PEDOGENESIS OF A LITHOSEQUENCE IN THE NORTHERN GUINEA SAVANNA OF KADUNA STATE, NIGERIA

BY

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IN

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DECLARATION

I hereby, declare that the contents of this thesis are products of original research work executed by me. Extraneous sources of information have been duly acknowledged through references and citations. The subject matter herein has not been presented in any previous application for higher degree at the Ahmadu Bello University or any other University.

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This thesis titled "Pedogenesis of a Lithosequence in the Northern Guinea Savanna of Kaduna State, Nigeria" by Lemuel Musa Maniyunda, meets the regulations governing the award of the degree of DOCTOR OF PHILOSOPHY of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This thesis is dedicated to ***God*** who said,

"May the peoples praise you, O God

May all the peoples praise you.

*Then the **land** will yield its harvest,*

And our God, will bless us". ***Psalms 67[5-6].***

And to my family

Lydia (beloved wife),

Laura-Ee, Levianna and LyevirHyel

(my lovely daughters).

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ABSTRACT

Lithosequence of soils developed on four basement complexes, namely Older Granites (OG), Quartzites (QZ), Mica Schists (MS) and Migmatite Gneiss (MG) was conducted on crest position in the Northern Guinea Savanna of Kaduna State, Nigeria

with a view to explaining their pedogenesis. Three pedons were dug on each parent material. Soil morphological, physicochemical and mineralogical properties were examined and classified for their sustainable uses. Results indicated that soil morphological properties were generally similar, except for variation in depth and structure. The soils were generally deep to very deep (135 – 190cm), but had restrictions due to parent materials on quartzite and mica schist (QZ1, MS2 and MS3) and presence of plinthite on migmatite gneiss. Dark brown colour dominated the surface, while strong brown in subsurface horizons with wider variation in the deeper subsurface horizons (10YR, 7.5YR and 5YR). Texture of surface soil was sandy loam and was attributed to erosion and eluviation of clay resulting in textural variation with soil depth. The subsoils had clay to sandy clay with sandy clay loam in the deeper portion of the subsurface horizons. The soils were dominated by sub-angular blocky structure except soils on mica schist which had platy structure in the subsoils. Sand dominated fine earth portion of the soils (ranged between 271 and 691 gkg^{-1}) and their subfractions were significantly influenced by parent materials and horizon differentiation. Particle density varied between 2.56 and 2.68 Mgm^{-3} and bulk density between 1.34 and 1.79 Mgm^{-3} in the soils. Water retention difference was generally slightly low and varied between 0.64 and 33.26 cm. Parent materials had significant influence on some chemical properties such as exchangeable Ca, TEB, EA, CECs, base saturation and ESP. Higher values of exchangeable Ca, TEB, EA, CECs and base saturation were in soils developed on MS followed by OG and QZ and least values were in soils on MG. These variations were attributed to leaching of bases and difference in pedogenic development (age). The chemical properties of the soils indicated strongly acid to neutral pH (5.30 - 6.90). Total exchangeable bases ranged between 2.92 and 8.98 cmol (+) kg^{-1}, cation exchange capacity (CEC - NH_4OAc)

were low to high, and moderate base saturation dominated the soils. The values of organic carbon (10.00 gkg^{-1}) and total nitrogen (1.00 gkg^{-1}) were generally low. Micronutrients (available and total forms) were all in adequate quantity, with available Fe, Mn and total Zn significantly influenced by parent materials. Parent materials and pedogenesis significantly influenced pedogenic forms of iron oxide and crystallization was in the order of soils on mica schist < quartzites < older granite < migmatite gneiss, whereas forms of manganese oxides were significantly influenced by horizonation. Kaolinite, diaspore, muscovite and illite dominated the mineralogy of clay fraction of the soils. Nature and extent of weathering of parent materials caused variation in mineralogy of the soil and their moderate pedogenic development. Mineral composition reflected soils on migmatite gneiss as most weathered and those on mica schist as least weathered. Contents of major and trace elements (total oxide) in the soils were not significantly influenced by difference in parent material, except for K_2O ($P < 0.05$), TiO_2 and Cr_2O_5 ($P < 0.01$). Parent materials significantly influenced relative weathering intensity of most total elemental oxides, with significantly lowest relative retention mostly in soils on MG and highest in soils on MS, thus reflecting variation in their pedogenic development (age). Parent materials and pedogenic age were prominent factors that affected soil properties, thereby influenced their pedogenesis. The main pedogenic processes include weathering of parent materials, relative accumulation and depletion of major and trace elements, structural differentiation and plinthization, braunification, humification, melanization, leaching, argilluviation, desilication, allitization and ferritization. According to the USDA *Soil Taxonomy,* all the pedons on migmatite gneiss were classified as Typic Plinthustalf at the subgroup level. Pedons on mica schists MS1 and MS2 were classified as Typic Haplustalf, while MS3 was classified as Kanhaplic Haplustalfs.

Soils on quartzite were classified as Lithic Haplustalf (Pedon QZ1), Kanhaplic Haplustalf (Pedon QZ2) and Typic Kandiustalf (Pedon QZ1). Pedons on older granite were classified as Typic Kanhaplustalf (OG1), Typic Haplustalf (OG2) and Kandic Paleustalf (OG3). In the World Reference Base Classification System, all the pedons on older granite and quartzite were classified as Haplic Lixisol, whereas those on migmatite gneiss as Plinthic Lixisol. Pedons on mica schist (MS1 and MS2) were classified as Haplic Luvisols, whereas MS3 as Haplic Lixisol. Management options suggested include construction of contour ridges and bunds, and cultivation of cover crops. Effective post harvest crop residue incorporation, application of farm yard manure and incorporation of legumes in crop rotation fields, as well as use of organo-mineral fertilizers will sustain the soils for crop production. Fertilizer application should be timely in judicious quantity and by burying to remedy their deficiencies.

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CHAPTER ONE

INTRODUCTION

Nature of parent material is said to profoundly influence the development and characteristics of soils (Brady and Weil, 2005). Differentiation in soil characteristics due to variations in parent material is reffered to as Lithosequences. In small regions with uniform climate, the nature of the parent material is probably more important than any other single factor in determining the characteristics and productivity of a

soil (Olaitan and Lombin, 1984). The weathering processes of disintegration and decomposition that give rise to the regolith are in general, a destructive processes. Thus, rocks and minerals are destroyed or altered and soluble nutrients are subject to loss through leaching. It seems incongruous that these same seemingly destructive processes can promote the genesis of natural bodies called soils (Brady and Weil, 2005).

Basement complex rocks are principally composed of igneous and metamorphic rocks such as granites, gneisses, migmatites, quartzites, schist and the metamorphosed derivatives of ancient sediments. The basement complex occupy about 50% of Nigeria's surface area while the sedimentary formations occupy the remainder (Oyawoye, 1970; Ogezi, 2002). The basement complex parent materials have been reported to cover almost entirely the whole of Kaduna state (Osazuwa, 1994). Therefore, knowledge of the relationship between the basement complex rock parent materials and the soil formation along with their properties will help in the sustainable use and management of these resources.

Several studies have been carried out on soil development over basement complex rocks in Nigeria (Doyne and Watson, 1933; Smyth and Montgomery, 1962; Ojanuga, 1975; Fagbami, 1981; Esu, 1987; Mosugu, 1989; Fasina *et al.*, 2007a, 2007b), however most studies relating soils and basement complex rocks were carried out in southwestern Nigeria within the Southern Guinea savanna and the forest zones on toposequences (Moormann et al., 1975; Fagbami, 1981; Moormann, 1981; Essoka *et al.*, 2007; Fasina *et al.*, 2007a, 2007b). Similarly, in the Northern Guinea savanna, most of the available information on basement complexes are related to toposequence (Malgwi, 1979; Esu, 1987; Esu *et al.,* 1987; Ezenwa and Esu, 1999; Malgwi *et al.*,

2000, Yaro, 2005). Ogunwale (1973) and Mosugu (1989) studies focused on climosequences on sandstones and bio-climosequence on granites respectively. Information on lithosequence within basement complex rocks in the Northern Guinea savanna area is scanty, mostly at a reconnaissance level and were conducted on granitic parent material (Mustapha and Singh, 2003; Hassan *et al.*, 2004; Mustapha and Fagam, 2007), with virtually little or no information on quartzites and mica-schists areas.

Most previous studies treated the basement complex rocks as one unit due to the intricate nature of their complexity, and as at present there is no study that has been carried out in detail to compare individual components of the basement complex rocks. Yet rocks of the basement complex are variable both in mineral assemblage and reactions to soil forming factors, hence likely to produce soils highly variable in properties and uses. Therefore, detailed information on the genesis, properties and classification of soils on the individual component parent material will provide a scientific basis for proper decision making in the sustainable use and management of these soil resources.

The study was therefore carried out with the purpose of establishing the effects of the individual component lithologies; older granites, quartzites, mica schists and migmatite gneisses on soil genesis, characteristics and their classification for sustainable use and management of their resources in the Northern Guinea Savanna of Kaduna State, Nigeria. The following specific objectives will be studied:

1 To determine the morphological, physical, chemical and mineralogical properties of the soils developed on older granites, quartzites, mica

schists and migmatite gneisses within the basement complexes in Kaduna state, Nigeria.

2 To determine the pedogenic processes involved in the different soils and assess if the parent materials has influence it significantly.

3 To classify the soils using USDA Soil Taxonomy classification system of (Soil Survey Staff, 2010) and correlate with the World Reference Base for Soil Resource (WRB) (FAO, 2006).

4 To recommend possible management options for sustainable use of these soils on the various parent material in the Northern Guinea Savanna area of Kaduna State, Nigeria.

CHAPTER TWO

LITERATURE REVIEW

2.1 FORMS AND DISTRIBUTION OF BASEMENT COMPLEX ROCK PARENT MATERIALS

Soil parent materials vary in many characteristics, some of the most important are the degree of consolidation or induration, texture and mineralogy (Fanning and Fanning, 1989; Brady and Weil, 2005). Basement complex rocks constitute igneous and metamorphic rocks, and they occupy 50% of Nigeria's surface area while the

sedimentary formations occupy the reminder (Ogezi, 2002; FDALR, 1990). The largest of this area lie north of Niger and Benue rivers and include parts of Northwestern and North-Central States (Kano, Kaduna, Katsina, Benue, and Plateau) and North-East States (Borno, Taraba and Adamawa States). Other areas where basement complexes can be found are the greater part of Kwara, Kogi and Western States as far as Abeokuta (FDALR. 1990) and the eastern parts of Nigeria (Figure 1).

The **Older Granites** (The Pan African) are considered to be metamorphosed coarse grained, acidic, intrusive igneous rocks (Hunt, 1972). Older granites include rocks of wide range of composition, texture, colour and structure. It may consist of granites, granodiorites, syenitic, gabbroic, dolecritic and charnocknitic rocks, pegmatites and various other gneissic rocks of varying textures (Oyawoye, 1970). They range from small plutons to large batholiths that form smooth-doomed hills and island or lone hills, called "inselbergs." The coarse grained granites include porphyritic granite, biotite, hornblende granite and fine-grained granites and fayalite-quartz (Osazuwa *et al.,* 1994). The granitoids occur within the migmatites and the metsediments with which they share some metamorphic tectonic history (Oluyide, 1995).

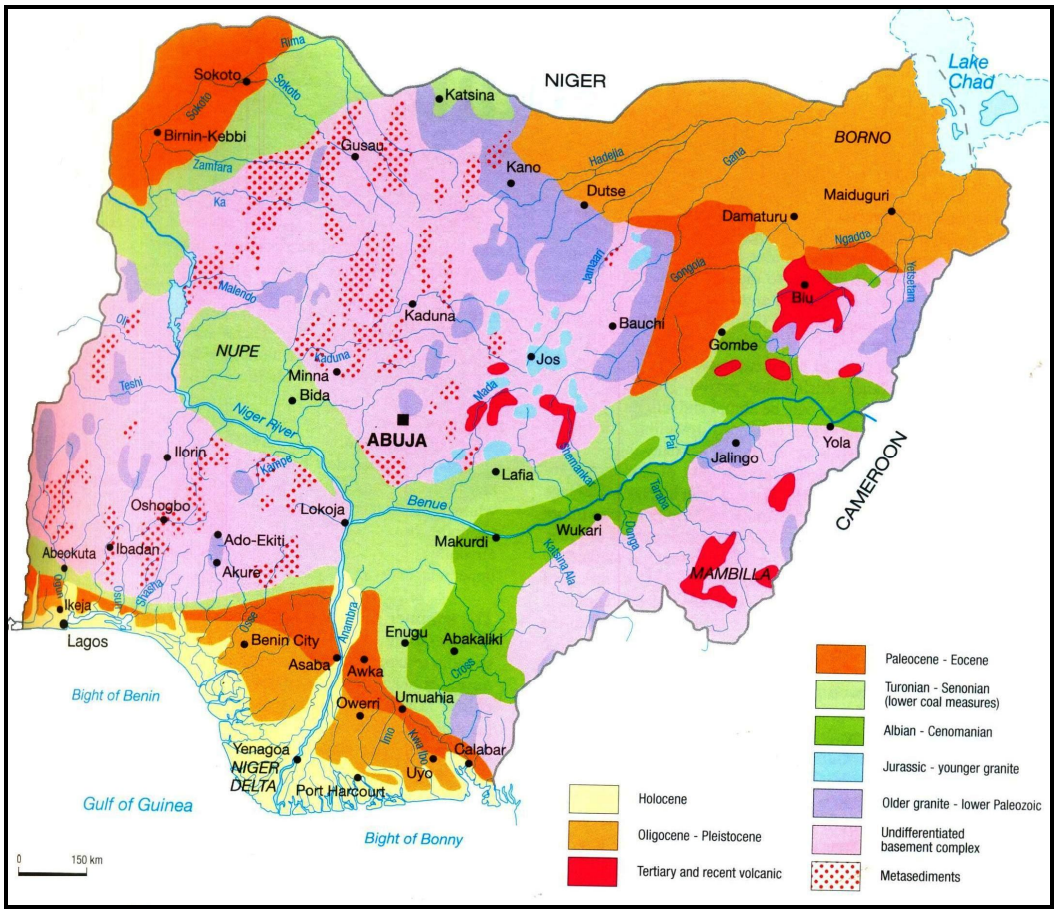


Figure 1 Geological Map of Nigeria. (Source: Ogezi, 2002)

Oyawoye (1970) classified older granites of Nigeria into two groups as: (a) the porphyroblastic older granites and (b) the granite-gneisses and gneissose-granites. Granites and granite-gneiss average approximately 25% quartz, 65% or less orthoclase (potassium) feldspar, with less amount of mica, biotite, and small amount of hornblende (Buol *et al.,* 1980).

The **Schists** or **metasedimentary** or **supracrustal belts** are foliated (thin platy), rich in mica (chlorite or sericite) metamorphic rock (Hunt, 1972), with varying amounts of quartz, and with very small amounts of other weatherable minerals (Buol *et al.,* 1980). Various types and grades of schists occur in the basement complex. The most widespread are biotite schists. They form lowland between quartzites ridges and never present in continuous outcrops (Oyawoye, 1970). They are structurally controlled, elongate, approximately N-S to NNE-SSW trending synformal Precambrian belts composed of metasediments and metavolcanics with rare mafic-ultramafic rocks close to major deep-seated lineaments. The rock group consists of mica schists, phyllites, amphibolites and some ferruginous quartzites (Banded Iron Formation) and serpentinites found around Birnin Gwari, Malumfashi, and Katsina (Ajibade, 1976; Osazuwa *et al.,* 1994). Important associated mineral resources include ironstone, gold, manganese and marble (Ogezi, 2002).

Quartzite is a hard, metamorphic rock which was originally sandstone in formation. May be coarse or fine –grained; the recrystallized quartz form a tight cement between the grains. It consist almost entirely of silicon dioxide (SiO_2) (Hunt, 1972). Quartzites are the most obvious of the metasediment in the field as ridges (Oyawoye, 1970).

Quartzites often occur in various shades of pink and red due to varying amounts of iron oxide. Other colours are due to impurities of minor amounts of other minerals.

Quartzite is usually white to gray, but some ferruginized varieties display reddish bands and have manganeferrous horizons (Wright and McCurry, 1970; Okunlola and Okoroafor, 2009). They vary in texture from massive quartzite to quartz schist. They are irregular medium to fine-grained crystals. They occur as low- lying outcrops. Muscovite is commonly present in fine flakes but some schistose quartzites are rich in muscovite. Various other minerals been noted in the quartzites. They include tourmaline, staurolite, sillaminite and haematite. Some quartzites have sufficiently high haematite/magnetite content to be considered as possible iron ores (Oyawoye, 1970; Osazuwa *et al.,* 1994).

Orthoquartzite is a very pure quartz sandstone composed of usually well rounded quartz grains cemented by silica (99% SiO_2). Meta-quartzite is made of individual quartz grains that have recrystalized along with the former cementing material to form an interlocking mosaic of quartz crystals. Quartzite is very resistant to chemical weathering and often forms ridges and resistant hilltops. They occur within north-south trending ridges paralleling the Tsofon- Birnin – Gwari – Funtua road (Oluyide, 1995).

The **gneiss (crystalline complex)** are metamorphic rocks that are banded, commonly with quartz, feldspar, micas, or other minerals in separate layers (Hunt, 1972). They may consist of layers of coarse grains, usually quartz or feldspar, alternating with layers of fine grained minerals.

Migmatites form of gneiss are the most widespread group of rocks. They form the ground mass in which all other rocks seem to occur. They are found in one form or the other everywhere in the basement complex (Oyawoye, 1970). Migmatitic complex include banded gneisses, migmatitic-gneisses, transitional gneisses, auger gneiss and

pegmatitics. Banded gneiss is one of the more abundant types. The rock consist of alternating light and dark coloured density of individual bands. Either of the dark or light bands may be locally dominant. Migmatitic gneiss is the most extensive rocks in Kaduna State and it usually occupies low plains. Some members are in Kaduna - Zaria area. The main mineral resources are marble and banded iron formation (Osazuwa *et al.,* 1994).

2.2 PEDOGENESIS ON BASEMENT COMPLEX ROCKS

The major pedogenic factors on basement complex have been reported by various researchers to include, climate, geology and geomorphological processes of creep action and erosional wash, while pedogenic processes include leaching, hydrolytic weathering, pedoturbation, braunification, plinthization, colluvial deposit, clay and iron-oxyhydroxide eluviations and illuviation (Ojanuga *et al.,* 1976; Fagbami, 1981; Esu *et al.,* 1987; Fasina *et al.*, 2005; Fasina *et al.,* 2007a). Smyth and Montgomery (1962), Olaitan and Lombin (1984) and Brady and Weil (2005) conclude that the nature of parent rock was a major factor in the determination of soil type and on the rate of soil profile development. In general, the younger the soil the greater the influence of, and relationship of, soil properties to the soil parent material. As weathering and pedogenic processes proceed, some features of the initial material are lost (Buol *et al.,* 1980; Douglas *et al.,* 1988). However, they stated that, it is not safe to conclude that in weathered and old soils the influence of parent material become less important.

Young (1976) stated that the main variables in parent material that affects soil formation are the degree of consolidation, grain size and composition. Grain size was considered to be the main determinant of soil texture, having a far greater effect than

climate (Olaitan and Lombin, 1984). The significance of this effect is that texture influences many other soil properties, including organic matter content, cation exchange capacity, profile drainage and moisture retaining capacity, and all these are properties of agricultural importance. Similarly, the composition of parent material is of fundamental importance for the properties of tropical soils. Fagbami (1979, 1981) observed that most of the soils developed on three parent rocks, namely banded gneiss, granitic gneiss and quartzite-schist had well developed argillic horizons. Nye (1954) and Le Riche (1973) observed that downward movement of clay $(<.5\mu m)$ was accompanied by movement of extractable Al_2O_3 and Fe_2O_3, thus identifying these as part of the mobile fraction (Blume and Schwertmann, 1969, Juo *et al.,* 1974). Le Riche (1973) also recognized that the sesquioxide fraction may not necessarily result from pedogenic breakdown of minerals only, but may even be derived from initial igneous rocks.

Esu (1987) studied the relationship between soil genesis on basement complex along a toposequence in Keffi, Nigeria and observed that plinthic horizons were below 50cm depth in the middle slope position. However in the crestal to upper slope position as well as at the break of slopes where erosion is very active, the plinthite is either very close to the surface or exposed to the extent that it hardens irreversibly to petroplinthite horizons accompanied by the gravelly petroplinthic materials (Ojanuga, 1985). Fasina *et al.* (2005) stated that many iron/manganese concretions occurs in most profiles studied and infer that plinthization as a pedogenic process may be responsible for the development of the upland soils in the area. This usually has serious limitation to crop production.

2.3 EFFECTS OF BASEMENT COMPLEX ROCKS ON SOIL PROPERTIES

2.3.1 Morphological Properties

Ojanuga (1985) stated that the soils developed from basement complex rocks in the savanna region of Nigeria are often shallow to moderately deep and often stony. Soil depth or thickness of solum were found to increase down slope from 60cm at the crest and upperslope to 200cm at the lower slope position (Idoga *et al.*, 2007). Moormann (1981) reported that solum was shallow in quartzite regolith. Deep solum (>100cm) were reported in the forest region on the diferent basement complex rocks, however, solum depth was restricted in the valley bottom because of high water table at about 50cm depth and suggested variation in land use types between such areas and the upland soils (Essoka *et al*. 2007; Fasina *et al.*, 2007b). Similarly, upland soils of Ibadan area, Nigeria were found to be deep and well drained with coarse grain material (Moormann *et al.*, 1975).

Soils developed from Precambrian basement complex of metamorphic and igneous rocks are well drained, through to somewhat poorly drained in nature were reported by Esu and Ojanuga (1985). Ojanuga (1975) observed the influence of topography and drainage, noting that soils on lower slopes are well-drained, but the valley bottoms are poorly drained. Ezenwa and Esu (1999) reported that the soils were well drained with moderately weak structural development in the surface horizon that are exposed to severe erosion hazard (Esu and Ojanuga, 1985). They, however, possess well developed argillic subsoils which are weak to moderately structured.

Soil texture is sandy to sandy loam in the top soils over argillic subsoils which vary in texture from sandy clay loam to clay loam (Moormann, 1975; Ojanuga, 1985; Esu and

Ojanuga, 1985; Esu, 1987; Ezenwa and Esu, 1999; Essoka *et al.*, 2007). Esu and Ojanuga (1985) noted that soil texture consists of sandy loam or loam over gravelly clay loam with notably high silt fractions and Ap horizons relatively low in clay. The colour ranges from dark brown, brown, strong brown, to yellowish red (Ojanuga, 1985)

Stonelines and gravel layers are a common feature of the middle to upper members of the toposequence, and are best developed on the crest (Moormann, 1981). The stonelines on basement complex are usually at a shallow depth, overlaying the material weathered *in situ*. Fagbami (1981) reported that the presence of stonelines in the soils formed on basement complex of southwestern Nigeria were related to the lithology of the area. It was observed that stonelines developed most frequently and prominently in the banded gneiss, less in quartzite-schists and least in granite-gneiss.

2.3.2 Physical Properties

Soils formed from saprolite derived from granitic rocks by geochemical weathering tend to be coarse. Soils developed in saprolite from mica schist tend to be silty and less coarse than those formed from granitic saprolite (Buol *et al.,* 1980). The Ap horizons of soils in upland segments of the landscape generally had the highest sand content with correspondingly low clay content. The low content of clay in the surface horizons of the upland soils of northern Nigeria have been attributed to surficial erosion which removes greater amount of silt and clay than sand (Esu *et al.,* 1987).

Fasina *et al.* (2005; 2007a) studied soils formed on granitic parent material of Humid Southwestern Nigeria. The Ap horizons of all the pedons irrespective of their location on the topography have very high sand content with low clay content. Relatively, low clay content and high silt fraction charcterised the Ap horizons of soils formed in the

prembrian basement complex rocks in the Northern Guinea Savanna (Esu and Ojanuga, 1985; Ezenwa and Esu, 1999). The high content of silt reflects the fact that most of the soils were formed from coarse colluvial material (Hill wash) or by aeolian process as loessial deposits. This tends to suggest that erosion is a marked pedogenic process in this area. Presence of gravel at varying depth is a common feature of those soils formed in the upland portion of landscape derived from granitic parent material of Humid Southwestern Nigeria (Okusami and Oyediran, 1985; Fasina *et al.* 2007a). Similarly, high gravel (8.67- 46.84%) content were observed in soils developed on diferent basement complex (quartzite-schist, granite and gneiss) of southwestern region (Aiboni, 2000). Soils formed on basement complex were noted to be higher in gravel content compared to those on sedimentary rocks in southwesten Nigeria (Ewulo *et al.,* 2000). This dominant presence of gravel in the soils developed on basement complexes tend to be associated more with the parent material than any other factor of soil formation.

Particle density of basement complex formed soils in Samaru, Zaria were found to range between 2.5 g cm^{-3} and 2.65 g cm^{-3} along toposequence (Malgwi, 1979). The particle density was observed to increase with depth in the profile and decrease on the surface horizons along the toposequence towards the lower slope position (Malgwi, 1979; Idoga *et al*., 2007). They associated the pattern of distribution of the particle density with organic matter content of the soils. Bulk density was observed to be lowest in the surface horizon of Samaru soils and increased progressively with depth (Malgwi *et al.* 2000; Idoga *et al*., 2007). This is similar to the findings of Essoka *et al.* (2007) in soil developed on gneiss and grnodiorite in Cross River Forest zone.. The

total porosity were noted also to be high in the surface horizon and decreased with depth.

2.3.3 Chemical Properties

2.3.3.1 *Soil pH, Exchangeable Cations and Cations Exchange Capacity*

The soil reaction indicates a generally moderate acidic condition (pH 5.3 – 6.2) (Ojanuga, 1975, 1985; Esu, 1987). Essoka *et al*. (2007) found that there was no significant difference in the pH of soils developed over different parent material of basement complex rocks. The values of pH ranged between 4.3 and 5.6 for both soils on granodiorite and gneiss. Soil reaction was reported to be almost neutral (pH 6.06 – 6.73) along a toposequence in Abeokuta (Aiboni, 2000). This was similar to the findings of Mosugu (1989) in Sudan Savanna soils formed on granite parent material.

Exchangeable Ca and Mg dominate exchange complex of soils on basement complexes in Nigerian savanna (Esu, *et.al.*, 1987; Kparmwang, 1993; Ezenwa and Esu, 1999). Exchangeable K is rated moderate to low. Cation exchange capacity of soils developed on basement complexes are reported to be generally low [6cmol (+) kg^{-1} soil] which may be in agreement with the kaolinitic nature of soil clay and low organic matter content (Ojanuga, 1975, 1985; Esu, 1987). Esu and Ojanuga (1985) observed that available nutrients, particularly Ca, Mg, K and N are relatively high in the soils developed on granite and gneiss in the Alfisols in Kaduna area, whereas, Ezenwa and Esu (1999) stated that available nutrients, particularly exchangeable Ca, Mg, K and Na are relatively low. Cation exchange capacity and base saturation percentage were reported to be low irrespective of landscape position of soils derived from basement complex rocks (Esu *et al.*, 1987). Similarly, low effective cation exchange capacity (ECEC) was reported on granite formed soil of southwest Nigeria

(Fasina *et al.*, 2005). Jaiyeoba (2006) found that variation in base elements and cation exchangeable capacity are more strongly related to lithology than climatic or relief parameters. However, soil pH and percent base saturation are influenced more by rainfall than parent material, altitude and slope position.

2.3.3.2 *Organic Carbon and Phosphorus*

The organic carbon content of many soils formed on different basement complex parent materials are low, mostly less than 2% especially in Northern Guinea savanna (Ojanuga, 1975, 1985; Esu, 1987; Fasina *et al.,* 2005). The low organic matter content was reported to be associated with rapid mineralization of organic matter in tropics, degradative effect of cultivation and other land use and mangement practices (Fasina *et al.*, 2005). Both Esu and Ojanuga (1985) and Ezenwa and Esu (1999) found that available phosphorus are generally low to very low (0.50 – 17.50 $mgkg^{-1}$) in soils formed on the precambrian basement complex rocks in Northern Guinea Savanna. Esu and Ojanuga (1985) attributed the low to very low available phosphorus to presence of low organic matter in the soils. Available phosphorus was found to be generally limited (5.18 – 9.12 $mgkg^{-1}$) in the granitic soils of Bauchi (Hassan and Raji, 2007). This may be attributed to high content of Fe (8.56 – 205.00 $mgkg^{-1}$) and Al oxides (16.40 – 164.00 $mgkg^{-1}$) in the profiles and recommended phosphorus application after liming for optimum crop yield.

Contrary to the nature of the soils developed on basement complex rocks in the savanna region, Essoka *et al.* (2007) reported that topsoils of the rainforest zone were had medium values for organic carbon, total nitrogen and available phosphorus, but reduced with depth as observed in the savanna soils.. The medium rating in nutrients content may be attributed to the flush vegetation in the area. Aiboni (2000) found that

soils developed on basement complex in Abeokuta had low to moderate rate of organic carbon and moderate to high available phosphorus. Organic based nutrient content in soils tend to follow bioclimatic pattern than lithology.

2.3.3.3 *Micronutrients*

Mosugu *et al.* (1991) in a study on zinc distibution in older granite in Nigeria, found DTPA extractable Zn distribution to be more influenced by parent material than by bioclimatic effect. The content of Zinc was adequate in all the climatic zones studied except for Southern Guinea savanna where it was observed to be deficient. The influence of parent materials on content and distribution of micronutrients (boron and zinc) were studied in Bauchi State, Nigeria (Mustapha and Fagam, 2007) and were found to be adequate in both Zn and B for crop growth. The result of the study indicated that parent material only influenced Zn distribution and not boron in the soils. Content of copper was found to be low in 50% of soils on basement complex rocks in Galambi District of Bauchi Local Government Area in Bauchi State, Nigeria (Mustapha and Singh, 2003). Iron and Mn were rated high, whereas Zn was rated medium in the soils. Olatunji *et al.* (2007) reported that micronutrients content of Cu, Fe, Mn and Zn of soils developed on banded gneisse and quartzite schist parent material were all adequate as their values were higher than the critical values. Fasina *et al.* (2005) also observed adequate levels of Zn, Fe, Cu and Mn in soils derived from granite in southwest Nigeria. However, only Cu was found to be signficantly higher in soils formed from quartzite schist parent material than on banded gneiss. Extractable micronutrients (Zn, Fe, Cu and Mn) were also reported to be above the critical available levels in soil developed on older and younger laterite with patches of biotite gneiss parent material (Yaro *et al.*, 2007). They observed that generally, the

micronutrient content were lower in the plinthite horizons than the non-plinthite horizons, and higher in the Ap than the subsoil horizons.The lower micronutrient content in the plinthite horizons implies that plinthite (iron oxides) will affect micronutrient content of soils.

2.3.4 Sesquioxides

The profile distribution of various forms of iron, manganese and aluminium oxides are useful criteria in the interpretation of pedogenic processes, such as podsolization, gleization and lessivation (Blume and Schwertmann, 1969; Juo *et al.,* 1974; Juo, 1981). The presence of amorphous Fe, Mn and Al oxides may have a significant influence on soil properties such as phosphate retention and aggregate formation (Juo, 1981). However, in Nigeria the amount of amorphous iron oxides is relatively small in most of the Alfisols and Ultisols derived from acidic parent rocks (Juo *et al.,* 1974; Juo, 1981). The content of oxalate-extractable iron oxides in these soils ranged from 0.05 to 0.2%, which comprised less than 10% of the total free iron oxides.

The amount of total free iron oxides present in the soil is influenced by the type of parent rock from which the soil materials developed. Soils derived from ferromagnessian rocks, such as basalt and amphibolite, generally contain much higher amounts of Fe dithionite form. Alfisols, Ultisols and Oxisols derived from basic parent materials is also considerably higher than in soils derived from acidic parent rocks, although the active iron ratio may not be significantly different (Juo, 1981). Hassan *et al.* (2004) observed that the distribution of active sesquioxide ratio within profiles of granitic soils in Bauchi showed irregular pattern except at the middle slope position which increased with depth, and they therefore, concluded that the soils are pedologically older and with greater iron crystallinity.

Total iron mean value in soils formed from different parent material decreased in the order; basalts > basement complex > coastal sand > shale. Free iron oxides were higher in well drained soils constituting about 61% of total Fe and only 9% in the poorly drained soils. Co-migration of clay- free Fe was observed in the well drained soils and not in the poorly drained (Udo, 1980). This implies that both drainage condition and parent material influence distribution of sesquioxides.

Pedogenic distribution of pyrophosphate extractable Fe and Al in plithitic soils in a landscape developed over basement complex in Zaria, Nigeria showed that the crystalline form of Fe and Al were higher in the plithitic horizons compared to the non-plinthitic horizons (Abdourahamane and Yaro, 2007). However, amorphous forms (pyrophosphate extractable) of Fe and Al were generally lower in the plithitic horizons than in the non-plithitic horizons (Abdourahamane and Yaro, 2007).

2.3.5 Mineralogical Properties

Moormann *et al.,* (1975), Ojanuga (1975) and Esu (1987) reported that kaolinite dominates the clay fraction which tends to influence the CEC of soils developed from basement complex rocks in Nigerian savanna. This could be due to high weathering intensity of soils in the tropics especially the more humid climates (Buol *et al.,* 1980). Esu (1987) reported that the subsoil gravel is high in kaolinite and some quantity of quartz and amorphous form of mica were also reported by Ojanuga (1979). Moormann *et al.,* (1975) reported that apart from kaolinite dominating soil developed on basement complex of Ibadan, goethite was found in all the soils. The presence of micas in the clay fraction are indicative of a relatively low degree of weathering in these soils. Kaolinite was also dominant mineral in the clay fraction of soils formed on basement complex in guinea savanna of Nigeria and quartzite-schist parent

material in eastern part of Maharashtra, India (Ezenwa and Esu, 1999; Niranjane *et al.,* 2005 respectively). Niranjane *et al.* (2005) however, reported that quartz and goethite were additional minerals observed in the clay fractions. Drainage condition of soils greatly affects the mineralogy of basement complex rocks of granites and gneisses (Ojanuga, 1979). Kaolinite is usually less dominant in a poorly drained environment (e.g. Fadama) as compared to vermiculite (Ojanuga, 1975; Esu, 1987).

Buol *et al.* (1980) observed that soils formed from granites in the cooler and /or more arid climates tend to have more vermiculite-illite-montmorillonite in the clay fraction.

Soils formed on schists were also reported to have illite (clay mica) and vermiculite, except in older and more highly weathered soils in which kaolinite is predominant, and in soils in which significant amount of montmorillonite is present (Buol *et al.,* 1980). Soils formed in residuum from chloritic schists are likely to be clayey, plastic, and rich in montmorillonite, and possibly contain excessive amounts of magnesium.

Husain (2010) using X-ray diffraction, observed that the forest soils developed on low metamorphic grade of phyllites and quartzites of different areas of Mussoorie was characterised by illite as the dominant mineral in the silicate clay with appreciable amount of kaolinite, mixed layer minerals, chlorite and small amounts of vermiculites, calcite and quartz.

2.4 GEOCHEMISTRY AND SOIL DEVELOPMENT

Elemental chemistry has been used widely in pedogenetic studies to identify source of soil parent materials. It has also been used to evaluate parent material uniformity in soil profile, and to measure losses and gains of elements that result from soil development (Barshad, 1965; Muir and Logan, 1982; Bussaca and Singer, 1989).

During early pedogenesis, the chemical composition of a soil will be highly controlled by the composition of the geological parent material, whereas the chemical composition of mature soils strongly reflects the effects of weathering environment (Bussaca and Singer, 1989; Brady and Weil, 2005; Thanachit *et al*., 2006). With time, soil composition diverges progressively from that of the parent material under the influence of pedogenic processes determined by vegetation, topography and, in particular, climate. The divergence may be due to redistribution of elements within soil fabric, between profile horizons and between soils within landscape. The process of elements mobilization and redistributions varied as were affected differently by various pedogenic processes including dissolution of primary minerals, formation of secondary minerals, redox processes, transportation of materials and ion exchange (Thanachit *et al*., 2006).

Pedogenic changes have been assessed using silica-sesquioxide ratio (Mohr *et al*., 1972; Bravard and Righi 1989; Yakubu and Ojanuga, 2009). Barshad, (1965), Evans and Adams (1975) Smeck and Wilding (1980) and Bussaca and Singer (1989) made use of internal indices to measure weathering and pedogenic development more accurately. Oxides of silicon (Si), titanium (Ti) and zirconium (Zr) total elements have been used as index elements as they have been reported to dominate quartz, rutile and zircon minerals (resistant to weathering) respectively (Marshall, 1977) and their choice were based on the presence of index element in both soil and parent material, their resistance to weathering processes and relative immobility (Smeck and Wilding, 1980; Muir and Logan, 1982; Bussaca and Singer, 1989). The use of index elements used for determination of relative accumulation (gain) and depletion (loss) of elements in soils have been useful in determination of extent of weathering and

pedogenic development (age) (Mohr *et al*., 1972; Bravard and Righi 1989; Bussaca and Singer, 1989; White, 1995; Aide and Smith-Aide, 2003; Muhs *et al.,* 2001). Several studies reported titanium to be slowly mobilized in soil profiles by mineral weathering (Smeck and Wilding, 1980; Bussaca and Singer, 1989), hence Bussaca and Singer (1989) suggested use of Zr as stable index element. Muhs *et al.* (2001) reported similar trends in relationship and a similar degree of explanation whether Ti or Zr was used as stable index element. Choice of stable index element should therefore be guided by assessment of their relative immobility in soils.

Pedogenic studies using geochemistry cut across major elements (Si, Al, Fe, Mn, Ti, Mg, Ca, Na and K), trace elements (Mo, Cu, Zn, Zr, Ba, Co, Ni, Pb, Sr, Y, Th, U, V, etc), heavy rare earth elements (lanthanide elements; La to Sm) and light rare earth elements (lanthanide elements; Eu to Lu) (Short, 1961; Huang and Gong, 2001; Aide and Smith-Aide, 2003; Marques *et al.*, 2004a,b; Caspari *et al*., 2006; Lasheras Adot *et al*., 2006; Thanachit *et al*., 2006). Geochemistry of iron and aluminium under slightly acid and oxidizing conditions indicated relative accumulation, whereas, mobile cations (Si, Ca, Mg, K, Mn and Na) move to lower position in slope or leached out of soils (Caspari *et al*., 2006; Thanachit *et al*., 2006). Kendrick and Graham (2004) similarly reported loss of Si, Na and K, and attributed it to loss of feldspar in the soils. They reported that Si loss in surface horizons was adequate to account for pedogenic Si accumulation in subsoils and was equivalent to amount of pedogenic Fe oxide; hence serve as indicator of relative soil age in the soils. Bussaca and Singer (1989) reported more enrichment of Si, K, Ti and Zr with less enrichment of Na, Mg, Al, Ca and Fe in silt fraction of chronosequence in Sacramento Valley, California. The more enriched elements may be associated with resistant minerals present in silt fraction,

whereas Fe may have accumulated in clay fraction. Marques *et al*. (2004b) reported that trace elements with an enrichment factor ≥ 1.2 such as Sc, V, Cr, Zr, Nb and Th were strongly accumulated in tropical soils. These elements possessed a 3+, 4+ or 5+ charge in their most stable oxidation state in acid, well aerated soils. Tetravalent (Zr and Th) and pentavalent cation (Nb) occurred as phosphate, silicate or oxide minerals that were highly resistant to weathering and therefore persisted in the soils. Divalent cations (Mn, Co, Ni, Cu, Zn, Sr, Ba and Pb) were depleted (enrichment factor ≤ 0.4) through leaching process because they cannot be in-corporated into the molecular structures of kaolinite, gibbsite, hematite or goethite without causing a charge imbalance (Marques *et al.*, 2004b).

Study of soil geochemistry is not only important in pedogenesis, but offers a means by which background levels of heavy metals in soils are defined, thus leading to assessment of their behavior in soils and their input as pollutants (Lasheras Adot *et al*., 2006).

2.5 CLASSIFICATION OF SOILS DEVELOPED ON BASEMENT COMPLEX ROCKS

Soils developed on basement complex rocks vary greatly in their properties resulting in a wide range of classification. Tomlinson (1965) and Klinkenberg and Higgins (1968) classified the soils developed on basement complex of northern Nigeria using the French Soil Classification System and identified the soils between Zaria, Kaduna and Birnin Gwari areas to be Ferruginous Tropical Soils on sandy parent material and on crystalline acid rocks. Enwezor *et al.* (1989) used the USDA and the FAO/UNESCO classification systems to classify the soils as Alfisols and Luvisols

respectively. Their classification was based on the characteristics of the soil to be moderately weathered and leached with high base saturation.

Ojanuga (1979) and Malgwi (1979) classified the soils in the Samaru in Zaria environment as Tropaquepts, Haplustalfs and Paleustalfs. Using the FAO/UNESCO Soil Legend, Malgwi (1979) placed the soils as Eutric Glyeysols, Glyic Luvisols and Eutric Nitosols. Esu (1982) classified the soils on basement complex rocks within Kaduna area as Paleustalfs and Ustifluvents. Plinthustalf and Paleustult were also recorded in some basement complex of Kaduna area (Ezenwa and Esu, 1999).

One phenomenon common to soils on basement complex rocks, irrespective of zone is the occurrence of plinthite at variable depth, thereby necessitating their classification as Plinthustalfs or Plinthustults (Esu and Ojanuga, 1985; Esu, 1987; Esu *et al.,* 1987; Mosugu, 1989; Kparmwang, 1993; Ezenwa and Esu, 1999). Esu and Ojanuga (1985) observed that Plinthustults were found on the somewhat poorly drained soils. Fasina *et al.* (2005) classified soils formed on granitic parent material of humid Southwestern of Nigeria as Typic Kandiudult, Typic plinthudult, Psammaquent, Plinthic Hapludox and Typic Dystrudept. Fagbami (1981) observed that most of the soils developed on banded gneiss, granitic gneiss and quartzite-schist were classified as Alfisols because of their well developed argillic horizons.

The soils of this study area were classified as Nearly level to gently undulating plains on undifferentiated basement complex of 0-2% slope (Mapping Unit 15g) FDALR, 1990). The soils are composed of deep, well drained, Typic Haplustalfs; deep well drained Oxic Paleustalfs; well drained OxicTropudalfs (very gravelly subsoil); and other soils of minor extent. Similarly, Ojanuga (2006) classified these soils as soils on gently undulating plains with broad convex uplands had narrow valley, scattered

vegetated inselbergs and low outcrops. Those at the upland were considered mainly as Ferric Luvisols, Ferric Acrisols and Ferric Cambisols, and those at the valley bottomlands associated with poor drainage were reffered to as Gleyic Luvisols, Eutric Fluvisols (FAO/UNESCO). At present, no detailed soil survey (at large scale) information has been available at the Birnin Gwari area. However, the soils have been studied at reconnaissance level and estimates made of the main soil series in the major land system (Tomlinson, 1965; Klinkenberg and Higgins, 1968; Bennett *et al*., 1979; Enwezor *et al.,* 1989; FDALR, 1990; Ojanuga, 2006).

2.6 MANAGEMENT OF SOILS DEVELOPED ON BASEMENT COMPLEX ROCKS

The starting point in the management of soils is a clear understanding of their properties and the processes responsible for them so that appropriate management techniques can be proffered for a particular soil or groups of soils with similar ecological conditions (Moormann *et al.,* 1975; Ojanuga, 2006). This calls for characterization and mapping of soils. The general problem affecting tropical soils developed on basement comple rocks is the rapid decline in organic matter content after forest clearing, which may be overcome by residue management and appropriate crop rotations (Moormann *et al.,* 1975). Sanchez (1981) stated that the main limiting factors within savanna Oxisol-Ultisols include alluminium toxicity and phosphorus deficiency, water stress caused by short-term droughts during the rainy season and generally defiency of most other nutrients (Fasina *et al.*, 2005). Fasina *et al.* (2005) recommended appropriate fertilizer use on farm lands by combining organic and inorganic fertilizers. These fertilizers should be applied based on appropriate soil test. Post harvest incorporation of plant residue into soil is recommended instead of the

usual burning of crop residue. In areas with occurrence of plinthite or petroplinthite minimum tillage is recommended along with soil cover (mulch) to prevent further erosion. Yassoglou *et al.* (2010) studied red soils developed on mica schists and gneisses adjacent to marble or calcareous mica schists in Greece and recommended the following management practices; erosion control, preservation of organic matter, minimum tillage, split application of N using non-acidifying fertilizers, irrigation, soil water conservation, and sheltered agriculture.

Low pH and low available P content in soils formed on basement complex can be improved by careful application of lime to neutralize exchangeable aluminum and by planting of promiscuous soybeans variety (Onyekwere *et al.,* 2005; Brady and Weil, 2005) thereby making these soils suitable for crop production. However, in most of savanna soils the pH is not extremely acidic to require the use of lime, instead use of non acidifying fertilizers is recommended.

CHAPTER THREE

PHYSICAL SETTING AND ENVIRONMENT OF THE STUDY AREA

3.1 LOCATION

The study areas are located in four sites situated within older granite, quartzite, mica schist and migmatite gneiss rocks, within the northern guinea savanna ecological zone of Kaduna State, Nigeria (Figure 2). The soils formed on the older granitic parent material were sampled in the south eastern part of Kaduna around Kujama in Chikun Local Government Area (Kaduna-Kachia route). The older granite site lies within latitude 10°27'55.7"N to 10°28'41.4"N and longitude 07°38'30.2"E to 07°39'27.3"E (Figure 3). Soils developed on migmatite gneiss parent material were sampled in Igabi Local Government area along Kaduna–Birnin Gwari route. The sites lies within latitude 10°35'04.2"N to 10°37'46.6"N and longitude 07°22'16.8"E to 07°24'50.3"E. Soils developed on mica-schists parent materials were sampled within Birnin Gwari Local Government Area (along Kaduna-Birnin Gwari route). Geographically, the sites lies within latitude 10°43'04.5"N to 10°43'43.2"N and longitude 06°44'59.1"E to 06°46'43.6"E. The soils formed on quartzites parent materials were sampled within Birnin Gwari Local Government Area, west of Birnin Gwari town. The site is situated between latitude 10°34'52.6"N and 10°35'31.2"N and longitude 06°11'14.0"E and 06°11'25.7"E.

3.2 GEOLOGY

The project sites are within the Kaduna plains; a series of nearly level to gently undulating plains above which rise some ironpan-capped surfaces (called mesas) and hills of granite and gneiss. The underlying geology is the basement complex of metamorphic and igneous rocks (Mortimore, 1970).

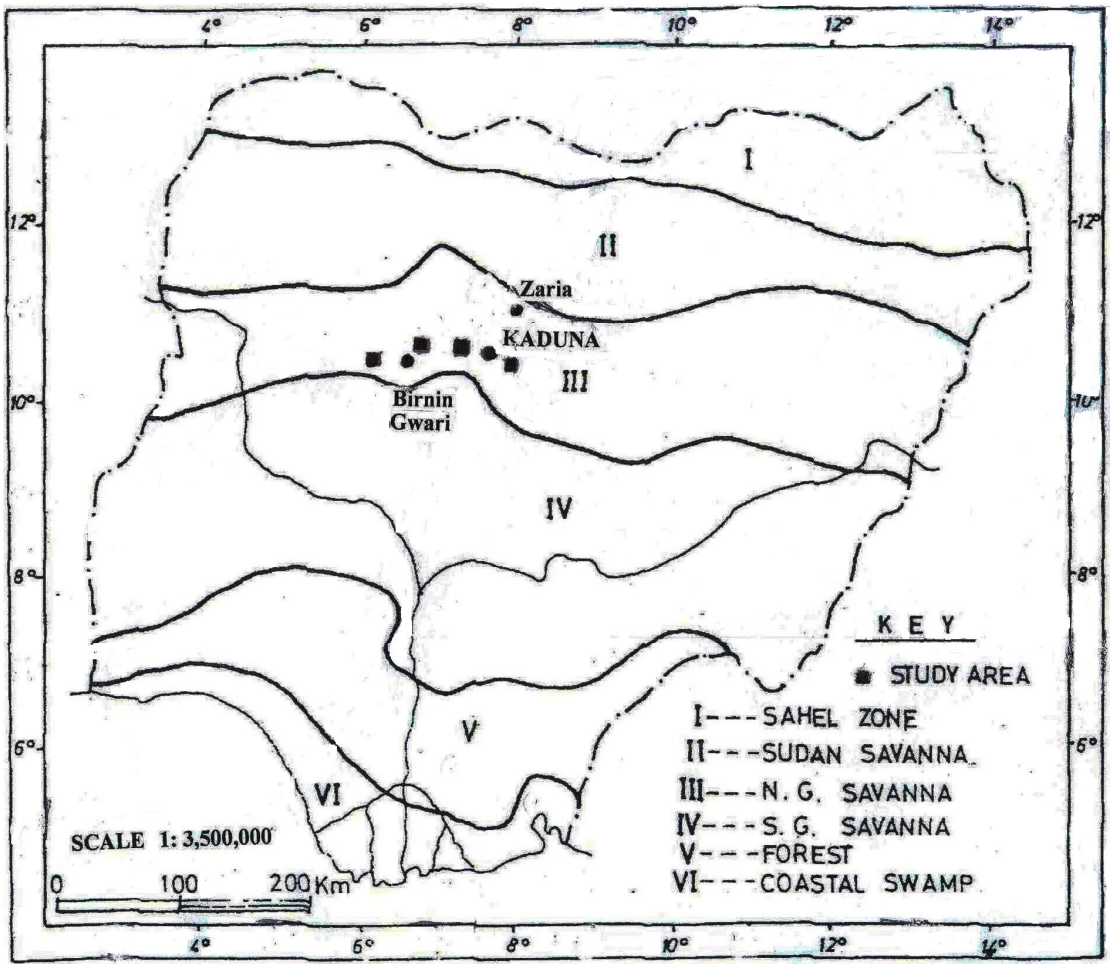


Figure 2 Ecological Map of Nigeria showing sampling sites.

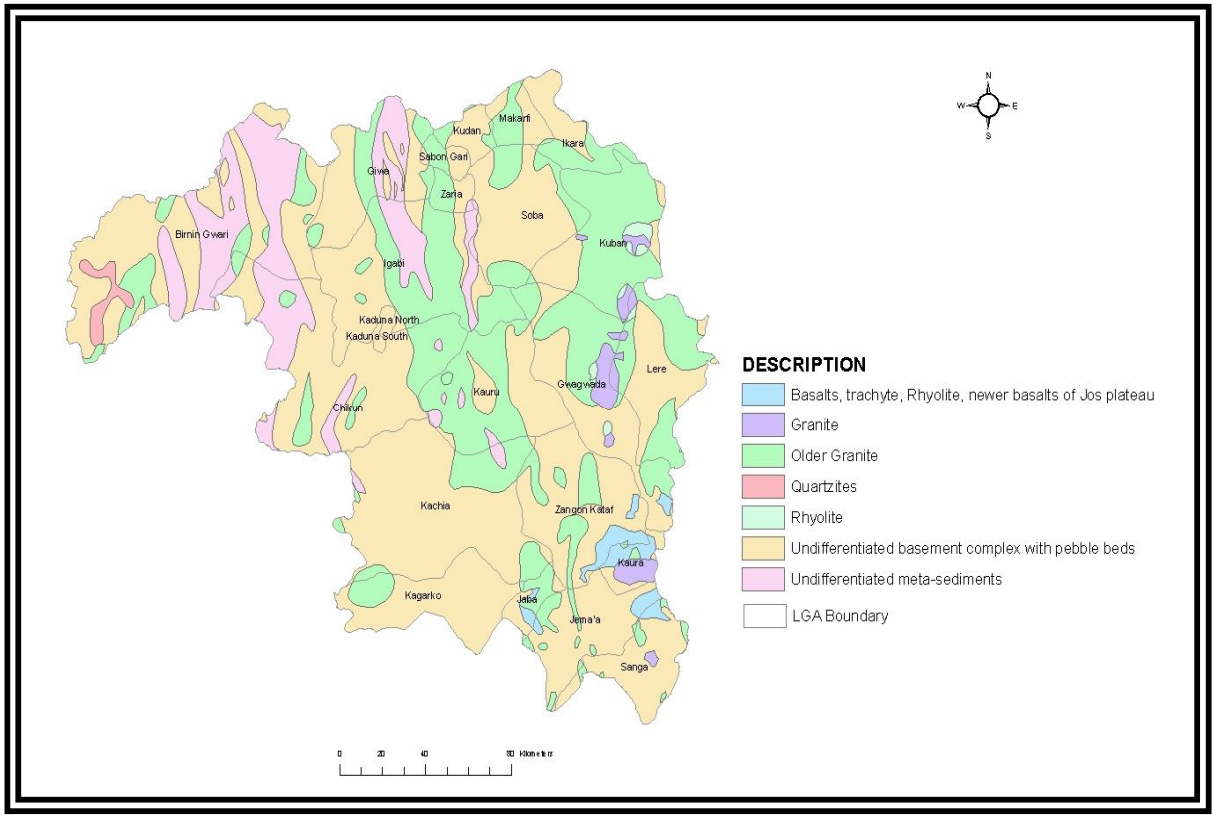


Figure 3 Geological Map of Kaduna State indicating Project Sites (■)
Courtesy: National Bureau of statistics (2009)

The unweathered rocks consist principally of ancient crystalline gneiss/migmatites and several north-south running belts of relatively low grade metasediments. The metasediments are comprised of quartzites, amphibolites, phyllites and schists (Osazuwa *et al.,* 1994; Wadrop and Mai, 1994; Oluyide, 1995). These are evident in the outcroppings to the west of Zaria and throughout the western part of the study area in Birnin Gwari Local Government Area (Figure 3). The rocks are rich in quartz and low in divalent cations (Bennett *et al.*, 1979).

The older granites manifest themselves in the shape of the north-south trending lines of smooth doomed inselbergs prominents near Zaria and south of Kaduna city (Russ, 1957; Osazuwa *et al.,* 1994; Wadrop and Mai, 1994; Oluyide, 1995).

3.3 GEOMORPHOLOGY AND DRAINAGE

The study area is within the Northcentral High Plain that is more appropriately identified as the Gusau-Kaduna-Minna Plain (Ojanuga, 2006). The area consists of an extensive, almost level to gently undulating, slightly dissected plain broken in places by groups of rocky hills and inselbergs. These are due to outcrops of granitic gneisses or quartzite hills and granite whalebacks (Ojanuga, 2006; Mc Curry, 1973). Much of the area lies between an elevation of 400m (west of Birnin Gwari) and 800m (southwest of Zaria) above sea level. The general height difference between valleys and adjacent crustal areas is about 20 to 40m. Typical cross-sections consists of (a) a broad crustal area with scattered ironpan capping (b) long planar, middle slopes of less than 3^0 and (c) short, steepened lower slopes showing signs of accelerated erosion (Bennett *et al.*, 1979).

The study areas around Kaduna are drained on the Northeastern part by the Kaduna River and on the west by Tubo River which is a tributary that drains into the Kaduna

River. The Birnin Gwari area is drained by the Kusheriki, Mariga and Tubo-Damari Rivers.

3.4 CLIMATE

The climatic data obtained from Kaduna area are the closest stations to the soil sites of soils developed on the older granite and gneiss parent material with available data on close latitude on the same climatic zone (Northern Guinea Savanna). The climatic data of Kaduna from Kowal and Knabe (1972) is presented in Table 1 and the more recent records from the Kaduna State Water Board is presented in Table 2. The summary of the climatic data obtained from Birnin Gwari Water Board Weather Station provide information on the climatic data of the soils formed on mica schist and quartzite parent materials (Table 3).

3.4.1 Rainfall

Rainfall is one of the most important climatic factors and its seasonal variability and amount are of overriding importance in pedological studies.

The seasonal distribution of mean monthly rainfall and the annual rainfall (1286 mm) for Kaduna is presented in Tables 1 and 2. The data showed that the peak rainfall in the area occurs in the months of July, August and September. Much of the rainfall, particularly between July and September were associated with storms of high intensity. The more recent rainfall data of 1969 to 2008 (1079 mm/annum) indicated a reduction in the annual amount of rainfall compared to earlier records between 1921 and 1971 (1286 mm/annum). The rainfall data (1,202 mm/ annum) obtained from the Kaduna International Airport which was the weather station within migmatite gneiss parent material site also indicated similar pattern with Kaduna State Water Board station report.

Table 1: Summary of Climatic Data of Kaduna Area (1921 – 1971)

Month	Rainfall (mm)	Sunshine (hr)	Insolation (Cal $cm^{-2}day^{-1}$)	Air Temp. (^{o}c)	Evapotrans. (mm)
Jan	0.5	8.8	89	23.2	129
Feb	2.5	9.4	118	25.7	138.4
Mar	10.7	8.3	177	27.9	154.2
Apr	71.2	7.7	224	28.0	141.5
May	146.1	7.8	242	26.8	134.4
Jun	178.1	7.3	231	24.9	109.7
Jul	217.2	5.7	207	23.9	96.8
Aug	296.2	4.4	185	23.4	84.3
Sept	275.6	6.4	223	24.3	99.3
Oct	82.6	8.4	232	24.9	114.8
Nov	4.6	9.3	145	23.6	118.9
Dec	0.3	9.3	88	23.3	122.7
Total/ Monthly Mean	1286.0	7.7	180	25.0	1454.9
Years of Record	50	15	15	50	15

Source: Kowal and Knabe (1972)

Table 2: Summary of Monthly Climatic Data of Kaduna North (1969 – 2008)

Month	Rainfall (mm)	Rainfall* (mm)	Air Temperature (^{o}c) Max.	Min.	Mean	Rel.Hum. (%)	Evap. (mm)
Jan	0.0	0.0	34.8	14.8	24.8	45	208
Feb	0.0	1.3	36.3	16.0	26.2	42	262
Mar	2.9	7.0	38.0	19.3	28.7	55	312
Apr	41.1	45.4	38.5	20.3	29.4	59	299
May	115.2	122.0	36.0	20.5	28.3	78	234
Jun	160.0	171.1	32.5	19.5	26.0	77	166
Jul	200.8	228	31.5	20.0	25.8	78	207
Aug	288.1	307.3	30.0	20.0	25.0	82	164
Sept	222.1	249.8	32.0	20.0	26.0	78	207
Oct	45.5	68.9	33.8	18.5	26.2	61	169
Nov	3.2	1.4	34.5	17.0	25.8	39	217
Dec	0.0	0.0	33.8	15.5	24.7	45	199
Total/ Monthly Mean	1079	1202.1	34.3	16.8	26.4	56	2149
Years of Record	1979-2008	1969-2008	1988	-	2008	2003-2008	1988-2008

Source: Kaduna State Water Board (Kaduna North station).
*(Kaduna Airport)

Table 3: Summary of Climatological Data for Birnin Gwari

Month	Rainfall	Open Pan Evapor.	Rel. Humidity		Temperature		
			Max.	Min.	Max.	Min.	Mean
	(mm)	(mm)	(-------%-------)		(----------°c----------)		
Jan	0.0	254.7	58.7	05.1	34.8	11.3	23.1
Feb	5.7	282.8	61.2	07.7	36.3	13.6	25.0
Mar	4.8	315.3	77.8	08.8	37.7	15.2	26.5
Apr	54.3	286.5	81.6	14.2	36.7	15.4	26.1
May	143.0	222.5	89.2	38.0	34.0	20.0	27.0
Jun	177.7	179.4	77.4	53.6	31.9	20.8	26.4
Jul	240.4	146.9	91.6	51.3	30.4	19.8	25.1
Aug	263.4	154.8	91.8	52.7	30.8	19.9	25.4
Sept	221.4	163	90.7	53.6	31.3	20.0	25.7
Oct	68.3	178.5	88.3	49.0	33.1	17.9	25.5
Nov	0.7	198.7	72.4	17.0	34.3	12.2	23.3
Dec	0.0	219.6	58.3	10.2	34.3	10.1	22.2
Total/ Monthly Mean	1,179.7	2,822.3 235.2	78.3	30.1	33.8	16.8	25.1

Source**:** Kaduna State Water Board, Birnin Gwari Meteorological Station; **(**1978-2004)

The Birnin Gwari project sites have distinct wet and dry seasons. The mean annual rainfall is reported as 1,197.7mm (Table 3) and the rainy season normally begins in April and ends in early October. During the months of November to March, the area is subject to cool, dry north easterly winds (Harmattan), which yield virtually no rain. Over these months, vegetative growth decreases to a minimum, the soil solum dries out and pedogenetic processes are slowed down. From April to May, the seasons change, the moist south-westerly winds bring rains, vegetative activities start again and the processes that develop the soil solum become intensified again.

Rainfall distribution seems to vary from season to season, similarly with its starting and ending. Blair Rain *et al.* (1977) using data of Kowal and Knabe (1972) computed the length of raining season in Kaduna to be 150 days. They also indicated that the starting date varies between May 11 - 20 to finish in October 1st – 10th (Bennett *et al.*, 1979). From this rainfall distribution pattern, soil moisture regime for the study area is inferred to be ustic moisture regime.

3.4.2 Temperature

The mean monthly record of temperature from Kaduna shows a range of 22.2^{o}C to 27.0^{o}C in a year. Recent records (1988 - 2008) (Table 2) indicated an increase in the mean monthly temperature (24.7^{o}C to 29.4^{o}C). The air temperature usually drops during the harmattan period of November to February and increases in March until it attains a peak in April just before the rains begin. The temperature then drops to a very low value in August and then rises to its secondary peak in October. The mean annual temperature is about 25.0^{o}C. The mean monthly temperature consecutively from February to October is less than 5^{o}C. Therefore, the soil temperature regime may

be considered as isohyperthermic, as it is expected that the variation will be less in soil as to the atmospheric temperature.

The Birnin Gwari study area record indicated high temperatures, with relatively small annual range. The maximum temperature ranged between 30.4^{o}C and 37.7^{o}C with the minimum temperture ranging from 10.1^{o}C to 20.8^{o}C.

3.4.3 Pattern of Radiation

The mean monthly global radiations and actual sunshine hours as recorded by Kowal and Knabe (1972) over a 15 year period in Kaduna is presented in Table 1. The mean daily number of sunshine hours in Kaduna area, per annum is 7.7 hours, while the monthly global radiations range from 88 to 242 cal cm^{-2} day^{-1} with an annual mean of 180 cal cm^{-2} day^{-1}.

3.4.4 Evaporation

The mean monthly values of evaporation in Kaduna range between a minimum average of 84.3mm in August and a maximum average of 154.2mm in March (Table 1). The total annual evapotranspiration of 1454.9mm is in excess of the total annual rainfall of 1286.0mm. The factors responsible for such high evapotranspiration rates are the high rates of solar radiation and wind action. There are only four months in a year (late May to September) when rainfall is in excess of evapotranspiration; over most of the remaining eight months, there is moisture deficit in the soil.

The climatic data of Kaduna North (Table 2) indicated evaporation to be as high as 2149 mm/annum and only three months in a year is when rainfall is in excess of evaporation, thus increasing the period of moisture deficit in soil compare to earlier report of Kowal and Knabe (1972). This may be attributed to global warming.

The mean amount of evaporation in rainy season (June to October) of Birnin Gwari area is 2,822.3mm (Table 3). Rainfall was observed to be in excess of evaporation only in the month of July to September as the area was observed to have high mean monthly evaporation (Table 3).

3.4.5 Relative Humidity

In Kaduna, mean monthly relative humidity range between 39% in November and 82% in August. The peak period of relative humidity is between May to September which is related to the period of rainfall establishment in the area for the crop growing season.

The relative humidity of Birnin Gwari shows that the mean maximum humidity decreased from about 91.8% in August to 58.3% in December. The mean minimum relative humidity ranged between 5.1% and 53.6%. The mean minimum relative humidity is observed to be greater than 50% only in the months when rainfall were fully established (>100mm).

3.4.6 Wind

There are two principal wind currents that influence the climate of the environment. The northeast trade wind brings dry, cool and dust laden air referred to as harmattan. The other wind is from the southwest wind bearing moisture, giving cloudy weather with thunderstorm (Higgins 1963). The confluence of these two air masses form the "Intra Tropical Front" (ITF). Following the passage of this front, a single rainy season occurs across the environment. The mean wind speed recorded was 1216km day^{-1}.

3.5 VEGETATION

The study areas are situated within the Northern Guinea Savanna zone. It is characterized by open, subhumid, broad-leaved savanna woodland vegetation at varying stages of regrowth, with short to medium grasses (Keay, 1959). The vegetation on the whole has been greatly disturbed either by grazing, burning, tree-falling for firewood and timber, and cultivation. Few of the common woody tree and shrub species in the area include; *Isoberlina doka, Uapaca togoensis, Parkea clappertoniana, Butterospermum* spp*, Termarindus indica, Daniellia oliveri, Terminalia, Acacia* spp, *Combretum glutinosum* and *Detarium microcarpum* (Olorode, 2002; Jackson, 1970; Higgins, 1963). The area is covered with more extensive grasses of *Aristida, Pennisetum, Andropogon, Hyparrhenia and Ctenium* (Olorode, 2002).

3.6 LAND USE

The major types of land use in the study areas include arable farming, forestry, logging, mining, livestock farming as well as industrial and urban development.

A wide range of crops are grown in this zone consisting of grains, roots and tubers, legumes and vegetables. Farm sizes are usually in the range of 2 – 7ha (Ojanuga, 2006). Arable farming is based mainly on subsistence farming through a system of bush fallowing shifting cultivation in areas where population is sparse. Small parcels of land are cleared and planted to annual crops. The main food crops include; sorghum, millet, soyabeans, cowpeas, and sweet potatoes. Cash crops include; maize, yam, rice, tomatoes, cabbage, carrots, onions, sugar cane, groundnuts, and cowpea (FDALR, 1990; Ojanuga, 2006). Some fruit trees include mango, guava cashew and pawpaw.

Logging for timber and firewood is vastly modifying the soilscape through soil compaction by log carrying trucks and exposure of soils to erosion owing to removal of vegetative cover. The government has tried to arrest the situation by setting up a number of forest reserves for controlled tree-falling but these measures do not appear to have gone far enough.

Livestock farming is practiced mainly by the Fulanis, who rear the animals either for milk production or subsequent fattening for slaughter. Most farm families also own a few stock of sheep, goats, cattle and poultry, which are kept in compounds and fed on groundnut and cowpea haulms as well as sorghum stalks during rainy season and allowed to graze during dry season.

Quite often minerals of economic importance are discovered in their natural environments by farmers or non-specialists. Minerals such as gold, tantalite, kyanite, clay and iron ore are exploited at a small scale (Oluyide, 1995). Granites have been quarried for road, slab and tiles construction.

CHAPTER FOUR

MATERIALS AND METHODS

4.1 FIELD STUDIES

The field study involved exploratory survey to identify sites, collection of ecoclimatic and geological maps, soil sampling and morphological description of profile pits.

4.1.1. Field Exploratory Survey

Field exploratory survey was conducted for the purpose of identifying suitable landscape areas for the study. Chikun Local Government Area, arround Kujama was explored for the soils developed on the older granitic parent material site. The migmatite gneiss parent material site was explored in Igabi Local Government Area and Birnin Gwari Local Government Area (along Kaduna-Lagos route) was explored for the mica schist and quartzite sites.

Information was obtained from the ecoclimatological zones map and superimposed on the geological map of Kaduna State (Figure 3) in order to ensure that the areas of study were within the Northern Guinea Savanna zone. Topo maps (1:50,000) were used to further identify suitable crestal position within each of the basement complex rocks parent material sites identified on the geological map.

Detailed field study was later carried out by siting and digging of profile pits at crest slope position and their geographical coordinates were established using global positioning system (GPS; Garmin 12 model).

4.1.1 Soil Sampling

To achieve the objectives of the study, soils were sampled from three profile pits based on genetic horizons at crest-slope position within cultivated fields on each of the four (4) parent material locations of the study area.

4.1.2 Soil Morphological Properties

Soil morphological properties were described in the field following the procedure described in the USDA Soil Survey Manual (Soil Survey Staff, 1951; Soil Survey Division Staff, 1993). The following features were observed and described; soil depth, colour, mottling, structure, texture, consistence, horizon boundary, roots, concretions and pores.

4.2 LABORATORY ANALYSIS

Soil samples collected from the various pedogenic horizons were air-dried in the laboratory, crushed with porcelain pestle and mortar and sieved to remove, material greater than 2mm (gravel). Percent gravel to total soil was calculated. The less than 2mm material was used to carry out Laboratory analysis.

4.2.1 Particle Size Analysis

Soil samples were dispersed in 5% calgon (sodium hexametaphosphate) solution on a reciprocating shaker. The particle size distribution was determined by the hydrometer method as described by Gee and Bauder (1986).

4.2.2 Bulk Density of the Soils

Undisturbed core samples were used for bulk density determination in the laboratory by oven drying as described by Blake and Hartge (1986a).

4.2.3 Particle Density of the Soils

The particle density was determined after the removal of entrapped air in soils using the pycnometer method as described by Blake and Hartge (1986b).

4.2.4 Total Porosity (T.P)

Total porosity was calculated mathematically (Danielson and Sutherland, 1986) from the particle density (ρ_p) and bulk density (ρ_b) of the soils using the formula;

$$T.P\ (\%) = 100\left(1 - \frac{\rho_b}{\rho_p}\right)$$

4.2.5 Available Water Capacity (AWC) and Water Retention Difference (WRD)

Available water capacity (AWC) was determined by calculating the difference in moisture content at field capacity (33kPa) and permanent wilting point (1500kPa) pressure (USDA, NRCS, 1995) using pressure plate method as described by Klute (1986) from the formula. Water retention difference (WRD) was obtained by the formula below (USDA, NRCS, 1995).

$$AWC\ (\%) = FC\ (\%) - PWP\ (\%)$$

Where AWC = Available water capacity
FC = field capacity
PWP = permanent wilting point

$$WRD\ (cm) = \{\frac{FC\ (\%) - PWP\ (\%)}{100}\} \times (\rho_b / \rho_w) \times D$$

Where ρ_p = density of water
ρ_b) = bulk density of soil
D = depth of soil horizon in cm.

4.2.6 Soil Reaction (pH)

Soil pH was determined in both water and 0.01 M $CaCl_2$ solution at a 1:1 soil/water or solution ratio. On equilibration, pH was read with a glass electrode on a pye Unicam Model 290Mk pH meter. Delta pH (dpH) values {pH ($CaCl_2$)-pH (H_2O)} will be calculated.

4.2.7 Exchangeable Bases

Exchangeable bases (Ca, Mg, K and Na) was determined using NH_4OAc saturation method as described by Thomas (1982). Potassium and sodium was read from the undiluted extract on a Galenkamp flame analyser. Before the determination of calcium and magnesium, the extracts were diluted 10 times with the addition of 2ml of 6.5% lanthanum chloride solution to prevent ionic interference. Calcium and magnesium were read on a Pye Unicam model Sp 192 atomic absorption spectrophotometer (AAS) at 423 and 285 nM wavelength respectively.

4.2.8 Exchange Acidity

The soil was leached with 1M KCl solution. Total exchange acidity (H+Al) was determined by titration of the extract with standard NaOH solution (Thomas, 1982). The exchangeable aluminium was determined colorimetrically as described by IITA (1979). The difference between total exchange acidity and exchangeable aluminium gave the amount of exchangeable hydrogen.

4.2.9 Cation Exchange Capacity

The cation exchange capacity (CEC) was determined by the neutral (pH 7.0) NH_4OAc saturation method (Rhoades, 1982). The effective CEC was obtained by summation of

the exchangeable bases and exchange acidity (IITA, 1979). CEC of clay fraction was calculated using the method proposed by Sombroek and Zonneveld (1971) as follows.

$$\text{CEC (clay)} = \frac{\text{CEC (soil)} - (3.5\%\ \text{C})}{\%\ \text{clay}} \times 100$$

4.2.10 Base Saturation (BS) Percentage

The base saturation percentage was calculated for both CEC (NH_4OAc) and ECEC from the formula:

$$\%\ \text{B.S} = \frac{\text{Total exchangeable bases}}{\text{CEC or ECEC}} \times 100$$

4.2.11 Exchangeable Sodium Percentage (ESP)

The exchangeable sodium percentage was calculated as the proportion of the CEC (NH_4OAc) occupied by sodium cations as follows.

$$\text{ESP} = \frac{\text{Exchangeable sodium}}{\text{CEC } (NH_4OAc)} \times 100$$

4.2.12 Electrical Conductivity (EC)

Electrical conductivity was determined at a 1: 2.5 soil/water ratio using a wheatstone bridge at 25^{o}C (Udo *et al*., 2009).

4.2.13 Organic Carbon (O.C)

The organic carbon was determined by the Walkley-Black dichromate wet oxidation method as described by Nelson and Sommers (1982). Concentrated sulphuric acid was used as a catalyst to activate the reaction.

4.2.14 Total Nitrogen (T.N)

The total nitrogen content of the soils was determined using the micro-Kjeldahl technique as described by Bremner and Mulvaney (1982).

4.2.15 Available Phosphorus (AP)

Available phosphorus was determined following the procedure described by IITA (1979) using the Bray- 1 extraction method (Bray and Kurtz, 1945). The phosphorus in solution was determined colorimetrically by the modified single solution procedure using ascorbic acid (Murphy and Riley, 1962).

4.2.16 0.1M HCl Extractable Cationic Micronutrients (Cu, Fe, Mn, and Zn).

Available cationic micronutrients were extracted with 0.1M HCl solution by shaken soil paste for 4 hours and then centrifuged at 10,000rpm. The Cu, Fe, Mn and Zn contents in the extract was determined on the AAS at 325, 373.9, 280 and 214 m wavelenghts respectively.

4.2.17 Total Cationic micronutrients (Cu, Fe, Mn, and Zn) by the Aqua-Regia Acids.

The soil sample was digested using aqua – regia acid (a mixture of 3 parts of HCl to 1 part of HNO_3) but not allowed to dry completely. The digest was transferred using deionised water and filled to mark (USDA NRCS, 2004). The cations (Cu, Fe, Mn and Zn) was determined in the solution on the AAS at 325, 373.9, 280 and 214 nm wavelenghts respectively.

4.2.18 Citrate – Bicarbonate – Dithionite (CBD) Extractable Iron and Manganese (Fe_d& Mn_d).

Free iron and manganese were extracted following the method of Mehra and Jackson (1960) as described by IITA (1979). The content of Fe and Mn in extract was determined after ten times dilution on a Pye Unicam model Sp 192 atomic absorption spectrophotometer (AAS) at 280nM and 373.9nM wavelengths respectively.

4.2.19 Acid Oxalate Extractable Iron and Manganese (Fe_{ox} and Mn_{ox})

Amorphous inorganic form of Fe and Mn oxides was extracted using ammonium oxalate (pH 3) in the dark (Mckeague and Day, 1966) using the modified Tamm's method as described by IITA (1979). Iron and Mn in the extract were determined following the method discussed in 4.2.16.

4.2.20 Pyrophosphate Extractable Iron and Manganese (Fe_p and Mn_p)

Amorphous organic form of Fe and Mn oxides was extracted using pyrophosphate solution as described by Mckeague, 1967). Iron and Mn in the extract were determined following the method discussed in 4.2.16.

4.3 MINERALOGICAL ANALYSIS

4.3.1 Pretreatment and Separation of Samples for Mineralogical Analysis

Specimens for mineralogical analysis were prepared by first removing exchangeable cations, organic matter and sesquioxides from the samples following the method described by Kunze and Dixon (1986). The samples were separated by soaking in 5% Calgon solution for 24 hours and then shaken for 24 hours. The samples were separated by series of siphoning, centrifugations and decantation into the sand, silt and clay fractions.

4.3.2 X-Ray Diffraction Analysis of the Silt and Clay Fractions

The silt and clay fractions were saturated with magnesium ions and were made ready for X-ray diffraction (XRD) analysis at the National Steel and Raw Materials Exploration Agency, Malali, Kaduna. The mineralogy of the silt and clay fractions were determined by X-ray diffractometry. Diffraction patterns were obtained using CuKα radiation and a Shimadzu X-ray diffractometer (XRD-6000). The samples were

step-scanned between 2 and 45° 2θ using scanning speed of 4° min^{-1} at sampling pitch of 0.020° and a preset time of 0.30 second. Oriented specimens were prepared by air drying on a standard glass slide for the examination.

4.3.3 Total Elemental Oxides Analysis

The total elemental oxides analysis of the soil samples were carried out at the National Geoscience Research Laboratories Centre, Barnawa Kaduna. The total elemental oxides were determined using energy dispersing X-ray fluorescence (EDXRF) XRF SPEC (Minipal 4). The < 2 mm soil samples were further grind to 150 μm and the powdered samples were used for the analysis. The conditions for analysis set were as followed:

(i) Mo filter at 30 kV for rare earth elements

(ii) Kapton filter at 20kV for Si, Al, P, etc

(iii) Filter (none) at K kV for alkaline and alkaline earth elements.

The relative intensity of weathering of total elemental oxides was determined by choosing titanium as the suitable indexing element (Marshall, 1977; Muhs *et al.*, 2001). The relative gain or loss of element was estimated using relative retained element (Ro) formula (White, 1995; Caspari *et al*., 2006).

$$R_o = \frac{X_h}{X_p} \times \frac{Ti_p}{Ti_h}$$

Where, X_h = element of interest in horizon to estimate

X_p = element of interest in parent material (rock)

Ti_h = index element (Titanium) in horizon to estimate

Ti_p = index element (Titanium) in parent material (rock).

R_o >1 = Relative accumulation of element (Gain)

1 = No relative accumulation or depletion of element

<1 = Relative depletion of element (Loss)

0 = Element absent in soil.

4.4 STATISTICAL ANALYSIS

Descriptive statistics (standard skewness and /or standard kurtosis) were used to assess the normal distribution of data for the parameters analysed in the laboratory (Agbenin, 1995; StatPoint, 2005). Values outside the range of ±1.96 indicated significant departure from normality (StatPoint, 2005). The data of parameters that were not normally distributed were analysed using non-parametric approaches. The list of parameters that were normally and not normally distributed are presented below.

A Normally Distributed Parameters

Physical properties: Total sand, silt, clay, bulk density, particle density, field capacity and permanent wilting point.

Chemical properties: pH (H_2O), pH ($CaCl_2$), ΔpH, K, exchange acidity, base saturation (summation), base saturation (NH_4OAc), exchangeable sodium percent, organic carbon, iron (dithionite, pyrophosphate and total), clay/iron dithionite ratio, manganese (total) and zinc (total).

Total elemental oxides: Al_2O_3, BaO, Cr_2O_5, CuO, Fe_2O_3, Mn_2O_3, SiO_2 and TiO.

B Skewed (Not Normally) Distributed Parameters

Physical properties: Gravel, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, Silt/ clay ratio, total porosity, available water capacity and water retention difference.

Chemical properties: Ca, Mg, Na, total exchangeable bases, effective CEC, CEC (NH_4OAc), CEC (clay), EC, TN, AP, Fe (available), Cu (available, total), zinc (available), Fe_{ox}/Fe_d, Mn (available), Mn_d, Mn_p, Mn_{ox}, and Mn_{ox}/Mn_d.

Total elemental oxides: CaO, Ga_2O_5, K_2O, MoO_3, NiO, PbO, Rb_2O, SrO, Y_2O_5, ZnO and ZrO_2.

Two factor Analysis of variance (ANOVA) was used to analyse the variation between the parent materials and between the surface and subsoil horizons using complete randomized design (CRD). The four (4) parent materials and horizons (surface and subsurface) were regarded as the treatments, whereas, the three profiles on each parent material were considered as the replications. Correlation analyses were conducted to determine the relationship between the parameters. The data of parameters that were normally distributed were analysed parametrically using Statgraphic Centurion XV computer soft-ware packages to determine the relationships between the various soil parameters (StatPoint, 2005).

Kruskal Wallis non parametric one way ANOVA test was used to compare difference between the various parent materials. Mann-Whitney non-parametric t-test was used to compare difference between surface and subsoil horizons. Spearmann rho ranked correlation was used for the non parametric data. Parameters that had significant difference were then contrasted using Fisher's Protected Least Significant Difference (LSD) test. All the statistical analyses were carried out at 95% confidence level. Non parametric test were carried out using statistical package for social science (SPSS Statistics 17.0).

4.5 SOIL CLASSIFICATION

Soil classification was carried out according to the USDA system – Soil Taxonomy (Soil Survey Staff, 2010) and World Reference Base for Soil Resources 2006 (FAO, 2006).

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 MORPHOLOGICAL PROPERTIES

Soil morphological properties considered include soil depth, structure, consistence, concretions, roots, pores and horizonation. Summary of these morphological properties are presented in Table 4, and details of profile descriptions are given in Appendix A. Detail morphological properties are discussed below.

5.1.1 Soil Depth

The soils were generally deep to very deep (135 – 190cm). Soils on older granites (OG) were very deep ranging between 183cm and 190cm and had no major restrictions within the pedons (Plate 1). The soils on quartzites (QZ), mica schist (MS) and migmatite gneiss (MG) were very deep except for pedons QZ1, MS2 and MG1 that were deep (Table 4). The depth of some soils on quartzites and mica schist were restricted due to presence of partially decomposed rocks (QZ1, MS2 and MS3) (Plate 2 and 3) encountered between 14 and 72cm. The depths of soils on migmatite gneiss were all restricted by the presence of concretions and plinthite within 48 - 172cm depths (Plate 4). The depth of plinthite were within range of those reported by Osher and Buol (1998) and Yaro (2005) on soils developed on landscape position in eastern Madre de Dios, Peru and on plinthitic landscape on upper slope to crest positions on basement complex of Zaria respectively.

Table 4 Morphological properties of the pedons of studied areas

Horizon	Depth (cm)	Munsell colour Moist	Dry	Mottle colour	Texture	Structure	Consistence Wet	Moist	Dry	Boundary	Other features
					SOILS ON OLDER GRANITE						
Profile - OG 1											
Ap	0 – 26	10YR 4/2	7.5YR 3/2	-	SL	1msbk	sssp	fi	sh	cw	Very few thin clay cutans on ped faces; common fine pores; many fine roots.
Bt1	26-75	7.5YR 4/6	7.5YR5/8	-	C	2vcsbk	sp	fr	h	cw	Few thin clay cutans on pores; many medium pores; few medium roots.
Bt2	75 -119	7.5YR 5/8	7.5YR 5/8	-	GSCL	2mabk	ssp	fr	vh	ds	Very few thin clay cutans on pores; common very fine pores; few very fine roots
BC	119-183	7.5YR 4/6	7.5YR 4/6	-	SCL	1mabk	sspo	fr	h	-	Few fine pores; few very fine roots; common weathered older granitic rocks.
Profile - OG 2											
Ap	0 – 17	7.5YR 4/3	7.5YR 3/2	-	SL	2msbk	sssp	fi	h	cw	Common fine pores; many very fine roots.
Bt1	17-70	10YR 3/6	10YR 4/6	-	C	3csbk	sp	fr	h	gw	Common fine pores; many very fine roots.
Bt2	70 -190	10YR 5/6	10YR 6/8	-	SCL	2msbk	ssp	fr	h	-	Few fine pores; many iron concretions.
Profile - OG 3											
Ap	0 – 23	7.5YR 3/2	7.5YR 5/4	-	SL	1msbk	sssp	fi	sh	gs	Common medium pores; many fine roots.
BA	23-57	7.5YR 4/4	7.5YR 5/4	5YR 4/6	CL	1vcsbk	ssp	fr	sh	gw	Very few thin clay cutans on pores; common medium pores; common medium roots.
Bt1	57 -121	7.5YR 4/6	7.5YR 5/8	-	CL	2vcabk	sp	fr	sh	di	Common fine pores; few medium roots.
Bt2	121-185	10YR 5/6	10YR 5/6	5YR 4/6	C	2msbk	sp	fr	h	-	few fine pores; few fine roots.

Table 4 Contd.: Morphological properties of the pedons of studied areas

Horizon	Depth (cm)	Munsell colour Moist	Dry	Mottle colour	Texture	Structure	Consistence Wet	Moist	Dry	Boundary	Other features
					SOILS ON QUARTZITES						
Profile - QZ 1											
Ap	0 – 14	10YR 3/2	10YR 4/2	-	GSL	1msbk	sssp	fi	h	gw	Few fine pores; few fine roots.
AC	14-40	7.5YR 4/4	7.5YR5/4	-	VGSL	1fc	sssp	fi	h	gi	Common fine roots; common weathered quartzites.
C1	40 -98	7.5YR 4/6	7.5YR 5/6	-	EGC	2mc	sp	fi	h	as	Few fine pores; few fine roots; common weathered quartzites.
C2	98-135	7.5YR 4/6	7.5YR 5/6	-	SCL	1mc	sp	fi	h	-	Few common pores; encountered weathered quartzite rocks.
Profile - QZ 2											
Ap	0 – 19	7.5YR 4/4	7.5YR 5/4	-	SL	1msbk	sopo	fr	s	gs	Common fine pores; many fine roots.
Bt1	19-51	7.5YR 4/6	7.5YR 5/8	-	SC	1msbk	sp	fr	h	gw	Common medium pores; common fine roots.
	Bt2	51 -84	7.5YR 4/6	7.5YR 5/8	-	C	2msbk	sp	fr	h	di Very few thin patch cutans on animal channels; few fine pores; few fine roots; ant channels and nests
	Bt3	84-139	5YR 4/6	5YR 6/6	2.5YR 4/6	SC	2msbk	sp	fr	h	dw Vew medium pores.
	Btc	139-187	5YR 4/6	5YR 6/6	2.5YR 4/6	SCL	1mabk	sp	fi	vh	- Few medium pores; common iron manganese concretion.
Profile -QZ 3											
Ap	0 – 19	7.5YR 4/4	7.5YR 5/4	-	SL	1cabk	sopo	fr	sh	gs	Few very fine pores; common very fine roots.
AB	19-40	10YR 4/4	10YR 5/4	-	SCL	2vcsbk	ssp	fr	h	gw	Common medium pores; common medium roots.
	Bt1	40 -63	7.5YR 4/6	7.5YR 6/6	-	C	2msbk	sp	fi	sh	cs Very few thin patch clay cutans on pores; common very fine pores; few very fine roots
	Bt2	63-97	7.5YR 4/6	7.5YR 6/6	-	C	2msbk	sp	fi	vh	gw- Few fine pores; few very fine roots.
BC	97-167	10YR 5/6	10YR 5/8	-	SC	2msbk	sp	fi	h	-	Few medium pores; few weathered quartzites; encountered weathered quartzite rocks at 167cm.

Table 4 Contd.: Morphological properties of the pedons of studied areas

Horizon	Depth (cm)	Munsell colour Moist	Dry	Mottle colour	Texture	Structure	Consistence Wet	Moist	Dry	Boundary	Other features
					SOILS ON MICA SCHIST						
Profile - MS 1											
Ap	0 – 18	10YR 3/2	10YR 4/3	-	SL	1mabk	sp	fi	sh	gs	Few thin continuous clay cutans on pores; many fine pores; common medium roots.
Bt1	18-54	10YR 4/6	10YR 5/6	-	SCL	2msbk	sp	fr	sh	gw	Few moderate clay cutans on root and animal channels; many fine pores; common medium roots
Bt2	54 -177	10YR 4/6	10YR 5/6	-	SCL	1msbk	sp	fr	sh	-	Very few thin patch clay cutans on pores; many fine pores; many fine roots.
Profile - MS 2											
Ap	0 – 16	10YR 4/3	10YR 5/3	-	SL	1msbk	sspo	fr	sh	gw	Common medium pores; many very fine roots.
Btc	16-37	7.5YR 4/6	7.5YR 5/6	5YR 5/8	SCL	1msbk	sp	fi	vh	gw	Few fine pores; few fine roots.
BC	37-72	10YR 5/2	10YR 5/2	7.5YR 5/8	GSCL	1msbk	sp	fi	h	gi	Very few thin cutans on root channels; few fine pores; few medium roots;few Fe-Mn concretions
C	72-143	10YR 5/2	10YR 5/2	7.5YR 6/8	GSCL	1cp	sp	fi	vh	-	Few fine pores; few fine roots; encountered fractured rocks.
Profile - MS 3											
Ap	0 – 19	10YR 4/3	10YR 5/3	-	SL	2msbk	sssp	fi	sh	gw	Very few moderate clay cutans on termite channels and ped faces; common fine pores; few fine roots; few termite channels and nests common medium pores; many fine roots.
Bt	19-42	7.5YR 4/6	7.5YR 5/6	-	CL	1mp	sp	fr	h	gi	Common fine pores; few medium roots
	C1	42 -96 7.5YR 5/2	7.5YR 6/3	-		SCL	3mp	sspo	fi	sh	di Few fine pores; few very fine roots.
	C2	96-168 10YR 5/2	10YR 6/2	-		SCL	2mp	sssp	fr	sh	- Few fine pores; few medium roots.

Table 4 Contd.: Morphological properties of the pedons of studied areas

Horizon	Depth (cm)	Munsell colour Moist	Dry	Mottle colour	Texture	Structure	Consistence Wet	Moist	Dry	Boundary	Other features
					SOILS ON MIGMATITE GNEISS						
Profile -MG 1											
Ap	0 – 15	7.5YR3/4	7.5YR 4/3	-	SL	1mabk	sssp	fr	h	gs	Very few (patches) thin clay cutans on pores; many fine pores; common very fine roots; few ant channels.
Bt	15-47	5YR 5/8	5YR6/8	2.5YR 4/8	SCL	3msbk	sp	fr	h	cw	Very few thin clay cutans on pores; few fine pores; common very fine roots.
Btcv1	47 -103	2.5YR 4/8	2.5YR 5/8	2.5YR 4/8	SCL	2msbk	sp	fr	h	as	Few fine pores; common iron – manganese concretions
	Btcv2	103-147 2.5YR 4/8	2.5YR 5/8	-		GSCL	1fsbk	sspo	fi	h	- Few fine pores; many iron –manganese concretions; encountered petroplinthite.
Profile - MG 2											
Ap	0 – 18	7.5YR 4/4	7.5YR 5/4	-	SL	1mabk	sssp	fi	h	cs	Common fine pores; many very fine roots.
AB	18-44	7.5YR 5/4	7.5YR 6/6	-	CL	1cabk	sp	fi	h	gs	Few moderate humus cutans on ped faces; common fine pores; few very fine roots.
Bt1	44 -78	5YR 4/6	5YR 6/8	-	C	2csbk	sp	fr	sh	dw	Common medium pores; few very fine roots; few termite channels.
Bt2	78-123	5YR 5/8	5YR 6/6	-	CL	2msbk	sp	fr	h	aw	Common fine pores; few very fine roots; very few termite channels.
BCcv	123-167	2.5YR 4/8	2.5YR 6/8	-	GSCL	2mc	sssp	fr	h	-	Very few (patch) thin clay cutans; few fine pores; many iron –manganese concretions; encountered petroplinthite.
Profile - MG 3											
Ap	0 – 25	7.5YR4/3	7.5YR 5/4	-	SCL	1mabk	sssp	fi	h	cw	Common fine pores; many very fine roots.
Bt1	25 -47	5YR 5/8	5YR 6/8	-	SCL	2csbk	sp	fi	h	dw	Few fine pores; few very fine roots.
Bt2	47-89	5YR 5/8	5YR 6/8	-	C	2msbk	sp	fr	h	as	Very few thin clay cutans on pores and deccay roots; few fine pores; few very fine roots; few iron nodules common fine pores; very few termite channels
BCcv	89-162	2.5YR 4/8	2.5YR 5/8	2.5YR 4/8	GSCL	1msbk	sp	fr	h	-	Few fine pores; many iron concretions;



Plate 1: Older granite pedon with horizons differentiation and traces of saprolite (OG1)



Plate 2: Quartzite pedon showing saprolite weathering (QZ1)



Plate 3: Mica schist pedon indicating platy structure (MS3)



Plate 4: Migmatite gneiss pedon with plinthite, concretions and traces of saprolite (MG3)

Earlier studies by several workers (Fagbami, 1981; Raji, 1995; Ezenwa and Esu, 1999; Idoga *et al.,* 2007) attributed the extent of soil depth to parent material, erosion and slope of the area. Ogunkunle (2009) reported that soils on upper to mid slope position developed on basement complex rocks were found to be deep and attributed shallow depth on crest to erosion process.

Soil depth restriction due to parent materials (QZ1, MS2 and MS3) and plinthite (all soils on MG) could be managed by construction of contour ridges and bunds to improve the soils for quality seedbed and increase rooting depth (Kang *et al.*, 1991; Odunze, 2006; Senjobi and Ogunkunle, 2011). The practice of contour ridges along with cultivation of cover crops could conserve the soils against surface runoff erosion that might expose the plinthite horizons to harden irreversibly and render the soil unsuitable for arable crop production (FAO, 2006; Fasina *et al*., 2007a; Senjobi and Ogunkunle, 2011).

5.1.2 Soil Colour

Variation in soil colour was generally more pronounced between horizons than between soils on the different parent materials. Surface horizons were dominantly dark brown and brown colours (7.5YR 3/2 and 7.5YR 4/4 moist). Other notable colours within Ap horizons were dark yellowish brown and very dark grayish brown (10YR 4/2 and 10YR 3/2, moist). The dark brown colouration of surface horizon (Ap) was attributed to humification resulting in melanization (Raji, 1995).

Strong brown (7.5YR 4/6, moist) colour dominated the Bt subsurfacel horizon, indicating braunification as a significant pedogenic process occurring in these soils (Buol *et al.*, 1980). Ande (2010) reported similar occurrence in soils formed on basement complex rocks in the humid tropical rainforest of Nigeria. Lower horizons

of the subsurface horizons were observed to vary between 10YR, 7.5YR and 5YR in soils on older granite (OG), quartzite (QZ) and mica schist (MS). Red (2.5YR) colour was observed in all the pedons on migmatite gneiss (MG). The yellowish red to red colour dominating at lower subsurface horizons were attributed to ferritization process (Fanning and Fanning, 1989; Raji, 1995). This great variation in colour noted in the profiles from surface to lowest part of the subsoil were reported by other workers in different parts of Nigeria (Raji, 1995; Ogunkunle, 2009; Yakubu and Ojanuga, 2009; Ande, 2010). Brady and Weil (2005) attributed red or brown colours in subsoil to presence of oxidized iron oxides in well drained uplands in the tropics.

Few to many mottles of red (2.5YR 4/6) and yellowish red (5YR 4/6) colours were observed in some subsurface horizons of some of pedons formed in the different parent materials and were aggregating to form Fe-Mn concretion or nodules.

Soils on quartzite and mica schists parent materials were brown (7.5YR 4/4) in the surface horizons. Subsurface horizons of soils on quartzites were observed to vary between strong brown and dark yellowish brown (7.5YR 4/6 and 10YR 4/6, moist) colours, whereas, the subsoil of mica schists were brown to grayish brown (7.5YR 5/2 and 10YR 5/2, moist). Soils developed on migmatite gneiss varied between dark brown and brown (7.5YR 3/4 and 7.5YR 4/4) in the surface horizons. The subsurface horizons varied between dark yellowish brown and yellowish brown (10YR 4/6 and 10YR 5/6, moist) colours, with yellowish red (5YR 4/6) few to many mottles in some parts of the subsurface horizons aggregating to form Fe-Mn concretions or nodules.

5.1.3 Soil Texture

All surface horzons of soils in this study were found to be sandy loam with the exception of pedon 1 on quartzite and pedon 3 on migmatite gneiss which was

gravelly sandy loam and sandy clay loam respectively. The coarse textured surface characteristic is a common feature associated with soils formed from basement complex rocks (Esu, 1987; Esu *et al.*, 1987; Ezenwa and Esu, 1999). This may be attributed to erosion of fine particle by surface run off down the slope from the crestal position and their illuviation into the subsoils (Esu *et al.,* 1987; Maniyunda, 1999; Fasina *et al.,* 2007a; Ande, 2010). Ridging and incorporation of crop residues with farm yard manure when carried out at land preparation would control soil erosion, crusting and improve physicochemical conditions of crop root zones (Adeoye, 1985; Tarawali *et al.*, 2001; Odunze, 2006).

The subsoils on older granites were dominantly clay and clay loam, with gravelly sandy clay loam and sandy clay loam in the lower portion of subsurface horizons of pedons 1 and 2 on older granite. This may be attributed to coarsive nature of older granite parent material.

The subsurface horizons of soils formed on quartzites parent material were mostly sandy clay and clay. Soil texture changed with increase in depth within Bt horizons of soil profiles in the order of clay to sandy clay to sandy clay loam in deeper horizons and might be attributed to eluviation - illuviation of clay to form zone of maximum clay accumulation (argilluviation). The subsurface horizons of pedon 1 on quartzite were characterised by high amount of gravels influencing their textural classification to be very gravelly sandy loam and extremely gravelly clay, thus indicating weathering process being active and pedogenesis had not yet reached advanced stage in the soil. The subsoils of soils formed on mica schist were dorminantly sandy clay loam, except for presence of gravels in pedon 2 on mica schist affecting soil texture to be gravelly sandy clay loam.

Migmatite gneiss subsoils were characterised by presence of clay, clay loam and sandy clay loam. The lowest horizons of all pedons on MG were gravelly sandy clay loam. The gravelly particle was attributed to plinthization of these horizons. Similar findings were reported on lateritized basaltic soils and on plinthitic landscape in Northern Guinea savanna of Nigeria (Kparmwang, 1993; and Yaro, 2005).

5.1.4 Soil Structure

Most of the soils in this study were found to be medium sub-angular blocky with few fine and coarse blocky structures. The structures were mostly moderately developed with few strongly and weakly developed. Pedon 1 on quartzite was observed to develop weak fine and moderate medium crumb structures in the subsoils which tend to be associated with recent formation. The subsoils of MS3 were completely medium platy structure and the lowest horizon of pedon 2 on mica schist (C horizon) was weakly coarse platy structured. The platy structure in the mica schist subsurface horizons were associated with the nature of parent material, and development of structure tend to be transformed into blocky structure as obtained in pedon 1 on mica schist. Soils on OG had coarser and strongly developed blocky structure than soils on MG. Structural development of the soils were therefore considered to be in the order of MS < QZ < MG < OG.

5.1.5 Soil Consistence

The consistences of surface horizons were generally slightly sticky and slightly plastic (wet) except for pedons 2 and 3 of quartzites that were non-sticky and non-plastic (wet). In the subsoils, they varied between sticky and slightly plastic (wet) and sticky and plastic (wet) consistence. The increase in cohesion and adhesion consistence feature of these soils down the profiles was related to increase in illuviation, as was

observed with sticky and plastic (wet) consistence in the argillic horizons having clay or clay loam texture.

All the soils were oberved to vary between friable and firm (moist) consistence. Under dry condition, most of soils had slightly hard to hard consistence, except for pedon 2 on quartzite where the surface horizon was soft (dry). This may be attributed to high content of sand in the horizon. Very hard (dry) consistence were observed in few subsoils horizons of pedons QZ2, QZ3 and MS2, and were found to be within the argillic horizons. This aligned with the findings of Raji (1995) and Maniyunda (1999) on ancient sand dunes of Sokoto and on loess and basement complexes of Funtua respectively that increase in consistences was attributed to increase in clay content.

5.1.6 Horizonation

Generally, horizonation was more pronounced between the Ap and subsoil than within the subsoil horizons. Surface horizons of soils formed on older granites and migmatite gneiss were generally clearly wavy to gradually smooth, and may be ascribed to melanization from the humification of organic matter in the Ap horizons. The surface horizons of soils on quartzites and mica schist varied between gradually wavy and smooth. Horizon differentiations in the subsoils were mostly gradually wavy and some few were gradually to diffusely irregular horizonation. Transitional horizons were virtually in all the different soils. They have combined features of corresponding horizons with diffuse wavy to irregular boundary. This was also noted by Ande (2010) in pedons of upper to crest slope position on basement complex rocks in the humid Tropical Rainforest of Nigeria.

The wavy boundary observed to be common in all the soils developed in different basement complex parent materials could be attributed to cultivated ridges in most of

the sites where furrows ponded water influenced the movement of materials into the profiles.

The presence of clay cutans and mottles were helpful in horizon differentiation in the sub-soils. The subsoil horizons of migmatite gneiss were characterised by presence of plinthite. Platy structure was found only in soils on mica schist and was attributed to the nature of parent material (mica schist) as it disintegrates and decomposes into soil. Horizon differentiations were abrupt in the lower subsoil horizons of soils formed on migmatite gneiss parent material and were associated to the formation of plinthite.

5.1.7 Miscellaneous Observations

Surface (Ap) horizons and the transitional horizons (AB, BA and AC) had common medium pores to common fine pores. The upper portions of subsurface horizons had common fine pores and the pores decreased in density and size with increase in depth. This may be attributed to argilluviation into the pores.

There were many fine to common very fine roots observed in the Ap horizons of soils formed on the different parent materials. The immediate horizons underlying Ap horizons were observed to have common medium roots to many fine roots. However, soils on migmatite gneiss had few very fine roots. Generally, the density and size of roots decreased with increase in soil depth. High density of roots in Ap and their corresponding transitional horizons could be due to zones of root activities.

Thin clay cutans were observed in pore spaces, soil surfaces and root surfaces in most of the pedons of the different parent material and indicating that the B horizons had argillic horizons (Soil Survey Staff, 2010). Presence of few ants and termite channel and nests were observed within the various soil profiles indicating some degree of

faunal pedoturbation within these profiles (Buol *et al.*, 1980; Fanning and Fanning, 1989).

The presence of iron and manganese concretions along with mottles in B horizons of some of the pedons in each parent materials indicated accumulation and aggregations of iron and manganese oxides resulting in plinthization. Plinthite was more pronounced in the soils formed on migmatite gneiss and might be attributed to level nature of crest and parent material with period of pedogenic exposure resulting in increased Fe illuviation.

The presence of several inselbergs of older granitic rock (Plate 5) in the study sites indicated that the soils developed from older granitic parent materials. The several hills of mica schist with exposed parent material undergoing weathering (Plate 6) and the undulating topography assisted in identification of sites for soils formed on this parent material. Similarly, ridges of quartzite rock (Plates 7a and7b) found in the site of soils formed on quartzite parent material and the presence of weathered quartzite in pedon 1 on quartzite establishes their formation on this rock. Migmatite gneiss sites were mostly plane crest with some meso relief of exposed petroplinthite (Plate 8).

5.2 SOIL PHYSICAL PROPERTIES

The parameters considered under soil physical properties include particle size distribution, particle density, bulk density, total porosity and moisture retention at various levels. Data for particle size distribution and sand subfraction were presented in Tables 5.



Plate 5: Inselberg of older granite on site



Plate 6: Weathered mica schist with coarse flakes



Plate 7a: Quartzite hill showing North-South ridge



Plate 7b: Quartzite hill undergoing weathering



Plate 8: Migmatite gneiss site showing plain crest with exposed petroplinthite mound.

Table 5: Particle size distribution and textural classes of soils of studied areas

Pedon	Depth	Gravel	Sand subfractions					Total Sand	Silt	Clay	Si/C	Texture
			VCS	CS	MS	FS	VFS					
	(cm)	(---------- gkg^{-1} ----------)										
						Soils on Older Granites						
Pedon OG 1												
Ap	0 - 26	10	135	253	104	59	100	651	227	122	1.86	Sandy Loam
Bt1	26 - 75	40	193	108	41	31	18	391	187	422	0.44	Clay
Bt2	75 - 119	200	225	192	70	35	29	551	167	282	0.59	Gravelly Sandy Clay Loam
BC	119 – 183	80	238	198	82	49	44	611	147	242	0.61	Sandy Clay Loam
Pedon OG 2												
Ap	0 - 17	20	111	216	138	62	64	591	247	162	1.52	Sandy Loam
Bt	17 - 70	30	96	131	73	38	32	371	227	402	0.56	Clay
Btc	70 - 190	90	238	185	78	47	43	591	167	242	0.69	Sandy Clay Loam
Pedon OG 3												
Ap	0 - 23	40	97	171	111	66	89	531	327	142	2.30	Sandy Loam
Bt	23 - 57	30	113	126	74	47	51	411	247	342	0.72	Clay Loam
Btc	57 - 121	50	68	90	62	46	65	331	287	382	0.75	Clay Loam
Btc	128 - 160	40	63	79	48	32	48	271	287	442	0.65	Clay

Table 5 Contd.: Particle size distribution and textural classes of soils of studied areas

Pedon	Depth	Gravel	Sand subfractions					Total Sand	Silt	Clay	Si/C	Texture
			VCS	CS	MS	FS	VFS					
	(cm)	(----------gkg^{-1} ----------)										
						Soils on Quartzites						
Pedon QZ 1												
Ap	0 - 14	300	39	128	220	194	108	691	227	82	2.77	Gravelly Sandy Loam
AC	14 - 40	500	47	131	219	161	91	651	207	142	1.46	Very Gravelly Sandy Loam
C1	40 – 98	770	118	189	70	46	25	371	207	422	0.49	Extremelly Gravelly Clay
C2	98 – 135	160	106	126	116	110	73	531	147	322	0.46	Sandy Clay Loam
Pedon QZ 2												
Ap	0 - 19	60	34	138	286	213	99	771	147	82	1.79	Sandy Loam
Bt1	19 - 51	70	82	153	160	88	47	531	107	362	0.30	Sandy Clay
Bt2	51 – 84	50	93	120	108	60	34	414	127	462	0.27	Clay
Bt3	84 - 139	60	111	128	131	90	31	491	127	382	0.33	Sandy Clay
Btc	139 –187	40	111	132	135	91	42	511	147	342	0.43	Sandy Clay Loam
Pedon QZ 3												
Ap	0 - 19	90	48	154	254	209	84	751	147	102	1.44	Sandy Loam
AB	19 - 40	60	73	194	208	116	59	651	147	202	0.69	Sandy Clay Loam
Bt1	40 – 63	150	128	152	97	45	29	451	127	422	0.31	Clay
Bt2	63 – 97	50	105	130	79	45	32	391	147	462	0.32	Clay
BC	97 - 167	90	125	136	91	62	36	451	167	382	0.44	Sandy Clay

Table 5 Contd.: Particle size distribution and textural classes of soils of studied areas

Pedon	Depth	Gravel	Sand subfractions					Total Sand	Silt	Clay	Si/C	Texture
			VCS	CS	MS	FS	VFS					
	(cm)	(----------gkg^{-1} ----------)										
						Soils on Mica Schists						
Pedon MS 1												
Ap	0 - 18	30	85	134	160	123	108	611	227	162	1.40	Sandy Loam
Bt	18 - 54	20	82	115	109	105	79	491	207	302	0.69	Sandy Clay Loam
Btc	54 - 177	30	103	115	112	103	58	491	207	302	0.69	Sandy Clay Loam
Pedon MS 2												
Ap	0 - 16	40	57	126	175	186	146	69.1	187	122	1.53	Sandy Loam
Bt	16 - 37	320	113	125	103	93	77	511	207	282	0.73	Gravelly Sandy Clay Loam
BC	37 – 72	240	114	108	83	90	56	451	227	322	0.70	Gravelly Sandy Clay Loam
C	72 - 143	30	82	109	104	76	27	398	273	329	0.83	Clay Loam
Pedon MS 3												
Ap	0 - 19	90	38	116	148	156	73	531	367	102	3.60	Sandy Loam
Bt1	19 - 42	260	107	129	88	87	80	491	267	242	1.10	Gravelly Sandy Clay Loam
Bt2	42 – 96	110	98	112	86	95	120	511	267	222	1.20	Sandy Clay Loam
BC	96 – 168	70	84	109	100	126	72	491	287	222	1.29	Sandy Clay Loam

Table 5 Contd.: Particle size distribution and textural classes of soils of studied areas

Pedon	Depth	Gravel	Sand subfractions					Total Sand	Silt	Clay	Si/C	Texture
			VCS	CS	MS	FS	VFS					
	(cm)	(----------gkg^{-1} ----------)										
						Soils on Migmatite Gneisses						
Pedon MG 1												
Ap	0 - 15	50	126	203	133	63	93	618	233	149	1.56	Sandy Loam
Bt	15 - 47	40	136	151	82	54	55	478	193	329	0.59	Sandy Clay Loam
Btcv1	47 – 103	150	108	118	77	67	41	418	213	369	0.58	Clay Loam
Btcv2	103 – 147	470	188	178	81	56	55	558	153	289	0.53	Gravelly Sandy Clay Loam
Pedon MG 2												
Ap	0 - 18	30	70	216	117	80	120	618	273	109	2.50	Sandy Loam
AB	18 - 44	20	89	136	86	57	70	438	213	349	0.61	Clay Loam
Bt1	44 – 78	40	89	100	70	44	55	358	213	429	0.50	Clay
Bt2	78 - 123	30	98	122	80	44	54	398	213	389	0.55	Clay Loam
BCcv	123 –167	470	190	167	77	49	54	538	173	289	0.60	Gravelly Sandy Clay Loam
Pedon MG 3												
Ap	0 - 25	0	100	216	183	71	48	618	173	209	0.83	Sandy Clay Loam
Bti	25 - 47	30	90	150	134	54	43	478	173	349	0.50	Sandy Clay Loam
Bt2	47 – 89	20	79	98	85	65	51	378	173	449	0.39	Clay
BCcv	89 – 162	340	115	137	110	84	52	498	173	329	0.53	Gravelly Sandy Clay Loam

5.2.1 Particle Size Distribution

Gravel content varied between 10 and 200 (mean, 53), 40 and 770 (175), 20 and 320 (113) and 0 and 470 (122) gkg^{-1} of total soil in the older granites (OG), quartzites (QZ), mica schists (MS) and migmatite gneisses (MG) respectively. There was no significant variation in the mean values of gravel content of soils between surface and subsurface horizons. However, it was observed that there was significant difference in the mean values of the gravel content of soils between parent materials. The soils varied significantly in their mean values of gravel from each other in the order of QZ > MG > MS > OG. The variation in gravel content might have been influenced by extent of weathering of parent materials and plinthization process in soils on MG. The mean high value (122 gkg^{-1}) of gravel in soils on migmatite gneiss was ascribed to aggregation of iron oxides to form nodules. Kparmwang (1993) and Yaro (2005) attributed formation of nodules by iron oxide to advance in pedogenic age. The higher proportion of gravel was peculiar to Btcv horizons and low in other subsoil horizons of MG, and was similar to soils formed on the older granites. Sand dominated particle size fraction of fine earth (< 2mm) portion in all soils formed from the different parent materials. This confirms previous findings on soils formed on basement complex rocks in different regions of Nigeria (Malgwi, 1979; Esu *et al.,* 1987; Maniyunda, 1999; Malgwi *et al.*, 2000; Odunze, 2006; Mustapha and Fagam, 2007; Fasina *et al.,* 2007; Voncir *et al.,* 2008; Obi and Akinbola, 2009; Ande, 2010).

Total sand fraction ranged between 531 and 651 (mean, 591), 691 and 771 (738), 531 and 691 (611) and 618 (618) gkg^{-1} in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. Correspondingly, the subsoil horizons values also varied between 271 and 611 (441), 371 and 651 (495), 398 and 51.1 (479) and 358 and 558 (454) gkg^{-1}. There was no significant difference between

the means of sand particles of various soils on the parent materials, though the particles vary in the decreasing order of QZ (mean, 547 gkg^{-1}) > MS (515 gkg^{-1}) > MG (492 gkg^{-1}) > OG (482 gkg^{-1}). The variation indicated that soils on parent materials that metamorphosed from sedimentary rock seem to have higher sand particles than those from igneous origin.

The sand fraction in surface (Ap) horizons were found to be significantly higher than in the subsoil horizons. The sand particles contents decreased with increase in depth within the soil profiles, but increased in the BC and C horizons where saprolite was encountered. The distribution pattern might be attributed to the degree of weathering of parent rocks. The decrease in content of sand in the Bt horizon may be attributed to illuviation of clay into the Bt horizons. It was noted that there was no significant difference as with regard to the interactive effect of parent material and horizons on sand particle distributions. On further comparism of the various aggregate particles of sand, the very coarse sand, coarse sand and medium sand were not significantly different, while the coarse sand was significantly higher than fine sand and very fine sand. There was no significant difference observed between the mean values of fine sand and very fine sand. When the means valus of each of the sand subfractions were tested statistically, all subfractions were significantly different both between parent materials (Figure 4 and Table 6) and between the surface and subsurface horizons (Table 7). The mean values of very coarse sand were statistically similar for OG and MG, though OG was significantly higher than QZ and MS which were at par. Coarse sand subfraction was similar for OG, QZ and MG, and was significantly higher than MS. Medium sand fraction of soil on quartzite was significantly higher than soils on OG, MS and MG, but values in soils on OG, MS and MG were at par. The fine sand

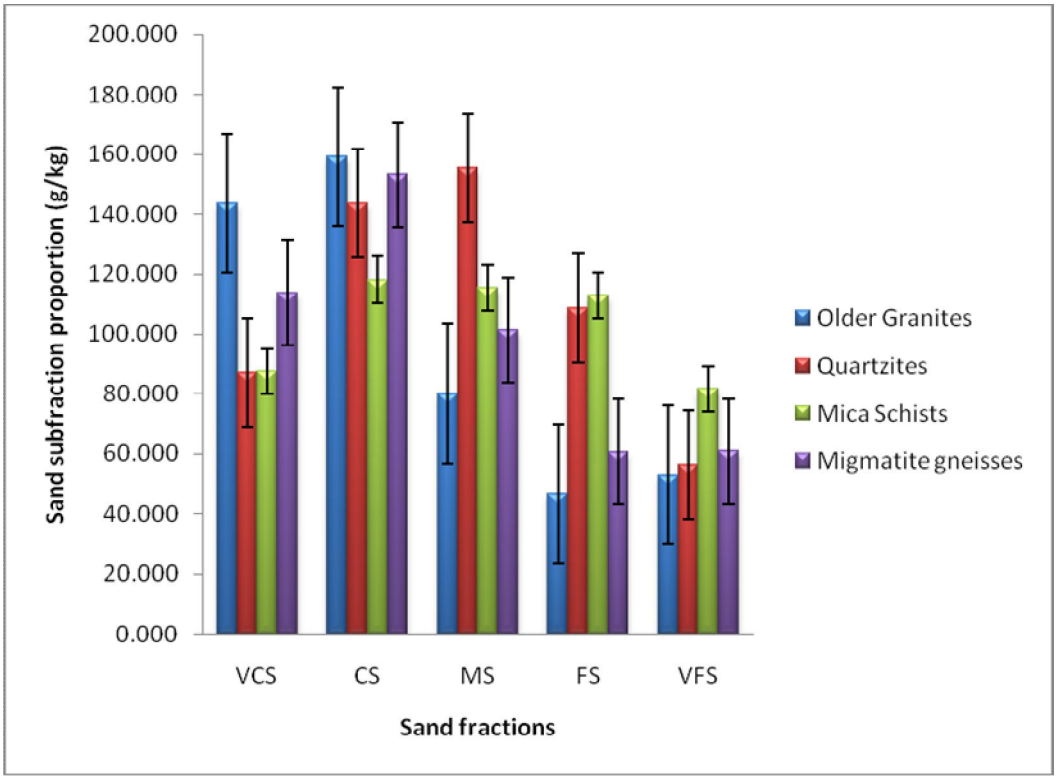


Figure 4: Histogram of proportion of fractions of sand particles in the parent materials

Table 6: Ranking of means of physical properties of parent materials

Parameter	Unit	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
Gravel	gkg^{-1}	52.7d	175.0a	112.7c	130b	7.51	*
V.coarse sand	gkg^{-1}	143.4a	87.1c	87.5bc	113.7ab	1.91	**
Coarse sand	gkg^{-1}	159.0a	143.6a	118.0b	153.2a	1.33	*
Medium sand	gkg^{-1}	80.1b	155.3a	115.3b	101.2b	1.38	**
Fine sand	gkg^{-1}	46.5b	108.7a	112.7a	60.6b	1.01	**
V. fine sand	gkg^{-1}	53.0	56.4	81.5	60.8	0.97	NS
Total sand	gkg^{-1}	481.9	546.7	515.3	491.8	3.87	NS
Silt	gkg^{-1}	228.2ab	155.6c	247.5a	197.6b	2.04	**
Clay	gkg^{-1}	289.3	297.7	237.2	310.5	3.24	NS
Bulk density	Mgm^{-1}	1.55	1.50	1.52	1.52	0.05	NS
Part. density	Mgm^{-1}	2.62	2.60	2.60	2.60	0.01	NS
Total porosity	%	40.8	42.1	41.8	43.3	2.57	NS
Field capacity	%	18.0	17.1	20.4	19.6	2.15	NS
PWP	%	11.2	10.9	10.3	11.1	1.47	NS
AWC	%	6.8b	5.7b	10.1a	8.4a	3.02	*
WRD	cm	6.2	3.0	7.8	4.8	1.85	NS
Si/C	-	0.97ab	0.82b	1.25a	0.79b	0.20	*

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Table 7: Ranking of means of physical properties of horizons

Parameter	Unit	Surface Horizon	Subsurface Horizon	SE±	LOS
Gravel	gkg^{-1}	63.3	140.5	2.57	NS
V. coarse sand	gkg^{-1}	78.3b	116.2a	0.91	*
Coarse sand	gkg^{-1}	172.6b	134.6a	0.91	**
Medium sand	gkg^{-1}	164.1a	97.5b	1.13	**
Fine sand	gkg^{-1}	122.8a	69.9b	1.15	**
V. fine sand	gkg^{-1}	94.3a	52.1b	0.55	**
Total sand	gkg^{-1}	639.4a	468.8b	1.81	**
Silt	gkg^{-1}	231.8a	194.7b	1.37	*
Clay	gkg^{-1}	128.8b	336.5a	1.19	**
Bulk density	Mgm^{-1}	1.49	1.53	0.02	NS
Part. density	Mgm^{-1}	2.60	2.60	0.02	NS
Total porosity	%	42.42	41.95	0.01	NS
Field capacity	%	12.53b	20.66a	1.02	**
PWP	%	5.92b	12.49a	0.54	**
AWC	%	6.62	8.01	0.77	NS
WRD	cm	1.89b	6.47a	0.93	*
Si/C	-	1.93a	0.62b	0.13	**

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

subfractions of QZ and MS were statistically similar and significantly greater than OG and MG which were at par. Mean values of very fine sand subfraction were not statistically different for all the soils. The nature of variation in the sand subfractions were similar to trend reported by Buol *et al.*, (1980). They stated that soils formed in saprolite from mica schists tend to be silt and less coarse than those formed from granitic and gneissic saprolites. The mean values of surface horizons of coarse, medium, fine and very fine sands were found to be highly significant ($P < 0.01$) than their subsoil horizons. The subsurface horizon of the very coarse sand was observed to be highly significantly greater ($P < 0.01$) than the surface horizon (Table 7).

The silt particle varied between 227 and 327 (mean, 267), 147 and 227 (174), 187 and 367 (260) and 173 and 273 (226) gkg^{-1} in the surface horizons of older granites, quartzites, mica schists and migmatite gneiss respectively. The subsurface horizons corresponding values varied between 147 and 287 (215), 107 and 207 (151), 187 and 367 (243) and 153 and 213 (189) gkg^{-1}. The proportion of silt in the surface (Ap) horizons were found to be significantly higher than the subsoil horizons. This finding agreed with that of Maniyunda (1999) and Yaro (2005) for soils in northern guinea savanna region. Most of the soils tend to have regular distribution of silts in various subsoil horizons with slight decrease with increased in soil depth. Similar findings were reported by Obi and Akinbola (2009) on Basement complexes of southwestern Nigeria. The parent materials indicated a highly significant difference ($P< 0.01$) in silt content. This implied that, parent material influenced silt content of soils formed on different basement complex rocks in the study area. On comparing their means values, it was observed that soils on mica schist parent material were not significantly different with those developed on older granites. However in silt content, mica schist

soils were significantly higher than soils on migmatite gneiss and quartzite in silt content. The soils on older granite and migmatite gneisses were found to be significantly higher than soils on quartzites. There was no significant difference observed as with regard to the interactive effect of the parent material and horizons on silt distribution.

Clay content were found to range between 122 and 162 (mean, 142), 82 and 102 (89), 102 and 162 (129) and 109 and 209 (156) gkg^{-1} in respective surface horizons of older granites, quartzite, mica schists and migmatite gneiss. Their corresponding subsurface horizons values ranged between 242 and 442 (345), 142 and 462 (355), 222 and 329 (278) and 289 and 449 (357) gkg^{-1}. The proportion of clay in the surface (Ap) horizons were found to be significantly lower ($P<0.01$) than the subsoil horizons. Mean clay content in the subsurface was about three times greater than the mean surface values. The increase in clay with soil depth is attributed to erosion of clay in the surface horizon and illuviation into subsurface horizon, as was also reported by several researchers (Ojanuga, 1979; Esu, 1982; Kparmwang, 1993; Raji, 1995; Obi and Akinbola, 2009). Faning and Faning (1989), Van Ranst and De Coninek (2002) and Obi and Akinbola, (2009) attributed the process to surface coarsening and/or subsurface thining through translocation (lessivage, solution and gravitation setting). Surface winnowing involves preferential removal of fine grains from the surface. The clay content increased with depth to its peak within the Bt horizons and decreased thereafter with depth. This indicated possible clay migration by eluviations - illuviation processes resulting in argilluviation. This was further affirmed by the presence of clay cutans in soil pores, animal channels and ped surfaces. There was no

significant difference between mean values of clay particle of soils on the different parent materials.

The silt clay ratio varied between 1.52 and 2.30 (mean, 1.89), 1.44 and 2.77 (2.00), 1.40 and 3.60 (2.18) and 0.83 and 2.50 (1.63) in the surface horizons of older granite, quartzite, mica schist and migmatite gneiss respectively. Correspondingly, the subsoil horizons values varied between 0.44 and 0.75 (0.63), 0.27 and 1.46 (0.50), 0.69 and 1.29 (0.90) and 0.39 and 0.61 (0.54). Silt to clay ratio was highest in the Ap horizons, followed with a sharp reduction in the subsoil horizons and remained fairly constant, but increased within AC, BC and C horizons. The higher ratio in the Ap horizons compared to subsoil horizons may be attributed to eluviation of clay from the surface horizons and their erosion down the slope from crestal position as reported also by Esu *et al.*, 1987). Higher silt to clay ratio in the AC, BC and C horizons compared to other horizons within the subsoils might be ascribed to low degree of weathering in horizon overlying and within saprolite horizons as indicated by Sombroek and Zonneveld (1971) but differ in ratio probably due to weathering processes. The silt/clay ratio at surface (Ap) horizons were found to be significantly higher than the subsoil horizons ($p < 0.01$), thus implying that the subsoil significantly weathered compared to the surface horizon. Mean values of silt to clay ratio of the soils were all higher than the 0.15 critical value considered to be highly or intensively weathered (Van Wambeke, 1962; Nwokocha *et al.*, 2003; Yakubu and Ojanuga, 2009), hence soils in this study were considered to be moderately weathered.

5.2.2 Particle Density (ρ_p)

Particle density values for the surface horizons were found to vary between 2.58 and 2.64 (mean, 2.61), 2.56 and 2.64 (2.60), 2.56 and 2.62 (2.59) and 2.56 and 2.61 (2.58) Mgm^{-3} in the older granites, quartzites, mica schists and migmatite gneiss respectively. The corresponding subsoil horizon values varied between 2.56 and 2.64 (2.62), 2.56 and 2.62 (2.60), 2.55 and 2.68 (2.60) and 2.56 and 2.64 (2.60) Mgm^{-3} (Table 8). There was no significant difference observed in mean values of the particle density both between parent materials and between surface and subsurface horizons.

This might imply that the soils were formed from similar geological formations (basement complex rocks). Mean values of particle density for these soils were within the range of 2.60 to 2.75Mgm^{-3} reported for mineral soil by Brady and Weil (2005). The mean values fell slightly below the values reported for some Samaru soils (Kowal, 1968; Yaro, 2005), but were also within values reported by Idoga *et al.* (2007) along a toposequence at Samaru Nigeria. Particle density values of soils on older granites increased from surface horizons to subsoil horizons and remain fairly constant in the subsurface horizons, whereas soils on migmatite gneiss increased in their particle density with increased in depth within the subsurface horizons. This implied that the soil forming process was insitu and were similarly reported also by Buol *et al.* (1980) and Malgwi *et al*. (2000). Esu (1982) attributed lower values of particle density to presence of organic matter. The particle density values of quartzite and mica schist soils were irregular in the subsurface horizons. This may be associated with the geological formation of the parental materials.

Table 8: Bulk density, particle density, total porosity and water retention properties of the soils studied

Pedon	Depth	Bulk density	Particle density	Total porosity	FC	PWP	AWC	WRD
	(cm)	(---- Mgm^{-3} ----)		(----------%----------)				(cm)
Soils on Older Granites								
Pedon OG 1								
Ap	0 - 26	1.58	2.58	38.76	8.6	3.7	4.9	2.01
Bt1	26 - 75	1.64	2.63	37.64	20.5	15.3	5.2	4.18
Bt2	75 - 119	1.69	2.62	35.50	20.1	13.0	7.1	5.28
BC	119 – 183	1.71	2.61	34.48	17.9	14.1	3.8	4.16
Pedon OG 2								
Ap	0 - 17	1.49	2.61	42.91	11.1	6.5	4.6	1.17
Bt	17 - 70	1.43	2.63	45.63	19.4	10.6	8.8	2.89
Btc	70 - 190	1.68	2.62	35.88	24.2	11.0	13.2	33.26
Pedon OG 3								
Ap	0 - 23	1.52	2.64	42.42	14.2	9.1	5.1	1.78
Bt	23 - 57	1.44	2.56	43.75	18.0	12.8	5.2	2.55
Btc	57 - 121	1.44	2.65	45.66	21.6	13.2	8.4	7.74
Btc	128 - 160	1.41	2.63	46.39	22.4	13.8	8.6	7.76
Soils on Quartzites								
Pedon QZ 1								
Ap	0 - 14	1.56	2.56	39.06	10.8	5.7	5.1	1.11
AC	14 - 40	ND	2.58	ND	10.6	5.6	ND	ND
C1	40 – 98	ND	2.61	ND	22.9	16.0	ND	ND
C2	98 – 135	1.53	2.63	41.83	25.6	18.1	7.5	4.25
Pedon QZ 2								
Ap	0 - 19	1.53	2.59	40.93	6.7	4.5	2.2	0.64
Bt1	19 - 51	1.42	2.62	45.80	17.4	12.8	4.6	2.09
Bt2	51 – 84	1.45	2.57	43.58	20.9	17.1	3.8	1.82
Bt3	84 - 139	1.52	2.61	41.76	21.1	16.7	4.4	3.68
Btc	139 –187	1.64	2.56	35.94	21.1	15.7	5.4	4.25
Pedon QZ 3								
Ap	0 - 19	1.24	2.64	53.03	7.8	3.6	4.2	0.99
AB	19 - 40	1.52	2.59	41.31	11.7	9.2	2.5	0.80
Bt1	40 – 63	1.50	2.55	41.18	20.0	5.9	14.3	4.93
Bt2	63 – 97	1.38	2.64	47.73	21.5	4.4	11.1	5.21
BC	97 - 167	1.64	2.59	36.68	20.6	17.2	3.4	3.90

ND: Not determine

Table 8 Contd.: Bulk density, particle density, total porosity and water retention properties of the soils studied

Pedon	Depth (cm)	Bulk density (---- Mgm^{-3} ----)	Particle density	Total porosity (----------%----------)	FC	PWP	AWC	WRD (cm)
			Soils on Mica Schists					
Pedon MS 1								
Ap	0 - 18	1.51	2.62	42.37	15.3	8.9	6.4	1.74
Bt	18 - 54	1.40	2.61	46.36	20.8	13.5	7.3	3.68
Btc	54 - 177	1.38	2.68	49.63	21.9	12.3	9.6	9.26
Pedon MS 2								
Ap	0 - 16	1.43	2.56	44.14	23.0	5.1	17.9	4.10
Bt	16 - 37	1.70	2.59	34.36	19.9	12.4	7.5	2.68
BC	37 – 72	1.79	2.55	29.80	10.3	5.5	4.8	3.01
C	72 - 143	1.56	2.60	40.00	27.9	14.0	13.9	15.4
Pedon MS 3								
Ap	0 - 19	1.48	2.60	43.08	11.3	6.1	5.2	1.46
Bt1	19 - 42	1.66	2.63	38.78	18.5	12.0	6.5	2.41
Bt2	42 – 96	1.45	2.56	43.36	19.7	10.3	9.4	7.36
BC	96 – 168	1.34	2.56	47.66	21.9	12.3	9.6	9.26
			Soils on Migmatite Gneisses					
Pedon MG 1								
Ap	0 - 15	1.48	2.58	42.64	12.0	5.7	6.3	1.40
Bt	15 - 47	1.57	2.57	38.91	19.0	11.2	7.8	3.92
Btcv1	47 – 103	1.58	2.58	38.76	22.1	14.2	7.9	6.99
Btcv2	103 – 147	1.61	2.59	37.84	20.5	13.8	6.7	4.75
Pedon MG 2								
Ap	0 - 18	1.50	2.56	41.41	10.3	4.1	6.2	1.67
AB	18 - 44	1.58	2.56	38.76	19.4	12.2	7.2	2.96
Bt1	44 – 78	1.52	2.62	41.98	23.0	13.4	9.6	4.96
Bt2	78 - 123	1.39	2.63	47.15	19.5	13.0	6.5	4.07
BCcv	123 –167	1.58	2.64	40.15	14.3	11.7	2.6	1.81
Pedon MG 3								
Ap	0 - 25	1.61	2.61	38.31	19.3	8.0	11.3	4.55
Bti	25 - 47	1.45	2.57	43.58	25.2	11.4	13.8	4.40
Bt2	47 – 89	1.40	2.64	46.97	24.8	11.2	13.6	8.00
BCcv	89 – 162	1.48	2.63	43.73	24.7	14.7	10.0	12.28

5.2.3 Bulk Density (ρ_b)

The bulk density were found to vary between 1.49 and 1.58 (mean, 1.53), 1.24 and 1.56 (1.44), 1.43 and 1.51 (1.47) and 1.48 and 1.61 (1.53) Mgm^{-3} in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding, subsoil horizons values varied between 1.41 and 1.71 (1.56), 1.38 and 1.64 (1.52), 1.34 and 1.79 (1.53) and 1.39 and 1.61 (1.52) Mgm^{-3} (Table 8).

Bulk density values of the surface horizons were observed to be lower than the subsoil horizons, except for pedons 1 and 3 on older granite, though, there was no significant difference observed between the surface and subsurface soils. Higher bulk density values of surface horizons might likely be ascribed to surface compaction due to mechanical or animal traction, and better structural development in subsurface horizons and was similarly reported in Nigerian savanna soils (Esu, 1982; Raji, 1995; Raji *et al.*, 1996). Bulk density values varied irregularly in the subsoils, except for soils on migmatite gneiss, where values decreased with depth and then increased in the lowest horizons. This could be related to the plinthitic horizons, similar observations were made by several workers (Daniel *et al.*, 1978; Perkins and Kaihula, 1981; Yaro, 2005). Highest values of bulk density in the subsoils were observed in the Bt and BC horizons where there is maximum clay accumulation, corroborating the findings of Anderson *et al.* (1988) and Raji (1995), though there was no significant correlation observed between bulk density with clay particles in these soils.

5.2.4 Total Porosity

Total porosity values ranged between 38.76 and 42.91 (41.36), 39.06 and 53.03 (44.34), 42.37 and 44.14 (43.20) and 38.31 and 42.64 (40.79) percent for respective

surface horizons of older granites, quartzites, mica schists and migmatite gneisses. For the corresponding subsoil horizons values ranged between 34.48 and 46.39 (40.62), 36.68 and 47.73 (41.49), 29.30 and 49.63 (41.24) and 37.84 and 61.72 (44.08) percent. There was no significant difference in mean values of total porosity between parent materials. This implied that parent materials did not significantly influence soil pore spaces. Bulk density, gravel, very coarse and coarse sand particles significantly influenced soil total porosity negatively (r = - 0.348*, - 0.921**, - 0.543** and - 0.303* respectively) (Table 9). The significant negative correlation with these soils physical properties imply that their increase in soil will contribute to reduction in soil porosity (Brady and Weil, 2005). Therefore, addition of organic matter as a management option will improve total porosity of the soils.

The surface horizons were observed to have higher total porosity values compared to subsoils, though not statistically significant. The values were similar to those reported by Malgwi *et al.* (2000), but slightly higher than those reported by Idoga *et al.* (2007). The surface values tend to support free water movement, good aeration and ease of root penetration (Malgwi *et al.,* 2000). Total porosity values were found to decrease with depth in the subsoils of OG, QZ and MG soils. The lowest values were observed in the subsoils horizons that have plinthite concretions. The irregular decrease in value was as low as 34% in the lowest horizons (BC and C), might be associated with presence of saprolite and poor structural development. Low values noted in the horizons directly underlying Ap might likely be associated with crust formation in cultivated soils of savanna environment as reported by other researchers (Kowal, 1972; Jones and Wild, 1975; Adeoye, 1985; Brady and Weil, 2005) in savanna soil of Nigeria.

Table 9: Correlation matrix for physical properties of studied areas.

	Gravel	VC. Sand	C. Sand	M. Sand	F. Sand	VF. Sand	Sand	Silt	Clay
VC. Sand	0.170								
C.Sand	-0.004	0.356*							
M. Sand	-0.053	-0.487***	0.297*						
F. Sand	0.182	0.525***	-0.064	0.814***					
VF. Sand	-0.015	-0.447**	0.049	0.502***	0.630***				
Sand	0.129	-0.096	0.611***	0.721***	0.605***	0.592***			
Silt	-0.192	-0.255	-0.296*	-0.177	-0.002	0.411**	-0.193		
Clay	-0.077	0.299	-0.423**	-0.639***	-0.651***	-0.753***	-0.878***	-0.299	
Si/C	-0.090	-0.376	0.148	0.414**	0.486***	0.775***	0.540***	0.618***	-0.826***
BD	0.294*	0.547***	0.301*	-0.147	-0.104	-0.152	0.084	-0.100	-0.033
PD	-0.051	0.006	-0.090	-0.240	-0.243	-0.173	-0.206	-0.013	0.207
TP	-0.348*	-0.543***	-0.303*	-0.086	0.057	0.170	-0.157	0.104	0.102
FC	-0.031	0.110	-0.455**	-0.370**	-0.257	-0.482***	-0.597***	-0.142	0.649***
PWP	0.105	0.317*	-0.314*	-0.427**	-0.300*	-0.570***	-0.582***	-0.197	0.662***
AWC	-0.168	-0.025	-0.328*	-0.262	-0.198	-0.153	-0.226**	-0.028	0.207
WRD	0.015	0.249	-0.388**	-0.537***	-0.365**	-0.485***	-0.176	0.000	0.529***

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 9 Contd.: Correlation matrix for physical properties of studied areas.

	Si/C	BD	PD	TP	FC	PWP	AWC
BD	-0.001						
PD	-0.177	-0.246					
TP	-0.020	-0.776***	0.217				
FC	-0.554***	-0.119	0.300*	0.148			
PWP	-0.633***	0.154	0.231	-0.058	0.673***		
AWC	-0.144	-0.283*	0.155	0.234	0.723***	-0.005	
WRD	-0.437***	-0.051	0.342*	0.048	0.652***	0.231	0.690***

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

5.2.5 Field Capacity

The water content at field capacity were found to range between 8.6 and 14.2 (mean, 11.30), 6.7 and 10.8 (8.43), 11.3 and 23.0 (16.53) and 10.3 and 19.3 (13.87) percent in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. Values for the underlying horizons ranged between 18.0 and 24.2 (20.51), 10.6 and 25.6 (19.42), 10.3 and 35.4 (21.80) and 14.3 and 25.2 (21.25) percent. There was no significant difference between water retention at FC for soils developed on different parent materials and may be attributed to similarity in particle size fractions (sand and clay content) in the soils as they were observed to significantly influenced water retention at field capacity (r = - 0.597***, 0.649***) (Table 9). The surface horizons were observed to retain less amount of water than the subsoil horizons, except in pedon 2 of mica schist. The water content at field capacity for soils on older granites and quartzites tend to increase with depth, except for pedon 1 on older granite which had a decreasing pattern in the subsurface horizons with increase in soil depth. Soils on migmatite gneiss followed similar pattern with those of OG and QZ, except that there was a decrease in field capacity in the horizons with concretions compared with immediate overlying horizon. This may be attributed to concretion effects which reduces pore spaces, thereby reducing amount of water retain at field capacity (FC). The subsoils were significantly higher in water retention at field capacity ($P<0.01$) than surface horizons. This may be attributed to the distributive pattern of soil particles within the profiles. This was confirmed by the highly significant negative correlation between sand fragments and total sand particle (r values for coarse sand, -0.416**; medium sand, -0.525**; fine sand, -0.398**; very fine sand, -0.454**; total sand, -0.597**) (Table 9). This implies that sand negatively influenced moisture retention (positively drain moisture). Increase in clay content in

subsoils contributed significantly to moisture retention as indicated by highly significant correlation (P< 0.001; r = 0.649**). This was corroborated by Bosch *et al.,* (1994) and Yaro (2005). Similarly, the Si/C ratio negatively correlated though highly significant with FC, implying that coarse material encourages drainage of moisture, whereas finer materials retains higher amount of moisture retention. There was a weak negative correlation between bulk density and FC indicating that bulk density (compaction) reduced water retention at FC, but not significant. Particle density (PD) was observed to be positively associated (r = 0.300*) with water retention at field capacity.

5.2.6 Permanent Wilting Point (PWP)

Water content at permanent wilting point (PWP) varied from 3.7 to 9.1 (mean, 6.43), 3.2 to 5.7 (4.60), 5.1 to 8.9 (6.70) and 4.1 to 8.0 (5.93) percent in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. For the subsurface horizons values varied from 10.6 to 15.3 (13.00), 4.4 to 18.1 (12.61), 5.5 to 14.0 (11.60) and 11.2 to 14.7 (12.68) percent. The values were similar to findings of Maniyunda (1999) but slightly lower than values reported by Esu (1982) in soils of Kaduna area and may be attributed to the higher clay content in soils of the Kaduna area studied by Esu (1982). There was no significant difference in water retention at PWP between the soils formed from the various parent materials. Similarly, particle size distribution and pore spaces as factors that influenced water retention at FC, influenced water retention at PWP. This was confirmed by the highly significant correlation between water retention at FC and PWP (r = 0.673**). The surface soil significantly retained less amount of water compared to the subsoil horizons (P < 0.01) and was due to significant amount of clay in subsoils compared to

surface horizons. The soils were observed to have inconsistent pattern of moisture retention at PWP within the subsoil horizons of their profiles.

5.2.7 Available Water Content (AWC)

The available water content (AWC) was found to range between 4.6 and 5.1(mean, 4.87), 2.2 and 5.1 (3.83), 5.2 and 17.9 (9.83) and 6.2 and 11.3 (7.93) percent in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsoil horizon values ranged between 3.8 and 13.2 (7.54), 2.5 and 14.3 (6.26), 4.8 and 22.6 (10.20) and 2.6 and 13.8 (8.57) percent. From the mean values only soils on MS have the capacity to retain enough moisture to support plant growth, as it was within 9.5 to 12.5% considered adequate for plant growth by FAO (1979). The soils were observed to vary significantly ($P < 0.05$) in mean values of AWC between the different parent materials in the order of MS > MG > OG > QZ. Coarse sand and total sand contents were found to significantly correlate negatively with AWC ($r = -0.328^*$, -0.383^{**} respectively). This implied that coarse sand might be the main fraction of total sand that significantly contributed to decrease in AWC with increase in its content. Other fractions had similar influence, but were not significant in their contribution to reduction in AWC. The surface horizons were observed to be lower in their AWC compared to the subsurface horizons, except for pedons QZ 3, MS 2 and MG 2 where the surface horizons AWC were higher than some of their subsoil horizons and might be due to lower bulk density values in surface horizons causing increase in pore space for more water retention. Mean values of AWC were not statistically different between surface and subsoil horizons. It was observed that there was no regular variation pattern shown in the AWC within the profiles of the various soils. Therefore, variation in nature of surface and subsoil

horizons did not significantly influence AWC of these soils as does the parent material from which the soils were formed.

5.2.8 Water Retention Difference (WRD)

Water retention difference (WRD) was observed to vary between 1.17 and 2.01 (mean, 1.65), 0.64 and 1.11 (0.91), 1.46 and 4.10 (2.43) and 1.40 and 4.55 (2.54) percent in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. The values for the corresponding subsoil horizons varied between 2.55 and 33.26 (8.48), 0.80 and 5.21 (3.60), 2.41 and 34.48 (9.79) and 1.81 and 12.28 (5.41) percent. There was no significant difference between soils formed on the different parent materials. The subsurface horizons were significantly higher ($P < 0.05$) in WRD compared to the surface horizons and the relationship had been attributed to the trend in particle size distribution and bulk density within the soil profiles. The Spearmann rho's correlation coefficient for non parametric data indicated particle size distributions played a significant role in the distributive nature of WRD, when compared to factors such as bulk density, particle density and total porosity ($P > 0.05$) (Table 9). The correlation coefficient between WRD and coarse sand, medium sand, fine sand, very fine sand, total sand and silt/clay ratio were highly significantly and negatively correlated (Table 9), except, for clay particle that was positively correlated and is highly significant ($r = 0.529^{***}$). This implied that finer particles in the soils had higher WRD, and tends to influence the micro-porosity than total porosity which did not have significant positive effect on the WRD of the soils and was also reported by Yaro (2005). Water retention difference significantly correlated negatively with chemical properties such as organic carbon ($r = -0.384^{**}$) and total nitrogen ($r = -0.480^{***}$). This implies that as WRD increases, dilution also

increases and would eventually cause leaching of these nutrients and soluble salts in these soils.

5.3 SOIL CHEMICAL PROPERTIES

The soil chemical properties considered are: soil reaction, exchangeable bases, exchange acidity, cation exchangeable capacity, base saturation, exchangeable sodium percentage and electrical conductivity and are presented in Table 10.

5.3.1 Soil pH

The soil pH was found to vary between 5.49 and 6.25 (mean, 5.76), 6.01 and 6.11 (6.02), 5.84 and 6.13 (5.95) and 5.70 and 6.41 (6.02) in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding, subsoil horizons values varied between 5.48 and 6.29 (5.87), 5.78 and 6.27 (6.01), 5.90 and 6.44 (6.27) and 5.30 and 6.90 (6.05) (Table 10). Soils on OG were rated strongly acid and MG rated strongly acid to neutral, whereas, soils on both QZ and MS were rated moderately to slightly acid (Soil Survey Division Staff, 1993). This implies a need to avoid use of acidifying fertilizer on the soils on OG and MG as it may renders nutrients inavailable for crops utilization. From the statistical analysis, it was observed that there was no significant variation in pH both between parent materials and between horizons (Tables 11 & 12 respectively). This is contrary to the findings of Jaiyeoba (2006) that pH values of soils in Nigerian savanna were significantly influenced by difference in parent materials. The contrary opinion might be because all the soils of this study were developed on basement complexes; hence variation might not be as reported by Jaiyeoba (2006).

Table 10: Chemical properties of soils of the studied areas

Pedon	Basal Depth (cm)	pH H_2O	pH $CaCl_2$	ΔpH	Exchangeable Bases Ca	Mg	K	Na	TEB	EA H+Al	ECEC	CEC (OAc)	CEC (Clay)	BS (ECEC)	BS (OAc)	ESP	EC
					(----------cmol(+)kg^{-1}----------									(----------%----------)			dSm^{-1}
Soils on Older Granites																	
Pedon OG 1																	
Ap	26	5.49	5.00	-0.49	3.33	0.27	0.49	0.15	4.24	0.6	4.84	5.60	20.78	87.60	75.71	8.75	0.050
Bt1	75	5.48	5.10	-0.38	4.00	0.63	0.51	0.14	5.28	0.8	6.08	8.4	14.13	86.35	62.86	6.07	0.025
Bt2	119	5.55	5.50	-0.05	4.33	0.73	0.48	0.13	5.67	0.6	6.27	6.7	17.34	90.43	84.63	7.16	0.028
BC	183	5.76	5.40	-0.36	4.33	0.73	0.42	0.17	5.65	0.6	6.25	8.6	29.82	90.40	65.40	4.88	0.030
Pedon OG 2																	
Ap	17	5.53	5.00	-0.53	3.67	0.39	0.52	0.23	4.81	0.8	5.61	5.7	10.15	85.74	84.39	9.12	0.056
Bt	70	5.50	4.90	-0.60	2.33	0.33	0.43	0.18	3.27	1.0	4.27	8.3	14.20	76.58	39.40	5.18	0.018
Btc	190	5.90	5.40	-0.54	5.50	0.95	0.52	0.28	7.25	0.6	7.85	7.9	27.49	92.36	91.77	6.58	0.019
Pedon OG 3																	
Ap	23	6.25	5.80	-0.45	5.04	0.79	0.57	0.40	6.80	1.0	7.80	8.5	38.82	87.18	80.00	6.71	0.090
Bt	57	6.29	5.10	-1.19	5.67	0.90	0.46	0.34	7.37	0.6	7.97	9.3	20.68	92.47	79.25	4.95	0.028
Btc	121	6.07	4.99	-1.08	5.50	1.08	0.54	0.29	7.41	0.8	8.21	8.6	21.26	90.26	86.16	6.28	0.025
Btc	160	6.22	4.94	-1.28	5.33	1.43	0.55	0.29	7.60	1.00	8.60	9.9	21.47	88.37	76.77	5.56	0.029

Table 10 Contd.: Chemical properties of the soils of the studied areas

Pedon	Basal Depth (cm)	H_20	pH $CaCl_2$	ΔpH	Exchangeable Bases Ca	Mg	K	Na	TEB	EA H+Al	ECEC	CEC (OAc)	CEC (Clay)	BS (ECEC)	BS (OAc)	ESP	EC
					(----------cmol(+)kg^{-1}----------)									(----------%----------)			dSm^{-1}
Soils on Quartzites																	
Pedon QZ 1																	
Ap	14	6.03	5.46	-0.57	4.67	0.59	0.63	0.26	6.15	0.6	6.75	11.5	91.31	91.11	53.48	5.48	0.050
AC	40	6.27	5.30	-0.97	3.33	0.52	0.49	0.19	4.53	0.8	5.33	8.7	44.18	84.99	52.07	5.63	0.018
C1	98	6.21	5.43	-0.78	4.17	0.89	0.53	0.36	5.95	1.0	6.95	8.0	18.15	85.61	74.38	6.63	0.006
C2	135	6.02	5.34	-0.68	4.67	1.21	0.47	0.37	6.72	0.8	7.52	11.2	34.39	89.36	60.00	4.20	0.009
Pedon QZ 2																	
Ap	19	6.11	5.39	-0.72	3.67	0.45	0.33	0.18	4.63	0.6	5.23	9.5	72.80	88.53	48.74	1.89	0.035
Bt1	51	6.08	5.51	-0.57	3.83	0.92	0.43	0.22	5.40	0.8	6.20	6.7	11.19	87.10	80.60	3.28	0.013
Bt2	84	6.23	5.34	-0.89	3.83	0.80	0.46	0.33	5.42	0.6	6.02	9.5	16.80	90.03	57.05	3.47	0.008
Bt3	139	6.03	5.43	-0.60	4.33	1.08	0.50	0.26	6.17	1.2	7.37	10.0	24.16	83.72	61.70	2.60	0.008
Btc	187	5.78	5.44	-0.34	4.33	1.04	0.36	0.25	5.98	0.3	6.78	9.1	18.46	88.20	65.71	2.75	0.009
Pedon QZ 3																	
Ap	19	6.01	5.04	-0.97	3.17	0.400.43		0.12	4.12	0.6	4.72	15.3	122.41	87.29	26.93	2.81	0.016
AB	40	5.79	4.84	-0.95	2.83	0.40	0.37	0.10	3.70	0.8	4.50	4.8	13.07	82.22	77.08	7.71	0.010
Bt1	63	5.80	4.77	-1.03	4.50	0.86	0.47	0.19	6.02	0.4	6.42	6.7	13.90	93.77	89.85	7.01	0.008
Bt2	97	6.06	4.92	-1.04	4.83	1.18	0.47	0.17	6.65	0.8	7.45	7.8	16.14	89.26	85.26	6.03	0.008
BC	167	5.86	5.31	-0.55	4.00	1.14	0.45	0.19	5.78	0.8	6.58	6.8	17.45	87.84	85.00	6.62	0.008

Table 10 Contd.: Chemical properties of soils of the studied areas

Pedon	Basal Depth (cm)	H_20	pH $CaCl_2$	ΔpH	Exchangeable Bases Ca	Mg	K	Na	TEB	EA H+Al	ECEC	CEC (OAc)	CEC (Clay)	BS (ECEC)	BS (OAc)	ESP	EC
					(cmol(+)kg^{-1})									(%)			dSm^{-1}
Soils on Mica Schists																	
Pedon MS 1																	
Ap	18	5.89	5.07	-0.82	4.50	0.78	0.44	0.41	6.13	0.60	6.73	7.9	27.66	91.08	77.59	5.57	0.060
Bt	54	5.93	4.99	-0.94	3.17	0.66	0.41	0.16	4.40	0.80	5.20	9.2	27.03	84.62	47.83	4.46	0.010
Btc	177	6.11	4.76	-1.35	2.67	0.36	0.47	0.21	3.71	0.40	4.11	5.6	16.72	90.27	66.25	8.39	0.004
Pedon MS 2																	
Ap	16	6.13	5.12	-1.01	6.83	1.51	0.42	0.22	8.98	0.40	9.38	10.1	63.98	95.74	88.91	4.16	0.035
Bt	37	6.22	5.46	-0.76	4.67	1.42	0.37	0.21	6.67	0.40	7.07	11.0	35.10	94.34	60.64	3.36	0.022
BC	72	6.15	5.63	-0.52	6.83	1.77	0.46	0.34	9.40	0.60	10.00	10.9	31.72	94.00	86.24	4.22	0.025
C	143	6.44	5.93	-0.41	8.00	1.61	0.43	0.38	10.42	0.60	11.02	14.3	42.64	94.56	72.87	3.01	0.046
Pedon MS 3																	
Ap	19	5.84	5.26	-0.58	4.33	0.45	0.38	0.13	5.29	0.25	5.54	5.6	20.24	95.49	94.46	6.79	0.032
Bt1	42	5.90	5.46	-0.44	4.50	0.62	0.37	0.14	5.63	0.25	5.88	5.9	15.37	95.75	95.42	6.27	0.026
Bt2	96	6.32	5.67	-0.65	3.67	0.75	0.51	0.14	5.07	0.25	5.32	5.4	21.53	95.30	93.89	9.44	0.009
BC	168	6.03	4.96	-1.07	2.17	0.44	0.33	0.11	3.05	0.60	3.65	5.7	23.83	83.56	53.51	5.79	0.007

Table 10 Contd.: Chemical properties of soils of the studied areas

Pedon	Basal Depth (cm)	pH H_2O	pH $CaCl_2$	ΔpH	Exchangeable Bases Ca	Mg	K	Na	TEB	EA H+Al	ECEC	CEC (OAc)	CEC (Clay)	BS (ECEC)	BS (OAc)	ESP	EC
					(----------cmol(+)kg^{-1}----------)									(----------%----------)			dSm^{-1}
Soils on Migmatite Gneisses																	
Pedon MG 1																	
Ap	15	5.96	5.39	-0.57	3.67	0.47	0.36	0.16	4.66	1.20	5.86	5.9	21.35	79.52	78.98	6.10	0.100
Bt	47	5.50	5.32	-0.18	3.33	0.44	0.43	0.08	4.28	0.80	5.08	6.0	10.86	84.25	71.33	7.17	0.017
Btcv1	103	6.32	5.10	-1.22	2.33	0.29	0.37	0.11	3.10	1.00	4.10	6.3	15.76	75.61	49.21	5.87	0.018
Btcv2	147	6.21	4.88	-1.33	2.17	0.29	0.36	0.10	2.92	0.80	3.72	6.6	22.13	78.49	44.24	5.45	0.007
Pedon MG 2																	
Ap	18	6.41	5.63	-0.78	4.03	0.46	0.44	0.24	5.17	0.80	5.97	6.0	34.30	86.60	86.17	7.33	0.009
AB	44	6.50	5.54	-0.96	3.84	0.67	0.56	0.16	5.23	0.40	5.63	6.6	14.99	92.90	79.24	8.48	0.100
Bt1	78	6.44	5.58	-0.86	3.83	0.95	0.34	0.29	5.41	0.40	5.81	5.9	11.40	93.12	91.69	5.76	0.027
Bt2	123	6.26	5.55	-0.71	3.17	0.83	0.35	0.28	4.63	0.60	5.23	7.1	17.01	88.53	65.21	4.93	0.015
BCcv	167	6.90	5.66	-1.24	2.83	0.73	0.31	0.25	4.12	0.60	4.72	7.8	25.80	87.29	52.82	3.97	0.020
Pedon MG 3																	
Ap	25	5.70	5.14	-0.56	2.83	0.47	0.47	0.18	3.95	0.60	4.55	5.5	17.65	86.81	71.82	8.55	0.220
Bti	47	5.50	5.08	-0.42	3.00	0.54	0.36	0.11	4.01	0.50	4.51	5.4	12.07	88.91	74.26	6.67	0.016
Bt2	89	5.30	4.88	-0.42	2.67	0.40	0.36	0.10	3.53	0.30	3.83	7.9	16.16	92.17	44.68	4.56	0.021
BCcv	162	5.60	4.60	-1.00	2.17	0.45	0.87	0.08	3.57	0.60	4.17	7.0	20.23	85.61	51.00	12.43	0.006

Table 11: Ranking of means of chemical properties of parent materials

Parameter	Unit	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
pH (H_20)	-	5.84	6.01	6.09	6.05	0.16	NS
pH ($CaCl_2$)	-	5.19	5.25	5.30	5.26	0.15	NS
ΔpH	-	0.63	0.76	0.78	0.79	0.15	NS
Exch. Ca	$cmol(+)kg^{-1}$	4.46a	4.01ab	4.67a	3.07b	0.53	**
Exch. Mg	$cmol(+)kg^{-1}$	0.75	0.82	0.94	0.54	0.16	NS
Exch. Na	$cmol(+)kg^{-1}$	0.50	0.46	0.42	0.43	0.05	NS
Exch. K	$cmol(+)kg^{-1}$	0.24	0.23	0.22	0.16	0.04	NS
TEB	$cmol(+)kg^{-1}$	5.94a	5.52ab	6.25a	4.20b	0.71	**
EA	$cmol(+)kg^{-1}$	0.76a	0.72a	0.47b	0.69a	0.10	**
ECEC	$cmol(+)kg^{-1}$	6.70ab	6.27ab	6.93a	4.86b	0.74	**
CEC (OAc)	$cmol(+)kg^{-1}$	7.90bc	8.97a	8.33b	6.46c	0.92	*
CEC Clay	$cmol(+)kg^{-1}$	21.5bc	36.7a	29.6b	18.4c	5.20	*
Base Sat. (Σ)	%	88.0b	87.8b	92.3a	86.1b	2.11	*
Base Sat.	%	75.2a	65.6b	73.1a	66.2ab	6.81	*
ESP	%	4.48a	4.72b	5.59ab	6.71a	0.89	**
EC	dSm^{-1}	0.036ab	0.015c	0.025c	0.044a	0.13	**

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Table 12: Ranking of means of chemical properties of horizons

Parameter	Unit	Surface Horizon	Subsurface Horizon	SE±	LOS
pH (H_20)	-	5.94	6.02	0.07	NS
pH ($CaCl_2$)	-	5.28	5.24	0.06	NS
ΔpH	-	-0.67	-0.77	0.06	NS
Exch. Ca	$cmol(+)kg^{-1}$	4.15	3.96	0.26	NS
Exch. Mg	$cmol(+)kg^{-1}$	0.59b	0.81a	0.08	*
Exch. Na	$cmol(+)kg^{-1}$	0.46	0.45	0.02	NS
Exch. K	$cmol(+)kg^{-1}$	0.22	0.21	0.02	NS
TEB	$cmol(+)kg^{-1}$	5.41	5.43	0.35	NS
EA	$cmol(+)kg^{-1}$	0.67	0.66	0.06	NS
ECEC	$cmol(+)kg^{-1}$	6.08	6.16	0.35	NS
CEC (OAc)	$cmol(+)kg^{-1}$	8.09	7.86	0.61	NS
CEC Clay	$cmol(+)kg^{-1}$	45.12a	20.94b	5.73	**
Base Sat. (Σ)	%	88.55	88.34	1.05	NS
Base Sat.	%	75.35a	68.67	4.11	NS
ESP	%	6.11	5.75	0.50	NS
EC	dSm^{-1}	0.063a	0.017b	0.01	**

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Soil pH (H_2O) values reported in this study were within range reported by Ezenwa and Esu (1999), Raji and Mohammed (2000), Fasina *et al.* (2007a) and Law-Ogbomo and Nwachokor (2010) on basement complexes in different parts of Nigeria. The trend of pH in these soils tends to indicate the inherent nature of their parent material and was also related to leaching of bases. Soils on OG were observed to decrease in pH (H_2O) from the surface horizons to the subsoil horizons and increased in the lower subsoil horizons. The MS soils were found to increase from the surface to subsoil. The soils formed on QZ and MG were irregular in their distribution within the soil profiles, but the lowest values of pH in soils on QZ were in the deepest horizons.

Soil pH ($CaCl_2$) values were found to vary between 5.00 and 5.80 (mean, 5.20), 5.04 and 5.46 (5.30), 5.07 and 5.26 (5.15) and 5.14 and 5.63 (5.39) in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding, subsurface horizon values varied between 4.90 and 5.50 (5.17), 4.77 and 5.51 (5.43), 4.76 and 5.93 (5.36) and 4.60 and 5.66 (5.22). The variation of pH ($CaCl_2$) in soil profiles were observed to be similar to that of pH (H_2O). It was also observed that there was no significant variation in pH both between horizons and between parent materials.

Change in pH (ΔpH) values varied negatively from 0.05 to 1.28 (mean, 0.63), 0.34 to 1.04 (0.76), 0.41 to 1.35 (0.78) and 0.18 to 1.33 (0.79) in the profiles of older granites, quartzites, mica schists and migmatite gneisses respectively. Change in pH did not significantly vary between the soils and therefore soils on basement complexes may be considered to be similar in their surface net charges. The values were observed to be negative in all the soils; hence had net negative charges. Similar findings were reported parts of Nigeria (Kparmwang, 1993; Raji, 1995; Maniyunda, 1999; Yaro,

2005; Law-Ogbomo and Nwachokor, 2010). Partiff (1980) and Uehera and Gillman (1981) reported that ΔpH values < -0.5 indicate a dominance of exchange sites of clay by variable charge minerals, whereas values > -0.5 may be possibly due to presence of high negative charge density on their colloids or 2:1 clay minerals (Gallez *et al.* (1976) as noted in the clay mineralogy of soils in this study (mica schist). The difference in soil pH of water and $CaCl_2$ were observed to vary irregularly with increase in depth of soils formed on OG parent material. Soil pH in quartzite increased with depth and decline at the deepest horizons. The ΔpH was found to increase with increase in depth within the subsoil in soils developed on MS, except for pedon MS 2 which showed consistent decreased with increase in soil depth. The soils on MG were found to increase irregularly with depth with highest values obtained in their deepest horizons.

5.3.2 Exchangeable Bases

Exchangeable calcium dominated exchange sites, occcupying about 74% of total exchangeable bases. The dominance of Ca on the exchange sites was reported by other works in Nigerian savanna soil (Esu, 1987; Mosugu, 1989; Kparmwang, 1993; Raji, 1995). Exchangeable calcium values ranged between 3.33 and 5.04 (mean, 4.01), 3.17 and 4.67 (3.84), 4.33 and 6.83 (5.22) and 2.83 and 4.03 (3.51) cmol(+)kg^{-1} in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. For the underlying horizons values ranged between 2.33 and 5.67 (4.62), 2.83 and 4.83 (4.06), 2.17 and 8.00 (4.46) and 2.17 and 3.84 (2.93) cmol (+) kg^{-1}. The values of exchangeable Ca was rated medium to high for the soils developed on OG and MS and medium for the soils on QZ and MG (Enweazor *et al*., 1989; Esu 1991).

Parent material was observed to significantly influence exchangeable Ca, but there was no significant difference between horizons. Calcium was found to be similar in soils developed on OG, MS and QZ, but soils on OG and MS contained Ca in significantly higher quantity compared to soils on MG (Table 11). Content of exchangeable Ca was not significantly different in soils on QZ and MG parent materials. The values of exchangeable Ca in these soils were higher than those reported by Odunze (2006) and may be attributed to difference in land use, leaching and type of basement complex formation. Exchangeable calcium tends to increase from surface to subsurface horizons in soils formed in older granites. Soils on QZ showed decreased in Ca beneath the surface horizons and thereafter tend to increase with depth. Soils on MS and MG were observed to decrease with increase in depth through the profiles, except for pedon 2 on migmatite gneiss which increased with depth within the subsoil. Exchangeable Ca was observed to correlate significantly with other cations (Mg, K and Na) and pH (0.01m $CaCl_2$) (Table 13). The significant correlation with other exchangeable bases may be due to leaching and crop uptake of Mg and K influencing their distribution pattern to be similar.

Exchangeable magnesium (Mg) was next to calcium in content. Its values in the surface horizon varied between 0.27 and 0.79 (mean, 0.48), 0.40 and 0.59 (0.48), 0.45 and 1.51 (0.91) and 0.46 and 0.47 (0.47) cmol (+) kg^{-1} respectively on older granites, quartzites, mica schists and migmatite gneisses. The corresponding, subsurface horizon values varied between 0.33 and 1.43 (0.85), 0.40 and 1.21 (0.91), 0.44 and 1.77 (0.95) and 0.29 and 0.95 (0.56) cmol (+) kg^{-1}. The surface soils were rated as low to medium for OG, medium for QZ and MG, and medium to high for MS. In the subsoils, it was medium to high for OG, QZ and MS, and low to medium for MG.

There was no significant difference in content of exchangeable Mg between the soils, as difference between parent materials did not significantly influenced their values. Exchangeable Mg content in the subsoil was significantly higher than the surface horizons (Table 12). Exchangeable Mg increased with increase in soil depth especially in the subsurface horizons in soils formed on OG and QZ, and was irregularly distributed in profiles of soils on MS and MG. Coarse sand and total sand correlated negatively with exchangeable Mg (r = -0.338* and -0.320* respectively) and implied that increase in coarse texture material reduced Mg in the soils through leaching as they were known to have less charge surface. Clay particles correlated significantly (positively) (r = 0.354*) and therefore contributed to retention of exchangeable Mg for crop utilization. This was also affirmed with a significant positive correlation with base saturation. The present pH range of the soils tends to influence availability of Mg (Table 13); hence, further decline in soil pH may affect availability of Mg negatively.

Exchangeable sodium (Na) varied between 0.49 and 0.57 (mean, 0.53), 0.33 and 0.63 (0.46), 0.38 and 0.44 (0.41) and 0.36 and 0.47 (0.42) cmol (+) kg^{-1} respectively in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding, subsurface horizon values varied between 0.42 and 0.55 (0.49), 0.36 and 0.53 (0.45), 0.33 and 0.51 (0.42) and 0.31 and 0.87 (0.43) cmol (+) kg^{-1}.

Table 13: Correlation matrix for chemical properties of soils of the studied area.

	$pH(H_2O)$	$pH(CaCl_2)$	ΔpH	Exch. Ca	Exch. Mg	Exch. Na	Exch. K	TEB	EA
$pH(CaCl_2)$	0.505***								
ΔpH	0.549***	-0.440**							
Exch. Ca	0.248	0.441**	-0.188						
Exch. Mg	0.350	0.388**	-0.031	0.787***					
Exch. Na	-0.131	-0.165	0.018	0.359*	0.179				
Exch. K	0.458**	0.448*	0.034	0.629***	0.606***	0.128			
TEB	0.286*	0.438**	-0.147	0.980***	0.871***	0.380**	0.678**		
EA	0.096	-0.015	0.100	-0.085	-0.044	0.203	0.142	-0.055	
ECEC	0.294*	0.437**	-0.138	0.963***	0.870***	0.378**	0.675***	0.887***	0.040
CEC (OAc)	0.234	0.231	0.005	0.519***	0.531***	0.150	0.438**	0.568***	0.046
CEC Clay	0.187	0.142	0.073	0.341	0.238	0.056	0.092	0.335	-0.077
BS (ECEC)	0.130	0.319*	-0.167	0.619***	0.516***	0.068	0.304*	0.608***	-0.718***
BS	0.061	0.255	-0.186	0.516***	0.394**	0.113	0.276	0.503***	-0.113
ESP	-0.280	-0.325*	0.023	-0.314*	-0.410***	-0.548***	-0.334*	-0.318*	-0.030
EC	-0.060	0.146	-0.200	0.332*	0.010	0.074	0.087	0.255	0.105

Table 13 Contd.: Correlation matrix for chemical properties.

	ECEC	CEC(OAC)	CEC clay	BS (ECEC)	BS (OAc)	ESP
CEC (OAc)	0.595***					
CEC Clay	0.346*	0.617***				
BS (ECEC)	0.515***	0.213	0.135			
BS	0.447***	-0.367**	-0.376**	0.472***		
ESP	-0.360	-0.664***	-0.398**	-0.053	0.348*	
EC	0.243	0.068	0.178	0.022	0.159	0.220

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

All the soils were rated high in both surface and subsurface horizons as they were > 0.3 cmol (+) kg^{-1} critical values for high Na in Nigerian soil (Enweazor *et al*., 1989; Esu 1991). Exchangeable Na distribution was irregular in all the soils. Differences both between parent materials and between horizons did not significantly influenced exchangeable Na in these soils; hence basement complex rocks as parent material similarly contributed exchangeable Na in their soils. Exchangeable Na was found to correlate significantly with exchangeable Ca and exchange acidity (Table 13), this may be attributed to similarity in their distribution pattern. The significant correlation observed between exchangeable Na with total exchangeable bases (TEB), effective cation exchangeable capacity (ECEC) and exchangeable sodium percentage (ESP) may be attributed to the contributory effect of exchangeable Na on the determination (calculation) of these properties.

Exchangeable potassium (K) varied between 0.15 and 0.40 (mean, 0.26), 0.12 and 0.26 (0.19), 0.13 and 0.41 (0.25) and 0.16 and 0.24 (0.19) cmol (+) kg^{-1} respectively in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding, subsoil horizon values varied between 0.13 and 0.34 (0.23), 0.10 and 0.37 (0.24), 0.11 and 0.38 (0.21) and 0.08 and 0.29 (0.16 cmol (+) kg^{-1}. The surface horizons of QZ were rated low to medium, MS were low to high, MG was rated as medium and OG as medium to high in exchangeable K. In the subsoils, the rating was low to high for OG, QZ and MS and low to medium for MG (Enweazor *et al*., 1989; Esu 1991). There was no consistent distribution pattern in the profiles of soils on MS and MG. Exchangeable K was higher in Ap horizon and decreased in the immediate underlying horizons, and then increased inconsistently with increased with depth in soils formed in OG and QZ parent materials. Both parent materials and

horizons did not significantly influenced variation in exchangeable K. The highly significant correlation with pH (H_2O and $CaCl_2$) indicated that pH strongly influence content of exchangeable K in these soils. The highly significant correlation with exchangeable Ca and Mg (Table 13) indicated that leaching that influence distribution of exchangeable Ca and Mg similarly influenced distribution of exchangeable K as indicated by the significant correlation between exchangeable K with TEB (r = 0.678**). Increase in ECEC and cation exchange capacity (CEC) (NH_4OAc) was observed to significantly affect exchange K positively (Table 13), hence increase in CEC would provide more exchange cites to accommodate exchange potassium.

Exchangeable bases were observed to occur in the order Ca > Mg > Na > K and were similarly reported for soils on basement complex (Hassan *et al.,* 2004; Odunze, 2006; Fasina, 2007a, b). There was slight variation in the order with reference to Na > K as reported by other researchers on soils in the savanna region (Esu and Ojanuga, 1985; Esu, 1987; Raji, 1995; Malgwi *et al.,* 2000). The variation may be associated with the present study been carried out on crest slope position where loss of K through erosion and leaching might be more, as K is more susceptible to leaching than Na.

Total exchangeable Bases (TEB) ranged between 4.24 and 6.80 (mean, 5.28), 4.12 and 6.15 (4.97), 5.29 and 8.98 (6.80) and 3.95 and 5.17 (4.59) cmol (+) kg^{-1} in the surface horizons of older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding, subsurface horizons values ranged between 3.27 and 7.60 (6.25), 3.70 and 6.72 (5.67), 3.05 and 10.42 (6.04) and 2.92 and 5.41 (4.08) cmol (+) kg^{-1}. Parent materials significantly influenced TEB of the soils. Total exchangeable bases values indicated that soils on MS were at par with those on OG and QZ. However, soils on MS were significantly higher in TEB compared to soils on

migmatite gneiss. The direction of variation of TEB in these soils indicated leaching of exchangeable bases with advancement in pedogenesis; hence soils MS was regarded as pedogenically youngest and those on MG (contained plinthite) as oldest. Similarly, Kparmwang (1993) reported lowest values of TEB on the lateritized basalts (contained plinthite), and also rated the soils as pedogenically oldest. Soil pH was observed to significantly correlate TEB (Table 13), thus imply that pH significantly influence TEB.

The values of TEB were within the range reported by Samndi *et al.* (2006) in southern guinea savanna and higher than those reported by Ezenwa and Esu (1999) on basement complexes in northern guinea savanna of Nigeria. The variation between these soils may be attributed to differences in parent material and land use. Total exchangeable bases increased from surface to subsoil in soils on OG. Soils on QZ had high values of TEB in surface soils but decreased in the under laying horizon and thereafter increased with depth. The MG soils showed consistent decreased with depth especially in the subsoil. Soils on MS showed inconsistent distribution pattern. The variation in distribution pattern between the soils indicated leaching of exchangeable bases increased with advancement in soil development as leaching was more directional in soils on MG compared to the other soils. Soil properties such as exchangeable Ca, Mg, Na, K, various forms of CEC and base saturation significantly correlated with TEB (Table 13). This was due to their summative contribution to TEB.

5.3.3 Exchange Acidity

The exchangeable acidity values for the surface horizons were found to vary between 0.6 and 1.00 (mean, 0.80), 0.6 (0.60), 0.25 and 0.6 (0.42) and 0.60 and 1.20 (0.87)

cmol (+) kg^{-1} in soils on older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding subsurface horizon values varied between 0.60 and 1.00 (0.75), 0.40 and 1.20 (0.75), 0.25 and 0.80 (0.49) and 0.30 and 1.00 (0.64) cmol (+) kg^{-1}. The values were similar to findings of Raji and Mohammed (2000) on basement complexes. There was no regular distribution pattern observed within profiles in all soils developed on the different parent materials. However, there was significant difference between soils formed on the different parent materials. On comparing means, soils on OG, MG and QZ were similar in their exchange acidity and significantly higher than soils on MS parent material (Table 11). This could be attributed to higher amount of leaching of exchangeable bases in soils on OG, MG and QZ compared to MS as observed in their TEB values.

Perkins and Lawrence (1982) reported that exchange acidity (H^+) replace bases and pH decreases with continued leaching. The trend was observed in the present study in relation to mean values of pH, exchange acidity and TEB in soils on the different parent materials. Available water content correlated significantly with exchange acidity (r = -0.326*), thus increase in AWC decrease exchange acidity through leaching of exchangeable aluminum and hydrogen. Similarly, there was a highly significant correlation with percentage base saturation (r = - 0.718**) (Table 14), thus increase in exchange acidity decrease percentage base saturation. This may be attributed to competition for available exchange cation sites along with the exchangeable bases. Therefore increase in exchange acidity decrease percentage base saturation.

5.3.4 Cation Exchange Capacity

The values of cation exchange capacity (CEC - NH_4OAc) was found to range between 5.6 and 8.5 (6.6), 9.5 and 15.3 (12.1), 5.6 and 10.1 (7.87) and 5.5 and 6.0 (5.8) cmol (+) kg^{-1} in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values ranged between 6.7 and 9.9 (8.39), 4.8 and 11.2 (8.12), 5.4 and 14.3 (8.50) and 5.4 and 7.9 (6.66) cmol (+) kg^{-1}. The soils were rated low to medium in the surface horizons of OG, MS and MG, and medium to high in QZ. The subsoil horizons were low to medium in QZ and MG, low to high in MS and medium in OG (Enwezor *et al*., 1989; Esu 1991). This implies that nutrient retention will be low in soils on OG, MS and MG and would require split dose of fertilizer in judicious quantity for crop growth. Parent materials significantly influenced CEC-NH_4OAc values with mean value of CEC-NH_4OAc of soils on QZ significantly higher than those on MS, OG and MG. Soils on MS and OG were not significantly different but MS was significantly higher in CEC than soils on MG. Soils on OG and MG were observed to be statistically similar (Table 11). The mean values of CEC-NH_4OAc were higher than those reported by Odunze (2006) and Voncir *et al.* (2008) and lower than values reported by Samndi *et al.* (2006) on established forest soils in southern guinea savanna of Nigeria. The lower values compared to those reported by Samndi *et al.* (2006) might be due to organic matter contribution by the forest and the basaltic parent material. Most of the soil had lower values of CEC - NH_4OAc in surface horizon compared to subsurface horizons, except for soils on QZ which were higher in their Ap horizons. Generally, the subsoil horizons were characterized by irregular distribution trend. There was no significant difference in CEC - NH_4OAc values influenced by horizons.

Table 14: Correlation matrix of physical properties verses chemical properties of soil studied.

	Gravel	Sand	Silt	Clay	Si/C	BD	PD	TP	FC	PWP	AWC	WRD
pH(H_2O)	0.288*	-0.108	0.193	0.009	0.045	-0.046	-0.082	0.168	-0.005	0.074	-0.088	0.019`
pH($CaCl_2$)	0.102	0.054	0.180	-0.140	0.179	0.422**	-0.184	-0.269	-0.190	0.075	-0.309*	-0.156
ΔpH	0.209	-0.125	0.016	0.113	-0.108	-0.445***	-0.077	0.425**	0.151	0.001	0.183	0.159
Exch. Ca	0.072	-0.096	0.167	0.012	0.133	0.230	-0.088	-0.207	0.025	-0.019	0.002	-0.010
Exch. Mg	0.144	-0.320*	-0.079	0.354*	-0.262	0.124	-0.017	-0.099	0.317*	0.295*	0.092	0.224
Exch. Na	0.037	-0.071	0.135	0.049	0.056	0.066	0.096	0.024	0.031	0.025	0.056	0.142
Exch. K	0.042	-0.198	0.187	0.101	0.016	0.082	0.101	-0.113	0.064	0.168	-0.063	0.056
TEB	0.093	-0.158	0.109	0.109	0.031	0.199	-0.056	-0.180	0.106	0.095	-0.003	0.044
EA	-0.006	-0.113	0.023	0.167	-0.108	-0.023	0.144	0.057	-0.094	0.171	-0.259	-0.141
ECEC	0.106	-0.139	0.086	0.110	0.020	0.233	-0.072	-0.225	0.082	0.104	-0.037	0.016
CEC (OAc)	0.167	-0.057	-0.164	0.090	-0.050	0.050	0.075	-0.064	0.051	0.171	-0.180	-0.087
CEC Clay	0.239	0.482***	0.135	-0.563***	0.542***	0.097	-0.084	-0.153	-0.205	-0.211	-0.176	-0.179
BS (ECEC)	-0.107	-0.044	0.166	-0.038	0.138	0.131	0.064	-0.016	0.117	-0.104	0.264	0.114
BS	-0.238	-0.139	0.282	-0.002	0.137	0.190	-0.204	-0.129	0.029	-0.157	0.166	0.101
ESP	0.026	-0.033	0.266	-0.096	0.124	0.017	0.024	0.113	0.084	-0.117	0.232	0.227

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Coarse sand particle correlated significantly but negatively with CEC-NH_4OAc (r = -0.312*). This may be due to poor surface charge nature of sand particles in soils. Soil properties such as exchangeable Ca, Mg, K and TEB had positive significant correlation ($P < 0.01$) with CEC-NH_4OAc, thus implying that increase in CEC increased opportunity for exchangeable bases to occupy surface charge space. Various forms of CEC correlated significantly ($P < 0.01$) with CEC-NH_4OAc.

Effective cation exchange capacity (ECEC) was found to range between 4.84 and 7.80 (6.08), 4.72 and 6.75 (5.57), 5.54 and 9.38 (7.22) and 4.55 and 5.97 (5.44) cmol (+) kg^{-1} in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. Values for the underlying horizons ranged between 4.27 and 8.60 (6.93), 4.50 and 7.52 (6.47), 3.65 and 11.02 (6.82) and 3.72 and 5.81 (4.68) cmol (+) kg^{-1}. The surface horizons were rated medium in all the soils and in subsurface horizons of OG and QZ, but low to high and low to medium in MS and MG respectively (Enwezor *et al*., 1989; Esu 1991; Soil Survey Division Staff, 1993). Parent material significantly influenced ECEC values of the soils. On comparing the means, soils on MS, OG, and QZ were found to be similar in their ECEC and soils on MS was found to be significantly higher than soils on MG parent material (Table 11). The mean values were higher than those reported by Odunze (2006) for some Alfisols in Kaduna State. The subsurface horizons had higher values of ECEC compared to surface horizons in soils formed on OG and QZ. Soils on MS had higher ECEC values in their surface horizons compared to the subsurface horizons, except in pedon 2 of mica schist where there was increase in subsoils with depth above the value of the surface horizon. The soils formed on MG showed a decrease in ECEC with increase in depth throughout the profile. Soil pH ($CaCl_2$) was found to significantly correlate

($P < 0.01$) with ECEC, hence pH may had significantly influenced ECEC of these soils. Soil properties such as exchangeable Ca, Mg, Na, K and TEB were observed to significantly correlate positively with ECEC (Table 13), therefore these properties would significantly influence ECEC of soils.

The ECEC values were all lower than the CEC - NH_4OAc. This trend was attributed to the fact that CEC of tropical soils are highly pH dependent (Uehera and Gillman, 1981; Balasubramanian *et al.*, 1984; Osher and Buol, 1998). This might also be attributed to pH of the soils (<7), since ECEC measures charge at the soil pH, whereas the CEC - NH_4OAc measures on the soil colloids at pH 7 (Osher and Buol, 1998).

Cation exchange capacity of clay (CEC-clay) was found to vary between 10.15 and 38.82 (23.25), 72.80 and 122.41 (95.51), 20.24 and 63.98 (37.29) and 17.65 and 34.30 (24.43) cmol (+) kg^{-1} clay in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizons value varied between 14.20 and 29.82 (20.80), 13.07 and 44.18 (20.72), 15.37 and 42.64 (26.74) and 10.86 and 25.80 (16.64) cmol (+) kg^{-1} clay. The values of CEC-clay of the surface horizons were noted to be higher compared to the subsoil horizons in the soils formed on all the different parent materials, and was statistically different (Table 12). The values increased with increase in depth in the subsoil, except for pedons QZ1 and MS1 which had irregular variation with depth in the subsoil horizons. The mean value of CEC-clay of soils on QZ was found to be significantly higher than those of soils on MS, OG and MG. Soils on MS and OG were not significantly different but MS was significantly higher than soils on MG (Table 11). Soils on OG and MG were statistical be at par. The values of CEC-clay indicate that soils developed on MS and the surface horizons of soils on QZ seems to be dominated

by high activity clay (HAC) and soils on OG, MG and subsoils of QZ were dominated by low activity clay (LAC). Juo (1980) set boundary limit between HAC and LAC to be 24 cmol (+) kg^{-1} clay (FAO, 2006; Soil Survey Staff, 2010). The trend in the soils indicates that as soils advance in their development, transformation seems to occur from HAC to LAC minerals. Dominant presence of low activity clay (LAC) in soils on OG, MG and subsoil horizons of QZ imply that nutrient minerals are likely to be lost through leaching (Sanchez, 1976). Therefore, there will be need to raise the CEC through the use of organic matter and additions of bases through appropriate chemical fertilizers (Kang *et al.*, 1991; Fasina *et al.*, 2007a) program. Application of nitrogen using non-acidifying fertilizers should be done on split doses (Enwezor *et al.*, 1989; Yassoglou *et al.*, 2010) to avoid leaching due to the low activity clay condition.

Cation exchange capacity significantly correlated with medium sand, fine sand, very fine sand and total sand (Table 14). Soil pH (H_2O) significantly correlated with CEC-clay (r = 0.330*). Soil properties such as exchangeable Ca, K and TEB significantly correlated with CEC-clay (Table 13), implying that increase in clay content may increase clay surface charges for exchangeable bases to occupy.

5.3.5 Base Saturation

Base saturation (NH_4OAc) ranged between 75.71 and 84.39 (80.03), 26.93 and 53.48 (43.05), 77.59 and 94.46 (87.33) and 71.82 and 86.17 (78.99) percent in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values ranged between 39.40 and 91.77 (73.32), 52.07 and 89.85 (71.70), 47.83 and 95.42 (67.73) and 44.24 and 91.69 (62.37) percent. The soils were generally rated high in their base saturation, except for some few horizons that were rated low (Udo *et al.*, 2009). The dominant occurrence

of moderate to high base saturation in these soils might that these soils were not excessively leached of their bases. Parent materials significantly influenced base saturation. On comparing their means, soils on OG, MS and MG were found to be at par, but OG and MS were significantly higher than soils on QZ and means of soils on MG and QZ were similar. Similarly, Jaiyeoba (2006) reported that base saturation variation was significantly influenced by parent materials. The surface horizons were observed to be higher than the subsoil for OG, MS and MG and the values decreased with increase in depth in the subsoil of soils developed on MS and MG, but irregular variation was noted in subsurface horizon of OG. Soils on QZ had lower values in the surface horizon than the subsoil horizons. When the mean values were compared statistically, it is observed that there is no significant difference between the surface soil and subsoil. Fine sand was correlated negatively (r = -0.285*) with base saturation, might imply that increase in fine sand decreased base saturation as it did not significantly contributed to exchange cites. Total exchangeable bases, exchangeable Ca and Mg were found to significantly correlate with base saturation as they contribute to base saturation of soils. Cation exchange capacities were observed to correlate negatively (Table 12) as they serve denominator in determining base saturation. Increase in base saturation tends to increase exchangeable sodium percentage (r = 0.348*).

Base saturation (ECEC) ranged between 76.58 and 92.47 (87.98), 82.22 and 93.77 (87.78), 83.56 and 95.75 (92.25) and 75.61 and 93.12 (86.14) percent in soils developed on older granites, quartzites, mica schists and migmatite gneisses respectively. All the soils were rated low to high in their content Udo *et al.* (2009). The lowest value was observed in soils on MG and the highest value was in soil on

MS. When the mean values were compared statistically, it was observed that the parent materials significantly influenced base saturation of the soils. The mean values indicated soil on MS was found to be significantly higher base saturation (ECEC) than that of soils on OG, QZ and MG. The means of soils on OG, MG and QZ were statistically similar. The variation trend tends to indicate decrease in base saturation with advancement in pedogenic age. Values of base saturation (ECEC) were higher than base saturation (NH_4OAc) and were significantly correlated (r = 0.472***) with each other. Mean values of the soils tend to be influenced similarly by their parent material and pedogenic exposure. Both base saturation mean values were lowest in soils on MG, hence indicated that leaching and pedogenic age significantly reduced their values. Coarse sand was observed to correlate negatively (r = -0.285*), and be implying that increase in coarse sand decreased base saturation. Total exchangeable bases, exchangeable Ca, Mg, and K were found to significantly correlate with base saturation (Table 13). Exchange acidity highly correlated negatively (r = -0.718**) with base saturation, this indicates that exchangeable bases contribute to base saturation, and similarly increase in exchange acidity in the soils will reduce base saturation.

5.3.6 Exchangeable Sodium Percentage (ESP)

Exchangeable sodium percentage (ESP) varied from 6.71 to 9.12 (mean, 8.19), 1.89 to 5.48 (3.39), 4.16 to 6.79 (5.51) and 6.10 to 8.55 (7.33) percent in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied from 4.88 to 7.16 (5.83), 2.60 to 7.71 (5.08), 3.01 to 9.44 (5.62) and 3.97 to 12.43 (6.53) percent. Parent material significantly influenced ESP of the soils. The mean values of ESP of soils on MG,

OG and MS were not significantly different, but MG soil was significantly higher than QZ soil. There was no significant difference observed between soils on OG, MS and QZ. The mean value of ESP in the surface soils was observed to be statistically similar with the subsoil ($P > 0.05$). All the soils were considered to be non sodic presently as the values were less than 15% critical limit (Brady and Weil, 2005). The soils on OG were observed to have higher values in the Ap horizons, with inconsistent increase in subsoil horizons with increase in depth. Soils on QZ had lower values in the Ap horizons with irregular variation pattern in subsoil horizons. Soils on MS and MG varied irregularly within their profiles. Soil pH ($CaCl_2$) was found to correlate negatively with ESP ($r = - 0.325^*$). Exchangeable Ca, Mg and K were found to negatively correlate with ESP, whereas Na correlated positively. This may be associated with the competitiveness of these exchangeable bases against exchangeable Na for the available soil surface charges.

5.3.7 Electrical Conductivity (EC)

Electrical conductivity (EC) ranged between 0.5 and 0.9 (0.65), 0.016 and 0.50 (0.034), 0.032 and 0.06 (0.043) and 0.009 and 0.22 (0.11) dSm^{-1} in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values ranged between 0.018 and 0.03 (0.025), 0.006 and 0.018 (0.01), 0.004 and 0.046 (0.019) and 0.006 and 0.10 (0.025) dSm^{-1}. On comparing the mean values statistically, the surface soil was significant higher than the subsoil. The soils were observed to vary significantly ($P < 0.05$) in mean values of EC between the different parent materials in the order of OG > MS > MG > QZ. Therefore variation between surface and subsoil horizons and between parent materials significantly influence distribution of soluble salts in these soils studied. The

EC values of soils on QZ and MS were rated low, MG was low to medium and OG was low to high (Udo *et al.,* 2009). The soils were rated as non saline as the values were below 4.00 dSm^{-1} critical level considered for saline soils (Brady and Weil, 2005). The surface horizons were observed to be higher in ECe values for all the soils, except for pedon MG2. The values of EC consistently increased with increase in depth of soils on OG, but there was no consistent variation pattern in the subsoils of soils on QZ, MS and MG. Gravel content was found to significantly correlate negatively with EC (r = -0.368**). This implied that more gravel content significantly contributed to decrease in soluble salts. This may be ascribed to low surface area thereby increase loss through erosion and leaching. However, fine materials (very fine sand and silt) correlated positively with EC (Table 14). Water retention properties (FC, PWP and WRD) also correlated negatively with EC (Table 14). This indicates that increase in moisture retention decrease soluble salt content of these soils. Calcium, PBS, organic carbon and total nitrogen significantly influenced soluble salt in these soils. This indicated organic matter may be a significant source of soluble salts.

5.4 MACRONUTRIENTS

The selected macronutrients considered for discussion in this section are organic carbon (OC), total nitrogen (TN) and available phosphorus (AP). The data obtained related to these parameters are presented in Table 15.

Table 15: Organic carbon, total nitrogen, available phosphorus and micronutrients of soils of the studied areas

Pedon	Depth	Organic Carbon (------ gkg^{-1} ---------)	Total N.	Avail. P. (-- $mgkg^{-1}$ --)	Fe HCl	Fe Total %	Mn HCl (---------- $mgkg^{-1}$ ----------)	Mn Total	Cu HCl	Cu Total	Zn HCl	Zn Total
						Soils on Older Granites						
Pedon OG 1												
Ap	0 - 26	8.78	0.70	14.00	32.86	2.90	12.80	210	0.963	12.03	7.50	23.44
Bt1	26 - 75	6.98	0.53	1.75	17.14	5.98	6.56	315	0.963	36.09	6.25	46.88
Bt2	75 - 119	5.19	0.18	3.50	22.86	9.96	2.88	420	0.481	36.09	11.25	78.13
BC	119 – 183	3.99	0.35	7.00	71.43	3.98	1.00	105	1.444	12.03	11.25	78.13
Pedon OG 2												
Ap	0 - 17	8.74	0.35	21.00	25.71	2.98	17.44	315	0.481	24.08	5.63	31.25
Bt	17 - 70	7.42	0.70	14.00	18.57	3.98	4.80	210	0.481	12.03	13.12	62.50
Btc	70 - 190	3.59	0.18	12.25	7.29	7.97	2.88	210	1.444	36.09	8.13	46.88
Pedon OG 3												
Ap	0 - 23	8.58	0.35	21.00	17.14	7.97	14.80	210	0.481	36.09	7.50	31.25
Bt	23 - 57	6.38	0.35	15.75	18.57	9.96	6.56	420	0.963	12.03	6.88	23.44
Btc	57 - 121	1.40	0.18	19.25	18.57	11.95	5.44	315	0.963	24.06	5.63	31.25
Btc	128 - 160	1.20	0.18	12.25	14.29	9.96	2.88	420	0.481	24.06	6.25	46.88

Table 15 Contd.: Organic carbon, total nitrogen, available phosphorus and micronutrients of soils of the studied areas

Pedon	Depth	Organic Carbon	Total N.	Avail. P.	Fe HCl	Fe Total	Mn HCl	Mn Total	Cu HCl	Cu Total	Zn HCl	Zn Total
		(------ gkg^{-1} ---------)		(-- $mgkg^{-1}$ --)		%	(---------- $mgkg^{-1}$ ----------)					
						Soils on Quartzites						
Pedon QZ 1												
Ap	0 - 14	11.57	1.05	7.00	17.14	1.99	21.20	525	1.444	36.09	5.00	62.50
AC	14 - 40	6.98	0.53	5.25	7.14	3.98	12.80	315	1.444	24.06	6.25	78.13
C1	40 – 98	1.00	0.18	7.00	45.71	2.90	8.60	105	0.962	12.03	7.50	62.50
C2	98 – 135	0.40	0.18	5.25	28.57	1.99	4.80	105	1.444	24.06	3.75	46.88
Pedon QZ 2												
Ap	0 - 19	10.17	0.53	5.25	17.14	5.98	17.44	525	0.963	48.13	8.13	62.50
Bt1	19 - 51	7.58	0.53	3.50	28.57	3.98	14.88	420	0.963	36.09	5.63	46.88
Bt2	51 – 84	4.99	0.18	3.50	35.71	7.97	8.60	315	0.963	24.06	5.63	62.50
Bt3	84 - 139	2.20	0.18	5.25	30.00	9.96	6.56	210	1.925	36.09	4.38	46.88
Btc	139 –187	0.80	0.18	7.00	37.14	5.98	5.44	210	1.444	24.06	8.13	46.88
Pedon QZ 3												
Ap	0 - 19	8.18	0.35	15.75	18.57	1.99	19.80	420	0.481	48.13	7.50	62.50
AB	19 - 40	6.19	0.35	15.75	8.57	3.98	14.80	315	0.963	48.13	5.63	46.88
Bt1	40 – 63	2.39	0.53	5.25	12.86	7.97	6.56	315	1.444	60.16	10.00	31.25
Bt2	63 – 97	1.00	0.18	2.63	17.14	5.98	5.44	210	0.963	12.03	14.38	46.88
BC	97 - 167	0.40	0.18	1.75	27.14	3.98	4.80	420	0.481	24.06	4.38	78.13

Table 15 Contd.: Organic carbon, total nitrogen, available phosphorus and micronutrients of soils of the studied areas

Pedon	Depth	Organic Carbon	Total N.	Avail. P.	Fe HCl	Fe Total	Mn HCl	Mn Total	Cu HCl	Cu Total	Zn HCl	Zn Total
		(------ gkg^{-1} ---------)		(-- $mgkg^{-1}$ --)		%	(---------- $mgkg^{-1}$ ----------)					
						Soils on Mica Schists						
Pedon MS 1												
Ap	0 - 18	7.98	0.70	8.75	38.86	1.99	8.60	630	0.096	36.09	5.00	46.88
Bt	18 - 54	2.99	0.35	5.28	37.14	7.97	6.00	210	0.048	24.06	6.88	62.50
Btc	54 - 177	1.60	0.18	4.90	25.71	5.98	20.88	210	0.096	24.06	8.75	62.50
Pedon MS 2												
Ap	0 - 16	6.63	0.70	5.25	41.43	3.98	8.60	315	0.193	36.09	6.25	46.88
Bt	16 - 37	3.19	0.53	1.75	28.57	3.98	6.56	210	0.096	24.06	5.00	46.88
BC	37 – 72	2.00	0.18	1.40	27.14	5.98	5.44	315	0.048	48.13	5.63	78.13
C	72 - 143	0.80	0.18	3.50	25.71	3.98	12.80	315	0.048	24.06	6.88	93.75
Pedon MS 3												
Ap	0 - 19	6.98	0.53	3.50	34.29	2.90	19.20	315	0.193	24.06	7.50	31.25
Bt1	19 - 42	3.39	0.18	3.50	20.00	5.98	6.56	420	0.048	36.09	4.38	46.88
Bt2	42 – 96	1.80	0.35	1.75	25.71	7.97	5.44	210	0.048	24.06	5.63	46.88
BC	96 – 168	1.20	0.18	5.25	30.00	5.98	6.56	315	0.048	36.09	3.75	62.50

Table 15 Contd.: Organic carbon, total nitrogen, available phosphorus and micronutrients of soils of the studied areas

Pedon	Depth	Organic Carbon (------ gkg^{-1} ---------)	Total N.	Avail. P. (-- $mgkg^{-1}$ --)	Fe HCl	Fe Total %	Mn HCl (---------- $mgkg^{-1}$ ----------)	Mn Total	Cu HCl	Cu Total	Zn HCl	Zn Total
						Soils on Migmatite Gneisses						
Pedon MG 1												
Ap	0 - 15	7.78	0.70	12.25	31.43	5.98	12.80	315	0.048	36.09	11.25	78.13
Bt	15 - 47	6.94	0.70	8.75	44.29	3.98	5.44	210	0.144	60.16	8.13	62.50
Btcv1	47 – 103	1.39	0.35	3.50	42.86	3.98	1.00	105	0.096	72.19	17.50	93.75
Btcv2	103 – 147	0.60	0.18	13.13	41.43	3.98	2.88	105	0.048	24.06	14.38	78.13
Pedon MG 2												
Ap	0 - 18	6.48	0.70	35.00	30.00	3.98	14.80	315	0.241	24.06	9.38	93.75
AB	18 - 44	3.92	0.53	14.00	27.14	5.98	10.80	210	0.193	36.09	8.13	62.50
Bt1	44 – 78	2.89	0.53	12.25	38.57	5.98	6.56	105	0.096	36.09	6.25	46.88
Bt2	78 - 123	1.39	0.18	5.25	37.14	7.97	2.88	315	0.144	12.03	8.75	46.88
BCcv	123 –167	1.00	0.18	4.38	15.71	3.98	1.00	105	0.048	24.06	5.00	31.25
Pedon MG 3												
Ap	0 - 25	5.19	0.70	5.60	28.57	2.90	11.92	315	0.096	24.06	2.50	62.50
Bti	25 - 47	3.40	0.53	5.25	24.14	3.98	5.44	105	0.048	12.03	2.50	46.88
Bt2	47 – 89	1.85	0.35	5.25	38.86	5.98	2.88	210	0.048	12.03	10.63	46.88
BCcv	89 – 162	1.00	0.18	4.38	37.29	7.97	2.00	105	1.444	24.06	14.38	62.50

5.4.1 Organic Carbon (OC)

Organic carbon content in the surface horizon varied between 8.58 and 8.78 (8.70), 8.18 and 11.57 (9.97), 6.63 and 7.98 (7.20) and 5.19 and 7.78 (6.48) gkg^{-1} in the respective surface horizons of the older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied between 1.20 and 7.42 (4.52), 0.40 and 7.58 (3.08), 0.80 and 3.39 (2.12) and 0.60 and 6.94 (2.44) gkg^{-1}. The soils were generally low in organic carbon except for surface horizons of pedon 1 and 2 on quartzite that were rated medium. The generally low OC content of these soils might be due to continuous cultivation without fallow, bush burning, high rate of mineralization due to high temperature and crop removal for livestock feeding, fuel wood, fencing and building purposes (Jones and Wild, 1975; Esu *et al*., 1987; Bownan *et al.,* 1990; Raji *et al.,* 1996; Odunze, 1998). The mean OC content of the surface soil was found to be significantly higher than the subsoil ($P < 0.01$) (Table 16). There was also significant difference between the soils developed on the different parent materials. The mean value of OC of soils on OG, QZ and MS were statistically similar, while values on OG and QZ were significantly higher than the mean values of OC in soils on MG. However, soils on MS and MG were observed to be statistically at par (Table 17). Similar content and trend was reported by Ezenwa and Esu (1999) and Ande (2010) on basement complexes in northern guinea savanna and in humid rainforest of Nigeria respectively. The sharp decrease in organic carbon with depth from Ap horizons to the subsoil horizons may be attributed to high organic matter accumulation and microbial activity. (Mortland, 1970; Ogunwale, 1973). This was supported by the highly significant negative correlation with clay (r=-0.651***).

Table 16: Ranking of means of macronutrients and micronutrients of horizons

Parameter	Unit	Surface Horizon	Subsurface Horizon	SE±	LOS
Organic C	gkg^{-1}	8.09a	3.01b	0.43	**
Total N	gkg^{-1}	0.61a	0.32b	0.03	**
Available P	$mgkg^{-1}$	12.86a	6.79b	1.75	**
HCl Fe	$mgkg^{-1}$	22.76	27.69	3.87	NS
Total Fe	%	3.40b	6.05a	0.73	**
HCl Mn	$mgkg^{-1}$	16.91a	5.97b	0.90	***
Total Mn	$mgkg^{-1}$	376.25a	261.08b	35.17	**
HCl Cu	$mgkg^{-1}$	1.12	0.95	0.15	NS
Total Cu	$mgkg^{-1}$	32.08	28.94	4.65	NS
HCl Zn	$mgkg^{-1}$	6.93	7.76	1.07	NS
Total Zn	$mgkg^{-1}$	52.74	56.38	5.34	NS

LOS (P): NS > 0.05, ** ≤ 0.01, *** ≤ 0.001
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Table 17: Ranking of means of macronutrients and micronutrients of parent materials

Parameter	Unit	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
Organic C	gkg^{-1}	5.66a	4.56a	3.51ab	3.37b	0.95	*
Total N	gkg^{-1}	0.37	0.37	0.37	0.45	0.85	NS
Available P	$mgkg^{-1}$	12.89a	6.44b	4.07b	9.92a	2.50	**
HCl Fe	$mgkg^{-1}$	22.86b	23.67b	30.41ab	33.88a	0.47	**
Total Fe	%	7.05	4.90	5.15	5.13	0.77	NS
HCl Mn	$mgkg^{-1}$	7.09b	10.84a	10.33a	6.18b	0.32	*
Total Mn	$mgkg^{-1}$	286	315	315	242	0.53	NS
HCl Cu	$mgkg^{-1}$	0.83	1.14	0.88	1.07	0.40	NS
Total Cu	$mgkg^{-1}$	24.06	32.66	30.62	30.54	0.66	NS
HCl Zn	$mgkg^{-1}$	8.13	6.88	5.97	9.14	0.22	NS
Total Zn	$mgkg^{-1}$	45.46b	55.81ab	56.82ab	57.82a	0.39	**

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Organic matter positively correlated and significantly with coarse sand, medium sand, fine sand, very fine sand and total sand (Table 18). This may be associated with erosion of finer particle on surface horizon where organic matter tends to accumulate. Chemical properties such as CEC, EC, total nitrogen and available phosphorus were significantly correlated and positively with OC (Tables 19 and 20) this implied that organic matter significantly contributed to the CEC of these soils and served as reservoir for soluble salts TN and AP and had been reported by other researchers (Sanchez, 1981; Goh, 1980; Jones and Wild, 1975; Ogunsola *et al.,* 1989). The significantly negative correlation between OC and Mg (r = -0.383**) might be ascribed to the difference in their distribution pattern as exchangeable Mg was leached into the subsurface horizons and had its higher concentration in the underlying horizons compared to surface horizon where the highest accumulation of OC was found.

5.4.2 Total Nitrogen (TN)

Total nitrogen content for the surface horizons were found to vary between 0.35 and 0.70 (mean, 0.47), 0.35 and 1.05 (0.64), 0.35 and 0.70 (0.64) and 0.70 (0.70) gkg^{-1} in the older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding subsurface horizon values varied between 0.18 and 0.70 (0.33), 0.18 and 0.53 (0.29), 0.18 and 0.53 (0.27) and 0.18 and 0.70 (0.37) gkg^{-1}. Total nitrogen was rated low (<1.5 gkg^{-1}) in all the soils, both in their surface and subsurface horizons. Total nitrogen was higher in the surface horizon and decreased through the profile with increase in depth and may be attributed to contribution by organic matter and nitrogen fertilizer application. Similar trend was reported by Ezenwa and Esu (1999). The mean TN content of surface soil was found to be significantly higher than the subsurface horizon ($P < 0.01$). There was no significant difference between the soils developed on the different parent materials (Table 17).

Table 18: Correlation matrix of physical properties verses macronutrients and micronutrients

	OC	TN	AP	HCl Fe	Total Fe	HCl Mn	Total Mn	HCl Cu	Total Cu	HCl Zn	Total Zn
Sand	0.610***	0.378**	0.211	-0.087	-0.466***	0.495***	0.333**	0.190	0.276	-0.085	0.098
Silt	0.117	0.150	0.215	-0.018	0.087	0.157	0.067	-0.224	-0.107	-0.082	-0.106
Clay	-0.651***	-0.395**	-0.245	0.111	0.411**	-0.561***	-0.356*	-0.077	-0.256	0.119	-0.043
Si/C	0.622***	0.404**	0.323*	-0.160	-0.309*	0.555***	0.313*	-0.028	0.153	-0.117	-0.060
BD	-0.057	-0.015	-0.161	-0.021	-0.110	-0.160	-0.061	0.102	0.206	-0.075	0.227
PD	-0.156	-0.337	0.018	-0.164	0.117	-0.279	-0.082	-0.238	-0.227	0.091	-0.201
TP	0.014	-0.017	0.201	0.008	0.124	0.145	-0.015	-0.056	-0.182	0.072	-0.178
FC	0.688***	-0.466**	-0.258	0.219	0.290*	-0.556***	-0.377**	-0.019	-0.237	0.034	0.054
PWP	-0.605***	-0.568***	-0.250	0.300*	0.296*	-0.564***	-0.297*	-0.024	-0.207	-0.079	0.079
AWC	-0.332*	-0.015	-0.095	0.104	0.106	-0.324*	-0.215	0.002	-0.141	0.188	0.011
WRD	-0.384**	-0.480***	-0.264	0.131	0.234	-0.683***	-0.201	-0.073	-0.220	0.198	0.098

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 19: Correlation matrix of chemical properties verses macronutrients and micronutrients

	OC	TN	AP	HCl Fe	Total Fe	HCl Mn	Total Mn	HCl Cu	Total Cu	HCl Zn	Total Zn
pH(H_2O)	-0.251	-0.199	-0.038	0.049	0.089	0.017	-0.097	0.054	0.003	-0.046	0.138
pH($CaCl_2$)	0.050	-0.012	-0.177	-0.005	-0.032	0.076	-0.112	0.072	0.114	-0.202	0.195
ΔpH	-0.290*	-0.163	0.118	-0.069	0.131	-0.004	0.026	0.078	0.004	0.083	-0.056
Exch. Ca	-0.008	-0.097	-0.048	-0.243	0.186	0.160	0.145	0.208	0.073	-0.185	-0.075
Exch. Mg	-0.383**	-0.334*	-0.289*	-0.107	0.243	-0.106	-0.030	0.119	-0.055	-0.316*	-0.056
Exch. Na	0.060	-0.059	0.135	0.331*	0.236	0.096	0.111	0.186	-0.028	-0.029	-0.049
Exch. K	-0.041	-0.177	0.132	-0.188	0.105	0.143	0.058	0.110	-0.124	-0.295	-0.157
TEB	-0.092	-0.181	-0.083	-0.208	0.216	0.108	0.113	0.185	0.044	-0.231	-0.082
EA	0.098	-0.019	0.327*	-0.063	0.068	-0.012	-0.062	-0.077	0.067	0.128	0.260
ECEC	-0.092	-0.153	-0.075	-0.199	0.199	0.120	0.081	0.178	0.029	-0.214	-0.061
CEC (OAc)	0.034	-0.174	-0.072	-0.097	-0.042	0.035	0.138	0.091	-0.006	-0.065	0.134
CEC Clay	0.407**	-0.018	0.049	-0.073	-0.281*	0.211	0.342*	0.065	-0.002	-0.118	0.168
BS (ECEC)	0.067	-0.035	-0.295*	-0.123	0.142	0.053	0.105	0.138	-0.036	-0.167	-0.330*
BS	-0.007	0.080	0.040	-0.148	0.205	0.181	-0.019	0.169	0.104	-0.070	-0.265
ESP	-0.003	0.165	0.190	-0.103	0.041	0.016	0.072	0.036	-0.011	0.126	-0.076
EC	0.345***	0.492**	0.266	-0.127	-0.161	0.353*	0.221	-0.045	0.153	-0.097	-0.001

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 20: Correlation matrix of macronutrients and micronutrients

	OC	TN	AP	HCl Fe	Total Fe	HCl Mn	Total Mn	HCl Cu	Total Cu	HCl Zn
TN	0.740***									
AP	0.347*	0.283*								
HCl Fe	-0.128	0.039	-0.122							
Total Fe	-0.307*	-0.453**	0.019	-0.248						
HCl Mn	0.711***	0.613***	0.295*	-0.066	0.437**					
Total Mn	0.430**	0.220	0.048	-0.272	0.003	0.384**				
HCl Cu	0.120	0.293*	0.161	0.184	-0.062	0.172	-0.090			
Total Cu	0.299*	0.165	-0.052	-0.171	-0.021	0.327*	0.183	0.091		
HCl Zn	-0.014	0.078	0.086	0.160	0.097	-0.301*	-0.158	0.138	-0.087	
Total Zn	-0.122	-0.008	-0.075	0.218	-0.210	-0.135	0.072	-0.089	0.137	0.280

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Total nitrogen correlated significantly and positively with medium sand, very fine sand and total sand (Table 18). This may be associated with higher proportion of coarse particles. Erosion of finer particle occurs on the surface horizon where TN tends to accumulate due to OC decomposition and mineralization. Clay and Si/C ratio were significantly correlated with TN (r = -0.395** and 0.404** respectively). This might be ascribed to the dissociated migration of clay and organic matter in these soils resulting in different distribution trend within soil profiles. Higher moisture retention seems to reduce TN content as indicated by the significant correlation with water retention properties such as FC, PWP, AWC and WRD (Table 18). Total nitrogen significantly correlated with OC (r = 0.747**) imply that high amount of total nitrogen is significantly reserved in organic matter.

5.4.3 Available Phosphorus (AP)

Available phosphorus was found in the surface horizon to vary between 14.0 and 21.0 (18.75), 5.25 and 15.75 (9.33), 3.50 and 8.75 (5.83) and 5.60 and 35.00 (17.62) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsoil horizons value varied between 1.75 and 19.25 (10.72), 1.75 and 15.75 (5.65), 1.40 and 5.25 (3.41) and 3.50 and 13.13 (7.61) $mgkg^{-1}$. There was no significant difference observed between mean values of the soils developed on the different parent materials. Hence, other factors (fertilizer application and organic matter) contributed more to AP in these soils rather than parent materials. Soils on OG and MG were rated low to high, those on QZ low to medium and for MS was low. The Ap horizons have higher values of AP compared to sub-surface horizons and varied irregularly with depth within the sub-soil horizons of soils on OG, MS and MG. Higher values of AP in surface horizons

may be attributed to fertilizer application and supply from organic matter. Mosugu (1989), Pam (1990), Kparmwang (1993) and Raji (1995) reported similar findings in older granites, basaltic soils and ancient sand dunes in savanna in Nigeria. However, the values were higher than those reported along toposequence on basement complex rocks in Bauchi, Nigeria (Voncir *et al.,* 2008). Soils on QZ had irregular variation through their profiles. Available phosphorus was observed to negatively correlate significantly with gravel (r = -0.391**) indicating weathering of parent rock to release more AP. Exchange acidity significantly correlated with AP. Available phosphorus significantly correlated with OC and TN (Table 20), imply that AP and TN occured mostly in the organic form in these soils. The low content of OC, TN and AP (subsoil horizons of older granite soils) could be substantially increased through effective post harvest crop residue incorporation instead of their usual burning, application of farm yard manure and incorporating legumes in crop rotation fields, as well as use of organo-mineral fertilizers (Jones, 1971; Brady and Weil, 2005; Havlin *et al.,* 2005; Odunze, 2006; Fasina *et al*., 2007a; Ogunkunle, 2009). Fertilizers containing these elements will be required to be applied timely in judicious quantity and by burying to remedy the deficiency.

5.5. Available and Total Micro-nutrients

Some selected micronutrients including iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn) in HCl acid extractable and total forms were considered in this study for the purpose of determining their present status. Data obtained are presented in Table 15.

5.5.1 Available and Total Iron (Fe)

Available iron content in the surface horizon varied between 17.14 and 32.86 (25.24), 17.14 and 18.57 (17.62), 34.29 and 41.43 (38.19) and 28.57 and 31.43 (30.00) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and

migmatite gneisses. The corresponding subsoil horizons value varied between 4.29 and 71.43 (21.97), 7.14 and 45.71 (25.32), 20.00 and 37.14 (27.50) and 15.71 and 44.29 (35.04) $mgkg^{-1}$. The parent materials significantly influenced available Fe in the soils (P: <0.01) (Table 21). The mean values of available Fe for soils developed on MG and MS were not significantly different, but MG soils had significantly higher mean values of available Fe than in soils on OG and QZ. Soils on MS were to be statistically similar to OG and QZ. The soils were rated low to high for soils on OG, medium to high for QZ and high for soils on MS and MG (Soil Survey Division Staff, 1993). Available Fe was irregular distributed in all the soils. When the mean values of available Fe were compared statistically, there was no significant difference between the surface and subsoil values of available iron. The values were generally within the range reported in ancient sand dunes (Raji, 1995), basement complexes in Bauchi (Mustapha and Singh, 2003) and plinthitic landscape of Zaria (Yaro, 2005). However, the values were lower than those reported by Yaro *et al.* (2002) on dung NPK (DNPK) plot at Samaru, Zaria. The difference may be attributed to organo fertilizer application in soil of Samaru area.

Moisture retention at permanent wilting point (PWP) weakly correlated significantly (0.300*) (Table 18) with available Fe. This may imply that moisture retention at this pressure level (1500 mPa) tend to discourage adsorbtion of Fe and making it available for crop utilization. The significant correlation observed with exchangeable Na (r = 0.331*) might be related to their distribution pattern that tend to be similar in these soils.

Total iron content in the surface horizon varied between 2.90 and 7.97 (4.62), 1.99 and 5.98 (3.32), 1.99 and 3.98 (2.96) and 2.90 and 5.98 (4.29) % in the respective

Table 21: Correlation matrix of sesquioxides verses macronutrients and micronutrients

	OC	TN	AP	HCl Fe	Total Fe	HCl Mn	Total Mn	HCl Cu	Total Cu	HCl Zn	Total Zn
$Fe_{ox/d}$	-0.719***	-0.458***	-0.231	0.193	0.373**	-0.623***	-0.250	0.006	-0.118	0.215	0.126
Fe_{ox}	-0.252	-0.327*	-0.311*	0.049	0.160	-0.048	0.054	-0.115	-0.049	-0.243	-0.150
Fe_p	-0.072	0.011	-0.041	0.123	0.060	-0.007	-0.195	-0.072	-0.028	0.110	0.241
Mn_d	-0.320*	-0.269	-0.265	0.093	0.171	-0.357*	-0.131	0.164	0.011	0.129	-0.016
Mn_{ox}	-0.033	-0.038	-0.017	0.209	-0.202	0.130	-0.043	0.141	0.117	-0.149	-0.134
Mn_p	0.375**	0.571***	0.164	0.170	-0.315*	0.581***	0.199	0.268	0.318*	-0.184	0.003
$Fe_{ox/d}$	0.529***	0.105	0.015	-0.212	-0.283*	0.530***	0.376**	-0.124	0.114	-0.288*	-0.179
$Mn_{ox/d}$	0.270	0.202	0.148	0.102	-0.371*	0.440**	0.091	0.070	0.204	-0.305*	-0.160
Clay/ Fe_d	0.028	-0.011	0.073	-0.272	-0.044	0.004	-0.202	-0.163	-0.159	-0.137	-0.164

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied between 3.98 and 11.95 (7.97), 1.99 and 9.96 (5.33), 3.98 and 7.97 (5.98) and), 3.98 and 7.97 (5.38) %. All the soils were rated high in total Fe content (Soil Survey Division Staff, 1993). The total iron content of these soils were slightly lower than the values reported in basaltic soils (Kparmwang, 1993) and in plinthite landscape soils (Yaro, 2005) and may be attributed to more accumulation of Fe due to advancement in pedogenic age of their soils compared to soils of the present study. The content of total Fe increased regularly with increased in soil depth in soils formed on OG, MS and MG, except at the lowest horizon that decreased. Content of total Fe in Pedon MG1 was observed to be constant in the subsoil horizons. Soils developed on QZ had irregular distribution pattern within their profiles. There was no significant difference in mean values of total iron in the different soils. However, the subsoil mean value was highly significant and greater than the surface soil (Table 16).

Total iron correlated negatively with total sand fraction and positively with clay (Table 18). This may be attributed to Fe occurrence in tropical soils as clay or coating clay surfaces (Agbenin and Tiessen, 1995; Raji *et al.,* 2000). Moisture retention at FC and PWP were also noted to significantly influence distribution of total iron in soils (Table 18). Soil organic carbon, TN and CEC of clay significantly correlated negatively with total Fe (Table 19 and 20). Iron (Fe_d), ($Fe_{x/d}$) and $Mn_{x/d}$ were observed to significantly influenced total iron content (r = 0.373**, -0.283* and -0.371* respectively) (Table 19). This indicated formation and distribution of total iron was significantly influenced by pedogenic processes such as ferritization and plinthization.

5.5.2 Available and Total Manganese (Mn)

The available manganese (0.1M HCl extractable) content in surface horizon varied from 12.80 to 17.40 (15.00), 17.40 to 21.00 (19.50), 8.60 to 19.20 (20.00) and 11.90 to 14.80 (13.20) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. Values in the underlying horizons, the corresponding values varied from 1.00 to 6.60 (4.10), 4.80 to 14.80 (8.50), 5.40 to 20.90 (6.70) and 1.00 to 10.80 (4.10) $mgkg^{-1}$. The mean values of available Mn in soils on MS and QZ were observed to be significantly higher than those on MG and OG soils. The variation may be influenced by their inherent nature and origin of metamorphism. The soils were rated high in their content, except in subsurface horizons of OG, QZ and MG soils which were rated as medium to high. The values were within range reported on basement complex rocks of Bauchi (Mustapha and Singh, 2003), lateritized basalts (Kparmwang, 1993) in northern guinea savanna and less than other basalts in the region. Generally, the soils highest values were in the Ap horizons and decreased regularly with depth in the profiles. Similar trend was reported by Kparmwang (1993), Raji (1995) and Yaro (2005) and attributed the trend to contribution from organic matter. This was confirmed by the highly significant difference between surface and subsoil mean value (Table 16, and the significant correlation with organic matter ($r = 0.711^{***}$).

Available manganese correlated positively with total sand and negatively with clay (Table 18). This could be attributed to similar distribution pattern between available Mn and sand opposite with clay. Moisture retention properties (FC, PWP, AWC and WRD) were all observed to significantly influence available Mn content negatively (Table 18). Soil organic carbon and TN significantly correlated positively with

available Mn (Table 20). This indicates that organic matter was a major contributor of available Mn in these soils. Organic carbon was also found to correlate with Mn by Katyal and Sharma (1991), Kparmwang *et al.* (1998), Kparmwang *et al.* (2000), Yaro *et al.* (2002), Havlin *et al.,* (2005). Iron (Fe_d), Mn_d and crystalline forms of Fe and Mn were observed to significantly correlate inversely with available Mn content (Table 21). Pyrophosphate extractable Mn highly significantly correlated with available Mn (r = 0.530***). This implies that available Mn may be strongly retained in these soils in organic matter – Mn complexation. Hence, affirming that available Mn was more strongly retained in soils by organic matter.

Total manganese content in surface horizon varied from 210 to 315 (245), 420 to 525 (490), 315 to 630 (420) and 105 to 315 (350) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied from 105 to 420 (302), 105 to 315 (267), 210 to 420 (276) and 105 to 525 (210) $mgkg^{-1}$. All the soils were rated high in their content. The values reported for total Mn were within the range found in soils studied by several workers in Nigerian savanna (Kparmwang, 1993; Raji, 1995; Yaro, 2005). Total manganese irregular decreased with depth in profiles of QZ, MS and MG. Soils on OG to exhibit irregular decrease in their distribution with increase in depth of soils. Mean value of surface soil was significantly greater ($P < 0.01$) than the subsurface horizon mean value (Table 16). The irregular variation with increase in soil depth indicated total Mn distribution might have been influenced by several pedogenic processes such as Mn – organic matter complexation and leaching. Similar trend was observed by Raji (1995), Sharma *et al.* (2000) and Yaro (2005) on different soils. This may be attributed to contribution by organic matter as indicated by their

significant correlation (r = 0.430**). Incorporation of organic matter into these soils would significantly contribute to increase total Mn content. There was no significant difference between the mean values of total Mn of soils, though the soils were observed to vary in their mean values in order of QZ = MS > OG > MG (Table 17) and may be attributed to inherent characteristics of parent materials. This indicates that as pedogenic development advances, organic matter contribution of Mn in these soils may be greater than parent materials.

5.5.3 Available and Total Copper (Cu)

Available copper content for the surface horizons were found to vary between 0.48 and 0.96 (mean, 0.64), 0.48 and 1.44 (0.96), 0.90 and 1.93 (1.60) and 0.48 and 2.41 (1.28) $mgkg^{-1}$ in the older granites, quartzites, mica schists and migmatite gneisses respectively. In subsoil horizons, the corresponding values varied between 0.48 and 1.44 (0.90), 0.48 and 1.93 (1.18), 0.48 and 0.96 (0.602) and 0.48 and 1.93 (1.01) $mgkg^{-1}$. Means of available Cu were not significantly different both between horizons and between the soil parent materials. Available copper was rated medium to high in soils of QZ and MG, except in the surface and subsoil horizons of OG and MS respectively. Available Cu in soils on OG irregularly increased with increase in soil depth, whereas those on QZ and MG had irregular distribution pattern in the profiles and was similarly observed by Kparmwang *et al.* (2000) in soils of Benue valley and by Raji (1995) in the ancient sand dunes of Sokoto, Nigeria. Raji (1995) and Kparmwang *et al.* (2000) attributed higher values in the lowest horizon to contribution from weathering of Cu- bearing minerals in the parent materials. Soils on MS had higher values of available Cu in their surface horizons compared to the subsoil horizons. The values were lower than those reported in different basaltic soils

of Northern Guinea Savanna of Nigeria by Kparmwang (1993), but were within the range reported by Raji (1995), Yaro (2005) and Yaro *et al*. (2007). Most physical and chemical properties were poorly correlated with available copper, except total nitrogen (r = 0.293*). Yaro *et al.* (2002) reported poor correlation with physicochemical properties in DNPK plots studied at Samaru, Nigeria.

Total copper content varied in the surface horizon from 12.03 to 36.09 (24.06), 36.09 to 48.13 (44.12), 24.06 to 36.09 (32.08) and 24.06 to 39.09 (28.07) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsoil horizons value varied from 12.03 to 36.09 (24.06), 12.03 to 60.16 (29.53), 24.06 to 48.13 (30.08) and 12.03 to 72.19 (31.28) $mgkg^{-1}$. All the soils were rated high in total Cu (Soil Survey Division Staff, 1993). The mean values of total Cu of soils did not indicate any significant variation both between horizons and between parent materials. The mean values of total Cu in the soils decrease in order of QZ > MS > MG > OG (Table 17) and the trend could be attributed to inherent status, but also indicated variation in the postulated order of pedogenic development of the soils (loss in total content indicate advances in soil development). The total content of Cu was similar to those reported by Kparmwang (1993), Raji (1995) and Yaro (2005), and the decreasing pattern was associated to the pedogenic age of the soils.

The distributions of total Cu in most of the profiles of all the soils formed on the different parent materials had irregular distribution pattern. Most physical and chemical properties were not significantly correlated with total Cu as was obtained with the available Cu. However, available cupper was significantly correlated with OC, available Mn and pyrophosphate extractable Mn (r = 0.299*, 0.327*, 0.318*,

respectively), thus indicating some similarity in distribution pattern. Therefore, the amount of total Cu may be influenced by organic matter as it may undergo complexation (Brady and Weil, 2005).

5.5.4 Available and Total Zinc (Zn)

Available zinc (0.1M HCl extractable) content for surface horizon values varied between 5.63 and 7.50 (mean, 6.88), 5.00 and 8.13 (6.88), 5.00 and 7.50 (6.25) and 2.50 and 11.25 (7.71) $mgkg^{-1}$ in the older granites, quartzites, mica schists and migmatite gneisses respectively. The corresponding subsoil horizon values varied between 5.63 and 13.13 (8.60), 3.75 and 14.38 (6.88), 3.75 and 8.75 (5.86) and 2.50 and 17.50 (9.57) $mgkg^{-1}$. All the soils were rated high as the values were greater than $1mgkg^{-1}$ (Cox and Kamprath, 1972; Soil Survey Division Staff, 1993). Mean values of available Zn were not significantly different both between horizons and between the soil parent materials. The soils available Zn decreased in the order of MG > OG > QZ > MS (Table 17). It may be attributed to inherent status of parent material release of more available Zn as the soils advances in their pedogenic development. The distribution of available Zn was irregular in all the soils formed on the different parent materials. Similar trend was reported by Yaro *et al.* (2002) on soils on DNPK long term plot at Samaru, Zaria. The values in these soils were similar to those found in basaltic soils (Kparmwang, 1993), but slightly higher than those reported in ancient sand dunes of north western Nigeria (Raji, 1995) and basement complex rock soils of Bauchi State (Mustapha and Fagam, 2007; Voncir *et al*., 2008).

Most physicochemical properties were poorly correlated with available Zn and similar finding was reported by Yaro (2005). It correlated significantly with exchangeable Mg and K (r = -0.316*, -0.295* respectively), including other exchangeable bases

(poorly negative), indicating that available Zn is a poor competitor with exchangeable bases for adsorption on soil surfaces. Available Mn correlated negatively with available Zn (r = -0.301*) indicating inverse variation in distribution pattern.

Total Zn content varied in surface horizons from 23.44 to 31.25 (28.65), 62.50 (62.50), 31.25 to 46.88 (41.67) and 62.50 to 93.75 (78.13) $mgkg^{-1}$ in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsoil horizons value varied from 31.25 to 78.13 (51.76), 31.25 to 78.13 (53.98), 46.88 to 93.75 (62.50) and 46.88 to 93.75 (59.38) $mgkg^{-1}$. The means of soils for Zn were not significantly different between the horizons, but there was a highly significant difference between the soils. The mean values of soils on MG, MS and QZ were statistically similar, but MG soil was significantly higher than OG soil. The means of MS, QZ and OG were at par. This may be attributed to nature of parent materials rather than horizonation or other pedogenic processes. All the soils formed on the different parent materials were rated high. The values were slightly lower than those obtained in basaltic soils (Kparmwang, 1993), but were within the range reported in older granites in Nigerian savanna (Mosugu, 1989). The distributions of total Zn in OG and MS were noted to be regular with increase in soil depth. Soils on QZ and MG showed irregular distribution pattern with increase in depth.

Physicochemical properties might not have significantly influenced total Cu as there was no significant correlation with total Cu as was obtained with the available Cu. Similar trend was observed on plinthitic soils on landscape in Samaru, Zaria (Yaro, 2005). However, available cupper significantly correlated with OC, available Mn and pyrophosphate extractable Mn (r = 0.299*, 0.327*, 0.318*, respectively), thus

indicating some similarity in their distribution pattern. Havlin *et al*. (2005) reported that organic matter serve as a major contributor to both available and total Zn content in soils as it undergo complexation.

5.6 PEDOGENIC FORMS OF IRON AND MANGANESE OXIDES

The pedogenic forms of iron, manganese and active ratios that were determined in this study are discussed in this section presented in Table 22.

5.6.1 Pedogenic Forms of Iron Oxides

The citrate-bicarbonate-dithionite extractable iron oxide (Fe_d total free iron oxides) content in the surface horizons varied between 0.71 and 0.86 (0.79), 0.57 and 0.59 (0.58), 1.29 and 1.71 (1.43) and 1.29 and 2.00 (1.56) % in the respective surface horizons on older granites, quartzites, mica schists and migmatite gneisses. The values for the underlying horizons varied between 1.43 and 2.86 (2.11), 1.43 and 2.86 (2.09), 1.71 and 2.86 (2.39) and 1.43 and 3.49 (2.52) %. Parent materials significantly influenced Fe_d and mean values of soils on MG and MS were statistically similar and might be attributed to higher amount of ferromagnesian minerals in these soils. Soil on MG was significantly higher than those on QZ and OG, which were at par with MS soils (Table 23). Udo (1980) similarly reported that parent material influenced relative distribution of free iron oxides. Total free iron oxide values for the underlying horizons were observed to be significantly higher than the overlying horizons (Table 24). The significantly higher proportion of total free iron oxide obtained in the subsoil might be associated with co-translocation Fe with clay from surface to subsoil horizon through eluviations - illuviation processes (Blume and Schwertmann, 1969; Juo *et al.,* 1974).

Table 22: Iron and manganese oxides and their active ratios of soils of the studied areas

Pedon	Depth	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/ Fe_d
		<---------- % ---------->								
					Soils on Older Granites					
Pedon OG 1										
Ap	0 - 26	0.714	0.143`	0.343	0.041	0.010	0.012	0.20	0.249	17.09
Bt1	26 - 75	1.429	0.214	0.343	0.041	0.005	0.006	0.15	0.124	29.53
Bt2	75 - 119	1.714	0.429	0.172	0.061	0.005	0.006	0.25	0.084	16.45
BC	119 – 183	1.714	0.357	0.172	0.061	0.015	0.012	0.21	0.250	14.12
Pedon OG 2										
Ap	0 - 17	0.800	0.286	0.257	0.061	0.010	0.018	0.36	0.167	20.25
Bt	17 - 70	1.714	0.286	0.257	0.081	0.005	0.012	0.17	0.063	23.45
Btc	70 - 190	2.857	0.357	0.343	0.122	0.010	0.006	0.13	0.084	8.47
Pedon OG 3										
Ap	0 - 23	0.857	0.286	0.257	0.041	0.005	0.006	0.33	0.124	16.57
Bt	23 - 57	2.286	0.500	0.257	0.081	0.005	0.006	0.22	0.063	14.96
Btc	57 - 121	2.857	0.571	0.343	0.102	0.010	0.012	0.20	0.100	13.37
Btc	128 - 160	2.286	0.429	0.172	0.081	0.005	0.006	0.19	0.063	19.34

Table 22 Contd.: Iron and manganese oxides and their active ratios of soils of the studied areas

Pedon	Depth	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/ Fe_d
		<---------- % ---------->								
					Soils on Quartzites					
Pedon QZ 1										
Ap	0 - 14	0.571	0.214	0.343	0.081	0.010	0.012	0.38	0.126	14.36
AC	14 - 40	0.714	0.286	0.428	0.102	0.005	0.012	0.40	0.050	19.89
C1	40 – 98	1.429	0.429	0.428	0.163	0.015	0.006	0.30	0.094	29.53
C2	98 – 135	2.286	0.500	0.172	0.081	0.010	0.006	0.22	0.126	14.09
Pedon QZ 2										
Ap	0 - 19	0.586	0.214	0.172	0.102	0.015	0.018	0.37	0.150	13.99
Bt1	19 - 51	2.571	0.357	0.086	0.122	0.020	0.024	0.14	0.167	14.08
Bt2	51 – 84	2.000	0.429	0.343	0.081	0.010	0.018	0.22	0.126	23.10
Bt3	84 - 139	1.714	0.357	0.257	0.122	0.010	0.012	0.21	0.084	22.29
Btc	139 –187	2.857	0.429	0.257	0.061	0.010	0.012	0.15	0.167	11.97
Pedon QZ 3										
Ap	0 - 19	0.571	0.214	0.428	0.061	0.010	0.012	0.38	0.167	17.86
AB	19 - 40	2.286	0.357	0.257	0.061	0.031	0.036	0.16	0.502	8.84
Bt1	40 – 63	2.571	0.286	0.257	0.102	0.015	0.018	0.11	0.150	16.41
Bt2	63 – 97	2.000	0.571	0.343	0.081	0.005	0.006	0.29	0.063	23.10
BC	97 - 167	2.571	0.286	0.257	0.061	0.010	0.006	0.17	0.167	14.86

Table 22 Contd.: Iron and manganese oxides and their active ratios of soils of the studied areas

Pedon	Depth	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/ Fe_d
		<---------- % ---------->								
					Soils on Mica Schists					
Pedon MS 1										
Ap	0 - 18	1.286	0.643	0.257	0.041	0.010	0.018	0.50	0.249	12.60
Bt	18 - 54	2.857	0.571	0.514	0.061	0.005	0.012	0.20	0.084	10.57
Btc	54 - 177	2.286	0.429	0.343	0.102	0.015	0.006	0.19	0.15	13.21
Pedon MS 2										
Ap	0 - 16	1.714	0.571	0.343	0.081	0.015	0.018	0.33	0.189	7.12
Bt	16 - 37	2.286	0.429	0.172	0.081	0.010	0.018	0.19	0.126	12.34
BC	37 – 72	2.571	0.571	0.343	0.122	0.015	0.012	0.22	0.126	12.52
C	72 - 143	2.857	0.357	0.343	0.102	0.010	0.012	0.13	0.100	11.52
Pedon MS 3										
Ap	0 - 19	1.286	0.643	0.086	0.061	0.010	0.018	0.50	0.167	7.93
Bt1	19 - 42	1.714	0.571	0.172	0.081	0.015	0.012	0.33	0.189	14.12
Bt2	42 – 96	2.571	0.643	0.428	0.102	0.005	0.006	0.25	0.050	8.63
BC	96 – 168	2.000	0.429	0.343	0.061	0.102	0.012	0.21	0.167	11.10

Table 22 Contd.: Iron and manganese oxides and their active ratios of soils of the studied areas

Pedon	Depth	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/ Fe_d
		<---------- % ---------->								
Soils on Migmatite Gneisses										
Pedon MG 1										
Ap	0 - 15	1.286	0.357	0.428	0.061	0.005	0.018	0.28	0.084	11.59
Bt	15 - 47	2.571	0.429	0.428	0.102	0.010	0.012	0.17	0.100	12.80
Btcv1	47 – 103	3.100	0.286	0.514	0.143	0.005	0.012	0.09	0.036	11.90
Btcv2	103 – 147	2.724	0.286	0.172	0.081	0.010	0.006	0.11	0.126	10.61
Pedon MG 2										
Ap	0 - 18	2.000	0.286	0.257	0.061	0.010	0.024	0.14	0.167	5.45
AB	18 - 44	2.286	0.214	0.172	0.081	0.010	0.018	0.09	0.126	15.27
Bt1	44 – 78	1.429	0.214	0.172	0.102	0.015	0.018	0.15	0.150	30.02
Bt2	78 - 123	3.143	0.214	0.514	0.407	0.015	0.012	0.07	0.038	12.38
BCcv	123 –167	1.714	0.429	0.172	0.102	0.010	0.012	0.25	0.100	16.86
Pedon MG 3										
Ap	0 - 25	1.386	0.214	0.257	0.102	0.005	0.031	0.15	0.050	15.08
Bti	25 - 47	2.000	0.214	0.428	0.061	0.015	0.012	0.11	0.251	17.45
Bt2	47 – 89	3.486	0.286	0.257	0.407	0.026	0.012	0.08	0.063	12.88
BCcv	89 – 162	2.714	0.143	0.343	0.143	0.005	0.006	0.053	0.036	12.12

Table 23: Ranking of means of iron and manganese oxides and their active ratios of parent materials

Parameter	Unit	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
Fe_d	%	1.75b	1.77b	2.13ab	2.30a	0.15	*
Fe_{ox}	%	0.35b	0.36b	0.53a	0.27c	0.03	***
Fe_p	%	0.27	0.29	0.30	0.32	0.46	NS
Mn_d	%	0.070	0.092	0.081	0.143	0.42	NS
Mn_{ox}	%	0.008	0.013	0.011	0.011	0.39	NS
Mn_p	%	0.009	0.014	0.013	0.015	0.46	NS
$Fe_{ox/d}$	-	0.22b	0.25ab	0.28a	0.13c	0.01	**
$Mn_{ox/d}$	-	0.12	0.15	0.15	0.10	0.48	NS
$Clay/Fe_d$	-	17.60a	17.46a	11.06b	14.19b	0.55	*

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Table 24: Ranking of means iron and manganese oxides and their active ratios of horizons

Parameter	Unit	Surface Horizon	Subsurface Horizon	SE±	LOS
Fe_d	%	1.09b	2.27a	0.18	**
Fe_{ox}	%	0.34	0.39	0.03	NS
Fe_p	%	0.29	0.30	0.04	NS
Mn_d	%	0.066b	0.108a	0.02	**
Mn_{ox}	%	0.010	0.011	0.00	NS
Mn_p	%	0.017a	0.012b	0.00	**
$Fe_{ox/d}$	-	0.33a	0.18b	0.02	***
$Mn_{ox/d}$	-	0.16a	0.12b	0.03	*
$Clay/Fe_d$	-	13.32	15.79	0.75	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

The process was triggered by redox process (Fanning and Fanning, 1989). All the soils increased in Fe_d with increase in depth and were irregular in the deeper portion of subsurface horizon. The highest values (3.10 – 3.49 %) were within plinthite horizons (Btcv) of the soils on MG. The values were higher than those reported by Aghimien *et al.* (1988), Maniyunda (1999), Raji et *al.* (2000), Ibia (2002) and Essoka and Esu (2003), but lower than values reported in basaltic soils (Kparmwang, 1993).

Variation in total free oxides for different study areas compared to the present one indicated that moisture regime and drainage condition of soils influenced content of total free iron (Juo *et al.,* 1974; Udo, 1980). Iron oxide (Fe_d) significantly correlated (negatively) with total sand, clay (positively) and all moisture retention parameters (Table 25). This implies that drainage and moisture regime of soils significantly influenced Fe_d formation, translocation and accumulation processes (redox process) (Juo *et al.,* 1974; Udo, 1980; Perkins and Lawrence, 1982; Aghimien *et al.,* 1988). The significantly negative correlation values obtained between Fe_d with organic carbon (r = -0.719***) and total nitrogen (r = -0.458***). This may be a reflection of inhibitory effect of soil organic matter on Fe oxide as reported by Samndi *et al.* (2006).

The oxalate extractable iron oxide (Fe_{ox}) (amorphous form) in the surface horizons varied between 0.14 and 0.27 (0.24), 0.21 (0.21), 0.57 and 0.64 (0.62) and 0.21 and 0.36 (0.29) % in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. In subsurface horizons, the corresponding values varied between 0.21 and 0.576 (0.39), 0.29 and 0.57 (0.40), 0.36 and 0.64 (0.50) and 0.14 and 0.43 (0.27) %.

Table 25: Correlation matrix between physical properties and forms of iron, manganese oxides and their active ratios.

	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/Fe_d
Sand	-0.563**	-0.176	-0.053	-0.338*	0.041	0.319*	0.411**	0.381**	-0.310*
Silt	-0.144	0.267	0.037	-0.169	-0.280	-0.036	0.214	-0.103	-0.184
Clay	0.617***	0.041	0.034	0.398**	0.040	-0.269	-0.533***	-0.359*	0.406*
Si/C	-0.592***	0.026	-0.074	-0.343*	-0.155	0.239	0.544***	0.193	-0.342*
BD	0.013	-0.012	-0.279*	-0.049	-0.002	-0.045	-0.055	0.112	0.005
PD	-0.017	-0.002	-0.136	0.103	-0.059	-0.328*	0.027	-0.216	0.302*
TP	0.020	-0.088	0.091	0.055	0.004	0.049	0.007	-0.109	0.060
FC	0.612***	0.142	0.100	0.334*	-0.038	-0.404**	-0.476***	-0.248	-0.034
PWP	0.517***	0.096	-0.082	0.176	-0.045	-0.390**	-0.403**	-0.188	-0.108
AWC	0.344*	0.062	0.210	0.306*	-0.074	-0.180	0.403**	-0.305*	-0.195
WRD	0.381**	0.031	0.172	0.435**	-0.062	-0.518***	-0.511***	-0.393**	-0.093

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 26: Correlation matrix between chemical properties and forms of iron, manganese oxides and their active ratios.

	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$	Clay/Fe_d
pH(H_2O)	0.054	0.176	-0.035	0.326*	-0.057	-0.004	0.042	-0.238	-0.080
pH($CaCl_2$)	-0.099	0.089	-0.129	0.120	0.072	0.098	0.134	-0.013	-0.038
ΔpH	0.136	0.086	0.077	0.210	-0.099	-0.016	0.012	-0.173	-0.050
Exch. Ca	0.032	0.417**	-0.126	-0.082	0.012	-0.096	0.314*	0.107	0.012
Exch. Mg	0.278	0.443**	-0.125	0.120	0.062	-0.137	0.053	-0.072	0.062
Exch. Na	-0.076	-0.172	0.100	0.032	-0.384**	-0.369**	0.130	-0.273	0.319*
Exch. K	-0.068	0.248	-0.092	0.127	0.060	-0.020	0.233	-0.030	0.202
TEB	0.080	0.421**	-0.124	-0.010	0.011	-0.133	0.281	0.050	0.064
EA	-0.119	-0.195	0.179	-0.055	-0.388**	-0.139	-0.014	-0.298*	0.254
ECEC	0.076	0.397**	-0.122	-0.026	-0.027	-0.118	0.261	0.028	0.071
CEC (OAc)	-0.090	0.055	0.073	0.110	-0.074	-0.176	0.237	-0.155	0.136
CEC Clay	0.461**	-0.136	0.124	-0.092	-0.150	-0.105	0.443**	-0.005	-0.297*
BS (Σ)	0.041	0.361**	-0.278	0.088	0.313*	0.039	0.146	0.202	-0.117
BS	-0.061	0.344*	-0.177	-0.093	0.093	0.110	0.079	0.191	-0.119
ESP	-0.008	-0.163	0.124	-0.149	-0.189	-0.084	-0.116	-0.021	-0.021
EC	-0.349*	-0.226	-0.112	-0.272	-0.131	-0.329*	-0.298*	0.081	0.060

LOS (P): * ≤ 0.05, ** ≤ 0.01

The parent materials significantly influenced variation in Fe_{ox} between the soils (Table 23). The mean value of soils on MS was significantly greater than QZ, OG and MG. Soils on QZ and OG were at par and were significantly greater than MG. This trend indicated a decrease in Fe_{ox} with pedogenic age as higher value was found in soil on MS (pedogenically youngest) and lowest value of amorphous Fe in soil on MG (oldest). This was related to the finding of Yaro (2005) that amorphous Fe was lowest in plinthitic soils compared to non-plinthitic soils on landscape at Samaru, Zaria. The values of Fe_{ox} were generally within range of soils on older granite and basalts reported in Northern Guinea Savanna (Mosugu, 1989; Kparmwang, 1993), but higher than values reported on aeolian materials (Ogunsola *et al*., 1989; Raji, 1995; Maniyunda, 1999; Owonubi *et al*., 2003). Amorphous Fe regularly increased with depth and decreased in the lowest horizon of soils on OG. Content of Fe_{ox} in soils on QZ irregularly increased with depth. Amorphous Fe was irregularly distributed within soils on MS and MG.

Chemical properties such as exchangeable Ca, Mg, total exchangeable bases and ECEC highly significantly correlated with Fe_{ox} (Table 26) indicate probable increase in exchange sites with increase in iron oxide (Fe_{ox}). Agbenin and Tiessen (1995) and Raji *et al*. (2000) attributed the relationship to coating of clay surfaces by Fe oxides. The distribution of Fe_{ox} was inversely proportional to the distribution pattern of total nitrogen ($r = -0.327^*$) in these soils. This implied that different factors influenced their accumulation and distribution in these soils

Sodium pyrophosphate extractable iron oxide (Fe_p) (organo - complexed form) ranged between 0.26 and 0.34 (0.29), 0.17 and 0.43 (0.31), 0.09 and 0.34 (0.23) and 0.26 and 0.43 (0.31) % in the respective surface horizons of older granites, quartzites, mica

schists and migmatite gneisses. The corresponding subsurface horizon values varied between 0.17 and 0.34 (0.26), 0.09 and 0.43 (0.28), 0.17 and 0.51 (0.33) and 0.17 and 0.51 (0.32) %. Both parent materials and horizon did not significantly influenced variation in Fe_p in the soils. The values of Fe_p were higher than the range reported by Raji *et al.* (2000) and Abdourahamane and Yaro (2007), but lower than the range reported in wetland soils in Nigeria (Olaleye *et al.,* 2000). The variation might be due to difference in amount of organic matter generated by vegetations in the different ecological zones of the various studies. The values were within range reported in established forest in Southern Guinea Savanna of Nigeria (Samndi *et al.,* 2006). The soils generally had irregular distribution of their Fe_p in their profiles, whereas MS irregularly increased with depth in the soil profiles. Irregular distribution pattern of Fe_p was also reported by Abdourahamane and Yaro (2007).

Pyrophosphate extractable iron oxide did not correlate significantly with most soil properties as their distribution was irregular in these soil profiles. It only correlated significantly with bulk density (r = -0.279*).

5.6.2 Active Iron and Clay /Dithionite Iron Ratio

Active iron oxide ratio ($Fe_{ox/d}$) in the surface horizons were found to range between 0.20 and 0.36 (0.30), 0.37 and 0.38 (0.37), 0.33 and 0.50 (0.44) and 0.14 and 0.28 (0.19) in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The underlying horizon values varied between 0.13 and 0.25 (0.19), 0.11 and 0.40 (0.21), 0.13 and 0.33 (0.22) and 0.05 and 0.25 (0.12). Active Fe ratio generally decreased with increase in depth of soils. Parent materials significantly influenced crystallization in these soils (Table 23). Crystallization was highest in soils on MG and significantly higher than in soils on OG, QZ and MS. Soils on OG and QZ

were similar, but OG was significantly higher than MS. The variation order in relation to the parent material indicates the direction of pedogenic age of the soils. The mean value of the surface soil was significantly greater than the subsoil ($P < 0.001$) (Table 24). This implied that crystallization of iron oxide is significantly greater in subsurface horizons compared to the surface horizons (Blume and Schwertmann, 1969; Lekwa and Whiteside, 1986). Schwertmann (1969) and Samndi *et al.* (2006) attributed lower proportion of crystallization of Fe oxide in surface soils compared to subsoil to inhibitory effect of soil organic matter on Fe_{ox} crystallization. High proportion of Fe in the subsoils were in the crystalline form as the values were less than or equal to 0.2 reported by Blume and Schwertmann (1969). The values of active iron ratio were less than 0.5 regarded by Alexander (1974) as rating for old age or high degree of weathering, thus indicated that the soils in this study advanced in their pedogenic age which are characteristics of tropical soils.

Active iron correlated significantly and positively with total sand ($r = 0.411^{**}$) and Si/C ($r = 0.544^{***}$) and clay ($r = -0.533^{***}$). Increase in sand and silt weathering to clay increased active Fe co-migration and coating of clay surface, thus increased in Fe crystallization increased in clay. Chemical properties such as exchangeable Ca, CEC clay and EC correlated positively with $Fe_{ox/d}$ ratio; implying that Ca and soluble salts significantly compete with iron oxide for adsorbtion on clay surfaces. Crystallization reduces clay surface area and may have been attributed to reduction in CEC of clay. Organic carbon significantly correlated with $Fe_{ox/d}$ ratio ($r = 0.529^{***}$) indicating that crystallization is inhibited by organic matter through the soil profiles. There was a significant negative correlation ($r = -0.724^{***}$) observed between $Fe_{ox/d}$ with total free iron oxide. This implies that increase in Fe_d significantly contributed to crystallization

in these soils. Inversely, there was a positive significant correlation with amorphous iron (r = 0.408**), therefore indicated that amorphous iron oxide decrease as soils advance in their development (age).

Clay / dithionite iron ratio in the surface horizon varied between 16.57 and 20.25 (17.97), 13.99 and 17.86 (15.40), 7.12 and 12.60 (9.22) and 5.45 and 15.08 (10.71) in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied between 8.47 and 29.53 (17.46), 8.84 and 29.53 (18.01), 8.63 and 14.12 (11.75) and 10.61 and 30.02 (15.23). Clay/ dithionite ratio for soils on QZ and MS were irregularly distributed in their profiles, whereas, clay/ dithionite ratio for soils on OG and MG regularly decreased with depth in some portion of their profiles except for pedon MG 2 which had an irregular distribution. This indicates that with advancement in pedogenic development in these soils, independent migration of clay and Fe_d (QZ and MS) shift towards partial co-migration (OG and MG) (Juo, *et.al.*, 1974). The means of clay/ dithionite Fe ratios of surface and subsoil were not significantly different. This indicates that there partial co migration between clay and iron in these soils and more clay seems to be illuviated into the subsoil than Fe oxide. Parent materials significantly influenced mean values of clay/Fe_d ratio (P: <0.05) (Table 23). The significant correlation between clay/Fe_d ratio with clay, particle and Si/C ratio significantly influence co migration between clay and Fed. Clay/ iron dithionite ratio significantly correlated with exchangeable sodium (Table 25) and might be an indication of similarity in distribution pattern of exchangeable Na and co migration between clay and Fe_d.

5.6.3 Pedogenic Forms of Manganese Oxides

The citrate-bicarbonate-dithionite extractable manganese oxide (Mn_d) (total free oxides) in the surface horizons varied between 0.041 and 0.061 (0.048), 0.061 and 0.102 (0.081), 0.041 and 0.081 (0.061) and 0.061 and 0.0102 (0.075) % in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. In subsurface horizons, the corresponding values varied between 0.041 and 0.122 (0.079), 0.061 and 0.163 (0.094), 0.061 and 0.122 (0.089) and 0.061 and 0.407 (0.163) %. There was no significant difference in the mean values of soils formed in the different parent materials, but mean values ranked in the order of OG < MS < QZ < MG. The lowest mean value observed in OG soil was attributed to coarse particle size (high total sand) materials that caused leaching out and translocation away of Mn_d, as shown by significant negative correlation between sand and Mn_d ($r = -0.338$). The mean value of Mn_d in subsurface horizon was significantly higher than the surface soil (Table 24). The values reported in this study were less than those reported in loess over basement complex soil in subhumid region (Maniyunda, 1999), but higher than those reported in plinthite landscape by Yaro (2005) and on inland valley soils by Essoka and Esu (2003). The variations might be due to difference in parent materials and ecological zones. All the soils increased in Mn_d content with increase in depth of soil, but decreased in the lowest horizon of soils on QZ, MG and MS. The highest value of Mn_d (0.407%) was observed in subsurface horizon of soils on MG. The relative accumulation of Mn_d in the subsurface (Bt) horizons was attributed to eluviation-illuviation processes, and probably related to release of Mn oxides from silicates (Blume and Schwertmann, 1969; Nahon *et al.,* 1989).

The illuviation and accumulation of total free manganese oxide in subsurface horizons might have been significantly influenced by clay content and moisture regime (FC, AWC and WRD) of the soils as indicated by their highly significant positive correlation (Table 25). The significant correlation between clay and Mn_d suggested their co-migration. Nahon *et al.* (1989) and Birnie and Peterson (1991) attributed Mn oxide accumulation to temporary water logging conditions in the oxidizing zones of soil profiles. Increase in soil pH (H_2O) increased Mn_d content of these soils as noted in their significant correlation (r = 0.326*). Dithionite form of iron oxide significantly correlated (r = 0.465**) with Mnd. This may be due to similarity in their distribution pattern. Organic carbon and available Mn distribution within the soil profiles were in opposite direction with Mn_d, hence their significant negative correlation (Table 27).

Oxalate extractable manganese oxide (Mn_{ox}) (amorphous form) in surface horizons varied between 0.005 and 0.010 (0.009), 0.010 and 0.015 (0.012), 0.010 and 0.015 (0.012) and 0.005 and 0.010 (0.006) % in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied between 0.005 and 0.015 (0.008), 0.005 and 0.031 (0.013), 0.005 and 0.015 (0.011) and 0.005 and 0.026 (0.012) %. The mean values had no significant difference both between parent materials and between horizons. All the soils had an irregular distribution pattern, except for pedons 2 and 3 on migmatite gneiss increased with increase in depth but decreased in the lowest horizons. Soils on OG regularly increased with depth and decreased in the lowest horizon. The values were similar to those reported on plinthite landscape by Yaro (2005).

Table 27: Correlation matrix of forms of iron, manganese and their active ratios.

	Fe_d	Fe_{ox}	Fe_p	Mn_d	Mn_{ox}	Mn_p	$Fe_{ox/d}$	$Mn_{ox/d}$
Fe_{ox}	0.223							
Fe_p	0.131	-0.069						
Mn_d	0.465**	-0.184	0.223					
Mn_{ox}	0.185	-0.056	-0.211	0.373**				
Mn_p	-0.151	-0.141	-0.217	-0.072	0.368**			
$Fe_{ox/d}$	-0.724***	0.408**	-0.105	-0.335*	-0.136	0.010		
$Mn_{ox/d}$	-0.213	0.013	-0.251	-0.555**	0.600**	0.404**	0.189	
Clay/ Fe_d	-0.280*	0.175	0.179	-0.038	-0.113	-0.162	0.176	-0.087

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Exchangeable Na and exchange acidity (EA) highly significantly correlated with Mn_{ox} (Table 26) indicating increase in exchange Na and EA increased amorphous iron (Mn_{ox}). The distribution of Mn_{ox} was similar with Mn_d as indicated by the significant correlation (r = 0.373**) in these soils.

Pyrophosphate extractable manganese oxide (Mn_p) in the surface horizons varied between 0.006 and 0.018 (0.012), 0.012 and 0.018 (0.014), 0.018 (0.018) and 0.018 and 0.031 (0.024) % in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. Values of the underlying horizons varied between 0.006 and 0.012 (0.008), 0.006 and 0.036 (0.014), 0.006 and 0.018 (0.011) and 0.006 and 0.018 (0.012) %. The mean values had no significant difference between parent materials (Table 23). Soils on OG, QZ and MS decreased irregularly with increase in soil depth, but decreased regularly in soils on MG. The mean values were significantly higher in the surface soil compared to the subsoil (Table 24) and was attributed to influence of organic matter on Mn_p distribution (r = 0.375*).

Pyrophosphate extractable manganese oxide was similar in distribution pattern with total sand in these soils as they significantly correlated with one another (Table 25). Other physical properties such as particle density, FC, AWC and WRD significantly correlated negatively with Mn_p (Table 25). Similarly, exchangeable Na and EC were also negatively correlated with Mn_p (Table 26). The positive correlation between Mn_P with total nitrogen (Table 26) might be due to their similarity in distribution pattern, and also total nitrogen was significantly contributed from organic matter in the soils. The significant correlation observed with Mn_{ox}, and $Mn_{ox/d}$ (Table 27) indicates that the distribution pattern of Mn_p was similar to that of amorphous form, but differed with the crystalline form. This affirmed the variation between surface and subsoil

values of mica schist soil in both Mn_d and $Mn_{x/d}$. The highly significant correlation between Mn_p with available Mn (r = 0.581***) implied that pyrophosphate extractable Mn might be major source and reservoir for available Mn.

5.6.4 Active Manganese Oxide Ratio

Active manganese oxide ratio ($Mn_{ox/d}$) in the surface horizons were found to range between 0.12 and 0.25 (0.18), 0.13 and 0.17 (0.15), 0.17 and 0.25 (0.20) and 0.05 and 0.17 (0.10) in the respective surface horizons of older granites, quartzites, mica schists and migmatite gneisses. The corresponding subsurface horizon values varied between 0.06 and 0.25 (0.10), 0.05 and 0.50 (0.15), 0.05 and 0.19 (0.12) and 0.04 and 0.25 (0.10). There was no significant variation observed between the soils developed from the different parent materials (Table 23), however, the soils varied in the order of MG > OG > QZ = MS. Active manganese oxide ratios decreased irregularly with increase in depth of soils on OG, MS and MG. Those on QZ had irregular distribution pattern, but highest ratio was found within surface horizons. The irregular decrease in $Mn_{ox/d}$ ratio with increase in depth of soils indicated increase in crystallization process with increase in soil depth as influenced by the longer moisture regime in subsurface horizons compared to surface horizons. Soils on QZ varied irregularly with depth. The mean value of the surface soil is significantly greater than the subsoil (Table 24), hence implied crystallization of manganese oxide was significantly greater in the subsoil compared to the surface soil.

Active manganese oxide ratio correlated significantly with total sand and clay (Table 25), thus implied that increase in sand decrease crystallization and vice versa with clay. Increase in exchange acidity favours crystallization as indicated by their significant correlation (r = -0.298*). The negative significant correlation with Mn_d (r

= -0.555*) indicated that crystallization contribute to total free MnO_2 in soils. There was a highly significant correlation (positive) between Mn_{ox} and Mn_p (Table 27) and indicated similarity in their distribution pattern.

5.7 MINERALOGY OF SOILS

The mineralogy of silt and clay fractions of the surface (Ap) and subsoil (upper and deepest) horizons of the soils developed on the different parent materials are discussed in this section.

5.7.1 Mineralogy of Silt Fraction

The X – ray diffractograms of silt fraction indicated soils developed on older granite were dominated by halloysite (3.67, 3.65, 3.64, 2.24 ´ peaks), followed by gibbsite (4.80, 4.77, 4.74 ´ peaks) and kaolinite (9.02, 8.85 ´ peaks) (Figure 5). Similarly, Eswaran and Heng (1976) reported dominant peak of halloysite in Alfisols and attributed it to transformation in more acidic and leaching condition. Gibbsite accumulation in Bt horizon of soils on OG might be attributed to more weathering process occurring in this horizon. Kaolinite was observed in subsoils of OG and increased with increase in soil depth.

Soils on QZ, MS and MG were dominantly pyrolusite (3.70, 3.69, 3.67 ´ peaks) mineral followed by diaspore (3.99, 3.98 ´ peaks), muscovite (8.84, 4.85, 3.99 ´ peaks) and gibbsite (3.90, 3.69, 3.66 ´ peaks) (Figures 5, 6, 7). Other minerals observed in small to trace amount in silt fraction include, paragonite, montmorillonite and maghemite.

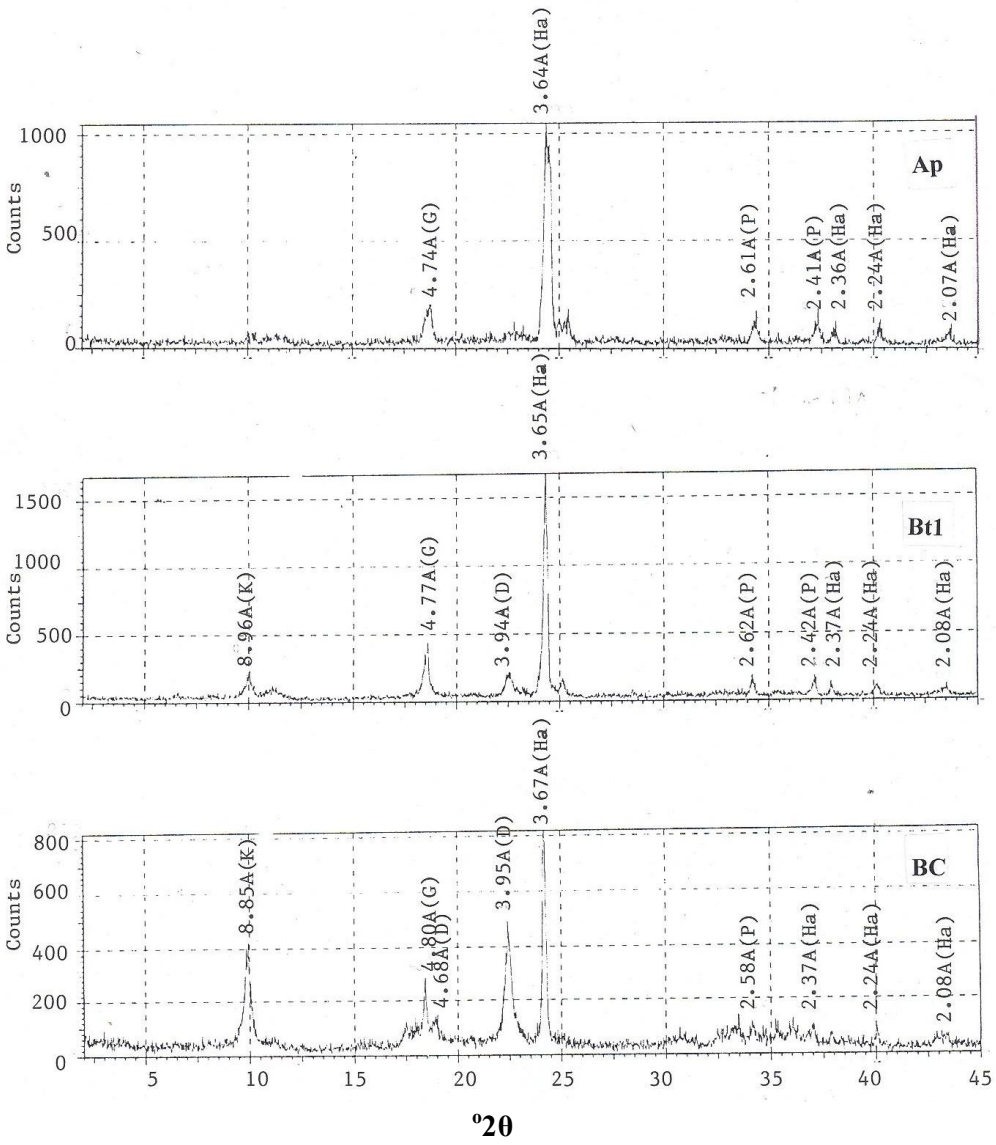


Figure 5. X-ray diffractograms of silt particle of Pedon OG1 showing Ap, Bt1 and BC horizons. Ha = Halloysite, G = Gibbsite, D = Diaspore, K = Kaolinite, P = Paragonite.

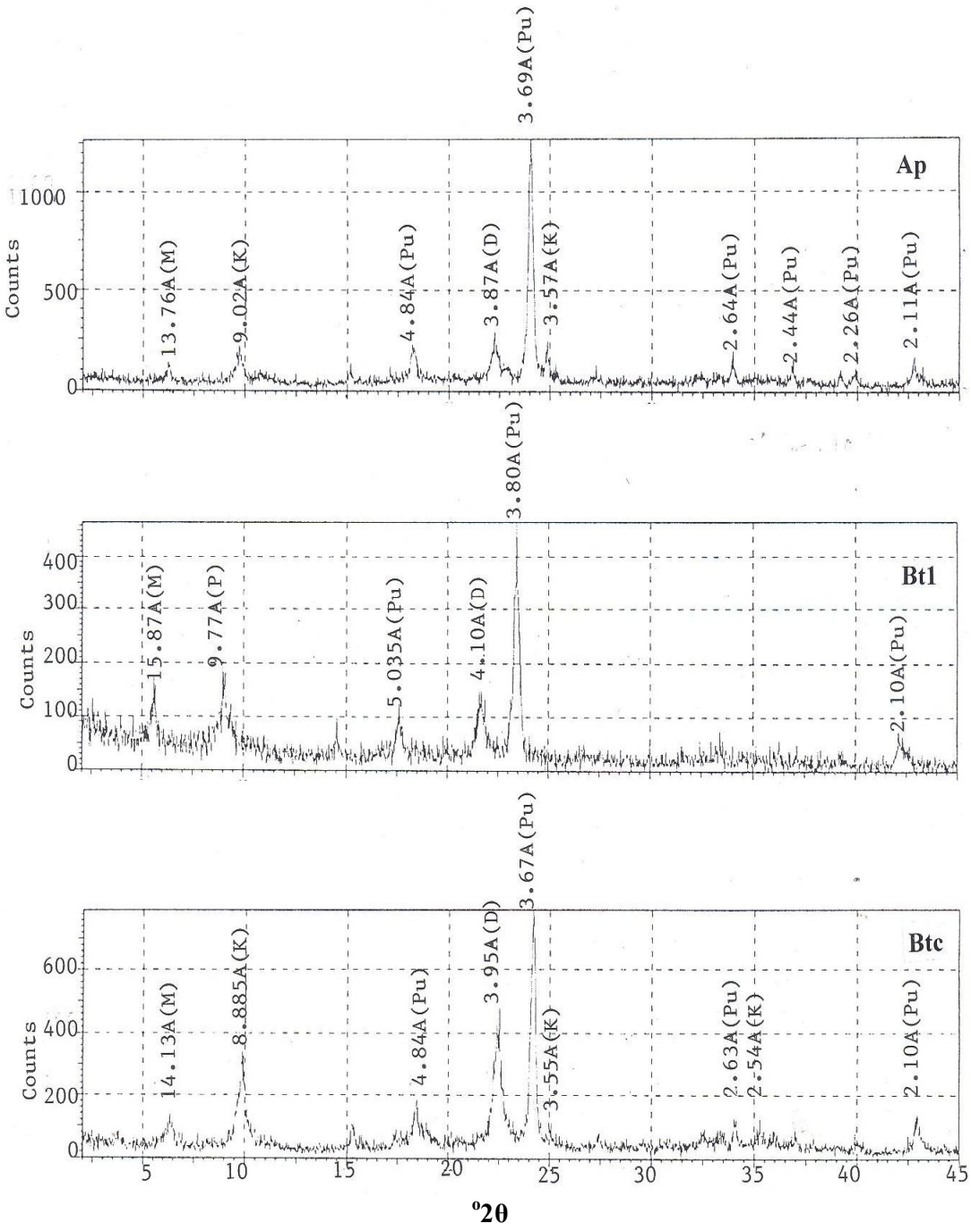


Figure 6. X-ray diffractograms of silt particle of Pedon QZ2 showing Ap, Bt1 and Btc horizons. Pu = Pyrolusite, D = Diaspore, K = Kaolinite, M = Montmorillonite.

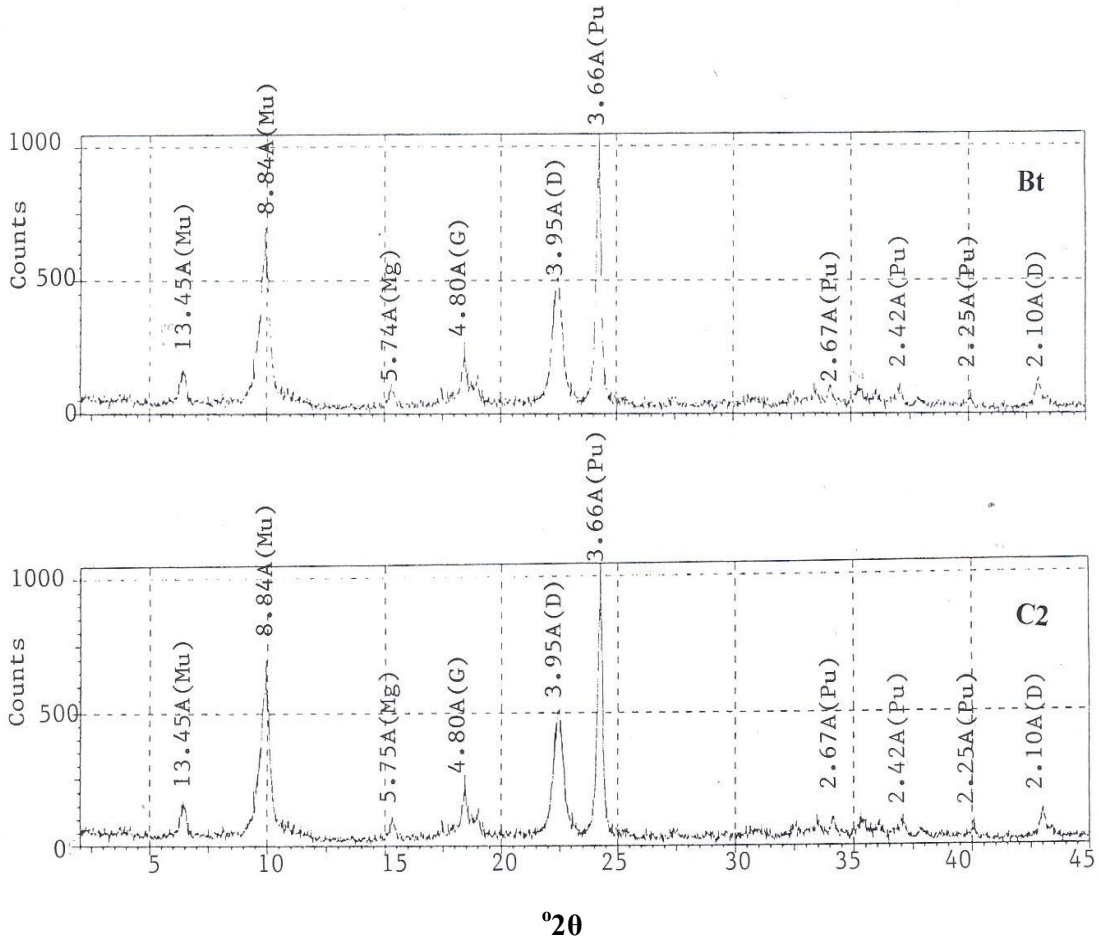


Figure 7. X-ray diffractograms of silt particle of Pedon MS3 showing Ap, Bt and C2 horizons. Pu = Pyrolusite, Mu = Muscovite, D = Diaspore, G = Gibbsite, Mg = Maghemite.

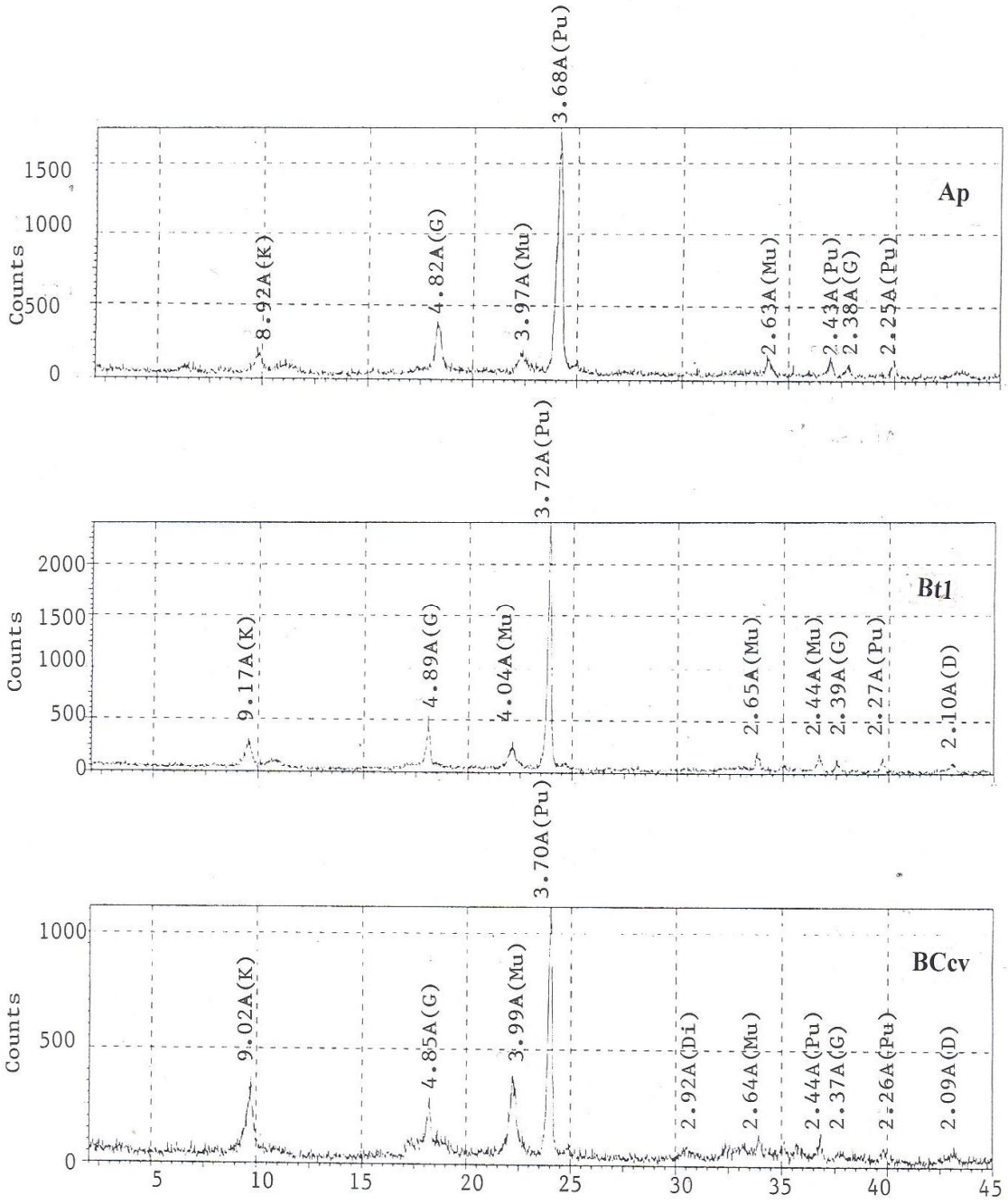


Figure 8. X-ray diffractograms of silt particle of Pedon MG2 showing Ap, Bt1 and BCcv horizons. Pu = Pyrolusite, G = Gibbsite, K = Kaolinite, Mu = Muscovite, D = Diaspore, Di = Dickite.

The soil developed on quartzite was dominated by pyrolusite (5.035, 3.69, 2.76, 2.11 ´ peaks) mineral. The peak intensity of pyrolusite was highest in surface horizon and decreased significantly in the subsoil horizons. Diaspore (4.10, 3.95, 3.87 ´ peaks) and kaolinite (9.02, 8.885 ´ peaks) had similar distribution with higher amount in Ap and Btc horizons than Bt1 horizon, though montmorillonite accumulated more in the Bt1 horizon (Figure 5). This trend might be attributed to variation in drainage conditions within the horizon and accumulation of diaspore and kaolinite as weathering advanced in this soil. Similarly Ojanuga (1979) attributed montmorillonite to poor drainage and kaolinite to well drained soils.

The silt fraction of soils on mica schist had similar intensity of pyrolusite, muscovite diaspore and gibbsite minerals in both Bt and C2 horizons (Figure 6). This indicated that the minerals were product of low weathering of mica schist parent material as little or no change was observed in their profile mineralogy and might be inherited from the parent material. The highest peak of muscovite in silt fraction of the soils of this study was in soils on mica schist and therefore soil on MS was regarded least weathered.

Mineralogy of silt fraction of soil on MG indicated more prominent peaks by pyrolusite and gibbsite minerals and their more accumulation in Bt1 subsoil horizon over Ap and BCcv horizons (Figure 7). This might be attributed to gibbsite, pyrolusite and diaspore formation as a result of pedogenic transformation and more weathering (age) compared to soils on OG, QZ and MS. Mc Kenzie (1982) and Muggler *et al.* (2007) reported that presence of product of weathered minerals such as pyrolusite, gibbsite, kaolinite, and diaspore indicate advanced weathering. Muscovite and

kaolinite minerals increased with increase in depth of soils on MG and indicated that the minerals were inherited from the parent material.

The wide variation in mineralogy of silt fraction of these soils were influenced by differences in parent materials, pedogenic processes and age, as also reported by Marshall (1977), Brady and Weil (2005) and Mella and Mermut (2010) that wide variation in mineralogy of Alfisols were attributed to moderate weathering .

5.7.2 Mineralogy of Clay Fraction

The X – ray diffractograms of clay fraction of the selected pedons (OG1, QZ2, MS3 and MG2) on the various parent materials are shown in Figures 8, 9, 10 and 11.

Clay fraction of soil on OG was dominated by kaolinite prominent sharp peaks (8.92, 8.87, 3.97, 3.95 ´ peaks) followed by small amount of pyrollusite (3.68, 3.67, 2.55, 2.54 ´ peaks) and trace amount of interlayer chlorite-vermiculite (21.90, 13.70 ´ peaks) muscovite and diaspore (Figure 8). Dominance of kaolinite might be as a product of dehydrated halloysite under warm dry condition that was initially weathered into the silt fraction from feldspar (Graham and O'Green, 2010).

Chlorite-vermiculite intergrades detected in both Bt1 and BC horizons indicated that they were inherited from the parent material and might be product of transformation of mica as also reported by Nornberg (1980), and Muggler *et al.* (2007) stated that mica transformation to mixed-layer clay minerals under acid condition may further transform to kaolinite.

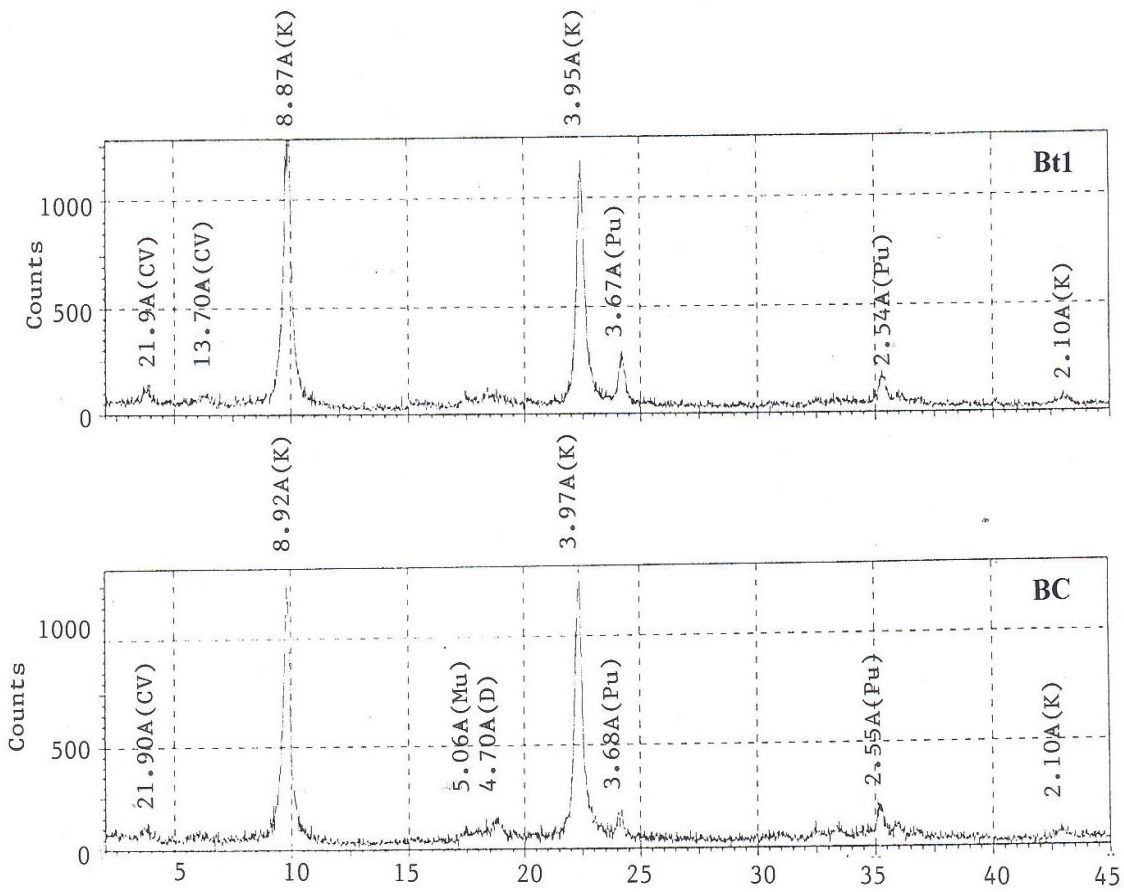


Figure 9. X-ray diffractograms of clay particle of Pedon OG1 showing Ap, Bt1 and BC horizons. K = Kaolinite, Pu = Pyrolusite, CV = Chlorite-Vermiculite, M = Montmorillonite, D = Diaspore.

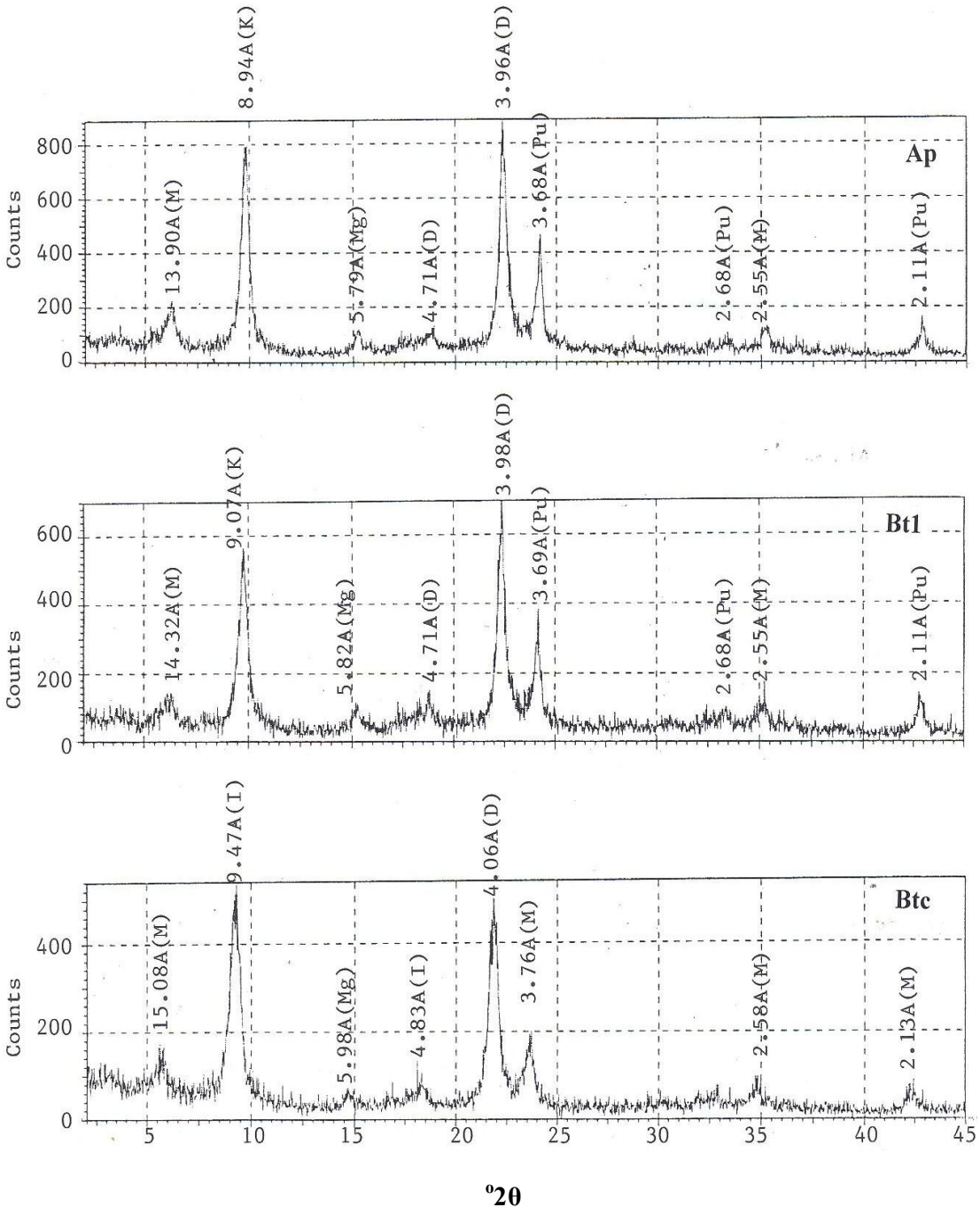


Figure 10. X-ray diffractograms of clay particle of Pedon QZ2 showing Ap, Bt1 and Btc horizons. D = Diaspore, K = Kaolinite, I = Illite, Pu = Pyrolusite, M = Montmorillonite, Mg = Maghemite.

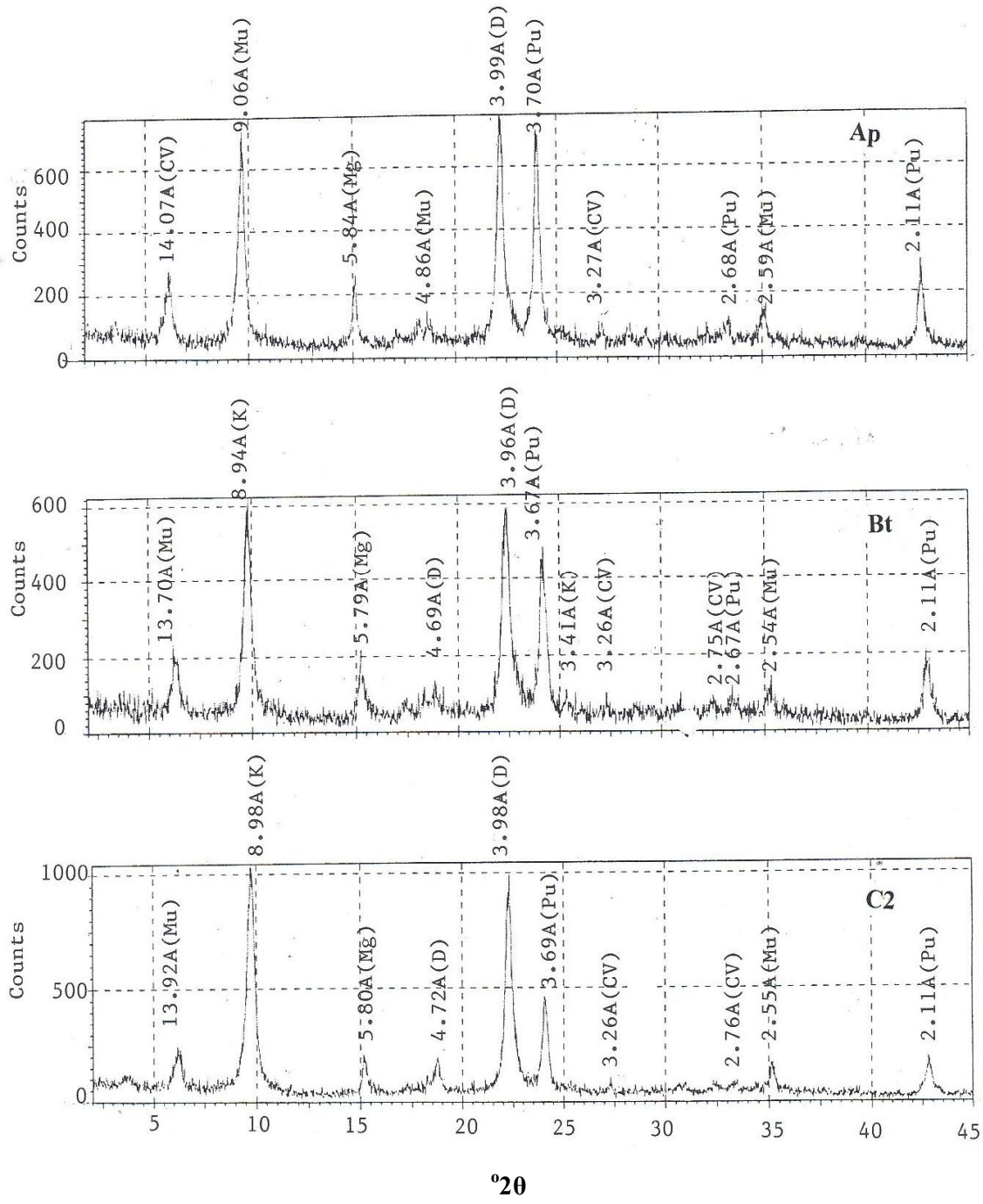


Figure 11. X-ray diffractograms of clay particle of Pedon MS3 showing Ap, Bt and C2 horizons. K = Kaolinite, D = Diaspore, Pu = Pyrolusite, Mu = Muscovite, Mg = Maghemite, CV = Chlorite-Vermiculite.

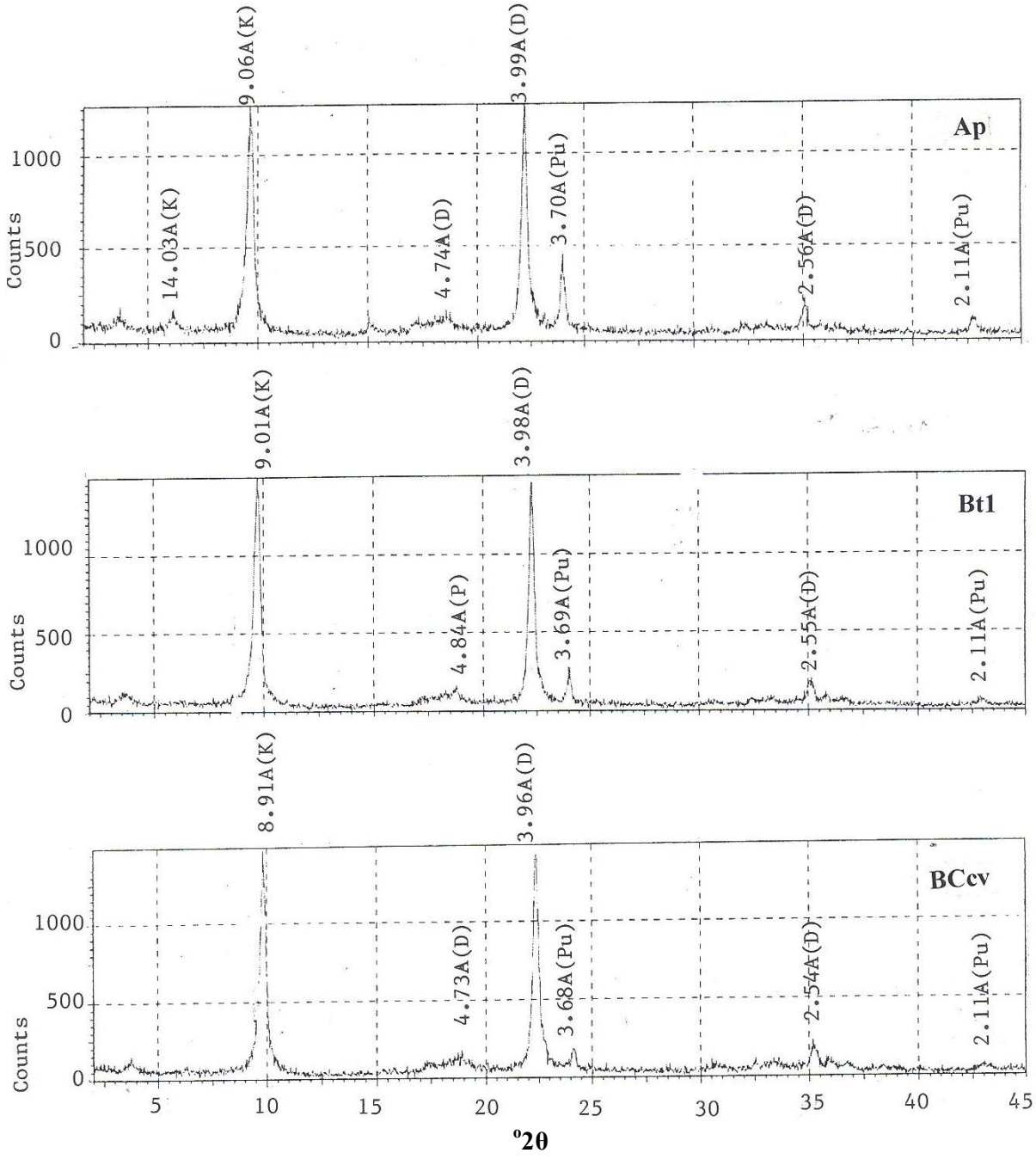


Figure 12. X-ray diffractograms of clay particle of Pedon MG2 showing Ap, Bt1 and BCcv horizons. K = Kaolinite, D = Diaspore, Pu = Pyrolusite, P = Paragonite.

Soils on quartzite were predominantly diaspore (3.98, 3.96 ´ peaks) and kaolinite (9.07, 8.94 ´ peaks) in the surface and upper subsoil horizons. Diaspore (form of gibbsite) and kaolinite were weathered product of feldspars and increased in relative abundance with soil age. These minerals were followed by pyrolusite (3.69, 3.68, 2.11 ´ peaks) and montmorillonite (15.08, 14.32, 13.90 ´ peaks). The lowest subsoil (Btc) horizon was dominated by illite (9.47 ´ peaks) and diaspore (4.06 ´ peaks). Trace amount of maghemite mineral was observed in all the horizons of soils on QZ and might have been product of parent material weathering. The wide variation in mineral composition of these soils influenced their mineralogical classification to be mixed mineralogical class (Wysocki *et al.,* 1988; Soil Survey Staff, 2010).

Soils on mica schist were dominated by muscovite (13.92, 13.7, 9.06 ´ peaks), kaolinite (8.98, 8.94 ´ peaks) and diaspore (3.99, 3.98, 3.96 ´ peaks) (Figure 10). They were followed by pyrolusite (3.70, 3.69, 3.67 ´ peaks) and small to trace amount of maghemite and chlorite-vermiculite. The wide variation in mineral composition of soils on MS suggested that MS soils were the least weathered among soils formed on the different parent materials. Their constant distribution within the profile indicated they were inherited from the parent material (Cook, 1973; Wysocki *et al.*, 1988; Fanning and Keramidas, 1989). Pyrolusite decreased with increase in depth and might be attributed to pedogenic formation as a result weathering and not inherited from parent material.

In soils developed on migmatite gneiss parent material, clay fraction was dominated by diaspore (3.99, 3.98, 3.96, 2.56, 2.55, 2.54 ´ peaks) and kaolinite (9.06, 9.01, 8.91 ´ peaks) with prominent sharp peaks in all the horizons (Figure 11). They were followed by pyrolusite (3.70, 3.69, 3.68 ´ peaks). Diaspore was dominantly present in

all horizons and might have been formed from desilication due to advance weathering stage as reported by Muggler *et al.* (2007). Pyrolusite was high in surface horizon and decreased with increase in soil depth and might be due to more favourable drainage condition (longer oxidation) in Ap horizon promoting crystallization of MnO_2 compared to subsoil (Bt1 and Btcv) horizons. Among them, kaolinite was reported in several highly weathered soils in Nigerian savanna and associated with well drained condition and lowered pH (Ojanuga, 1979; Ezenwa and Esu, 1999; Yaro, 2005). Diaspore minerals dominated clay fraction indicated that soils on MG were the most weathered among soils formed on the different parent materials. The increase in intensity of weathering may be due to increase in acidity of the soils (Marshall, 1977; Nornberg, 1980; Brady and Weil 2005). The increase in intensity of diaspore and kaolinite along with their slight variation in composition of clay fraction in soil on MG may be attributed to advance weathering state (Mella and Mermut, 2010). Soils on MG, therefore were regarded the most weathered among the soils in this study. Soils on MG were considered most weathered as were dominated by diaspore and kaolinite followed by pyrolusite, and may be attributed to acidic condition and leaching of exchangeable bases favouring kaolinization and accumulation of sesquioxides. Soils on QZ were dominantly diaspore followed by kaolinite and illite and were considered to be more weathered compared to soils on OG (predominantly kaolinite). Hence order of weathering of minerals in soils of this study were in the order of MG > QZ > OG > MS.

5.8 TOTAL ELEMENTAL OXIDES AND RELATIVE WEATHERING INTENSITY

The total elemental oxides of the representative soils formed on the various parent materials that were determined in this study are discussed in this section and their percentage composition are presented in Table 28. The relative intensity of weathering of these total elemental oxides indicating their retention (gain /loss) is presented in Table 29.

5.8.1 Major Elemental Oxides

The contents of major elements (total oxide form) from X - ray fluorescence indicated SiO_2 dominated the soils (ranged between 46.1 and 78.7%) followed by Fe_2O_3 and Al_2O_3 (5.20 to 22.85% and 7.60 to 22.00% respectively). Calcium oxide, K_2O, MnO and TiO_2 were all less than 5.20% (Table 28). Differences in basement complex parent material did not significantly vary most major elemental oxides of the soils, except for K_2O and TiO_2 (Table 30). Mean values of K_2O in soils on MS and QZ were statistically at par and significantly higher than soils on OG and MG which were at par. The mean content of TiO_2 of soils developed on MG, OG and QZ were at par, but MG was significantly higher in TiO_2 than MS. However, soils on MS were at par with OG and QZ in mean content of TiO_2. Pedogenic age was considered to have contributed to variation in leaching of K_2O and accumulation of TiO_2. Hence, these soils exposure to pedogenic processes may be ranked in order of MS < OG $\simeq$ QZ < MG.

Table 28: Percentage total element oxides of soils studied.

Pedon	Depth (cm)	SiO_2	Al_2O_3	CaO	K_2O	TiO_2	Fe_2O_3	MnO	Rb_2O	SrO	BaO	ZrO_2	V_2O_3	Cr_2O_5	ZnO
Soils on Older Granites:			Pedon OG 1												
Ap	0 - 26	72.2	8.90	0.47	1.14	2.02	5.60	0.06	0.00	trace	0.06	0.89	0.10	trace	trace
Bt1	26 - 75	54.4	20.0	0.37	1.01	2.25	20.40	0.07	0.00	trace	0.18	0.72	0.10	0.02	0.020
Bt2	75 - 119	49.4	18.0	0.31	0.70	2.04	21.99	0.10	0.00	trace	0.19	0.76	0.10	0.03	0.010
BC	119 – 183	48.6	20.0	0.31	0.58	2.08	21.17	0.03	0.00	trace	0.18	1.10	0.01	0.03	0.000
P. Rock		54.4	10.0	4.49	7.73	2.38	14.70	0.13	0.00	0.06	0.01	0.10	0.10	trace	trace
Soils on Quartzites:			Pedon QZ 2												
Ap	0 - 19	75.2	9.40	0.55	2.72	1.57	9.57	0.16	0.02	0.02	0.21	0.63	0.07	0.03	trace
Bt1	19 - 51	53.7	19.0	0.37	2.26	2.12	17.33	0.09	trace	trace	0.18	0.39	0.10	0.02	0.02
Bt2	51 – 84	45.3	22.0	0.33	2.07	2.39	22.22	0.07	0.06	0.02	0.20	0.46	0.12	0.03	0.03
Bt3	84 - 139	46.1	22.0	0.33	2.10	2.25	21.44	0.06	0.10	trace	0.20	1.00	0.12	0.03	0.06
Btc	139 –187	46.1	22.0	0.33	2.20	2.35	22.85	0.09	0.02	0.01	0.23	0.20	0.10	0.03	0.01
P. Rock		91.8	2.40	0.19	0.13	0.01	4.120	0.01	trace	trace	trace	trace	trace	trace	trace
Soils on Mica Schists:			Pedon MS 3												
Ap	0 - 19	78.7	8.92	0.57	2.01	1.70	5.20	0.09	trace	0.02	0.14	0.30	0.06	0.03	0.01
Bt1	19 - 42	58.6	17.0	0.40	3.43	1.78	14.30	1.00	0.06	trace	0.17	0.47	0.10	0.04	0.01
Bt2	42 – 96	49.6	16.0	trace	5.10	1.99	18.70	0.05	0.07	0.03	0.35	0.41	0.20	0.04	trace
BC	96 – 168	55.2	18.0	trace	2.37	1.89	17.65	0.04	0.19	0.14	0.17	3.00	0.20	0.07	0.06
P. Rock		43.3	19.1	0.001	12.7	2.25	14.69	0.11	trace	0.09	trace	0.37	0.01	0.04	trace
Soils on Migmatite Gneisses:			Pedon MG 2												
Ap	0 - 18	72.3	7.60	1.97	0.77	2.24	7.04	0.10	0.02	0.04	0.25	1.00	0.07	0.03	0.07
AB	18 - 44	54.1	18.0	0.44	0.52	2.21	16.00	0.03	trace	trace	0.10	0.73	0.08	0.04	0.02
Bt1	44 – 78	51.0	18.0	0.39	0.55	2.48	17.70	0.01	trace	trace	0.10	0.82	0.11	0.03	trace
Bt2	78 - 123	54.3	18.0	0.35	0.55	2.46	16.00	0.01	0.16	trace	0.06	0.79	0.30	0.04	0.10
BCcv	123 –167	48.9	19.0	0.28	0.42	2.07	22.28	0.03	trace	trace	0.17	0.73	0.10	0.04	0.01
P. Rock		65.0	16.1	4.29	2.68	0.43	5.35	0.07	0.21	0.01	0.08	0.02	0.04	0.02	trace

Table 28 Contd.: Percentage total element oxides of soils studied.

Pedon	Depth (cm)	CuO	MoO_3	PbO	NiO	Ga_2O_5	Y_2O_5
Soils on Older Granites:			Pedon OG 1				
Ap	0 - 26	trace	trace	trace	trace	trace	trace
Bt1	26 - 75	0.03	trace	trace	0.02	0.01	trace
Bt2	75 - 119	0.04	6.80	0.02	0.03	0.02	trace
BC	119 – 183	0.04	trace	trace	0.02	0.02	trace
P. Rock		trace	trace	0.01	0.01	0.01	trace
Soils on Quartzites:			Pedon QZ 2				
Ap	0 - 19	0.02	0.00	0.01	0.02	0.01	0.04
Bt1	19 - 51	0.02	0.00	0.01	0.03	0.01	0.00
Bt2	51 – 84	0.05	0.00	0.02	0.02	0.02	0.05
Bt3	84 - 139	0.06	0.00	0.00	0.05	0.02	0.10
Btc	139 –187	0.02	0.00	0.01	0.02	0.01	0.02
P. Rock		trace	0.00	trace	0.01	trace	trace
Soils on Mica Schists:			Pedon MS 3				
Ap	0 - 19	0.02	trace	0.01	0.01	trace	0.01
Bt1	19 - 42	0.02	5.40	0.02	0.02	0.01	trace
Bt2	42 – 96	0.04	trace	0.02	0.04	trace	0.03
BC	96 – 168	0.03	trace	0.10	0.20	0.07	0.17
P. Rock		trace	trace	0.02	0.39	0.02	0.02
Soils on Migmatite Gneisses:			Pedon MG 2				
Ap	0 - 18	0.03	0.00	0.04	0.04	trace	trace
AB	18 - 44	0.04	0.00	0.01	0.04	0.01	trace
Bt1	44 – 78	0.04	0.00	0.02	0.03	trace	trace
Bt2	78 - 123	0.04	0.00	0.10	0.28	0.01	0.30
BCcv	123 –167	0.04	0.00	0.02	0.03	0.01	trace
P. Rock		trace	0.00	0.01	0.01	0.01	0.00

Table 29: Relative retention (Gain/Loss) of total element oxides of soils studied.

Pedon	Depth (cm)	SiO_2	Al_2O_3	CaO	K_2O	Fe_2O_3	MnO	Rb_2O	SrO	BaO	ZrO_2
Soils on Older Granites:			Pedon OG 1								
Ap	0 - 26	1.564	1.049	0.123	0.174	0.449	0.562	0	0.002	7.07	10.49
Bt1	26 - 75	1.058	2.116	0.087	0.138	1.468	0.570	0	0.002	19.04	7.62
Bt2	75 - 119	1.066	2.100	0.081	0.106	1.745	0.897	0	0.002	22.17	8.87
BC	119 – 183	1.022	2.288	0.079	0.086	1.648	0.264	0	0.002	20.60	12.59
Soils on Quartzites:			Pedon QZ 2								
Ap	0 - 19	0.005	0.025	0.018	0.133	0.015	0.255	1.529	1.091	13.38	40.38
Bt1	19 - 51	0.003	0.037	0.009	0.082	0.020	0.103	0.005	0.005	8.49	18.30
Bt2	51 – 84	0.002	0.038	0.007	0.067	0.023	0.074	2.510	0.711	8.37	19.29
Bt3	84 - 139	0.002	0.041	0.008	0.072	0.023	0.070	4.356	0.004	8.89	44.44
Btc	139 –187	0.002	0.036	0.007	0.072	0.024	0.100	0.851	0.277	9.79	8.51
Soils on Mica Schists:			Pedon MS 3								
Ap	0 - 19	2.406	0.618	754.4	0.209	0.469	1.023	1.32	0.225	1852.94	1.11
Bt1	19 - 42	1.711	1.125	505.6	0.341	1.230	1.149	733.15	0.001	2148.88	1.61
Bt2	42 – 96	1.295	0.947	0.113	0.454	1.440	0.493	757.54	0.385	3957.29	1.25
BC	96 – 168	1.518	1.122	0.119	0.222	1.430	0.476	2261.91	1.773	2023.81	6.44
Soils on Migmatite Gneisses:			Pedon MG 2								
Ap	0 - 18	0.214	0.091	0.088	0.055	0.253	0.266	0.019	0.960	0.60	12.0
AB	18 - 44	0.162	0.218	0.020	0.038	0.582	0.083	0.0001	0.003	0.24	8.88
Bt1	44 – 78	0.136	0.194	0.016	0.036	0.574	0.025	0.0001	0.003	0.22	8.89
Bt2	78 - 123	0.146	0.195	0.014	0.036	0.523	0.025	0.1330	0.003	0.13	8.63
BCcv	123 –167	0.156	0.245	0.014	0.033	0.865	0.089	0.0001	0.003	0.44	9.48

Table 29 Contd.: Relative retention (Gain/Loss) of total element oxides of soils studied.

Pedon	Depth (cm)	V_2O_3	Cr_2O_5	ZnO	CuO	MoO_3	PbO	NiO	Ga_2O_5	Y_2O_5
Soils on Older Granites:			Pedon OG 1							
Ap	0 - 26	1.15	1.18	1.18	1.18	1.18	0.01	0.02	0.022	0.131
Bt1	26 - 75	1.08	253.87	211.56	359.64	1.06	0.01	2.12	1.322	0.118
Bt2	75 - 119	1.19	396.67	116.67	466.67	79333	2.33	3.50	2.917	0.130
BC	119 – 183	1.07	331.83	1.14	400.48	1.14	0.01	2.29	2.861	0.127
Soils on Quartzites:			Pedon QZ 2							
Ap	0 - 19	4.46	1.59	0.01	1.08	0	0.38	0.02	0.382	0.093
Bt1	19 - 51	4.72	0.85	1.13	0.99	0	0.43	0.02	0.519	0.002
Bt2	51 – 84	5.02	1.13	1.42	2.01	0	0.84	0.01	0.795	0.068
Bt3	84 - 139	5.33	1.20	2.76	2.76	0	0.01	0.03	0.889	0.148
Btc	139 –187	4.26	1.28	0.47	0.81	0	0.43	0.01	0.255	0.028
Soils on Mica Schists:			Pedon MS 3							
Ap	0 - 19	6.11	1.04	66.18	277.94	1.324	0.33	0.03	0.001	0.806
Bt1	19 - 42	9.72	1.23	126.40	303.37	68258.43	1.26	0.06	0.053	0.005
Bt2	42 – 96	17.40	1.35	1.13	429.65	1.13	1.13	0.12	0.001	1.475
BC	96 – 168	18.32	2.35	714.29	380.95	1.19	5.95	0.61	0.347	8.800
Soils on Migmatite Gneisses:			Pedon MG 2							
Ap	0 - 18	0.34	0.29	138.21	59.51	0	0.75	0.77	0.004	0.006
AB	18 - 44	0.39	0.39	38.91	68.10	0	0.12	0.78	0.389	0.006
Bt1	44 – 78	0.48	0.28	0.17	67.62	0	0.32	0.52	0.003	0.006
Bt2	78 - 123	1.31	0.34	174.80	66.42	0	1.59	4.89	0.489	17.48
BCcv	123 –167	0.52	0.41	20.77	87.25	0	0.43	0.62	0.415	0.007

Table 30: Ranking of mean percent (%) of total element oxides of parent materials

Element oxide	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
SiO_2	56.23	53.28	60.53	56.12	2.38	NS
Al_2O_3	16.73	18.48	14.98	16.12	0.74	NS
CaO	0.37	0.38	0.24	0.69	0.75	NS
K_2O	0.86b	2.27a	3.23a	0.56b	0.42	**
TiO_2	2.10ab	2.14ab	1.84b	2.29a	0.10	*
Fe_2O_3	17.29	18.68	13.96	15.80	1.60	NS
MnO	0.066	0.095	0.069	0.035	0.16	NS
Rb_2O	0.000	0.040	0.079	0.036	0.04	NS
SrO	0.000	0.008	0.047	0.007	0.02	NS
BaO	0.153	0.204	0.208	0.136	0.04	NS
ZrO_2	0.87	0.54	0.80	0.81	0.31	NS
V_2O_5	0.097	0.102	0.140	0.132	0.42	NS
Cr_2O_5	0.022b	0.025b	0.046a	0.038ab	0.01	*
ZnO	0.008	0.026	0.019	0.040	0.02	NS
CuO	0.027	0.033	0.029	0.037	0.00	NS
MoO_3	1.70	0.000	1.35	0.000	1.50	NS
PbO	0.005	0.009	0.036	0.039	0.02	NS
NiO	0.018	0.028	0.068	0.084	0.05	NS
Ga_2O_5	0.013	0.012	0.020	0.007	0.01	NS
Y_2O_5	0.000	0.043	0.054	0.060	0.06	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Distribution of silicon oxide, CaO, MnO and K_2O decreased irregularly with soil depth and might be attributed to desillication of SiO_2 in the subsoil horizons, and biocycling and leaching of these oxides (CaO, MnO and K_2O) in these soils. Silicon oxide significantly correlated with calcium oxide (r = 0.541*) and manganese oxide (r = 0.474*), thus affirming similarity in their distribution pattern. Titanium oxide content was fairly constant with increase in depth of soils and was reflected in its not significant correlation with most elements (Table 31). Aluminum oxide and Fe_2O_3 contents were similar in distribution pattern and were significantly and positively correlated (r = 0.937***). Their contents increased irregularly with increase in soil depth and sharp increase was noted between surface and subsoils. The significant increase in the subsoil horizons of Al_2O_3 and Fe_2O_3 might be attributed to their illuviation.

Examination of relative weathering intensity indicated that difference in parent materials significantly influenced relative retention of all major element oxides (Table 32). Relative depletion of major element oxides was more pronounced in soils on MG and QZ compared to OG and MS soils and may be attributed to inherent nature of the parent materials and their exposure to pedogenic processes. Potassium oxide and MnO were relatively depleted in all the soils, whereas, SiO_2, Al_2O_3, CaO and Fe_2O_3 were relatively depleted but with accumulation in MS (SiO_2, CaO and Fe_2O_3) and OG (SiO_2, Al_2O_3, and Fe_2O_3) (Table 32).

Table 31: Correlation matrix for total element oxides of soils studied.

	SiO_2	Al_2O_3	CaO	K_2O	TiO_2	Fe_2O_3	MnO	Rb_2O	SrO	BaO
SiO_2	-									
Al_2O_3	-0.0.946***	-								
CaO	0.541*	-0.596**	-							
K_2O	0.023	-0.058	-0.062	-						
TiO_2	-0.593**	0.528*	-0.080	-0.473*	-					
Fe_2O_3	-0.961***	0.937***	-0.771***	-0.134	0.474*	-				
MnO	0.474*	-0.424	0.338	0.562*	-0.566*	-0.324	-			
Rb_2O	-0.184	0.217	-0.283	0.515*	0.062	0.125	-0.240	-		
SrO	0.097	-0.106	-0.035	0.495*	-0.260	-0.077	-0.025	0.507	-	
BaO	-0.186	0.047	-0.223	0.494*	-0.183	0.260	0.397	0.294	0.520*	-
ZrO_2	-0.019	0.031	-0.126	-0.387	-0.021	0.130	-0.327	0.130	-0.126	-0.190
V_2O_5	-0.332	0.288	-0.682**	0.162	0.301	0.238	-0.504*	0.612**	0.014	-0.080
Cr_2O_5	-0.288	0.259	-0.420	-0.145	-0.051	0.297	-0.331	0.344	0.205	0.177
ZnO	-0.073	0.113	-0.048	-0.080	0.410	0.007	-0.218	0.470*	0.124	-0.131
CuO	-0.659	0.642**	-0.557*	-0.400	0.453	0.648**	-0.398	0.176	-0.190	0.213
MoO_3	-0.091	0.070	-0.067	0.115	-0.255	0.126	0.320	-0.052	-0.271	0.035
PbO	-0.048	0.029	-0.281	-0.071	0.153	-0.001	-0.331	0.454	0.363	-0.165
NiO	-0.127	0.157	-0.348	-0.146	0.222	0.072	-0.424	0.508*	0.075	-0.289
Ga_2O_5	-0.300	0.386	-0.582*	-0.046	-0.089	0.342	-0.167	0.280	-0.199	-0.035
Y_2O_5	-0.114	0.169	-0.283	0.457	0.207	0.067	-0.319	0.793***	0.464	-0.258

LOS (P): * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Table 31 Contd.: Correlation matrix for total element oxides of soils studied.

	ZrO_2	V_2O_3	Cr_2O_5	ZnO	CuO	MoO_3	PbO	NiO	Ga_2O_5	Y_2O_5
ZrO_2	-									
V_2O_5	0.109	-								
Cr_2O_5	0.158	0.372	-							
ZnO	0.172	0.344	0.339	-						
CuO	0.271	0.597*	0.398	0.254	-					
MoO_3	-0.059	0.000	0.059	-0.103	0.024	-				
PbO	0.098	0.460	0.695**	0.389	0.144	0.173	-			
NiO	0.450	0.541	0.594**	0.574*	0.212	-0.078	0.557*	-		
Ga_2O_5	0.355	0.410	0.660**	0.457	0.264	0.238	0.087	0.375	-	
Y_2O_5	-0.106	0.543*	0.441	0.408	0.255	-0.327	0.221	0.350	0.309	-

LOS (P): * ≤ 0.05, ** ≤ 0.01

Table 32: Ranking of mean of relative retention (Gain/Loss) of total element oxides of parent materials

Element oxide	Older Granites	Quartzite	Mica Schist	Migmatite Gneiss	SE±	LOS
SiO_2	1.455a	0.003d	1.312b	0.162c	0.06	***
Al_2O_3	1.888a	0.035d	0.813b	0.188c	0.04	***
CaO	0.915b	0.010b	315.11a	0.030b	87.56	**
K_2O	0.126b	0.085bc	0.307a	0.040c	0.04	**
Fe_2O_3	1.327a	0.021c	1.142a	0.559b	0.08	***
MnO	0.573a	0.120b	0.785a	0.098b	0.15	**
Rb_2O	0.000b	1.850a	938.48a	0.031b	262.60	***
SrO	0.002	0.403	0.596	0.194	0.31	NS
BaO	17.22b	9.78b	2495.73a	0.326b	324.60	***
ZrO_2	9.89b	26.19a	2.60b	9.57b	5.75	**
V_2O_5	1.13b	4.76b	12.89a	0.606b	1.65	**
Cr_2O_5	245.88a	1.21b	1.49b	0.342b	21.45	***
ZnO	82.64	1.157	227.00	74.57	122.03	NS
CuO	306.99a	1.529b	347.98a	69.78b	25.32	***
MoO_3	19834.18a	0.000b	17065.52a	0.000b	0.00	***
PbO	0.59	0.42	2.17	0.64	0.96	NS
NiO	1.178a	0.019c	0.206b	1.517a	0.82	NS
Ga_2O_5	1.78a	0.57ab	0.10c	0.26bc	0.31	*
Y_2O_5	0.13	0.07	2.77	3.50	3.51	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001

Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

Silicon oxide correlated negatively with most elements in these soils (Table 31), though not significantly correlated. The significant negative correlation with aluminum oxide, titanium oxide, iron oxide, and copper oxide indicate that SiO_2 decreased relative to increase of these elements in these soils. Caspari *et al.* (2006) reported on metamorphic soils that were largely illitic that with decrease in SiO_2, Al_2O_3 and Fe_2O_3 increased in the soils. Aluminum oxide was noted to significantly correlate positively with iron, titanium and copper oxides (r = 0.937***, 0.528* and 0.662** respectively) and may be associated with similarity in their distribution pattern. As soils advance in their development, Al_2O_3 and Fe_2O_3 have been reported to be transported and accumulate within the subsoil horizons (allitization and ferritization respectively) (Mohr *et al.,* 1972; Buol *et al.,* 1980; Fanning and Fanning, 1989). Allitization (Al_2O_3 enrichment) ferritization (Fe_2O_3 enrichment) and desillication (SiO_2 depletion) processes occur in soils simultaneously (Jackson, 1965; Mohr *et al.,* 1972; Buol *et al.,* 1980), thus reflected the significant negative correlation between Al_2O_3, Fe_2O_3 with SiO_2 (Table 31).

Relative intensity of weathering of SiO_2, Al_2O_3 and Fe_2O_3 showed that soils on OG and MS were relatively enriched, whereas QZ and MG soils were relatively depleted (Table 29 and 32). Kendrick and Graham (2004) attributed SiO_2, enrichment (accumulation) in soil to increase in silication. The present study found that SiO_2, Al_2O_3 and Fe_2O_3 relative enrichment (OG and MS soils) in soils depended more on initial weathering of parent material and with advancement in pedogenesis relative depletion dominated the soils (QZ and MG). Similarly, Thanachit *et al*. (2006) attributed early geochemical differentiation to parent material composition and chemical composition of matured soils to weathering environment. On Comparing the

relative intensity of weathering statistically, older granite soil was significantly more pronounce in relative accumulation of SiO_2 compared to all other soils (MS, MG and QZ). All the soils differed significantly from each other in the intensity of their relative weathering of SiO_2, Al_2O_3 and Fe_2O_3 in the sequence of OG > MS > MG > QZ (Table 32). Difference in horizons were found to significantly influenced relative retention of major elements (SiO_2, Al_2O_3 and Fe_2O_3) indicating significant desilication, allitization and ferritization in subsoils than surface horizons (Table 33).

The whole trend of relative weathering intensity indicated by mean relative retention of major element oxides in the soils were ranked in the following sequence:

Soils on Older granite	$Al_2O_3 > SiO_2 > Fe_2O_3 > CaO > MnO > K_2O$
Soils on Quartzite	$MnO > K_2O > Al_2O_3 > Fe_2O_3 > CaO > SiO_2$
Soils on Mica schist	$CaO > SiO_2 > Fe_2O_3 > Al_2O_3 > MnO > K_2O$
Soils on Migmatite gneiss	$Fe_2O_3 > Al_2O_3 > SiO_2 > MnO > K_2O > CaO$

The trend of major element oxides showed that relative retention of elements was similar between soils on OG and MS, except that there was an interchange of position in the sequence between Al_2O_3 and CaO. Calcium oxide was most relatively retained element in MS and imply that less weathering and leaching occurred in this soil, as calcium have been reported to be most sensitive to weathering and leaching and was used as indicator of pedogenic age (Beavers *et al*., 1963; Jones and Beavers, 1966), thus indicate that MS soil was the youngest in pedogenic development. Following position of CaO in sequence of soils in the various parent materials, order of pedogenic development of the soils is MS < OG < QZ < MG. The relative retention sequence for soils on MG indicated dominance of Fe_2O_3, Al_2O_3 and SiO_2, also indicated soils on MG to be the most weathered among all the soils.

Table 33: Ranking of mean of relative retention (Gain/Loss) of total element oxides of parent materials

Parameter	Surface Horizon	Subsurface Horizon	SE±	LOS
SiO_2	1.047a	0.591b	0.38	***
Al_2O_3	0.446b	0.764a	0.24	***
CaO	188.56	36.16	112.34	NS
K_2O	0.143	0.127	0.03	NS
Fe_2O_3	0.297b	0.828a	0.14	***
MnO	0.527	0.316	0.13	NS
Rb_2O	0.72b	268.60a	84.71	**
SrO	0.552	0.227	1.94	NS
BaO	468.50	587.74	394.57	NS
ZrO_2	16.00	11.77	5.66	NS
V_2O_5	3.01	5.39	1.47	NS
Cr_2O_5	1.025	71.03	19.08	**
ZnO	51.39	100.83	41.94	NS
CuO	84.93	188.34	57.87	***
MoO_3	1.25b	244599.38a	3592.94	**
PbO	0.369	1.060	0.28	NS
NiO	0.208	1.113	0.30	NS
Ga_2O_5	0.100b	0.804a	0.18	*
Y_2O_5	0.259	0.203	0.76	NS

LOS (P): NS > 0.05, * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001,
Note: Means followed by the same letters in the rows are not significantly different at 5% LOS.

This affirmed previous reports that as weathering advances, relative retention of sesquioxides and their minerals dominate soils (Blume and Schwertmann, 1969; Alexander, 1974; Lekwa and Whiteside, 1986; Muhs *et al.*, 2001; Yakubu and Ojanuga, 2009). The sequences showed that dominantly retained elemental oxides were reflection or key constituent of dominant minerals.

Despite, there was no significant variation in content of most major element oxides in the soils, the significant variation of relative retention of all major total elements indicated that weathering intensity (pedogenic age) significantly varied among the different soils.

5.8.2 Trace Elemental Oxides

Trace elements (total oxide form) were generally less than 1%, except for MoO that reached 5.40% and 6.80% in soils on OG and MS respectively, but MoO was not detected in both parent rocks and soils of QZ and MG. Similarly, Rb_2O was not detected in both soils and parent rock of older granite (Table 28). Differences in basement complex parent material did not significantly vary mean content of most trace element oxides of the soils, except for Cr_2O_5 (Table 30). The mean values of Cr_2O_5 in soils on MS and MG were not significantly different, but MS soil was significantly higher than soils on QZ and OG. Soils on QZ, MG and OG were at par. Aubert and Pinta (1977) attributed variation in content of Cr_2O_5 in soils to parent materials. Trace elements (Rb_2O, BaO, ZnO, Y_2O_5 and SrO) were irregularly distributed within soil profiles. Zirconium oxide was fairly constant within soil profiles and relatively accumulated in all the soils. This might be attributed to its resistance to weathering, more stable, less mobile and present in weathering resistant zircon mineral as also reported by other workers (Barshad, 1965; Marshall, 1977;

Smeck and Wilding, 1980; Bussaca and Singer, 1989; Muhs *et al.*, 2001; Aide and Smith-Aide, 2003; Thanachit *et al.,* 2006). Vanadium oxide, Cr_2O_5, Ga_2O_5, PbO, CuO and NiO irregularly increased with increase in soil depth and might be an indication of their insitu sourced from the parent materials.

Relative weathering intensity indicated parent materials significantly influenced relative retention of most trace element oxides, except for SrO, ZnO, PbO and Y_2O_5 (Table 32). Soils on MG had the least relative retention of more trace elements than other soils, and soils on MS relatively retained more trace elements than the other soils followed closely by OG soils. This trend indicated soils on MG had greatest exposure to pedogenic processes followed by QZ, then OG, with the least in MS soils. Difference in horizons significantly influenced relative retention of trace elements in subsoils than surface horizons (Table 33) and may be attributed to illuviation of weathered elements into subsoils.

The mean values of relative retention of total trace elements of the soils indicated that ZrO_2, CuO, ZnO and MoO were relatively accumulated in all soils, whereas SrO relatively depleted in all the soils. Rubidium oxide, PbO, NiO, Ga_2O_5 and Y_2O_5 were either relatively depleted or accumulated in the soils. Barium oxide, V_2O_5, and Cr_2O_5 relatively accumulated in MS, OG and QZ soils, but depleted in MG soils (Table 32). The whole trend of relative weathering intensity indicated by the mean relative retention of trace element oxides in soils formed on the various parent materials were ranked in the following sequence:

Soils on Older granite	$MoO_3 > CuO > Cr_2O_5 > ZnO > BaO > ZrO_2 > Ga_2O_5 > NiO > V_2O_5 > PbO > Y_2O_5 > SrO > Rb_2O$
Soils on Quartzite	$ZrO_2 > BaO > V_2O_5 > Rb_2O > CuO > Cr_2O_5 > ZnO > MoO_3 > Ga_2O_5 > PbO > SrO > Y_2O_5 > NiO$
Soils on Mica schist	$MoO_3 > BaO > Rb_2O > CuO > ZnO > V_2O_5 > Y_2O_5 > ZrO_2 > PbO > Cr_2O_5 > SrO > NiO > Ga_2O_5$
Soils on Migmatite gneiss	$ZnO > CuO > ZrO_2 > Y_2O_5 > NiO > MoO_3 > PbO > V_2O_5 > Cr_2O_5 > BaO > Ga_2O_5 > SrO > Rb_2O$

Mica schist soil had few trace elements that were depleted (Sr, Ni, Ga), followed by OG (Pb, Y, Sr, Rb) and trace elements that depleted increased in soils on QZ (Ga, Pb, Sr, Y, Ni) and the highest was observed in soils on MG (Pb, V, Cr, Ba, Ga, Sr, Rb). This indicates that with advancement in weathering, there would be relative depletion of more trace elements compared to relative accumulation. The general trend showed that inherent characteristics of the parent materials and pedogenic age strongly influenced weathering of the trace elements and was similarly observed by Thanachit *et al* (2006) on soils developed on a catena on basalt in northeast Thailand.

5.9 SOIL CLASSIFICATION

5.9.1 Diagnostic Surface Horizons (Epipedons)

(1) The Ap epipedons had low colour values (3 – 5) and low chroma (2 – 4) but were too thin to be recognised as a mollic or umbric epipedon.

(2) The epipedons were Ap horizons that were too thin, too light, poor in bivalent cations, low in phosphorus, to be either anthtropic, follistic, histic, melanic or plaggen epipedons.

(3) All the Ap horizons overly illuvial horizons (argilic and kandic horizons).

Therefore, all the soils possess an ochric epipedon.

5.9.2 Diagnostic Subsurface Horizons

All the pedons developed on the different parent materials had significant accumulation of illuviated layer of lattice silicate clays formed below eluvial horizons. There were also thin clay cutans in pores in some of the pedons. The subsurface horizons were argillic B horizon excluding pedons OG1, QZ3 and MG1, because they had:-

1. Three (3) percent more clay (absolute) in the argillic horizons than the eluvial horizon in profiles which contained less than 15 percent total clay in their fine earth fraction and 20% or more clay (relative) in profiles with between 15 and 40% clay in their eluvial horizons.
2. A total thickness of argillic horizon was more than 15cm in all the pedons where they occurred and
3. Some thin clay films in pores and on ped surfaces in the Bt horizons.

Subsurface horizons of pedons OG1, QZ3 and MG1 were regarded to have kandic horizon because they had:

1. Twenty percent (20%) or more clay (relative) in profiles with between 20 and 40% clay in their eluvial horizons.
2. A total thickness that was more than 30cm in all the pedons where they occurred.
3. An apparent CEC of 16 cmol (+) or less per kg clay (1N NH_4OAc pH7) in 50% or more of its thickness between the point where the clay increase requirement were met and either a depth of 100cm below that point.
4. A regular decrease in organic-carbon content with increase in depth without any fine stratification.

5.9.3 Soil Moisture Regime

Annual rainfall in the study areas ranged between 1079 and 1286mm. It was concentrated within the months of May to October (6 months) (Tables 1, 2 and 3). The soils were moist in the moisture control section for more than 180 cumulative days when conditions are suitable for plant growth (Soil Survey Staff, 1975, 1999, 2010). The soils were dry for more than 90 cumulative days. Therefore, all the pedons were inferred to have ustic soil moisture regime.

5.9.4 Soil Temperature Regime

The mean annual air temperature ranged between 25.0 and 26.4^{o}C in the different study areas. The mean hottest and coldest temperature differ between the range of 4.7 and 4.8^{o}C for the different study areas. The mean soil temperature at the control section i.e., 50cm depth was >22^{o}C with difference of <5^{o}C, (Table 1, 2 and 3) (Soil

Survey Staff, 1999). Therefore, the Soil temperature that prevails is probably the isohyperthermic type (Soil Survey Staff, 1999, 2010).

5.9.5 Classification

5.9.5.1 U.S.D.A Soil Taxonomy System:

At the order level, all the soils were classified as Alfisols because they had argillic horizons and did not have plaggen epipedon. They were all Ustalfs at the suborder level because of the ustic moisture regime.

At the great group level, all the pedons on migmatite gneiss were further classified as Plinthustalf because they had horizons within 150cm of the mineral soil surface in which plinthite either forms a continuous phase or constitutes one-half or more of the volume. Pedon QZ3 was classified as Kandiustalf because it had a Kandic horizons without densic, paralithic or petroferric contact and no decrease in clay content of 20% or more (relative) from the maximum content with increase in depth within 150cm of the mineral soil surface. Pedon OG1 was classified as Kanhaplustalf because it had a Kandic horizon. Whereas, Pedon OG3 was classified as Paleustalf because it had no densic, lithic or paralithic contact and no decrease in clay content of 20% or more (relative) from the maximum content with increase in depth within 150cm of the mineral soil surface. The lower part of the argillic horizons have hue of 7.5YR or redder with many coarse redox concentration with hue of 7.5YR or redder. Pedons OG1, QZ1, QZ2, MS1, MS2, and MS3 were classified as Haplustalfs because they had no plinthite that constitutes one half or more of the horizons within 150cm of the mineral soil surface, and do not meet the conditions required for classification of the other 7 great groups of Ustalfs.

At the subgroup level, all the pedons developed on migmatite gneiss were classified as Typic Plinthustalf because they fit the core definition for Plinthustalf. Pedon OG1 was classified as Typic Kanhaplustalf because it did not have other special features of Kanhaplustalf. Similarly, Pedon QZ3 did not have other special features of Kandiustalf and was therefore classified as Typic Kandiustalf. Pedon OG3 was classified as Kandic Paleustalf because it had CEC of less than 24 cmol (+) kg^{-1} clay in more than 50% of its upper 100cm. Similarly, Pedons QZ2 and MS3 had CEC of less than 24 cmol (+) kg^{-1} clay in more than 50% of its upper 100cm, hence were classified as Kanhaplic Haplustalfs. Pedon QZ1 was classified as Lithic Haplustalf because it had lithic contact within 50cm of the mineral soil surface. Pedons OG2, MS1 and MS2 were classified as Typic Haplustalf because they had no other special features of Haplustalfs hence fit the core definition for Haplustalf.

At the family level, pedons MG2 and MG3 on the migmatite gneisses were classified as Typic Plinthustalfs, fine, mixed, subactive, isohyperthermic, because the pedons contain 35 - < 60% clay within the fine earth fraction, no specific mineral group dominating and had cation-exchange activity (CEA) of less than 0.24 in the control section. It had a fine particle size class, mixed mineral class and subactive cation-exchange activity class. Similarly, pedon QZ2 was classified as Kanhaplic Haplustalf, fine, mixed, subactive, isohyperthermic. Pedons OG1 and QZ3 were classified as Typic Kanhaplustalf, fine, mixed, isohyperthermic and Typic Kandiustalf, fine, mixed, isohyperthermic respectively. Cation exchange activity (CEA) was excluded as it is irrelevant. Pedon MG1 was classified as Typic Plinthustalf, fine-silty, mixed, subactive, isohyperthermic because it had less than 15% gravel and 18 – 35% clay. Pedons OG2 and MS1 were classified as Typic Haplustalf, fine-silty, mixed,

semiactive, isohyperthermic because they had CEA value between 0.24 and 0.4 in the control sections. Pedons MS2 and MS3 were classified as MS2 Typic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic and Kanhaplic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic respectively, because they had greater than 15% gravel and 18 – 35% clay. Pedon QZ1 was classified as Lithic Haplustalf, loamy skeletal, mixed, semiactive, isohyperthermic because it had greater than 35% rock fragment and less than 35% clay within the fine earth fraction in the control section. The pedons have loamy skeletal particle size class. Pedon OG3 was classified as Kandic Paleustalf, fine, mixed, semiactive, isohyperthermic. The summary of the USDA *Soil Taxanomy* classification is presented in Table 34.

5.9.5.2 World Reference Base for Soil Resources 2006 Classification System

Using the FAO/UNESCO Soil map of the world Legend (1990) and World reference base for soil resources 2006 (FAO, 2006), pedons MS1 and MS2 were placed in the Group Luvisols. These are soils having argic B horizon with a CEC (NH_4OAc) of 24 cmol(+)kg^{-1} clay or more and a base saturation (NH_4OAc) of 50% and more in the B horizons. At the unit level, both pedons were placed as Haplic Luvisols because they have simple normal horizon sequences in their profiles and none of the preceeding qualifiers fits into the classification. Pedon MS2 was further classified into the phase level as Arenic. This was due to texture of loamy fine sand or coarser in a larger, 30cm thick within 100cm of soil surface.

Table 34: Summary of soil classification USDA and WRB Names of Pedons studied

Pedon	USDA	WRB 2006
Older Granites		
OG1	Typic Kanhaplustalf, fine, mixed, isohyperthermic	Haplic Lixisols, epiclayic.
OG2	Typic Haplustalf, fine-silty, mixed, semiactive, isohyperthermic	Haplic Lixisols, epidystric.
OG3	Kandic Paleustalf, fine, mixed, semiactive, isohyperthermic	Haplic Lixisols.
Quartzites		
QZ1	Lithic Haplustalf, loamy skeletal, mixed, semiactive, isohyperthermic	Haplic Lixisols, skeletic.
QZ2	Kanhaplic Haplustalf, fine, mixed, subactive, isohyperthermic	Haplic Lixisols, endoclayic.
QZ3	Typic Kandiustalf, fine, mixed, isohyperthermic	Haplic Lixisols, endoclayic.
Mica schists		
MS1	Typic Haplustalf, fine-silty, mixed, semiactive, isohyperthermic	Haplic Luvisols.
MS2	Typic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic	Haplic Luvisols, arenic.
MS3	Kanhaplic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic	Haplic Lixisols.
Migmatite gneisses		
MG1	Typic Plinthustalf, fine-silty, mixed, subactive, isohyperthermic	Plinthic Lixisols, chromic.
MG2	Typic Plinthustalf, fine, mixed, subactive, isohyperthermic	Plinthic Lixisols, chromic.
MG3	Typic Plinthustalf, fine, mixed, subactive, isohyperthermic	Plinthic Lixisols, endoclayic.

All the other pedons were placed at the Group level as Lixisols because they have an argic B horizon with a CEC (NH_4OAc) of less than 24 cmol (+) kg^{-1} clay and a base saturation (NH_4OAc) of 50% and more in the B horizons. At the unit level, pedons on older granites, quartzites and pedon MS3 were assigned prefix qualifier Haplic because they have simple normal horizon sequences in their profiles and none of the preceeding qualifiers fits into the classification. Pedon OG1was further classified as Haplic Lixisol, epiclayic phase, because it had clay texture 30cm or more thick within 50cm of soil surface. Pedons QZ2 and QZ3 were classified as Haplic Lixisol, endoclayic phase, because they have a layer of clay texture 30cm or more thick within 50cm and 100cm of soil surface. Pedon OG2 is classified as Haplic Lixisol, epidystric phase, because it had less than 50% base saturation between 20cm and 50cm of soil surface. Pedon QZ1 was classified as Haplic Lixisol, skeletic phase, because it had average gravel of 40% or more over a depth of 100cm from the soil surface.

Pedons on migmatite gneisses were assigned prefix qualifier Plinthic because they had plinthic horizon starting within 100cm of the soil surface. Pedons MG1 and MG2 were further classified as Plinthic Lixisol, chromic phase, because they had a munsell hue redder than 7.5YR subsurface layer 30cm thick within 150cm of soil surface. Pedon MG3 was further classified as Plinthic Lixisol, endoclayic phase, because it had a layer of clay texture 30cm or more thick within 50cm and 100cm of soil surface. The summary of the World reference base 2006 classification is presented in Table 34.

5.10 SOIL MANAGEMENT OPTION

Soils of this study were classified as Lixisols and Luvisols (FAO, 2006). The soils were considered to be fertile and suitable for a wide range of agricultural uses, but susceptible to structural deterioration under heavy machinery tillage, erosion and readily leachable due to their low activity clay characterization in the tropical sub humid climate (Kang *et al.*, 1991; FAO, 2006). The major constraints of these soils to sustainable crop production were identified as: soil depth restrictions caused by plinthite layer (48 – 172cm depth) in pedons on quartzite and partially decomposed parent material between 14cm and 72cm depths (QZ1, MS2 and MS3), erosion, leaching, weak structural development in the surface horizons, slightly high bulk densities (1.60 – 1.79 Mgm^{-3}), slightly low total porosity, low water retention, dominance of low activity clay (LAC) (< 24 cmol (+) kg^{-1} clay) affecting CEC and low soil organic carbon (< 10 gkg^{-1}) and total nitrogen (< 1.00 gkg^{-1}). Constraints of soils identified can be managed through the following suggested options.

Some of the pedons on QZ and MS have soil depth restriction due to parent materials (between 14cm and 72cm depths) and those on MG were all restricted by plinthite (48 – 172cm depth). Construction of contour ridges and bunds would improve the soils for quality seedbed and increase rooting depth (Kang *et al.*, 1991; Odunze, 2006; Senjobi and Ogunkunle, 2011). The practice of contour ridges along with cultivation of cover crops would conserve the soils against surface runoff erosion that might expose the plinthite horizons to harden irreversibly and render the soil unsuitable for arable crop production (FAO, 2006; Fasina *et al*., 2007a; Senjobi and Ogunkunle, 2011).

The surface horizons were coarse textured with gravelly sandy loam and sandy loam, thus susceptible to soil erosion. In order to use these soils for optimal crop production, ridging and incorporation of crop residues with farm yard manure should be carried out at land preparation. These would control soil erosion, crusting and improve physicochemical conditions of crop root zones (Tarawali *et al.*, 2001; Odunze, 2006).

Most of the soils were observed to have weak structural development in the surface horizons. Mechanized land preparation will increase structural destruction, hence application of organic matter and use of simple but efficient tools operated manually or powered by animal driven for land clearing, tillage, seeding, fertilizer application and harvesting will reduce effect of mechanize structural destruction (Odunze, 2006; Ogunkunle, 2009).

The bulk densities and total pore space values of these soils were rated to be moderate. Available water capacity was considered to be low. The use of heavy equipment in these soils could lead to increased bulk density and reduced pore spaces with associated consequences. Incorporation of organic matter into these soils to improve soil aeration and moisture availability for sustainable crop production ia therefore recommended (Brady and Weil, 2005; FAO, 2006; Odunze, 2006; Ogunkunle, 2009).

The soil reaction was considered to range from strongly acid to neutral (pH), electrical conductivities and ESP showed that the soils are non-saline and non-sodic in their present state. Liming or salinity management of the soils is however not recommended, but there is the need to monitor pH level and avoid use of acidifying fertilizers.

Soils on OG, MG and subsoil horizons of QZ were dominated by low activity clay (LAC). This implies that nutrient minerals in these soils were more likely to be lost through leaching (Sanchez, 1976). There is therefore a need to raise the CEC through the use of organic matter and additions of bases through application of appropriate chemical fertilizers (Kang *et al.*, 1991; Fasina *et al*., 2007a) program. With the leaching condition due to LAC, application of nitrogen using non-acidifying fertilizers should be done on split doses (Enwezor *et al.*, 1989; Yassoglou *et al.*, 2010).

The soil organic carbon and total nitrogen content were low. Available phosphorus content was low in some subsoil horizons of older granite soils. The low organic matter has to be substantially increased through effective post harvest crop residue incorporation instead of their usual burning, application of farm yard manure and incorporating legumes in crop rotation fields, as well as use of organo-mineral fertilizers (Jones, 1971; Brady and Weil, 2005; Havlin *et al.,* 2005; Odunze, 2006; Fasina *et al*., 2007a; Ogunkunle, 2009). Fertilizers containing nitrogen and phosphorus elements will be required to be applied timely in judicious quantity and by burying to remedy the deficiency.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

The study was carried out on soils developed on older granites, quartzites, mica schists and migmatite gneisses parent materials on crest positions of Northern Guinea Savanna of Kaduna State, Nigeria. The study was carried out to evaluate the effect of different parent materials on soil genesis, characteristics and their classification for sustainable use and management of the soil resources. To achieve these objectives, the morphological, physical, chemical and mineralogical properties were determined. The soils were classified using USDA Soil Taxonomy classification system of (Soil Survey Staff, 2010) and correlate with the World Reference Base for Soil Resource (WRB) (FAO, 2006).

Morphologically, soils were generally deep to very deep (135 – 190cm), with restriction due to parent materials (QZ1, MS2 and MS3) and plinthite. Variation in colour was due mainly to pedogenic processes occurring in these soils. Dark brown colouration in the surface horizon (Ap) was attributed to humification resulting in melanization and strong brown (7.5YR 4/6, moist) colour dominated the Bt subsurface horizons indicated braunification. Yellowish red to red colours dominated lower portion of subsurface horizon of soils on migmatite gneiss was attributed to plinthization process. The soils

were dominated by sub-angular blocky structure except soils on mica schists which had a platy structure in the subsoils and were associated to the nature of parent material.

The soil surface were characterized by coarse textured materials attributed to erosion of fine particles by surface run off down the slope from the crestal position and their illuviation into the subsoils. Soil texture varied with increased in depth within the subsoil (Bt) of the profiles in the order of clay to sandy clay to sandy clay loam in the deeper horizons, and were attributed to illuviation of clay. High amount of gravels influenced textural classification of soils in various parts of the subsoils and were attributed to weathering of parent materials in the younger soils (MS and QZ1) and plinthite in soils on migmatite gneiss.

The soils significantly varied in their mean gravel content values from each other in the order of QZ > MG > MS > OG, and were related to the extent of weathering of the parent materials and plinthization in migmatite gneiss. Sand dominated particle size fraction of the fine earth (< 2mm) portion in all soils formed from the different parent materials. The mean values of most of sub-fractions of sand were significantly different both between parent materials and the horizons; therefore both parent materials and pedogenesis have significantly influenced sand content of the soils. Moisture retention was slightly low in the soils and were strongly influenced by content of both sand and clay particles.

Chemical properties of the soils indicate strongly acid to neutral pH (5.30 - 6.90), medium to high exchangeable bases (Ca, Mg, Na, K), low to high cation exchange capacity (CEC - NH_4OAc) and moderate base saturation influencing their classification as Alfisols. The parent materials significantly influence content of exchangeable Ca,

TEB, EA, various forms of CECs, base saturation and ESP. The soils were generally low in organic carbon and total nitrogen content and the low content of nutrients in these soils were attributed to continuous cultivation, bush burning, high rate of mineralization, and crop removal for other purposes without incorporation. Micronutrients (available and total forms) were all present in adequate quantity in all the soils. The mean content of available Fe, Mn and total Zn were significantly influenced by parent materials.

Parent materials and pedogenesis significantly influenced mean values of both dithionite, oxalate forms of iron and active iron ratio in the soils. The variation order of active iron ratio (MS > QZ > OG > MG) indicate the direction of pedogenic age (crystallization) of the soils. Forms of manganese oxides were significantly influenced by horizons, thus affirming effect of organic matter on manganese content in soils.

Nature of parent materials and the extent of weathering of the soils influenced wide variation (mixed minerals) in mineralogy of silt fraction of these soils; thus referred to as moderately weathered, hence influenced the properties and classification of the soils as Alfisols. Mineralogy of clay fraction was widely varied with predominantly kaolinite, diaspore, muscovite and illite minerals, and was attributed to difference in parent material and their moderate pedogenic development. The minerals dominating the soils reflected soils on migmatite gneiss as most developed and those on mica schist as least developed.

The contents of major and trace elements (total oxide form) were similar in the soils, except for K_2O, TiO_2 and Cr_2O_5 that were significantly varied by the parent materials. Relative weathering intensity significantly varied the amount of most total elemental oxides that were relatively retained (accumulated or depleted) in the soils, except for SrO,

ZnO, MoO_3, PbO and Y_2O_5. This implies that parent materials significantly influenced relative weathering intensity of these elements in these soils.

The trends of the major total element oxides showed the relative retention of elements and correlated with the dominant minerals constituting the different soils. Thus reflecting pedogenic age of the soils in the order of MG > OG $\simeq$ QZ > MS.

Parent materials and pedogenic age of the soils were factors that prominently affected the soil properties, thereby influenced their pedogenesis. The main pedogenic processes in the soils were weathering of parent materials, accumulation or loss of major and trace elements, erosion, structural differentiation, braunification, humification, melanization, leaching, eluviations-illuviation, allitization, argilluviation, plinthization (crystallization) and partial migration of clay and free oxides.

The soils were all classified as Ustalfs at the suborder level. The presence of plinthite in soils on migmatite gneisses keyed them into the great group Plinthustalfs. Soils on mica schist and some of quartzite and older granite were classified as Haplustalf at the great group level as they had no other special features. Pedons QZ3, OG1 and OG3 were classified as Kandiustalf, Kanhaplustalf and Paleustalf respectively at the great group level because they have kandic horizons and redder colour with many coarse redox concentrations respectively.

Major constraints of the soils to sustainable crop production were identified and relevant management options were suggested. Management options recommended for management of poor physical properties were construction of contour ridges and bunds,

and cultivation of cover crops. Soil chemical and nutrient conditions could be improved through effective post harvest crop residue incorporation instead of the normal practice of burning. Application of farm yard manure and incorporation of legumes in crop rotation fields, as well as use of organo-mineral fertilizers are other possible options. Fertilizers are suggested to be applied timely in judicious quantity and by burying to remedy their deficiencies.

Future research on these soils should pay greater attention to soils on quartzites and mica schists and should cover other slope positions for better extrapolation of results.

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APPENDIX A: SOIL PROFILE DESCRIPTIONS

Profile No	**OG 1**
General Site Information	
Location	Kujama, 17Km to Kaduna along Kachia road (10°28'41.4"N & 07°39'27.3"E)
Elevation	695m
Taxonomic Classification	(USDA) Typic Kanhaplustalf, fine, mixed, isohyperthermic
Soil Parent Materials	Older granite
Geology	Basement Complex
Geomorphology	Gently undulating plain with Rock outcrop
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Maize-Late Millet
Drainage	Well drained
Depth to water table	Not encountered at 183cm depth
Depth to impenetrable layer	Not encountered within 183cm depth
Surface characteristics	Cultivated ridges and Rock outcrops
Described by	Prof. B.A. Raji & L. M. Maniyunda
Date sampled	1st June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-26	Dark grayish brown (10YR 4/2, moist); grayish brown (7.5YR 3/2, dry) sandy loam; moderate medium sub-angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), slightly hard (dry); very few thin clay cutans on ped faces; common fine pores; many fine roots; clear wavy boundary.
Bt1	26-75	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/8, dry) clay; moderate very coarse sub-angular blocky structure; slightly sticky and plastic (wet), friable (moist), hard (dry); few thin clay cutans on pores; many medium pores; few medium roots; clear wavy boundary.
Bt2	75-119	Strong brown (7.5YR 5/8, moist); strong brown (7.5YR 5/8, dry) gravelly sandy clay loam; moderate medium angular blocky structure; sticky and slightly plastic (wet), friable (moist), very hard (dry); very few thin clay cutans on pores; common very fine pores; few very fine roots; diffuse smooth boundary.
BC	119-183	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 4/6, dry) sandy clay loam; weak medium angular blocky structure; slightly sticky and non-plastic (wet), friable (moist), hard (dry); few fine pores; few very fine roots; common weathered older granitic rocks.

Profile No	**OG 2**
General Site Information	
Location	Kujama, 17Km to Kaduna along Kachia road ($10^{o}28'37.5"$N & $07^{o}39'17.9"$E)
Elevation	698.4m
Taxonomic Classification	(USDA) Typic Haplustalf, fine-silty, mixed, semiactive, isohyperthermic
Soil Parent Materials	Older granite
Geology	Basement Complex
Geomorphology	Gently undulating plain with Rock outcrop
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Maize + sorghum
Drainage	Well drained
Depth to water table	Not encountered at 190cm depth
Depth to impenetrable layer	Not encountered within 190cm depth
Surface characteristics	Cultivated harrows
Described by	Prof. B.A. Raji & L. M. Maniyunda
Date sampled	1st June, 2010

Horizon Description

Horizon	**Depth (cm)**	**Description**
Ap	0-17	Brown (7.5YR 4/3, moist); brown (7.5YR 3/2, dry) sandy loam; moderate medium sub-angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), hard (dry); common fine pores; many very fine roots; clear wavy boundary.
Bt1	17-70	Dark yellowish brown (10YR 3/6, moist); dark brown (10YR 4/6, dry) clay; strong coarse sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); common fine pores; few very fine roots; gradual wavy boundary.
Bt2	70-190	Yellowish brown (10YR 5/6, moist); brownish yellow (7.5YR 6/8, dry) sandy clay loam; moderate medium sub-angular blocky structure; slightly sticky and plastic (wet), friable (moist), hard (dry); few fine pores; many iron concretions.

Profile No	**OG 3**
General Site Information	
Location	Kujama, 16Km to Kaduna along Kachia road ($10^{o}27'55.7"N$ & $07^{o}38'30.2"E$)
Elevation	667.2m
Taxonomic Classification	(USDA) Kandic Paleustalf, fine, mixed, semiactive, isohyperthermic
Soil Parent Materials	Older granites
Geology	Basement Complex
Geomorphology	Gently undulating plain with large Rock outcrop
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Onion – Upland rice
Drainage	Well drained
Depth to water table	Not encountered at 185cm depth
Depth to impenetrable layer	Not encountered within 185cm depth
Surface characteristics	Cultivated ridges and Inselbergs
Described by	Prof. B.A. Raji & L. M. Maniyunda
Date sampled	1st June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-23	Dark brown (7.5YR 3/2, moist); brown (7.5YR 5/4, dry) sandy loam; weak medium sub-angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), slightly hard (dry); common medium pores; many fine roots; gradual smooth boundary.
BA	23-57	Dark brown (7.5YR 4/4, moist); brown (7.5YR 5/4, dry) clay loam; yellowish red (5YR 4/6) few fine faint mottles; weak very coarse sub-angular blocky structure; slightly sticky and plastic (wet), friable (moist), slightly hard (dry); very few thin clay cutans on pores; common medium pores; common medium roots; gradual wavy boundary.
Bt1	57-121	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/8, dry) clay loam; moderate very coarse angular blocky structure; sticky and plastic (wet), friable (moist), slightly hard (dry); common fine pores; few medium roots; diffuse irregular boundary.
Bt2	121-185	Yellowish brown (10YR 5/6, moist); yellowish brown (10YR 5/6, dry) clay; yellowish red (5YR 4/6) common fine faint mottles; moderate medium sub-angular blocky structure; sticky

and plastic (wet), friable (moist), hard (dry); few fine pores; few fine roots.

Profile No	**QZ 1**
General Site Information	
Location	Mai Dangi village in Birnin Gwari LGA ($10^{o}34'54.3"N$ & $06^{o}11'25.7"E$)
Elevation	420.9m
Taxonomic Classification	(USDA) Lithic Haplustalf, loamy skeletal, mixed, semiactive, isohyperthermic
Soil Parent Materials	Quartzites
Geology	Basement Complex
Geomorphology	Gently undulating plain with quartzite ridge
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Maize + Sorghum
Drainage	Well drained
Depth to water table	Not encountered at 135cm depth
Depth to impenetrable layer	Weathered quartzite rocks encountered from 14cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	3rd June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-14	Very dark grayish brown (10YR 3/2, moist); dark grayish brown (10YR 4/2, dry); gravelly sandy loam; weak medium sub-angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), hard (dry); few fine pores; few fine roots; gradual wavy boundary.
AC	14-40	Brown (7.5YR 4/4, moist); brown (7.5YR 5/4, dry) very gravelly sandy loam; weak fine crumb structure; slightly sticky and slightly plastic (wet), firm (moist), hard (dry); common fine roots; common weathered quartzites; gradual irregular boundary.
C1	40-98	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/6, dry) extremely gravelly clay; moderate medium crumb structure; sticky and plastic (wet), firm (moist), hard (dry); few fine pores; few fine roots; common weathered quartzites; abrupt smooth boundary.

C2	98-135	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/6, dry) sandy clay loam; weak medium crumb structure; sticky and plastic (wet), firm (moist), hard (dry); few common pores; encountered weathered quartzite rocks.

Profile No **QZ 2**

General Site Information

Location	Mai Dangi village in Birnin Gwari LGA ($10^{o}34'52.6"$N & $06^{o}11'14.0"$E)
Elevation	416.8m
Taxonomic Classification	(USDA) Kanhaplic Haplustalf, fine, mixed, subactive, isohyperthermic
Soil Parent Materials	Quartzites
Geology	Basement Complex
Geomorphology	Gently undulating plain with quartzite ridge
Topography	Crest (2- 4%)
Vegetation	Savanna Park land
Land use	Ground nut + Sorghum
Drainage	Well drained
Depth to water table	Not encountered at 187cm depth
Depth to impenetrable layer	Not encountered at 187cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	3rd June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-19	Brown (7.5YR 4/4, moist); brown (7.5YR 5/4, dry); sandy loam; weak medium sub-angular blocky structure; non-sticky and non-plastic (wet), very friable (moist), soft (dry); common fine pores; many fine roots; gradual smooth boundary.
Bt1	19-51	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/8, dry) sandy clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); common medium pores; common fine roots; gradual wavy boundary.
Bt2	51-84	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/8, dry) clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); very few thin patch

		cutans on animal channels; few fine pores; few fine roots; ant channels and nests; diffuse irregular boundary.
Bt3	84-139	Yellowish red (5YR 4/6, moist); reddish yellow (5YR 6/6, dry) sandy clay; red (2.5YR 4/8) common fine faint mottles; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); few medium pores; diffuse wavy boundary.
Btc	139-187	Yellowish red (5YR 4/6, moist); reddish yellow (5YR 6/6, dry) sandy clay loam; red (2.5YR 4/8) common medium faint mottles; weak medium angular blocky structure; sticky and plastic (wet), firm (moist), very hard (dry); few medium pores; common iron – manganese concretion.

Profile No **QZ 3**

General Site Information

Location	Ungwan Bula village in Birnin Gwari LGA (10^o 35' 31.2" N & 06^o 11' 22.6" E)
Elevation	424.8m
Taxonomic Classification	(USDA) Typic Kandiustalf, fine, mixed, isohyperthermic
Soil Parent Materials	Quartzites
Geology	Basement Complex
Geomorphology	Gently undulating plain with quartzite ridge
Topography	Crest (2-4%)
Vegetation	Savanna Park land
Land use	Ground nut
Drainage	Moderately well drained
Depth to water table	Not encountered at 167cm depth
Depth to impenetrable layer	Not encountered at 167cm depth
Surface characteristics	Cultivated harrows
Described by	Maniyunda, L.M.
Date sampled	3rd June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-19	Brown (7.5YR 4/4, moist); brown (7.5YR 5/4, dry); sandy loam; weak coarse angular blocky structure; non-sticky and non-plastic (wet), friable (moist), slightly hard (dry); few very fine pores; common very fine roots; gradual smooth boundary.
AB	19-40	Dark yellowish brown (10YR 4/4, moist); yellowish brown (10YR 5/4, dry) sandy clay loam; moderate very coarse sub-angular blocky structure; slightly sticky and plastic (wet), friable (moist), hard (dry); common medium pores; common medium roots; gradual wavy boundary.

Bt1	40-63	Strong brown (7.5YR 4/6, moist); reddish yellow (7.5YR 6/6, dry) clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), slightly hard (dry); very few thin patch clay cutans on pores; common very fine pores; few very fine roots; clear smooth boundary.
Bt2	63-97	Strong brown (7.5YR 4/6, moist); reddish yellow (7.5YR 6/6, dry) clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), very hard (dry); few fine pores; few very fine roots; gradual wavy boundary.
BC	97-167	Yellowish brown (10YR 5/6, moist); yellowish brown (10YR 5/8, dry) sandy clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), hard (dry); few medium pores; few weathered quartzites; encountered weathered quartzite rocks at 167cm.

Profile No **MS 1**

General Site Information

Location	Tashan Tsuntsaye village in Birnin Gwari LGA, along Kaduna – Birnin Gwari road. (10^o 43' 31.2" N & 06^o 46' 29.9" E)
Elevation	(543.3m)
Taxonomic Classification	(USDA) Typic Haplustalf, fine-silty, mixed, semiactive, isohyperthermic
Soil Parent Materials	Mica-schists
Geology	Basement Complex
Geomorphology	Moderate undulating plain with Mound (Hill)
Topography	Crest (2-4%)
Vegetation	Savanna Park land
Land use	Maize
Drainage	Well drained
Depth to water table	Not encountered at 177cm depth
Depth to impenetrable layer	Not encountered at 177cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	4th June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-18	Very dark grayish Brown (10YR 3/2, moist); brown (10YR 4/3, dry); sandy loam; strong medium angular blocky structure; sticky and plastic (wet), firm (moist), slightly

		hard (dry); few thin continuous clay cutans on pores; many fine pores; common medium roots; gradual smooth boundary.
Bt1	18-54	Dark yellowish brown (10YR 4/6, moist); yellowish brown (10YR 5/6, dry) sandy clay loam; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), slightly hard (dry); few moderate clay cutans on root and animal channels; many fine pores; common medium roots; gradual wavy boundary.
Bt2	54-177	Dark yellowish brown (10YR 4/6, moist); yellowish brown (10YR 5/6, dry) sandy clay loam; weak medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), slightly hard (dry); very few thin patch clay cutans on pores; many fine pores; many fine roots.

Profile No	**MS 2**
General Site Information	
Location	After Koriga village in Birnin Gwari LGA, along Kaduna – Birnin Gwari road. (10^{o} 43' 04.5" N & 06^{o} 46' 43.6" E)
Elevation	(544.2m)
Taxonomic Classification	(USDA) Typic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic
Soil Parent Materials	Mica-schists
Geology	Basement Complex
Geomorphology	Moderate undulating plain
Topography	Crest (2-4%)
Vegetation	Savanna Park land
Land use	Ground nut + Maize
Drainage	Moderately well drained
Depth to water table	Not encountered at 143cm depth
Depth to impenetrable layer	Encountered weathered rock and thick mica flakes at 72cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	4^{th} June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-16	Brown (10YR 4/3, moist); brown (10YR 5/3, dry); sandy loam; weak medium sub-angular blocky structure; slightly sticky and non-plastic (wet), friable (moist), slightly hard (dry); common medium pores; many very fine roots; gradual wavy boundary.
Btc	16-37	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/6, dry) gravelly sandy clay loam; yellowish red (5YR 5/8) few fine faint mottles; weak medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), very hard (dry); few fine pores; few fine roots; few Fe- Mn concretions; gradual wavy boundary.
BC	37-72	Grayish brown (10YR 5/2, moist); grayish brown (10YR 5/2, dry) gravelly sandy clay loam; yellowish red (7.5YR 5/8) common medium distinct mottles; weak medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), hard (dry); very few thin cutans on root channels; few fine pores; few medium roots;few Fe-Mn concretions; gradual irregular boundary.
C	72-143	Grayish brown (10YR 5/2, moist); grayish brown (10YR 5/2, dry) gravelly sandy clay loam; reddish yellow (7.5YR 6/8) common fine distinct mottles; weak coarse platy structure; sticky and plastic (wet), firm (moist), very hard (dry); few fine pores; few fine roots; encountered fractured rock.

Profile No **MS 3**

General Site Information

Location	Gayam (Kogin Gyeda) village in Birnin Gwari LGA, along Kaduna–Birnin Gwari road. (10^{o} 43' 43.2" N & 06^{o}44'59.1"E)
Elevation	(424.8m)
Taxonomic Classification	(USDA) Kanhaplic Haplustalf, fine-loamy, mixed, semiactive, isohyperthermic
Soil Parent Materials	Mica-schists
Geology	Basement Complex
Geomorphology	Moderate undulating plain
Topography	Crest (0-2%)
Vegetation	Savanna Park land
Land use	Soya beans + Maize
Drainage	Well drained
Depth to water table	Not encountered at 168cm depth
Depth to impenetrable layer	Encountered weathered thick mica flakes at 42cm depth
Surface characteristics	Cultivated ridges

Described by	Maniyunda, L.M.
Date sampled	4th June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-19	Brown (10YR 4/3, moist); brown (10YR 5/3, dry); sandy loam; moderate medium sub-angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), slightly hard (dry); very few moderate clay cutans on termite channels and ped faces; common fine pores; few fine roots; few termite channels and nests; gradual wavy boundary.
Bt	19-42	Strong brown (7.5YR 4/6, moist); strong brown (7.5YR 5/6, dry) gravelly sandy clay loam; weak medium platy structure; sticky and plastic (wet), friable (moist), hard (dry); common fine pores; few medium roots; gradual irregular boundary.
C1	42-96	Brown (7.5YR 5/2, moist); light brown (7.5YR 6/3, dry) sandy clay loam; strong medium platy structure; slightly sticky and non-plastic (wet), firm (moist), slightly hard (dry); few fine pores; few very fine roots; gradual wavy boundary.
C2	96-168	Grayish brown (10YR 5/2, moist); light brownish gray (10YR 6/2, dry) sandy clay loam; moderate medium platy structure; slightly sticky and slightly plastic (wet), friable (moist), slightly hard (dry); few fine pores; few medium roots.

Profile No **MG 1**

General Site Information

Location	East of Nigeria Army Signal Office, Afaka, along Kaduna- Lagos route. ($10^{o}35'04.2"N$ & $07^{o}22'23.8"E$)
Elevation	625.2m
Taxonomic Classification	(USDA) Typic Plinthustalf, fine-silty, mixed, subactive, isohyperthermic
Soil Parent Materials	Migmatite gneiss
Geology	Basement Complex
Geomorphology	Gently undulating plain
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land

Land use	Sorghum + Late Millet
Drainage	Moderately well drained
Depth to water table	Not encountered at 147cm depth
Depth to impenetrable layer	Iron- manganese concretion encountered at 47cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	5th June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-15	Dark brown (7.5YR 3/4, moist); brown (7.5YR 4/3, dry) sandy loam; weak medium angular blocky structure; slightly sticky and slightly plastic (wet), friable (moist), hard (dry); very few (patches) thin clay cutans on pores; many fine pores; common very fine roots; few ant channels; gradual smooth boundary.
Bt	15-47	Yellowish red (5YR 5/8, moist); reddish yellow (5YR 5/8,dry) sandy clay loam; light red (2.5YR 6/8) few fine faint mottles; strong medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); very few thin clay cutans on pores; few fine pores; common very fine roots; gradual smooth boundary.
Btcv1	47-103	Red (2.5YR 4/8, moist); red (2.5YR 5/8,dry) sandy clay loam; light red (2.5YR 6/8) few fine faint mottles; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); few fine pores; common iron –manganese concretions; abrupt smooth boundary.
Btcv2	103-147	Red (2.5YR 4/8, moist); red (2.5YR 5/8,dry) gravelly sandy clay loam; weak fine sub-angular blocky structure; slightly sticky and non-plastic (wet), firm (moist), hard (dry); few fine pores; many iron –manganese concretions; encountered petroplinthite.

Profile No	**MG 2**
General Site Information	
Location	East of Federal College of Forrestry Mechanization Afaka, Kaduna. ($10^{o}35'13.1"N$ & $07^{o}22'16.8"E$)
Elevation	627m
Taxonomic Classification	(USDA) Typic Plinthustalf, fine, mixed, subactive, isohyperthermic
Soil Parent Materials	Migmatite gneiss

Geology	Basement Complex
Geomorphology	Gently undulating plain
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Maize + Sorghum
Drainage	Well drained
Depth to water table	Not encountered at 167cm depth
Depth to impenetrable layer	Concretion encountered at 123cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	6th June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-18	Brown (7.5YR 4/4, moist); brown (7.5YR 5/4, dry) sandy loam; moderate medium angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), hard (dry); common fine pores; many very fine roots; clear smooth boundary.
AB	18-44	Brown (7.5YR 5/4, moist); reddish yellow (7.5YR 6/6, dry) clay loam; weak coarse angular blocky structure; sticky and plastic (wet), firm (moist), hard (dry); few moderate humus cutans on ped faces; common fine pores; few very fine roots; gradual smooth boundary.
Bt1	44-78	Light reddish brown (5YR 6/4, moist); reddish yellow (5YR 6/8, dry) clay; moderate coarse sub-angular blocky structure; sticky and plastic (wet), friable (moist), slightly hard (dry); common medium pores; few very fine roots; few termite channels; diffuse wavy boundary.
Bt2	78-123	Yellowish reddish (5YR 5/8, moist); reddish yellow (5YR 6/6, dry) clay loam; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); common fine pores; few very fine roots; very few termite channels; abrupt wavy boundary.
BCcv	123-167	Red (2.5YR 4/8, moist); light red (2.5YR 6/8, dry) gravelly sandy clay loam; moderate medium crumb structure; slightly sticky and slightly plastic (wet), friable (moist), hard (dry); very few (patch) thin clay cutans; few fine pores; many iron – manganese concretions; encountered petroplinthite.

Profile No **MG 3**

General Site Information

Location	South of Tsamiya village, Afaka, Kaduna (10°37'46.6"N & 07°24'50.3"E)

Elevation	625.2m
Taxonomic Classification	(USDA) Typic Plinthustalf, fine, mixed, subactive, isohyperthermic
Soil Parent Materials	Migmatite gneiss
Geology	Basement Complex
Geomorphology	Gently undulating plain with laterite outcrops
Topography	Crest (0 - 2%)
Vegetation	Savanna Park land
Land use	Sorghum + Maize
Drainage	Moderately well drained
Depth to water table	Not encountered at 162cm depth
Depth to impenetrable layer	Petroplinthite encountered from 89cm depth
Surface characteristics	Cultivated ridges
Described by	Maniyunda, L.M.
Date sampled	7th June, 2010

Horizon Description

Horizon	Depth (cm)	Description
Ap	0-25	Brown (7.5YR 4/3, moist); brown (7.5YR 5/4, dry) sandy clay loam; moderate medium angular blocky structure; slightly sticky and slightly plastic (wet), firm (moist), hard (dry); common fine pores; many very fine roots; clear wavy boundary.
Bt1	25-47	Yellowish red (5YR 4/8, moist); reddish yellow (5YR 6/8, dry); sandy clay loam; moderate medium sub-angular blocky structure; sticky and plastic (wet), firm (moist), hard (dry); few fine pores; few very fine roots; diffuse wavy boundary.
Bt2	47-89	Yellowish red (5YR 4/8, moist); reddish yellow (5YR 6/8, dry); clay; moderate medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); very few thin clay cutans on pores and deccay roots; few fine pores; few very fine roots; few iron nodules; abrupt smooth boundary.
BCcv	89-162	Red (2.5YR 4/8, moist); red (2.5YR 5/8, dry); weak medium sub-angular blocky structure; sticky and plastic (wet), friable (moist), hard (dry); few fine pores; many iron concretions; encountered petroplinthite and weathered parent material.