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Soil Development and Fertility Characteristics of Inland Valleys in the Rain Forest Zone of Nigeria: Mineralogical Composition and Particle-Size Distribution*[1]

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ABSTRACT

The particle-size distribution and mineralogical composition of the clay (< 2 μm) and fine-sand (0.25–0.10 mm) fractions in soils of two inland valleys in Abakaliki and Bende, Southeast Nigeria, were investigated to provide basic information on soil-forming processes and agricultural potentials. These soils were silty or clayey, deriving from Cretaceous or Tertiary shale materials. The particle-size distribution and its computation on a clay-free basis revealed relatively remarkable lithologic breaks in a couple of pedons. The effect of lithologic discontinuities on soil mineralogical composition was not, however, conspicuous. Petrographic investigation revealed that quartz predominantly comprised the fine-sand fraction in the soils at both study sites. Nevertheless, the clay mineralogical composition of the soils was a mixture of kaolinite, irregularly interstratified smectite-illite intergrades (S/I), hydroxyl-Al interlayered 2:1 type clays (HICs), vermiculite, smectite, halloysite and illite along with fine-sized quartz in Abakaliki. The soils of Bende predominantly contained smectite, which was partially interlayered with hydroxyl-Al and kaolinite. It is suggested that seasonal floodwater has slowed the disintegration of weatherable clay minerals inherited from the shale, while quartz originating from the sandstone is predominant in the fine-sand fraction. Additionally, a possible soil-forming process observed at the both study sites was ferrolysis, which was indicated by a clear decreasing pattern of HICs downward in the soil profiles. The entry of S/I and vertical distribution patterns for a couple of clay minerals in the pedon suggested that the soils in Abakaliki have developed under the significant influence of aeolian dust delivered by the Harmattan. The findings might describe a site-specific deposition pattern of Harmattan dusts as well as hydromorphic soil-forming processes in the wetlands of the inland valleys.

Key Words: aeolian dust, ferrolysis, hydromorphic soil, hydroxyl-Al interlayered 2:1 type clays, Southeast Nigeria

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INTRODUCTION

Agricultural development has generated strong interest in the inland valley ecosystems of West Africa. In particular, those parts receiving seasonal rainfall are considered to have potential for intensive cultivation of swamp rice (JICA, 2003; Wakatsuki and Masunaga, 2005). With this in mind, Issaka *et al.* (1996, 1997) and Buri *et al.* (1999, 2000) investigated general soil fertility status of inland valleys in West Africa. Afterwards, Abe *et al.* (2006, 2007a) reported the mineralogical properties of these soils. They revealed that the soils in the inland valleys of West Africa generally showed very low fertility

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characteristics such as acidic reactions, low values of effective cation exchange capacity and sandy texture. These characteristics were associated with the poor mineralogy, *i.e.*, the predominance of 1:1 type phyllosilicates in the clay fraction (< 2 μm) and highly resistant minerals in the fine-sand fraction (212–20 μm). Major soils in West Africa derive from Precambrian metamorphic and/or igneous rocks (*i.e.*, basement complex) and consequently have been subjected to intensive and prolonged weathering (Udo, 1978; Windmeijer and Andriesse, 1993). This resulted in the widespread distribution of siliceous or low activity clay soils not only in the uplands but also in the lowlands of the region (Kang and Spain, 1986; Abe *et al.*, 2006, 2007a).

On the other hand, Abe *et al.* (2006) found that the soils containing relatively large amounts of 2:1 type clays preferentially occurred in the eastern part of West Africa (centered on Nigeria) and suggested that soil mineralogy in the region might reflect the nature of parent materials rather than the relief and climate. However, Jungerius and Levelt (1964) reported that clay mineralogy of soils developed on sedimentary rocks in eastern Nigeria was kaolinitic. Eshett *et al.* (1989, 1990) also described kaolinitic soils on a sedimentary toposequence in southwestern Nigeria. Okusami *et al.* (1987) documented the predominance of kaolinite in some alluvial soils of Nigeria. Meanwhile, there have been many studies reported that 2:1 type clay minerals, *e.g.*, smectite, were increasingly observed in poorly-drained soils (Jungerius and Levelt, 1964; Gallez *et al.*, 1975; Ojanuga, 1979; Eshett *et al.*, 1989, 1990; Møberg and Esu, 1991) regardless of the predominance of kaolinite in most lowland soils in West Africa (Abe *et al.*, 2006). These conflicting findings indicate the need to accumulate scientific information on soil mineralogy in terms of the pedogenesis in this area. The scarcity of information has also made soil classification at the family level of Soil Taxonomy impossible and has created impediments to the understanding of the pedogenesis as a tool for agro-technological transfer in the region.

Our previous work (Abe *et al.*, 2007b) reported that the soils showed distinctive textures in Abakaliki and Bende, Southeast Nigeria. These soils were silty or clayey reflecting the nature of parent materials, *i.e.*, Tertiary or Cretaceous shale, although most soils in the inland valleys in West Africa showed sandy texture (Buri *et al.*, 1999, 2000). These findings also drove speculation as to the distinctive mineralogy of these soils, which has not been so far explored. The present study, therefore, aimed to clarify the nature of the parent materials and the clay mineralogy of the soils in Abakaliki and Bende by employing particle-size analysis, petrographic investigation and X-ray diffraction (XRD) measurement.

MATERIALS AND METHODS

The study area is subject to the rainforest climate in Nigeria, having a mean annual rainfall of 1 600–2 000 mm and mean daily temperature of approximately 27 °C. The rainfall pattern is bimodal, being characterized by two split rainy seasons (usually April to August and October to January). A dry dust-laden wind, the Harmattan, blows from the Sahara Desert during the main dry season (normally November to March) (Afeti and Resch, 2000; Goudie and Middleton, 2001). In this region, we investigated two representative inland valleys, one near Abakaliki (6° 15′ N, 8° 8′ E) and the other in Bende (5° 30′ N, 7° 40′ E). The inland valley in Abakaliki displays a saucer-shaped depression on a very gently undulating peneplain, while that of Bende has an undulating or rolling topography. The geology of the study area comprises in general shale with occasional appearance of sandstone. The soils of Abakaliki derive from preweathered shale from the Cretaceous era, while Bende has segregated geological substrates, *i.e.*, Tertiary shale rich in 2:1 type phyllosilicates in the bottom part but sandstones mainly composed of quartz in the upland. On a toposequence for each inland valley, soil samples were collected from pedogenetic horizons (Table I). Further description of the study site as well as physicochemical and morphological properties of the soils have been reported previously (Abe *et al.*, 2007b).

The particle-size distribution was obtained by repeated dispersion, sedimentation and sieving (Jackson, 1956). The sand fraction (2–0.05 mm) was further fractionated by sieving into the following fractions: very coarse sand (2–1 mm), coarse sand (1–0.5 mm), medium sand (0.5–0.25 mm), fine sand (0.25–0.1 mm), and very fine sand (0.1–0.05 mm). The particle-size distribution was also calculated

TABLE I

Soil samples collected from pedogenetic horizons on a toposequence from inland valleys in Abakaliki and Bende, Southeast Nigeria

Pedon	Location	Horizon
		Abakaliki
AK 1	Fringe	Ap (0–20 cm), A2 (20–40 cm), Bwg1 (40–81 cm), Bgw2 (81–111 cm), Bwg3 (111–170 cm), BCg (170–194 cm)
AK 2	Upper bottom	Ag (0–28 cm), A2g (28–47 cm), 2Bwg (47–74 cm), 2Bg (74–109 cm), 2BCg (109–150 cm)
AK 3	Lower bottom	Apg (0–28 cm), A2feg (28–54 cm), B1g (54–100 cm), B2g (100–158 cm)
AK 4	Lower fringe	Apg (0–30 cm), Bwg1 (30–50 cm), Bwg2 (50–98 cm), BCg (98–148 cm)
AK 5	Upper fringe	Ap (0–20 cm), AB (20–50 cm), 2Bw (50–76 cm), 2Bwfeg (76–95 cm), 3BCg (95–135 cm), 3Cg (135–170 cm)
		Bende
BD 1	Lower bottom	Ap (0–21 cm), Bw1 (21–50 cm), Bwg2 (50–85 cm), Bwg3 (85–100 cm), BCg (100-158 cm)
BD 2	Upper bottom	Ap1 (0–20 cm), Apg2 (20–52 cm), Bwg1 (52–89 cm), Bwg2 (89–120 cm), 2BCg (120–165 cm)
BD 3	Lower fringe	Ap (0–20 cm), Bw1 (20–73 cm), Bw2 (73–100 cm), BC (100–152 cm)
BD 4	Upper fringe	Ap (0–18 cm), Bw1 (18–30 cm), Bw2 (30–75 cm), BC (75–144 cm)

on a clay-free basis using the sand sizes according to Soil Survey Staff (2006). objective of calculating particle size distribution on a clay-free basis was to remove the effect of possible relocated clays and to assess lithologic discontinuities in the soil (Smith and Wilding, 1972; Soil Survey Staff, 2006).

Sub-samples of the fine sand fraction were mounted on a glass slide under a cover slip with 1.54 index of reflection oil (Canada balsam) for the petrographic examination. Minerals were identified according to their optimal properties, *e.g.*, color, shape, pleochroism, birefringence and extinction. Mineralogical composition of the clay fraction (< 2 μm) was examined by X-ray diffraction (XRD) analysis using an X-ray diffractometer (XRD-6000, Shimadzu, Tokyo) with Co-filtered CuKα radiation. Oriented clay specimens were prepared on a glass slide using the smear mount method (Theisen and Harward, 1962) after saturation with Mg and K, respectively. The XRD measurement was applied to K-clays at room temperature, 300 and 550 °C. The Mg-clays were measured respectively with and without glycerol permeation at room temperature. Clay minerals were identified according to Moore and Reynolds (1997). In an additional experiment, the clay samples were treated with Na-citrate to remove hydroxyl-Al in the interlayer of 2:1 type phyllosilicates, as described by Tamura (1958).

RESULTS

Particle-size distribution on a clay-free basis and clay content of the soils are shown in Fig. 1. In this study, proportions of the fine sand, very fine sand and medium sand fractions were given particular attention since these size-fractions dominated the total sand fraction and were present in most parts of quartz, as shown in Table II. The results indicated relatively remarkable lithologic discontinuities at 47–74 cm depth, and at both 50–76 and 95–135 cm depth in the pedons AK 2 and AK 5, respectively. A lithologic break was also detected at 120–165 cm depth in the pedon BD 2. In contrast, the other pedons, *i.e.*, AK 1, AK 3 and AK 4 in Abakaliki, and BD 1, BD 3 and BD 4 in Bende, did not include clear lithologic discontinuities. In addition, abrupt textual changes were found at A2 and A2feg horizons in the pedons AK 1 and AK 3, respectively. These horizons were not, however, designated as lithologic discontinuities since they were situated directly beneath the plow layers and were probably influenced by agricultural practices (Soil Survey Staff, 2006).

Petrographic investigation revealed that heavy minerals constituted only a very small portion in the fine-sand fractions, and that quartz accounted for most of the light grains counted (Table II). Small quantities of other resistant minerals such as zircon and tourmaline were also identified. In contrast, less resistant minerals such as muscovite and feldspars and easily weatherable minerals like biotite (Allen and Hajek, 1989) were found at very low contents, usually in subsurface soils. The color of fine sand grains of the hydromorphic horizons in the pedons ranged from colorless to light gray.

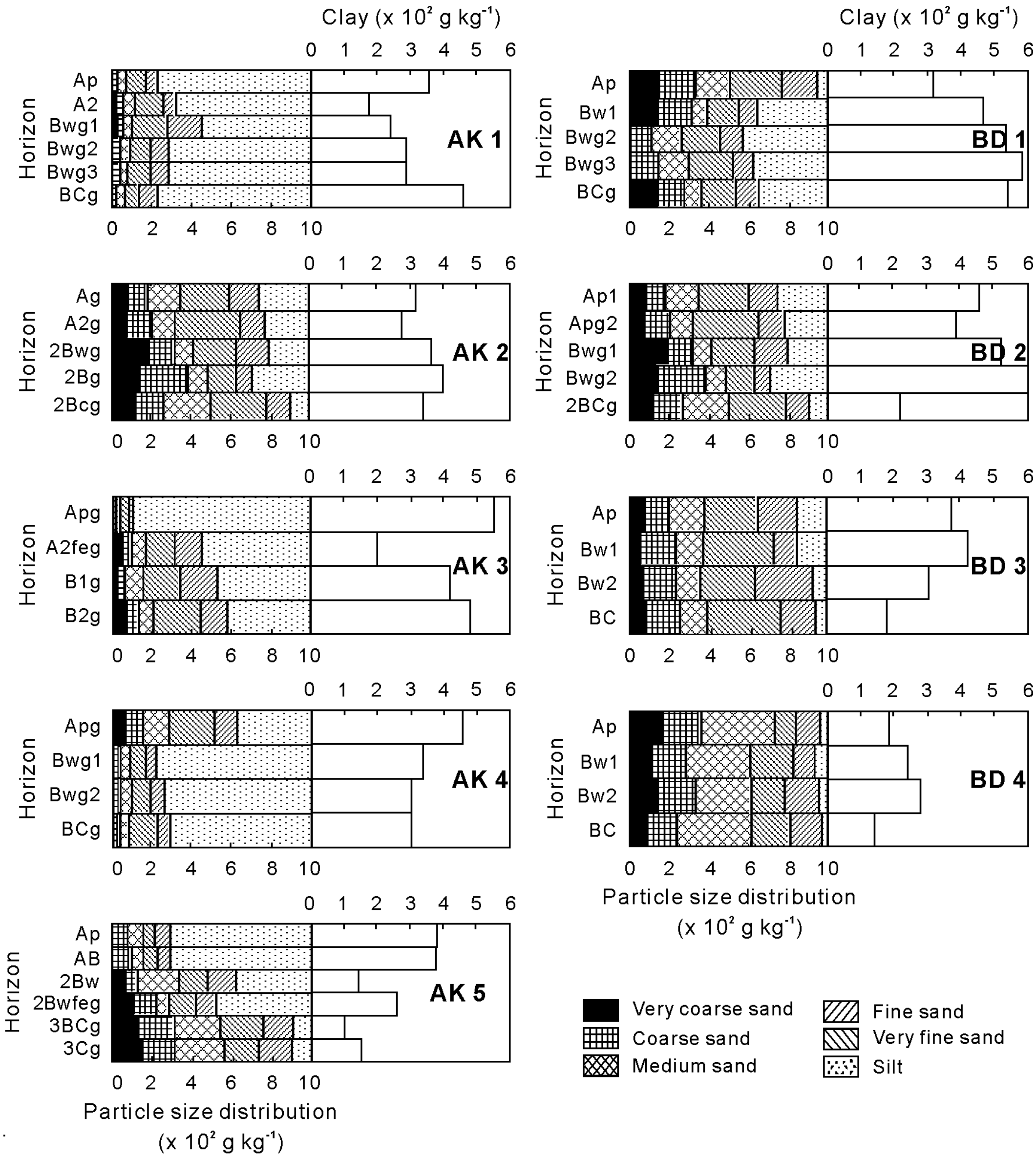

Fig. 1 Particle size distribution on a clay-free basis and clay content of the soils in pedons AK 1–5 of Abakaliki and BD 1–4 of Bende.

The XRD diagrams of the clay fraction in selected samples from Abakaliki are shown in Fig. 2. A basal reflection around 1.4 nm for air-dried Mg-clay and its shift near 1.8 nm after glycerol solvation represented the entry of smectite. The persistent peak around 1.4 nm with glycerol showed the presence of vermiculite. Diffraction around 1.2 nm and nearby 1.0 nm on K-saturated clays at room temperature was also supportive information for the existence of smectite and vermiculite, respectively. Nevertheless, asymmetry of the peak around 1.4 nm and its shoulder towards the higher 2θ angle on air-dried Mg specimens were evidence for the presence of smectite-illite interstratified (S/I) (Egashira and Iwashita, 1992). The structure of I/S had an irregular interstratification due to the absence of a significant diffraction at the low angle range (Sawhney, 1989). A remained shoulder of the peak at 1.0 nm toward the

TABLE II

Mineralogical composition[a)] in the fine-sand fraction (0.25–0.10 mm) of the soils in Abakaliki and Bende, Southeast Nigeria

Study site	Pedon	Horizon	Feldspar	Muscovite	Biotite	Quartz	Zircon	Tourmaline	Opaque
Abakaliki	AK 1	A2	(X)	(X)	-	XXXX	(X)	-	-
		Bwg2	-	(X)	-	XXXX	-	-	-
		BCg	-	(X)	(X)	XXXX	-	-	-
	AK 2	Ag	X	-	-	XXXX	-	-	-
		2Bwg	(X)	-	X	XXXX	-	-	(X)
		2BCg	-	-	X	XXXX	-	-	-
	AK 5	AB	-	(X)	-	XXXX	-	-	-
		2Bwfeg	-	(X)	(X)	XXXX	-	(X)	(X)
		3BCg	-	(X)	-	XXXX	-	-	-
Bende	BD 1	Ap1	(X)	-	-	XXXX	(X)	-	-
		Bwg2	(X)	X	X	XXXX	(X)	-	(X)
		BCg	(X)	X	X	XXXX	-	-	-
	BD 3	Ap	(X)	(X)	-	XXXX	(X)	-	-
		Bw1	-	(X)	-	XXXX	-	-	-
		BC	-	(X)	-	XXXX	-	-	-

[a)]- = absent; (X) = trace; X = scarce; XXXX = predominant.

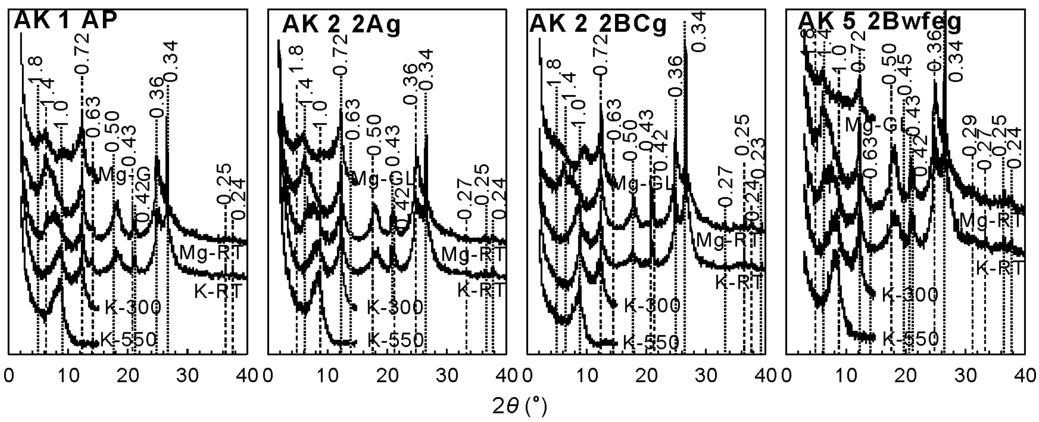

Fig. 2 Selected X-ray diffraction patterns of the clay fraction (< 2 μm) from the soils in Abakaliki. Numerals within the figure indicates *d*-spacing in nanometers. Mg-GL stands for Mg-clay with glycerol permeation, Mg-RT for Mg-clay at room temperature, K-RT for K-clay at room temperature, K-300 for K-clay at 300 °C, and K-550 for K-clay at 550 °C.

lower 2θ angle on K specimens at 300 and/or 550 °C indicated the presence of hydroxyl-Al interlayered 2:1 type clays (HICs) in collaboration with incomplete expansion of interlayer space (001 reflection) with glycerol solvation (Barnhisel and Bertsch, 1989).

The treatment with Na-citrate can remove the hydroxyl-Al in the interlayers of HICs, which would result in the recovery of its shrinkability under heating and expandability with glycerol permeation (Tamura, 1958; Barnhisel and Bertsch, 1989). With Na-citrate treatment, there were distinct peaks near 1.8 nm and around 1.4 nm after Mg saturation and glycerol salvation, as well as around 1.2 nm and near 1.0 nm on air-dried K-saturated specimens, respectively (Fig. 3). This indicated the coexistence of hydroxyl-Al interlayered-smectite and -vermiculite, chiefly the former, in HICs of the Abakaliki soils. On the other hand, the absence of chlorite as well as the existence of kaolinite was indicated by the diffraction at 0.72 nm on K-clay disappeared by heating at 550 °C (Fig. 2). This peak tended to be rather broad and asymmetrical towards the low angle side, which can be referred to as coexistence of halloysite. There was also a substantial amount of quartz as indicated by a sharp-shaped peak at 0.43 and 0.34 nm. A basal reflection at 0.63 and 0.42 nm originated from lepidocrocite and goethite, respectively. XRD analysis indicated that the soils in Abakaliki contained kaolinite, S/I, HICs, vermiculite, smectite, halloysite, illite and fine-grained quartz. Lepidocrocite and goethite, which are common properties of the soils under hydromorphic conditions (Schwertmann and Taylor, 1989), were also observed in some horizons.

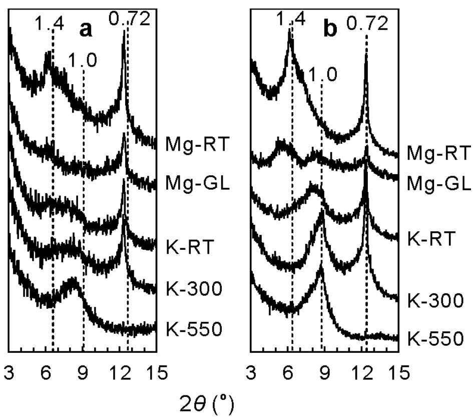

Fig. 3 X-ray diffraction patterns of the clay fraction (< 2 μm) from horizon Bwg1 of pedon AK 4 in Abakaliki, before (a) and after (b) the treatment with Na-citrate. See Fig. 2 for the descriptions of the numerals within the figure, Mg-GL, Mg-RT, K-RT, K-300, and K-550.

Meanwhile, the soils of Bende were characterized by the predominance of smectite and kaolinite in the clay fraction (Fig. 4). A small amount of HICs, illite, lepidocrocite, goethite, quartz and/or K-feldspars (diffraction at $2\theta = 0.33$ nm) were also found in some horizons. In the soils of Bende, HICs were probably composed solely of hydroxyl-Al interlayered smectite because vermiculite was not detected at all.

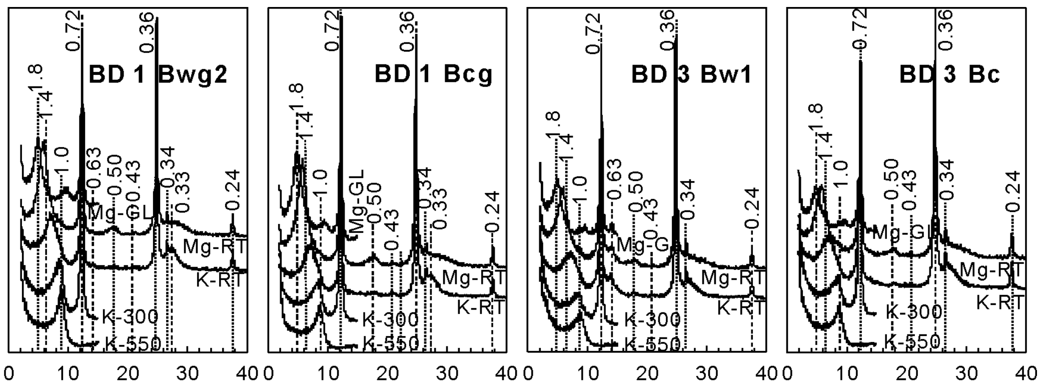

Fig. 4 Selected X-ray diffraction patterns of the clay fraction (< 2 μm) from the soils in Bende. See Fig. 2 for the descriptions of the numerals within the figure, Mg-GL, Mg-RT, K-RT, K-300, and K-550.

Clay mineralogical composition in corresponding horizons and pedons to primary minerals is summarized in Table III. In the soils of Abakaliki, the distribution trend of I/S, and smectite was relatively equivocal in the pedons except for vermiculite and illite, which showed a significant increasing pattern down the soil profile. In contrast, the contents of kaolinite and HICs clearly decreased with depth in the pedons. In Bende, the content of smectite and illite significantly increased with soil depth, whilst the amount of kaolinite and HICs declined.

As a consequence, the soils in Abakaliki and Bende were classified at the family level of Soil Taxonomy (Soil Survey Staff, 2006; Table IV). As common mineralogical and cation-exchage activity classes, these

TABLE III

Mineralogical composition in the clay fraction (< 2 μm) of the soils in Abakaliki and Bende, Southeast Nigeria

Pedon	Horizon	Kaolinite	Halloy-site	Illite	Vermi-culite	Smectite	Smectite-illite	HICs[a]	Quartz	Others
AK 1	A2	XXX[b]	X[b]	X	X	X	XX[b]	XX	XX	Lepidocrocite X; goethite, X
	Bwg2	ND[b]	ND	ND	ND	ND	ND	ND	ND	ND
	BCg	ND	ND	ND	ND	ND	ND	ND	ND	ND
AK 2	Ag	XXX	X	(X)[b]	X	X	XX	XX	XX	Goethite, X
	2Bwg	XXX	X	X	XX	X	XX	X	XXX	Goethite, X
	2BCg	XXXX	(X)	X	XX	X	XX	-[b]	XXX	Chlorite (X); goethite, X
AK 5	AB	XXX	X	-	X	X	XX	XX	XXX	Lepidocrocite X; goethite, X
	2Bwfeg	XXX	(X)	(X)	XX	X	XX	X	XXX	Lepidocrocite (X); goethite, X
	3BCg	ND	ND	ND	ND	ND	ND	ND	ND	ND
BD 1	Ap1	XXXX	-	(X)	-	XXX	-	X	X	Lepidocrocite (X); goethite, (X)
	Bwg2	XXX	-	(X)	-	XXXX	-	(X)	X	Feldspars X; lepidocrocite (X); goethite, (X)
	BCg	XXX	-	X	-	XXXX	-	-	X	Feldspars X; lepidocrocite (X); goethite, (X)
BD 3	Ap	XXXX	-	-	-	XXX	-	X	X	Lepidocrocite (X); goethite, (X)
	Bw1	XXXX	-	-	-	XXX	-	X	X	Lepidocrocite X
	BC	XXX	-	(X)	-	XXXX	-	(X)	X	Lepidocrocite (X)

[a] Hydroxyl-Al interlayered 2:1 type clays.
[b] - = absent; (X) = trace; X = scarce; XX = common; XXX = abundant; XXXX = predominant; ND = not determined.

TABLE IV

Taxonomic classification at the family level of the soils in Abakaliki and Bende, Southeast Nigeria

Site	Pedon	Soil taxonomic classification[a]
Abakaliki	AK 1	Fine-silty, siliceous, semiactive, isohyperthermic Fluvaquentic Epiaquepts
	AK 2	Fine-silty, mixed, subactive, isohyperthermic Aeric Fluvaquentic Epiaquepts
	AK 3	Fine, mixed, semiactive, isohyperthermic Aeric Fragiaquepts
	AK 4	Fine-silty, siliceous, subactive, isohyperthermic Fluvaquentic Epiaquepts
	AK 5	Fine-silty over sandy, siliceous, subactive, isohyperthermic Typic Fragiudepts
Bende	BD 1	Fine, smectitic, isohyperthermic Fluvaquentic Epiaquepts
	BD 2	Fine, smectitic, isohyperthermic Fluvaquentic Epiaquepts
	BD 3	Fine-loamy, siliceous, subactive, isohyperthermic Fluvaquentic Humaquepts
	BD 4	Fine-loamy, siliceous, subactive, isohyperthermic Fluvaquentic Humaquepts

[a] Soil Survey Staff (2006).

soils had siliceous and sub- or semi-active characteristics, respectively, except for the pedons BD 1 and BD 2, which were smectitic.

DISCUSSION

Both the laboratory mechanical analysis and the field morphologic observation could not detect any argillic horizons in all the examined pedons (Abe *et al.*, 2007b; Fig. 1). Hence, the lessivage would not be significant in the soils of Abakaliki and Bende. The contrasting sand sizes and thus possible lithologic discontinuities in the subsoils of the pedons AK 2, AK 5 and BD 2 (Fig. 1) were generally in agreement with the field morphologic characteristics and irregular distribution pattern of organic carbon as described by Abe *et al.* (2007b). Lithologic discontinuities would result from differences in energy at the time of deposition (Soil Survey Staff, 2006). This might also reflect the topographic disparity which determines flooding pattern and intensity. Although the particle-size analysis could only detect relatively clear lithologic breaks in these pedons, possible minor discontinuities would be taken into consideration in the other pedons. The effect of lithologic discontinuities on the soil mineralogical composition was not, however, conspicuous in this study.

There was no significant difference in the mineralogical composition of the fine-sand fractions between Abakaliki and Bende (Table II) despite the disparity of the nature and age of parent materials as well as of the clay mineralogy (Table III). The fine-sand mineralogy was uniformly dominated by quartz, which is very common in lowland soils in West Africa as a result of prolonged and intensive weathering processes (Oyediran, 1990; Møberg and Esu, 1991; Abe *et al.*, 2007a). In this study, however, the fine-sand quartz would originate from the sandstone erodes from surrounding uplands rather than the weathering residues of the shale, as the geological component in the study area is alternate strata of shale and sandstone. In addition, weatherable clay minerals significantly co-existing in the clay fraction, as stated below, could prevent the intensive weathering process at the study sites. Less resistant minerals such as muscovite and feldspars and easily weatherable minerals like biotite in the fine-sand fraction (Allen and Hajek, 1989) were found in some subsurface horizons, in particular, in the valley bottoms (*i.e.*, the pedons AK 2 and BD 1) even though their amounts were very low. It appears that high water tables and/or saturated moisture conditions have preserved the weatherable minerals in the bottoms. The light gray dominant color of the grains and thus the loss of Fe from the soils suggest soil-forming processes under seasonal development of anaerobic conditions.

In contrast to the fine-sand fraction, the clay fraction consisted significantly of weatherable 2:1 type phyllosilicates in both the study sites (Table III). The distinctive clay mineralogy of the soils at the study sites would primarily originate from the parent materials, *i.e.*, Cretaceous or Tertiary shale rich in 2:1 type clay minerals. Unamba-Oparah *et al.* (1987) documented a similar mineralogy in poorly drained soils of the neighboring area having a similar geological origin. This was contrasting mineralogy to major soils in West Africa, which are dominated by kaolinite (Abe *et al.*, 2006) deriving from Precambrian igneous and/or metamorphic rocks (Udo, 1978; Windmeijer and Andriesse, 1993). A distribution pattern of vermiculite and illite within the individual pedon in Abakaliki and that of smectite and illite in Bende suggest their inheritance from local geological components rather than the *in situ* neoformation. This gave a clear contrast to the distribution of kaolinite. Jungerius and Levelt (1964) reported that poorly drained soils from a preweathered shale in East Nigeria significantly contained smectite in contrast to well-drained soils of the same geological origin. Other researchers (Gallez *et al.*, 1975; Ojanuga, 1979; Eshett *et al.*, 1989, 1990; Møberg and Esu, 1991) also pointed out that the 2:1 type clay minerals, *e.g.*, smectite, were increasingly observed in poorly-drained soils in Nigeria. Therefore, we concluded that high water table and/or saturated moisture conditions could have helped the preservation of some weatherable clay minerals such as illite and halloysite in the soils of the study sites.

Another soil-forming process that probably occurred at the study sites is aeolian deposition. This process is, however, considered to be much more prominent in Abakaliki than Bende because of the entry of S/I, an unstable mineral under natural weathering environments, in the Abakaliki soils. Wilke *et al.* (1984) reported that the Harmattan deposits in Kano and Sokoto, Northern Nigeria contained up to 30% of irregular illite-smectite mixed layer minerals. A relatively ambiguous distribution pattern of S/I, smectite and illite in the soil profiles of Abakaliki also suggest a significant influence by the Harmattan dust. There are two possible reasons for different effects of Harmattan dust on Abakaliki and Bende: (i) Abakaliki is situated on a significant pathway for Harmattan dust from the Chad Basin where the 2:1 type clay rich soils have been developed, and (ii) the landform of the inland valley in Abakaliki accelerated the accumulation of the aeolian deposits. The soils distributed along the Gulf of Guinea have been widely developed under the influence of aeolian deposits from the Sahara Desert (Møberg *et al.*, 1991; Tiessen *et al.*, 1991; Mizota *et al.*, 1996; Afeti and Resch, 2000). However, the style and degree of aeolian dust contribution to the pedogenesis would be site-specific due to the inhomogeneity of the source and/or spatial variations in dust deposition (Wilke *et al.*, 1984). The findings of the present study might describe well the site-specific influence of Harmattan dust.

On the other hand, *in situ* neoformation of HICs was suggested by their decreasing pattern in the soil profiles, similar to that of kaolinite. Partial chloritization of smectite and vermiculite could often be observed under hydromorphic conditions (Brinkman, 1970; Wakatsuki *et al.*, 1984; Barnhisel and Bertsch, 1989). This would be responsible for the interlayering of hydroxyl-Al under the ferrolysis (Brinkman, 1970). This process has also been suggested by the distribution and saturation percentage of exchangeable Al and iron activity index (Abe *et al.*, 2007b). The soils of Abakaliki contained a higher amount of HICs than those of Bende. Rapid changes of water table as indicated by the presence of Fe/Mn concretions in the pedons (Abe *et al.*, 2007b) might be responsible for the preferential occurrence of HICs in the soils in Abakaliki. The favorable formation of HICs in Abakaliki might also be attributed to the period of rice farming. The Abakaliki site has been under rice cultivation for hundreds of years but the Bende one only for decades. In this regard, Wakatsuki *et al.* (1984) reported significantly detectable clay mineralogical alterations including hydroxyl-Al interlayering in smectite in soils under paddy cultivation for 75 years. HICs are regarded as resistant minerals, which show substantial tolerance to weathering (Soil Survey Staff, 2006). Clay degradation under hydromorphic conditions, *i.e.*, partial chloritization of smectite and/or vermiculite by the ferrolysis, led to the reduction in nutrient holding capacity of the soil (Barnhisel and Bertsch, 1989). This might account for low values of the effective cation exchange capacity of the soils in Abakaliki and Bende in spite of their relatively high clay contents as reported by Abe *et al.* (2007b). Soil taxonomic classification also indicated the low activity of the soils as they were categorized into siliceous and sub- or semi-active classes. In such soils with poor mineralogical properties and thus low nutrient-holding capacity, the external input of organic manures are considered to be one of the effective options to improve soil fertility characteristics.

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