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Quaternary paleosols and sediments on the Balearic Islands as indicators of climate changes

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ABSTRACT

Paleosols and sediments are suitable objects for reconstructing paleoclimate. To obtain a high climatostratigraphic resolution in the Western Mediterranean, we investigated geoarchives with paleosols and sediment layers in cliff profiles of two alluvial fans on Mallorca, their pedostratigraphy covered the Late Pliocene, Pleistocene and Holocene. The sites were analysed in terms of colour, $CaCO_3$, $\delta^{13}C$ and $\delta^{18}O$ isotopes, and micromorphology.

The sequence of El Toro (SW Mallorca) comprises 44 partly polygenetic paleosols and sediment layers, where redness is mostly pronounced in Late Pliocene and Early Pleistocene layers, but also partly in younger periods. The Eemian to Würmian sequence of Colonia de Sant Pere (NE Mallorca) consists of yellowish–red beach sand deposits and fine red sediments, while the overlying brunified Holocene soil on loess follows shorter dry periods under moderate climate conditions with a declined pedogenetic intensity. Apart from iron weathering and hematite formation processes, soil reddening also requires polygenesis with frequent secondary climatic oscillations under distinctly alternating moisture conditions. Consequently, the current Mediterranean climate alone is not sufficient for soil reddening.

Polygenetic development of the respective paleosols and sediments was underlined by micromorphological studies, showing an alternation of carbonate-rich sediments with predominantly decalcified, brunified and partly recalcified paleosols. Shrink–swell cracks reflect seasonal Mediterranean climate conditions already during the Early Pleistocene.

Altogether, pedogenesis was most intense during the Late Pliocene and Early Pleistocene as enhanced by comparatively humid Mediterranean conditions, but then gradually decelerated. The sediments developed under comparatively drier and partly cooler climate conditions with a reduced open or even absent vegetation cover enhancing surface erosion. Paleosols and sediments on the Balearic Islands thus reflect a pronounced climatic cyclicity in the Western Mediterranean since the Late Pliocene.

1. Introduction

Natural climate variability is mainly driven by orbital and axial variations in the Earth's positions, better known as Milankovitch cycles. The paleoclimate reflects this cyclicity by oscillations of $\delta^{18}O$-isotopic curves in marine sediments (Shackleton, 1995), where the Quaternary is subdivided by frequent alternations with interglacial–glacial cycles. Land surfaces respond accordingly by oscillating $\delta^{13}C$-isotopic curves reflecting a limited or absent vegetation cover under dry conditions (Hodge et al., 2008) which promotes erosion/sedimentation. In contrast, a dense vegetation cover under humid climate conditions protects soils and enhances pedogenesis (Rohdenburg, 1970). Paleosol-sediment successions consequently reflect alternating interglacial–glacial cycles and are thus suitable subjects to reconstruct paleoclimatic conditions. Overlapping multiple soil horizons are regarded as sequences of pedocomplexes and are thus summarised as pedostratigraphic units (Catt, 1990). The correlation of $\delta^{18}O$-isotope records with pedostratigraphy largely contributes to the documentation and understanding of global paleoclimate cycles. Though it has to be considered that such successions can be incomplete due to erosion, detailed micromorphological investigations provide further insight into different pedogenetic stages (Bronger, 2003).

Appropriate environments for pedogenesis require geomorphodynamic stability to provide geoarchives with a detailed climatostratigraphic resolution. We investigated geoarchives that are mainly located in marine cliffs of alluvial fans and slope sediments. These geomorphic surfaces are of vital importance for the genesis and development of soils (cf. Ruhe, 1956). On alluvial fans, the soil texture generally varies from coarser in proximal, to coarse and fine in medial, and fine in distal position (McCraw, 1968). Fossil soils document geomorphodynamic stable conditions (no sediment accumulation) on each respective alluvial fan (Gile and Hawley, 1966). Pedostratigraphy may however be complicated by partial and complete incision, by (climatically driven) decreased sedimentation rates or by a shifting runoff base (Wright and Alonso-Zarza, 1990).

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Alluvial fans frequently contain carbonate precipitates especially under semi-arid climates (Nickel, 1985). Decalcification and secondary carbonate accumulation however require a seasonal climate with (semi-)humid conditions providing excess rainfall and downward transport of seepage water (Faz et al., 2001; Günster and Skowronek, 2001; Ortiz et al., 2002) and allowing calcrete genesis (Rohdenburg and Sabelberg, 1973; Wagner et al., 2011). Preconditions of brunification and clay illuviation are moderate acidification with iron oxide (goethite, hematite) formation and the subsequent relocation of fine clay (Fedoroff, 1997). The Fe_o/Fe_d and Fe_d/Fe_t ratios provide further information about the progressive transformation of ferrihydrite into goethite and hematite (Aniku and Singer, 1990) and give insight into the soil development stage (Arduino et al., 1986; Bronger et al., 1984).

Our study particularly highlights the pedogenetically-induced reddening in conjunction with past environmental conditions, which is an issue that has been discussed controversially (e.g. Günster and Skowronek, 2001; Scarciglia et al., 2006; Schwertmann et al., 1982; Torrent et al., 1980, 1983; Yaalon, 1997). The estimation of colour using Munsell soil colour charts is highly subjective and biased by lighting conditions, sample preparation and the set of Munsell colour charts. The precision of colour description can be improved by using spectrophotometers which measure colour spectra (Barrett, 2002; Post et al., 1994). The spectral data can be converted to colour indexes or used directly for qualitative and quantitative analyses (Viscarra Rossel et al., 2006). Using for example the CIE (1931) colour index allows the description of brightness (L*) and chromacity coordinates on red–green (a*) and blue–yellow (b*) scales. Barron and Torrent (1986) used spectrophotometry and the CIE system to predict the amount of hematite in soil samples. This technique allows insights into prevailing past soil moisture and soil temperature regimes by using a precise determination of the factor redness.

Paleosols and sediments are suitable objects to study past climate changes. The Mediterranean region builds a bridge between the temperate climates on the one hand, and the subtropical and tropical climate zones on the other.

The geomorphological diversity on Mallorca is climatically induced (Butzer, 1961), and pedocomplexes in paleosol-sediment successions correlate with Pleistocene interglacial–glacial cycles (Rohdenburg and Sabelberg, 1973). According to Rose et al. (1999), the Quaternary in the Balearic Islands is predominantly biostratigraphically defined. They detected numerous climate changes in the last 140 ka on Mallorca by sedimentological and isotope-geochemical studies. While characterising the according paleosols on coastal alluvial fans as relict weathering soils, fossil soils and soil complexes, a detailed description with regard to pedogenetic processes was not provided. Hillaire-Marcel et al. (1996) and Tuccimei et al. (2007) recognised repeated sea-level changes with three highstands during the OIS 5e and OIS 5c/5a in the Bahía de Palma. Dorale et al. (2010) further detected rapid sea-level changes around 81 ka BP along the southeastern coast of Mallorca.

We chose two mighty paleosol-sediment sequences which can be characterised by relict weathering soils, fossil soils and soil complexes in coastal alluvial fans of Mallorca. Detailed investigations were conducted at the sites of El Toro (SW Mallorca) and Colonia de Sant Pere (NE Mallorca) (Fig. 1), since they cover at least six resp. two glacial–interglacial cycles of the Pleistocene and Holocene (Rohdenburg and Sabelberg, 1973), hence providing comprehensive information with regard to Quaternary climatic conditions.

Our investigations shall provide information about Quaternary climate conditions and their relation to pedogenetic and sedimentary processes in the Western Mediterranean. The objectives of this study are therefore: (1) to establish a pedostratigraphical system of paleosol-sediment sequences on the Balearic Islands; (2) to reconstruct the most common processes of paleosol and sedimentary genesis in the Pleistocene and Holocene; and (3) to determine climatic preconditions for soil reddening.

2. The investigated paleosol-sediment sequences

The cliff section nearby El Toro in the southwest of Mallorca (Cala Penyes Roges) is directly adjoined to a south-eastern aligned fault margin of the Sierra Norte. Its base body formed during the latest Pliocene to Early Quaternary above Miocene limestone (Solé Sabaris, 1962), while the influence of continuous tectonic deformation to the climatically driven pedogenesis was limited to local erosion/sedimentation events (Rohdenburg and Sabelberg, 1973). The 28 m mighty, exposed cliff profile El Toro (SW Mallorca, 2°28′20–50″E, 39°29′50–60″N) is 1450 m in length (Fig. 1) and contains 44 fossil soils. Based on the accordance of marine transgression/regression cycles, Rohdenburg and Sabelberg (1973) not only confirmed a detailed correlation of the six interglacial–glacial cycles at El Toro ("Ses Penyes Rotjes") with the "Lower Series" and "Upper Series" in Central Europe after Kukla (1969), but also assigned sedimentary cycles and their according soil complexes consistent with the glacial cycles of Kukla (1969). The paleosols can be grouped into soil complexes that can each be divided into several subcycles. The identification of the Brunhes/Matuyama boundary in the glacial cycle D (MIS 19, ~781 ka) substantiated an Early Quaternary to Pliocene age for the major part of the profile (Fig. 2).

The Alcudia Bay that is situated along the north-eastern coast of Mallorca predominantly consists of Pliocene eolianites and Plio-Pleistocene conglomerates (Muhs et al., 2010). They were exposed by marine excavation in the Middle and Late Pleistocene (Butzer, 1962). The south-eastern part of the bay received sediments from Quaternary alluvial fans of the Tyrrhen II/III complex during the last transgression prior to its regression in Würmian Late Glacial Maximum (Solé Sabaris, 1962). Since 140 ka, they receive sediments of the Massís d'Artà from the north-eastern border area of the Sierra de Levante (Rose et al., 1999). A coastal alluvial fan is exposed in distal position north-easterly of Colonia de Sant Pere (3°17′10–15″E, 39°44′30″N, Fig. 1). Rohdenburg and Sabelberg (1973) identified three sedimentary units for this exposure: The Lower Sand Complex (LSC, mainly of coarse beach sands) and the Lower Red Series (LRS, with loamy, reddish sediments) are assigned to the Early Glacial (stadial cycle 1), while the Upper Series (US, with gravel and mighty sand-bodies) correlate with the Late Glacial (stadial cycles 2 and 3).

3. Material and methods

The paleosols and sediments are designated according to FAO (2006) and Soil Survey Staff (2010). The pedogenetic horizons were selected in order to give a representative overview of Bw, Bt and Ck horizons. The accumulations of pedogenic carbonates are designed as Bk, while secondary carbonate accumulations in formerly lime-free horizons are illustrated as Btk. Calcretes with at least 50% calcium carbonate (by volume) are designed as Bkk. Any other calcareous sediment that lacks specific pedogenic features is referred to as Ck (of which some horizons were not suitable for the following sampling procedures). Our pedostratigraphic record of the investigated sites is based on the nomenclature of Rohdenburg and Sabelberg (1973) who conducted extensive and detailed geomorphological studies.

The nomenclature of the paleosol-sediment series with the sedimentary cycles (Z, A–F) and paleosol complexes of El Toro (Fig. 3a, b) refers to the stratigraphy provided in the complete profile of the Quaternary paleosol-sediment-series of El Toro (thereby named as "Ses Penyes Rotjes"), Supplement b in Rohdenburg and Sabelberg (1973). The profile of Colonia de Sant Pere refers to Fig. 7 in the same publication (thereby named as "Colonia de San Pedro"). The newly introduced sedimentary cycles (F, G) indicate the Eemian and Würmian resp. Holocene time of soil genesis.

Luminescence datings (IRSL, TL) were determined by samples taken under complete darkness by multiple aliquot additive doses. Due to anomalous fading, their reliability is however limited and