Soil Development and Fertility Characteristics in West African Lowlands

西アフリカの低地における土壌生成と肥沃度特性

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西アフリカの低地における土壌生成と肥沃度特性

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To My Family and Friends

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BIOGRAPHY OF THE AUTHOR

The author was born in Arakawa, Tokyo, Japan in June 30th, 1977 and has grown in several local cities in Japan such as Yonezawa (Yamagata), Misato and Hanyu (Saitama), Morioka (Iwate), Matsue (Shimane), and Tottori (Tottori). He was awarded B.Sc. from Department of Agronomy and Forestry, Faculty of Agriculture, Iwate University, Morioka in 2001 and M.Sc. from Department of Ecological and Environmental Engineering, Graduate School of Life and Environmental Science, Shimane University, Matsue in 2004. He completes Ph.D. at Department of Bioenvironmental Science, United Graduate School of Agricultural Sciences, Tottori University, Tottori in 2007. During his post-graduate course, to commit some collaborative research projects, he joined several institutes such as International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, Centro Technlogico Agropecuario en Bolivia (CETABOL), Santa Cruz, Bolivia, National Cereals Research Institute (NCRI), Baddegi, Nigeria, International Livestock Research Institute (ILRI) and World Agroforestry Centre (ICRAF), Nairobi, Kenya, Technische Universität München (TUM), Freising-Weihenstephan, Germany and National Institute for Agro-Environmental Sciences (NIAES), Tsukuba, Japan.

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CHAPTER 1

Soil Fertility and Rice Production in West Africa in the Face of Food Insecurity and Environmental Degradation: General Introduction

Sub-Saharan Africa is the only remaining region of the world where per capita food production has remained stagnant over the past 40 years (Hirano 2001; Sanchez 2002). Sub-Saharan Africa is also the only region where hunger prevalence is over 30% and the number of malnourished people is still increasing (Sanchez and Swaminathan 2005). In this area absolute poverty, which is characterized by an income of less than US$1 per person per day, is coupled with an increasingly damaged natural resource base (Sanchez 2002). For example, subsistence farmers have removed large amount of nutrients from their soils without sufficient quantities of manure and fertilizer to replenish the soil over decades. This has resulted in a very high average annual depletion rate, i.e. 22 kg of nitrogen, 2.5 kg of phosphorus and 15 kg of potassium per hectare of cultivated land over last 30 years in 37 African countries. This corresponds to an annual loss equivalent to US$4 billion in fertilizer (Sanchez *et al.* 1997).

This dissertation focuses on the West African sub-region where rice is an important staple food. Rice consumption in West Africa has rapidly increased science 1970s, which has been caused by a rapid increase of the per capita consumption (Japan International Cooperation Agency 2003). Any shortage of the domestic supply to meet the increasing demand for rice has been supplemented by imports resulting in a steady increase of imports to a record-breaking 3.4 million tons (milled basis) in 1998. This amount was equivalent to nearby US$1 billion (Japan International Cooperation Agency 2003). One of the most possible reasons creating the problem is the low land productivity of rice. For 20 years from the early 1960s to the early 1980s, the productivity of rice production in West Africa remained virtually unchanged at 1.0-1.2 ton ha^{-1} on a milled rice basis without recording a substantial increase in yield (Wakatsuki 2002; Japan International Cooperation Agency 2003).

This is parallel to the fact that upland rice farming is common under traditional shifting cultivation in West Africa (West Africa Rice Development Association 2004) despite its lower yield and higher susceptibility to land degradation than lowland paddy production (Wakatsuki 2002; Wakatsuki and Masunaga 2005). This is in a strong contrast to rice cultivation in Monsoon Asia where lowland rice farming is predominant and yields are usually higher than 3.0 ton ha^{-1}. On the other hand, West Africa has a relatively long history of lowland rice cultivation. The African rice (*Oryza glaberrima* Steud.) was domesticated in the central Niger delta at least more than two thousand years ago (Carpenter 1978) although over 90% of the rice cultivars have been replaced with the Asian rice (*O. sativa* L.) at the moment (Wakatsuki 2002). Some traditional lowland rice farming systems have been developed in the region, for instance in the Nupeland of central Nigeria (Ishida *et al.* 1998; 2001). The land system of Nupe farmers can be described as rainfed or irrigated quasi-paddy fields (Wakatsuki 2002). It is considered to be a rudimental stage of the *sawah** development, a high-productive and sustainable rice production system in lowlands. However, the *sawah* system, originally developed in Asia, has been neither developed nor introduced, except for the pioneer work of Taiwanese teams (Hsieh 2003), in West Africa whereas many ecological and cultural backgrounds are noticed in the region to accept the *sawah* technology (Wakatsuki 1991; 1994; Wakatsuki and Masunaga 2005). In particular, inland valleys and flood plains are considered to be suitable ecological environments to introduce the *sawah* system (Wakatsuki 2002). Hereby, there is a need to accumulate basic information on inland valleys and flood plains of West Africa in order to examine the adaptability and feasibility of paddy farming system in the region because ecological and economic sustainability of paddy rice system has been well demonstrated in Asia (Kyuma and Wakatsuki 1995) but little in West Africa (Wakatsuki *et al.* 1998; Wakatsuki and Masunaga 2005). From this viewpoint, Issaka *et al.* (1996; 1997) and Buri *et al.* (1999; 2000) investigated physicochemical

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[*] The term refers to a leveled and bounded rice field with an inlet and outlet for the irrigation and drainage.

properties of soils of inland valleys and flood plains in West Africa and highlighted their very low fertility status as compared to paddy soils in tropical Asia (Kawaguchi and Kyuma 1986). Most soils in West Africa derive from Pre-Cambrian Basement Complex (igneous and metamorphic rocks) and showed very poor fertility characteristics at advanced weathering stages (Moormann and Veldcamp 1978; Udo 1978; Windmeijer and Andriesse 1993). These low fertility soils are assumed to occupy also vast areas of other Sub-Saharan regions (Eswaran *et al.* 1997). As compared to physicochemical properties and thus fertility characteristics of the soils, mineralogy of these soils, however, have been far less documented despite its importance for better understanding of the soil genesis, general properties as well as agricultural potential.

The objective of the present thesis is to assess soil characteristics to explore the soil-forming processes and agricultural potential of lowlands (inland valleys and flood plains) in West Africa in relation to the rice production. In this context, a general introduction and necessary background have been provided in this chapter to help understanding the objective of this dissertation. The second step will be made to discuss mineralogical properties of lowland soils in the region providing a couple of chapters, i.e. clay mineral composition and primary mineral characteristics in Chapter 2 and 3, respectively. These chapters will be able to reinforce the findings of Issaka *et al.* (1996; 1997) and Buri *et al.* (1999; 2000). Based on the results of these two chapters, further soil assessment was carried out intensively in two inland valleys from Southeast Nigeria to delve into the research topics. Physicochemical properties and morphological features (Chapter 4), as well as clay mineralogy and parent material nature (Chapter 5) of the soils in these two sites will be discussed in relation to soil-forming processes and agricultural potential. In Chapter 6, all findings obtained in this study will be summarized. I will also provide Japanese summary of this thesis in the final chapter (Chapter 7).

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CHAPTER 2

Clay Mineral Composition of Lowland Soils in West Africa

2.1. Introduction

Inland valleys, the upper reaches of river systems, display a widespread topography within West Africa. Inland valleys offer a major potential for intensified and sustainable land use (Andriesse and Fresco 1991; Andriesse *et al.* 1994; International Institute of Tropical Agriculture 1990; West Africa Rice Development Association 1997), especially for small-scale irrigated rice cultivation in the valley bottoms (Association of International Cooperation of Agriculture and Forestry (AICAF) 2003; Japan International Cooperation Agency 2003; Wakatsuki *et al.* 1998), because of higher water availability and soil fertility compared with adjacent uplands (Inland Valley Consortium 1997; Windmeijer and Andriesse 1993). Regardless of their potential, less than 15% of the total area of inland valleys is being cultivated because of a lack of appropriate land management techniques (International Institute of Tropical Agriculture 1990; Inland Valley Consortium 1997; West Africa Rice Development Association 1997). In addition to inland valleys, flood plains display another typical geographical configuration suitable for rice cultivation in West Africa. In general, flood plain soils are more fertile than inland valley soils (Buri *et al.* 1999; 2000; Issaka *et al.* 1996; 1997) and flood plains are considered to be relatively more suitable for medium- to large-scale irrigated rice cultivation with higher investments (Wakatsuki 1998). The total area occupied by inland valleys and flood plains in West Africa is estimated to be 22–52 and 12–25 million hectares, respectively (Windmeijer and Andriesse 1993). Out of this area, 9 million hectares each of inland valleys and flood plains are considered to have potential for irrigated rice cultivation (Wakatsuki 2002). Sawah-based irrigated rice farming in the lowlands can contribute to overcoming food insecurity and to restoring the degraded watersheds in West Africa (Wakatsuki *et al.* 1998; Wakatsuki and Masunaga 2005).

In general, the fertility status of the West African lowland soils is significantly low (Kyuma *et al.* 1986; Windmeijer and Andriesse 1993). Comprehensive investigations of the soil characteristics of inland valleys and flood plains conducted by Issaka *et al.* (1996, 1997) and Buri *et al.* (1999, 2000) revealed lower soil fertility than that of paddy soils in tropical Asia and Japan (Kawaguchi and Kyuma 1977). As described in Moormann and Veldkamp (1978) and Kang *et al.* (1991), it is generally recognized that poor mineralogical characteristics, dominated by 1:1 type silicate minerals and Fe and Al oxides with variable charge, are probably responsible for the low or very low fertility status of the soils of tropical Africa. This has been corroborated by many studies of upland soils. However, there are few scientific reports examining the lowlands and they are not well documented. Issaka *et al.* (1997) and Buri *et al.* (1999) assumed a predominance of highly weathered low-activity clays in inland valley and flood plain soils based on low values of clay activity indices (i.e. effective cation exchange capacity (ECEC)/clay, $\text{cmol}_c\ \text{kg}^{-1}$). The clay activity indices of the inland valley and flood plain soils were 29.2 and 23.9 $\text{cmol}_c\ \text{kg}^{-1}$, respectively, and were considerably lower than those recorded in paddy soils in tropical Asia, 46.4 $\text{cmol}_c\ \text{kg}^{-1}$, and in Japan, 60.8 $\text{cmol}_c\ \text{kg}^{-1}$. In West Africa, the soil constituents are derived from very old geological materials and may consist of low-activity clays at an advanced weathering stage (Kosaki 2002).

Determination of the soil mineralogical characteristics is essential to gain information about basic soil properties for suitable land management. To date, little attention has been paid to the mineralogical characteristics of West African lowland soils. Therefore, the objective of the present study was to determine comprehensively the clay mineralogical composition of lowland (inland valley and flood plain) soils of West Africa.

2.2. Materials and Methods

Study area

Based on the plant growth period and precipitation, the study region was divided into four main agro-ecological zones: equatorial forest (EF), Guinea savanna (GuS), Sudan savanna (SuS) and Sahel savanna (SaS) (Fig. 1) (Windmeijer and Andriesse 1993). In general, the vegetation and soils were distributed according to the climatic conditions and the latter also reflected the parent materials, relief and plants and animals. The Pre- Cambrian Basement Complex rocks cover a wide area over this region and consist of igneous rocks such as granite and basalt as well as metamorphic rocks like quartzite, schist and slates. In the Chad Basin, Benin lowlands and western Senegal, where wide stretches of sedimentary rocks occur, the Basement Complex has merely been covered by these relatively younger rocks at varying depths (Udo 1978). In contrast, the addition of seasonal aeolian dust from the Sahara desert and relatively new volcanic materials from Mt Cameroon, the only active volcano in this region, may possibly have affected the soil formation process in the Sahel region and eastern part of West Africa, respectively (Delvaux *et al.* 1989; Mizota *et al.* 1996).

Field sampling

Major agro-ecological zones and sampling sites are illustrated in Fig. 1. The 87 topsoil samples were selected from the same soil samples as those used by Issaka *et al.* (1996; 1997) and Buri *et al.* (1999; 2000). These samples were collected from 47 locations of inland valleys and 40 locations of flood plains across the four agro-ecological zones within seven West African countries, Cote d'Ivoire, Ghana, Guinea, Mali, Nigeria, Niger and Sierra Leone from 1983 to 1989. The soil samples were air-dried, gently ground and passed through a 2-mm mesh sieve prior to analysis. The physicochemical properties of these soil samples were reported by Issaka *et al.* (1996; 1997) and Buri *et al.* (1999; 2000).

X-ray diffraction analysis

The clay (<2 µm) fraction was separated by gravity sedimentation and siphoning

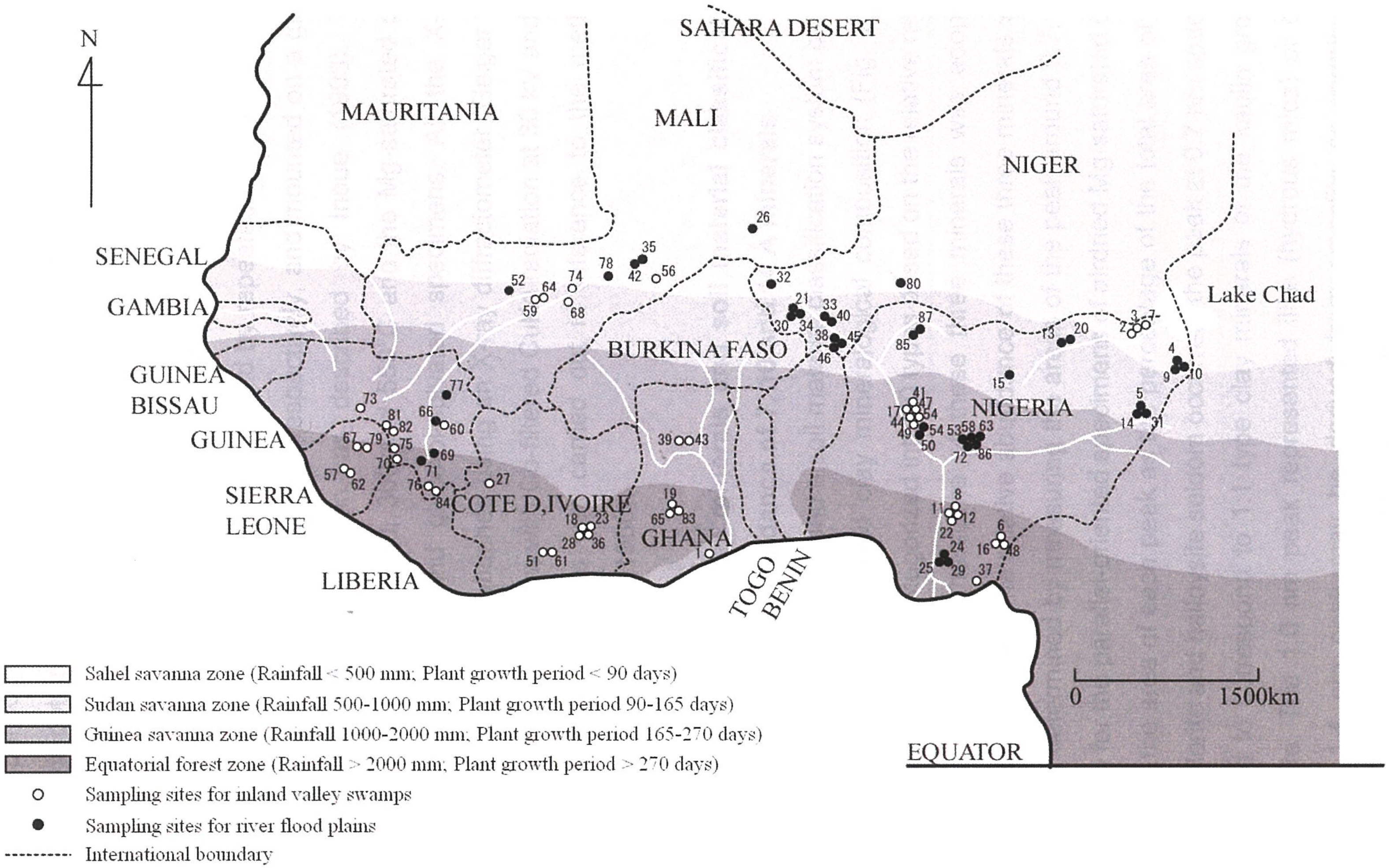

Figure 1 Selected soil sampling sites and major agro-ecological zones in West Africa.

after ultrasonic dispersion (35 kHz, 200 W, 15 min) at pH 10. To remove the organic matter, the fractions obtained were treated with 10% hydrogen peroxide (w/w) on a hot plate. No iron removal treatment was carried out because the amounts of iron soluble in the dithionite–citrate–bicarbonate and acid oxalate solution were generally low in these samples (Buri 1999; Issaka 1997). Clays saturated in potassium (K) and magnesium (Mg) were prepared by repeated treatment with 1.0 mol L^{-1} KCl and 0.5 mol L^{-1} $MgCl_2$ solution, respectively, and mounted on a glass plate as a parallel-oriented specimen, as described by Inoue (1993). The K-saturated clay was analyzed at 20, 300 and 550°C and the Mg-saturated clay was analyzed using air-dried and glycerol-solvated specimens. All the X-ray diffraction (XRD) patterns were obtained using an X-ray diffractometer (Geiger flex of Rigaku Company, Tokyo, Japan) with Co-filtered CuKα radiation at 30 kV and 20 mA. Identification of the minerals was carried out in reference to the method described by Brown and Brindley (1980).

Semi-quantitative analysis of clay minerals and soil material classification system based on the relative abundance of 7, 10 and 14 Å minerals

Kawaguchi and Kyuma (1974) proposed a soil material classification system based on a triangular diagram for simplified clay mineralogical composition (Fig. 2) in which the soils materials were categorized into 10 types based on the relative ratios of 7, 10 and 14 Å minerals (the name of these three minerals was adopted conventionally in the system). The relative abundance of these three minerals was semi-quantitatively determined by measuring the areas of the peak around 0.7, 1.0 and 1.4 (to 1.5) nm for the parallel-oriented specimens of airdried Mg-saturated clay and by calculating the area of each peak as the percentage of the total area of the three peaks. As chlorite and halloysite seldom occurred, the peak at 0.7 nm spacing can be considered to correspond to 1:1 type clay minerals of the kaolin group, particularly kaolinite. The 1.0 nm peak represented illite (hydrous mica) or clay micas, while the 1.4 nm peak may be derived from smectite or vermiculite (Kawaguchi and Kyuma 1977). This method could be appropriate for evaluating soil

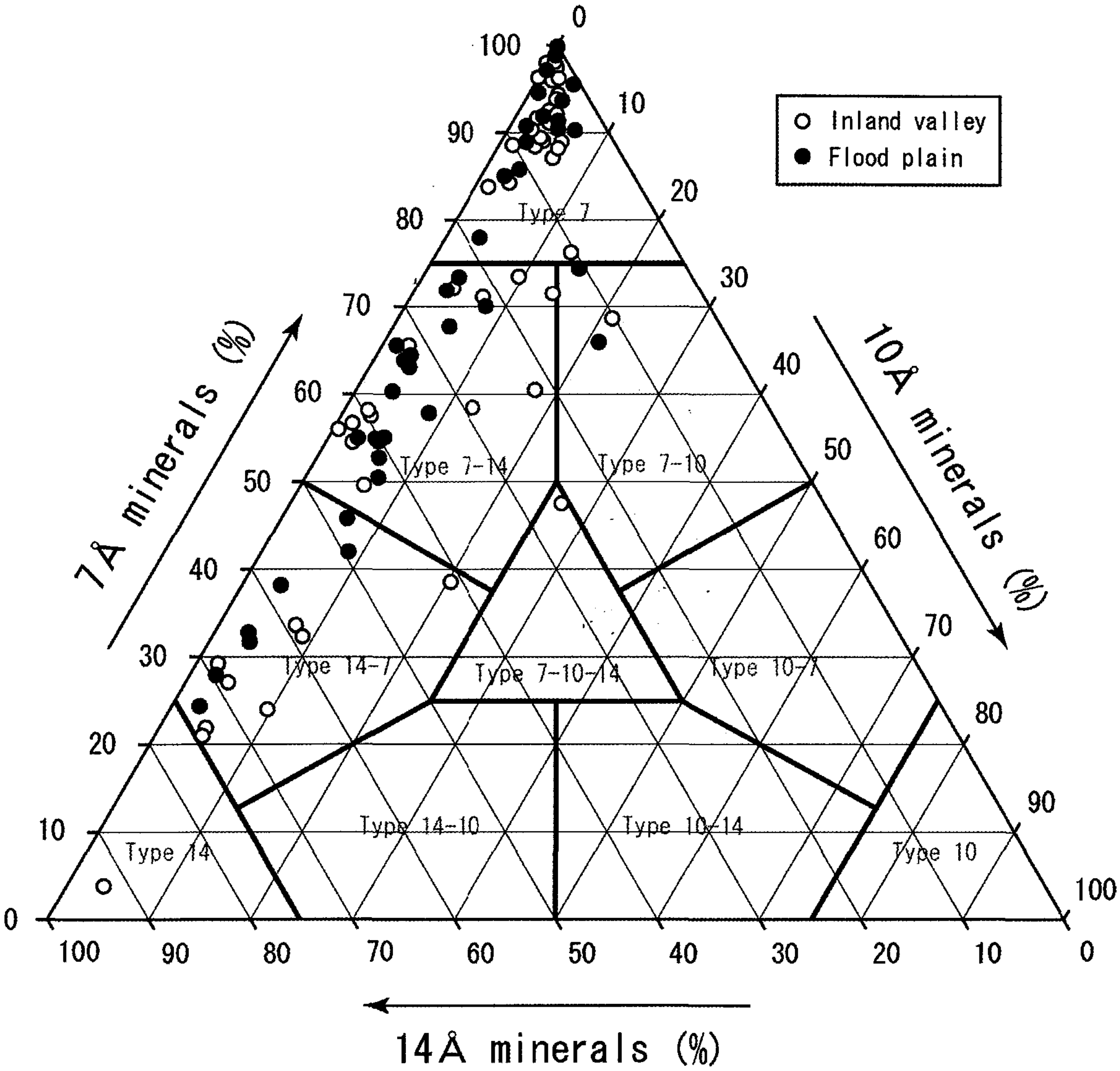

Figure 2 Triangular diagram for clay mineral classification using the relative abundance of 7, 10 and 14 Å minerals. The classification system was originally proposed by Kawaguchi and Kyuma (1974).

mineralogical characteristics over wide study areas.

2.3. Results and Discussion

Relative abundance of 7, 10 and 14 A minerals and soil classification

The clay mineralogical composition of the samples analyzed was plotted in a triangular diagram based on the relative abundance of 7, 10 and 14 Å minerals in the XRD pattern of air-dried Mg-clay (Fig. 2). The 7 Å minerals predominated and the contents of the 14 Å minerals were usually low in these soils. Approximately 90% of the samples contained less than 10% of 10 Å minerals in relation to the total content of crystalline minerals.

The mean abundance of the three minerals in the West African lowland soils is presented in Table 1 according to the topography and agro-ecological zones and was compared with the abundance in paddy soils in tropical Asia (Kawaguchi and Kyuma 1977). The mean ratios of 7, 10 and 14 Å minerals in the soils of West Africa were 68.4%, 5.1% and 26.6%, respectively, with a high variability in the abundance of minerals. It was suggested that these samples comprised mainly low-activity clays, such as 1:1 type kaolin minerals, and contained a small amount of hydrous mica clay (i.e. illite) and relatively high-activity 2:1 type clays such as smectite and vermiculite. Compared with the paddy soils of tropical Asia, the West African lowland soils contained more 7 Å minerals and less 10 Å and 14 Å minerals. The content of the 7 Å minerals was higher in the EF and GuS zones than in the drier zones (i.e. SuS and SaS zones). In contrast, the content of the 14 Å minerals was highest in the SuS and SaS zones and lower in the humid EF and GuS zones. This possibly resulted in the formation of more fertile soils in drier zones than in humid zones, as reported by Issaka *et al.* (1997) and Buri *et al.* (2000). In particular, the flood plain soils in the GuS zone were distinctively rich in 7 Å minerals and poor in 14 Å minerals. The inland valley soils in the GuS zone also showed a lower content of 14 Å minerals than those in the other climatic zones. These findings

Table 1. Mean abundance of 7, 10 and 14 Å minerals of lowland topsoils (0-15 cm) in West Africa compared with the abundance in paddy soils in tropical Asia.

Region	7-Å minerals (%)		10-Å minerals (%)		14-Å minerals (%)	
	Mean	S.D.[a]	Mean	S.D.	Mean	S.D.
Lowland soils in West Africa (n=87)	**68.4**	**23.8**	**5.1**	**5.1**	**26.6**	**23.1**
Inland valleys (n=47)	*68.2*	*25.8*	*5.6*	*6.0*	*26.2*	*24.8*
Equatorial forest zone (n=26)	69.6	24.5	3.9	4.5	26.6	22.6
Guinea savanna zone (n=13)	69.3	25.3	8.5	7.6	22.2	24.3
Sudan and Sahel savanna zones (n=8)	62.2	32.9	6.4	5.9	31.5	33.8
Flood plains (n=40)	*68.5*	*21.6*	*4.5*	*3.8*	*27.0*	*21.2*
Equatorial forest zone (n=5)	68.9	20.1	5.0	0.9	26.1	19.3
Guinea savanna zone (n=9)	86.4	9.8	6.5	6.8	7.1	4.0
Sudan and Sahel savanna zones (n=26)	62.2	21.9	3.8	2.5	34.0	21.1
Paddy soils in tropical Asia (n=410)[b]	**46.4**	**23.3**	**13.9**	**14.4**	**39.7**	**23.8**

[a] Standard deviation

[b] Kawaguchi and Kyuma (1977)

corresponded to the lowest base status of the soils in the GuS zone (Buri *et al.* 2000; Issaka *et al.* 1997). In contrast, 10 Å minerals were relatively abundant in the GuS zone, which may reflect the unique characteristic of aeolian dust deposits in the GuS zone. According to Issaka *et al.* (1997) and Buri *et al.* (2000), the value of exchangeable K was the lowest in the EF zone and tended to rise toward a drier zone. Despite the higher content of 10 Å minerals, as revealed in the present study, inland valley soils in the GuS showed a very low content of exchangeable K. In contrast, soils in the SuS and SaS zones exhibited a higher content of exchangeable K. Thus, the value of exchangeable K appears to be less related to the amount of 10 Å minerals.

No significant differences were observed in the clay mineralogical composition between the inland valley and flood plain soils (Table 1). This result is in agreement with the findings of Buri *et al.* (1999), who expected that the mineralogical characteristics of the inland valley and flood plain soils would be similar because of the similarity in the value of ECEC/clay in both inland valley and flood plain soils, although the flood plain soils were more fertile than the inland valley ones. Thus, the lower clay content, rather than the clay mineralogy, may be responsible for the lower fertility of the inland valley soils compared with the flood plain soils. The mean clay content of the topsoil of the flood plains, which was 431 g kg^{-1}, was almost threefold higher than that of the inland valley topsoils (145 g kg^{-1}), as reported by Buri *et al.* (1999).

Table 2 shows the distribution of the soil clay mineral types in the inland valley and flood plain soils and among the agroecological zones according to the soil classification system of Kawaguchi and Kyuma (1974). Type 7 accounted for approximately 42.5%, while Types 7-14 and 7-10 accounted for 34.5% and 3.4% of the whole samples in West Africa, respectively, indicating that more than 80% of the total samples were classified into clay mineral types rich in the 7 Å minerals (i.e. Types 7, 7-14 and 7-10). This is similar to the results obtained by Kosaki (2002).

Table 2. Distribution of soil clay mineral types in West African lowlands compared with the distribution in paddy soils in tropical Asia

Region	Clay mineral types[a] (%)									
	7	7-14	14-7	7-10	7-10-14	14	10	10-7	10-14	14-10
Lowland soils in West Africa (n=87)	**42.5**	**34.5**	**17.2**	**3.4**	**1.1**	**1.1**	**0.0**	**0.0**	**0.0**	**0.0**
Inland valleys (n=47)	*46.8*	*29.8*	*17.0*	*2.1*	*2.1*	*2.1*	*0.0*	*0.0*	*0.0*	*0.0*
Equatorial forest zone (n=26)	50.0	30.8	19.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guinea savanna zone (n=13)	38.5	46.2	0.0	0.0	7.7	7.7	0.0	0.0	0.0	0.0
Sudan and Sahel savanna zones (n=8)	50.0	0.0	37.5	12.5	0.0	0.0	0.0	0.0	0.0	0.0
Flood plains (n=40)	*37.5*	*40.0*	*17.5*	*5.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Equatorial forest zone (n=5)	40.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guinea savanna zone (n=9)	77.8	0.0	0.0	22.2	0.0	0.0	0.0	0.0	0.0	0.0
Sudan and Sahel savanna zones (n=26)	23.1	50.0	26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Paddy soils in tropical Asia (n=410)[b]	**14.8**	**22.0**	**22.9**	**9.1**	**10.9**	**10.5**	**0.0**	**2.8**	**0.8**	**5.2**

[a] See Fig. 2

[b] Kawaguchi and Kyuma (1977)

Thus, we conclude that soils rich in 1:1 type clay minerals covered wide areas of the lowlands in West Africa. In contrast, Type 14-7 soils accounted for 17.2% and only occurred in Nigeria. Type 14 with a predominance of 14 Å minerals was identified only in a vertic soil in southeastern Ghana. The site numbers 1, 2, 3, 4, 7, 9 and 10 in Fig. 1, which were collected from Vertisols or vertic soils, predominantly contained 14 Å minerals and were classified into Type 14 or Type 14-7. An equal amount of 7, 10 and 14 Å minerals was observed in the samples at site number 39, Nyanpkara in the northern part of Ghana. Hence, the clay mineral type of these samples belonged to Type 7-10-14 in Table 3. Types 7-10 and 7-10-14, which showed a relatively high content of 10 Å minerals, accounted for only 4.5% of the total samples because of the limited occurrence of 10 Å minerals. The other clay mineral types (i.e. Types 10, 10-7, 10-14 and 14-10) were not identified at all in the present study. There was a predominance of Type 7 and Type 7-14, while other clay mineral types were less predominant in the lowland soils of West Africa compared with the paddy soils of tropical Asia (Kawaguchi and Kyuma 1977). With respect to the agro-ecological zones, clay mineral types (i.e. Type 7, Type 7-14 and Type 7-10) rich in 7 Å minerals tended to be more abundant in the EF and GuS zones than in the SuS and SaS zones, which may reflect a severe weathering process under high rainfall. In contrast, Type 14-7 predominated in the drier zones, namely SuS and SaS.

The geographical distribution of the clay mineral types within West Africa is illustrated in Fig. 3. Soils rich in 14 Å and/or 10 Å minerals were mainly distributed in the eastern part of West Africa. All the samples from Guinea and Sierra Leone and some of the samples from the western region of Mali were classified into Type 7. This trend could be attributed to topographical and agroecological factors. The highest rainfall and strongest weathering occurred in Guinea and Sierra Leone (Windmeijer and Andriesse 1993). These weathered soil materials were deposited in the inland deltas of Mali. However, the clay mineral types containing 14 Å minerals were scattered in high rainfall areas in the equatorial zones of Cote

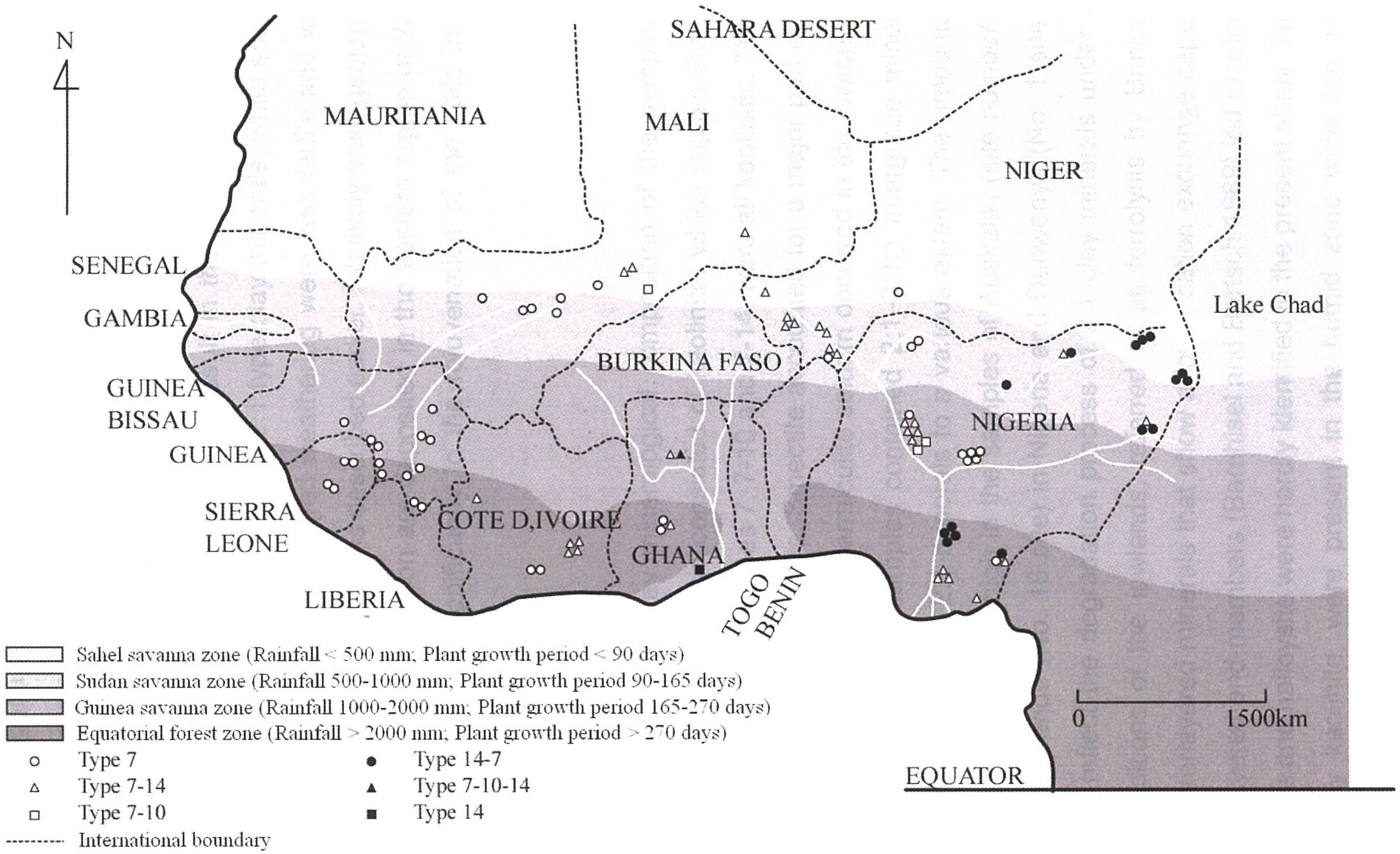

Figure 3 Geographical distribution of soil clay mineral types in the lowlands of West Africa.

d'Ivoire, Ghana and Nigeria as well as in the SuS and SaS zones of Mali, Niger and Nigeria. Thus, the mineralogical characteristics of the lowland soils of West Africa reflected the nature of the parent materials and were also affected by the climatic conditions and relief. The geological formation of recent alluvial deposits, and the rejuvenation and presence of basic rocks may result in the genesis of relatively fertile soils, characterized by the presence of 2:1 type clay minerals, while soils of very old geological origin under prolonged weathering were less fertile and were dominated by 1:1 type clay minerals. As described earlier, relatively fresh geological materials derived from Mt Cameroon are deposited in the eastern region of West Africa, which may contribute significantly to the rejuvenation of the soils in the region (Delvaux *et al.* 1989).

Clay mineralogical composition

Further information about the clay mineralogical composition of the samples is given in Table 3. Most 7 Å minerals consisted of kaolinite, which implies that the soils rich in 7 Å minerals, namely Types 7, 7-10 and 7-14, were all kaolinitic. The 10 Å minerals originated mostly from illite. Smectite accounted for a major part of the 14 Å minerals in most samples and vermiculite seldom occurred in the lowlands of West Africa. In contrast, some samples contained 2:1–2:1:1 intergrade minerals such as hydroxy-Al interlayered 2:1 minerals to a various extent. The amounts of these minerals were remarkably high in the samples of Abakaliki (site numbers 8, 11, 12 and 22) and Bende (No. 16 site) in Nigeria and Dahwenya (No. 1 site) in Ghana. This may reflect the degradation process of 2:1 clay minerals under the hydromorphic conditions of the lowlands, referred to as ferrolysis by Brinkman (1970). Hydroxy-interlayered minerals that show a lower cation exchange capacity than the noninterlayered end-members (Barnhisel and Bertsch 1989) led to a lower soil fertility. Chlorite and halloysite were hardly identified in the present study. The 7 Å minerals, mostly kaolinite, were present in the humid zone while the 14 Å minerals, mainly smectite, were found in drier zones, except in the region with deposits of volcanic materials in West Africa. These results were in agreement with

Table 3 Clay mineralogical composition of lowland topsoils (0-15 cm) in West Africa.

Site No.	Site location	Country	Topo-graphy [a]	Agro-eco zone [b]	Clay type	Clay mineralogical composition [c, d]									
						Sm	Vt	HIC	It	Kt	Qz	Fds	Gb	Go	Others
1	Dahwenya	Ghana	IVs	GuS	14	++++	+	+++	-	+	+	-	-	-	-
2	Mongonu-1	Nigeria	IVs	SaS	14-7	++++	tr	+	+	++	+	tr	-	-	-
3	Mongonu-2	Nigeria	IVs	SaS	14-7	++++	-	tr	+	++	+	tr	-	-	-
4	Lumda-1	Nigeria	FPs	SaS	14-7	+++	tr	++	+	++	+	tr	-	-	-
5	Dwam/Yola-2	Nigeria	FPs	SuS	14-7	+++	tr	-	+	++	+	tr	-	-	-
6	Bende-2	Nigeria	IVs	EF	14-7	++++	tr	tr	-	+++	+	-	-	-	-
7	Mongonu-3	Nigeria	IVs	SaS	14-7	++++	-	-	+	++	+	tr	-	-	-
8	Abakaliki-5	Nigeria	IVs	EF	14-7	tr	-	+++	tr	++	++	-	tr	+	-
9	Lumda-2	Nigeria	FPs	SaS	14-7	++++	+	tr	+	+++	+	+	-	-	-
10	Lumda-3	Nigeria	FPs	SaS	14-7	++++	-	tr	+	+++	+	tr	-	-	-
11	Abakaliki-3	Nigeria	IVs	EF	14-7	tr	-	+++	tr	+++	++	-	-	-	-
12	Abakaliki-2	Nigeria	IVs	EF	14-7	++	-	++	+	+++	++	-	-	+	-
13	Gashua-1	Nigeria	FPs	SuS	14-7	++++	tr	-	+	+++	+	-	-	-	-
14	Dwam/Yola-1	Nigeria	FPs	SuS	14-7	+++	tr	-	+	+++	++	tr	-	-	-
15	Kadawa	Nigeria	FPs	SuS	14-7	+++	tr	-	tr	+++	+	tr	-	-	-
16	Bende-3	Nigeria	IVs	EF	7-14	+	-	+++	-	++++	+	-	-	-	-
17	Gadza/Bida-3	Nigeria	IVs	GuS	7-14	+++	-	-	+	+++	++	-	-	-	-
18	WARDA-4	Côte d'Ivoire	IVs	EF	7-14	+++	-	+	-	++++	-	-	-	-	-
19	Dwinyama-1	Ghana	IVs	EF	7-14	+++	tr	tr	-	++++	+	-	-	-	-
20	Gashua-2	Nigeria	FPs	SuS	7-14	+++	-	-	+	+++	+	-	-	-	-
21	Koutoukale-3	Niger	FPs	SuS	7-14	+++	+	-	+	++++	+	-	-	-	-
22	Abakaliki-1	Nigeria	IVs	EF	14-7	+++	-	++	++	+++	++	-	+	+	-
23	WARDA-3	Côte d'Ivoire	IVs	EF	7-14	+++	-	-	tr	++++	+	tr	-	-	-
24	Atani-1	Nigeria	FPs	EF	7-14	+++	tr	+	+	+++	+	tr	tr	-	-
25	Atani-2	Nigeria	FPs	EF	7-14	+++	-	-	+	++++	+	tr	tr	-	-
26	Gao	Mali	FPs	SaS	7-14	++	+	-	+	++++	++	-	-	-	-
27	WARDA-2	Côte d'Ivoire	IVs	EF	7-14	+++	-	tr	tr	++++	+	tr	tr	-	-
28	Touba	Côte d'Ivoire	IVs	EF	7-14	+++	-	-	tr	++++	+	-	-	-	-
29	Atani-4	Nigeria	FPs	EF	7-14	+++	-	+	+	++++	+	-	tr	-	-
30	Koutoukale-2	Niger	FPs	SuS	7-14	+++	-	-	tr	++++	+	-	-	-	-
31	Dwam/Yola-3	Nigeria	FPs	SuS	7-14	++	-	-	-	++++	+	-	-	-	Ch tr
32	Ayorou	Niger	FPs	SaS	7-14	+++	+	-	+	++++	+	-	-	-	-
33	Koutoukale-1	Niger	FPs	SuS	7-14	+++	-	-	+	++++	tr	-	-	-	-
34	Seberi-1	Niger	FPs	SuS	7-14	+++	-	-	tr	++++	tr	-	-	-	-
35	Korienza-2	Mali	FPs	SaS	7-14	++	-	tr	+	++++	+	-	-	-	-
36	WARDA-1	Côte d'Ivoire	IVs	EF	7-14	+++	-	-	-	++++	+	-	-	-	-
37	Oronaja	Nigeria	IVs	EF	7-14	++	-	-	+	++++	+	+	-	-	-
38	Sakawa-1	Niger	FPs	SuS	7-14	++	tr	-	+	++++	+	-	-	-	-
39	Nyanpkala-1	Ghana	IVs	GuS	7-10-1	++	tr	-	++	+++	+++	-	-	tr	-
40	Seberi-2	Niger	FPs	SuS	7-14	++	-	-	tr	++++	+	-	-	-	-
41	Gadza/Bida-5	Nigeria	IVs	GuS	7-14	++	+	+	+	++++	++	-	-	+	-
42	Korienza-1	Mali	FPs	SaS	7-14	++	-	-	+	++++	+	-	-	-	-
43	Nyanpkala-2	Ghana	IVs	GuS	7-14	++	-	-	++	++++	+++	-	-	-	-
44	Gadza/Bida-1	Nigeria	IVs	GuS	7-14	++	tr	tr	+	++++	+	-	-	-	Hm tr
45	Sakawa-2	Niger	FPs	SuS	7-14	++	-	-	+	++++	+	-	-	-	-
46	Sakawa-3	Niger	FPs	SuS	7	++	-	-	+	++++	+	-	-	-	-
47	Gadza/Bida-4	Nigeria	IVs	GuS	7-14	++	-	+	+	++++	+	-	-	-	-
48	Bende-5	Nigeria	IVs	EF	7	+	-	+	tr	++++	+	-	-	tr	-
49	Gadza/Bida-6	Nigeria	IVs	GuS	7-14	++	-	-	+	++++	++	-	-	-	-
50	Nupeko/Bida-4	Nigeria	FPs	GuS	7-10	+	-	-	++	++++	+++	tr	tr	tr	-

Table 3 Continued.

Site No.	Site location	Country	Topography [a]	Agro-eco zone [b]	Clay type	Clay mineralogical composition [c, d]									
						Sm	Vt	HIC	It	Kt	Qz	Fds	Gb	Go	Others
51	Daloa-1	Côte d'Ivoire	IVs	EF	7	+	-	-	tr	++++	+	+	-	-	-
52	Niono	Mali	FPs	SuS	7	+	-	-	tr	++++	+	-	-	+	-
53	Makurdi-3	Nigeria	FPs	GuS	7	+	-	-	tr	++++	+	tr	-	-	-
54	Nupeko/Bida-1	Nigeria	FPs	GuS	7-10	+	-	-	++	++++	++	-	-	-	-
55	Gadza/Bida-2	Nigeria	IVs	GuS	7	+	-	-	+	+++	+++	+	-	+++	-
56	Dogon	Mali	IVs	SaS	7-10	+	-	-	++	++++	++	-	-	tr	-
57	Sawulia-1	Sierra Leone	IVs	EF	7	tr	tr	-	tr	++++	+	-	++	-	-
58	Massina-2	Mali	IVs	SuS	7	+	-	-	+	++++	+	-	-	-	-
59	Makurdi-1	Nigeria	FPs	GuS	7	+	-	-	+	++++	++	+	-	-	-
60	Baro-2	Guinea	IVs	GuS	7	tr	tr	-	+	++++	+	-	tr	-	-
61	Daloa-2	Côte d'Ivoire	IVs	EF	7	+	-	-	tr	++++	+	tr	-	-	-
62	Sawulia-2	Sierra Leone	IVs	EF	7	-	-	+	+	++++	+	-	+	-	-
63	Massina-1	Mali	IVs	SuS	7	-	-	+	+	++++	+	-	tr	+	-
64	Makurdi-2	Nigeria	FPs	GuS	7	+	-	-	+	++++	++	+	-	-	-
65	Dwinyama-3	Ghana	IVs	EF	7	+	-	-	+	++++	+	-	-	-	-
66	Baro-1	Guinea	FPs	GuS	7	tr	-	+	tr	++++	+	+	tr	-	-
67	Falaba-1	Sierra Leone	IVs	EF	7	-	-	+	tr	++++	+	-	+	+	-
68	San	Mali	IVs	SuS	7	tr	-	-	+	++++	+	-	-	-	-
69	Kankan	Guinea	FPs	EF	7	-	-	+	tr	++++	+	-	+	-	-
70	Niandan river	Guinea	FPs	EF	7	-	-	+	tr	++++	+	tr	tr	-	-
71	Gueckedou	Guinea	IVs	EF	7	tr	-	-	tr	++++	+	tr	++	-	-
72	Makurdi-4	Nigeria	FPs	GuS	7	tr	-	-	tr	++++	+	tr	-	-	-
73	Mamou	Guinea	IVs	GuS	7	-	-	+	+	++++	+	+	+	+	-
74	Djenne	Mali	IVs	SuS	7	tr	-	-	+	++++	+	-	-	-	-
75	Kissidougou	Guinea	IVs	EF	7	tr	-	-	+	++++	++	tr	-	-	-
76	Nzerekore-1	Guinea	IVs	EF	7	-	-	tr	-	++++	+	-	tr	tr	-
77	Siguire	Guinea	FPs	GuS	7	tr	-	-	+	++++	+	-	+	-	-
78	Mopti	Mali	FPs	SaS	7	tr	-	-	+	++++	+	-	-	-	-
79	Falaba-2	Sierra Leone	IVs	EF	7	tr	-	-	tr	++++	tr	-	+	-	-
80	Birinin Koni	Niger	FPs	SaS	7	tr	-	-	tr	++++	+	-	-	tr	-
81	Heremakono-1	Guinea	IVs	GuS	7	-	-	tr	-	++++	+	-	+	-	-
82	Heremakono-2	Guinea	IVs	GuS	7	tr	-	-	tr	++++	+	-	tr	-	-
83	Dwinyama-2	Ghana	IVs	EF	7	-	-	tr	tr	++++	+	+	+	-	-
84	Nzerekore-2	Guinea	IVs	EF	7	-	-	tr	-	++++	+	-	+	-	-
85	Argungu-1	Nigeria	FPs	SuS	7	-	-	-	-	++++	++	-	-	tr	-
86	Makurdi-5	Nigeria	FPs	GuS	7	-	-	-	+	++++	+++	tr	-	tr	-
87	Argungu-2	Nigeria	FPs	SuS	7	-	-	-	-	++++	tr	-	-	-	-

[a] IVs, inland valleys; FPs, flood plains

[b] EF, equatorial forest zone; GuS, Guinea savanna zone; SuS, Sudan savanna zone; SaS, Sahel savanna zone

[c] See Fig. 2

[d] Abbreviations: Ch, chlorite; Fds, feldspars; Gb, gibbsite; Go, goethite; HIC, hydroxy-interlayered clays; Hm, hematite; It, illite; Kt, kaolinite; Qz, quartz; Sm, smectite; Vt, vermiculite

-, none; tr, trace; +, scarce (<10.0%); ++, common (10.0-25.0%); +++, abundant (25.0-50.0%); ++++, predominant (> 50.0%)

the findings of Kang *et al.* (1991) and Windmeijer and Andriesse (1993), who suggested that the granitic Basement Complex of the humid zones of West Africa was dominated by low-activity 1:1 type clay minerals, whereas the metamorphic Basement Complex of the drier northern zone mainly consisted of relatively highactivity 2:1 type clay minerals.

In addition, most samples contained small to large amounts of quartz in the clay fraction. A negligible amount of feldspars was also found in some samples. It has been reported that fine-sized primary minerals can usually be identified in the clay fraction of various soils (Drees *et al.* 1989; Huang 1989). Iron and aluminum minerals, such as goethite and gibbsite, respectively, were observed in small amounts in some samples. The sample at site number 55 (Gadza/Bida in Nigeria) showed an exceptionally high content of goethite, while site numbers 57 (Sawulia in Sierra Leone) and 71 (Gueckedou in Guinea) contained a relatively large amount of gibbsite. These three sites were located in the fringes of IVs and the soils were probably formed under more aerobic conditions than the other sites. Gibbsite particularly was found in the samples from Guinea and Sierra Leone where precipitation is the highest (Windmeijer and Andriesse 1993), resulting in a severe weathering process. There was more gibbsite than goethite because Fe tends to occur in a reduced form under seasonally developing reduced conditions and can rapidly be lost through leaching (Hsu 1989). Prolonged and intensive weathering led to the formation of low-activity clays with free Fe and Al oxides in some parts of West Africa (Juo *et al.* 1973; Okusami *et al.* 1986), although the contents of such oxides in these samples were generally low (Buri 1999; Issaka 1997), presumably because of the hydromorphic conditions prevailing in the lowlands.

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CHAPTER 3

Primary Mineral Characteristics of Lowland Soils in West Africa

3.1. Introduction

In Chapter 2, the clay mineral composition of 87 topsoil (0-15 cm) samples from lowlands in West Africa was examined by X-ray diffraction (XRD) analysis, which was characterized by a predominance of kaolinite and a small amount of 2:1 type phyllosilicate minerals such as smectite and illite. These findings confirmed the low fertility status of lowland soils in the region, as reported by Issaka *et al.* (1996; 1997) and Buri *et al.* (1998; 1999).

Although highly weathered tropical soils generally showg7 a relatively monotonous mineralogy, these soils still reflect the nature of the parent material in general (Schwertmann and Herbillon 1992). In addition, lowland soils are largely underdeveloped in terms of pedogenesis and thus parent materials are particularly important to evaluate the soil fertility (Kyuma *et al.* 1986). Until today, only few attempts have been made to assess the primary mineral properties of lowland soils in West Africa.

The present study describes the primary mineral characteristics of topsoil samples collected from 87 locations in inland valleys and flood plains in seven West African countries (Côte d'Ivoire, Ghana, Guinea, Mali, Nigeria, Niger and Sierra Leone) using XRD analysis and petrographic measurement.

3.2. Materials and Methods

Brief description of the sampling sites and soils used for this study is shown in Table 1. The physicochemical properties of the samples are reported by Issaka *et al.* (1996; 1997) and Buri *et al.* (1998; 1999), while the clay mineral composition is described in Chapter 2.

The fine-sand fraction (20-212 μm) was obtained using sedimentation and sieving. Organic matter was digested with 10% (w/w) hydrogen peroxide on a hot plate. No iron removal treatment was applied as iron contents extracted under the DCB system were generally low in these samples (Issaka 1997; Buri 1999). The fraction obtained was ground and mounted on a non-reflectable silicon plate following the method of Marumo (1993). The operating condition of an X-ray diffractometer (Geiger flex of Rigaku Co., Tokyo) was reported previously (see Chapter 2) except for the used angle range (5-40° 2θ). In addition, petrographic measurement was conducted after the gravity separation of fine-sand using bromoform solution (s.g. 2.89). Mineral grains were identified according to their optical properties (e.g. color, shape, pleochroism, birefringence and extinction).

3.3. Results and Discussion

XRD patterns of the fine-sand fraction from some representative samples are shown in Fig. 1, and primary mineral composition of the samples determined by the XRD analysis has been summarized in Table 1. Quartz was predominant in all the samples as indicated by diffractions at 0.427, 0.334, 0.246 and 0.228 nm (Fig. 1). The XRD analysis differentiated two types of feldspars, i.e. potassium-feldspars (K-Fds, diffractions between 0.332 and 0.318 nm but usually at 0.324 nm) and calcium- or sodium-feldspars (Ca/Na-Fds, reflection around 0.319 nm), as described by Shirozu (1988). Several diffractions between 0.42 and 0.34 nm were also due to feldspars although the value of *d*-spacing varied significantly depending on their structure. Feldspars were usually identified in these samples although their contents were very limited in most samples. On the other hand, K-Fds are more common in lowland soils of West Africa than Ca/Na-Fds, since K-Fds (orthoclase) would be more stable against the weathering than Ca/Na-Fds (plagioclase) (Oba and Nagatsuka 1988). However, other minerals could be hardly identified by the

Table 1 General description of the sampling sites and primary mineral composition of the topsoil (0-15 cm) samples revealed by the XRD analysis.

Site No.	Location	Country	Topography [a]	Agro-eco zone [b]	Soil Taxonomy	Clay types [c]	Primary minerals [d]			
							Qt	K-Fds	Pg	Others
1	Dahwenya	Ghana	IVs	GuS	Typic Tropaquept	14	++++	—	++	Ov tr?
2	Mongonu-1	Nigeria	IVs	SaS	Typic Pellustert	14-7	++++	++	+	—
3	Mongonu-2	Nigeria	IVs	SaS	Typic Chromustert	14-7	++++	++	+	—
4	Lumda-1	Nigeria	FPs	SaS	Typic Pellustert	14-7	++++	tr	—	—
5	Dwam/Yola-2	Nigeria	FPs	SuS	Tropic Fluvaquent	14-7	++++	++	++	—
6	Bende-2	Nigeria	IVs	EF	Fluvaquentic Epiaquept	14-7	++++	+	—	—
7	Mongonu-3	Nigeria	IVs	SaS	Oxic Ustropept	14-7	++++	tr	—	—
8	Abakaliki-5	Nigeria	IVs	EF	Typic Fragiudept	14-7	++++	—	—	—
9	Lumda-2	Nigeria	FPs	SaS	Typic Chromustert	14-7	++++	tr	—	—
10	Lumda-3	Nigeria	FPs	SaS	Oxic Ustropept	14-7	++++	+	—	—
11	Abakaliki-3	Nigeria	IVs	EF	Aeric Fragiaquept	14-7	++++	—	—	—
12	Abakaliki-2	Nigeria	IVs	EF	Fluvaquentic Epiaquept	14-7	++++	—	—	—
13	Gashua-1	Nigeria	FPs	SuS	Tropic Fluvaquent	14-7	++++	++	tr	—
14	Dwam/Yola-1	Nigeria	FPs	SuS	Typic Tropaquent	14-7	++++	+++	+++	—
15	Kadawa	Nigeria	FPs	SuS	Typic Tropaquent	14-7	++++	+	—	—
16	Bende-3	Nigeria	IVs	EF	Fluvaquentic Humaquept	7-14	++++	tr	—	—
17	Gadza/Bida-3	Nigeria	IVs	GuS	Typic Tropaquept	7-14	++++	+	—	—
18	WARDA-4	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7-14	++++	+	+	—
19	Dwinyama-1	Ghana	IVs	EF	Typic Tropaquept	7-14	++++	—	tr	—
20	Gashua-2	Nigeria	FPs	SuS	Typic Tropaquept	7-14	++++	++	tr	—
21	Koutoukale-3	Niger	FPs	SuS	Tropic Fluvaquent	7-14	++++	+	—	—
22	Abakaliki-1	Nigeria	IVs	EF	Fluvaquentic Epiaquept	14-7	++++	—	—	—
23	WARDA-3	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7-14	++++	+	+	—
24	Atani-1	Nigeria	FPs	EF	Typic Kandiudult	7-14	++++	++	++	—
25	Atani-2	Nigeria	FPs	EF	Tropic Fluvaquent	7-14	++++	++	++	—
26	Gao	Mali	FPs	SaS	Typic Tropaquent	7-14	++++	+	tr	—
27	WARDA-2	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7-14	++++	+++	+	Ca tr?
28	Touba	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7-14	++++	++	++	—
29	Atani-4	Nigeria	FPs	EF	Typic Tropaquept	7-14	++++	+++	++	—
30	Koutoukale-2	Niger	FPs	SuS	Tropic Fluvaquent	7-14	++++	tr	tr	—
31	Dwam/Yola-3	Nigeria	FPs	SuS	Typic Kandiustalf	7-14	++++	—	—	—
32	Ayorou	Niger	FPs	SaS	Tropic Fluvaquent	7-14	++++	+	+	—
33	Koutoukale-1	Niger	FPs	SuS	Tropic Fluvaquent	7-14	++++	tr	—	—
34	Seberi-1	Niger	FPs	SuS	Typic Pellustert	7-14	++++	tr	tr	—
35	Korienza-2	Mali	FPs	SaS	Typic Tropaquept	7-14	++++	tr	—	—
36	WARDA-1	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7-14	++++	+	+	—
37	Oronaja	Nigeria	IVs	EF	Typic Tropaquept	7-14	++++	+	tr	—
38	Sakawa-1	Niger	FPs	SuS	Typic Udifluvent	7-14	++++	+	tr	—
39	Nyanpkala-1	Ghana	IVs	GuS	Tropic Fluvaquept	7-10-14	++++	—	—	—
40	Seberi-2	Niger	FPs	SuS	Typic Pellustert	7-14	++++	tr	—	—
41	Gadza/Bida-5	Nigeria	IVs	GuS	Typic Kandiustult	7-14	++++	tr	—	—
42	Korienza-1	Mali	FPs	SaS	Typic Tropaquent	7-14	++++	—	—	—
43	Nyanpkala-2	Ghana	IVs	GuS	Typic Kandiustalf	7-14	++++	—	—	—
44	Gadza/Bida-1	Nigeria	IVs	GuS	Typic Tropaquept	7-14	++++	+	tr	—
45	Sakawa-2	Niger	FPs	SuS	Typic Ustropept	7-14	++++	tr	—	—
46	Sakawa-3	Niger	FPs	SuS	Typic Udifluvent	7	++++	+	tr	—
47	Gadza/Bida-4	Nigeria	IVs	GuS	Aqutic Quartzipsamment	7-14	++++	tr	—	—
48	Bende-5	Nigeria	IVs	EF	Aqutic Kandiudult	7	++++	—	—	—
49	Gadza/Bida-6	Nigeria	IVs	GuS	Typic Kandiustult	7-14	++++	tr	—	—
50	Nupeko/Bida-4	Nigeria	FPs	GuS	Typic Kandiustalf	7-10	++++	++	+	Mv tr

Table 1 Continued.

Site No.	Location	Country	Topo-graphy [a]	Agro-eco zone [b]	Soil Taxonomy	Clay types [c]	Primary minerals [d]			
							Qt	K-Fds	Pg	Others
51	Daloa-1	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7	++++	+	tr	—
52	Niono	Mali	FPs	SuS	Oxic Ustropept	7	++++	tr	—	—
53	Makurdi-3	Nigeria	FPs	GuS	Tropic Fluvaquent	7	++++	+	—	—
54	Nupeko/Bida-1	Nigeria	FPs	GuS	Typic Tropaquept	7-10	++++	++	+	—
55	Gadza/Bida-2	Nigeria	IVs	GuS	Typic Tropaquept	7	++++	tr	—	—
56	Dogon	Mali	IVs	SaS	Typic Tropaquept	7-10	++++	+	—	—
57	Sawulia-1	Sierra Leone	IVs	EF	Typic Tropaquept	7	++++	++	—	—
58	Massina-2	Mali	IVs	SuS	Typic Tropaquept	7	++++	tr	—	—
59	Makurdi-1	Nigeria	FPs	GuS	Typic Ustifluvent	7	++++	tr	—	—
60	Baro-2	Guinea	IVs	GuS	Typic Tropaquept	7	++++	—	—	—
61	Daloa-2	Côte d'Ivoire	IVs	EF	Typic Tropaquept	7	++++	++	+	—
62	Sawulia-2	Sierra Leone	IVs	EF	Typic Tropaquept	7	++++	+	—	—
63	Massina-1	Mali	IVs	SuS	Typic Tropaquept	7	++++	+	—	—
64	Makurdi-2	Nigeria	FPs	GuS	Typic Udifluvent	7	++++	+	—	—
65	Dwinyama-3	Ghana	IVs	EF	Typic Kandiustalf	7	++++	—	—	—
66	Baro-1	Guinea	FPs	GuS	Typic Tropaquept	7	++++	++	—	Ch +?
67	Falaba-1	Sierra Leone	IVs	EF	Typic Tropaquept	7	++++	++	+	Ch tr?
68	San	Mali	IVs	SuS	Tropic Fluvaquept	7	++++	tr	tr	—
69	Kankan	Guinea	FPs	EF	Typic Ustropept	7	++++	++	+	Ch ++?
70	Niandan river	Guinea	FPs	EF	Tropic Fluvaquent	7	++++	++	—	Gb tr
71	Gueckedou	Guinea	IVs	EF	Typic Tropaquept	7	++++	+	tr	—
72	Makurdi-4	Nigeria	FPs	GuS	Aqutic Kandiudult	7	++++	+	—	—
73	Mamou	Guinea	IVs	GuS	Typic Tropaquept	7	++++	++	+++	—
74	Djenne	Mali	IVs	SuS	Typic Tropaquept	7	++++	+	—	—
75	Kissidougou	Guinea	IVs	EF	Typic Tropaquept	7	++++	+	—	—
76	Nzerekore-1	Guinea	IVs	EF	Typic Tropaquept	7	++++	tr	—	—
77	Siguire	Guinea	FPs	GuS	Tropic Fluvaquent	7	++++	+	—	—
78	Mopti	Mali	FPs	SaS	Tropic Fluvaquent	7	++++	tr	—	—
79	Falaba-2	Sierra Leone	IVs	EF	Typic Tropaquept	7	++++	++	tr	—
80	Birinin Koni	Niger	FPs	SaS	Typic Ustifluvent	7	++++	—	—	—
81	Heremakono-1	Guinea	IVs	GuS	Typic Tropaquept	7	++++	—	—	—
82	Heremakono-2	Guinea	IVs	GuS	Typic Tropaquept	7	++++	—	—	—
83	Dwinyama-2	Ghana	IVs	EF	Typic Tropaquept	7	++++	+++	+	Ch tr?; Ca, tr?; Gb tr
84	Nzerekore-2	Guinea	IVs	EF	Typic Tropaquept	7	++++	+	—	—
85	Argungu-1	Nigeria	FPs	SuS	Tropic Fluvaquent	7	++++	—	—	—
86	Makurdi-5	Nigeria	FPs	GuS	Typic Kandiustalf	7	++++	tr	—	—
87	Argungu-2	Nigeria	FPs	SuS	Tropic Fluvaquent	7	++++	—	—	—

[a] IVs, inland valleys; FPs, flood plains

[b] EF, equatorial forest zone; GuS, Guinea savanna zone; SuS, Sudan savanna zone; SaS, Sahel savanna zone

[c] Abe et al. (2006)

[d] Abbreviations: Ca, calcite; Ca/Na-Fds, calcium- or sodium-feldspars; Ch, chlorite; Gb, gibbsite; Mv, Muscovite; K-Fds, potassium feldspars; Ov, olivine; Qz, quartz; Zn, zircon

—, none; tr, trace; +, scarce; ++, minor; +++, common; ++++, predominant; ?, suspected

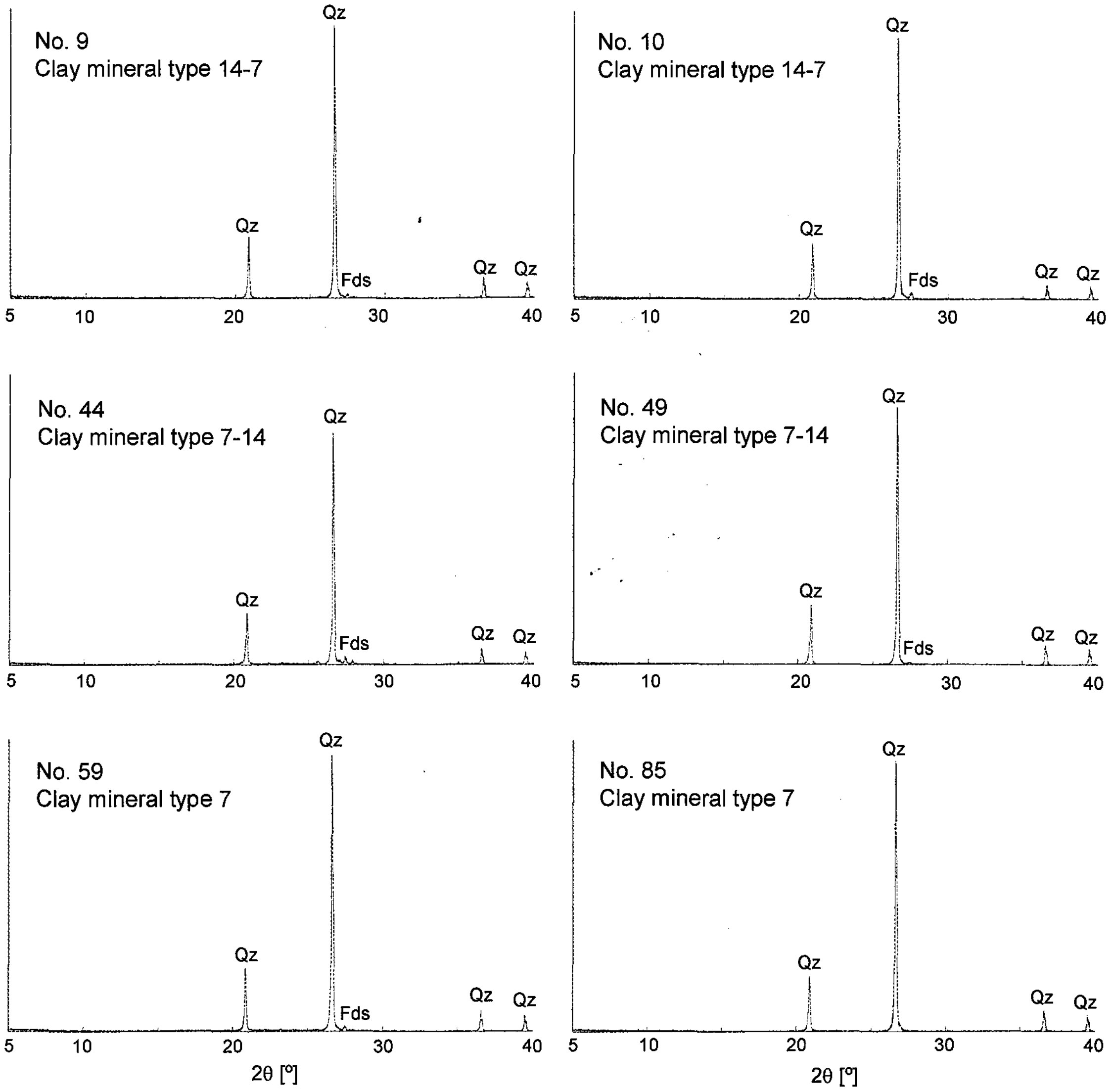

Figure 1 XRD patterns of the fine sand fraction (20-212 μm) of selected topsoil (0-15 cm) samples from lowlands in West Africa.

XRD analysis. For example, micas could be observed scarcely in the fine-sand fraction even in the soils at the site Nos. 39, 50, 54 and 56, which had a relatively high content of illite (see Chapter 2), because of the absence of diffraction at 1.0, 0.33 (biotite) or 0.31 nm (muscovite).

The petrographic investigation indicates that the mineral composition in the fine-sand fraction of some representative samples was predominantly consisted of quartz (84-93%) (Table 2), which ensured the results obtained by the XRD analysis (Table 1). In addition, a small amount of zircon was observed in these samples although the XRD analysis could not detect zircon since most intense peaks originated from zircon (0.330, 0.443 and 0.252 nm) would be masked by other minerals such as quartz and feldspars. Weatherable minerals such as feldspars and muscovite were also found at very low amounts in these samples but some of them were undetectable by the XRD analysis, as well. Accordingly, the XRD analysis was considered to be limited in the detection of very low contents of minerals, which could be identified by the petrographic measurement. But, even if other XRD-undetectable minerals existed in the fine-sand fraction, quartz and feldspars occupied most parts of this fraction. The total elemental analysis of these samples done by Buri *et al.* (2000) also supported these findings of this study as they described low total basic oxides (K_2O, CaO and MgO) levels but high contents of SiO_2, Al_2O_3 and Fe_2O_3 in addition to high Si/Al ratio.

XRD analysis and petrographic measurement revealed that the mineralogical composition of the fine-sand fraction was much more monotonous compared to the clay (Chapter 2). It was assumed in Chapter 2 that clay mineral composition of these soils reflected nature of parent materials rather than effects of climate and topography due to geographical distribution of soil clay mineral types. However, there was no oriented trends in primary mineral composition between soils had contrasting clay mineral types nor between soils in inland valleys and flood plains under different climate (Table 1). This result suggested that strong weathering over

Table 2 Primary mineral composition of the representative samples revealed by the petrographic measurement.

Site No.	Primary mineral composition (%)				
	Quartz	Muscovite	Feldspars	Zircon	Opaque
5	84	—	5	7	4
9	84	—	8	8	—
10	90	—	7	3	—
31	88	—	6	3	—
44	92	2	4	2	—
47	90	—	4	6	—
49	87	—	5	5	3
59	90	4	4	2	—
72	93	—	3	4	—
85	92	—	4	4	—

The composition was calculated as percentage of individual mineral grain to total grains counted.

long periods caused substantial destruction of weatherable minerals in the fine-sand fraction and shaded the inherent feature of parent rock regardless of the difference in clay mineral composition.

3.4. Conclusions

The present study demonstrated that prolonged and intensive weathering resulted in substantial destruction of weatherable minerals and endurance of resistant minerals like quartz in the lowland soils of West Africa. These findings reinforce the general understanding of the prevalence of siliceous soils in the region (e.g., Moormann and Veldcamp 1978) which had been without sufficient scientific corroboration.

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CHAPTER 4

Physicochemical Properties and Morphological Features of Inland Valley Soils in Southeast Nigeria

4.1. Introduction

It was estimated that 62% of the total rice production in West Africa was from the wetlands (West Africa Rice Development Association 2004), which highlighted a significant role of the lowland ecosystems in the rice production. In particular, inland valleys have been recognized to have great potentials for the production of swamp rice (Windmeijer and Andriesse 1993; West Africa Rice Development Association 2002; Wakatsuki and Masunaga 2005). Only 15% or less of total area of inland valleys in the region have been so far under cultivation despite their agricultural potentials (International Institute of Tropical Agriculture 1990; West Africa Rice Development Association 1997) because of the lack of knowledge of inland valley ecosystems. Andriesse and Fresco (1991) described rice growing environments in inland valleys based on agro-ecological characterization. Issaka *et al.* (1997), Buri *et al.* (1999) as well as Chapter 2 and 3 of this thesis reported general fertility status and material nature of inland valley soils over West Africa. These literatures have improved comprehensions to utilize inland valley ecosystems. However, intensive assessment on soil properties and thus agricultural potentials in specific locations has been still scanty. The inland valleys under the rain forest climate in Southeast Nigeria are a typical case. The soils in this area have formed in shale materials and thus are assumed to have distinctive properties although most soils in West Africa derive from igneous and metamorphic rocks (Windmeijer and Andriesse 1993). Therefore, we investigated physicochemical and morphological properties of the soils in two inland valleys of Abakaliki and Bende, Southeast Nigeria to evaluate the agricultural potential as well as soil-forming processes.

4.2. Materials and Methods

Two inland valley systems, one near Abakaliki (N6°15', E8°8') and the other in Bende (N5°30', E7°40'), were selected for this study (Fig. 1). Both sites are located in the southeastern part of Nigeria and are characterized by a tropical humid climate with an average annual precipitation of approximately 2000 mm in a bimodal distribution and a mean annual daily temperature of about 27°C. The Abakaliki site lies on a gently undulating peneplain, while the Bende site has a rolling topography. The soils of Abakaliki derive from Cretaceous black shale and siltstone, or shale and limestone while the geological materials of Bende are Tertiary clays, clayey sands and shale, clays and shale with limestone (Federal Survey 1992). Nevertheless, our field survey indicated that the inland valley of Bende showed a segregation of geological materials, i.e., sandstone in the upland but shale in the wetland. The Abakaliki site has been under swamp rice cultivation over hundreds of years, while the Bende site was just for decades. The overview of the sampling points at each site is given in Fig. 2. The profiles were described according to the recommended procedure by Food and Agriculture Organization (1977) using horizon designations of Soil Survey Staff (1981). Furthermore, U.S. Soil Taxonomy (Soil Survey staff 2006) was applied to classify the soils.

Soil samples obtained were air-dried and crushed to pass a 2 mm sieve. Bulk density was determined by the clod method (Blake 1965) using paraffin wax melted at 60-70°C. Particle size analysis was done using the hydrometer method (Bouyoucos 1962). Soil pH was measured potentiometrically in distilled water and 1.0 M KCl (1:1 soil liquid ratio) using a pH meter after equilibration for 30 min. Exchangeable bases (Ca, Mg, K and Na) were extracted with 1.0 M neutral NH_4OAc. Calcium and Mg were determined using an atomic absorption spectrometer (AAS), and K and Na were examined on a flame photometer. Exchangeable acidity (Al and H) were extracted with 1.0 M KCl and titrated according to Yuan's method (Yuan 1959). Effective cation exchange capacity (ECEC) is the summation of exchangeable bases and exchangeable acidity. Organic C was obtained by the chromic acid digestion method (Allison 1965). Total

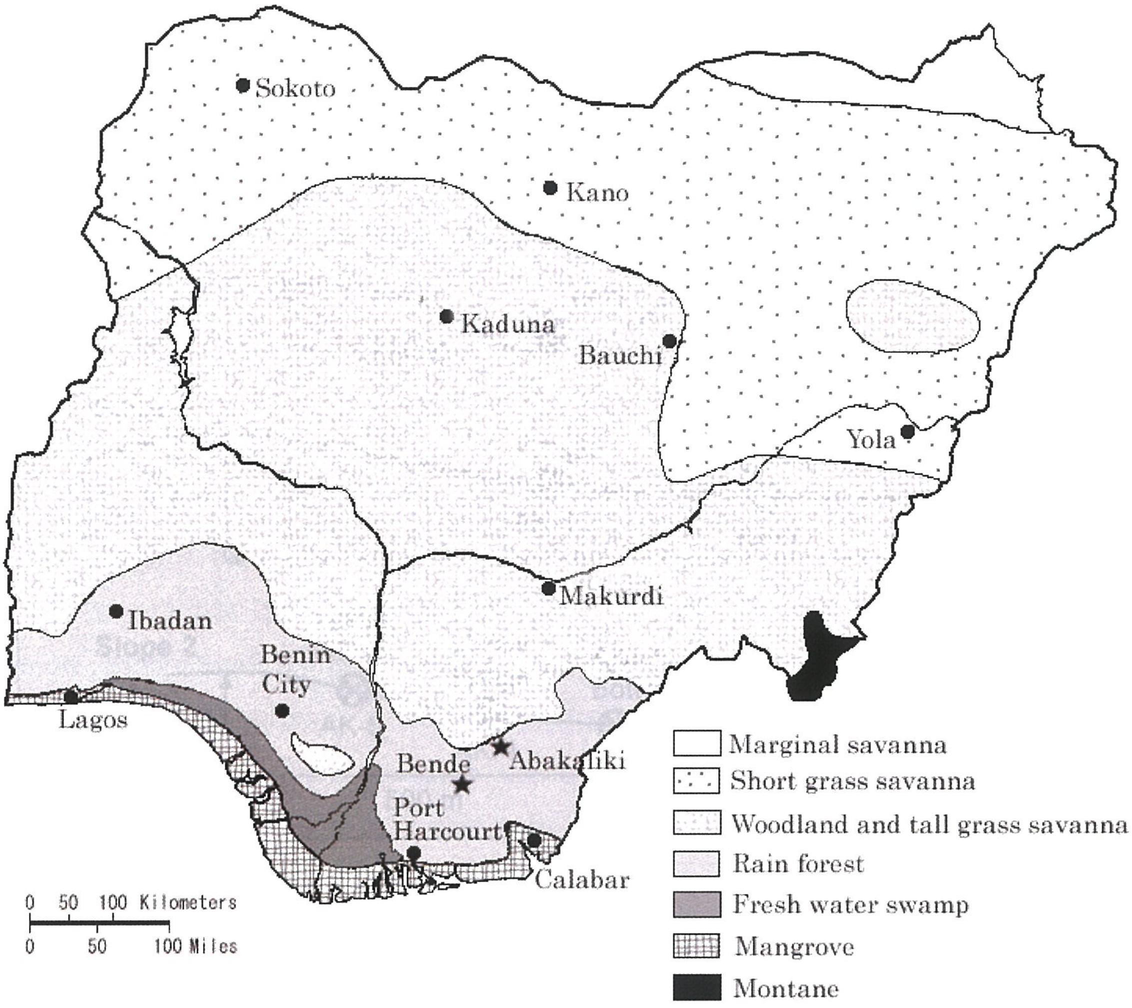

Figure 1 The study sites on the vegetation map of Nigeria
(adopted from Central Intelligence Agency (1979): Map No. 504014)

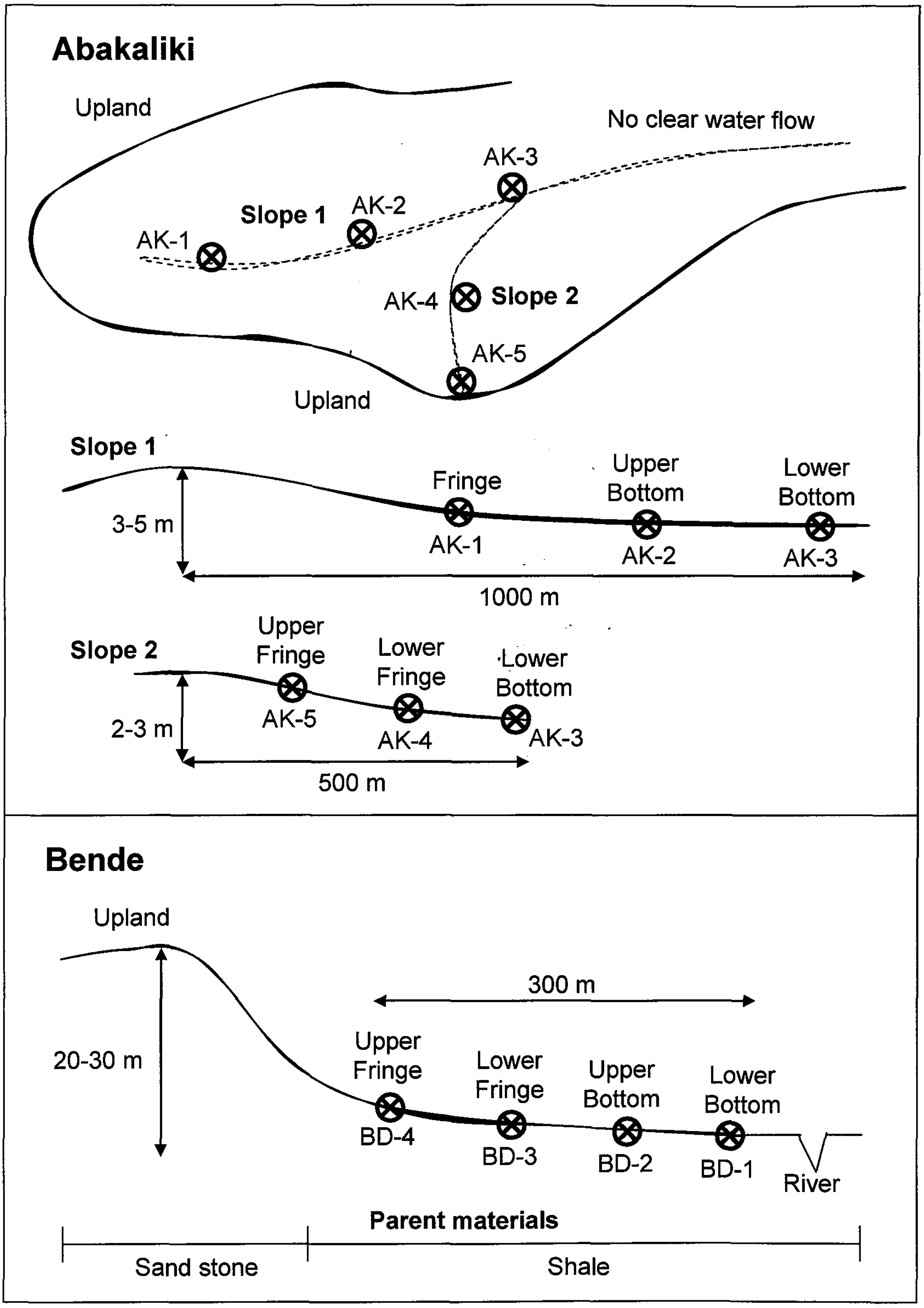

Figure 2 Brief description of the sampling points in the inland valleys.

N was examined by the macro-Kjeldahl method in a Tecator digester system, with N-estimation by a Technicon's auto-analyzer. Available P was obtained by the Bray-1 method followed by the colorimetric examination with molybdate. Free Fe (Fe_d) was extracted by the dithionite-citrate-bicarbonate (DCB) method according to Mehra and Jackson (1960). Amorphous Fe (Fe_o) soluble in acidified NH_4-oxalate was extracted twice from 1.0 g soil sample by 30 mL of Tamm-A reagent (Tamm 1922) after 1 hr shaking in the darkness. The concentration of Fe in the extractants was determined by AAS. The ratio of Fe_o/Fe_d was calculated as an index for activity of iron oxides (Nagatsuka 1973).

4.3. Results and Discussion

Morphological features

Field observations described morphological properties of the soils in Abakaliki and Bende (Table 1). All the pedons examined had some mottled horizons either at the epipedon or at the subsoil horizons, which reflected an annual cycle of a wet/dry soil moisture regime, i.e. hydromorphism. Grayish matrix color with low chroma of the pedons also indicated that these soils had developed under the influence of reduced conditions. However, AK-5, BD-3 and BD-4 located on the fringe had relatively brownish color regardless of the presence of mottles. The increasing redness of soils on the upslope would be ascribed to decreasing hydration of iron oxides, as described by Torrent *et al.* (1984). The preponderance of Fe/Mn concretions were observed at some subsoil horizons of all the pedons in Abakaliki in collaboration with fragipan at the horizon A2feg and 2Bwfeg in the pedons AK-3 and AK-5, respectively, while the soils in Bende had pedons free of concretions with exception of the pedon BD-1 (Table 1). This indicated rapid changes in aeration and concordant fluctuation of redox potentials in the soils of Abakaliki. Formation of horizons with Fe and Mn accumulation was commonly observed in seasonally flooded soils, which reflected the redistribution of Fe and Mn in the flooded profiles (Pickering and Veneman 1984). On the other hand, sub-angular blocky was the

Table 1. Morphological characteristics of the soils at the study sites.

Horizon	Depth (cm)	Color		Texture[a]	Structure[b]	Consistence[c]	Boundary[d]	Others
		Matrix	Mottle					
Pedon AK-1, Fluvaquentic Epiaquepts								
Ap	0-20	10YR6/4	10YR6/8	SiCL	2 m sbk	fr shs shp	a s	—
A2	20-40	10YR7/3	—	SiL	3 m sbk	fi shs shp	a s	—
Bwg1	40-81	10YR7/2	—	CL	3 m sbk	fi shs shp	a s	Fe/Mn concretion > 15%
Bwg2	81-111	10YR7/2	—	SiL	4 m sbk	fi vs vp	g s	Fe/Mn concretion < 10%
Bwg3	111-170	10YR7/2	5Y2/1	SiL	4 m sbk	fi s p	c s	Mn cocretion < 10%
BCg	170-194	10YR7/2	10YR5/6	L	3 m sbk	fi s p	—	Mn concretion > 20% & quartz gravels
Pedon AK-2, Fluvaquentic Epiaquepts								
Ag	0-28	2.5Y5/1	7.5YR5/6	SiCL	2 f sbk	fr shs shp	c s	—
A2g	28-47	10YR8/2	7.5YR5/6	CL	3 f sbk	fr shs shp	c s	—
2Bwg	47-74	10YR5/2	2.5YR3/6	SiCL	3 m sbk	fr shs shp	a s	Fe/Mn concretion > 15%
2Bg	74-109	7.5YR5/1	10YR6/6	SiC	3 m sbk	fr s p	d s	Mn concretion < 10%
2BCg	109-150	7.5YR5/1	10YR6/6	SiCL	3 m sbk	fr shs shp	—	Mn concretion > 15%
Pedon AK-3, Aeric Fragiaquepts								
Apg	0-28	7.5Y7/1	10YR5/8	C	2 f sbk	fr shs shp	a s	—
A2feg	28-54	7.5YR4/8	7.5YR2/1	L	ND[e]	ND	c s	Fe concretion > 80%
B1g	54-100	7.5Y7/1	10YR5/8	C	ND	ND	a s	Fe/Mn concretion < 10%
B2g	100-158	7.5Y7/1	10YR5/8	C	3 m sbk	fi s p	—	Quartz gravels
Pedon AK-4, Fluvaquentic Epiaquepts								
Apg	0-30	2.5Y5/1	7.5YR5/6	C	2 m sbk	fr shs shp	c s	—
Bwg1	30-50	10YR8/2	7.5YR5/6	SiCL	3 m sbk	fr shs shp	c s	—
Bwg2	50-98	10YR5/2	2.5YR4/6	SiCL	3 m sbk	fr shs shp	a s	Fe/Mn concretion > 15%
BCg	98-148	7.5YR5/1	10YR6/6	SiCL	4 c sbk	fr shs shp	—	Mn concretion < 10%
Pedon AK-5, Typic Fragiudepts								
Ap	0-20	7.5YR4/4	—	SiCL	2 f gr	fr shs shp	d s	—
AB	20-50	7.5YR4/4	—	SiCL	2 f sbk	fr shs shp	a s	—
2Bw	50-76	10YR5/6	—	SL	3 m sbk	fr shs shp	c s	—
2Bwfeg	76-95	7.5YR4/8	10YR5/6	L	ND	ND	a s	Fe concretion > 80%
3BCg	95-135	7.5Y7/1	10YR5/8	LS	3 m sbk	fi s p	g s	—
3Cg	135-170	7.5Y7/1	10YR5/6	SL	3 m sbk	fi s p	—	—
Pedon BD-1, Fluvaquentic Epiaquepts								
Ap	0-21	5YR3/2	—	SCL	2 m sbk	fr s p	c s	—
Bw1	21-50	7.5YR6/1	5YR4/3	C	3 m abk	fi vs vp	c s	—
Bwg2	50-85	7.5YR5/1	2.5YR3/4	C	4 m abk	vfi vs vp	g s	Mn concretion < 10%
Bwg3	85-100	7.5YR5/1	2.5YR4/8	C	4 c abk	vfi vs vp	c s	Mn concretion > 15%
BCg	100-158	7.5YR5/1	10YR5/8	C	4 c abk	fi vs vp	—	Mn concretion > 15%
Pedon BD-2, Fluvaquentic Epiaquepts								
Ap1	0-20	7.5YR3/2	—	C	2 f sbk	fr shs shp	c s	—
Apg2	20-52	10YR5/2	7.5YR5/6	SC	3 f sbk	fr s p	a s	—
Bwg1	52-89	2.5Y6/2	2.5YR4/8	C	4 m abk	fi vs vp	a w	—
Bwg2	89-120	2.5Y6/2	10R3/4	C	4 m abk	fi s p	c s	—
BCg	120-165	2.5Y6/1	2.5YR4/8	SCL	3 f sbk	fr s p	—	—
Pedon BD-3, Fluvaquentic Humaquepts								
Ap	0-20	10YR3/2	7.5YR4/6	SC	3 f sbk	fr shs shp	c s	—
Bw1	20-73	7.5YR6/1	7.5YR4/6	SC	3 m abk	fi s p	c s	—
Bw2	73-100	7.5YR6/1	—	SCL	4 m abk	fi vs vp	g s	—
BC	100-152+	7.5YR6/2	—	SL	3 m abk	fi vs vp	—	—
Pedon BD-4, Fluvaquentic Humaquepts								
Ap	0-18	10YR3/2	5YR4/8	SL	3 f sbk	fr shs shp	c s	—
Bw1	18-30	10YR5/2	5YR4/8	SCL	3 m sbk	fi s p	c s	—
Bw2	30-75	7.5YR6/1	7.5YR5/6	SCL	4 m abk	fi vs vp	a w	—
BC	75-144	7.5YR6/1	—	SL	2 f gr	vfr shs shp	—	—

[a] SiCL, silty clay loam; SiL, silty loam; CL, clay loam; L, loamy; SiC, silty clay; C, clayey; SL, sandy loam; LS, lomy sand; SC, sandy clay; SCL, sandy clay loam.

[b] 2, moderate; 3, strong; 4, very strong; m, medium; f, fine; c, coarse; sbk, subangular blocky; abk, angular blocky; gr, granular.

[c] fr, friable; fi, firm; vfi, very firm; vfr, very friable; shs, slightly sticky; vs, very sticky; s, sticky; shp, slightly plastic; vp, very plastic; p, plastic.

[d] a, abrupt; c, clear; g, gradual; d, diffuse; f, flat; s, smooth; w, wavy.

[e] ND, not determined

dominant structure in the pedons of Abakaliki while an angular blocky structure was found in some clayey horizons of Bende. All the profiles had a cambic horizon in the subsoil and aquic moisture regime except for the pedon AK-5 which represented udic moisture regime

Physical properties

Table 2 represents selected physicochemical properties of the soils at the study sites. The mechanical analysis, showed that the soils in Abakaliki were generally silty. The silt content ranged from 20.4 to 56.2% except in 3BCg and 3Cg horizons of the pedon AK-5 that contained 8.4 and 8.8% silt, respectively. In most cases in Abakaliki, clay content was higher than sand content. In contrast, the silt content of the pedons in Bende seldom exceeded 20.0%. The sand proportion decreased with increase in soil depth in the pedon BD-1, while in the other pedons of Bende the sand distribution was erratic. The pedons BD-1 and BD-2 at the bottom were clayey, while the pedons BD-3 and BD-4 on the fringe had a considerably high sand content. This might reflect the influence of transportation and deposition of materials from the upland into the lowland whereby coarse materials could deposit first. The particle size distribution at these two sites was considered to be distinctive among inland valleys in West Africa which usually had sandy texture (Buri *et al.* 1999). The soils in Abakaliki and Bende have formed on shale materials in Cretaceous or Tertiary era and thus had a relatively high content of tclay. In contrast, most soils in inland valleys of West Africa were characterized by low clay contents derived from Pre-Cambrian igneous and metamorphic rocks, called Basement Complex (Windmeijer and Andriesse 1993). The implication of soil particle size distribution on water movement is that the soils would have the ability to retain large amounts of water. The cultivation of swamp rice in Abakaliki and Bende should not be of much problem. However Abakaliki appear more promising for wet rice cultivation than Bende because the higher silt content in addition to clay in the soils of Abakaliki would enhance higher water retention compared to Bende. On the other hand, relative accumulation of clay at the surface horizons of all the pedons in Abakaliki

Table 2. Selected physicochemical properties of the soils at the study sites.

Horizon	Depth	Sand	Silt	Clay	Bulk density	pH		Exchangeable cations (cmol$_c$ kg^{-1})						ECEC	Organic C	Total N	Bray-1 P
	(cm)		(%)		(g cm^{-3})	H_2O	KCl	Ca	Mg	K	Na	Al	H	(cmol$_c$ kg^{-1})	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})
Pedon AK-1																	
Ap	0-20	14.4	50.0	35.6	1.65	4.9	4.6	1.27	0.54	0.24	0.13	1.78	0.80	4.76	19.7	1.3	2.4
A2	20-40	26.0	56.2	17.8	0.93	6.1	5.7	1.08	0.71	0.93	0.05	0.56	0.22	3.55	9.3	0.3	1.8
Bwg1	40-81	34.0	42.0	24.0	0.93	8.0	7.3	1.56	1.88	3.53	0.12	0.10	0.02	7.21	9.3	0.4	1.8
Bwg2	81-111	20.4	50.6	29.0	0.99	9.0	8.1	1.81	2.34	4.72	0.24	0.34	0.13	9.58	8.3	0.3	1.8
Bwg3	111-170	20.4	50.6	29.0	1.16	7.7	7.3	2.81	3.70	3.71	0.11	0.19	0.04	10.56	8.2	0.2	2.7
BCg	170-194	12.0	42.0	46.0	1.71	9.1	8.2	3.78	2.48	3.77	0.11	0.06	0.01	10.21	7.6	0.2	2.7
Pedon AK-2																	
Ag	0-28	14.6	53.4	32.0	1.43	5.1	4.8	0.46	0.30	0.32	0.06	2.89	0.17	4.20	9.3	0.4	1.4
A2g	28-47	34.0	38.5	27.5	1.19	4.2	4.0	0.89	0.40	0.18	0.14	2.92	0.37	4.90	20.8	1.3	2.1
2Bwg	47-74	12.0	51.5	36.5	1.05	6.0	5.6	1.81	2.14	2.04	0.09	1.90	0.50	8.48	9.5	0.4	0.9
2Bg	74-109	20.0	40.0	40.0	1.68	8.9	8.0	2.74	3.23	4.85	0.24	0.10	0.02	11.18	7.8	0.2	1.0
2BCg	109-150	14.5	51.5	34.0	1.41	8.3	7.5	3.97	3.90	4.91	0.03	0.25	0.05	13.11	7.8	0.3	1.8
Pedon AK-3																	
Apg	0-28	4.8	40.0	55.2	2.04	4.7	4.2	0.43	0.39	0.18	0.35	2.94	0.36	4.65	14.1	0.7	9.0
A2feg	28-54	36.0	44.0	20.0	1.22	4.8	4.6	1.18	1.77	0.17	0.11	2.40	0.59	6.22	13.6	0.8	1.5
B1g	54-100	30.5	27.5	42.0	1.04	6.3	6.0	5.91	5.09	0.50	0.13	0.56	0.07	12.26	9.1	0.4	1.2
B2g	100-158	30.0	22.0	48.0	1.70	7.4	6.8	8.92	4.69	0.77	0.13	0.10	0.03	14.64	8.1	0.3	1.0
Pedon AK-4																	
Apg	0-30	34.0	20.4	45.6	1.53	4.5	4.1	0.53	4.95	0.17	0.08	2.98	0.32	9.03	15.7	0.8	3.3
Bwg1	30-50	14.2	52.0	33.8	1.74	4.6	4.1	0.24	0.31	0.18	0.05	2.98	0.59	4.35	10.5	0.4	1.8
Bwg2	50-98	18.2	51.8	30.0	1.50	5.6	5.0	0.38	0.63	0.62	0.06	2.93	0.63	5.25	10.3	0.4	1.3
BCg	98-148	20.0	50.0	30.0	1.51	7.3	6.9	1.49	2.33	3.29	0.07	0.27	0.10	7.55	7.8	0.3	1.0
Pedon AK-5																	
Ap	0-20	18.0	43.8	38.2	1.93	5.0	4.6	0.86	1.14	0.13	0.10	1.01	0.15	3.39	11.8	0.5	3.6
AB	20-50	18.2	44.0	37.8	1.93	4.9	4.6	0.80	0.71	0.15	0.09	1.99	0.83	4.57	11.7	0.5	1.6
2Bw	50-76	53.4	32.4	14.2	1.11	4.7	4.2	0.62	0.57	0.18	0.08	2.80	0.82	5.07	11.9	0.6	1.4
2Bwfeg	76-95	38.0	36.0	26.0	1.13	5.4	5.1	0.27	0.21	0.14	0.02	0.20	0.03	0.87	6.8	2.0	1.8
3BCg	95-135	81.6	8.4	10.0	0.86	5.5	5.3	0.22	0.14	0.13	0.02	0.66	0.07	1.24	6.9	2.3	1.5
3Cg	135-170	76.0	8.8	15.2	0.88	4.6	4.2	0.30	0.34	0.18	0.07	3.25	0.65	4.79	10.9	0.6	3.1

Table 2. Continued.

Horizon	Depth	Sand	Silt	Clay	Bulk density	pH		Exchangeable cations (cmol$_c$ kg^{-1})						ECEC	Organic C	Total N	Bray-1 P
	(cm)	(%)			(g cm^{-3})	H_2O	KCl	Ca	Mg	K	Na	Al	H	(cmol$_c$ kg^{-1})	(g kg^{-1})	(g kg^{-1})	(mg kg^{-1})
Pedon BD-1																	
Ap	0-21	64.2	4.0	31.8	0.94	5.0	4.6	4.90	2.53	0.20	0.12	2.73	1.10	11.58	20.1	1.8	2.7
Bw1	21-50	34.0	19.6	46.4	1.08	4.9	4.6	3.42	2.10	0.16	0.10	2.89	1.31	9.98	15.8	1.2	1.8
Bwg2	50-85	26.0	20.0	54.0	1.87	5.0	4.5	4.97	3.07	0.21	0.24	3.14	1.66	13.29	11.6	0.9	1.5
Bwg3	85-100	25.8	16.2	58.0	2.01	4.9	4.6	3.16	2.60	0.18	0.14	3.25	1.70	11.03	9.8	0.7	1.5
BCg	100-158	30.0	16.8	53.2	1.82	5.1	4.8	3.70	2.93	0.22	0.24	2.03	1.27	10.39	9.2	0.5	0.6
Pedon BD-2																	
Ap1	0-20	40.0	14.3	45.7	0.89	4.9	4.6	6.44	3.19	0.21	0.22	1.97	0.80	12.83	23.9	2.3	3.2
Apg2	20-52	47.5	14.0	38.5	0.91	4.7	4.5	4.77	2.59	0.20	0.14	2.46	0.71	10.87	13.9	0.7	1.2
Bwg1	52-89	38.0	10.0	52.0	1.36	5.0	4.6	3.46	2.47	0.20	0.15	2.02	1.10	9.40	9.9	0.6	10.8
Bwg2	89-120	28.2	11.8	60.0	2.06	5.0	4.6	3.64	2.73	0.19	0.22	2.15	1.17	10.10	9.5	0.5	1.0
BCg	120-165	70.0	8.0	22.0	0.80	4.8	4.4	3.62	3.01	0.20	0.25	2.60	1.72	11.40	9.4	0.5	0.8
Pedon BD-3																	
Ap	0-20	52.1	10.6	37.3	0.94	5.2	4.8	0.61	0.49	0.17	0.09	2.63	1.70	5.69	20.2	1.2	1.0
Bw1	20-73	48.0	10.0	42.0	1.04	5.8	5.2	0.60	0.74	0.17	0.08	2.95	1.75	6.29	13.4	0.9	1.8
Bw2	73-100	63.5	6.2	30.3	0.96	4.7	4.3	0.71	0.91	0.17	0.10	2.72	1.81	6.42	13.1	0.7	0.6
BC	100-152+	76.0	6.2	17.8	0.80	5.0	4.8	0.63	0.60	0.19	0.25	1.98	1.29	4.94	11.5	0.5	1.8
Pedon BD-4																	
Ap	0-18	77.4	4.4	18.2	0.73	5.5	5.1	0.60	0.23	0.15	0.04	2.85	0.98	4.85	19.0	1.4	2.1
Bw1	18-30	70.0	6.0	24.0	0.92	5.3	5.0	0.51	0.32	0.16	0.04	2.24	1.29	4.56	4.2	0.4	1.6
Bw2	30-75	68.0	4.3	27.7	1.01	5.1	4.8	0.54	0.51	0.14	0.06	2.82	0.94	5.01	10.0	0.5	1.2
BC	75-144	82.2	3.8	14.0	0.85	5.1	4.9	0.34	0.26	0.15	0.05	2.16	1.87	4.83	8.2	0.3	10.2

might be a reflection of good land and water management practices such as the maintenance of fairly good paddies even though at rudimentary stage of *sawah* development. This would attribute to the nature of the parent materials in the region.

Bulk density of the soils ranged between 0.80 and 2.06 g cm^{-3}. No definite pattern of bulk density within the profile was observed, whereas the surface horizons of pedons in Abakaliki tended to have a higher value of bulk density than those in Bende site.

Chemical characteristics

The soils in Abakaliki generally had acidic horizons but their subsurface horizons were neutral to slightly alkaline except for the pedon AK-5 which had acidic subsoils (Table 2). In contrast, all the pedons in Bende showed acidic reaction throughout the whole profile. Correspondingly, the content of exchangeable bases was generally low, but the amount of exchangeable acidity was relatively high in these soils. Acidic nature of parent rocks and leaching effects under high rainfall seem to be responsible for the acidic reactions of the soils in the region (Eshett *et al.* 1990). The subsoil horizons of the pedons AK-1, AK-2, AK-3 and AK-4 in Abakaliki testified a high content of exchangeable bases, which was in accordance to high pH values, indicating leaching of bases in surface horizons and their accumulation in subsoils. On the other hand, the pedons BD-1 and BD-2 on the downslope of Bende showed a relatively high content of exchangeable bases throughout the profiles regardless of their acidic reactions. In contrast, the soils on the upslope, i.e. the pedon BD-3 and BD-4, contained less exchangeable bases. These results implied that the rolling topography of the inland valley of Bende (see Fig. 2) accelerated the translocation of the bases downward the slope and their accumulation at the valley bottom. The values of ECEC of these soils varied substantially from 0.87 to 14.64 $cmol_c$ kg^{-1} but were generally found at low levels. Although these soils had a relatively high content of 2:1 type phyllosilicates, interlayering of hydroxyl-Al in these minerals would reduce their nutrient-holding capacity (see Chapter 5). The content of organic C in surface horizons was relatively high because of the large biomass production in the humid climate. It ranged from 9.3 to 19.7 g C kg^{-1} for Abakaliki and from 19.0 to 23.9 g C kg^{-1} for Bende, and decreased with soil depth. Abrupt increases in organic C were observed at a stratified horizon in the subsoil of the pedon AK-5, while its substantial decrease at the Bw1 horizon of the pedon BD-4 would be due to tilling effects. The distribution of total N followed similar pattern as organic C, whereas its values ranged between 0.4 and 2.3 g N kg^{-1} at the surface horizon of these soils. In general, the Bray-1 P values of these soils were very low (1.0 to 9.0 mg P kg^{-1}) in which acidic reactions of the soils could be implicated for low levels of Bray-1 P. The acidic reactions, and the relatively high content of organic C and exchangeable acidity but low amount of exchangeable bases and available P were common in inland valley soils under humid tropical climate in West Africa (Issaka *et al.* 1997.; Buri *et al.* 1999).

Active Fe ratios (Fe_o/Fe_d) in the pedons at the study sites were generally low and decreased with soil depth (Fig. 3). This indicated that a higher proportion of Fe was found in more crystalline forms at the lower horizons which corroborated the presence of Fe concretions at the subsoil horizons in the Abakaliki soils and in the pedon BD-1 (Table 1). In hydromorphic soils, a zone of Fe accumulation indicated the zone of the fluctuating water table (Okusami *et al.* 1987). All the soils in Abakaliki and the pedons BD-1 and BD-2 had perched water tables, whereas the pedons BD-3 and BD-4 owed their hydromorphism mainly to high groundwater tables. On the other hand, the content of exchangeable acidity and percentage of Al saturation to ECEC could be useful indices for the soil horizon development which was sometimes obscured by subtle differences in morphological features in the tropical area (Okusami *et al.* 1987). In general, Al saturation has been found to be higher in hydromorphic soils (Ragland and Coleman 1959). A greater Al saturation at the upper horizons of the pedons AK-1 and AK-3 suggested in situ weathering of the horizons that had formed in homogenous parent materials. The pedon AK-2 showed a similar trend in Al saturation to AK-1 and AK-3 despite lithologic

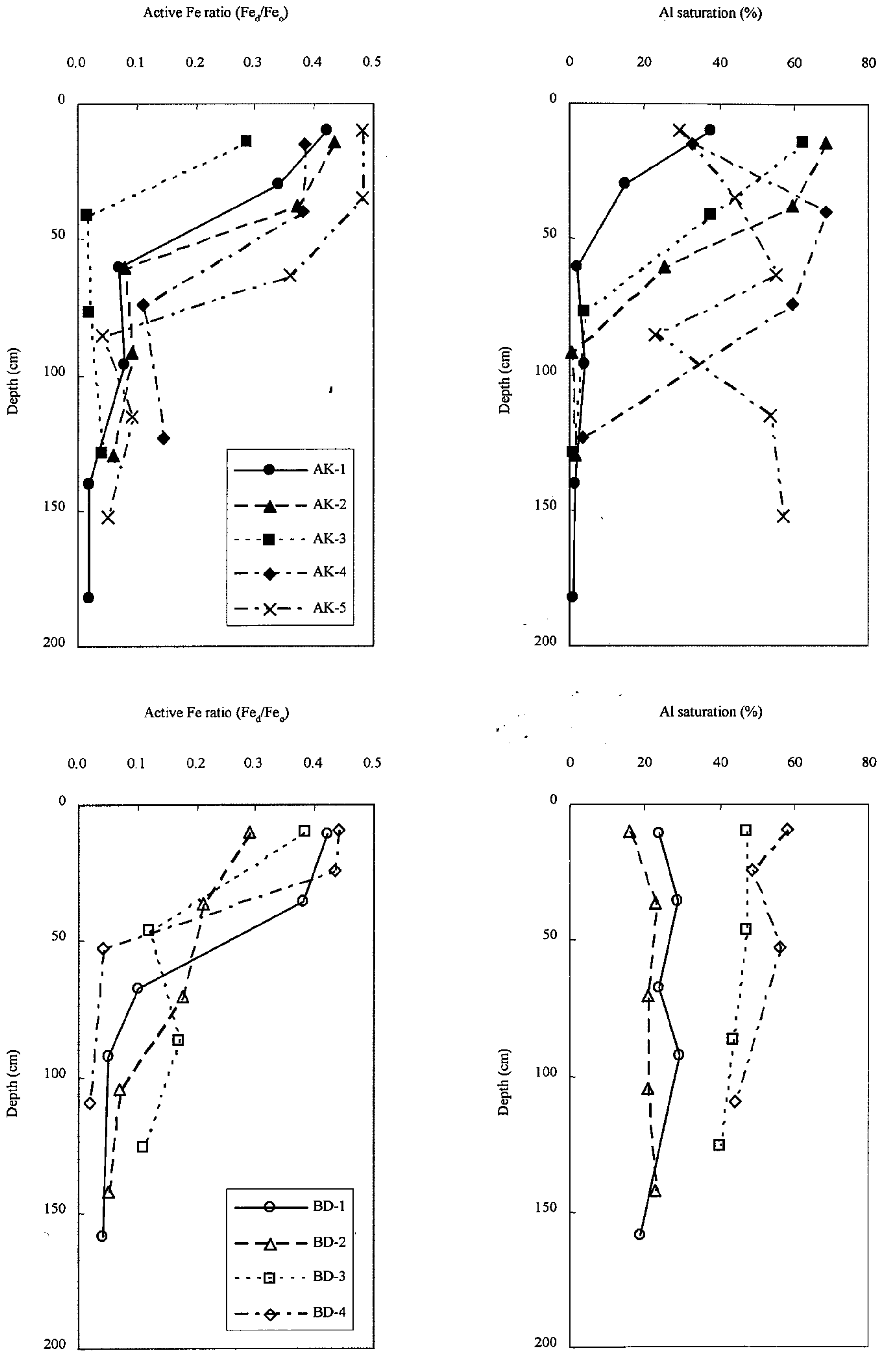

Figure 3 Distribution of active Fe ratio (Fe_o/Fe_d) and Al saturation (%) in the soils of the study sites.

discontinuity, while AK-5 having multi-parent materials represented its irregular distribution pattern. The relatively high Al saturation obtained in the pedons AK-4, AK-5, BD-3 and BD-4, and at the upper horizons of AK-2 and AK-3 (Fig. 3) would support the *ferrolysis* concept of Brinkman (1970) and the hypothesis of Buol *et al.* (1980) who proposed that clay mineral lattice destruction resulted in the release of Al ions. The *ferrolysis* was also well demonstrated by the presence of hydroxyl-Al interlayered 2:1 clays in these soils (see Chapter 5). A distinct accumulation of Al, especially in hydromorphic soils with perched water table (e.g., the pedon AK-4 in Fig. 3), could indicate the actively weathering zone of the solum since exchangeable Al was not considered as much mobile in the soil (Gotoh 1976).

4.4. Conclusions

The soils in Abakaliki and Bende sowed relatively high contents of clay and silt reflecting the nature of their parent materials, i.e. shale materials, which suggested their promising water-holding capacity. On the other hand, these soils generally showed poor fertility characteristics resulting from the severe weathering process and leaching effect under the influence of hydromorphic conditions and high precipitation. From the findings of the present study, it was concluded that the inland valleys in both sites would be suitable for the swamp rice cultivation if appropriate management practice, e.g. the *sawah* system, was applied with substantial resource investments. Hereby, the inland valleys in Abakaliki and Bende could be a reasonable exhibition site for the *sawah* technology transfer in the study area.

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CHAPTER 5

Clay Mineralogy and Parent Material Nature of Inland Valley Soils in Southeast Nigeria

5.1. Introduction

The agricultural development has induced a large interest in the inland valley ecosystems in West Africa. In particular, intensive use of the seasonally wet parts is regarded to the potential of swamp rice cultivation (Windmeijer and Andriesse 1993; Wakatsuki and Masunaga 2005). The previsous chapter (Chapter 4) reported the physicochemical and morphological properties of inland valley soils in Abakaliki and Bende, Southeast Nigeria to infer the soil-forming process and agricultural potential. Soils showed appropriate physical properties but poor fertility status in regard to wet rice farming. These characteristics were probably due to the nature of parent material and the intensive weathering under the humid conditions. On the other hand, literature investigations indicated that scarce information about soil mineralogy in the rain forest zone of Nigeria, which has made soil classification at family level of soil taxonomy impossible. This has created impediments on the understanding of the pedogenesis as a tool of the agro-technological transfer in the region because physicochemical properties of soils largely depend on the quality and quantity of clay minerals. We, therefore, investigated the nature of the parent material and the clay mineralogy employing X-ray diffraction (XRD) analysis, petrographic investigation and clay-free particle-size measurement, to reinforce the previous findings (Chapter 4).

5.2. Materials and Methods

General description of the study sites, physicochemical and morphological properties of the soils have been reported previously (Chapter 4).

The clay fraction (< 2 μm) was collected by the dispersion-sedimentation method

(Jackson 1956). The collection of the silt fraction (50-2 µm) was performed by means of sedimentation and decantation from the residues from clay separations. The fractionation of the sand particles (2-0.05 mm) was performed by sieving. Particle-size distribution was finally calculated on a clay-free basis. Mineralogical composition of the clay fraction was examined by 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 or K. In an additional experiment, clays were pretreated with Na-citrate to remove hydroxyl-Al in the interlayer of 2:1 type phyllosilicates, as described by Tamura (1958). The XRD measurement was applied to K-clays at room temperature, 300 and 550°C. The Mg-clays were mesured with and without glycerol permeation at room temperature. Clay minerals were identified according to Moore and Reynolds (1997). Sub-samples of the fine sand fraction (0.25-0.10 mm) 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.

5.3. Results

The objective of particle size distribution calculated on a clay-free basis is to remove the effect of possible translocated clay (Smith and Wilding 1972). In this study, proportions of the fine sand fraction in addition to the very fine sand (0.10-0.05 mm) or the medium sand (0.50-0.25 mm) fractions were used to indicate a lithologic discontinuity within individual pedons. These size-fractions dominated the sand fraction and were consisted in most parts of quartz (Table 1 and 2). The clay-free particle-size analysis indicated lithologic breaks at 47-74 cm depth, and at both 50-76 and 95-135 cm depth in the pedons AK-2 and AK-5, respectively. However, the pedons AK-1, AK-3 and AK-4 as well as all the profiles in Bende were likely to have homogeneous types of parent materials. These findings were in agreement

Table 1 Particle-size distribution as the clay-free basis in the soils of the study sites.

Horizon	Depth (cm)	Texture	VC sand (2-1 mm)	C sand (1-0.5 mm)	M sand (0.5-0.25 mm)	F sand (0.25-0.10 mm)	VF sand (0.10-0.05 mm)	Total sand	silt (50-2 μm)
Pedon AK-1									
Ap	0-20	SiCL	0.0	2.6	4.5	9.6	5.7	22.4	77.6
A2	20-40	SiL	1.6	3.6	6.2	14.1	6.1	31.6	68.4
Bwg1	40-81	CL	2.6	2.9	4.5	17.1	17.6	44.7	55.3
Bwg2	81-111	SiL	0.0	3.5	5.1	10.3	9.8	28.7	71.3
Bwg3	111-170	SiL	0.0	3.5	4.2	11.1	9.9	28.7	71.3
BCg	170-194	L	0.0	1.5	4.6	6.7	9.4	22.2	77.8
Pedon AK-2									
Ag	0-28	SiCL	0.0	3.1	4.7	6.8	6.9	21.5	78.5
A2g	28-47	CL	3.7	4.6	5.2	22.1	11.3	46.9	53.1
2Bwg	47-74	SiCL	0.0	4.1	3.1	5.2	6.5	18.9	81.1
2Bg	74-109	SiC	7.8	8.0	5.2	7.1	5.2	33.3	66.7
2BCg	109-150	SiCL	0.0	3.2	4.8	7.0	7.0	22.0	78.0
Pedon AK-3									
Apg	0-28	C	0.0	1.6	2.2	4.5	2.4	10.7	89.3
A2feg	28-54	L	4.9	4.5	7.7	13.8	14.1	45.0	55.0
B1g	54-100	C	2.8	3.4	9.5	17.8	19.1	52.6	47.4
B2g	100-158	C	6.5	6.4	7.7	23.3	13.8	57.7	42.3
Pedon AK-4									
Apg	0-30	C	6.4	9.2	12.5	22.8	11.6	62.5	37.5
Bwg1	30-50	SiCL	0.0	3.9	5.0	7.9	4.7	21.5	78.5
Bwg2	50-98	SiCL	0.0	3.9	5.7	9.4	7.0	26.0	74.0
BCg	98-148	SiCL	0.0	3.5	4.4	14.4	6.3	28.6	71.4
Pedon AK-5									
Ap	0-20	SiCL	0.0	7.6	7.9	5.5	8.1	29.1	70.9
AB	20-50	SiCL	0.0	9.4	6.1	7.2	6.6	29.3	70.7
2Bw	50-76	SL	6.1	6.2	21.1	14.2	14.6	62.2	37.8
2Bwfeg	76-95	L	10.3	11.6	6.0	13.5	10.0	51.4	48.6
3BCg	95-135	LS	12.6	18.2	23.3	21.2	15.4	90.7	9.3
3Cg	135-170	SL	14.6	16.5	25.0	17.0	16.5	89.6	10.4
Pedon BD-1									
Ap	0-21	SCL	14.6	18.2	17.0	26.4	17.9	94.1	5.9
Bw1	21-50	C	13.8	17.3	7.3	15.7	9.3	63.4	36.6
Bwg2	50-85	C	0.0	10.9	14.8	19.1	11.7	56.5	43.5
Bwg3	85-100	C	0.0	14.3	15.2	22.1	9.8	61.4	38.6
BCg	100-158	C	13.5	14.1	8.1	17.1	11.3	64.1	35.9
Pedon BD-2									
Ap1	0-20	C	8.3	9.6	16.6	24.7	14.5	73.7	26.3
Apg2	20-52	SC	7.8	12.3	11.9	32.7	12.5	77.2	22.8
Bwg1	52-89	C	18.5	12.9	9.6	21.5	16.7	79.2	20.8
Bwg2	89-120	C	14.0	24.3	10.0	13.7	8.5	70.5	29.5
BCg	120-165	SCL	11.5	14.6	23.3	28.3	12.0	89.7	10.3
Pedon BD-3									
Ap	0-20	SC	7.5	12.1	17.5	26.2	19.8	83.1	16.9
Bw1	20-73	SC	5.0	17.8	14.1	34.7	11.2	82.8	17.2
Bw2	73-100	SCL	6.5	16.4	12.0	27.5	28.7	91.1	8.9
BC	100-152+	SL	8.0	17.3	13.4	36.3	17.5	92.5	7.5
Pedon BD-4									
Ap	0-18	SL	16.6	18.6	36.8	10.5	12.1	94.6	5.4
Bw1	18-30	SCL	10.5	17.2	32.2	21.1	11.1	92.1	7.9
Bw2	30-75	SCL	13.3	19.2	27.5	17.2	16.8	94.0	6.0
BC	75-144	CL	8.8	14.4	37.4	18.7	16.3	95.6	4.4

SiCL, silty clay loam; SiL, silty loam; CL, clay loam; L, loamy; SiC, silty clay; C, clayey; SL, sandy loam; LS, lomy sand; SC, sandy clay; SCL, sandy clay loam

Table 2 Mineralogical composition in the fine sand fraction (0.25-0.10 mm) from the soils at the study sites.

Horizon	Depth (cm)	Feldspars	Muscovite	Quartz	Zircon	Biotite	Tour-maline	Opaque
Pedon AK-1								
A2	20-40	(X)	(X)	XXXX	(X)	—	—	—
Bwg2	81-111	—	(X)	XXXX	—	—	—	—
BCg	170-194	—	(X)	XXXX	—	(X)	—	—
Pedon AK-2								
Ag	0-28	X	—	XXXX	—	—	—	—
2Bwg	47-74	(X)	—	XXXX	—	X	—	(X)
2BCg	109-150	—	—	XXXX	—	X	—	—
Pedon AK-5								
AB	0-20	—	(X)	XXXX	—	—	—	—
2Bwfeg	76-95	—	(X)	XXXX	—	(X)	(X)	(X)
3BCg	95-135	—	(X)	XXXX	—	—	—	—
Pedon BD-1								
Ap1	0-21	(X)	—	XXXX	(X)	—	—	—
Bwg2	50-85	(X)	X	XXXX	(X)	X	—	(X)
BCg	100-158	(X)	X	XXXX	—	X	—	—
Pedon BD-3								
Ap	0-20	(X)	(X)	XXXX	(X)	—	—	—
Bw1	20-73	—	(X)	XXXX	—	—	—	—
BC	100-152	—	(X)	XXXX	—	—	—	—

—, absent; (X), trace; X, scarce; XXXX, predominant with the field morphologic characteristics and irregular organic C distribution (Chapter 4).

Petrographic investigation revealed that heavy minerals constituted only a very small portion and quartz comprised most of the grains counted in the fine-sand fractions (Table 2). Other resistant minerals such as zircon and tourmaline were also identified in the soils. The contents of weatherable minerals such as feldspars, muscovite, and biotite were very low and were usually found in subsoils. The color of fine sand grains of the hydromorphic horizons in the pedons ranged from colorless to light gray.

The XRD diagrams of the clay fraction in selected samples from Abakaliki are shown in Fig. 1. A basal reflection around 1.4 nm on air-dried Mg-clay and its shift to nearby 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 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 was evidence for the presence of smectite-illite interstratified (S/I) (Sawhney 1989). The structure of I/S seemed to have a irregular interstratification because of the absence of a significant diffraction at the low angle range. A remained shoulder of the peak at 1.0 nm toward the lower 2θ angle on K specimens at 300 and/or 550°C indicated the presence of hydroxyl-Al interlayered 2:1 clays (HICs) in collaboration with incomplete expansion of interlayer space (001 reflection) with glycerol solvation (Barnhisel and Bertsch 1989). Pretreatment with Na-citrate prior to the XRD measurement could remove the hydroxyl-Al in the interlayers of HICs, which resulted in an increase in its expandability after glycerol permeation and shrinkability after heating (Tamura 1958; Barnhisel and Bertsch 1989). The coexistence of hydroxyl-Al-interlayered smectite and -vermiculite in HICs of the Abakaliki soils is shown in Fig. 2. With

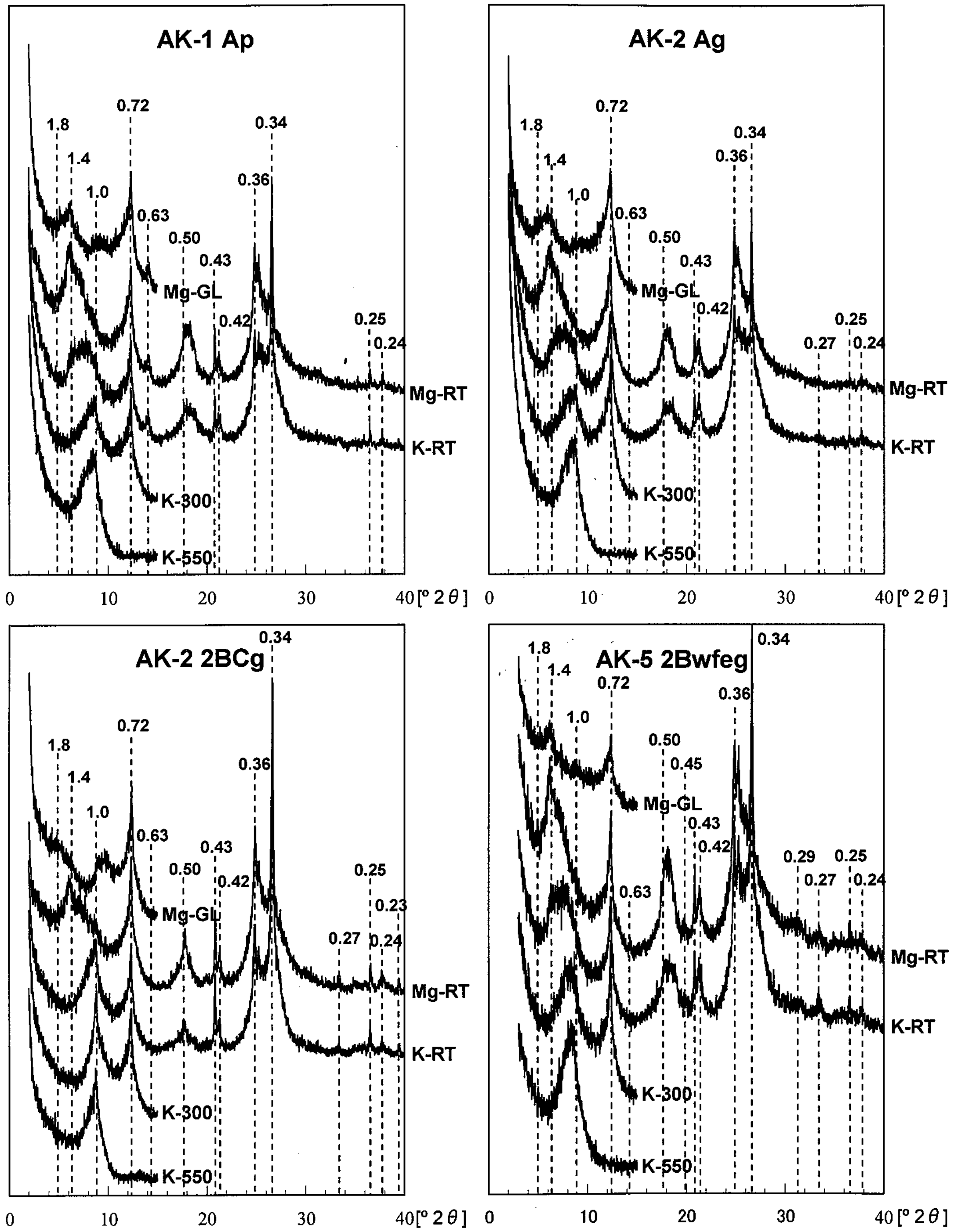

Figure 1 Selected XRD patterns of the clay fraction (< 2 μm) from the soils in Abakaliki. Numeric within the figure represents *d*-spacing in nanometers. Mg-GL, Mg-clay with glycerol permeation; Mg-RT, Mg-clay at room temperature; K-RT, K-clay at room temperature; K-300, K-clay at 300°C ; K-550, K-clay at 550°C.

Na-citrate treatment, there were distinct peaks nearby 1.8 nm and around 1.4 nm after Mg saturation and glycerol salvation, as well as around 1.2 nm and nearby 1.0 nm on air-dried K-saturated specimens, respectively. The diffraction at 0.72 nm on K-clay disappeared by heating at 550 °C, which showed the existence of kaolinite. In addition, there was 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. As a result of the XRD analysis, the soils in Abakaliki contained kaolinite, vermiculite, smectite, S/I, HICs, illite and fine-grained quartz. Lepidocrocite and goethite could also be found at some soil horizons. Meanwhile, the soils of Bende were characterized by the predominance of smectite and kaolinite in the clay fraction (Fig. 3). A small amount of HICs, illite, lepidocrocite, goethite, quartz and/or K-feldspars (0.33 nm) were also found at some horizons. At variance with the soils of Abakaliki, HICs in Bende were probably composed of solely hydroxyl-Al interlayered smectite because no vermiculite was detected in the soils of Bende. The width at the half height of some diagnostic peaks, e.g. (001) and (002) reflection of kaolinite, in the soils of Abakaliki was apparently larger than that of Bende (compare Fig. 1 with Fig. 3) indicating lower crystallinity (degree of structural order) of soil minerals in the soils of Abakaliki.

The clay mineralogical composition at selected horizons in representative pedons is summarized in Table 3. In the soils of Abakaliki, the content of 2:1 type clay minerals (vermiculite, smectite, HICs and I/S) generally decreased with soil depth, but an opposite trend was observed in the distribution of kaolinite. A similar trend was found in Bende where the content of smectite increased with soil depth in contrast to that of kaolinite. In particular, the content of HICs was obviously decreased downwards the pedons regardless of the difficulty in the proper quantification of individual 2:1 type phillosilicates. The soils on the downslope (BD-1) apparently contained more 2:1 type clay minerals but less kaolinite than that on the upslope (BD-3) in Bende.

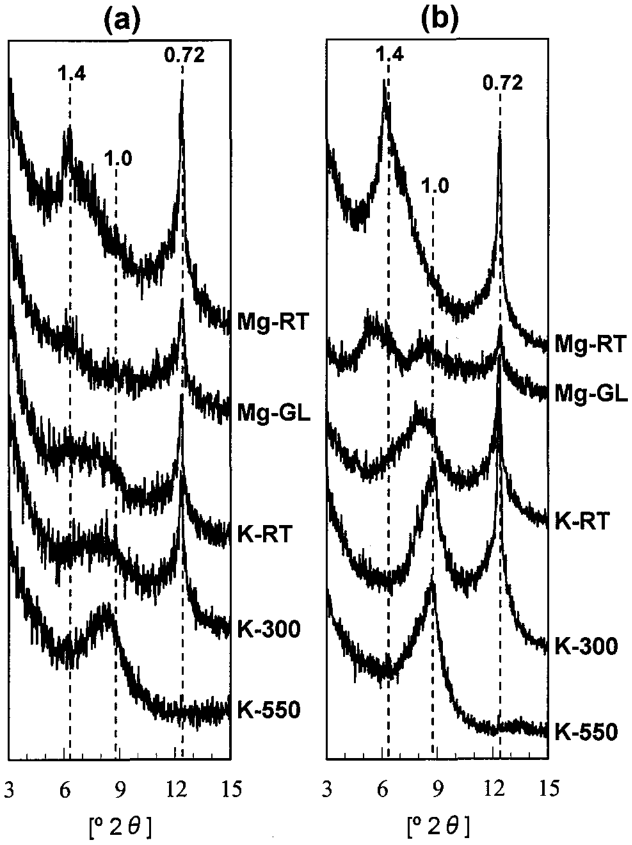

Figure 2 XRD patterns of the clay fraction (< 2 μm) from the Bwg1 horizon of the pedon AK-4 in Abakaliki, before (a) and after (b) the treatment with Na citrate. Numeric within the figure represents *d*-spacing in nanometers. Mg-GL, Mg-clay with glycerol permeation; Mg-RT, Mg-clay at room temperature; K-RT, K-clay at room temperature; K-300, K-clay at 300°C ; K-550, K-clay at 550°C.

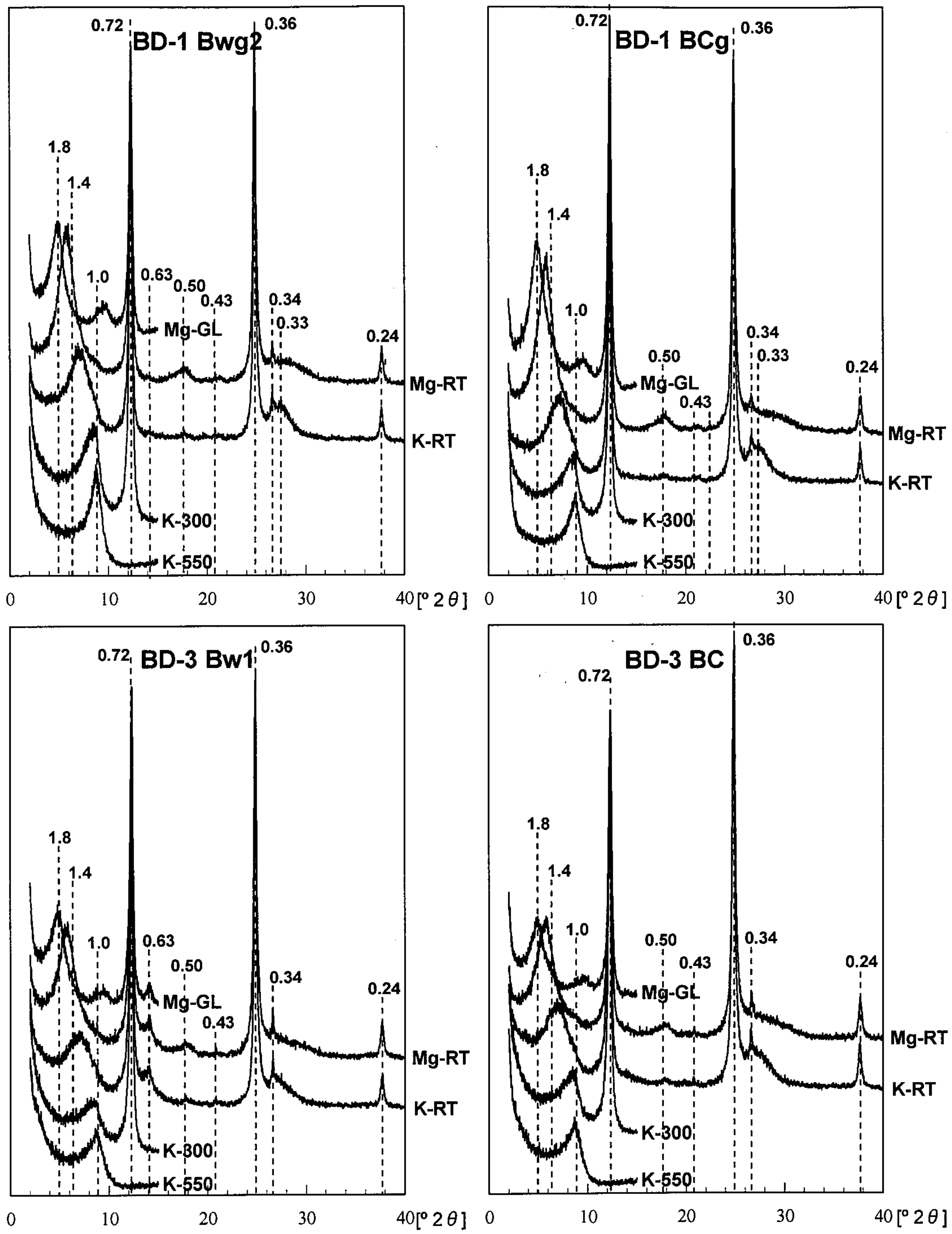

Figure 3 Selected XRD patterns of the clay fraction (< 2 μ m) from the soils in Bende. Numeric within the figure represents *d*-spacing in nanometers. Mg-GL, Mg-clay with glycerol permeation; Mg-RT, Mg-clay at room temperature; K-RT, K-clay at room temperature; K-300, K-clay at 300°C ; K-550, K-clay at 550°C.

Table 3 Mineralogical composition in the clay fraction (< 2 μm) from the soils at the study sites.

Horizon	Depth (cm)	Kaolinite	Illite	Vermiculite	Smectite	Smectite-illite	HIC	Quartz	Others
Pedon AK-1									
A2	20-40	XXX	X	XX	X	XX	XX	XX	Lepidocrocite X; Goethite X
Bwg2	81-111	ND	ND	ND	ND	ND	ND	ND	ND
BCg	170-194	ND	ND	ND	ND	ND	ND	ND	ND
Pedon AK-2									
Ag	0-28	XXX	(X)	XX	X	XX	XX	XX	Goethite X
2Bwg	47-74	XXX	X	XX	X	XX	X	XXX	Goethite X
2BCg	109-150	XXXX	X	XX	X	X	—	XXX	Chlorite (X); Goethite X
Pedon AK-5									
AB	0-20	XXX	—	XX	X	XX	XX	XXX	Lepidocrocite X; Goethite X
2Bwfeg	76-95	XXX	(X)	XX	(X)	XX	X	XXX	Lepidocrocite (X); Goethite X
3BCg	95-135	ND	ND	ND	ND	ND	ND	ND	ND
Pedon BD-1									
Ap1	0-21	XXX	(X)	—	XXXX	—	X	X	Lepidocrocite (X); Goethite (X)
Bwg2	50-85	XXX	(X)	—	XXXX	—	(X)	X	Feldspars X; Lepidocrocite (X); Goethite (X)
BCg	100-158	XXX	X	—	XXXX	—	—	X	Feldspars (X) Lepidocrocite (X); Goethite (X)
Pedon BD-3									
Ap	0-20	XXXX	—	—	XXX	—	X	X	Lepidocrocite (X); Goethite (X)
Bw1	20-73	XXX	—	—	XXXX	—	X	X	Lepidocrocite X
BC	100-152	XXX	(X)	—	XXXX	—	(X)	X	Lepidocrocite (X)

—, absent; (X), trace; X, scarce; XX, common; XXX, abundant; XXXX, predominant

HIC: hydroxyl-Al interlayered 2:1 clay; ND: not determined

As a consequence, the soils in Abakaliki and Bende were classified at family level (Soil Survey Staff 2006) as shown in Table 4.

5.4. Discussion

Formation of argillic horizons could not be observed in all examined pedons (see Chapter 4), which suggested that lessivage was not significant in the soils of Abakaliki and Bende. Hence, ,secondary minerals would form in situ under hydromorphic conditions without significant clay movement. Lithologic discontinuity in the pedons AK-2 and AK-5 (Table 1) suggested a substantial disruption during the sedimentation in Abakaliki, while the sedimentation process in Bende might happen under relatively calm water movement.

No significant differences in mineralogical composition of the fine-sand fractions could be detected between Abakaliki and Bende (Table 2) despite the disparity of the nature and age of parent materials as well as clay mineralogy (Table 3). Predominance of quartz in the fine-sand fraction resulting from severe weathering processes could obscure inheritance of original geological components, which was very common in lowland soils of West Africa (Chapter3). Only a small amount of muscovite and biotite was found at some subsurface horizons regardless of their instability under general pedogenic environments (Allen and Hajek 1989). In particular, these minerals in addition to feldspars remained mainly at the valley bottoms (e.g. the pedons AK-2 and BD-1). Therefore, it appears that high water tables and/or saturated moisture conditions have slowed down the weathering of these wheatherable minerals. Accordingly, they could still persist even in a minor content in the investigated soils despite the predominance of resistant minerals such as quartz, zircon and tourmaline in the investigated soils. Prolonged water saturation also has led to the loss of Fe from the soils resulting in the light gray dominant color of the grains. Goethite-lepidocrocite associations were common in soils with hydromorphic conditions (Schwertmann and Taylor 1989).

Table 4 Taxonomic classification of the soils at the study sites.

Pedon	Classification
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
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

The clay mineralogy of the soils at the study sites was characterized by a relatively high content of 2:1 type phyllosilicates (Table 3), which was distinctive among the soils in West Africa (Chapter 2). 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 south-western Nigeria. Okusami *et al.* (1987) documented the predominance of kaolinite in some alluvial soils of Nigeria. Meanwhile, 2:1 clay minerals, e.g. smectite, tended to be observed in poorly-drained soils in addition to kaolinite (Jungerius and Levelt 1964; Gallez *et al.* 1975; Ojanuga 1979; Eshett *et al.* 1989; 1990; Møberg and Esu 1991). However, the relatively high content of 2:1 type phyllosilicates in the soils of Abakaliki and Bende would be responsible for the distinctive nature of parent materials rather than pedogenic environments (e.g. topography and hydrology) since predominance of kaolinite was very common in lowland soils of West Africa (Chapter 2). The soils in Abakaliki and Bende had developed from shale materials in Cretaceous and Tertiary era, respectively (Federal Survey 1992), whereas most soils of West Africa derived from Precambrian igneous or metamorphic rocks (Windmeijer and Andriesse 1993). The soils in Abakaliki which are derived form the elder geological materials showed a lower crystallinity than those of Bende. This correlated with a less content of kaolinite but a higher amount of 2:1 type phyllosilicates in the soils in Abakaliki than those in Bende. From that a more advanced stage of the soil-weathering process was suggested for the sites in Abakaliki.

Partial chloritization of smectite and/or vermiculite as indicated by the entry of HICs in the soils of Abakaliki and Bende could often be observed under hydromorphic conditions (Wakatsuki *et al.* 1984; Barnhisel and Bertsch 1989). This would be responsible for the interlayering of hydroxyl-Al under *ferrolysis* (Brinkman 1970), which was also suggested by the distribution and saturation percentage of exchangeable Al in the investigated pedons (Chapter4). The content of HICs decreased with soil depth because the surface horizons could be more susceptible to water movement and thus to the fluctuation of redox conditions which would have enhanced the formation of HICs. Meanwhile, HICs were more common in the soils of Abakaliki than Bende. Rapid change in the depth of water table as indicated by the presence of Fe/Mn concretions in the pedons (Chapter 4) might be responsible for the preferential occurrence of HICs in the soils of Abakaliki. The favorable formation of HICs in Abakaliki as compared to Bende also might be attributed to the period of rice farming. Wakatsuki *et al.* (1984) reported significantly detectable clay mineralogical alterations including hydroxyl-Al interlayering in smectite in soils which were under paddy cultivation for more than 75 years. Clay lattice destruction 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 the low effective cation exchange capacity of the soils in Abakaliki and Bende in spite of their relatively high clay contents, as reported in Chapter 4. The influence of lithologic discontinuities on clay mineralogy in the pedons AK-2 and AK-5 was not conspicuous (Table 3). The content of quartz in the pedon AK-2, however, was exceptionally higher in the surface horizons than in the subsoils, which might reflect multi-parent material source. The toposequential clay transportation due to the runoff or erosion was suggested in Bende. Hereby, 2:1 type clay minerals (i.e. smectite and HICs) have relatively accumulated more in the lower position in contrast to kaolinite. This would be attributed to the rolling topography of Bende, which was well associated with the accumulation of exchangeable bases at the bottom.

The findings of the present study suggested that the extensive development of the *sawah** fields for sustainable rice production is recommended in Abakaliki if substantial resource investment is available. The gently undulating topography and good water holding capacity would be advantageous for land consolidation and water management at this site. In contrast, the rolling topography led to difficulties in an extensive land preparation at the sites in Bende. Better geological fertilization processes[†], however, could be more beneficial under the low-input subsistence agriculture in Bende than in Abakaliki.

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CHAPTER 6

Summary

Physicochemical, mineralogical and morphological characteristics of soils were investigated intensively in inland valleys of Southeast Nigeria as well as extensively in lowlands (inland valleys and flood plains) of West Africa to gain basic information towards the sustainable rice production in the region.

First of all, mineralogical composition in the clay fraction (< 2 μm) of 87 topsoil (0–15 cm) samples from inland valleys and flood plains in seven West African countries, namely Cote d'Ivoire, Ghana, Guinea, Mali, Niger, Nigeria and Sierra Leone, was examined using X-ray diffraction analysis (Chapter 2). The clay fraction of these samples consisted of 68.4% of 7 Å minerals (low-activity clays such as kaolin minerals), 26.6% of 14 Å minerals (relatively high-activity clays such as smectite and vermiculite) and 5.1% of 10 Å minerals (illite or clay micas), and showed a high variability in the composition. With respect to the soil material classification based on the relative abundance of these three types of minerals, Type 7 (rich in 7 Å minerals) accounted for 42.5% of the total samples, while 39.7% of all the samples were Types 7-10 and 7-14 with a predominance of 7 Å minerals and with negligible amounts of 10 and/or 14 Å minerals, respectively. Type 14-7 accounted for 17.2% of the total samples and was only recorded in Nigeria. The other clay mineral types (i.e. Types 7-10-14, 14, 10, 10-7, 10-14 and 14-10) that were composed mainly of 10 and/or 14 Å minerals, were hardly found in the West African lowland soils, whereas Types 14 and 7-10-14 were observed in a vertic soil of Southeast Ghana and in northern Ghana, respectively. In contrast, no significant differences in the clay mineralogical composition were found between the IV and FP soils. Geographical distribution of the soil types showed that the soils in the eastern part of West Africa contained more 14 Å and 10 Å minerals than those in the western part. Although the effect of agro-climatological differences was not conspicuous, soils in the Sahel and Sudan savanna zones showed a higher percentage of 14 Å clay minerals than those in the Guinea savanna and equatorial forest zones. The findings were as follows: (1) the low fertility status of the lowland soils in the region was closely associated with their poor mineralogical characteristics (i.e. predominance of 1:1 type clay minerals and a lower amount of 2:1 type clay minerals), (2) no significant differences in the mean clay mineralogical composition were observed between the IV and FP soils, indicating that the lower fertility of the IV soils mainly resulted from lower clay content, (3) the clay mineralogy of the West African lowland soils was more strongly influenced by the nature of the parent materials than by the climatic conditions and relief.

Secondary, the fine-sand fraction (20-212 μm) of the samples used in Chapter 2 was examined by the x-ray diffraction analysis and petrographic investigation so as to elucidate their primary mineral composition (Chapter 3). The mineralogical composition in the fine-sand fraction was predominantly consisted of quartz. A small amount of feldspars was also usually observed but other weatherable minerals were almost or completely absent in these samples. These findings suggested that quartz, a highly resistant mineral to the weathering, predominantly remained in the lowland soils of West Africa resulting from severe weathering over a long period.

Subsequently, physicochemical and morphological properties of the soils were investigated in two inland valleys from Abakaliki and Bende, Southeast Nigeria, where the soils derived from shale materials (Chapter 4). The result of particle size analysis suggested that the soils at both sites were fine-silty, fine-loamy or clayey and thus would have the ability of retaining high amount of water. On the other hand, the higher content of the clay and silt in the Abakaliki soils would enhance much more water retention than the Bende ones. The soils in Abakaliki, except for some subsoil horizons, generally had acidic reactions, low contents of exchangeable bases (Ca, Mg, K and Na) and high amounts of exchangeable acidity (Al and H) for which leaching effects under high precipitation in the area would be implicated. Bray-1 P values of these soils were generally low under such acidic conditions, while organic C and total N were found at relatively high levels in particular at the surface horizons reflecting large biomass production under humid climate. The Bende soils showed similar chemical properties to Abakaliki except for relative accumulation of exchangeable bases throughout the profile on the downslope possibly due to the rolling topography. This suggested that geological fertilization, i.e. afflux of nutrients released during the soil formation in the upland into the lowland, was more beneficial in Bende than Abakaliki. From the findings of the present study, we concluded that the soils both in Abakaliki and Bende had good texture for the *sawah* development but their poor chemical properties would be constraints for the agricultural production.

Finally, clay mineralogy and parent material nature were investigated in the study sites of Chapter 4 (Chapter 5). The clay-free size analysis in collaboration with the field morphological observation indicated lithologic discontinuities at subsurface horizons in a couple of pedons in Abakaliki. In contrast, all the pedons in Bende could consist of a homogenous parent material. Petrographic analysis revealed that quartz predominantly comprised the fine-sand fraction, while relatively weatherable minerals such as biotite, muscovite and feldspars hardly coexisted in these soils. This could reflect intensive and prolonged weathering processes under the humid climate in the region. The clay mineralogy of the soils was a mixture of kaolinite, vermiculite, smectite, smectite-illite interstratified (S/I), hydroxyl-Al interlayered 2:1 clays (HICs) and illite along with fine-sized quartz in Abakaliki. Vertical distribution of these minerals in the soils of Abakaliki showed that the mineralogical composition was little affected by the lithologic discontinuity. In contrast, smectite, which was interlayered with hydroxyl-Al to a minor extent, and kaolinite were predominant in the soils of Bende. The content of HICs remarkably decreased with depth in the soil profile at both sites suggesting natural occurrence of HICs. This could be due to interlayering of hydroxyl Al in 2:1 phyllosilicates such as smectite and vermiculite under hydromorphic conditions, which was involved in the *ferrolysis* process. Lessivage was not significant at both sites, whereas high water table and/or saturated moisture conditions have slowed the in situ weathering of minerals so that weatherable minerals still persist in the soils. On the other hand, clay lattice destruction under the *ferrolysis* would reduce a nutrient holding capacity of these soils regardless of their relatively high contents of 2:1 type phyllosilicates which was originated from shale as the parent material in the region.

CHAPTER 7

摘　要

西アフリカにおいて持続可能な稲生産システムを開発するための基礎情報として，土壌の理化学性，鉱物性，および，形態特性について，同地域の低地（内陸小低地および氾濫原）を広範囲に，また，ナイジェリア東南部の内陸小低地を集中的に調査した。

まず初めに，同地域7カ国（象牙海岸，ガーナ，ギニア，マリ，ニジェール，ナイジェリア，シエラレオネ）に分布する内陸小低地および氾濫原より採取した表土（0-15 cm）試料87点の粘土鉱物組成をX線回折分析により検討した。その結果，分析した試料中の粘土画分（< 2μm）が平均で68.4%の7Å鉱物（カオリン鉱物など低活性粘土），26.6%の14Å鉱物（スメクタイト，バーミキュライトなど比較的活性の高い粘土）および5.1%の10Å鉱物（イライトあるいは和水雲母）より構成されていることが明らかになった。これら三種類の鉱物の相対存在比に基づいた土壌材料分類法において，分析した全試料の42.5%が7型（7Å鉱物を顕著に含む．以下同様）に分類され，39.7%が7-10型（7Å鉱物が主だが，少量の10Å鉱物も含む。以下同様。）あるいは7-14型に分類された。14-7型は全試料の17.2%を占め，すべてナイジェリアに分布していた。西アフリカの低地土壌において，他の土壌粘土鉱物型（7-10-14型，14型，10型，10-7型，14-10型）はほとんど認められなかったが，ガーナ東南部および北部において14型および7-10-14型がそれぞれ観察された。一方，内陸小低地と氾濫原の粘土鉱物組成に有意な差異は認められなかった。土壌粘土鉱物型の地理的分布により，西アフリカ東部の土壌は，同西部の土壌より14Å鉱物と10Å鉱物を多く含有することが示された。農業生態的な差異の影響は明白ではないが，サヘルおよびスーダンサバンナ地帯の土壌は，ギニアサバンナおよび赤道森林帯の土壌よりも14Å鉱物の割合が高かった。本研究の結果は以下の通りである。（1）Issaka *et al.* (1997)およびBuri *et al.* (2000)により報告にされている西アフリカ地域土壌の低肥沃度は，その貧粘土鉱物特性（1:1型粘土鉱物が優占し，2:1型粘土鉱物含量が

低い)とよく関連していた。(2)内陸小低地と氾濫原土壌では粘土鉱物組成の平均値に違いはなかったため，氾濫原よりも内陸小低地の方が土壌の肥沃度が低いのは，粘土含量が高いことに起因すると考えられた。(3)西アフリカの低地土壌の粘土鉱物特性は，気候や地形よりも母材の性質の影響をより強く反映していた。

次に，前章(第二章)と同じ試料の細砂画分(20-212 μm)を用いて，西アフリカに分布する内陸小低地および氾濫原の表層土壌(0-15 cm)の一次鉱物組成をX線回折分析および岩石学的観察により検討した。すべての試料において石英が卓越しており，少量の長石は認められたが，他の易風化性鉱物はほとんど存在しなかった。西アフリカの低地土壌では，長年に渡る強い風化作用の結果として，易風化性鉱物のほとんどが消失し，石英のような風化抵抗性の高い鉱物が顕著に残存していることが示唆された。

続いて，東南ナイジェリアのアバカリキとベンデにある二つの内陸小低地の農業ポテンシャルおよび土壌生成過程を考察するため，それら頁岩質母材に由来する土壌の理化学的および形態学的特性を調査した。粒径組成分析の結果，両サイトの土壌は細シルト質，細壌土質あるいは粘土質であり，高い水分保持容量を有していると思われる。しかしながら，粘土およびシルト含量のより高いアバカリキの土壌がより多量の水分を保持できると考えられた。アバカリキの土壌は，下層を除いて一般的に酸性であり，交換性塩基含量が低く，交換酸度量が大きかった。このことは当該地域の高い降水量による洗脱の影響が関係していると思われる。これら土壌のブレイ1法による可給態リン酸の値は酸性条件のために概ね低いが，有機態炭素および全窒素含量は湿潤気候下での高いバイオマス生産量を反映して，とりわけ表層土壌において比較的高いレベルで認められた。ベンデ土壌はアバカリキに類似した化学特性を示すが，例外的に緩斜面下部の土壌断面おいて交換性塩基の相対的な集積が確認された。このことは，地質学的施肥効果(アップランドにおける土壌生成と低地への養分の集積)がアバカリキよりもベンデにおいてより大きいことを示唆している。本研究の結果より，アバカリキおよびベンデの土壌は両方

とも水田開発に望ましい土性をもつが，貧相な化学性が農業生産の制約になると結論付けた。

最後に，東南ナイジェリアのアバカリキとベンデにある二つの内陸小低地において，粘土画分（< 2 μm）および細砂画分（0.25-0.10 mm）の鉱物組成と粘土を除いた粒径組成を調査した。野外形態学的観測と共に，粘土を除外した粒径組成分析により，アバカリキの 2 つのペドンの下層土において母材の不整合性が示された。しかし，ベンデではすべての土壌断面が単一母材より生成したと考えられた。岩石学的調査により，これら土壌では細砂画分に石英が卓越しており，黒雲母，白雲母，長石のような他の易風化性鉱物はほとんど混在していないことが明らかになった。このことは調査地域の湿潤気候下における長年に及ぶ強い風化作用を受けた結果であると考えられる。アバカリキ土壌の粘土鉱物はカオリナイト，バーミキュライト，スメクタイト，スメクタイト－イライト混合層鉱物，層間にヒドロキシアルミニウムを固定した 2:1 型鉱物（HICs）およびイライトの混合物であり，細粒の石英も含んでいた。一方，ベンデ土壌ではその層間にヒドロキシアルミニウムを低度にもつスメクタイトとカオリナイトが卓越していた。アバカリキにおいて，母材の不整合性は鉱物組成にほとんど影響していなかった。両研究サイトにおいて，HICs の含量が土壌深度と共にはっきりと減少したため，HICs は自然生成であることが示唆された。HICs の生成はフェロリシス作用の結果であると考えられ，酸化還元的条件の下でスメクタイトやバーミキュライトのような 2:1 型層状ケイ酸塩鉱物にヒドロキシアルミニウムが層間固定されることに起因する。両サイトにおいて粘土の下層への移動は確認されなかった。したがって，地下水位が高いことと飽和水分条件により，原位置で鉱物の風化がゆっくりと進んだため，土壌中にまだ易風化性鉱物が残存していると考えられる。他方，本研究地域の土壌は，頁岩質母材に由来して 2:1 型粘土鉱物の含量が比較的高いにもかかわらず，フェロリシスによる粘土結晶構造の崩壊により，土壌の養分保持容量が小さくなったことが推察される。

LIST OF PUBLICATIONS

Abe SS, Masunaga T, Yamamoto S, Honna T, Wakatsuki T 2006: Comprehensive assessment of the clay mineralogical composition of lowland soils in West Africa. ***Soil Science and Plant Nutrition*** 52: 479-488. CHAPTER 2

Abe SS, Oyediran GO, Masunaga T, Yamamoto S, Honna T, Wakatsuki T 2007: Primary mineral characteristics of topsoil samples from lowlands of seven West African countries. ***Japanese Journal of Tropical Agriculture*** (in press). CHAPTER 3