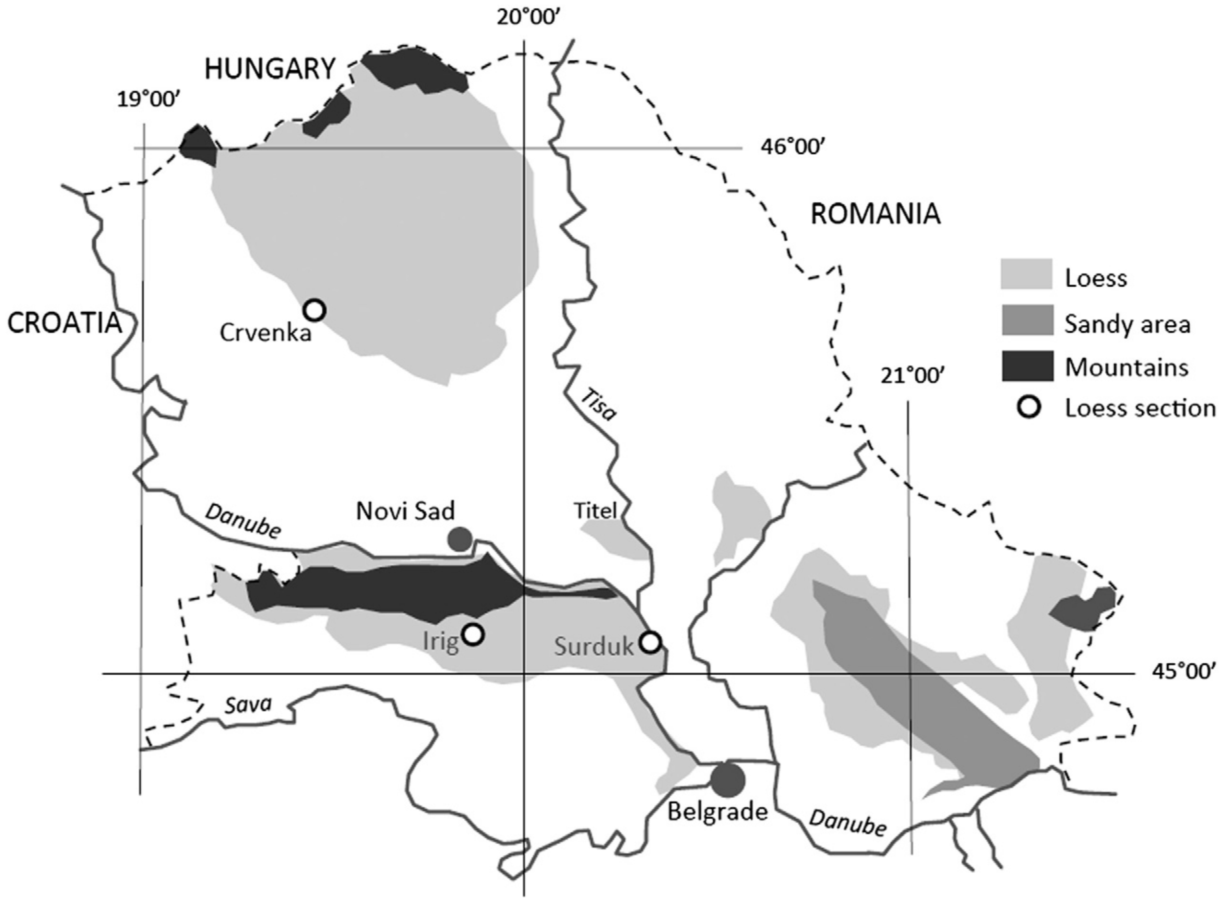

Fig. 1. Map of the Carpathian Basin with the location of the Surduk, Crvenka and Irig loess–paleosol sequences.

δ^{13}C record is driven by changes in temperature or precipitation based only on variations in grain size distributions or total organic carbon content (Hatté et al., 2013).

In order to further identify the driver(s) of sudden vegetation change in this area, the occurrence and relative distribution of branched glycerol dialkyl glycerol tetraethers (brGDGTs; Fig. 2) have been analyzed throughout the same loess–paleosol sequence at Surduk. BrGDGTs are membrane lipids produced by soil bacteria that occur ubiquitously in soils and peat (Weijers et al., 2006), and adapt the molecular structure of their membrane to changes in mean air temperature (MAT) and soil pH (Weijers et al., 2007a). Hence, past changes in MAT and soil pH can be reconstructed by using the MBT (methylation of branched tetraethers) and the CBT (cyclisation of branched tetraethers) indices, based on the amount of methyl branches (4–6) and cyclopentyl moieties (0–2) of the brGDGTs, respectively (Weijers et al., 2007a). The strength of this method is that variations in precipitation-induced soil pH and MAT are reconstructed based on the same suite of molecules, which is ideal to disentangle the influence of these two environmental parameters on e.g. vegetation change. Furthermore, also the relative abundance of brGDGTs compared to that of crenarchaeol (Fig. 2), an isoprenoid GDGT that is produced in soils by ammonia oxidizing archaea, has been shown to relate with soil moisture availability (e.g. Xie et al., 2012; Dirghangi et al., 2013), and can be quantified in the Branched and Isoprenoid Tetraether (BIT) index (Hopmans et al., 2004). Together with soil pH, the BIT index can thus be used as indicator for past precipitation changes. Recent studies from the Chinese Loess Plateau have indicated that brGDGTs indeed record past climatic changes, both in temperature as well as in precipitation intensity (e.g. Jia et al., 2013; Peterse et al., 2011, 2014).

A first attempt to reconstruct precipitation and MAT using brGDGTs in the nearby Crvenka loess–paleosol sequence indicated an early warming and higher than expected air temperatures during the past glacial–interglacial transition (Zech et al., 2012). The unexpected trends were attributed to a.o. incomplete peak separation of co-eluting brGDGT isomers during analysis using high performance liquid chromatography (HPLC), complicating the determination of the exact abundance of each brGDGT in the obtained chromatogram (Zech et al., 2012). This issue has recently been resolved by De Jonge et al. (2014), who proposed an optimized HPLC method that enables the separation of these isomers, adding to the reliability of the generated proxy records. Moreover, identification of the isomers (De Jonge et al., 2013) indicated that brGDGTs with a methyl branch on the 5′ or the 6′ position are related to temperature and pH, respectively, further separating the influence of these environmental parameters, and the accuracy of their use as paleothermometer (De Jonge et al., 2014). Hence, the use of this new method to generate GDGT-based climate records may provide new insights on past precipitation and temperature variability in continental Europe, and their subsequent influence on past vegetation dynamics.

2. Material and methods

2.1. Study site

The Surduk sequence is located in the north of Serbia, in the Vojvodina province in the southeastern part of the Carpathian Basin (45°40′ N, 20°20′E; 111 m above sea-level; Fig. 1). The Vojvodina area is characterized by the presence of thick loess–paleosol sequences mainly outcropping as high loess cliffs along the western bank of the Danube River and at the confluence between the Danube and tributaries, including the Tisa River east of the Titel Plateau (Fig. 1) (Marković et al., 2008; Antoine et al., 2009). The area currently lies at the border between Atlantic, Continental and Mediterranean climate zones and small