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Lower to middle Weichselian pedogenesis and palaeoclimate in Central Europe using combined micromorphology and geochemistry: the loess-paleosol sequence of Alsheim (Mainz Basin, Germany)

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ABSTRACT

Lower to middle Weichselian loess, loess derivatives and buried soils of the loess-paleosol sequence Alsheim (Central Europe) were characterised by particle size distribution, geochemical and micromorphological data. High rates of sedimentation with alternating phases of relocation are the main cause for a much less differentiation into Middle and Upper Weichselian loess-paleosol units of the Alsheim loess-paleosol sequence compared to other loess-paleosol sequences (e.g. Nussloch near Heidelberg), whereas the Lower Weichselian has distinct phases of pedogenesis resulting in Ah, Bw and Btw horizons.

To distinguish between different loess deposits locally and intraregional, the degree of fineness is an easily applicable and suitable tool, though inappropriate for interregional comparisons. The chemical index of alteration (CIA) is low (<50 = no weathering) for loess deposits in the Alsheim loess-paleosol sequence, which is in contrast to the worldwide compiled loess samples with CIA values ranging from >53 to <70 (Gallet et al., 1998). The highest weathering was detectable for Btw horizons with CIA values >70.

A direct quantitative estimation of mean annual palaeotemperature and mean annual palaeoprecipitation can be provided by calculations based on geochemistry of soil horizons and sediments. The present mean annual precipitation (MAP) in the Mainz Basin is 789 mm. In contrast, palaeoprecipitation data suggest a 150 mm higher amount for the Last Interglacial (Btw horizon), a much lower amount of around 300–400 mm MAPP (periods of loess and sandy loess deposition) and a MAPP of <500 mm for Weichselian Interstadials (humus zones and Bw horizons). The calculated mean annual palaeotemperature (MAPT) for Interstadials with 8.9 °C for Bw horizons or with 9.6 °C for humus zones (or to 2 K lower, considering the relation of the present MAT of the Mainz Basin with the MAT of Germany) seems to be a good approximation of the MAPT for Lower and Middle Weichselian Interstadials. A MAPT of 8.7 °C (or 6.7 °C) for Stadials (loess and sandy loess samples) is higher than other temperature estimations for Weichselian Stadials in Europe.

Micromorphology shows compacted granular structure and moderately to strongly developed pedality as characteristic properties for aquatic loess, whereas channel microstructure with no pedality is typical for loess deposits. Spongy microstructure suggests a classification of the Lower Weichselian Mosbach Humus Zones as Chernozems. The Eemian paleosol (Btw horizon in Als III) has only weak clay illuviation, characteristic for drier regions in Europe.

Palaeoclimate and soil formation of the Last Glacial–Interglacial cycle calculated from geochemistry and micromorphological data are in good accordance with other proxy data in Central Europe. This suggests that paleoclimate reconstruction based on palaeopedological analyses could be successfully implemented in Europe. Such data may provide a useful alternative to other proxies for correlating European records.

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1. Introduction

Loess-paleosol sequences are excellent terrestrial archives for Late Cenozoic climate change (e.g. Catt, 1991; Frechen et al., 2001; Kemp, 2001; Porter, 2001; Schatz et al., 2011). Whereas the broader application of luminescence dating techniques led to a deeper decipherment of loess-paleosol sequences (e.g. Roberts, 2008; Kadereit et al., 2010; Thiel et al., 2011), detailed micromorphological-sedimentological (e.g. Kemp et al., 1994; Xiao et al., 1995; Kühn et al., 2006a) and palaeopedological studies contributed to an improved understanding of past climate fingerprints in loess and corresponding environments (e.g. Kemp et al., 2006; Mason et al., 2008; Haesaerts et al., 2010; Marković et al., 2011; Zech et al., 2011).

Against the background of the fact that modern soils at the today's land surface have formed under present climate conditions, buried soils being in a similar developmental stage and having the same soil properties are most likely indicative to comparable climate conditions of the past (Catt, 1991). Nevertheless it has to be taken into account that not all paleosol properties necessarily reflect environmental conditions comparable with today (Kemp, 2001; Kühn et al., 2006b). If buried paleosols are not welded or accretionary they can be used as proxies for palaeoclimate conditions (e.g. Buggle et al., 2009; Sheldon and Tabor, 2009; Suchodoletz et al., 2009; Dreibrodt et al., 2010a; Pietsch and Kühn, 2012).

Many regions in loess areas have been settled since ancient times and are characterised by severe soil erosion caused by centuries of agriculture or viticulture (e.g. Lang, 1997; Kalis et al., 2003; Mäckel et al., 2003; Ruddiman et al., 2008; Fuller et al., 2011). As a result calcaric Regosols on slopes and Anthrosols or colluvial deposits on footslopes and in valley floors are widely spread (Leopold and Völkel, 2007; Dreibrodt et al., 2010b). These soils, however, are hardly climate-indicative, because they result predominantly from soil erosion and are therefore not suitable for a comparison with buried *in situ* paleosols. Without having the opportunity of a comparison of paleosols with modern soils within an area, only proxies – developed elsewhere – or directly taken from the palaeosols can yield information about the palaeoenvironment.

Aside from a precise characterisation of petrographic and elemental properties, geochemistry offers the possibility to get indicatory values on palaeoprecipitation and palaeotemperature from paleosol horizons (e.g. Sheldon and Tabor, 2009). Combined with micromorphology it provides essential information about weathering intensity, pedogenic processes, relocation processes and palaeoenvironmental conditions.

Micromorphological features of paleosols reflect soil forming process such as clay illuviation, calcification, decalcification, redoximorphosis or relocation, and hence reflect environmental conditions under which these soils formed (e.g. Bronger et al., 1994; Kemp, 1998; Fedoroff et al., 2010). Micromorphology gives additional information about the intensity of soil forming processes, i.e. about soil developmental stages and their succession (Pietsch and Kühn, 2009) and it helps to refine the pedostratigraphy of loess-paleosol sequences (Kühn et al., 2006a).

In this paper we focus on particle size distribution, geochemical and micromorphological data characterising particularly lower Weichselian loess and loess derivatives as well as weathering intensities of buried Bw, Btw and Ah (humus zones, Chernozem) soil horizons of a loess-paleosol sequence situated in Central Europe. By our knowledge, the use of geochemical data of distinct buried soil horizons in terms of palaeoenvironmental proxies is the first attempt to calculate palaeotemperature and palaeoprecipitation in Europe for the Late Cenozoic.

2. Local and regional setting

Several loess-paleosol sequences (numbers 1–4 in Fig. 1) have been investigated in the Mainz Basin in Germany. They show a high sensitivity to regional climate and environmental changes particularly since the penultimate glacial period (e.g. Frechen, 1999; Semmel, 1999; Frechen and Weidenfeller, 2000; Bibus et al., 2002). The Alsheim loess-paleosol sequence (number 1 in Fig. 1), is situated in the eastern part of the Mainz Basin, about 2 km west of the eastern rim of the Upper Rhine Rift.

Different sections of the loess-paleosol sequence were investigated (Fig. 2A), whereas the present contribution focuses particularly on sections Als I, Als IIb and Als III comprising sedimentation phases 3 to 5 and partly phase 2 in Als 3 (Fig. 2A).

The Alsheim loess-paleosol sequence includes humus-rich horizons (Ah), brown horizons (Bw, Bwt) intercalated by layers of loess and loess derivatives, and relocated humus-rich horizons/layers (Fig. 2B). The results of luminescence datings and paleomagnetic investigations revealed five sedimentation phases (including phases of soil formation) from the Saalian to the Weichselian period (after Techmer et al., 2006): (1) Saalian (168–163 ka): loess and aquatic loess, (2) Saale-Lower Weichselian (130–110 ka): loess, interglacial soil (Btw horizon), loess and LMHZ, (3) Lower Weichselian (109–70 ka): aquatic loess, loess, bog loess (MMHZ?), Bw horizon, aquatic loess, (4) Lower to Middle Weichselian (70–46 ka): loess, UMZH, aquatic loess, (5) Middle Weichselian (39–16 ka): loess, Eltiville Tephra, loess.

Fluvial gravel and sand build up the base of the Quaternary deposits lying on Tertiary limestone (Wiesbaden formation). Though oldest parts of the loess-paleosol sequence date to the penultimate glaciation (Saalian; sedimentation phase 1, Fig. 2A; cf. Techmer et al., 2006) a well-developed Bt or Btg horizon was not found, which usually reflect interglacial climate conditions in Central Europe (Catt, 1991). Buried Bt and Btg horizons with noticeable clay illuviation and redoximorphic features (e.g. Antoine et al., 1999; Kemp, 2001; Bibus et al., 2007) or with humus accumulation (Frechen, 1999; Bibus et al., 2002) frequently represent the soils of the Last Interglacial in middle Europe. The soil of the Last Interglacial in the Alsheim loess-paleosol sequence, however, shows only weakly developed features of clay illuviation and no humus accumulation and have to be therefore classified as a Btw horizon (Section Als I and III, Fig. 3).

The pedostratigraphy of Alsheim can be correlated to the loess-paleosol sequence of Mainz-Weisenau (e.g. Bibus et al., 2002) (Fig. 4). A stratigraphic equivalent of this Btw horizon is the uppermost Bt horizon in Mainz-Weisenau, which is assumed to be the remnant of the Luvisol of the Last Interglacial (Bibus et al., 2002). This horizon is truncated by periglacial layer consisting of Bt material in Mainz-Weisenau. Weichselian loess covers the Btw horizon of the Last Interglacial in Alsheim.

The humus-rich horizons are of Weichselian age and – based on the pedostratigraphy, luminescence datings and paleomagnetics (Techmer et al., 2006) – can be correlated with the Mosbach Humus Zones. The lower Mosbach Humus Zones (LMHZ, Als III in Fig. 3) and the upper Mosbach Humus Zones (UMHZ, Als I in Fig. 3) are developed as black coloured and well-structured horizons. A layer of bog-loess (Als III in Fig. 3) is stratigraphically intercalated between LMHZ and UMHZ. Based on its stratigraphic position the bog loess can be considered as an equivalent of the MMHZ (Middle Mosbach Humus Zone) of Mainz-Weisenau: the bog loess in Als III occurs between two humus zones (Fig. 4). The loess layer intercalated between bog loess and LMHZ has a maximum age of 89.1–97.1 ka (Figs. 3 and 4). The LMHZ is directly above the Btw horizon dating to the Last Interglacial (Techmer et al., 2006) and the mollusc shells (*Vallonia costata, Chondrula tridens, Trichia sp.,*