Pedological investigation of benchmark soils in the upland area of rainforest southwestern Nigeria

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The study characterized the benchmark soils within the rainforest region of southwestern Nigeria and established their taxonomic (USDA & FAO/UNESCO) and fertility capability classes. Eight profile pits were established and described. Rock and soil samples were collected for laboratory analyses. Soil samples were analyzed for some physical, chemical and mineralogical properties. Fine sand fraction was separated into heavy and light minerals with bromoform. Thin section of the bedrock sample and slides of fine sand fraction were prepared and examined under a petrographic microscope. Data were subjected to descriptive and inferential statistics. The soils were fairly deep, intensely weathered and well-drained with lithologic discontinuity at the lower slope. Bulk density values increased with profile depth varying from 1.17 - 1.67 g/cm^{-3}. Acidity was low, ranging between 5.1 - 6.5, organic matter content ranged from low to medium, with higher values at the surface horizons. Total nitrogen content ranged from low to medium, while available phosphorus ranged from medium to high on the surface soils and from low to medium in the subsurface horizons. The three methods used to determine cation exchange capacity (CEC) showed significant positive correlation ($P \leq 0.01$) with organic matter. However, values of CEC by $BaCl_2$-TEA (pH 8.2) method were higher and significantly different from those by NH_4OAc (pH 7) and effective cation exchange capacity (ECEC) methods. Quartz dominated the primary minerals in the bedrock. Rutile and opaque minerals dominated the heavy mineral portion of the fine sand fraction. The upper and mid slope soils were classified as Typic Isohyperthermic Paleustults and Plinthic Isohyperthermic Paleustults (USDA) while they are Chromic Lixisol and Plinthic Lixisol, respectively, in the FAO/UNESCO system. Fertility capability units were SCehik and SCrehik, respectively. Agronomic constraints of the soils were high leaching potential (e), high soil acidity (h), high P fixation potential (i), low content of weatherable minerals (k) and high gravel content (r).

Keywords: Pedology, upland soils, southwestern Nigeria

Soils provide food, fodder and fuel to meet basic human and animal needs. The growth in human population leads to increased need for food. This often results in more pressure on the soil. However, the potential of a soil to produce food is limited by its intrinsic characteristics, agro-ecological settings and management. Nigeria is endowed with abundant soil resources. It has a total land area of 923,768 km^2, out of which 329,334 km^2 (36.16%) is cultivated, with 300,736 km^2 (33.02%) under arable crop production, while 28,598 km^2 (3.14%) is for permanent crop production, leaving 581,434 km^2 (63.84%) for other purposes (CIA 2016). However, low productivities have been recorded for most of these soil resources (Mbagwu 1989). One of the probable reasons is that the soils were put into agricultural production, not according to their potentials, which most of the time left the soil degraded after use. Therefore, effective productive and sustainable utilization of the land resources call for a meaningful land-use planning programme which involves in-depth pedological studies that will reveal the soils limitations and potentials.

Some minimal pedological works had been carried out in southwestern Nigeria. For example, D'Hoore (1964) grouped the soils of the region as Tropical Ferruginous. Folster et al. (1971) suggested ferrallitic pedogenesis for some well drained soils occupying the upper to lower slope positions in the area.

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Smyth and Montgomery (1962) grouped the soils of the region on the basis of environmental characteristics and profile morphology into ‘series’ and ‘association’. According to Fasina et al. (2007), a soil survey was carried out within the region between 1951 and 1962 to describe and classify the soils and assess their potentials for cacao production. Modern agriculture requires that farmers have sufficient knowledge of the capability and nutrient status of the soils intended for cultivation. Such information, when available, enables the farmer to make informed choices of crops and/or livestock that are technically feasible (Harrison 1981; Beets 1982). This has given rise to the need for soil survey and soil evaluation studies prior to agricultural land uses.

This work undertakes the pedological study of the soils of Iwo association and their general fertility capability evaluation and classification. Soils of Iwo association are parts of the benchmark soils in the region accounting for about 46% of the region’s soils. Benchmark soils are those occurring in extensive areas so that their comprehensive characterization can contribute substantially to agricultural and other developments of an area (Msanya et al. 2003). Information on the benchmark soils and the results of experiments carried out on them can be extended to soils closely related in classification and geography. Such soils can be used as standards for widespread application and are keys to agro-technology transfer. Soils of Iwo association are readily available to farmers for cultivation. There is the need to assess their potentials and constraints for sustainable productivity. Dearth of pedological information about soils in the region is a major problem hindering solution to agricultural productivity. Therefore, the objectives of this study were to characterize and establish the taxonomic (USDA & FAO/UNESCO) and fertility capability classes of the soils.

Materials and methods

The study area

The study was carried out in an upland area within the humid rainforest region of southwest Nigeria (Figure 1). The area is underlain by the Precambrian basement complex rocks (Smyth and Montgomery 1962; Rahaman 1988). The climate is hot, humid tropical with distinct dry and rainy seasons. The area is situated within latitudes 7^o 32’N and 7^o 33’N and longitudes 4^o 32’E and 4^o 34’E. It experiences approximately 8 months (March – October) of annual rainfall that is bimodal in distribution pattern with peaks in June and September. It has about 4 months (November – February) of dry season annually. The mean annual rainfall is about 1400 mm, while the mean annual temperature is 27^{o}C (Okusami and Oyediran 1985).

Field work

Prior to the field work, relevant ancillary data (topographic and vegetation maps and climatic parameters) of the study area were gathered. Selection of the soil examination points was based on the physiographic positions of soils on the landscape. Thus, a soil profile pit was established at each physiographic position (upper slope, mid slope, lower slope and valley bottom) along the toposequences. Four soil profile pits were established along each of the two toposequences, making a total of eight profile pits with 43 soil samples. Morphological description of the identified genetic horizons was done following the FAO/UNESCO (2010) guidelines for soil profile description. The multiple subsampling method (Smeck and Wilding 1980) was employed to ensure representativeness of the samples collected from a given horizon, starting from the lowest genetic soil horizon to the uppermost, in order to prevent cross-contamination of the samples. Core samples were taken from each horizon and used for bulk density determination. Rock samples were collected for thin section preparation and primary mineral identification.

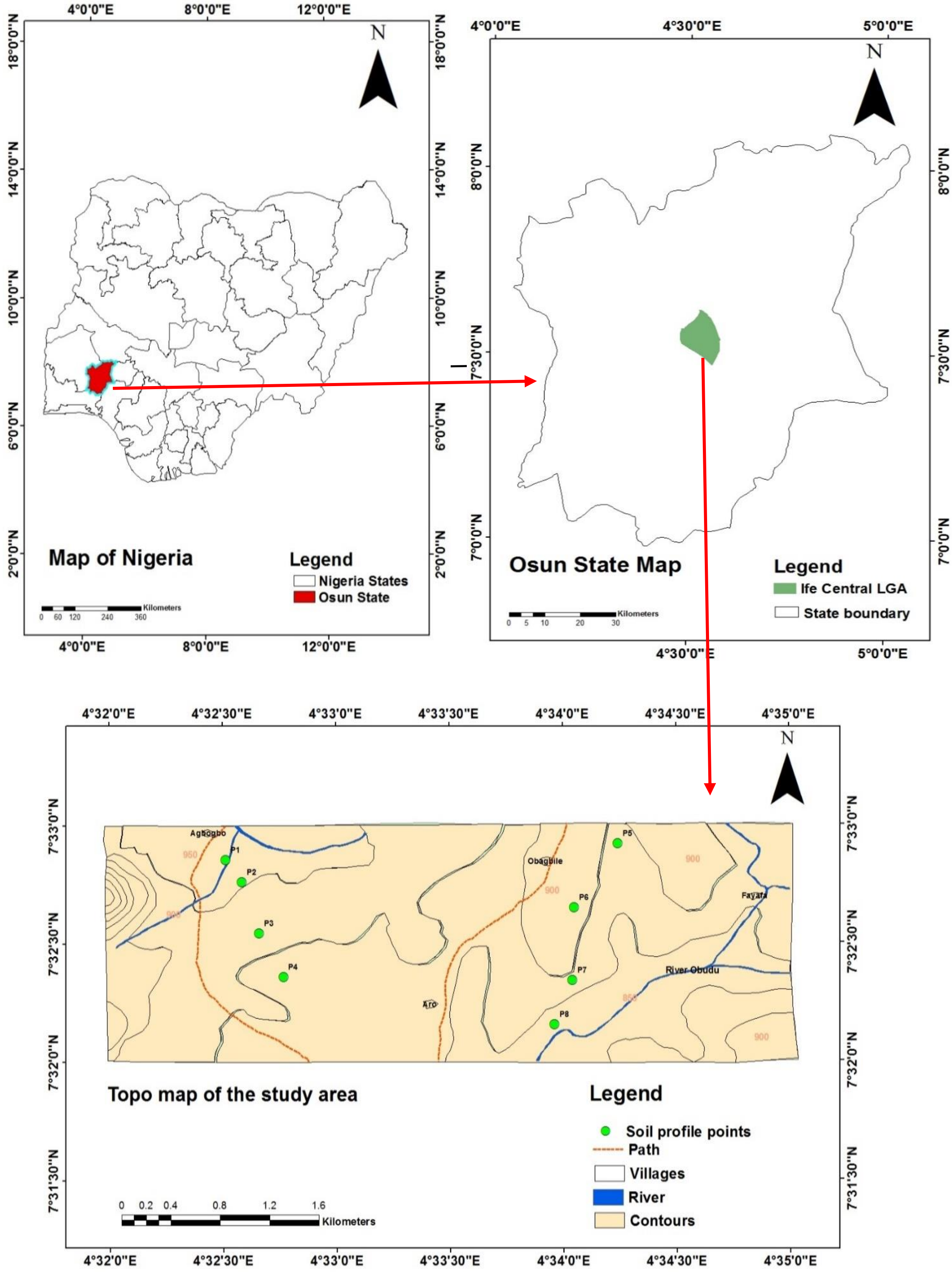


Figure 1: Maps of the study area showing the soil profile locations

Laboratory analyses

The soil samples collected were air-dried and passed through a 2 mm sieve to separate gravel content from the soil component. The less than 2 mm fraction was retained for physical, chemical and mineralogical analyses.

Physical analyses

The soil samples were analysed for the gravel content, particle-size distribution, bulk density and porosity. The gravel content was determined by finding the proportion of the soil retained by the 2 mm sieve and expressed as a percentage of the total weight of the soil. The particle size distribution analysis of the soil was carried out using the hydrometer method (Gee and Or 2002). The oven-dried total sand portion of each soil sample was fractionated into very coarse sand, coarse sand, medium sand, fine sand and very fine sand with the use of sieves (Buol et al. 2011). Each sand fraction was weighed and expressed as a percentage of the total sand. The bulk density of the soil samples was determined by the core method (Blake and Hartge 1986).

Chemical analyses

The soil pH was determined in both water and 1.0 M KCl employing a 1:1 soil/solution mixture (Thomas 1996) and the reading was taken with a digital pH meter after equilibration. Exchangeable acidity was determined by titration using 1.0 M KCl for extraction (Bertsch and Bloome 1996). Exchangeable cations were determined by extracting with neutral 1.0 N ammonium acetate solution (Thomas 1982). The concentrations of Ca, Mg, K and Na in the filtrate were then determined. Calcium, K and Na concentrations were determined using a flame photometer while Mg was determined using an atomic absorption spectrophotometer. The cation exchange capacity (CEC) was determined in 1 N ammonium acetate solution at pH 7 (neutral NH_4OAc) and $BaCl_2$-TEA solution at pH 8.2 (Sumner and Miller 1996; Burt 2014). Effective cation exchange capacity (ECEC) was calculated as the summation of exchangeable cations and exchangeable Al (Sumner and Miller 1996). Organic carbon was determined using the Walkley-Black method (Nelson and Sommers 1996). Total nitrogen was determined using the Kjeldahl method (Bremner 1996), while available phosphorus was determined by the Bray-1 method (Kuo 1996).

Mineralogical analyses

From each rock sample collected from the field a rectangular block 3 mm thick was cut with a diamond saw. The block was polished to produce a flat, smooth surface free of scratches. The block was carefully cleaned and cemented to a clean microscope slide with epoxy resin (Canada balsam with R. I.=1.54). Excess material was removed with a diamond cut-off wheel and the specimen was ground to a thickness of 0.03 mm with successively finer grades of abrasive powder (carborundum/ silicon carbide). The slide was carefully cleaned and dried after which a cover slide was put on it to produce a thin section (Innes and Pluth 1970; Cady et al. 1986; Burt 2014). The thin section produced was carefully examined under petrographic microscope for identification and enumeration of mineral make-up of the bedrock (Adetayo et al. 2013; Burt 2014). The fine sand was separated into light and heavy mineral fractions with a separating funnel using bromoform with specific gravity of 2.89 under a ventilated hood. The light and heavy mineral fractions were mounted on microscope glass slide with the aid of Canada balsam for the identification and enumeration of the weatherable minerals in the sample (Burt 2014). Identification of the minerals was made according to their optical properties while the relative amount of individual minerals present in the fraction was determined by counting with the use of cross wire method (Cady et al. 1986).

Results and discussion

Parent rock and morphological characteristics of the soils

The soils of the experimental sites were derived from the basement complex rocks, predominantly coarse-grained granite and gneiss (Elueze 1982). They are the parent rocks on which the soils of Iwo association are formed (Smyth and Montgomery 1962). Since the water table varied from the crest to the valley, the colour and texture of the soils changed in response to changes in slope position and drainage pattern. Soils occupying the upper- and mid-slope positions were well-drained, non-gravelly to very gravelly sandy-clay-loam, overlying slightly gravelly to very gravelly sandy-clay to clay subsoil, while those at the lower topographic position were somewhat moderately drained. However, there was lithologic discontinuity at the lower slope soils (profiles 4 and 7) as shown by the abrupt shift in texture, resulting from deposition of colluvial material one over the other, given the position of the soil on the landscape (Buol et al. 2011).

Table 1 details the morphological description of the soils. The soils were fairly deep with depth ranging between 135 – 200 cm. Prominent resistant quartz veins which continued through the saprolite into the soils were observed at the mid slope positions of the toposequences. This observation supports the hypothesis that the soils in these locations were mainly residual and formed *in situ* (Smyth and Montgomery 1962; Ojanuga 1978; Calvert et al. 1980; Amusan 1991). The soils had dark surface horizons ranging between 0 – 9 cm and 0 – 20 cm. The colour of the soils varied from dark-reddish brown through reddish-brown to yellowish-red. The variations in colour along the slope could be attributed to differences in the physiographic positions of the profile pits as well as drainage sequence of the soils (Gerrard 1981). It could also be ascribed to increasing hydration of iron as a result of seasonal movement of ground water table. The dark-reddish brown and reddish-brown colours of soils in the higher topographical sites is an indication of good drainage (Periaswamy and Ashaye 1982; Amusan 1991). When moisture increased and drainage became poorer down the landscape, hues became yellower. The reddish hues of the subsoils at the upper and middle slope positions indicated good internal drainage and proper aeration regimes for the greater part of the year. It could also be attributed to the presence of hematite (Kantor and Schwertmann 1974; Schwertmann 1992). The bright subsurface or reddening (ferruginization) of upland subsoils often results from the mobilization and subsequent immobilization of Fe during redox cycles in soils (Buol et al. 2011). This was considered an expression of dispersion during capillary rise through the soil and progressive oxidation of the mobile Fe, thereby causing braunification (Amusan 1991). Similar colour changes along a toposequence were reported by Fagbami (1981) and Okusami and Oyediran (1985). The colour of the surface horizons ranged from yellowish red (5YR 5/8) to dark-reddish brown (5YR 3/4). The darker colour of the surface horizons, compared to the subsurface horizons, could be attributed to organic material deposition from litter, which subsequently decomposed and mineralized (Olayinka 2009). However, the colour became lighter with depth in all the profile pits examined.

The surface soil horizons were coarser in texture and became finer with depth, except where lithologic discontinuities were encountered as in profiles pits 4 and 7. This observation agrees with previous studies (Ojanuga 1978; Okusami and Oyediran 1985; Amusan 1991; Ojetade et al. 2014). A concentration of coarse gravels and stones was observed in the upper subsoil of all the horizons studied. This could have resulted from the eluviation of fine materials from the horizons. This was responsible for the fine texture of the horizons below. This hypothesis was based on the occurrence of argillic (Bt) horizons and clay skin commonly observed in soil horizons below these slightly concentrated gravel layers, as was the case at the study site (Figures 2 and 3).

The structure of the surface horizons was generally moderate medium crumb. This could have resulted from the effects of vegetal cover on the soils, since plants roots bind soil particles thereby preventing loss of soil aggregates. The subsurface structure ranged from moderate medium sub angular blocky to moderate medium angular blocky. The surface soils were non-sticky and non-plastic, while the subsurface soils ranged from slightly sticky to very sticky and very plastic, which resulted from progressive increase in clay content with depth. Boundaries between the A and B horizons were clearly attributable to the darkening effect of organic matter on the surface horizons (Driessen et al. 2001). The boundaries of the B horizons of nearly all the profile pits were not easily discernible being mainly diffuse wavy. The subsoil had probably passed through a process of reorganization and homogenization, which had resulted into formation of "stronger" structure and well-expressed B-horizons. These morphological characteristics are indicative of advanced stage of weathering (Mohr et al. 1972; Naverrete et al. 2007). Root concentration was restricted to the surface horizons and decreased with depth in all the profile pits examined.

Table 1: Morphological description of the soils

Horizon	Depth (cm)	Colour (moist)	Texture[a]	Structure[b]	Consistency[c]	Concretions and stones[d]	Boundary[e]	Other remarks
				Profile 1 (upper slope): typic isohyperthemic paleustults				
A	0 - 15	5YR 3/4 (Dark reddish brown)	Ngrscl	2mcr	mfrnstnpl	st	dw	Common fine and very fine and few medium roots
AB	15 - 35	10YR 5/8 (Yellowish red)	Grscl	2msbk	mfrstpl	fst	dw	Few roots
Bt1	35 - 53	5YR 5/8 (Yellowish red)	Ngrcl	3mabk	mvfrvstvpl	fst	dw	Few roots
Bt2	53 - 65	5YR 4/6 (Yellowish brown)	Ngrcl	2msbk	mfrstpl	-	dw	Absence of roots
BC1	65 - 140	5YR 5/6 (Reddish brown)	Ngrsl	2fsbk	mfrstpl	-	dw	Absence of roots
BC2	140 - 200	2.5YR 4/6 (Red)	Ngrc	2msbk	mfrvstvpl	-	ND	Absence of roots
				Profile 2 (upper slope): typic isohyperthemic paleustults				
Ap	0 - 9	10YR 3/3 (Dark brown)	Vgrsl	2msbk	mvfrstpl	st	dw	Abundant fine and medium roots
AB	9 - 18	10 YR 4/4 (Strong brown)	Vgrsl	3mabk	mfrvstvpl	fst	dw	Few fine and medium roots
Bt1	18 - 57	10YR 5/8 (Yellowish brown)	Vgrc	3mabk	mfrvstpl	fst	dw	Few quartz materials
Bt2	57 - 140	7.5YR 5/6 (Strong brown)	Vgrc	2msbk	mfrvstvp	fr	dw	Frequent concretionary and quartz material
BCm	140 - 182	7.5YR 5/6 (Strong brown)	Vgrc	2msbk	mvfrstpl	-	ND	Absence of roots

[a] Texture: vgr = very gravelly, gr = gravelly, sgl = slightly gravelly, ngr = non gravelly, c = clay, l = loam/loamy, s = sand/sandy, scl = sandy clay loam, cs = sandy clay

[b] Structure: 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, vf = very fine, f = fine, m = medium

[c] Consistency: m = moist, w = wet, vfr = very friable, fr = friable, fm = firm, vfm = very firm, nst = non sticky, sst = slightly sticky, vst = very sticky,
st = sticky npl = non plastic, spl = slightly plastic pl = plastic, vpl = very plastic

[d] Concretions: vf = very few, f = few, fr = frequent, gr = gravel, st = stone, rd = rounded, bd = boulder

[e] Boundary: a = abrupt, c = clear, g = gradual, d = diffuse, s = smooth, w = wavy, ir = irregular, b = broken, ND = not determined

Table 1 (continued): Morphological description of the soils

Horizon	Depth (cm)	Colour (moist)	Texture[a]	Structure[b]	Consistency[c]	Concretions and stones[d]	Boundary[e]	Other remarks
Profile 3 (lower slope): plinthic isohyperthemic paleustults								
A	0 - 20	5YR 5/3 (Reddish brown)	Ngsl	2mcr	mfrsstnpl	st	dw	Frequent fine and medium roots
Bt	20 - 56	5YR 5/8 (Yellowish red)	Sgc	3mabk	mvfmsstspl	fst	dw	Few fine and medium roots
Bv1	56 - 110	5YR 6/6 (Reddish yellow)	Gc	3mabk	mvfmvstvpl	fst	dw	Plinthic layer with ironstone concretions and quartz materials
Bv2	110 - 160	5YR 6/8 (Reddish yellow)	Vgscl	2csbk	mfmvstpl	fr	ND	Plinthic layer with ironstone concretions and quartz materials
Profile 4 (lower slope): typic isohyperthemic paleustults								
A	0 - 20	5YR 4/4 (Yellowish brown)	Ngscl	2mcr	mfsstspl	-	cs	Frequent very fine, fine, and few medium roots
AB	20 - 35	7.5YR 5/6 (Strong brown)	Ngsc	2msbk	mfmstpl	fgr	dw	Frequent very fine, fine, and few medium roots
Bt1	35 - 67	7.5YR 6/6 (Reddish yellow)	Sgsc	2msbk	mfmstpl	fgr	dw	Few fine and medium roots
Bt2	67 - 97	7.5YR 7/6 (Reddish Yellow)	Sgscl	2msbk	mfmstpl	f	dw	Few gravels
2BC1	97 - 130	7.5YR 6/8 (Reddish yellow)	Gscl	2msbk	mfmstpl	frst	dw	Very few gravel and stones
2BC2	130 - 180	7.5YR 6/8 (Reddish yellow)	Sgsc	3csbk	mfmvstp	frst	ND	Frequent gravel, stones and quartz materials, presence of lithologic discontinuity

[a] Texture: vgr = very gravelly, gr = gravelly, sgl = slightly gravelly, ngr = non gravelly, c = clay, l = loam/loamy, s = sand/sandy, scl = sandy clay loam, cs = sandy clay

[b] Structure: 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, vf = very fine, f = fine, m = medium

[c] Consistency: m = moist, w = wet, vfr = very friable, fr = friable, fm = firm, vfm = very firm, nst = non sticky, sst = slightly sticky, vst = very sticky,
st = sticky npl = non plastic, spl = slightly plastic pl = plastic, vpl = very plastic

[d] Concretions: vf = very few, f = few, fr = frequent, gr = gravel, st = stone, rd = rounded, bd = boulder

[e] Boundary: a = abrupt, c = clear, g = gradual, d = diffuse, s = smooth, w = wavy, ir = irregular, b = broken, ND = not determined

Table 1 (continued): Morphological description of the soils

Horizon	Depth (cm)	Colour (moist)	Texture[a]	Structure[b]	Consistency[c]	Concretions and stones[d]	Boundary[e]	Other features
Profile 5: (upper slope): typic isohyperthemic paleustults								
A	0 - 18	7.5YR 3/2 (Dark brown)	sgscl	2mcr	mfrstnpl	st	cs	Frequent very fine, fine and medium roots
AB	18 - 45	5YR 6/6 (Reddish yellow)	Gscl	2msbk	mfrstnpl	st	dw	Common very fine, fine and medium roots
Bt1	45 - 71	5YR 6/8 (Reddish yellow)	gsc	2msbk	mfmstpl	st	dw	Few medium roots
Bt2	71 - 102	5YR 5/8 (Yellowish red)	Gsc	2msbk	mfmstpl	st	dw	No roots
BC1	102 - 133	7.5YR 5/6 (Strong brown)	Sgc	3msbk	mvfmstpl	-	dw	No roots
BC2	133 - 180	7.5YR 5/6 (Strong brown)	Sgsc	2msbk	mfmstpl	st	ND	Frequent gravel and stones
Profile 6 (mid slope): typic isohyperthemic paleustults								
Ap	0 - 18	5YR 4/4 (Reddish brown)	Sgls	1ccr	mfrrstnpl	st	cs	Frequent very fine, fine and medium roots
AB	18 - 46	5YR 5/8 (Yellowish red)	Gsc	1ccr	mfrstpl	St	cs	Common fine and medium roots
Bt1	46 - 72	7.5YR 5/6 (Strong brown)	Gc	2mabk	mfrstvpl	frst	dw	No roots
Bt2	72 - 110	7.5YR 5/6 (Strong brown)	Gsc	2mabk	mfmvstvpl	fst	dw	No roots
BC1	110 - 145	10YR 5/8 (Yellowish brown)	Sgc	2mabk	mfmvstvpl	fst	dw	No roots
BC2	145 - 200	7.5YR 5/6 (Strong brown)	Ngc	2msbk	mfmvstvpl	st	ND	No roots

[a] Texture: vgr = very gravelly, gr = gravelly, sgl = slightly gravelly, ngr = non gravelly, c = clay, l = loam/loamy, s = sand/sandy, scl = sandy clay loam, cs = sandy clay

[b] Structure: 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, vf = very fine, f = fine, m = medium

[c] Consistency: m = moist, w = wet, vfr = very friable, fr = friable, fm = firm, vfm = very firm, nst = non sticky, sst = slightly sticky, vst = very sticky,
st = sticky npl = non plastic, spl = slightly plastic pl = plastic, vpl = very plastic

[d] Concretions: vf = very few, f = few, fr = frequent, gr = gravel, st = stone, rd = rounded, bd = boulder

[e] Boundary: a = abrupt, c = clear, g = gradual, d = diffuse, s = smooth, w = wavy, ir = irregular, b = broken, ND = not determined

Table 1 (Continued): Morphological description of the soils

Horizon	Depth (cm)	Colour (moist)	Texture[a]	Structure[b]	Consistency[c]	Concretions and stones[d]	Boundary[e]	Other features
Profile 7 (lower slope): typic isohyperthemic paleustults								
Ap	0 - 18	7.5YR 4/4 (Brown)	Ngsl	2mcr	mfrnstnpl	-	dw	Frequent very fine, fine and medium roots
AB	18 - 42	7.5YR 5/6 (Strong brown)	Ngsc	2msbk	mfmsstspl	st	dw	Common fine and medium roots
Bt1	42 - 70	7.5YR 5/6 (Yellowish red)	Sgsc	2msbk	mfmstpl	st	dw	Few fine roots
Bt2	70 - 105	7.5YR 6/6 (Reddish yellow)	Sgscl	2msbk	mfmstpl	-	dw	Very few fine roots
2Bt3	105 - 146	7.5YR 5/6 (Strong brown)	sgl	2msbk	mfmsstspl	-	dw	Absence of roots
2BC	146 - 200	5YR 4/8 (Yellowish red)	Ngsl	2msbk	mfmsstspl	-	ND	Absence of roots
Profile 8 (lower slope): plinthic isohyperthemic paleustults								
A	0 - 19	10YR 3/3 (Dark brown)	ngscl	2fcr	mfrnstnpl	-	cs	Frequent very fine, fine and medium roots
AB	19 - 34	5YR 3/4 (Dark reddish brown)	Ngsc	2msbk	mfmsstspl	-	cs	Frequent very fine, fine and medium roots
B2	34 - 69	7.5YR 4/4 (Brown)	Sgsc	2msbk	mfmsstspl	fst	dw	Few very fine, fine and medium roots merges to plinthic layer
Bv	69 - 135	7.5YR 5/6 (Strong brown)	Gscl	2msbk	mfmsstspl	-	ND	No roots, plinthic layer with frequent concretionary and quartz materials

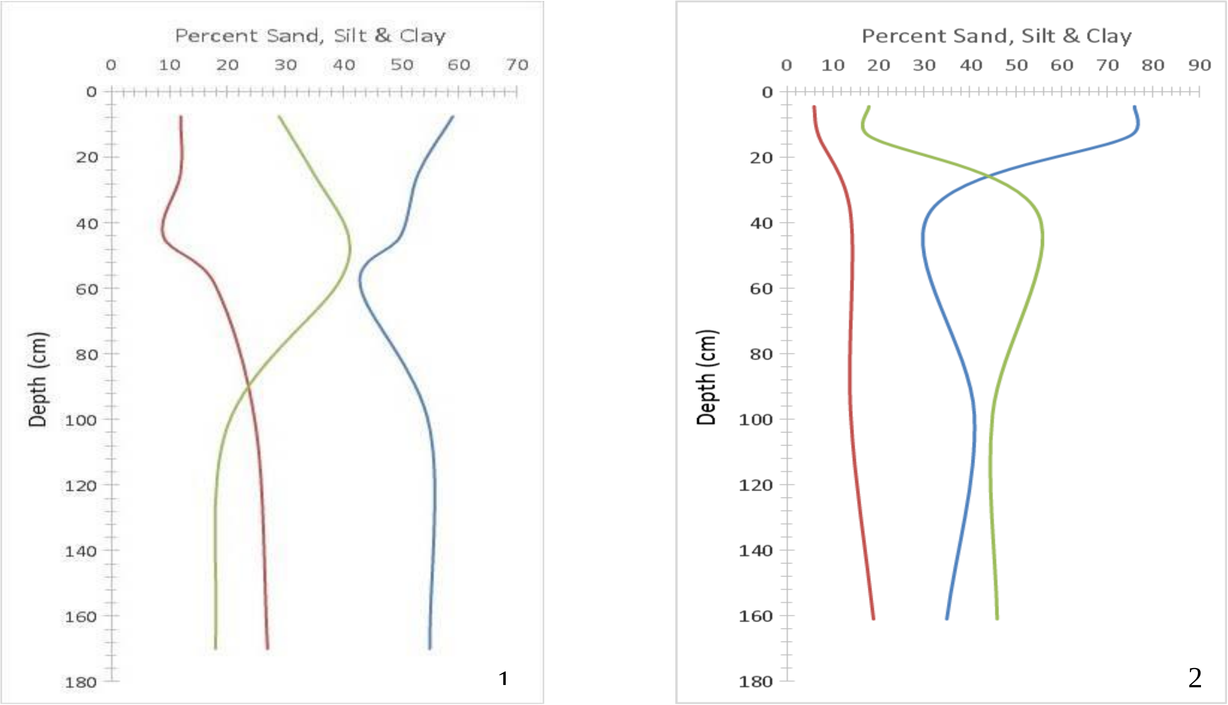
[a]Texture: vgr = very gravelly, gr = gravelly, sgl = slightly gravelly, ngr = non gravelly, c = clay, l = loam/loamy, s = sand/sandy, scl = sandy clay loam, cs = sandy clay

[b]Structure: 1 = weak, 2 = moderate, 3 = strong, cr = crumb, sbk = subangular blocky, abk = angular blocky, vf = very fine, f = fine, m = medium

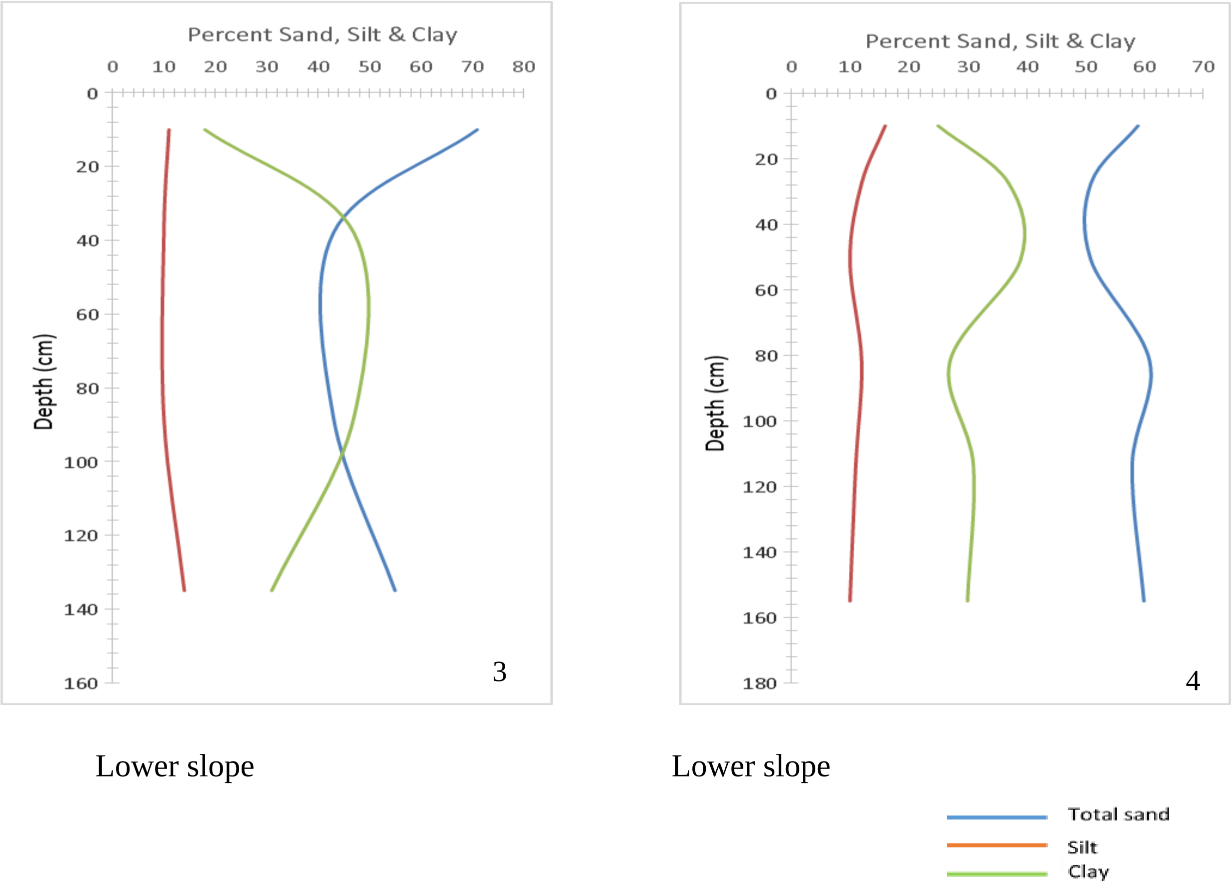
[c]Consistency: m = moist, w = wet, vfr = very friable, fr = friable, fm = firm, vfm = very firm, nst = non sticky, sst = slightly sticky, vst = very sticky,
st = sticky npl = non plastic, spl = slightly plastic pl = plastic, vpl = very plastic

[d]Concretions: vf = very few, f = few, fr = frequent, gr = gravel, st = stone, rd = rounded, bd = boulder

[e]Boundary: a = abrupt, c = clear, g = gradual, d = diffuse, s = smooth, w = wavy, ir = irregular, b = broken, ND = not determined



Upper – mid slope



Lower slope

Lower slope

Figure 2: Variation in particle size with depth (profile pits 1 – 4)

Physical characteristics of the soils

The results of the physical analyses of the soils are presented in Table 2. The vegetation on the soil aided good aggregation of the surface soils as reflected by the non-gravelly nature of the surface soils. The surface horizons of all the profile pits examined had lower gravel content compared to the subsurface horizons. The implication of this to crop production is that the roots are not likely to have much difficulty penetrating through the soil; also, cultivation of the soil and seed emergence would be easier.

Gravel content ranged from 6.6 – 62.5%. Lower gravel contents (6.6% and 8.5%) were recorded at the lower slope position (profile pits 8 and 4, respectively). The most probable reason for this is that the soils at the lower topographic position were formed from colluvial/alluvial parent material in which there had been sorting before deposition down slope, heavier materials having been dropped along the slope due to reduction in the carrying capacity of moving water during rainfall. The percentage gravel content by weight and its pattern of distribution were in line with previous studies (Ojanuga 1978; Ojo-Atere and Oladimeji 1983; Amusan 1991; Muda 2011). The total sand was higher on the surface soils than other soil separates and decreased with depth. The predominance of total sand fraction in the surface horizons was attributed to the preferential removal of clay and silt by soil erosion and percolating rainwater (Ojanuga 1975; Amusan 1991). There was a significant negative correlation (r = -0.826**) between the total sand and clay content (Table 3). The lower values of total sand content obtained in the B horizons are possibly due to the dilution effect of the illuvial clay. There was no consistent pattern of the various sand fractions. However, the very coarse sand fraction was more than other sand fractions, irrespective of topographic position. This could be attributed to the fact that the soils were formed from coarse-grained granite and gneiss. Consequently, the soils are coarse-textured (Smyth and Montgomery 1962; Makinde et al. 2009). The increase in clay content in the subsurface horizon, according to Ojanuga and Nye (1969), could be accounted for by the differential sorting of clay from surface horizon to subsurface horizon. In an earlier work by Smyth and Montgomery (1962), weathering, biological processes, physical, and at times, chemical processes were suggested to be the major causes of clay eluviation from the surface to the subsurface horizon.

The total sand content ranged from 29 – 73% while the clay varied from 16 – 55%. The subsurface horizons in all the profiles examined were more clayey than the surface horizons. Clay eluviation and differential sorting of materials are some factors that could be accountable (Smyth and Montgomery 1962). Clay eluviation could sometimes form clay bulge as was observed in some of the profile pits studied (Figures 2 and 3). The silt content did not show any regular pattern. However, it was consistently the least among the soil fractions and showed significant negative correlation (r = -0.373*) with clay content (Table 3). Lower silt content has been reported for many soils derived from the basement complex in southwestern Nigeria (Ojanuga 1978; Mbagwu et al. 1983; Okusami and Oyediran 1985; Amusan 1991; Ojetade et al. 2014). The trend of particle size distribution observed agrees with those of earlier researchers (Smyth and Montgomery 1962; Amusan 1991; Ogunkunle 1993; Akinbola et al. 2006; Muda 2011; Ojetade et al. 2014).

Bulk density values ranged from 1.12 – 1.64 gcm^{-3} and generally increased with depth. These values were within the range (1.0 – 1.6 gcm^{-3}) reported by Wild (1993) as ideal for agronomic activities in most mineral soils. Soils with low bulk densities are usually associated with high total porosity (Payne 1988). Russell (1976) and Payne (1988) reported that root penetration and seedling emergence were difficult when bulk density exceeded 1.6 gcm^{-3}. The porosity values obtained were generally high, varying from 37.15 - 57.62%. This was responsible for the well-drained and well-aerated nature of the soils.

Table 2: Physical properties of the soils

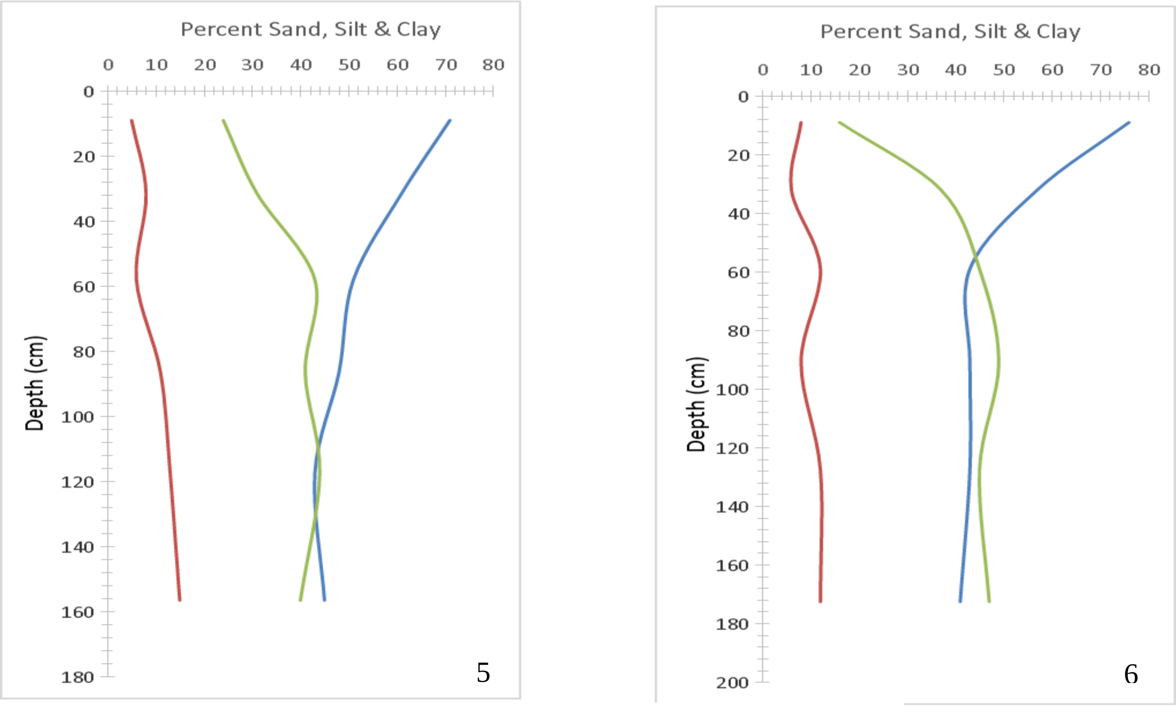
Horizon	Depth (cm)	Gravel content	VCS	CS	MS	FS	VFS	TS	Silt	Clay	BD	Porosity	Textural class
		(%)									(gcm^{-3})	(%)	
Profile 1 (upper slope): typic isohyperthemic paleustults													
A	0 - 15	19.5	18.2	11.0	10.5	15.6	3.6	59.0	12.0	29.0	1.20	54.63	SCL
AB	15 - 35	43.5	18.3	9.8	8.6	13.3	3.1	53.0	12.0	35.0	1.29	51.17	SCL
Bt1	35 - 53	54.6	24.2	9.3	6.5	8.3	1.8	50.0	9.0	41.0	1.17	55.66	SC
Bt2	53 - 65	54.4	14.8	8.1	6.7	11.1	2.2	43.0	18.0	39.0	1.38	47.98	CL
BC1	65 - 140	38.9	8.0	9.2	12.4	20.4	5.0	55.0	15.0	30.0	1.29	51.40	SC
BC2	140 - 200	29.1	10.2	11.2	11.3	17.1	5.2	55.0	11.0	34.0	1.37	48.44	SCL
Profile 2 (mid slope): typic isohyperthemic paleustults													
Ap	0 - 9	36.8	22.4	14.5	16.1	19.8	3.2	76.0	6.0	18.0	1.35	49.13	SL
AB	9 - 18	62.5	28.4	12.5	12.5	18.8	2.7	75.0	7.0	18.0	1.55	41.41	SL
Bt1	18 - 57	54.5	14.8	5.2	3.9	5.5	1.6	31.0	14.0	55.0	1.51	43.14	C
Bt2	57 - 140	31.5	17.6	8.3	5.7	7.4	2.0	41.0	14.0	45.0	1.57	40.72	C
BCm	140 - 182	33.6	12.5	8.2	5.3	7.6	1.4	35.0	19.0	46.0	1.50	43.25	C
Profile 3 (lower slope): plinthic isohyperthemic paleustults													
A	0 - 20	20.8	17.9	12.9	15.2	22.1	2.9	71.0	11.0	18.0	1.40	47.02	SL
Bt	20 - 56	35.8	15.6	8.2	7.7	9.7	1.8	43.0	10.0	47.0	1.43	46.10	C
Bv1	56 - 110	36.0	15.9	8.1	6.8	10.1	2.1	43.0	10.0	47.0	1.45	45.33	C
Bv2	110- 160	34.1	18.2	11.1	7.7	15.8	2.3	55.0	14.0	31.0	1.22	53.78	SCL
Profile 4 (lower slope): typic isohyperthemic paleustults													
A	0 - 20	8.5	11.3	9.7	12.7	21.2	4.1	59.0	16.0	25.0	1.47	44.37	SCL
AB	20 - 35	18.3	11.8	9.7	10.8	16.0	2.6	51.0	12.0	37.0	1.53	42.10	SC
Bt1	35 - 67	31.4	11.2	9.3	10.1	16.7	3.7	51.0	10.0	39.0	1.40	47.06	SC
Bt2	67 - 97	34.6	13.6	8.9	12.7	22.8	3.0	61.0	12.0	27.0	1.48	44.33	SCL
2BC1	97 - 130	43.2	15.0	12.0	11.2	16.6	3.1	58.0	11.0	31.0	1.47	44.68	SCL
2BC2	130 - 180	40.0	18.0	14.0	12.0	13.1	2.9	60.0	10.0	30.0	1.49	43.80	SC

VCS = very coarse sand (1 - 2 mm), CS = coarse sand (0.5 - 1.0 mm),
MS = medium sand (0.5 - 0.25 mm), FS = fine sand (0.25 - 0.1 mm),
VFS = very fine sand (0.1 - 0.05 mm), TS = total sand (0.05 - 2 mm), BD = bulk density,
SCL = sandy-clay-loam, SC = sandy-cay, CL = clay-loam, SL = sandy-loam, C = clay

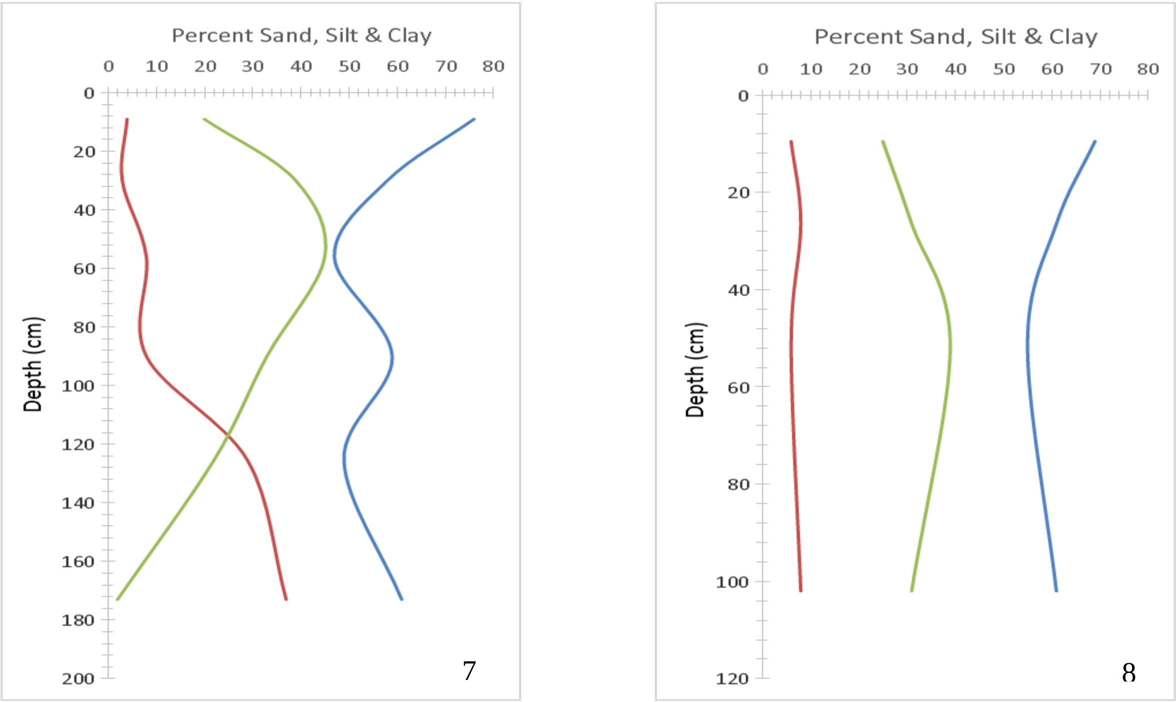
Table 2 (continued): Physical properties of the soils

Horizon	Depth (cm)	Gravel content	VCS	CS	MS	FS	VFS	TS	Silt	Clay	BD	Porosity	Textural class
			←			(%)				→	(gcm^{-3})	(%)	
Profile 5 (upper slope): typic isohyperthemic paleustults													
A	0 - 18	21.1	10.5	12.1	18.4	26.6	3.4	71.0	5.0	24.0	1.18	55.55	SCL
AB	18 - 45	42.3	12.7	10.5	14.7	20.5	2.5	61.0	8.0	31.0	1.38	47.86	SCL
Bt1	45 - 71	51.6	14.2	7.8	11.5	14.5	2.9	51.0	6.0	43.0	1.29	51.48	SC
Bt2	71 - 102	44.9	10.5	8.1	10.5	15.8	3.0	48.0	11.0	41.0	1.38	47.86	SC
BC1	102 - 133	33.2	10.6	7.4	9.2	13.5	2.3	43.0	13.0	44.0	1.44	45.71	C
BC2	133 - 180	42.1	13.9	8.9	8.5	10.8	2.8	45.0	15.0	40.0	1.41	46.75	SC
Profile 6 (mid slope): typic isohyperthemic paleustults													
Ap	0 - 18	17.5	10.4	10.6	18.7	32.3	4.1	76.0	8.0	16.0	1.51	43.10	SL
AB	18 - 46	42.9	14.4	10.2	11.9	17.0	3.5	57.0	6.0	37.0	1.53	42.26	SC
Bt1	46 - 72	46.0	14.2	8.9	8.0	10.0	2.0	43.0	12.0	45.0	1.32	50.17	C
Bt2	72 - 110	39.1	12.8	7.5	8.1	12.6	2.0	43.0	8.0	49.0	1.42	46.25	C
BC1	110 - 145	32.9	14.5	8.3	7.8	10.4	2.0	43.0	12.0	45.0	1.43	45.98	C
BC2	145 - 200	27.1	10.1	7.3	7.5	12.3	3.9	41.0	12.0	47.0	1.33	49.82	C
Profile 7 (lower slope): typic isohyperthemic paleustults													
Ap	0 - 18	13.8	8.9	9.8	18.5	33.5	5.2	76.0	4.0	20.0	1.50	43.29	SL
AB	18 - 42	18.9	14.1	10.2	13.8	17.6	2.3	58.0	3.0	39.0	1.64	37.15	SC
Bt1	42 - 70	25.2	9.9	9.3	10.3	14.7	2.8	47.0	8.0	45.0	1.56	41.03	SC
Bt2	70 - 105	37.4	14.8	11.1	15.4	15.0	2.7	59.0	8.0	33.0	1.54	41.91	SCL
2Bt3	105 - 146	25.9	2.9	7.5	15.9	20.1	2.7	49.0	9.0	42.0	1.28	51.59	SC
2BC	146 - 200	8.3	4.0	10.3	14.4	27.2	5.1	61.0	10.0	29.0	1.18	55.32	SCL
Profile 8 (lower slope): typic isohyperthemic paleustults													
A	0 - 19	13.0	11.8	9.1	15.7	28.0	4.5	69.0	6.0	25.0	1.12	57.62	SCL
AB	19 - 34	6.6	9.8	7.8	13.9	25.1	4.3	61.0	8.0	31.0	1.20	54.86	SC
B2	34 - 69	9.5	11.6	6.3	11.8	21.8	3.5	55.0	6.0	39.0	1.18	55.36	SC
Bv	69 - 135	31.8	14.7	12.2	17.7	12.1	4.3	61.0	8.0	31.0	1.45	45.21	SCL

VCS = very coarse sand (1 - 2 mm), CS = coarse sand (0.5 - 1.0 mm),
MS = medium sand (0.5 - 0.25 mm), FS = fine sand (0.25 - 0.1 mm),
VFS = very fine sand (0.1 - 0.05 mm), TS = total sand (0.05 - 2 mm), BD = bulk density,
SCL = sandy-clay-loam, SC = sandy-cay, CL = clay-loam, SL = sandy-loam,
C = clay



Upper – mid slope



Lower slope

Lower slope

Figure 3: Variation in particle size with depth (profile pits 5 – 8)

Table 3: Correlation analysis among the physical properties of the soils

	Total sand	Silt	Clay
	←	(%)	→
Silt (%)	-0.214		
Clay (%)	-0.826**	-0.373*	
Bulk density (gcm^{-3})	-0.120	-0.186	0.221

* Significant at P ≤ 0.05 ** Significant at P ≤ 0.01

Chemical characteristics of the soils

Table 4 shows chemical properties of the soils. The pH of the soils was generally low, ranging between 5.1 – 6.9 and 4.2 – 6.1 in water and 1 M KCl, respectively. This indicates that the soils were acidic. The acidic nature of the soils could have resulted from the uptake of basic cations by the plants and/or leaching. It could also be attributed to the coarse-textured nature of the soils which enhanced greater permeability and subsequent leaching which is prevalent in the humid tropics. Nye (1955) attributed the increase in acidity with profile depth to the transfer of basic cations from deeper horizons through absorption by plant roots to the plants' above-ground portions and their subsequent accumulation in the surface horizons through the decomposition of leaf litters. The pH difference, pH(KCl) – pH(H_2O), was negative in all the horizons of the profile pits studied indicating that the silicate mineralogy in the soil was dominant over oxidic mineralogy (Van Raij and Peech 1972; Navarrete et al. 2007) and/or that the soil colloids were still negatively charged (Mekaru and Uehara 1972) or the presence of negatively charged colloidal particles (Soil Survey Staff 2009).

The organic matter (OM) content of the soils ranged from 0.13 – 2.75%. Adepetu (1986) classified percentage soil OM contents into low (0 – 1.5%), medium (1.5 – 2.5%) and high (> 2.5%). Higher values of OM were recorded at the surface horizons and decreased with horizon depth across the profile pits examined. The higher content of OM at the surface could have resulted from the decomposition of leaf litter, phytocycling and enhanced activities of soil microbes due to better aeration and moisture regimes at the soil surface (Olayinka 2009).

Total nitrogen content ranged from low to medium. Higher values were found at the surface horizons in all the profiles pits examined, the trend being similar to that of OM. Available phosphorus content ranged from 5.92 – 14.08 ppm and 2.25 – 11.84 ppm for the surface and subsurface soils, respectively. The values of available P decreased with profile depth, this trend was also similar to that of OM content thus confirming the direct relationship between OM content and soil nutrients. Olayinka (2009) reported that soil OM serves as a storehouse and source of plant nutrients in tropical soils.

The contents of exchangeable bases across the profile pits examined were low. Smyth and Montgomery (1962) reported that the soils of the upland areas of central western Nigeria had low exchange capacity in keeping with the essentially kaolinitic nature of their clay content. The values for exchangeable calcium were higher than any of the other basic cations while the values for the exchangeable sodium were least in four profile pits (5, 6, 7 and 8) but higher than potassium in the other profile pits examined. The values of the exchangeable cations were higher at the surface than the subsurface soils (Table 4). Sehgal et al. (1972) attributed the relative abundance of exchangeable cations on the surface soil to the fact that it was being continuously recharged by mobile constituents liberated by the decomposition of organic residues, irrespective of its exposure to leaching and runoff.

The values for total exchangeable cations followed a similar trend to those of exchangeable bases. All the profile pits examined showed little or no variation with respect to exchangeable acidity and total acidity which were generally low.

The values for cation exchange capacity (CEC) were generally higher on the surface soils than the subsurface soils in all the profile pits examined. This could be attributed to the slightly higher OM content in the surface horizons. Kadeba and Benjaminsen (1976) reported that soil OM accounted for between 56 - 83% of variations in the CEC of top soils.

Table 5 shows comparative analysis of the three methods used to estimate the CEC of the soils. The methods were significantly different ($P \leq 0.05$) from one another with means of the values by $BaCl_2$-TEA method higher that the other two methods ($BaCl_2$-TEA = 22.15, NH_4OAc = 13.72, ECEC = 5.87 cmol/kg). This could be attributed to the fact that higher exchangeable acidity was extracted by $BaCl_2$-TEA, a similar observation was made by Amusan (1991).

Table 4: Chemical properties of the soils

		pH						Exchangeable cations					TEA					
Horizon	Depth (cm)	(H_2O)	(KCl)	ΔpH	OM	TN	AP	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	Al^{3+}	H^+	TA	CEC	ECEC	BS
					← (%)	→	(ppm)	←				(cmolkg^{-1})					→	(%)
Profile 1 (upper slope): typic isohyperthemic paleustults																		
A	0 - 15	5.7	4.7	-1.0	2.15	1.37	14.08	2.42	0.37	0.22	0.26	3.27	0.10	0.50	0.60	17.27	3.37	18.94
AB	15 - 35	5.8	4.6	-1.2	0.87	1.09	9.18	1.82	0.36	0.19	0.21	2.57	0.10	0.20	0.30	14.57	2.67	17.65
Bt1	35 - 53	5.8	4.6	-1.2	0.87	1.26	6.53	1.33	0.35	0.19	0.17	2.03	0.10	0.30	0.40	8.59	2.13	28.12
Bt2	53 - 65	5.7	4.7	-1.0	0.80	1.12	5.10	0.86	0.33	0.18	0.17	1.54	0.10	0.30	0.40	9.62	1.64	18.01
BC1	65 - 140	5.6	4.5	-1.1	0.54	1.09	8.37	0.71	0.29	0.15	0.14	1.29	0.30	0.20	0.50	12.69	1.59	10.18
BC2	140- 200	5.5	5.2	-0.3	2.15	1.12	6.94	0.79	0.34	0.16	0.11	1.39	0.10	0.40	0.50	6.59	1.49	21.12
Profile 2 (mid slope): typic isohyperthemic paleustults																		
Ap	0 - 9	6.4	5.4	-1.0	2.75	1.26	6.33	1.74	0.31	0.18	0.20	2.43	0.10	0.40	0.50	20.11	2.53	13.18
AB	9 - 18	6.5	5.4	-1.1	1.14	1.12	9.80	1.02	0.37	0.20	0.12	1.71	0.10	0.30	0.40	18.43	1.81	8.51
Bt1	18 - 57	5.6	4.3	-1.3	0.91	1.19	7.14	0.64	0.31	0.35	0.18	1.48	0.20	0.40	0.60	17.08	1.68	8.65
Bt2	57 - 140	5.5	5.3	-0.2	0.54	1.12	3.88	0.56	0.30	0.40	0.17	1.43	0.20	0.40	0.60	22.23	1.63	6.44
BCm	140- 182	5.6	4.3	-1.3	0.13	1.19	3.27	0.94	0.38	0.31	0.13	1.75	0.20	0.30	0.50	24.75	1.95	7.08
Profile 3 (lower slope): plinthic isohyperthemic paleustults																		
A	0 - 20	6.5	5.4	-1.1	1.74	1.26	13.27	1.25	0.35	0.20	0.22	2.03	0.10	0.30	0.40	16.83	2.13	12.04
Bt	20 - 56	6.1	5.2	-0.9	0.74	1.26	11.84	3.13	0.37	0.20	0.21	3.91	0.10	0.30	0.40	15.91	4.01	24.55
Bv1	56 - 110	5.9	4.7	-1.2	0.94	1.19	2.04	1.33	0.32	0.30	0.14	2.09	0.20	0.30	0.50	16.09	2.29	12.99
Bv2	110- 160	5.5	4.5	-1.0	0.80	1.12	2.65	1.09	0.35	0.25	0.12	1.81	0.20	0.10	0.30	17.41	2.01	10.42
Profile 4 (lower slope): typic isohyperthemic paleustults																		
A	0 - 20	5.8	5.1	-0.7	0.74	2.87	11.43	1.99	0.38	0.18	0.20	2.75	0.20	0.30	0.50	14.75	2.95	18.67
AB	20 - 35	5.4	4.3	-1.1	1.24	1.37	10.82	0.86	0.36	0.14	0.20	1.56	0.15	0.45	0.60	11.56	1.71	13.46
Bt1	35 - 67	5.5	4.5	-1.0	1.31	1.19	8.37	0.94	0.38	0.16	0.17	1.64	0.05	0.45	0.50	14.64	1.69	11.21
Bt2	67 - 97	5.8	4.8	-1.0	0.74	2.87	3.67	1.91	0.37	0.21	0.19	2.67	0.05	0.35	0.40	17.67	2.72	15.11
2BC1	97 - 130	5.3	4.2	-1.1	0.87	0.60	6.33	0.71	0.38	0.17	0.11	1.36	0.15	0.35	0.50	14.16	1.51	9.63
2BC2	130- 180	5.1	4.2	-0.9	0.70	0.49	5.50	0.69	0.34	0.14	0.11	1.28	0.10	0.30	0.40	14.08	1.38	9.09

OM = organic matter, AP = available phosphorus, TN = total nitrogen, TEB = total exchangeable bases, TEA = total exchangeable acidity, TA = total acidity, CEC = cation exchange capacity, ECEC = effective cation exchange capacity, BS = base saturation

Table 4 (continued): Chemical properties of the soils

Horizon	Depth (cm)	pH			OM	TN	AP	Exchangeable cations					TEA			CEC	ECEC	BS
		(H$_2$O)	(KCl)	ΔpH				Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	Al^{3+}	H^{+}	TA			
					←(%)	→	(ppm)	←					(cmolkg^{-1})				→	(%)
Profile 5 (upper slope): typic isohyperthemic paleustults																		
A	0 - 18	6.6	5.9	-0.7	2.62	1.54	7.76	5.65	0.38	0.61	0.23	6.87	0.20	0.10	0.30	28.46	7.07	31.41
AB	18 - 45	6.5	5.6	-0.9	0.80	1.58	11.02	9.25	0.39	0.44	0.18	10.26	0.10	0.40	0.50	21.87	10.36	36.05
Bt1	45 - 71	6.5	5.4	-1.1	1.01	1.33	7.76	9.57	0.40	0.61	0.26	10.84	0.10	0.25	0.35	28.24	10.94	38.39
Bt2	71 - 102	6.5	5.4	-1.1	0.67	1.12	4.08	8.86	0.36	0.49	0.21	9.92	0.10	0.35	0.45	29.32	10.02	33.84
BC1	102- 133	6.4	5.2	-1.2	0.27	1.12	5.92	10.05	0.40	0.58	0.12	11.15	0.10	0.40	0.50	33.15	11.25	33.64
BC2	133- 180	6.2	5.1	-1.1	0.60	1.16	7.96	10.36	0.21	0.46	0.11	11.13	0.20	0.20	0.40	34.33	11.33	32.43
Profile 6 (mid slope): typic isohyperthemic paleustults																		
Ap	0 - 18	6.0	4.9	-1.1	0.87	1.26	11.63	9.18	0.74	0.48	0.23	10.63	0.20	0.35	0.55	31.43	10.83	33.82
AB	18 - 46	6.9	5.0	-1.9	0.60	1.30	10.41	10.28	0.39	0.74	0.11	11.52	0.10	0.35	0.45	32.52	11.62	35.42
Bt1	46 - 72	5.7	4.6	-1.1	1.01	1.19	4.08	8.60	0.38	0.72	0.09	9.78	0.20	0.30	0.50	32.58	9.98	30.03
Bt2	72 - 110	5.4	4.4	-1.0	0.40	1.05	6.53	10.38	0.39	0.73	0.09	11.58	0.15	0.45	0.60	31.98	11.73	36.21
BC1	110- 145	5.2	4.3	-0.9	0.94	1.09	9.59	9.93	0.40	0.52	0.09	10.93	0.25	0.45	0.70	32.53	11.18	33.60
BC2	145- 200	5.3	4.3	-1.0	0.47	1.05	10.21	10.22	0.40	0.44	0.19	11.25	0.30	0.50	0.80	34.05	11.55	33.04
Profile 7 (lower slope): typic isohyperthemic paleustults																		
Ap	0 - 18	6.7	5.4	-1.3	0.94	1.23	5.92	8.41	0.35	0.27	0.22	9.25	0.05	0.45	0.50	31.99	9.30	31.40
AB	18 - 42	6.3	5.2	-1.1	0.60	1.16	11.43	9.74	0.36	0.25	0.20	10.55	0.10	0.30	0.40	31.15	10.65	33.86
Bt1	42 - 70	6.0	5.4	-0.6	0.94	1.05	7.55	8.32	0.37	0.31	0.20	9.19	0.20	0.10	0.30	29.55	9.39	28.73
Bt2	70 - 105	6.8	5.9	-0.9	1.01	1.09	2.86	10.01	0.38	0.44	0.18	11.01	0.10	0.30	0.40	33.41	11.11	32.95
2Bt3	105- 146	6.8	6.0	-1.2	0.80	1.05	4.08	9.02	0.40	0.53	0.19	10.13	0.15	0.35	0.50	30.53	10.28	33.18
2BC	146- 200	6.9	5.6	-1.3	0.34	1.05	6.12	10.05	0.34	0.45	0.14	10.97	0.05	0.35	0.40	32.37	11.02	33.90
Profile 8 (lower slope): typic isohyperthemic paleustults																		
A	0 - 19	6.7	5.8	-0.9	2.21	2.45	6.12	3.30	0.38	0.26	0.24	4.18	0.10	0.30	0.40	17.12	4.28	29.49
AB	19 - 34	6.7	5.6	-1.1	1.48	1.26	8.16	3.57	0.38	0.19	0.18	4.32	0.10	0.30	0.40	14.12	4.42	25.22
B2	34 - 69	6.7	5.6	-1.1	1.27	1.05	6.33	3.39	0.38	0.22	0.19	4.18	0.10	0.30	0.40	18.38	4.28	22.73
Bv	69 - 135	6.9	6.1	-0.8	0.67	1.05	2.25	3.85	0.33	0.27	0.12	4.57	0.15	0.25	0.40	20.77	4.72	22.00

OM = organic matter, AP = available phosphorus, TN = total nitrogen, TEB = total exchangeable bases, TEA = total exchangeable acidity, TA = total acidity, CEC = cation exchange capacity, ECEC = effective cation exchange capacity, BS = base saturation

Table 5: Comparison of methods of CEC determination of the soils

Horizon	Depth (cm)	BaCl$_2$-TEA pH 8.2	CEC NH$_4$OAc pH 7	Effective (ECEC)
		←	(cmolkg^{-1})	→
Profile 1 (upper slope): typic isohyperthemic paleustults				
A	0 – 15	17.27	16.15	3.37
AB	15 – 35	14.57	13.46	2.67
Bt1	35 – 53	8.59	7.23	2.13
Bt2	53 – 65	9.62	8.54	1.64
BC1	65 – 140	12.69	9.36	1.59
BC2	140 – 200	6.59	6.15	1.49

Table 5 continued: Comparison of methods of CEC determination of the soils

Horizon	Depth (cm)	CEC (cmolkg^{-1})		
		BaCl$_2$-TEA pH 8.2	NH$_4$OAc pH 7	Effective (ECEC)
Profile 2 (mid slope): typic isohyperthemic paleustults				
Ap	0 – 9	18.43	12.95	2.53
AB	9 – 18	20.11	17.95	1.81
Bt1	18 – 57	17.08	16.28	1.68
Bt2	57 – 140	22.23	18.33	1.63
BCm	140 – 182	24.75	21.41	1.95
Profile 3 (lower slope): plinthic isohyperthemic paleustults				
A	0 – 20	16.83	10.64	2.13
Bt	20 – 56	15.91	14.87	4.01
Bv1	56 – 110	16.09	15.64	2.29
Bv2	110 – 160	17.41	9.62	2.01
Profile 4 (lower slope): typic isohyperthemic paleustults				
A	0 – 20	14.75	9.62	2.95
AB	20 – 35	11.56	10.00	1.71
Bt1	35 – 67	14.64	9.23	1.69
Bt2	67 – 97	17.67	9.23	2.72
2BC1	97 – 130	14.16	10.13	1.51
2BC2	130 – 180	14.08	10.00	1.38
Profile 5 (upper slope): typic isohyperthemic paleustults				
A	0 – 18	21.87	20.77	7.07
AB	18 – 45	28.46	17.95	10.36
Bt1	45 – 71	28.24	13.33	10.94
Bt2	71 – 102	29.32	14.36	10.02
BC1	102 – 133	33.15	12.56	11.25
BC2	133 – 180	34.33	10.26	11.33
Profile 6 (mid slope): typic isohyperthemic paleustults				
Ap	0 – 18	31.43	18.46	10.83
AB	18 – 46	32.52	16.67	11.62
Bt1	46 – 72	32.58	15.38	9.98
Bt2	72 – 110	31.98	16.03	11.73
BC1	110 – 145	32.53	15.64	11.18
BC2	145 – 200	34.05	13.08	11.55
Profile 7 (lower slope): typic isohyperthemic paleustults				
Ap	0 – 18	29.45	18.59	9.30
AB	18 – 42	31.15	18.46	10.65
Bt1	42 – 70	31.99	18.97	9.39
Bt2	70 – 105	33.41	12.69	11.11
2Bt3	105 – 146	30.53	11.28	10.28
2BC	146 – 200	32.37	9.23	11.02
Profile 8 (lower slope): typic isohyperthemic paleustults				
A	0 – 19	14.18	13.46	4.28
AB	19 – 34	17.12	16.03	4.42
B2	34 – 69	18.38	12.95	4.28
Bv	69 – 135	20.77	14.62	4.72

The mineralogical characteristics of the soils

The parent rock mineralogy

Examination of thin section of the parent rock sample under plain polarized light and crossed polar revealed that quartz constituted the bulk (60%) of the minerals in the parent rock. Other minerals present were microcline (18%), biotite (10%), plagioclase (8%) and muscovite (4%) (Figure 4 and Plates 1a and b). The results are in line with those of the previous studies (Olarewaju 1986; Amusan 1991). Quartz is known to be very resistant to weathering. Consequently, the soils are coarse-textured, porous and well-drained. The parent rock still had some weatherable minerals available for plant uptakes. Wallander and Wickman (1999) reported that microcline and biotite are good sources of potassium, while biotite also supplies magnesium. This is very important in a region where the relatively high prices and limited geographical availability of potash have serious implications for agricultural markets that depend on imports of this fertilizer (Mohammed et al. 2014).

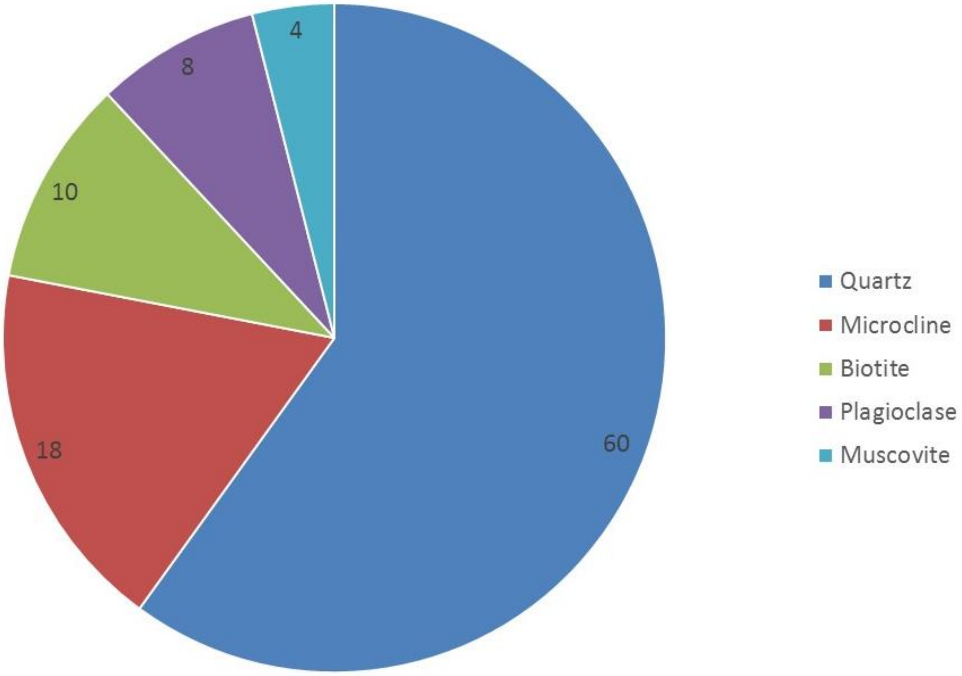


Figure 4: Modal mineral analysis by volume (%) of the parent rock

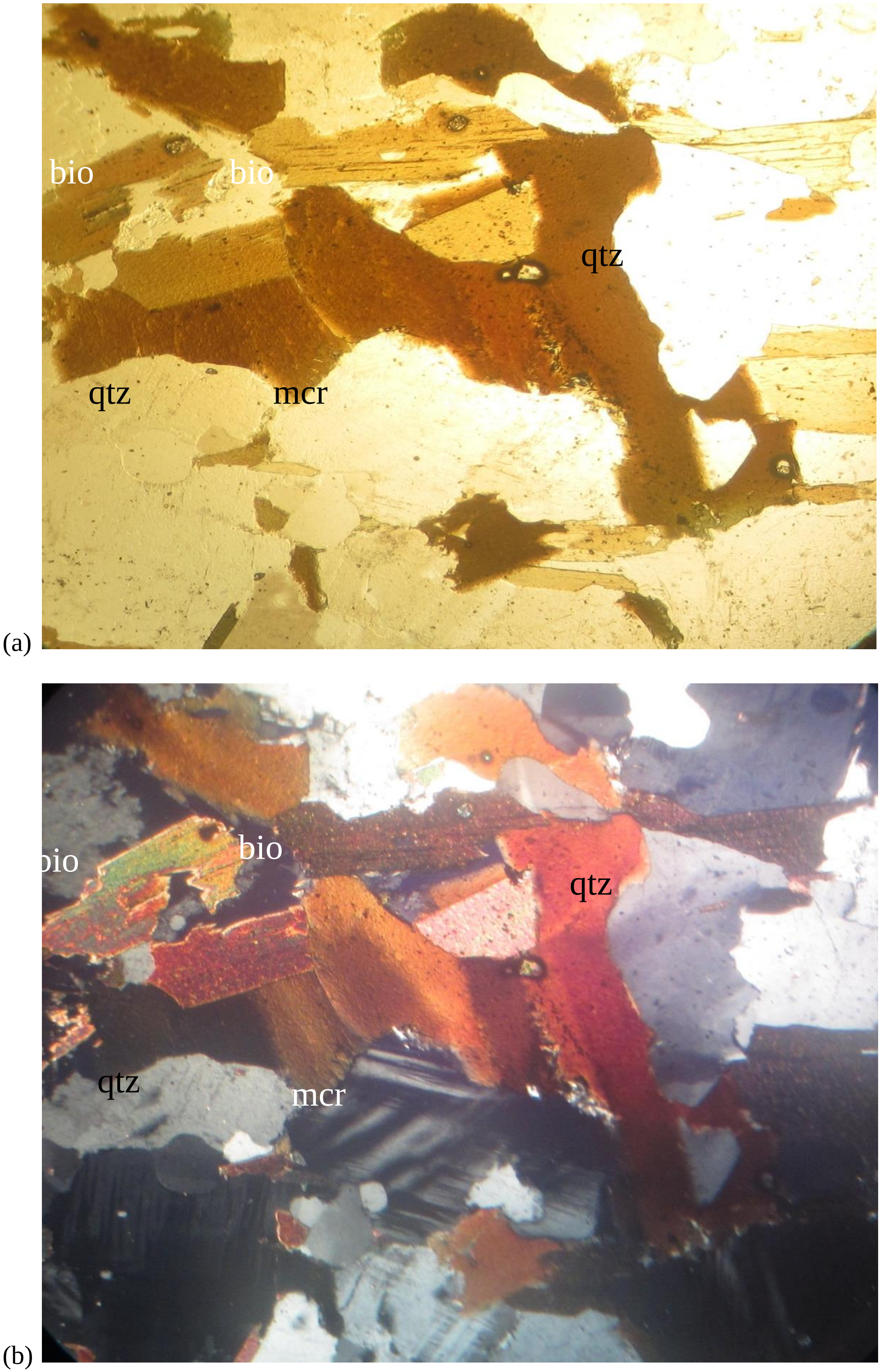


Plate 1: Photomicrographs showing mineral grains of the bed rock under:
(a) plain polarized light and (b) crossed polarized light.
Bio = biotite; qtz = quartz; mcr = microcline (mag. x 4)

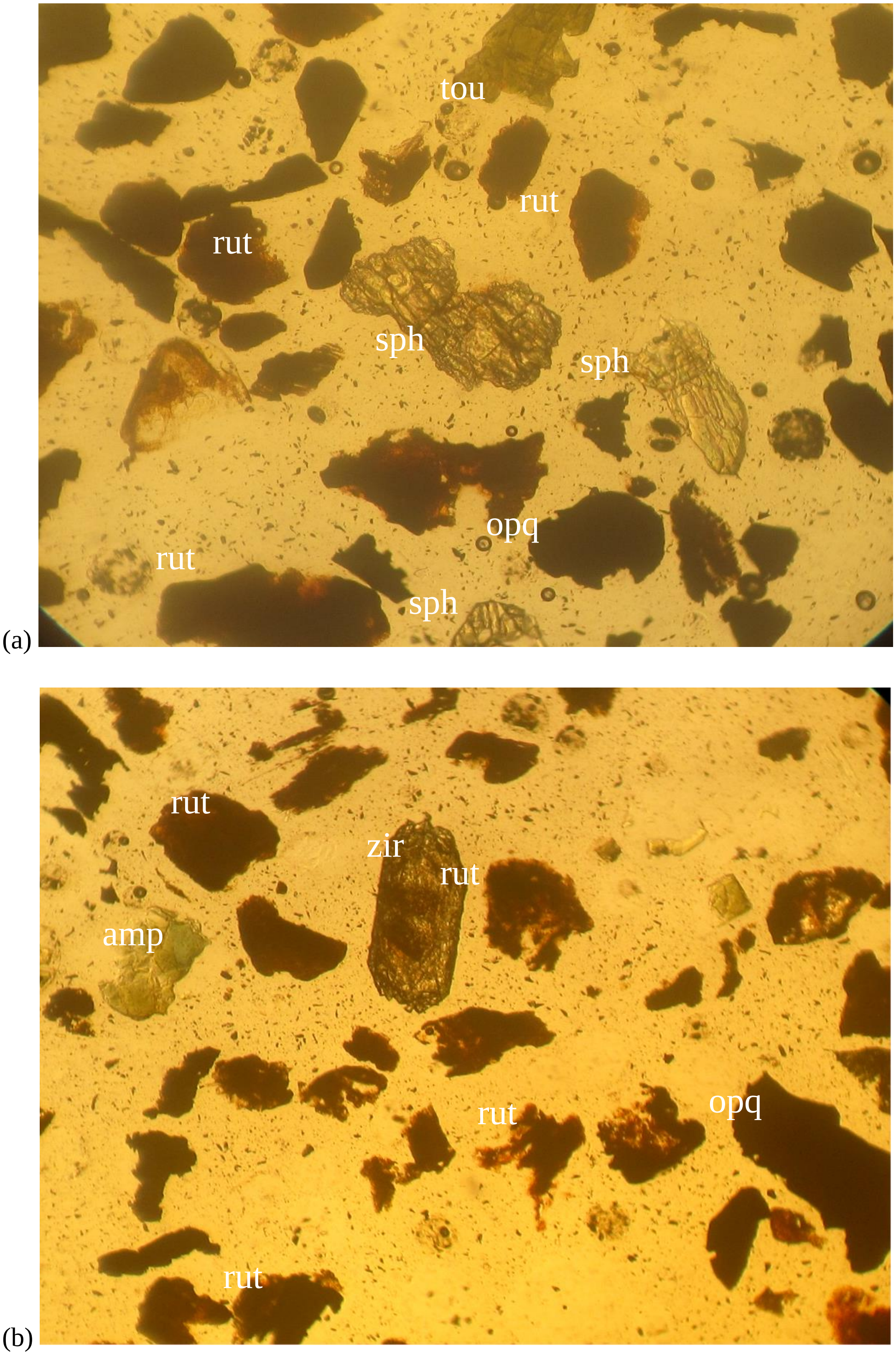


Plate 2: Photomicrographs showing mineral grains of fine sand fraction of Profile 1 under plain polarized light: (a) surface horizon and (b) subsurface horizon. amp = amphibole; rut = rutile; sph = sphene; opq = opaque mineral; zir = zircon (mag. x 10)

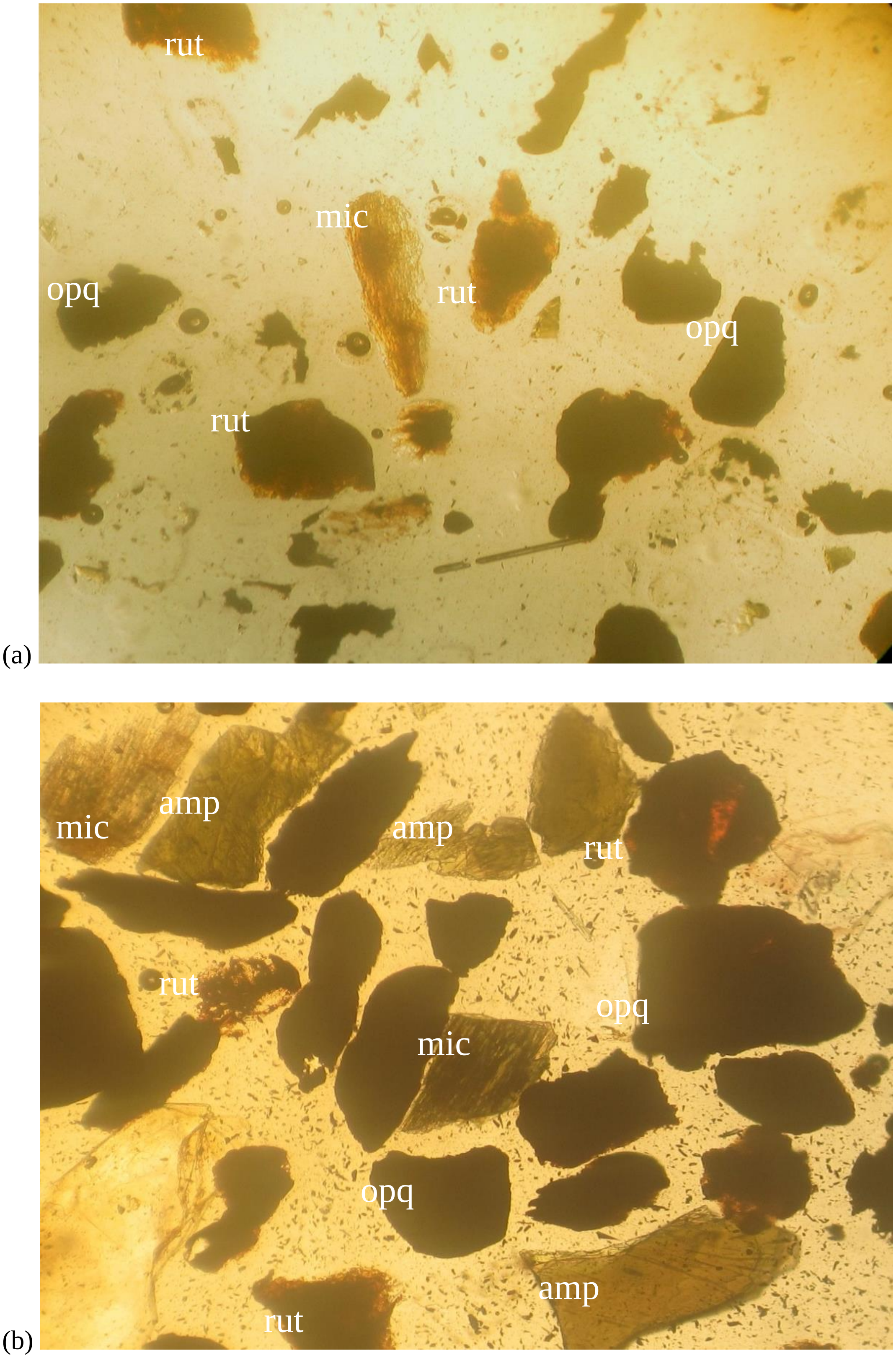


Plate 3: Photomicrographs showing mineral grains of fine sand fraction of Profile 2 under plain polarized light: (a) surface horizon and (b) subsurface horizon. amp = amphibole; mic = mica; rut = rutile; opq = opaque mineral (mag. x 10)

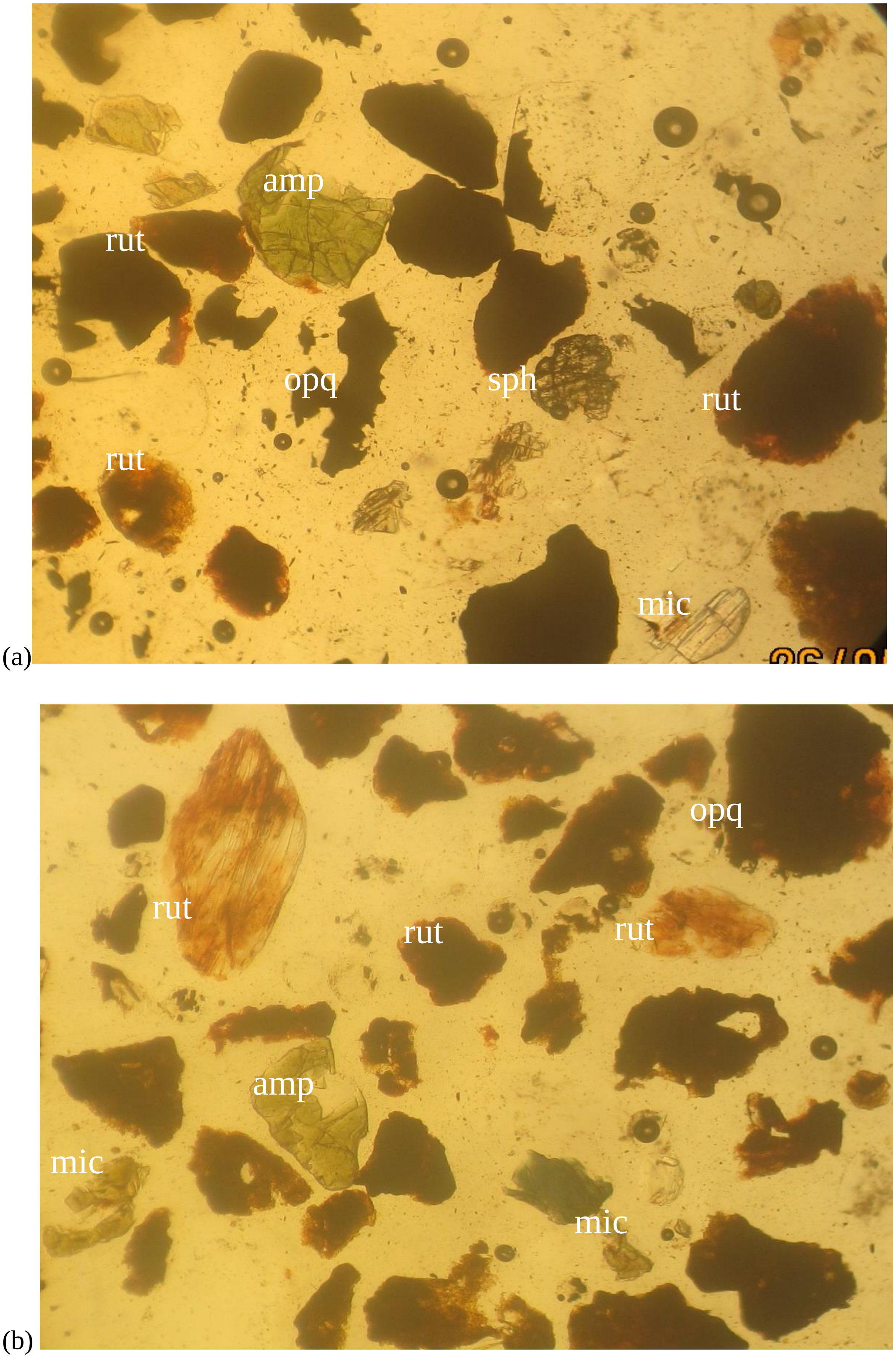


Plate 4: Photomicrographs showing mineral grains of fine sand fraction of Profile 3 under plain polarized light: (a) surface horizon and (b) subsurface horizon.
amp = amphibole; mic = mica; rut = rutile; sph = sphene; opq = opaque mineral (mag. x 10)

Specific gravity and petrographic analyses of fine sand

There were significant differences in the distribution of heavy and light mineral fractions with depth as revealed by specific gravity analysis (Table 6). Heavy liquid analysis using bromoform with specific gravity (s.g) of 2.89 showed that light minerals (s.g. < 2.89) constituted the bulk of the minerals present with a range of 62 – 98% while heavy minerals (s.g. > 2.89) ranged from 2 – 28%. There was a reciprocal relationship of the minerals with profile depth, the light mineral fraction decreased, while the heavy mineral fraction increased, with profile depth. This implies that the relative intensity of weathering decreased from A - horizon to C - horizon (Ojo-Atere and Ogunwale 1982; Amusan 1991). The dominant mineral found in the light fraction was quartz which was over 95% in all the horizons examined with plagioclase (feldspar) constituting about 5%. The dominant minerals found in the heavy mineral fraction were rutile (10 – 85%) and opaque minerals (6 – 80%), with trace amounts of other minerals including amphibole, sphene, tourmaline, mica and zircon in order of abundance (Table 7 and Plates 2 – 4). The presence of resistant minerals like quartz, tourmaline, rutile and zircon are indicative of the fact that the soils are highly weathered (Foss and Rust 1962).

Table 6: Percentage distribution of minerals in the fine sand fraction of the soils

Horizon	Depth (cm)	Mineral fraction	
		Light (s.g. < 2.89)	Heavy (s.g. > 2.89)
Profile 1 (upper slope): typic isohyperthemic paleustults			
A	0 - 15	92	8
AB	15 - 35	91	9
Bt1	35 - 53	91	9
Bt2	53 - 65	87	13
BC1	65 - 140	84	16
BC2	140 - 200	81	19
Profile 2 (mid slope): typic isohyperthemic paleustults			
Ap	0 - 9	97	3
AB	9 - 18	95	5
Bt1	18 - 57	94	6
Bt2	57 - 140	90	10
BCm	140 - 182	89	11
Profile 3 (lower slope): plinthic isohyperthemic paleustults			
A	0 - 20	96	4
Bt	20 - 56	96	4
Bv1	56 - 110	95	5
Bv2	110 - 160	95	5
Profile 4 (lower slope): typic isohyperthemic paleustults			
A	0 – 20	96	4
AB	20 – 35	96	4
Bt1	35 – 67	95	5
Bt2	67 – 97	96	4
2BC1	97 – 130	95	5
2BC2	130 – 180	95	5

s.g. = specific gravity

Table 6 (continued): Percentage distribution of minerals in the fine sand fraction of the soils

Horizon	Depth (cm)	Mineral fraction Light (s.g. < 2.89)	Heavy (s.g. > 2.89)
Profile 5 (upper slope): typic isohyperthemic paleustults			
A	0 – 18	98	2
AB	18 – 45	96	4
Bt1	45 – 71	95	5
Bt2	71 – 102	95	5
BC1	102 – 133	95	5
BC2	133 – 180	94	6
Profile 6 (mid slope): typic isohyperthemic paleustults			
Ap	0 - 18	97	3
AB	18 - 46	97	3
Bt1	46 - 72	94	6
Bt2	72-110	91	9
BC1	110 - 145	85	15
BC2	145 - 200	95	5
Profile 7 (lower slope): typic isohyperthemic paleustults			
Ap	0 – 18	95	5
AB	18 – 42	96	4
Bt1	42 – 70	96	4
Bt2	70 – 105	97	3
2Bt2	105 – 146	88	12
2BC	146 – 200	89	11
Profile 8 (lower slope): typic isohyperthemic paleustults			
A	0 – 19	99	1
AB	19 - 34	92	8
B2	34 - 69	92	8
Bv	69 - 135	62	28

s.g. = specific gravity

Table 7: Heavy mineral composition (%) of the fine sand fraction of the soils

Horizon	Depth (cm)	Rutile	Opaque	Amphibole	Mica (Muscovite)	Tourmaline	Sphene	Zircon
Profile 1 (upper slope): typic isohyperthemic paleustults								
A	0 - 15	10	80	5	-	3	2	-
AB	15 - 35	32	56	8	-	2	2	-
Bt1	35 - 53	40	46	7	2	3	1	1
Bt2	53 - 65	47	29	10	5	4	3	2
BC1	65 - 140	59	31	5	-	2	2	1
BC2	140 - 200	61	14	20	-	2	1	2

Table 7 continued: Heavy mineral composition (%) of the fine sand fraction of the soils

Horizon	Depth (cm)	Rutile	Opaque	Amphibole	Mica (Muscovite)	Tourmaline	Sphene	Zircon
Profile 2 (mid slope): typic isohyperthemic paleustults								
Ap	0 - 9	30	55	10	-	3	2	-
AB	9 - 18	31	50	15	4	-	-	-
Bt1	18 - 57	37	46	12	3	2	-	-
Bt2	57 - 140	43	30	18	5	-	4	-
BCm	140 - 182	49	26	18	3	3	1	-
Profile 3 (lower slope): plinthic isohyperthemic paleustults								
A	0 - 20	30	51	9	8	-	2	-
Bt	20 - 56	45	34	10	8	-	3	-
Bv1	56 - 110	60	21	10	7	2	-	-
Bv2	110 - 160	85	6	3	6	-	-	-
Profile 4 (lower slope): typic isohyperthemic paleustults								
A	0 - 20	58	8	22	3	7	2	-
AB	20 - 35	62	11	22	1	3	1	-
Bt1	35 - 67	73	20	5	2	-	-	-
Bt2	67 - 97	73	27	-	-	-	-	-
2BC1	97 - 130	77	13	10	-	-	-	-
2BC2	130 - 180	72	13	5	8	2	-	-
Profile 5 (upper slope): typic isohyperthemic paleustults								
A	0 - 18	96	-	3	1	-	-	-
AB	18 - 45	94	-	3	1	2	-	-
Bt1	45 - 71	95	-	2	2	-	1	-
Bt2	71 - 102	97	-	2	-	-	1	-
BC1	102 - 133	93	3	-	-	3	1	-
BC2	133 - 180	95	-	2	1	1	1	-
Profile 6 (mid slope): typic isohyperthemic paleustults								
Ap	0 - 18	97	-	-	-	-	3	-
AB	18 - 46	96	1	-	1	2	-	-
Bt1	46 - 72	99	-	-	-	-	1	-
Bt2	72 - 110	97	1	1	-	-	1	-
BC1	110 - 145	98	2	-	-	-	-	-
BC2	145 - 200	95	1	1	1	2	-	-
Profile 7 (lower slope): typic isohyperthemic paleustults								
Ap	0 - 18	96	1	3	-	-	-	-
AB	18 - 46	93	1	2	1	3		
Bt1	46 - 72	96		1	1	2	-	-
Bt2	72 - 110	100	-	-	-	-	-	-
2Bt3	110 - 145	96	1	2	1	-	-	-
2BC	145 - 200	97	-	-	3	-	-	-
Profile 8 (lower slope): typic isohyperthemic paleustults								
A	0 - 19	75	2	15	-	8	-	-
AB	19 - 34	75	3	13	5	-	4	-
B2	34 - 69	90	2	8	-	-	-	-
Bv	69 - 135	98	-	-	-	-	2	-

Classification of the soils

Local classification

The soil survey work carried out by Smyth and Montgomery in central western Nigeria (Smyth and Montgomery 1962) was used as a reference for the local classification of the soils. Factors taken into consideration were nature of the bedrock, form of parent material, physiographic position and soil morphology. The soils were derived from coarse-grained granites, gneisses and pegmatites. The parent rocks are resistant to weathering, frequently outcrop at the surface and give rise to relatively shallow soils. They are the parent rocks of the soils of Iwo association (Smyth and Montgomery 1962). Profile pits 01, 02, 05 and 06 were located at the mid to upper slope region, occupying gently-sloping positions of the topography and were believed to have been formed *in situ*. The profiles had shades of brown colour varying from dark reddish-brown to yellowish-brown in colour with clayey texture. The profiles were relatively deep with few ironstones and concretions. They were, therefore, classified as Iwo series. Profile pits 03 and 08 were well-drained and located at a break of slope position; a low level in the topography with horizons containing variable amounts of quartz, gravel, stones and frequent ironstone concretions, overlying a layer of almost impenetrable ironstone (petro-plinthite) at a depth of less than 100 cm. They were classified as Gambari series. Profile pits 04 and 07 are located at the lower slope position of the toposequences. They were derived from fine colluvial/alluvial material washed from higher sites. They occupied gentle to moderate slope at a low level in the topography. The soils were reddish-brown to yellowish-brown in colour with the presence of mottled clay at lower parts of the profiles and an almost uniform profile morphology. They were moderately-drained with evidence of lithologic break within the profile pits. This confirms that colluvial/alluvial materials were washed from higher sites. They are essentially devoid of stones and gravels to considerable depth. They were, therefore, classified as Oba series (Table 8).

Table 8: Classification of the soils

Profile no.	Classification		
	Local (Series)	Taxonomic	
		USDA	FAO/UNESCO
01	Iwo	Typic isohyperthermic paleustults	Chromic Lixisol
02	Iwo	Typic isohyperthermic paleustults	Chromic Lixisol
03	Gambari	Plinthic isohyperthermic paleustults	Plinthic Lixisol
04	Oba	Typic isohyperthermic paleustults	Chromic Lixisol
05	Iwo	Typic isohyperthermic paleustults	Chromic Lixisol
06	Iwo	Typic isohyperthermic paleustults	Chromic Lixisol
07	Oba	Typic isohyperthermic paleustults	Chromic Lixisol
08	Gambari	Plinthic isohyperthermic paleustults	Plinthic Lixisol

Taxonomic classification

The profiles studied showed an increase in clay content with soil depth, an indication of argillic horizon (Figures 2 and 3) and contained low SOM content, low ECEC and base saturation by CEC-Sum less than 35% (Table 5). These are the major differentiating characteristics of the order Ultisols (Soil Survey Staff 2009). Therefore, the soils are considered as Ultisols. Periaswamy and Ashaye (1982), Okusami and Oyediran (1985) and Amusan (1991) had similarly classified the soils of Iwo series which are members of Iwo association as Ultisol.

The profiles were mineral soils with low OM content, high in colour values and chromas. The soils are dry for more than 90 cumulative days but less than 180. The moisture regime of upland soils of southwestern Nigeria has been classified as being ustic (Periaswamy and Ashaye 1982; Okusami and Oyediran 1985), therefore, the soils are in Ustults suborder. The soil temperature regime in southwestern Nigeria is isohyperthermic (Amusan and Ashaye 1991) while the landscape is an old one that has remained geologically stable with ochric epipedon, hence pale and are typical for the profiles. Profiles 01, 02, 04, 05, 06 and 07 are therefore classified as Typic isohyperthermic paleustults, while profiles 03 and 08 with petro-plinthitic material within 100 cm of the soil surface, are qualified as *Plinthic isohyperthermic paleustults in the USDA Soil Taxonomy (Soil Survey Staff 2009). However, in the FAO/UNESCO system of soil classification, profiles 01, 02, 04, 05, 06 and 07 are classified as Chromic Lixisol due to the presence of argillic B horizon, low ECEC, low base saturation and high chroma. Profiles 03 and 08, with petro-plinthitic materials, were classified as Plinthic Lixisol (Table 8).

Fertility capability classification

The fertility capability classification (FCC) is a technical system that groups soils according to their agronomic constraints and management problems in terms of the nutrient supply capacity of the soils (Sanchez et al. 2003). The result of the fertility capability classification of the soils studied is shown in Table 9. The FCC units were formed by the combination of class designation from the three classification levels viz-a-viz type (topsoil texture), substratum type (subsoil texture) and certain other soil properties considered as condition modifiers or fertility constraints. Thus, the soils were classified according to whether a characteristic was present or not. The profiles were classified as SCehik, SCrehik, SCehik, SCehik, SCehik, SCrehik, SCehik and SCehik for profiles 01, 02, 03, 04, 05, 06, 07 and 08, respectively (Table 9). This implies that the eight profiles have sandy top soils and clayey subsoils. The dominant FCC unit of soils in the study area was SCehik (profiles 01, 03, 04, 05, 07 and 08) while profiles 02 and 06 belong to FCC unit SCrehik. The soils that belong to the same FCC units could be managed the same way since they have same agronomic constraints. Profiles 01, 03, 04, 05, 07 and 08 belonging to FCC unit SCehik have agronomic constraints of high leaching potential (e) because of the sandy (S) nature of the top soil which predisposed them to rapid leaching of the soil nutrients; high acidity (h), high P fixation potential (i) and low inherent nutrient reserve (k). Profiles 02 and 06 belonging to FCC unit SCehik in addition had high gravel content (r).

Table 9: Fertility capability classification (FCC) units of the soils

Profile no.	Topsoil	Subsoil	Condition modifiers					FCC unit
			r	e	h	i	k	
01	S	C	-	+	+	+	+	SCehik
02	S	C	+	+	+	+	+	SCrehik
03	S	C	-	+	+	+	+	SCehik
04	S	C	-	+	+	+	+	SCehik
05	S	C	-	+	+	+	+	SCehik
06	S	C	+	+	+	+	+	SCrehik
07	S	C	-	+	+	+	+	SCehik
08	S	C	-	+	+	+	+	SCehik

S = sandy, C = clay, r = gravel, e = leaching potential, h = acidic,
i = high P fixation, k = low nutrient reserve, + = present, - = absent

Conclusion

The soils were generally deep and well drained. Quartz constituted the bulk of the primary minerals present with smaller amounts of microcline, biotite, plagioclase and muscovite, while rutile and opaque minerals dominated the heavy mineral portion of the fine sand fraction. The soils were classified mainly as Ultisols with sandy top and clayey subsoils. Morphological, physical, chemical and mineralogical properties of the soils indicated that the soils of the study area were highly-weathered and intensely-leached.

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