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Biopores and root features as new tools for improving paleoecological understanding of terrestrial sediment-paleosol sequences

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ABSTRACT

The important role of roots and rhizosphere processes is accepted for the top soil, but still under debate for the deep subsoil including soil parent material. Especially for terrestrial sediments like loess and dune sands, roots and root traces are mostly recognized in profile descriptions, but not interpreted in the paleoenvironmental context. Further, synchrony of sediment deposition and root trace formation is commonly assumed. This is challenged by partially large maximum rooting depths of plants, exceeding the soil depth, and by frequent occurrence of secondary carbonates and biopores of potential root origin below recent soil and paleosols. To improve understanding of paleoenvironmental records in terrestrial sediment-paleosol sequences, recent roots and root traces, including calcified roots and root-derived biopores, were investigated in six soil, loess and dune sand profiles across Central and SE Europe. Visualization of small carbonate accumulations (diameter ≤1 mm), frequently called 'pseudomycelia', by X-ray microtomographic scanning, and morphologic comparison with rhizoliths (calcified roots; diameter mostly 3–20 mm, up to 100 mm possible) indicate root origin of the former, therefore requiring renaming to microrhizoliths. Quantification of roots, biopores, rhizoliths and microrhizoliths on horizontal levels yielded maximum frequencies of 2100 m^{-2}, 4100 m^{-2}, 196 m^{-2} and 12,800 m^{-2}, respectively. Considering the pore volume remaining from former root growth this indicates their significant contribution to structural properties of the sediments and paleosols. Depth distribution of roots and root traces was frequently related to soil and paleosols, respectively, and mostly showed maximum frequencies within or immediately below these units. Root traces are therefore not necessarily of similar age like the surrounding sediment, but are typically of younger age. The time lag between root traces and the surrounding stratigraphic unit can vary between small time periods (likely decades to centuries) in case of microrhizoliths and several millenia in case of larger rhizoliths penetrating several stratigraphic units. With assumed radii of former rhizosphere extension of 5 mm for microrhizoliths, a frequency of 12,500 m^{-2} corresponded to 100% rhizosphere area in the respective depth interval. These findings emphasize the meaning of root traces in sediment–paleosol sequences. Potential temporal and spatial inhomogeneity of root growth on the one hand, especially for shrub and tree vegetation, and occurrence of root remains of different age and origin in identical depth intervals on the other hand, hamper the assessment of the chronologic context of these with the surrounding sediment or paleosol. Nevertheless, root traces in terrestrial archives provide valuable information with respect to paleovegetation and paleoenvironmental conditions, if their chronological context is known.

1. Introduction

Paleoenvironmental and paleoclimate research in terrestrial ecosystems covers lacustrine, fluvial and eolian sediments and sediment–paleosol sequences, of which loess–paleosol sequences are regarded as one of the most continuous archives in the terrestrial, non-aquatic realm (Pye and Sherwin, 1999). Sediment–paleosol sequences are used e.g. to reconstruct local paleovegetation, which is often based on plant macrofossils (usually pollen; e.g. Sun et al., 1997), or in more recent studies also molecular proxies including e.g. lipid fractions (Xie et al., 2003; Zech et al., 2012). The major assumption of such studies is the synchrony of analyzed features with deposition of the respective sediment or paleosol unit. Thus, Retallack (1988) recommended field identification of paleosols by occurrence of root traces, because these,

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besides animal burrows and climate-dependent accumulations like calcretes or laterites, are one striking feature of soils and paleosols (Jenny, 1994). For steppe-like vegetation which is widely accepted to respresent the typical vegetation in areas of loess deposition (Liu et al., 1996; Sun et al., 1997), this is obvious because roots of this vegetation type comprise up to 80% of the total living plant biomass (Verchot et al., 2006). Even for other ecosystems like forests root contribution to soil organic matter was found to be larger than that of aboveground litter (Rasse et al., 2005). If this knowledge is transferred to paleosols, this relationship of paleosols and root remains can, however, be complicated by one or more of the following facts: i) Different degree or lack of preservation of root traces especially in case of fine roots due to their short longevity (Gaudinski et al., 2001; Strand et al., 2008); ii) strongly varying inter- and intraspecies rooting depth for grass, herb, shrub and tree species (Canadell et al., 1996); iii) temporal and spatial heterogeneity of root distribution (Silk, 1984); iv) varying depth of preserved root traces as secondary carbonates within or below the stratigraphic unit, depending on climatic factors (McFadden and Tinsley, 1985); and v) postsedimentary penetration of sediments by deep-rooting plants (Gocke et al., 2011).

In general, the meaning of root penetration and root-derived biomass was underestimated in loess research (Gocke et al., 2014). In numerous studies, profile charts indicate root traces (e.g. root-derived biopores) which are, however, often not taken into account within the profile description and interpretation. Only recently, Rasse et al. (2005), followed by Rumpel and Kögel-Knabner (2011) and Rumpel et al. (2012), suggested that a considerable part of deep subsoil organic matter (OM) might be of root and rhizomicrobial origin. Moreover, other authors argue for the relatively high persistence of root-derived carbon (Mendez-Millan et al., 2010), especially in the deep soil (Kell, 2012). In contrast to detailed root quantification in soil research (Schenk and Jackson, 2002), for paleoenvironmental studies roots and root traces in sediment–paleosol sequences are usually regarded only as a qualitative feature for paleosols, or in rare cases are investigated semi-quantitatively. For instance, approximate root densities were estimated to compare these features in different depth intervals of the profile (Sheldon and Tabor, 2009 and references therein), or relative portions of different carbonate features were estimated based on thin sections (Xiaomin et al., 1994; Kemp, 1999). In well drained parent material like dune sands and loess, root remains might be degraded rather fast, and preservation is only possible if either remaining pores, i.e. biopores, are preserved, or if roots are protected e.g. by carbonatic encrustation. Such secondary carbonate accumulations, called rhizoliths, occur frequently in terrestrial sediments, together with other types of secondary carbonates (Becze-Deák et al., 1997; Barta, 2011). In the following, the term rhizolith is used for ancient or recent roots that have been encrusted by secondary carbonate, which does not exclude that also parts of the root tissue were calcified. Rhizoliths were likely formed during the root's lifespan or shortly thereafter (Gocke et al., 2011). Besides rhizoliths, biopores of a diameter smaller than 1–2 mm also point to the former presence of roots. However, despite their potential of long-term preservation in calcareous terrestrial sediments like loess, biopores were usually not identified and included in any paleoenvironmental studies, so far. This is most likely due to the common investigation of vertical profile walls and not horizontal layers within the profile, which hampers the recognition of biopores, and possibly also of calcified roots.

Thus, we hypothesized that a considerable portion of rhizolith and biopore features in terrestrial sediments can be attributed to recent or former root growth and therefore can be connected in some way to paleosols, but might also occur in sediment units due to varying rooting depth of the corresponding source vegetation. The aim of this study was to elucidate the important role of roots and root traces in terrestrial sedimentary settings, as well as potential relationship of roots or root traces with the recent soil, paleosol or both, by giving three-dimensional insights into their frequencies. These were studied in various climatic and sedimentary settings across Central and SE Europe.

2. Study sites

Six soil, sediment and sediment–paleosol profiles were studied for distribution of roots and root feature in Germany, Hungary and Serbia (Fig. 1; Table 1).

2.1. Nussloch

The loess–paleosol sequence at Nussloch is situated in an active quarry of the HeidelbergCement AG, 10 km S of Heidelberg, SW Germany (Fig. 1) on the E side of the Rhine Rift Valley. Several profiles of the Late Pleistocene sequence comprising the last glacial–interglacial cycle were described e.g. by Antoine et al. (2001, 2009), Frechen et al. (2007) and Gocke et al. (2011). The profile investigated in the present study is located at the W margin of the quarry as described by Gocke et al. (2014). The profile comprises the recent soil, the Upper and Middle Pleniglacial subsequences and the uppermost part of the Lower Pleniglacial subsequence (Table 1). Rhizoliths with diameters up to ~30 mm and length of several dm up to ~1.5 m (Fig. 1B in Gocke et al., 2014) occur locally highly abundant within the Nussloch loess–paleosol sequence, but were scarcely mentioned so far. Radiocarbon dating of rhizoliths (3 kyears) and calcified root cells (6, 9 and 10 kyears) revealed their Holocene age at Nussloch (Frechen et al., 2007; Gocke et al., 2011) and its vicinity (Pustovoytov and Terhorst, 2004). Even presence of recent roots was mentioned in few studies of profiles at the Nussloch site, but their frequency was not described in high resolution (Zech et al., 2012; Gocke et al., 2014), which was performed in the current study.

2.2. Sopron

Two profiles in the surrounding of Sopron, NW Hungary, were investigated for root traces within and below the recent soil. Due to the city's position at the margin of the E Alps, various soil parent materials occur within short distances, including limestones, conglomerates, sandstones, fluvial sand and loess (Haas, 2012).

Profile Sopron A is situated N of Sopron in the Dudlesz Forest, which developed mainly on Sarmatian limestone and conglomerates. The 2 m thick profile consists of the recent soil overlying a buried Chernozem (Table 1). Potential relation of roots and root feature with either the topsoil or the buried soil was investigated. The soil parent material was not reached in this profile, but a profile (not investigated in the current study) located approximately 100 m distant, revealed the underlying fluvial sand and conglomerate.

Profile Sopron B is part of a small abandoned brickyard in the forest W of Sopron. Under the recent soil approximately 3.5 m of clayey, pale yellow loess is exposed (Table 1). The profile was first described by Huguet et al. (2013). Due to the concave outcrop wall, abundant thick roots of the recent tree vegetation (see Table 1) with diameter of up to 30 mm are exposed, most of which show initial encrustation by secondary carbonate (Fig. 2A).

2.3. Katymár

Close to Katymár, a village at the S border of Hungary 80 km WSW of Szeged, a Late Pleistocene loess section is exposed in a small brickyard (Sümegi et al., 2007). The section consists of original, unaltered loess, covered by a Chernozem (IUSS Working Group WRB, 2007). At the base of the section, a 30 kyears old paleosol (Willis et al., 2000) with a thickness of more than 0.5 m occurs. The lower boundary of this paleosol was not reached in the outcrop. Small carbonate accumulations (Fig. 2B) occurred abundant throughout the profile and might have been observed also in the nearby Madaras section ('slim fossil carbonate-filled roots' and 'small carbonated noodles'; Hupuczi and Sümegi, 2010). The paleosol and 0.8 m of overlying loess were included in the present study to assess occurrences of root traces.