Genesis and composition of paleosols and calcretes in a plio-pleistocene delta fan of the Costa Blanca (SE Spain)

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Abstract
A plio-pleistocene alluvial fan with a vertical series of 7 fossil soils and 7 calcrete complexes was investigated at the Spanish south-eastern coastline. Alternating sedimentation and soil formation suggest repeated cyclical climatic changes during the Late Pliocene and Early Pleistocene. The red paleosols and pedogenic calcretes developed under subtropical and Mediterranean conditions while the (soil) sediments and synsedimentary calcretes represent a (semi)arid climate.

Key Words
Paleopedology, calcretes, stratigraphy, climate change, Mediterranean.

Introduction

Calcretes in the alluvial fan near Campoamor in SE Spain have attracted several geological, geomorphological and pedogenetic studies (Rutte 1958; Rohdenburg and Sabelberg 1969; Blümel 1982). Calcretes are formed by surface cementation, subterranean crusts, surface (lamellae) crusts or subterranean lamellae crusts (Rutte 1958, 1960). Such processes were most likely favoured during moist interglacials, with emphasized seasonal fluctuations favouring the downward movement of seepage water in decalcified soils (Rohdenburg and Sabelberg 1969). Rubefication in paleosols and calcrete formation are however not related processes in this alluvial fan (Blümel 1982). This work includes a pedological and climatic interpretation of the soils in Campoamor and a detailed description and classification of the according calcretes. They are further compared with soils and calcretes in the Basin of Granada/Andalusia (Günster and Skowronek 2001) to substantiate previous findings of climatic development in the western Mediterranean by soil stratigraphy.

Methods

Texture, clay mineralogy, iron oxides, chemical composition and micromorphology of paleosols and calcretes were described according to standardized laboratory methods.

Results

Macroscopic description

The about 30 meters high cliff profile includes 7 fossil soils and 7 calcrete complexes exposed to the south. Strata are easily differentiated macroscopically by their colour and structure. The upper four meters of this soil-sediment-sequence are made up by a calcrete complex (k1) of at least four genetic stages. The following 20 meters are dominated by sandy, red (pedogenic?) calcretes, but also include intermediate conglomerates and (soil) sediments. Calcretes are mainly structured into two (k2, k3, k5) or three (k4) parts with a soft and nodular crust base, a harder top and a lamellae crust. The lower part of the cliff profile displays the marine regression during the late Pliocene. The following carbonate complex (k7) is a pseudo-conglomerate closing with fine-sandy (dune) sediments in the lower bed. Calcretes are described as Ck (K) horizon, the f prior to B or C horizons stands for the term “fossil” according to the German soil classification.

It results in the following fine stratigraphy of the cliff profile:

Depth(m)	Horizon		Description
0–0.50	Ck(K)	k1	pink (5YR7/3) and pinkish white (5yr8/2) calcrete; fluidal structure; coherent
–1.00	2Ck		pink (5YR8/3) carbonate cementation of conglomerate
–2.70	3Ck(K)		reddishbrown (2.5YR5/4) calcrete; fluidal structure; coherent
–4.00	4Ck(K)		pinkishwhite (5YR8/2) calcrete; chalk-like, soft
–4.50	1.fBwt-Bc		red (2.5YR4/8), carbonatic, gravel-free sandy clay loam; subpolyedric
–5.00	Ck(K)	k2	pink (5YR7/3) calcrete; coherent
–5.50	2Ck(K)		pinkish white (5YR8/2) calcrete; subangular blocky
–6.50	3Ck		yellowish red (5YR5/6), extremely calcareous, slightly gravelly silty clay loam; polyedric; (soil)sediment
–6.90	2.fBvt-Bk		dark yellowish brown (10YR4/6), strongly calcareous, slightly gravelly clay loam; subpolyedric
–7.50	Ck(K)	k3	pink (5YR8/4) calcrete; coherent
–8.00	2Ck(K)		pink (7.5YR8/4) calcrete; subangular blocky
–9.00	3.fBt		dark yellowish brown (10YR4/6) non-calcareous, gravel-free loamy sand; subangular blocky
–9.20	2Ck(K)	k4	light reddish brown (5YR6/4) calcrete; layered (coherent)
–10.20	3Ck(K)		pink (7.5YR8/4) calcrete; layered (coherent)
–11.20	3Ck(K)		pink (7.5YR8/4) calcrete; subangular blocky
–12.30	4Ck		reddish yellow (5YR6/8), strongly calcareous, slightly gravelly loamy sand; subangular blocky and layered (coherent); (soil) sediment
–12.60	5Ck		pink (5YR8/3) carbonate cementation of conglomerate
–13.40	4.fBwt		dark yellowish brown (10YR4/6), non-calcareous, gravel-free sandy loam; subangular blocky
–13.90	Ck(K)	k5	pink (5YR8/4) calcrete; layered (coherent)
–15.00	2Ck(K)		pink (5YR8/4) calcrete; fine-grained; layered (coherent)
–15.20	5.fBwt1		red (2.5YR5/6), non-calcareous, gravel-free silty clay loam; subangular to angular blocky
–16.20	2Bwt2		dark yellowish brown (10YR4/4), non-calcareous, gravel-free silty clay loam; angular blocky
–17.10	Bk		pink (5YR8/4) and red (2.5YR5/6) lime accumulation; angular blocky
–17.60	6.fBwt-Bk		dark yellowish brown (10YR4/4), strongly calcareous, slightly gravelly loam; angular blocky
–19.80	2Bk		pink (5YR8/4), extremely calcareous, slightly gravelly clay loam; angular blocky
–20.40	7.Bwt		red (2.5YR5/6), non-calcareous, slightly gravelly loamy sand; subangular blocky
–21.20	2Bk		pink (2.5YR8/4), extremely calcareous, slightly gravelly clay loam; angular blocky
–22.50	3Ck(K)	k6	light red (2.5YR6/7) calcrete; fine-grained; layered (coherent)
–23.80	4Ck(K)		light red (2.5YR6/8) calcrete; layered (coherent)
–24.80	4Ck(K)	k7	white (10YR8/1) calcrete; chalky; layered (coherent)
–27.60	5Ck(K)		pinkish white (2.5YR8/2) calcrete; sandy; layered (coherent)
–29.10	6Ck(K)		white (2.5YR8/0) calcrete; sandy; layered (coherent)
>29.10	7Ck(K)		light reddish brown (5YR6/4) carbonatece mentation of conglomerate; fluidal structure; load casts

Texture and chemistry

The textural distribution in decalcified soil is quite heterogeneous, with 16.7-86.5 % of sand, 3.7-49.3 % silt and 9.7-44.4 % clay (Table 1), while the mean values are 50.7 % (sand), 23.3 % (silt) and 26.0 % (clay). Sand domination can be ascribed to calcarenites of Pliocene age which have developed in the alluvial fan. Clay neogenesis can be deduced by distinctly higher clay contents in the soils (29 % average) as compared to the (soil) sediments (17 % average). Soil and (soil) sediment texture typically represent middle and lower (delta) alluvial fans.

Table 1. Grain size distribution of the soil and (soil) sediments [weight-%].

	Horizon	Gravel	CS	MS	FS	Sand	CSi	MSi	FSi	Silt	Clay
1.	fBwt-Bk	0.0	0.0	19.2	40.6	59.8	6.7	1.2	1.2	9.1	31.0
	3Ck	2.9	0.0	14.1	34.1	48.2	16.5	5.2	3.7	25.4	26.4
2.	fBwt-Bk	2.7	0.0	15.2	29.0	44.2	19.3	5.3	5.5	30.1	25.7
3.	fBwt-Bk	0.0	0.0	21.9	42.0	63.9	8.9	1.6	1.1	11.6	24.4
	3Ck(K)	0.0	0.0	42.5	36.9	79.4	2.9	1.6	1.4	5.9	14.6
	4Ck	0.0	0.1	60.1	26.3	86.5	3.2	0.4	0.1	3.7	9.7
4.	fBwt	0.0	0.1	20.3	30.5	50.9	16.0	9.2	5.2	30.4	18.6
5.	fBwt1	0.0	0.0	29.3	31.9	61.2	8.0	2.6	2.1	12.7	26.0
	2Bwt2	0.0	0.0	9.2	19.1	28.3	12.8	7.4	6.9	27.1	44.4
6.	fBwt-Bk	7.2	0.0	9.1	17.4	26.5	24.1	14.1	11.1	49.3	24.2
	2Bk	4.6	0.0	4.3	12.4	16.7	27.7	10.6	9.2	47.5	35.7
7.	fBwt	2.4	0.0	34.3	37.7	72.0	6.2	1.7	2.5	10.4	17.5
	2Bk	2.4	0.0	8.0	14.0	22.0	12.6	15.0	12.1	39.7	38.3

The pH values vary between 6.9 and 8.4 (Table 2) and well reflect de- and recalcification processes, since sediments (pH >7.8) and decalcified horizons (pH <7.6) can be differentiated from recalcified soil horizons (pH 7.7). Pedogenic iron oxides are rather rare with proportions of 0.003-0.084 % for the oxalate-soluble (Fe_o) and 0.10-1.10 % for the dithionite-soluble fraction (Fe_d). This is due to small concentrations of total iron (Fe_t) with a maximum of 1.49 % (Table 2). Small Fe_o/Fe_d ratios (0.030-0.086; Table 2) document the high crystallinity in the paleosols and (soil) sediments, while Fe_d/Fe_t ratios around 1 (Table 2) reflect advanced weathering. Intense reddening can be ascribed to the presence of hematite and a close correlation between Fe_d and redness rating according to Torrent *et al*. (1980, 1983) (r=0.72; n=13).

Table 2. Chemistry of the soil and (soil) sediments.

	Horizon	pH	$CaCO_3$(%)	Fe_o(%)	Fe_d(%)	Fe_t(%)	Fe_o/Fe_d	Fe_d/Fe_t
1.	fBwt-Bk	7.9	6.2	0.027	0.59	1.03	0.045	0.57
	3Ck	7.9	38.1	0.022	0.38	0.90	0.059	0.41
2.	fBwt-Bk	7.8	10.2	0.044	1.03	0.91	0.042	1.13
3.	fBwt-Bk	7.5	0.0	0.024	0.76	0.98	0.031	0.77
	3Ck(K)	8.1	38.7	0.006	0.12	0.35	0.050	0.34
	4Ck	8.4	34.7	0.003	0.10	0.27	0.030	0.37
4.	fBwt	7.4	0.0	0.037	1.10	0.91	0.033	1.20
5.	fBwt1	7.2	0.0	0.024	0.49	1.49	0.048	0.35
	2Bwt2	6.9	0.0	0.084	0.97	0.94	0.086	1.03
6.	fBwt-Bk	7.6	32.3	0.039	0.78	0.94	0.050	0.82
	2Bk	7.8	55.9	0.019	0.35	0.96	0.055	0.35
7.	fBwt	7.2	0.0	0.020	0.35	1.00	0.057	0.35
	2Bk	7.6	27.3	0.046	0.69	0.94	0.066	0.73

Clay mineralogy

The semi-quantitative composition of clay minerals in the soils and (soil) sediments is fairly uniform with illite (55-68 %) and smectite (20-37 %) dominance. They are inversely correlated (r=0.78; n=13). Chlorite and vermiculite (3-5 %) are identified in three horizons only. Kaolinite (3-13 %) is more common in Bwt horizons which may infer a neoformation during pedogenesis. It is however not clear whether this can be ascribed to parent material inheritance and/or alteration and neoformation under similar climatic conditions.

Carbonates

Calcretes contain 19.5-51.5 % Ca and 0.11-0.29 % Mg, with Ca/Mg ratios between 121 and 319. Dominant calcite and quartz may overlap (minor) smectite XRD peaks from random powders. A phreatic or lacustrine origin of the calcretes in the delta fan of Campoamor can be excluded. The colour of the calcrete dissolution is mainly between 5YR, 7.5YR and 10YR (only the synsedimentary calcrete (k7) and the conglomerate have colours of 5Y and 2.5Y, respectively). Since the carbonate dissolution contains only 0.01-0.11 % iron, the enrichment of carbonate-bound iron and following reddening mainly result from parent material detachment.

Micromorphology

Clay illuviation is indicated by thin iron oxides and clay coatings. Clay minerals (smectite in particular) were destroyed by intense shrink-swell processes inducing stress cutans which characterise changing wet and dry conditions. Since microstructure, colour, type and number of pedofeatures differ within the crust, the various parts reflect different pedogenetic stages. The lack of pedogenic features in the calcrete therefore clearly results from sedimentation.

Discussion and conclusions

The paleosols and calcretes in the delta fan of Campoamor were compared with alluvial fans of the Granada Basin (250 km to the south-west). The latter have developed between the Late Pliocene and Early Pleistocene. By comparison of both areas, the paleosols from Campoamor are distinctly further developed. This is clearly expressed by higher Fe_d/Fe_t ratios, a more intense rubefication and pronounced plasma mobility. The fossil soils of Campoamor are comparatively sandier with a more pronounced rubefication (i.e. redness rating). Because of the small specific surface of the sand, minimal amounts of iron oxides (Fe_d=0.35) are most likely sufficient for intense reddening. This is further supported by a high permeability and aeration of the substrate. Soil development can therefore be ascribed not only to climatic differences, but also to intense genesis as referred to parent material. Whereas the calcretes in the soils of the Granada Basin are (monogenetic) crusts according to Günster (1999), the differentiated composition of calcretes in Campoamor is a polygenetic product. Surface erosion and sedimentary fossilization were followed by secondary carbonatization and subsequent induration. Consequently, the latter represents at least two pedodynamic periods. At least 15 stages of soil formation can be reconstructed. While subtropical-mediterranean conditions supported pedogenetic processes, the accumulation of (soil) sediments and genesis of synsedimentary calcretes occurred under considerably drier, (semi-)arid conditions.

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