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Full Length Research Paper

The continental terminal as principal source of kaolinite in the Coastal area of West Africa

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Soils of the coastal region of West Africa present some specificities linked to the topography: they frequently occur in a well-defined and fairly regular sequence related to relief: the soil catena or toposequence. The objectives of this study were to (1) analyse kaolinite distribution on different landscape positions in the coastal area of the Saloum river Basin, west central Senegal, West Africa, in order to (2) demonstrate the influence of Continental Terminal (CT) sediments on local soil formation and mineral distribution. The described soils were distributed along the toposequence as Gleyic Hyposalic Solonchaks in the floodplain, Haplic Gleysols in the low terrace and Endogleyic Arenosols in the middle terrace. The middle terrace was characterized by a coarser soil texture (mainly sand) compared to the floodplain and the low terrace. The bulk mineralogy was dominated by quartz (SiO_2). The clay fraction of the soils was dominated by kaolinite (≥ 70%), smectite (around 25%), illite (≤ 2%), and illite-smectite mixed layers (trace amounts). More detrital (eolian dust inputs) than pedogenic (in situ weathering) kaolinite was identified. The widespread distribution of kaolinite in the entire toposequence and the influence of CT sediments in such distribution trend is the main finding of this study.

Key words: Kaolinite, clay minerals, West Africa, Continental terminal, eolian dust inputs.

INTRODUCTION

Soil mineral distributions provide information in order to understand the current behaviour of wetlands (O'Geen et al. 2008) and of arid lands (Reid et al. 1993), and help to interpret paleoenvironmental conditions (Amundson et al. 1989; Graham and O'Geen 2010). Clay minerals are frequently used as indicators of pedogenesis (Duzgoren-Aydin et al., 2002; Hong et al., 2012) because the clay minerals of a soil mark the mineralogical transformations due to soil-forming processes (Costantini and Damiani 2004). They are the “genetic signals” of pedogenic events (Bockheim and Gennadijev, 2000). Wilson (1999) indicated a strong influence of clay minerals to the major physical and chemical properties of the soil. He showed that questions concerning the origin, distribution, and formation of these minerals have assumed prominence in the study of soils (Owliaie et al. 2006). Evidence is hence growing for the ability of clay minerals to reconstruct the environmental conditions under which soils have formed. The mineralogical composition is a useful tracer to reconstruct the origin of sediments in estuarine and marine environments (Petschick et al., 1996; Heroy et al., 2003).

The coastal region of West Africa raises only a few meters above sea level. The mineral occurrence in such environment mainly depends on the interactions between the following parameters: the landscape position determining the level and dynamic of the water table, which in turn command water saturation and redox reactions in soils. Although these mechanisms and pathways likely determine the formation of Fe oxides, their relationship to parent material is by far more influential to the distribution and properties of clay minerals. Such relationship enables the prediction, under given climatic conditions, of the clay-mineral suite in soils, if the mineralogy of the parent rock is known and vice versa (Loi et al., 1982). Useful predictions however require uniformity of the parent material, what is not common in coastal areas undergoing marine and continental influences. The mineral inputs from eolian dust add to the local soil substrate directly derived from in situ weathering of bedrock. This continuous rejuvenation of soil material alters the equilibrium of the pedoenvironment and makes mineralogical studies more intricate. Souza-júnior et al.

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(2008) demonstrated the distinctive properties of minerals present in estuarine areas and linked it to their detrital origin, being a mixture of terrestrial and marine sediments. Terrestrial sediments are suspended in river water and washed to estuarine areas, while marine sediments are deposited intermittently during transgressive events, or continuously by tidal currents, although authigenesis will occur in these environments (Chamley, 1989).

Kaolinite [$Al_2Si_2O_5(OH)_4$] is a common clay mineral in soils of tropical regions (Zhu et al., 2012; Cheng et al., 2012). As one of the most abundant mineral in soils and sediments, its properties are such that it interacts with other soil elements to contribute to the mechanical stability of the soil column (Miranda-Trevino and Coles, 2003). It has a wide variety of applications in industry, particularly as paper filler and coating pigment (Murray, 2000; Pavlidou and Papaspyrides, 2008; Nkoumbou et al., 2009, Cheng et al., 2012).

Relatively few studies involving coastal plain soils of Africa have considered their mineralogical constitution. The objectives of the present work were to (1) analyse kaolinite distribution on different landscape positions in the coastal area of the Saloum river Basin, West Central Senegal, West Africa, in order to (2) demonstrate the influence of eolian dust inputs from the Continental Terminal (CT) sediments on local soil formation and mineral distribution.

MATERIAL AND METHODS

Site Characterization

The Saloum river basin, West-central of Senegal, West Africa, is located between 13°35'-14°20'N and 16°00'-16°50'W. It covers approximately 250.000 ha and is bounded to the west by the Atlantic Ocean (Figure 1). The climate of the Saloum region is of sudano-sahelian type with a high mean annual temperature (MAT) of 29°C, a high annual potential evapotranspiration ranging from 1.500 to 2.500 mm, and a mean annual precipitation (MAP) ranging from 600 to 800 mm per year, from north to south.

Rainfall is limited to the period from June through October (rainy season). The geology of the Saloum region consists on Holocene marine sediments underlain by Miocene deposits. The hydrologic system is the Saloum River, a tide influenced "inverse estuary", fed only by a limited river flow for two to three months during the rainy season and characterised by high salinities of more than 80‰ resulting from seawater encroachment and evaporation (Faye et al., 2003). Hydrodynamics are essentially governed by the penetration of the tidal wave and the strong evaporation regime, which develop in the vast system of interconnected tributaries (locally known as "bolons") and the mangrove forest within the delta (Barusseau et al., 1995).

The study site consists of a soil catena of about 1.5 km length and is located 50 km from the sea, 20 km west of the Kaolack town, beside a tributary of the Saloum River. The transect is oriented East-West and runs across the tributary with a general slope of 0.5 %. At the lower part of the toposequence (floodplain), soils are flooded and entirely devoid of vegetation. The area was formerly occupied by mangrove vegetation and plant remnants remain a prominent landscape feature (Lézine, 1997).

Field Work

Profile Description and Soil Sampling

The sequence of six soil profiles: floodplain (2), low terrace (2), middle terrace (2); was described in the field, and 29 soil samples were collected for laboratory analyses. The sampling transect was placed in such a way that influences of the landscape position could be reflected in soil properties. The Munsell soil colours were determined on moist samples. The reaction of carbonate to 10% hydrochloric acid (HCl) was determined in all samples.

Field Measurements

Topography was determined using a Theodolite. Soils were described after WRB (FAO 2006), in January-February 2007 and April-May 2008, during the dry season. Electrical conductivity (EC) and pH were estimated with field EC and pH-meters (WTW, 8120 - Weilheim, Germany) before a repetition in laboratory under standard conditions. Groundwater level (GWL) was estimated throughout soil profiles with a measuring tape, twice a week, during the dry season (January-February 2007 and April-May 2008) in the present study.

Laboratory Work

Soil Analysis

Bulk soil samples were air-dried at room temperature and passed through a 2 mm mesh sieve to obtain the fine earth fraction. Particle-size analysis was performed after removal of carbonates and organic matter (OM) by treatment with HCl (pH 4.5) and H_2O_2 (10 %) respectively, and of excessive salts by repeated addition of deionised water, centrifugation and decantation until the electrical conductivity (EC) dropped below 40 µS cm^{-1}. After subsequent addition of ammonia (NH_3) for water dispersion, overnight shaking and ultrasonic treatment, the sand fractions (63-2.000 µm) were obtained by wet sieving, while the silt (2-63 µm) and clay (<2µm) fractions were separated by pipette analysis after Köhn (Schlichting et al., 1995). Bulk density was measured for all horizons

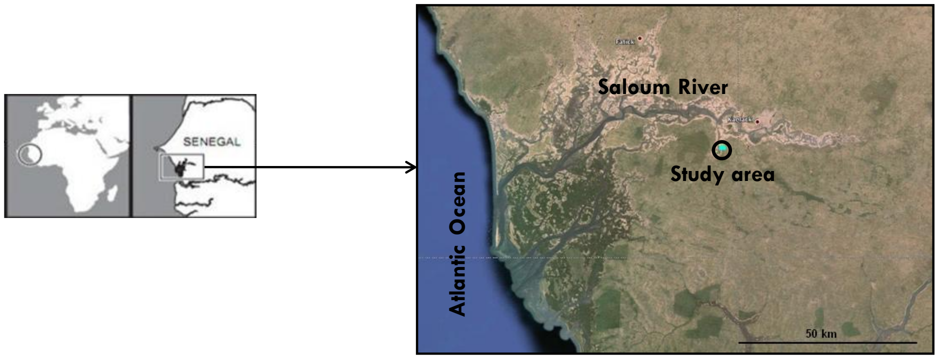


Figure 1. The Saloum river basin in Senegal(adapted from Google Earth, 2009).

using a steel cylinder of 100 cm^3. Soil samples were then oven-dried at 105°C and weighted to determine the soil bulk density in g cm^{-3}. Soil pH was measured in water at a soil: solution ratio of 1:2.5. The electrical conductivity was determined using a 1:5 soil: water extract (Schlichting et al., 1995).

Mineral Analyses

X-ray diffractometry (XRD) of fine earth was determined as powder. Clay mineralogy was determined by X-ray diffraction (XRD) of oriented clay specimens using a Siemens D-500 instrument with Cu Kα radiation. Different treatments of the clay samples included K and Mg saturation, heating to 110°C, 220°C, 400°C and 600°C of the K- and glycerol salvation of the Mg-saturated samples. The amounts of the different clay minerals were estimated on a semi-quantitative basis by using the computer package DIFFRAC AT V3.3 Siemens 1993. A Scanning Electron Microscope (SEM) LEO 420, equipped with a field emission cathode and coupled to an Energy Dispersive X-ray (EDX), INCA 400 system, was used to confirm the mineral composition. Soil profiles were divided into three parts: topsoil, central horizons, and subsoil; for this purpose.

Clay minerals are individually presented to assess their abundance in soil profiles. The method assumes that the available minerals in the sample sum to 100% and the individual mineral is a fraction of the total. Illite/Smectite mixed layers (I-S) was excluded from this semi-quantification; due to the trace amounts it shows in the entire toposequence. This fraction was therefore subtracted from the total sample (100%). Percentages of clay minerals are then recalculated from the total of sample without the I-S content.

RESULTS

Soil Texture

Solonchaks on the floodplain show a fine texture (silt clay loam). The clay content is higher in the Bjv horizon of P1 and Cjr horizon of P2 compared to the other profile horizons. The silt fraction decreases with depth throughout all profiles. The sand fraction shows an irregular depth distribution throughout all profiles (Figure 2). The fine texture of the floodplain soils supports less permeability on this lowest landscape position, promoting continuous upward fluxes of the saline groundwater (presence of salt crusts on soil surface). The low terrace soils show contrasted material with sandy loam upper horizons and sandy clay loam lower horizons. The clay fraction increases downward in these profiles. The sand fraction has the opposite trend, decreasing downward throughout all profiles (Figure 2). Soil material becomes coarser in the Endogleyic Arenosols on the middle terrace, from loamy sand to sand (Figure 2).

Soil pH

Soil pH decreases downward in the floodplain profiles. Values are in the neutral pH range (6-8) throughout all profiles, but drop to ≤ 5 in the subsoils of P1 and P2 (Table 1). Low terrace soils show the lowest pH values (3-5); values remain generally constant with depth on this intermediate landscape position (Table 1). The laboratory-measured pH is lower than the field-measured one (3 - 5 versus 5 - 6, respectively), most probably caused by the oxidation of pyrite during storage or preparation of samples. Drying and storage can significantly change soil pH values, but it is not easy to predict the results of drying and storage (Bloom et al. 2005). Bartlett and James (1980) reported a 0.6 unit increase after drying a 5.0 pH mineral soil. Soil pH increases generally with depth in the middle terrace profiles (Table 1).

Electrical Conductivity (EC)

Floodplain soils show the highest EC (from 5.5 to 55.5 dS m^{-1}). The highest values were yielded in the top- and subsoil of profiles (Table 1), suggesting significant inci-

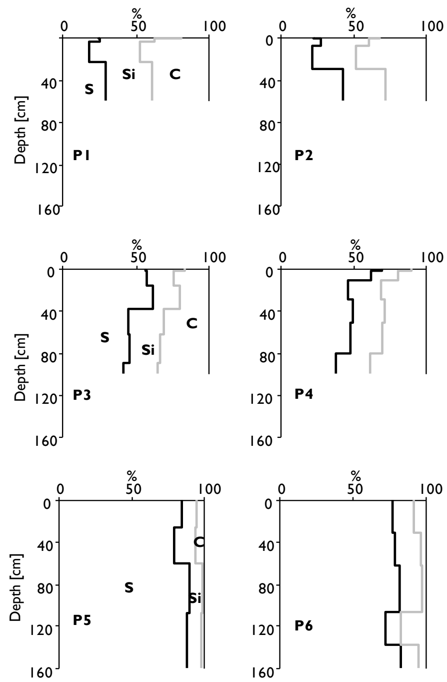


Figure 2 -Particle size distribution with depth (S = sand; Si=silt; C = clay).

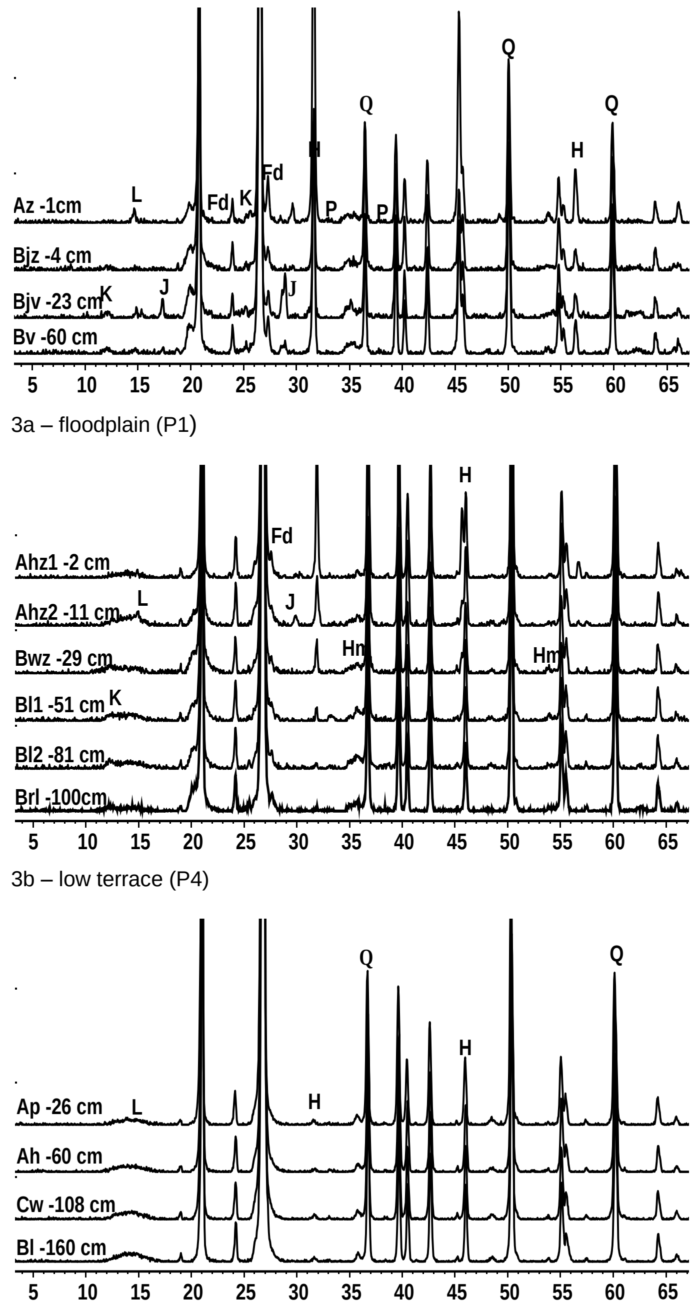
dence of the shallow saline groundwater and surface salt crusts. Such trend reflects the intense evaporation processes caused by high temperatures, which favour important capillary rise of the groundwater during the dry season on this lowest and bare landscape position. Low terrace profiles show EC values between 0.5 and 10 dS m^{-1}. The lowest EC values (≤1 dS m^{-1}) were yielded in the middle terrace profiles (Table 1).

Bulk Mineralogy

The bulk mineralogy is dominated by quartz (SiO_2). The downstream soils (floodplain and low terrace) contain particularly large concentrations of halite (NaCl). Feldspars, mainly albite ($NaAlSi_3O_8$) are identified in the floodplain and low terrace profiles only. The vicinity to the estuary explains the higher amounts of halite and albite in the floodplain soils, compared to the low terrace and middle terrace. Pyrite (FeS_2) is present in the floodplain while jarosite [$KFe^{III}_3(OH)_6(SO_4)$] is detected in the floodplain and the low terrace. Hematite (Fe_2O_3) is only detected in the low terrace, while lepidocrocite [γ-FeO(OH)] is present in all profiles (Figure 3).

Clay Minerals

Table 2 shows a semi-quantitative estimation of clay mineral suite in the investigated toposequence. Kaolinite is a dominant mineral with distinct peaks and nearly constant



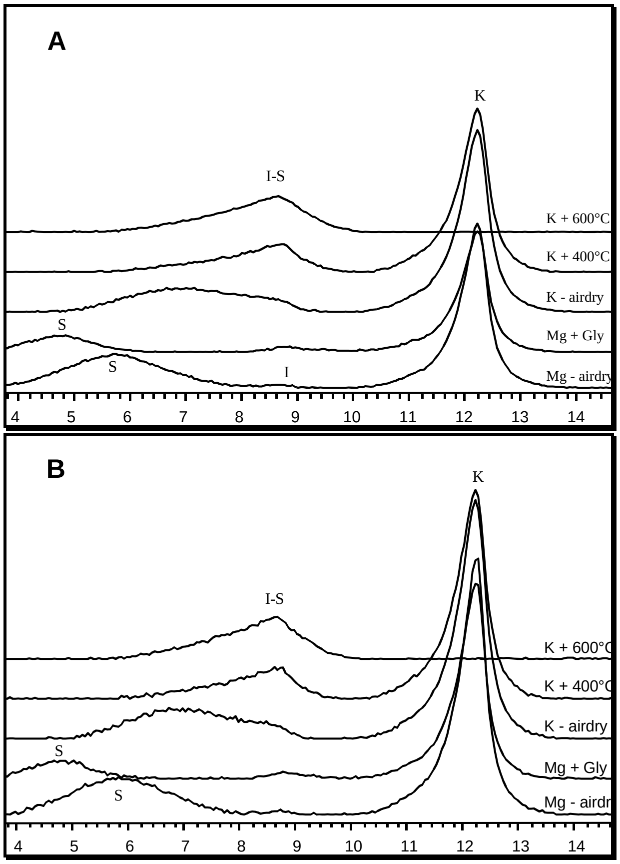
3a – floodplain (P1)

3b – low terrace (P4)

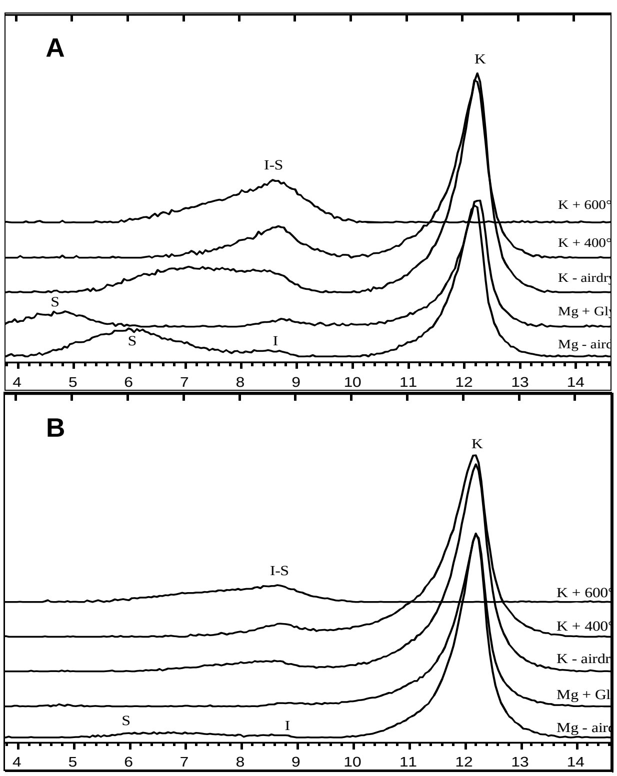
3c – middle terrace (P6)

Figure 3 - Bulk minerals in the floodplain (4a), low terrace (4b), and middle terrace (4c) profiles (analysis of the fine earth). Q: quartz; H: halite; Fd: feldspar; K: Kaolinite; P: Pyrite; J: Jarosite; Hm: Hematite; L: Lepidocrocite

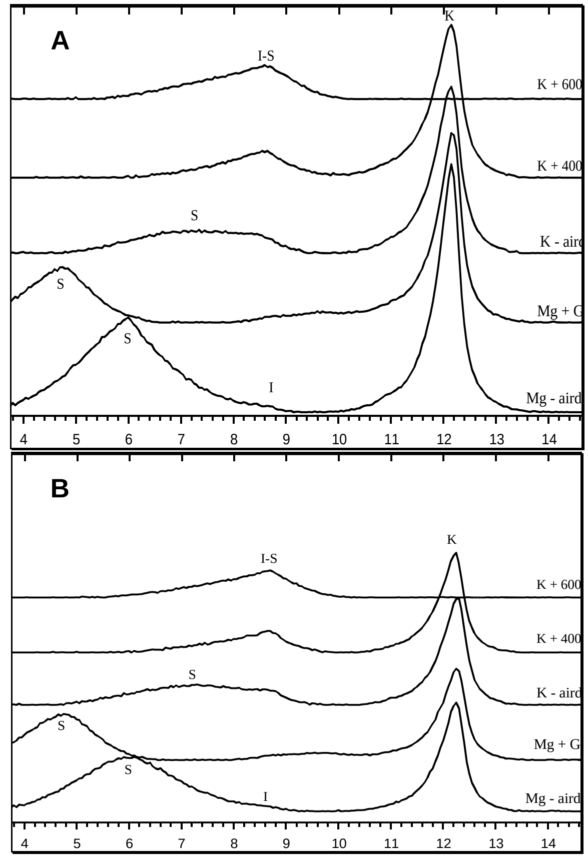
amounts with depth throughout all profiles (Figure 4). However, its spatial distribution reflects a gradual, but continuous diminution from low terrace profiles (84%) to 72% in the floodplain, and 62% in the middle terrace, which may indicate potential neoformation. Kaolinite also distinguishes by its high crystallinity. Smectite is also prevalent in all soils, but is distinctly more popular in the middle terrace (up to 35 %). In the low terrace through the aggressive environment (pH 3-5), smectite is strongly



4.1 - Floodplain soils (P1): topsoil (A) and subsoil (B)



4.2 - Low terrace soils (P4): topsoil (A) and subsoil (B)



4.3 - Middle terrace soils (P6): topsoil (A) and subsoil (B).

Figure 4 - Clay mineral distribution in studied soils: K = kaolinite; S = Smectite; I = Illite; I-S = Illite-smectite mixed layers.

reduced. The presence of illite in the floodplain indicates it is supplied by the marine to coastal environment. Its presence in the low terrace and middle terrace is restricted to traces.

DISCUSSION

Kaolinite Distribution as Hint to eolian Dust Inputs

Formation of pedogenic kaolinite and smectite is linked with topographic position (Tardy et al. 1973; Birkeland1999).
Generally, upslope clay-mineral suites are more depleted in Si relative to downslope clay-mineral suites, characterized by Si accumulation. As a consequence, the kaolinite formation in the tropics is favoured by alternate wet and dry seasons in higher parts of the landscape where drainage is unimpeded (Tardy et al. 1973), whereas the translocated Si accumulates downslope to enhance smectite formation (Birkeland 1999). It may however be noted that, unusual for tropical coastal plain environments, and unlike the normal distribution trends evoked by the above-mentioned authors, kaolinite predominates in soils on all landscape positions in the present study, suggesting regional accession of eolian dusts. A substantial input of detrital kaolinite from the continental uplands (high terrace and plateau) seems a

Table 1 -Soil characteristics along the investigated toposequence

Depth (cm)	Horizon	Colour (moist)	Texture (%)			pH		EC	Water soluble Ions ($cmol_{c+}\ kg^{-1}$)						Fe_d/Fe_t
									Anions		Cations				
			Sand	Silt	Clay	$CaCl_2$	H_2O	$dS\ m^{-1}$	SO_4^{2-}	Cl^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	
Floodplain – P1 : Gleyic Hyposalic Solonchak															
0-1	Az	7.5Y4/1	24.5	56.7	18.8	8.2	8.4	26.5	1.4	14.5	10	0.2	1	2.4	0,56
1-4	Bjz	7.5YR5/6	25.6	37.4	37	7.8	7.9	11	0.5	5.6	4.7	0.1	0.3	0.9	0,71
4-23	Bjv	7,5YR4/2	17.9	34.8	47.2	6.1	6.1	12	0.3	5.7	5.2	0.1	0.2	0.9	0,95
23-60	Bv	10YR3/3	29.4	31.4	39.2	4.5	4.5	15.5	0.4	8.2	7	0.1	0.2	1.2	0,60
Floodplain – P1 : Gleyic Hypersalic Solonchak															
0-1	Azm	5 Y 3/1 + 5 YR 5/8	22.8	45.7	31.5	7.8	7.9	55.5	2.6	37.7	33.2	0.3	2	5.1	0,39
1-8	Az	2.5 Y 4/1	27.6	32.9	39.4	7.8	8.0	9	0.4	4.3	3.8	0.2	0.3	0.9	0,64
8-30	Cjr	2,5 YR 3/1 + 10 YR 7/6	21.3	30.7	47.7	7.3	7.5	8.5	0.3	4.5	4.2	0.1	0.2	0.7	0,82
30-60	Cr	7.5 YR 2/2	42.3	30.5	27.2	5.0	5.0	14	0.4	7.8	6.5	0.1	0.2	1.9	0,89
Low terrace – P3 : Haplic Gleysol (Thionic)															
0-2	Ah1	7.5 YR 3/3	57.2	26.4	16.3	4.0	4.1	0.5	0.2	2.3	1.7	0.02	0.6	0.6	0,46
2-16	Ah2	10 YR 4/4	57.9	18.3	23.7	4.8	5.0	2.5	0.03	0.08	0.1	0.004	0.003	0.001	0,43
16-38	Bl1	7.5 YR 4/3	61.8	18.3	20	4.2	4.5	4.5	0.03	0.1	0.2	0.006	0.01	0.01	0,42
38-62	2Bl2	10 R 4/3	45.8	23.3	30.9	4.2	4.3	7.5	0.03	0.3	0.3	0.006	0.02	0.02	0,32
62-90	2Bl3	5 Y 6/1	46.0	21.3	32.7	4.5	4.5	9.5	0.04	0.4	0.4	0.008	0.03	0.03	0,32
90-100	2Brl	2.5 Y 5/2	41.8	23.6	34.6	4.9	4.7	1	0.04	0.4	0.4	0.01	0.03	0.03	0,31
Low terrace – P4 : Haplic Gleysol (Thionic)															
0-2	Ahz1	10 YR 3/3	70.4	19.7	9.7	4.5	4.4	1	0.2	5.5	2.8	0.1	0.9	2.2	0,45
2-11	Ahz2	10 YR ¾	62.5	18.3	19.1	3.9	3.9	0.5	0.5	3	1.2	0.07	1.8	1.2	0,51
11-29	Bwz	10 YR 4/6	46.7	22.4	31	3.8	3.9	4.5	0.04	2.4	1.1	0.06	0.3	0.9	0,30
29-51	Bl1	2.5 YR 4/6	50.0	21.4	28.6	3.7	3.7	3	0.03	1.6	0.8	0.04	0.2	0.6	0,30
51-81	Bl2	2.5 Y 6/2	48.7	21.3	30	3.8	3.9	2.5	0.03	1.1	0.7	0.03	0.2	0.3	0,33
81-100	Brl	2.5 Y 6/2	38.6	22.9	38.3	4.0	4.1	2	0.04	1.5	0.7	0.03	0.1	0.2	0,25
Middle terrace – P5 : Endogleyic Arenosol															
0-26	Ap	10 YR ¾	85.1	9.7	5.1	4.1	4.7	0.01	0.001	0.002	0.001	0.002	0.001	0.0004	0,70
26-60	Ah	10 YR ¾	79.8	14.0	6.2	4.2	4.7	0.04	0.001	0.002	0.001	0.001	0.001	0.0004	0,49
60-108	Cw	7.5 YR 8/3	90.4	8.6	0.8	4.6	5.3	0.02	0.001	0.002	0.0002	0.001	0.001	0.0001	0,74
108-160	Bl	7.5 YR 7/4	88.4	9.7	1.8	4.9	5.4	0.03	0.001	0.002	0.0004	0.001	0.001	0.0002	0,88
Middle terrace – P6 : Endogleyic Arenosol															
0-31	Ap	10 YR 2/2	77.6	15.3	7.1	4.6	4.9	0.03	0.001	0.002	0.001	0.001	0.001	0.001	0,40
31-62	AhC	10 YR 3/2	78.8	18.3	3	5.2	5.7	0.03	0.001	0.002	0.001	0.001	0.001	0.001	0,50
62-107	1Cw	7.5 YR 7/3	82.1	15.9	2	5.6	6.0	0.03	0.001	0.002	0.0004	0.001	0.001	0.001	0,43
107-138	2Bl	10 YR 6/3	72.9	10.7	16.4	5.8	5.8	0.20	0.002	0.004	0.007	0.002	0.002	0.002	0,12
138-160	1Bl	10 YR 8/2	83.5	12.5	4.3	6.0	6.4	0.05	0.002	0.002	0.001	0.001	0.0005	0.0002	0,47

convincing argument. This view is substantiated by a particular abundance of kaolinite in low terrace soils. Kaolinite on this intermediate landscape position most probably has two origins: detrital and pedogenic. Detrital (or terrigenous) kaolinite corresponds to the kaolinite carried with eolian dust material from continental uplands. Textural contrast-soils (TCS) well evidenced by Phillips (2001) in the South East of the United States (Ouachita Mountains, Arkansas; ridgetops in eastern Kentucky; the lower coastal plain of North Carolina; and the upper coastal plain of east Texas) were only identified throughout low terrace profiles.

The SEM and EDX analysis depicted amorphous kaolinite platelets on the low terrace position (Plate 1b) compared to the well-structured kaolinite crystals obtained on the floodplain (Plate 1a). This suggests detrital kaolinite on the previous landscape position. Pedogenic kaolinite is suggested with respect to the acid pedoenvironmental conditions (pH 3-5) prevailing on this

Table 2 -Semi-quantitative estimation of the clay mineral abundance in the topsoil, central horizons, and subsoil of the floodplain, the low terrace, and the middle terrace

Horizon	Depth (cm)	Kaolinite (%)	Smectite (%)	Illite (%)	Total (%)
Floodplain - P1 – Gleyic Hyposalic Solonchak					
Topsoil	0-4	75	23	3	100
Central horizons	4-23	67	32	1	100
Subsoil	23-60	71	28	1	100
Floodplain - P2 – Gleyic Hypersalic Solonchak					
Topsoil	0-8	83	14	3	100
Central horizons	8-30	64	35	1	100
Subsoil	30-60	70	29	1	100
Low terrace – P3 –Haplic Gleysol (Thionic)					
Topsoil	0-16	81	17	2	100
Central horizons	16-62	94	5	1	100
Subsoil	62-100	87	12	1	100
Low terrace – P4 –Haplic Gleysol (Thionic)					
Topsoil	0-11	85	13	2	100
Central horizons	11-51	91	8	1	100
Subsoil	51-100	67	32	1	100
Middle terrace - P5 – Endogleyic Arenosol					
Topsoil	0-60	82	17	1	100
Central horizons	60-108	72	26	1	100
Subsoil	108-160	75	23	1	100
Middle terrace – P6 – Endogleyic Arenosol					
Topsoil	0-62	41	58	1	100
Central horizons	62-107	47	52	1	100
Subsoil	107-160	58	40	2	100

intermediate landscape position. Such conditions favour the transformation of smectite into kaolinite.

The stability diagrams available in the literature show kaolinite stability under low values of pH-pK and $pSi(OH)_4$ at ambient pressure and temperature, typical conditions of acid, well-drained, and leached soils (Furquim et al. 2009). Floodplain soils contain less kaolinite compared to the low terrace, because the lowest position and the distance from the source significantly reduce the contribution of eolian dust inputs. The neutral soil pH induced by high base saturation limits pedogenic kaolinite formation from alteration of 2: 1 silicates, mainly smectite or illite.

As soils described by Furquim et al. (2009) in the Pantanal Wetland of Brazil, floodplain soils are alkaline due to their poor drainage, and as saline soils, they have high base saturation. Such conditions are opposite for the ideal formation of kaolinite. Pedogenic formation of kaolinite is therefore marginal on this lowest landscape position, while the major contribution is probably given by the inheritance from feldspars (mainly albite) (Figure 3). Kaolinite generally increases upwards in the floodplain profiles, while smectite decreases (Table 2), a trend already observed by Buol (1965). Although weathering of 2:1 silicates cannot be precluded, this process seems more likely to be due to selective translocation of smectite-rich, finer-clay particles, or to smectite formation in lower parts of the profile, or both (Allen and Hajek, 1989). Kaolinite in middle terrace appears essentially detrital. It originates most likely from the nearby uplands. Pedogenic kaolinite formation might be promoted by strong leaching caused by the high landscape position and permeability of soil material. Smectite is commonly altered to kaolinite, where weathering, especially leaching, is intense (Kantor and Schwertmann 1974; Karathanasis and Hajek 1983).

Evidence for airborne addition of kaolinite is also suggested with respect to the relative young parent material (Holocene sediments, according to Michel 1973; Marius 1985; Sadio 1991) which appears to be insufficient to produce appreciable amounts of the well-crystallized kaolinite yielded in the floodplain soils. It generally takes at least 10 000 years to produce a soil containing pedogenic kaolinite as a major constituent (Dixon 1989). Moreover, the highest Fe_d/Fe_t ratios (Fe_d/Fe_t> 0.5, on average) obtained in the floodplain profiles suggest matured soil material, contrasting with the recent sediment deposition on this lowest landscape position. This supports material input from highly weathered upland soils. Igwe et al. (2005) explained the occurrence of advanced weathering products such as kaolinite and crystalline Fe and Al in recent parent materials of the River Niger floodplain, eastern Nigeria to addition of intensive weathered material from the upland.

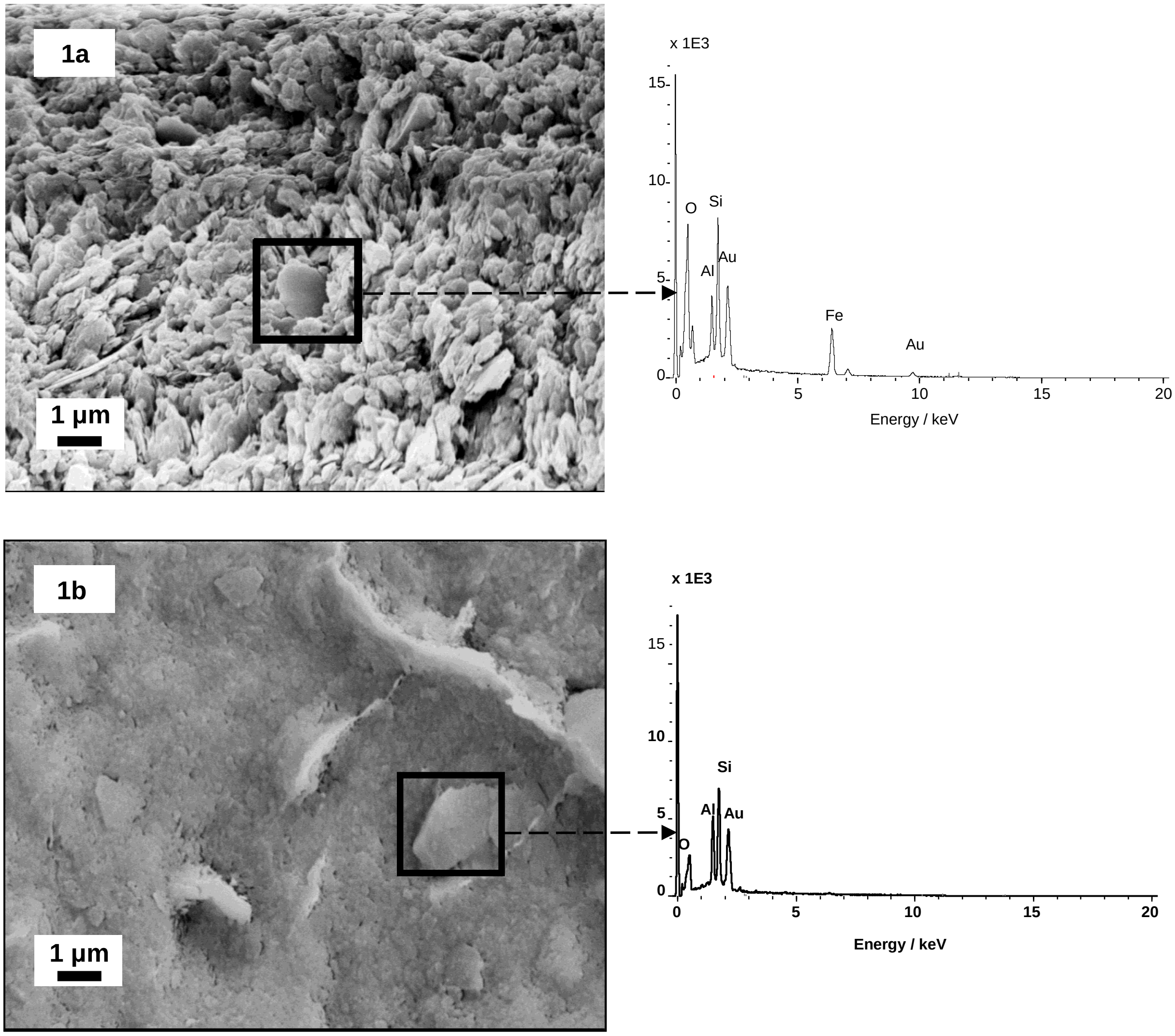


Plate 1. SEM and EDX showing kaolinite platelets in the floodplain (1a - P1: Gleyic Hyposalic Solonchak (Sulphatic); Bjv horizon: 4-23 cm) and low terrace (1b – P3: Haplic Gleysol (Thionic); Bl1: 16-38 cm.

The Continental Terminal as Major Source of Kaolinite in West Africa

As a natural region West Africa may be defined as lying south of the Ahaggar-Tibesti Mountains and west of the watershed separating Lake Chad from the Nile and Zaire drainage basins.

West Africa thus lies west of the topographic demarcation of high Africa from low Africa.

Geomorphologically, the West African region includes the coastal plain, the Guinea basement shields and the Taoudeni and Chad basins in the Western Sahara (Petters, 1991). The CT is composed by a thick series of ferruginised and argillaceous sandstones, mudstones and carbonaceous layers, deposited under fluviatile and lacustrine conditions (Wright et al. 1985); which has undergone a profound ferrallitic pedogenesis (Michel 1973; Kalck 1978; Lappartient 1985). Ferralitic alterations mostly occurred in the Pliocene period after the sinking of the Senegalo-Mauritanian basin, and are still highly dominant. It is covered by a series of Quaternary marine deposits formed in gulfs which spread widely in Western Mauritania (up to a maximum of 220 km at the latitude of Nouakchott) and to a lesser extent in Senegal (Giresse et al. 1988). The CT is thought to provide substantial inputs of highly weathered sediments responsible for the widespread incidence of kaolinite in West Africa. The probability for CT to be the major source of kaolinite in these soils is based on many considerations. It must be first borne in mind that the Saloum river basin belongs entirely to the Senegalo-Mauritanian basin. The latter is a Cretaceous-Tertiary basin formed by marine formations largely covered by huge continental formations described in Western Africa as CT (Giresse et al. 1988). This CT presents in many instances signs of neo-formation of kaolinite and significant silica movements (Conrad and Lappartient 1987), supporting neo-formation of authigenic kaolinite in the detrital CT formations, although the mechanisms governing such formation are still ambiguous. Apart from locally important occurrences of chlorite, kaolin and illitic minerals are the most abundant authigenic clays. However, despite the enormous wealth of literature on clay diagenesis in sandstones, there is no general agreement on the reaction-pathways leading to crystallization of these minerals and on the fluids responsible for the observed mineral reactions (Lanson et al., 2002).

The most influential contribution on mineralogical studies of mangrove soils of West Africa was given by Marius and Lucas (1991) (Souza-júnior et al. 2008). They identified important amounts of kaolinite and smectite (>90% of the clay mineral suite) in the mangrove soils of southwestern Senegal and related it to the CT for the former clay mineral and marine sediment inputs for the latter. Likewise, investigating Holocene deltaic sequences in the Saloum estuary, Ausseil-Badie et al. (1991) described a lower sandy-clay stratigraphic unit marked by a ratio of micaceous minerals/kaolinite close to 1:2. They attributed it to the CT influence in this region. Also Faye et al. (2003) found kaolinite as dominant clay mineral in the CT formations beneath the Holocene sediments of the Saloum region. Diara and Barusseau (2006) convincingly argued that the clayey paragenesis is highly constant in the Saloum delta: Kaolinite and smectite constitute more than 80% of the clay fraction and illite, more subsidiary, represents only 5 to 20%. Kaolinite constitutes more than 50% of the clayey assemblage of the sediments. Kalck (1978) supported that kaolinite is inherited from the alteration of the CT; illite originates from the same source. Herrmann (1996) found that lithogenic minerals of the CT, mainly kaolinite, dominate in some soils of the Houéto region (Benin) and argued further the dominance of kaolinite to be consistent with the results obtained by Fritz (1995) in similar areas of south Benin. He attributed the dominance of kaolinite in top- and subsoils of profiles in south Benin to the distinctly weathered sediments originated from the clay- and sandstone of the CT. Three conclusions may be drawn from the previous discussion: (1) the influence of the CT formations in the genesis of West-African landscape, (2) the widespread occurrence of kaolinite in West-African soils, and (3) the eolian dust origin of clay minerals in the coastal region of West Africa as mainly allochtonous component from regional sources or farther. This corroborates the provenience of kaolinite in studied soils from the CT formations. A general argument supports this line of reflexion: the Holocene sediments present in the coastal area of west central Senegal are simply too young to contain kaolinite as highly dominant clay mineral. The single explanation remains that kaolinite-rich sediments stemming from the highly weathered detrital formations of the CT are carried with eolian dusts in the coastal areas. Easterlies, mainly Harmattan, frequent in the West African region promote the mobilisation of kaolinite-rich CT sediments from the eastern uplands and their deposition on the western lowlands. Biscaye (1965) maintained that dusts such as those of the Harmattan haze of Africa contribute to the westward distribution of kaolinite from that continent.

CONCLUSION

Different hypotheses have been addressed to explain the origin of clay minerals in estuarine and coastal plain sediments.

Early studies concluded that clay minerals in these interface areas are strongly influenced by diagenetic processes arising from the fact that detrital clay particles are transported from a fresh-water environment to a saline environment (Chamley, 1989). Later work, however, failed to confirm the chemical and mineralogical changes proposed and a consensus has arisen that terrigenous inputs from various sources offer a far more convincing explanation for the majority of clay minerals found in estuarine and coastal sediments (Belzunce-Segarra et al., 2002). Our study demonstrated that kaolinite in the coastal area of West Africa mostly originates from the CT sediments. Terrigenous inputs exert thus the major influence in the distribution and properties of the clay minerals, mainly kaolinite. Mineralogical studies in this area have to take into account the different source areas of clay minerals. Such knowledge enhances understanding of pedogenesis at local as well as at regional level, and may help develop sustainable soil management strategies in the future.

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